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PHYSICAL FOUNDATIONS OF BIONIC MICROWAVE COMMUNICATION CHANNEL

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The monograph provides theoretical justification and experimental confirmation of the possibility of receiving useful information by a person through direct reception of pulsed electromagnetic microwave radiation (radio sound phenomenon). Based on bionics without the use of technical means of reception, it is shown that the occurrence of auditory sensations is a consequence of mechanical vibrations excited in the bone and tissue formations of the skull when absorbing the energy of pulses of electromagnetic microwave radiation. The parameters of complexly modulated microwave electromagnetic radiation are determined, providing at the receiving end an equal-loudness radio sound curve, described by the categories and terms of the theory of quadripoles. The possibility of receiving and transmitting useful information within the physiologically normally perceived range of sound frequencies has been demonstrated. A physical model of the communication channel has been created, showing in natural and model experiments the identity of the resulting auditory sensations. This made it possible for the first time to abandon the practice of conducting experiments on volunteers and to study the phenomenon of radio sound with acoustic analogues. The possibility of creating a bionic communication channel in the aquatic environment has been considered. de using ultrasound as a carrier. The book is

intended for specialists working in the field of electromagnetobiology, acoustics, bone hearing theory, biopics, and university students with relevant specializations.

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I dedicate this book to the blessed memory of my wife and friend Elena Abramovna Raikovetskaya-Tigranyan.

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PREFACE

In the book brought to the attention of readers, for the first time in domestic and foreign literature, data on the sensory acoustic effect of microwave frequencies, called “radio sound,” are systematized. Radio sound is the phenomenon of the appearance of an auditory sensation in a person when his head is irradiated with pulses of electromagnetic microwave energy. Today, — this is the only effect of the biological action of microwaves known to science that is objectively perceived by humans.

For the first time, the phenomenon of radio sound, after its accidental observation in the coverage area of a radar station antenna, was reproduced in laboratory conditions by the American physiologist A. Frey, and he also proposed the name of this phenomenon “radio sound”. A hypothetical consideration of the mechanism of the occurrence of auditory sensations from a physical point of view was first proposed by the American physicist J. Lin in his single-circuit concept of radio sound. However, this concept was unable to explain some fundamentally important aspects of the phenomenon under study.

The study of radio sound as a manifestation of the action of a pulsed microwave field on a whole organism is not only of scientific interest. Based on studying the characteristics of this phenomenon, fundamentally new ways of transmitting information to a person or animal can be developed. Naturally, the main direction of these studies was focused on the search and development of an information communication channel based on bionics. By that time, it was already clearly clear that the search for anatomical structures of the head capable of clearly playing the role of nonlinear elements or systems for converting the absorbed energy of microwave pulses into an information signal does not make sense. New approaches and methods were required for determining the functions of anatomical structures, allowing them to ultimately be described using mathematics. And if acts of primary interaction of biological structures with electrical

Since microwave magnetic radiation was at least to some extent amenable to comprehension, the issues of detection remained a huge blank spot for a long time.

The formalized detection function was introduced by the author of the book in the form of a thermal pulse formed in the bone and tissue formations of the skull when absorbing the energy of a microwave pulse and repeating the envelope of the radio pulse. In this case, the thermal impulse is considered as a source of mechanical vibrations, the spectral analysis of which occurs in the auditory system.

In the presence of complex modulated microwave radiation, the auditory analyzer will simultaneously separate two signals of the first harmonic of the pulse sequence (subcarrier) and the useful signal (message function). The separation of both signals occurs in different frequency groups and they should be subjectively perceived by a person simultaneously. But thanks to the masking effect, a person perceives only the function of the message. It seemed promising to explore the possibilities of creating a communication channel based on bionics in an aquatic environment using ultrasound as a carrier. An analysis of the literature data on the electrophysiology of dolphins showed that the hearing threshold curves of dolphins can be calculated using the methods and approaches used in studies of radio sound threshold curves. The two-circuit concept of the formation of auditory sensations in humans, proposed and developed by the author of the monograph, turned out to be acceptable when description of hearing threshold curves in dolphins.

As a result of our own research and analysis of literature data, we can talk about unified principles for constructing a bionic communication channel for transmitting useful information in various environments to humans and animals without the use of technical means of reception.

The author considers it his pleasant duty to express sincere gratitude to the staff of the microwave irradiation service of the Institute of Biological Physics of the USSR Academy of Sciences, Ph.D. V. V. Shorokhov, Ph.D. S.V. Koltun, engineers A.L. Gorokhov and A.A. Safroshkina, technicians I.V. Markin and S.A. Zherebina for their active participation in the work and constant help.

The author expresses his deep gratitude to the staff of the laboratory of comparative physiology of the sense organs of the Leningrad Institute of Evolutionary Physiology and Biochemistry named after. I. M. Sechenov to the head of the laboratory, Doctor of Biological Sciences I. A. Vartanyan, Candidate of Medical Sciences E. M. Tsirulnik for the opportunity to carry out work on audiometry in the laboratory and active participation in this work.

Special thanks to E. M. Tsirulnikov, now a Doctor of Medical Sciences, for reviewing the manuscript and making a number of valuable comments.

And yet, this book could not have appeared without the invaluable support and constant attention shown by my wife and friend Elena Abramovna Raykovetskaya-Tigranyan.

Doctor of Physical and Mathematical Sciences. full member of the Association of European Scientists in Electromagnetobiology

TIGRANYAN Robert Edmondovich

INTRODUCTION

This monograph presents materials on the study of the mechanism of the phenomenon of radio sound and the possibility of creating a bionic communication channel for transmitting information to a person without the use of technical means of reception using pulsed EMR microwave radiation.

The development of modern means of communication for transmitting and receiving useful information at a distance is mainly associated with the further complication of the technical devices that make up the communication channel in order to increase their tactical and technical data. These measures entail an increase in energy consumption, increase costs and require the development of new technologies.

The operation of a communication channel is subject to the influence of numerous external "parasitic" factors that interfere with the reception of useful information and, thereby, reduce the efficiency of the entire system as a whole. Increasing the noise immunity of a communication channel is currently one of the urgent tasks and requires attracting huge funds for its implementation.

One of the necessary conditions often imposed on a communication channel is its secrecy—the — impossibility of receiving information by other correspondents, on the one hand, and deep encryption of the transmitted information, on the other.

In modern conditions, one of the pressing issues is maintaining the operability of a communication channel in conditions of strong radio and electromagnetic radiation, for example, during an atomic explosion or under the influence of powerful pulsed electromagnetic fields during the operation of radar stations, as well as in time of installation of radio curtains or at a high level of acoustic noise. As a rule, modern technical means of communication are not always effective in such situations. In search of new principles for constructing systems and communication channels, people began to study some species of animals, both terrestrial and marine.

The ability of bats not only to emit and receive ultrasonic vibrations, but also to determine a target with high accuracy is known. The location system of dolphins is even more effective, which they use for many purposes — of hunting, navigation, and transmitting various information. A comparison of the dolphin location system with existing modern radar systems in terms of basic parameters shows [79] that nature has far surpassed human thought. At the same time, living beings created by nature, despite their complexity compared to any most modern technical system, have a reliability that is immeasurably greater than the reliability of technical systems. And in this regard, the search for ways to create a communication channel based on bionics, i.e., based on the study of the functions and principles of organization of biological systems, can be considered one of the most promising directions [5].

Currently, biological bionics is especially actively studying the properties of specialized receptors and elements of the nervous system of representatives of the animal world, using them for orientation in the surrounding space, when communicating, during hunting, etc. The mechanism of sound perception is being intensively studied by a person using electronic models that reproduce the frequency properties of the ear. Of great interest are works on creating models of the auditory system that can distinguish weak signals against a background of noise.

Communication systems may be of practical interest in special cases of combat use of military equipment, for example aircraft, in conditions of increased levels of external noise. In such a situation, the transformation of the speech frequency spectrum into mechanical vibrations perceived by human skin could help increase the likelihood of correct recognition of transmitted information and secrecy [5]. Thus, we can say that the bionic aspect, as applied to the development of new means of communication, consists in the refusal to use technical means of receiving information, i.e., in a fundamentally new approach to solving this problem.

Obviously, to transmit information over long distances, a carrier is needed that is perceived by a person in one way or another. There is a need to select a physical factor that plays the role of a carrier, to study possible ways of converting the energy of the carrier into a signal accessible for perception and analysis of the transmitted function of the message by the auditory system, i.e., it is necessary to study the capabilities of the human body with an inadequate mechanism perception of information.

In this case, there cannot be direct borrowing from living nature. However, the study of known biological phenomena and effects that have the potential to be used in creating a bionic communication channel can lead to the discovery of new principles of transmission and reception.

One of these effects may be the emergence of a complex auditory sensation in a person when his head is irradiated with pulses of electromagnetic radiation of ultra-high frequency (EMR microwave), which is called "radio sound" in the specialized literature. This phenomenon was first discovered in 1947 at one of the airfields in the United States, when persons maintaining radar stations accidentally found themselves in the coverage area of a radiating antenna. It was noted that people experience sounds of very different colors. This is the only known effect of the distant action of this factor, causing in a person its objective perception in the form of an auditory sensation.

A sufficient number of works in this area, both theoretical and experimental, have reliably shown the existence of radio sound as a real phenomenon.

For the first time, an attempt to explain the mechanism of the occurrence of radio sound was made by J. Lin. The hypothesis proposed by J. Lin is the most significant in the history of radio sound research. For the first time, the phenomenon of radio sound was considered from a physical point of view.

J. Lin proposed a thermoelastic concept of radio sound, based on the assumption that when a person's head is irradiated, as a result of the absorption of electromagnetic energy by brain tissue, a rapid expansion of these tissue thermoelastic shock, which excites mechanical vibrations. These vibrations give rise to sound sensations in humans. J. Lin's work is theoretical in nature and is mainly devoted to a computer calculation of the distribution of sound pressure amplitude inside a spherical model with infinite quality factor and acoustic and electrical parameters in values approaching those for brain tissue. The interpretation of radio sound he proposed was developed under the influence of earlier works by Foster and Finch, as well as White, who showed that when certain liquids are irradiated with microwave pulses, mechanical stresses arise in the absorbing medium.

Actually, the problem of temperature stresses in an elastic half-space arising as a result of sudden heating of its boundary was solved in the late 40s and early 50s by the Soviet mathematician V. I. Danilovskaya.

In accordance with the thermoelastic concept of J. Lin, the excitation of mechanical vibrations in the bone and tissue formations of the skull occurs due to the resonant properties of the head as an acoustic resonator.

Demonstration of the energetic capabilities of excited mechanical vibrations to activate the cochlea of the hearing organ [206] suggests the participation of the bone conduction mechanism in the transmission of these vibrations to the cochlea of the hearing organ. Work in this direction, however, did not receive further development.

At the same time, an analysis of the literature data has shown that when various types of non-ionizing radiation (microwaves, lasers, ultrasound, vibration) act on biological structures of the same type, in all cases the same effect occurs: the transformation of part of the absorbed energy of non-ionizing radiation into the energy of mechanical vibrations.

The questions discussed in the book allow us to regard the mechanism of radio sound as a particular manifestation of a general property of biological objects. The generation of acoustic vibrations in biological objects upon absorption of a pulse of microwave electromagnetic energy can play the role of a hidden mechanism.

nism leading to specific effects. Therefore, the very phenomenon of generation of acoustic vibrations in biological objects is of great scientific and practical interest. However, the single-circuit concept of radio sound, proposed by J. Lin, was unable to explain many of the issues that arose during the study of this phenomenon, and the main one was the discrepancy between the resonant frequency of the human head and the region of a sharp increase in the threshold on the radio sound threshold curve [234], whereas the opposite should have been observed—it was at a microwave pulse repetition rate equal to the resonance frequency that a low threshold should have been observed.

Direct human reception of pulsed electromagnetic microwave radiation required the study of "physical" connections of anatomical structures involved in the formation of a physiologically unconventional auditory sensation and quantitative assessments of bone conduction of sound in a wide frequency range.

Based on the analysis and generalization of the entire volume of psychophysical, electrophysiological experiments, theoretical works devoted to the excitation of mechanical vibrations, our own results on the study of the parameters of mechanical vibrations excited by microwave pulses in cylindrical and spherical liquid resonators and audiometry of auditory thresholds on bone conduction, the author of the monograph proposed a new concept of the formation of auditory sensation. Its essence lies in the assumption of the existence of a complex oscillatory system responsible for the perception of radio sound, which consists of at least two low-Q circuits with a coupling coefficient between them above the critical one. This approach made it possible to explain the complex spectral composition of the perceived auditory sensation, the shape of the threshold curves of radio sound, as well as some features in bone conduction audiograms that were obtained when recording auditory thresholds using a previously unused technique.

Based on the proposed concept, a two-circuit resonant electrical model has been developed and built, having functional analogues in the original. Model experiments show the identity of the amplitude-frequency response (AFC) of the model in the pulsed excitation mode and the mirror image of the threshold curves of the radio sound effect,

Almost all experiments to study the phenomenon of radio sound were carried out on volunteers, and the conclusions that various researchers then came to were based on the subjects' subjective assessments of their own sensations.

The electronic model proposed by the author of the monograph, which implements a new concept of the formation of the auditory sensation, made it possible to eliminate the need to conduct experiments on humans. Thus, for the first time, the phenomenon of radio sound began to be studied using the method of physical modeling.

Justification and confirmation in a model experiment of the possibility of transmitting information to a person without the use of technical means of reception using pulsed microwave radiation became possible only through the use of methods and principles of bionics and bionic modeling in the categories and terms of the theory of quadripoles.

Meanwhile, it was obvious that the excitation of an auditory sensation under these conditions, regardless of its interpretation, already creates the prerequisites for the creation of a fundamentally new communication channel based on the study of some physiological features of the anatomical structures of the human head and the physical patterns connecting these structures - tours. Here it would be possible to fully realize the informational effect of microwave radiation, i.e., try to find the law of change in the amount of emitted electromagnetic energy perceived by a person after decoding by anatomical structures in the form of useful information in the physiologically normal perceived range of sound frequencies.

The creation of a bionic communication channel for transmitting information to a person for the first time made it possible to abandon technical means of reception, which in some situations is would represent a qualitatively new interaction between man and the environment. However, the lack of knowledge about the characteristics of the emerging auditory sensations, about the very mechanism of the occurrence of these sensations, about the structures of the human head involved to one degree or another in the formation of the auditory image, did not allow us to talk about the implementation of a bionic communication channel as such .

The study of the conditions for the excitation of mechanical vibrations in a model experiment, their characteristics and energy, as well as the analysis of the known provisions of the theory of hearing as applied to the emergence of auditory sensations in humans in an inadequate way made it possible to theoretically substantiate the possibility of the existence of a bionic communication channel. At the same time, in a direct experiment, the possibility of modeling radio sound with acoustic analogues was shown, by directly exciting the tissues of the skull with a bone vibrator.

The correctness of the calculation of the characteristics of the bionic communication channel was confirmed in model and then in natural experiments on the transmission of useful information and its reception by a person without the use of technical means of reception.

The possibilities of implementing a bionic communication channel are not limited to the use of pulsed microwave EMR in the air. Excitation of mechanical vibrations in absorbing media by pulsed laser and ultrasonic radiation is known. Analysis of data from electrophysiological studies of dolphin hearing suggests the possibility of using the two-circuit concept of radio sound to explain the dependence of EP in the dolphin auditory cortex on the parameters of the tonal signal [126]. That is, we can talk about the universality of the methods and approaches discussed in the monograph for finding ways of communication between living beings.

The book is written in such a way as to give the reader a general picture of the development of radio sound research and to introduce him to the equipment and research methods. Radio sound - yav-unique and until some time research department it

The mechanisms were in the area of interest of a very limited circle of specialists and laboratories. Given the narrow focus of the topic, the author's desire to make the book accessible to non-specialists determined the style of presentation. That is why the path chosen by the author, a preliminary story using examples of the most illustrative and defining works in the field of research into the mechanism of radio sound, can be considered successful.

I would like to hope that the book will be useful to a wide range of readers. The work is intended for specialists working in the field of biophysics, electromagnetobiology, acoustics, hearing theory, and bionics.

Chapter I

HISTORY AND DEVELOPMENT OF RESEARCH OF THE RADIO SOUND PHENOMENON

The first report that pulse-modulated electromagnetic radiation can cause auditory sensations in humans dates back to 1956 [130]. The radar station operated at a carrier frequency of 1.3 GHz. The antenna emitted rectangular radio pulses with a duration of 2 μs, a power of 500 kW, and a repetition rate of 600 Hz. The sound was observed at a distance of 1.5...2 m from the emitting horn. Using a cylindrical (2/4 in diameter) screen, it was found that the most sensitive area of the head is the zone near the point located in the middle and slightly above the conventional line connecting the ear and eye. It is noted that the sound was felt enriched in high frequencies and had almost no fundamental frequency, i.e. 600 Hz. Two people who had a high-frequency hearing limit (HFH) near 5 kHz perceived the signal significantly worse than those whose hearing sensitivity extended to at least 15 kHz.

The systematic study of the discovered phenomenon began with the work of A. Frey [168]. The experiments used two oscillators with carrier frequencies of 1.31 and 2.982 GHz. The first generator emitted rectangular radio pulses with a duration of 6 μs with a frequency of 244 Hz, the second 1 μs, 400 Hz. The subjects were located at a distance of 6 m from the emitting antenna. The ears were closed with special plugs, which made it possible to reduce the level of ambient noise to 40...50 dB above the absolute hearing threshold (ATH), equal to 0.0002 dyn cm-2. 8 people took part in the experiments. A buzzing character was felt by all faces sound. The sensation arose without a noticeable latency period, immediately after turning on the generator or a person entering the irradiation zone. As the ambient noise decreased, the subjectively perceived volume of the radio sound increased. For all subjects, the sound source appeared to be located a short distance behind the head, regardless of their orientation relative to the emitter.

When determining threshold values, average values of power flux density (PPMD) were obtained - for a generator with a carrier frequency of 1.31 GHz - 0.4 mW cm2, for a generator operating at a frequency of 2.982 GHz - 2 mW cm-2.

When multiplying these values by the duty cycle, we obtain a pulse power flux density (PPD) of — 266.8 mW cm2 and 5 W cm-2, respectively. A parameter is used that has the meaning of the amount of energy transferred during the pulse action through a unit area, — the energy flux density (EFD). In this case, PES = 1.6 and 5 μJ cm-2.

Air and bone conduction audiograms were taken from the volunteers who participated in the experiment. Moreover, volunteers with different types of hearing impairments and with different pathologies were selected.

In Fig. 1-4 show audiograms for individual volunteers.

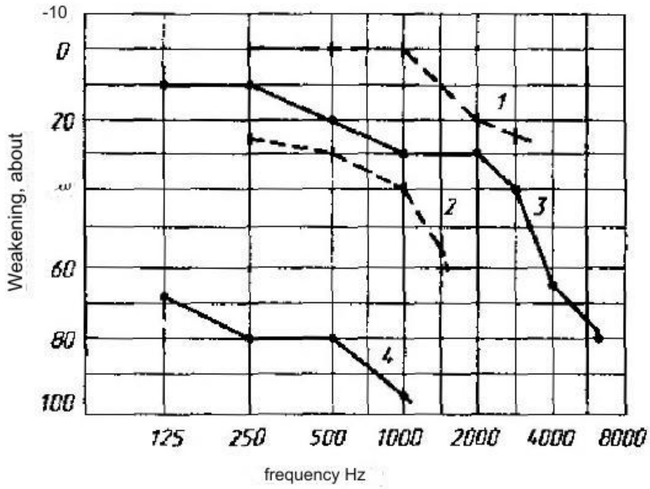
The results of the experiments and audiograms of volunteers allowed us to come to the following conclusions:

1. To perceive radio sound, it is necessary for a person to perceive an acoustic signal with a frequency above 5 kHz through bone conduction.

2. To perceive radio sound there is no need for the ability to perceive sound due to air conduction.

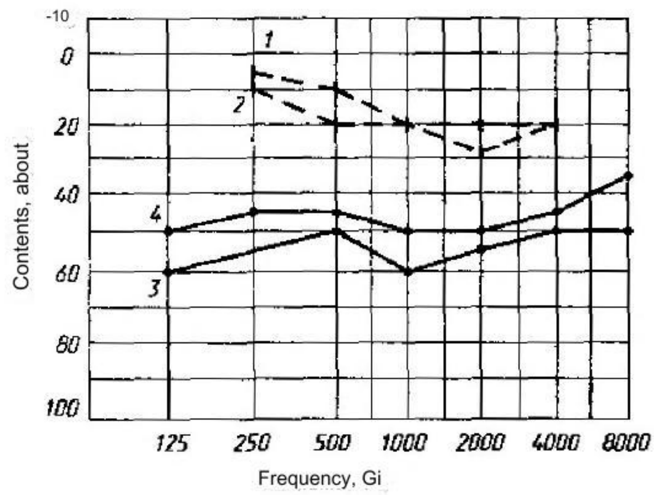
Thus, the first conclusion actually predetermined the search in further work for the mechanism of the occurrence of radio sound as a consequence of the physiological characteristics of human hearing. It was completely natural after this to direct efforts to search for the point of application of the electromagnetic field, which, as follows from the conclusions made in [169], most likely should have been located in the region of the hearing organs. Along with this, a principle appeared

It is fundamentally possible to consider some other structures as possible converters of a pulse-modulated microwave field into an auditory sensation.



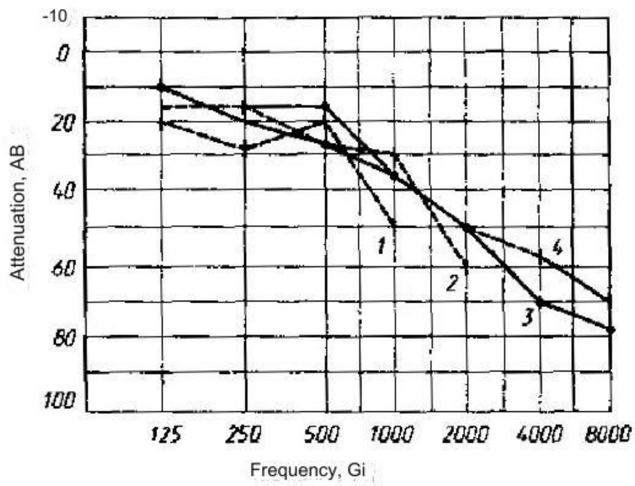
Rice. 1. Audiograms of subject No. 1: radio sound was not perceived even at 30 times the power density required for normal perception (mastoid process removed) (borrowed from [168]):

1 — bone conduction (right ear); — 2 bone conduction (left ear); 3 air conduction (right ear); — ear) air 4 conduction (left

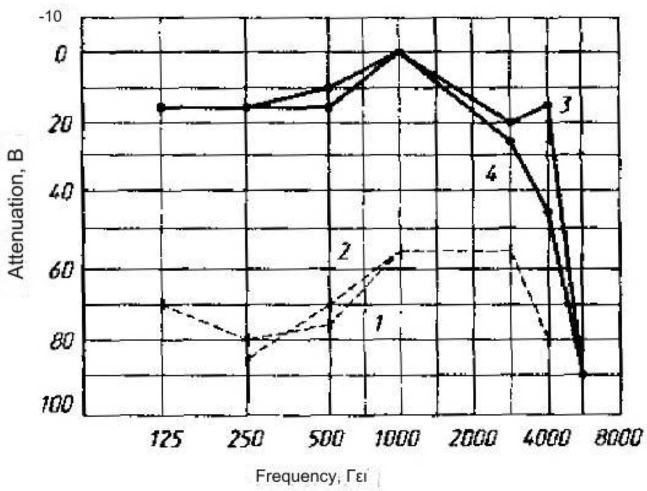


Rice. 2. Audiograms of subject No. 2: radio sound was perceived as follows the same as for those with normal hearing (the subject suffered from otosclerosis) (borrowed from [168]):

1 — bone conduction (right ear); 2 bone conduction (left ear); 3 air conduction (right ear); 4 — air conduction (left ear)



Rice. 3. Audiograms of subject No. 3: radio sound was not perceived (auditory nerve atrophy) (borrowed from [168]):
1 — bone conduction (right ear); 2 bone conduction (left ear); 3 - air conduction (right ear); — ear) air
4 conduction (left

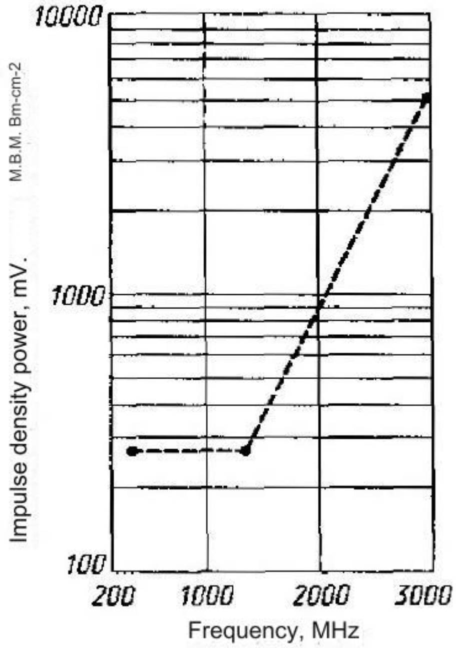


Rice. 4. Audiograms of subject No. 4: radio sound was not perceived despite normal acoustic hearing (borrowed from [168]): 1 bone conduction (right ear); 2 - bone conduction (left ear); 3 air conduction (right ear); 4 air conduction (left ear)

In the following works [169, 170], A. Frey established the problem dependence of the perception of radio sound on the carrier frequency and modulation mode. The studies were carried out at a level ambient noise 70...90 dB relative to the APS. Determine The study of radio sound perception thresholds showed that PPM is is the determining factor of influence, and the threshold is minimal in the range 425...1300 MHz and has a value of about 250 mW cm2, per pulse (Fig. 5). Screening method

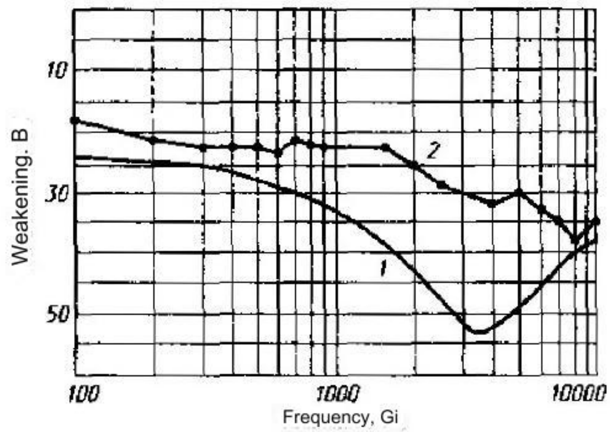
After studying different parts of the head, it was found that the effect is not a consequence of the effect of EMF on fillings or dental crowns. A direct effect on the eardrum was also excluded, since the presence and quality of the effect did not depend on the position of the subjects relative to the emitter.

Possibility of interaction Via EMF with neural computers lexes is questioned by the author due to the absence of any other sensory effects. All subjects unequivocally noted that reducing the influence of ambient noise using special plugs in the ear canal led to an increase in the effect (Fig. 6).



Rice. 5. Dependence of the threshold power on the EPM carrier (ambient noise level 70...90 dB) (borrowed from [169])

The experimental results also showed that the level of perception correlates with the peak power, and not with the average value of the power level. No dependence of the effect on the type of emitter and field polarization was found.



Rice. 6. Lowering the threshold for the perception of radio sound using anti-noise devices (borrowed from [169]):

1 — theoretical limit weakened by air protector;

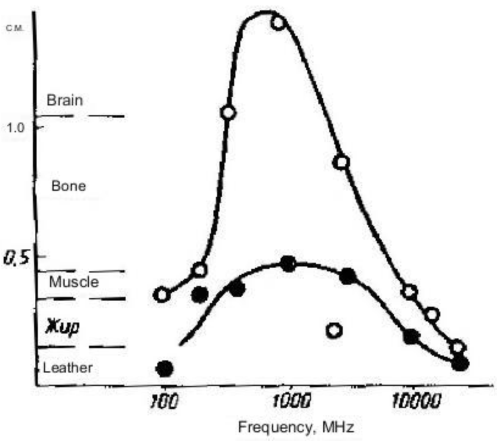
2 — anti-noise

Table I

Parameters of irradiation modes [169]

Generator	Carrier frequency, MHz	Pulse duration, MHz	Pulse repetition frequency, Hz
1	1,310	6	244
2	2,982	1	400
3	425	125	27
4	425	250	27
5	425	500	27
6	425	1000	27
7	425	2000	27
8	8,900	2.5	400

In table 1 shows the parameters of the irradiation modes. Experimental data and calculated calculations curves [169] of the depth of radiation penetration into brain tissue depending on the frequency existing (Fig. 7) allowed auto-work to determine what the most sensitive area resistance to microwave radiation, with precision from the point of view of case formation of the image, is temporal but-ear area. Because the calculations showed that the absorption high-power microwave field energy may also affect the cortical affairs, A. Frey came to the following important conclusions regarding possible application point action of the microwave field as an excitation radio sound driver (or as initial substance, launch-mechanism of perception radio sound):



Rice. 7. Calculated curve of the dependence of the penetration depth (cm) inside the head of EMR on the carrier frequency (borrowed from [169]):
⊙ — 20%; O 10% of incident power

1. The eardrum cannot be a pathogen, so how did people suffering from otosclerosis experience subjective distinct sensation of sound when irradiated with microwave pulses.

2. The cochlea of the auditory organs may be the causative agent of the auditory sensation when the head is irradiated with microwave pulses, but there is no experimental data confirming this assumption.

3. A direct effect of the microwave field on the brain is possible. However, A. Frey himself immediately posed the question: "If such a possibility exists in principle, then why does the pulsed microwave field not manifest itself in other objective sensations?"

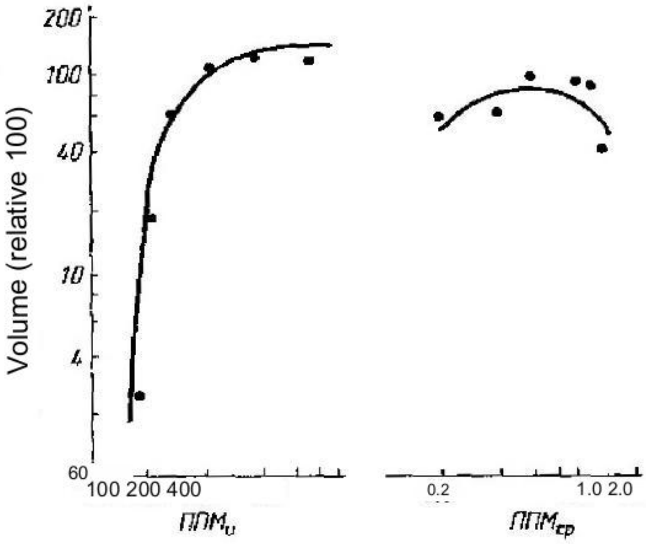
Thus, already in the first works in the field of radio sound research, questions were posed, the answers to which had to be sought at levels quite distant from each other.

In [160], the excitation of auditory sensations was studied when people were irradiated with EMFs with frequencies of 3; 6.5 and 9.5 GHz, modulated by rectangular pulses with a duration of 0.5 to 2.0 μs and a pulse repetition rate of up to 1 kHz at PPMSR = 5 mW cm² (PPMS about 5 W cm-2). It is noted that not a single subject heard sound when irradiated with a carrier frequency of 9 GHz, and only one felt the presence of radio sound at frequencies of 3 and 6.5 GHz during the first irradiation. For the rest, sound sensations arose only after 5-8 times of irradiation. According to the subjective assessment of the subjects, the apparent sound source was located on the side opposite to the radiation. It is significant that no one heard sound at a pulse duration of 0.5 μs. Irradiation with a pulse repetition frequency equal to or less than 100 Hz was perceived in the form of separate buzzing clicks; at a higher frequency the sound merged. This work is the first to indicate the dependence of the subjective assessment of the emerging auditory image on the pulse repetition rate. A. Frey could not explain the results of his research from the point of view of the presence of any mechanism, but his other works allow him to express some thoughts on this matter.

In Fig. Figure 7 shows that with increasing carrier frequency, the depth of penetration of radiation into brain tissue decreases, and the threshold level of peak power required for the formation of radio sound sharply increases. It's obvious that

The radiation levels used in [160] turned out to be insufficient for the formation of radio sound. The same conclusion can apparently be reached based on the fact that all subjects required repeated irradiation for the sensation of radio sound to arise.

A. Frey pointed out the different nature of perceived sounds in his works [169, 170, 176]. During irradiation, all subjects noted that radio sound manifested itself in the form of buzzing and hissing. A. Frey notes that the subjective assessment of the subjects indicates the high-frequency nature of the perceived radio sound. And the perception of radio sound itself manifests itself better in the carrier range of 0.3...3 GHz.



Rice. 8. subjective assessment of radio sound volume as a function microwave pulse energy density; b - subjective assessment of thunder bones of radio sound as a function of average microwave energy density. Axis radio sound volume levels are plotted in ordinates relative to the level volume at PPM equal to 100 mW cm (borrowed from [176])

In [176], the experimental dependence of the level of excited radio sound on the pulse power. In table 2. The data of the used values are given. values of pulse and average power flux densities at different microwave pulse durations, and in Fig. 8 — dependence of the level of "audibility" of radio sound on these parameters microwave radiation parameters. The experiments involved four specially trained observers with clinical normal hearing. During irradiation they were in an anechoic chamber. The subjects were first presented with an acoustic signal, the loudness of which was conventionally taken to be 100 units, and the loudness of the radio sound was assessed relative to this value (scaling method). By fixing one of the radiation parameters and changing others, the experimenters obtained from observers qualitative characteristics of the perceived sound. The authors note that the perceived loudness of radio sound in the experiments performed depends on the PMS and to a greater extent than on the PMS. An assessment of the minimum PPM required for the occurrence of a sound sensation gave a value of 80 mW cm-2. At a constant PES = 6.3 μJ cm-2, the volume decreased as the pulse duration increased above 30 μs. For durations of 10...30 μs, the volume remained the same. All subjects noted that radio sound has both tonal and timbre coloring. Both of these characteristics depended on the pulse repetition rate.

table 2

Values of average and pulse power
at various pulse durations (borrowed from [176])

No experiment	Pulse power, mW cm²	Average power, mW cm-2	Pulse duration, ISS
	Change	pulse power	
1	90	0.32	70
2	105	0.32	60
3	125	0.32	50
4	210	0.32	30
5	315	0.32	20
6	630	0.32	10
6a	630	1.26	40
	Change in average power		
1	370	0.19	10
2	370	0.37	20
3	370	0.55	30
4	370	0.93	50
5	370	1,11	60
6	370	1.29	70

Psychophysical experiments on people's perception of radio sound were also carried out by A. Guy et al. [183] at a carrier frequency of 2450 MHz with pulse durations from 0.5 to 32 μs.

The main goal of the experiments was to determine the threshold energy of the effect for different pulse durations. The experiments were carried out with the participation of two observers who were located in a shielded chamber. The ambient noise level was 45 dB relative to the ALS. One of the subjects had clinically normal hearing, and the second had a 55 dB decrease in sensitivity in the region of 3.5 kHz. Bone conduction audiograms were similar. It was found that for the first observer, regardless of the peak power and duration of the pulses, the threshold was in the region of 40 μJ cm-2 per pulse or 16 mJ kg specific absorbed energy (SEA) when calculated using the spherical model proposed in the work [187]. The use of special anti-noise plugs led to a decrease in the threshold PES from 35 to 28 μJ cm-2. The threshold of the second subject near 3.5 kHz was about 135 μJ cm-2. For very low repetition rates (~3 Hz), each pulse was perceived as a separate click, and a short series of pulses was perceived as a tone corresponding to the repetition rate. The threshold for a single pulse was the same as for paired pulses separated by several hundred microseconds if they carried the same total amount of energy.

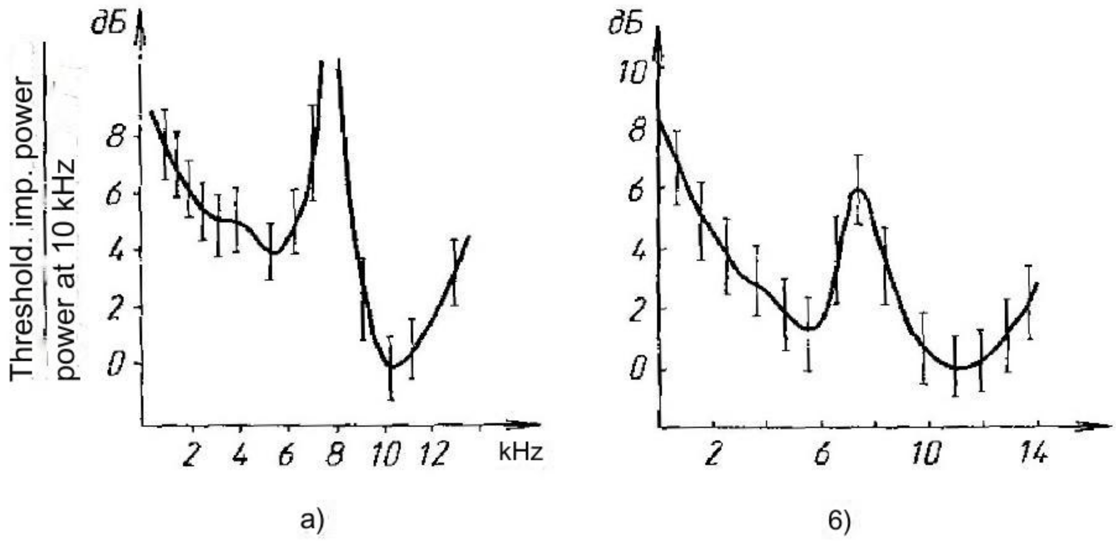
Kine and Riesman [143, 144] determined the threshold characteristics of radio sound perception in eight volunteer subjects for whom audiograms had previously been taken for both air and bone conduction. The irradiation was carried out at a carrier frequency of 3 GHz. The ambient noise level was 45 dB above the ABL. Five subjects heard clicks of the same nature as in the works [168, 183]. Three other subjects were able to hear radio sound only when the generator power was maximum and the pulse duration was increased to 20 μs. Thresholds were determined only for the first five subjects. It turned out that PPE varies from 2.3 to 20 μJ cm-2 (PPM from 225 to 2500 mW cm2) depending on the individual. Since air and bone conduction audiograms for normal sound were determined only up to a frequency of 8 and 4 kHz, respectively, it is impossible to correlate the fact of the absence of auditory sensations in three subjects with the sensitivity of their hearing organs to higher frequencies.

Paper [234] presents the results of studies of radio sound threshold curves in a wide range of microwave pulse parameters.

The experiments used a generator with a carrier frequency of 800 MHz and a maximum pulse power of 500 W. The pulse duration varied from 5...150 μs, repetition frequency from 50 to — 20,000 Hz. For all subjects (18 people), the high-frequency hearing limit was previously determined. The level of ambient noise in the room where the experiments were carried out was estimated at 40...60 dB above the ABL.

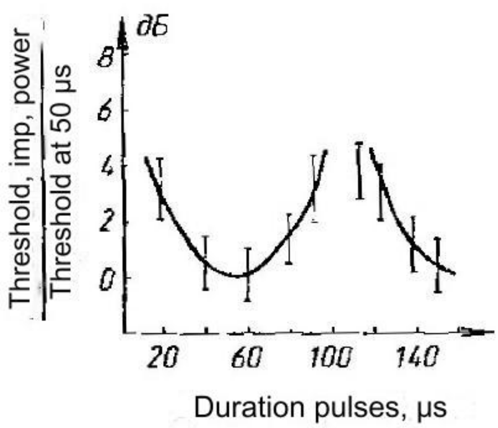
None of the subjects whose HFGS was below 10 kHz heard radio sound with pulse durations of 10...30 μs. Of the 15 observers with HFGS above 10 kHz, only one was unable to hear the sound of such modulation. Everyone who heard radio sound with a pulse duration of 10...30 μs (at the same time, the PPP on the surface of the head exceeded 0.5 W cm²) noted the polytonal nature of the sound sensation at a repetition frequency of up to 8 kHz and monotonal at a repetition frequency above 10 kHz. In all cases, the source of the sound seemed to be in the head.

In the experiments, the threshold characteristics of radio sound were measured depending on the repetition frequency and pulse duration. As the pulse repetition rate increased from 6 to 8 kHz, a decrease in volume was observed (an increase in the sensitivity threshold), while the sound became more monotonous, although it still contained at least three components. Observers with HFGS below 15 kHz in the zone of increased threshold completely lost the ability to perceive radio sound with the applied PPMs (~1 W-cm²), while observers with HFGS ≥ 17 kHz had only a slight increase in the threshold in this area (~0. 3 W cm2) (Fig. 9).



Rice. 9. Threshold curves of the effect of radio sound depending on the pulse repetition rate with a duration of 10...40 μs:
a - HFGS 14 kHz; b - HFGS 17 kHz [234]

In addition, it was noted that the former were unable to distinguish between signals with a repetition rate of 5 and 10 kHz. Subjects with a wider auditory range noted that the apparent pitch for 5 kHz was higher than for 10 kHz. For various pulse repetition frequencies, the duration of which in this series of experiments was 10 μs, the thresholds expressed in PES vary from 2 μJ cm-2 and mainly to 10 μJ cm2. Single pulses begin to be heard at PES = 45 μJ cm-2.



Rice. 10. Effect threshold curve radio sound effect depending on depending on the duration of the pulse at a frequency of 800 Hz

Complex threshold characteristics was discovered and for dependence on long-term pulse speed at constant their peak amplitude (Fig. 10). When changing the duration pulses from 5 to 50 μs thunderbone perceived radio sound increased, then with a long from 70 to 100 μs the sound diminished until it completely disappeared news, appeared again and melted over long periods of time stakh. And when approaching

With pulse durations of 110 µs, subjects noted a sharp change in the nature of the sensation: an abrupt — decrease in pitch and a movement of the apparent sound source from the head to the outside. It turned out that even people who had HFGS below 10 kHz and were not able to perceive radio sound at short pulse durations heard it at long ones. For other observers, with a gradual decrease in the pulse duration from 100 to 60 µs, a kind of "frequency locking effect" was observed [105, 113, 233], which consisted in the simultaneous perception of both high-frequency and low-frequency (i.e., manifested at long durations) radio sound when the duration was less than 50 µs, the latter disappeared. A break in irradiation for 2...4 s also led to the disappearance of low-frequency radio sound in the perception. The "frequency locking effect" is explained by a phenomenon known in psychoacoustics, which manifests itself in the existence of the so-called "uncertainty interval" in audiograms recorded with a Bekesy audiometer or a similar method [12, 107, 243-346].

The most important characteristic of the phenomenon under study, both from the point of view of the possibility of its subsequent interpretation in order to find the most optimal modulation mode, and from the point of view of searching for a possible mechanism, is the frequency range of the perceived radio sound. Knowing this characteristic would allow us to narrow the search and make it more targeted. It is this problem that is primarily devoted to work [96], in which, using the zero-beat method, it was possible to determine the boundaries of the frequency range of perceived radio sound under the experimental conditions under which it was usually studied.

Simultaneously with the irradiation of the subject's head with microwave pulses, an electrodynamic emitter powered by an audio frequency generator was switched on. The idea of the experiment was that if the repetition frequency of the field pulses and the frequency of sound vibrations are equal, the subject should hear zero beats. However, this did not happen. At any pulse repetition frequency from 0.8 kHz and higher, zero beats were recorded only if the frequency of the acoustic signal was above 8 kHz and corresponded to the overtone of the microwave pulse repetition frequency.

Table 3

Values of repetition frequencies of microwave pulses and tone signals, corresponding to the presence of zero beats according to the subjective assessment of the subjects (crosses indicate the moments when beats were noted)

Pulse repetition frequency, microwave, kHz	Tone frequency, kHz													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1								+	+	‡	+	+	+	+
2								+				+		+
3									+			‡		
4								+						
5										+				
6												+		
7														
8								+						
9									+					
10										+				
11											+			
12												+		
13													+	
14														+

In table Table 3 shows the values of microwave pulse repetition frequencies and acoustic signal frequencies at which zero beats were recorded.

The data presented in the table allowed us to come to the conclusion water that the lower limit of perceived radio sound lies in the 8 kHz region and extends to the HFGS. For more clear recording of zero beats, observers are provided with it was possible to adjust the amplitude and phase of the acoustic ical signal in such a way that complete suppression of sound sensation. It should be noted that these data were obtained at microwave pulse durations 5...10 μs.

Thus, the authors of this work concluded about the possibility of perceiving radio sound only for frequencies at starting from 8 kHz and above.

In [140], the authors attempted to reproduce the results of psychoacoustic studies [177, 224] by subjective comparison of two pulse sequences with different modulation modes, replacing the test audio signal with a microwave signal. However, the authors were unable to obtain the same result. There were methodological mistakes in the work, which could have been the reason for the failure.

Psychophysical studies of radio sound have mainly provided material confirming the presence of the effect and describing the forms of its manifestation depending on the parameters of pulsed EMR.

At the same time, none of the works revealed any integral mechanism of this phenomenon, in which the physiological features of any of the structures identified in [169] would manifest themselves clearly and unambiguously. However, by the time the work was completed [234], information had already appeared in the press about the results of studies that actually represented the first attempt to understand the process of formation of the auditory sensation in humans during irradiation with microwave pulses not from the point of view of physiology, but from the point of view of physics. Thermoelastic hypothesis proposed by K. Foster and E. Finch [166] and developed by J. Lin [54, 201-204, 206] is based on theoretical and experimental work on the generation of mechanical stresses and displacements in absorbing media by EMR pulses [141, 179, 181, 183, 225, 227 , 237] and on work on recording MPU in various animals when irradiated with MI EMF [148-150, 152, 219]. Considering three possible reasons that can cause vibrations of the skull and lead to the appearance of MPU, J. Lin, following the authors of [141], comes to the conclusion that the most probable of them is the thermoelastic expansion of brain tissue due to the absorption of EMF energy, since it can generate mechanical stresses that are at least three orders of magnitude greater than those from radiation pressure and generated by electrostriction by more than two orders of magnitude.

In the model proposed by J. Lin, it was assumed that the head was spherical and contained only the medulla. The distribution pattern of absorbed electromagnetic energy was approximated by a spherically symmetric function with a maximum in the center of the head

$$W=Wo \frac{\sin Nar/a}{N\pi r/a},$$

where — Wo is the peak level of absorbed energy per unit volume; r - radial variable; and the radius of the head is [202].

Using Duhamel's principle, the author finds a solution to the equation of motion for such a system in the form of a linear combination of harmonic spherically symmetric functions with an infinite set of multiple frequencies. The fundamental frequency was assumed to be equal to c/2a for a free surface and 1.43c/2a for a fixed surface, — where c is the speed of sound in brain tissue (1460 m s-1). It follows that the main resonance frequency for the head of a guinea pig (a = 0.5...2 cm) should be in the range of 40...70 kHz, and for a cat (a = 2.5...3. — 5 cm) from 30 to 40 kHz, which is in satisfactory agreement with the frequencies of the cochlear microphone potential (CMP) recorded in these animals: 50 and 38 kHz, respectively [148-150, 152]. The authors estimate the resonant frequency of the human head to be approximately 8 kHz [201].

Analyzing the results of quantitative calculations, the authors come to an extremely important conclusion, which is that when the energy of a single rectangular EMR pulse is absorbed by a sphere filled with a material with electrical and mechanical properties characteristic of brain matter, an elastic wave should be generated , the amount of pressure and displacement in which is sufficient for registration by the receptors of the hearing organ through bone conduction. All calculations were carried out for a pulse duration of 10 μs and a specific absorbed power (SAP) of 1 W cm^3, at which the heating from one pulse is 2.6 106 °C, and the level of generated pressure is 70.. .90 dB above APS. This pressure is 10...30 dB higher than the threshold for bone conduction [203, 205, 206], and according to other data [210, 211] even 30...50 dB. The calculated displacement values are also of the order of the experimentally recorded 10-10...10-11 cm [215, 218]. The fact that thermoelastics can lead to pressures and displacements

The only but extremely important positive conclusion that can be drawn from J. Lean's theory is the presence of tensions inside the skull, sufficient for their recording by the organ of hearing. All other material concerning the frequency of excited oscillations or the nature of the dependence of the oscillation amplitude on the pulse duration not only does not agree with the experimental data, but is also internally contradictory. For example, the statement that the perceived sound is monotonal, and its frequency is determined solely by the radius and acoustic properties of the spherical brain, does not correspond to reality, since many studies note a significant dependence of the quality of the perceived sound on the pulse repetition rate [133, 160, 173 , 176], and work [234] even provides experimental data on this matter. The statement about monotonality contradicts both psychophysical [104, 168, 234] and electrophysiological [226, 240, 241] experiments to determine the spectral composition of excited radio sound.

Works [195, 196] considered the possibility of the existence of two types of radio sound, "high-frequency" and "low-frequency," based on the results obtained earlier [234], as a consequence of the presence of two mechanisms leading to the formation of different auditory sensations. One low-frequency one was interpreted as a result of thermal expansion of tissues when absorbing a pulse of electromagnetic microwave energy (in accordance with the single-circuit concept of J. Lin), high-frequency as a — result of the action of the same pulse on neural structures - parametric — synchronization. However, these works were not further developed, and the mechanism for excitation of one or another type of radio sound remains at the level of assumptions.

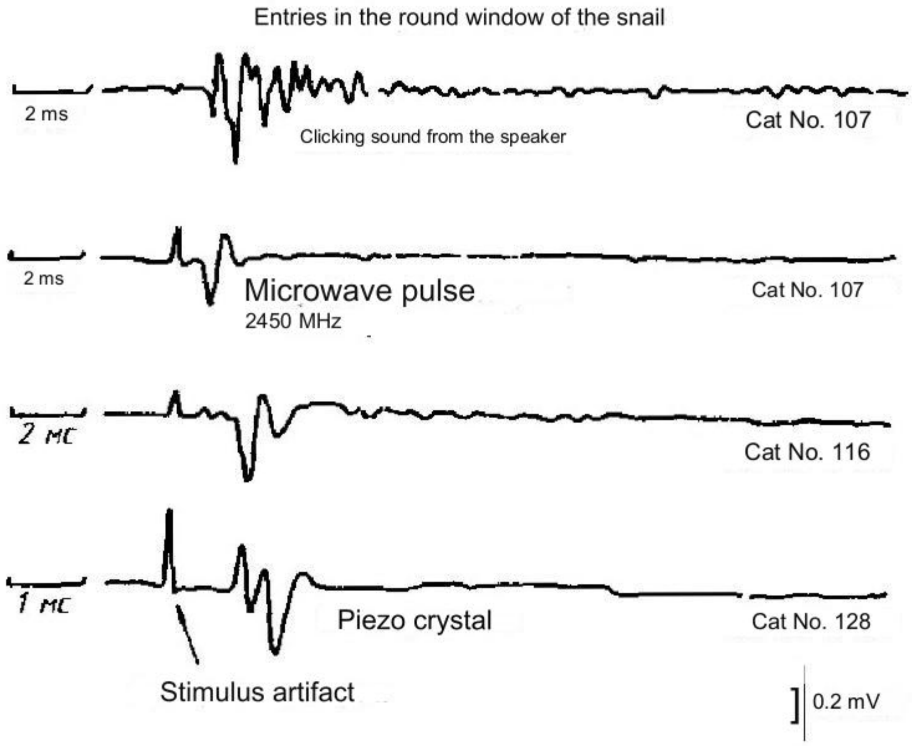
In [231], responses to pulsed microwave and acoustic stimulation were recorded at three points in the ascending pathways of the auditory system: in the VIII cranial nerve, the internal geniculate body, and the primary auditory cortex. At all these points, the same EPs were recorded for both types of stimulation. EPs did not occur after cochlea collapse. All experiments were carried out on cats with the following stimulation parameters: acoustic pulses had a duration of 10 μs and a frequency of 1 Hz, microwave radiation at 2450 MHz was modulated by pulses of duration 32 μs with a frequency of 1 Hz. The authors interpret their data to support the contention that radiosound occurs at the periphery of the auditory system, similar to the effect of a conventional acoustic stimulus, despite the fact that they were unable to record the MPA. A possible reason for the absence of registered MPUs, the authors believe, is the small amplitude of mechanical displacements. Indeed, in works [235, 236] it was shown that the magnitude of the acoustic stimulus required for the appearance of MPUs recorded by conventional equipment should be 40 dB higher than that to which the animal's behavioral response occurs.

In 1974, the first domestic work on the study of the effect of radio sound appeared [82]. The authors recorded changes in the EP of the auditory zone of the cerebral cortex of rabbits and white rats to an acoustic click, depending on the parameters of simultaneously presented MI microwave radiation.

The first one was published in 1973 [182], and then from 1975 to 1979. about ten more methodologically very similar works from the laboratory of A. Gai, devoted to electrophysiological studies of the effect of radio sound [148-151, 153-156, 183].

In the works [182, 183], EPs were recorded in the internal geniculate body and in the round window of the cochlea in cats in response to the influence of pulsed microwave and acoustic stimuli and the threshold EMR intensities were determined. Responses were recorded at both points at carrier frequencies of 918 and 2450 MHz. For these carriers, within the pulse duration range of 0.5...32 μs, the thresholds differ slightly and have a value of the order of 20 μJ cm2 per pulse. To an acoustic click, just as in [231], responses identical to responses to an EMR pulse were obtained (Fig. 11).

Among other phenomenological studies, noteworthy is the work [242], the essence of which was to determine the intensity of metabolic processes in the nuclei of the auditory pathway based on the amount of utilized [14C]2deoxy-D-glucose.



Rice. 11. Responses recorded in the auditory nerve of cats in response to acoustic and microwave impulses (borrowed from [231])

Thus, along with the abundance of phenomenological material on the study of radio sound, there is no sufficiently complete and consistent explanation for the transformation of the energy of IM EMR into an auditory sensation with all its features, specific manifestations and patterns. The thermoelastic model can only be a starting point for further research, since it shows the need to convert electromagnetic energy into acoustic and sufficient intensity of the latter for perception by the organ of hearing through bone conduction. Thus, it can be argued that J. Lin's model put forward in first place, among the most probable mecha- radio sound, the thermoelastic concept, however due to its limitations, could not explain many known interesting facts on the spectral composition and "quality" of perception perceived sound sensation, its dependence on frequency sequence of EMR pulses and their duration. The reason is The limitations of this model are at least in two significant simplifications of the real situation. For calculations, an idealized contour with an indefinite divided by the quality factor, and a single pulse was considered as an external influencing factor, and not a pulse sequence of a certain frequency. With this formulation of the problem, there could be no talk about any frequency characteristics of the model, not to mention some specific features of radio sound. Moreover, in [234] it is shown that in a full-scale experiment, at microwave pulse repetition rates close to the range of resonant frequency of the human head indicated by J. Lin (7...10 kHz), a sharp increase in the threshold is observed. Meanwhile, from the single-circuit resonant model a sharp decrease in the threshold should follow, as follows from [206].

It is important to note that consideration of a resonator with a finite quality factor, as well as modulation timing parameters, would necessarily lead to a reduction in the calculated threshold intensity levels for some combinations of frequencies and durations.

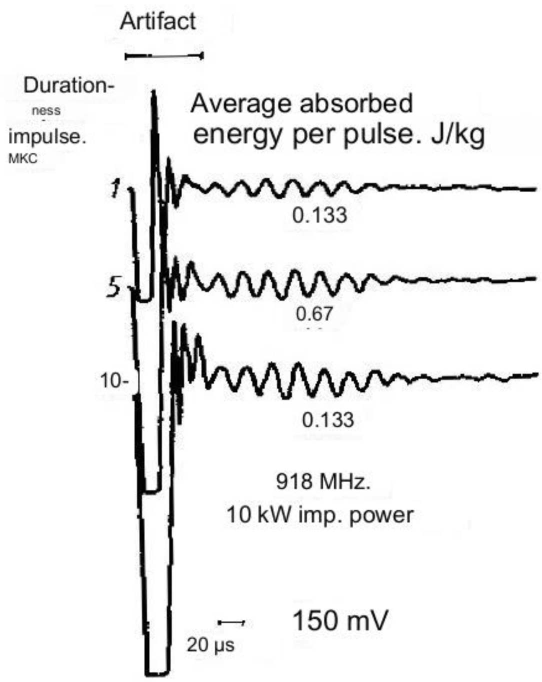
In fact, the first experimental work devoted to the objective assessment of one of the parameters of radio sound in the perceived frequency range appeared only in the late 70s [96].

There is another hypothesis about the possible mechanism of radio sound, based on thermoelastics. Its difference from the one discussed is the assumption that the transformation of electromagnetic energy into mechanical energy, essential for auditory perception, occurs directly in the cochlea of the hearing organ. This idea was first proposed by A. Frey [175], and was later used to explain the spectral characteristics of the evoked auditory response recorded in animals [226, 241-243]. The response spectrum was identical to the spectrum of a rectangular pulse of the same duration as the microwave pulse. Since the transformation of EMF energy into mechanical energy somewhere in the tissues of the head and the transmission of the latter through bone conduction to the organ of hearing is associated, according to the authors, with distortion of the original signal, an assumption arose about the transformation directly in the fluids of the cochlea, which should ensure minimum deviation of the signal from the primary one when transmitted to the organ of Corti. This approach, however, is not able to explain thread a number of experimental facts. The degree of manifestation of the effect should be influenced by the position of the subjects relative to the emitter, since the shielding factor of the cochlear structure will be significant. Experiments indicate the absence of such an influence [152, 168-170, 176]. In addition, based on this concept, it is difficult to explain the frequency-dependent nature of the effect shown in [104, 234]. Equality of spectral components should lead to the perception of low-frequency radio sound with complete masking of high frequencies [107, 115, 125], while the opposite occurs [130, 168, 234]. These same authors, supporting the idea of the possible existence the presence of two or more energy "conversion" mechanisms EMF in the auditory sensation, expressed in the works [195, 196], to explain the appearance of abnormally short latent pe- periods of responses to a microwave pulse in single elements of the nerve [242] suggested the possibility of direct action effects of EMF on hair cells of the organ of Corti. As the mechanism of such action was proposed to be considered generation of Maxwellian tensions between the tectorial membrane and reticular plate [240, 241]. To these ra- bots is adjacent to article [177], which also makes a pre- provision on the possibility of direct action of EMF on hair - cells of the organ of Corti.

At the same time, works were published on the results of electrophysiological studies of radio sound on laboratory animals in an attempt to trace possible pathways of EMR influence from the periphery of the auditory analyzer to the primary auditory cortex. They confirm in various independent ways the assumption that in animals, just like in humans, pulsed microwave EMF can cause auditory sensations [42, 171, 173-175, 184, 190, 192, 230].

The authors were unable to register MPA to a microwave stimulus; however, destruction of the cochlea through aspiration led to the disappearance of EP at both recording points. It is interesting that responses also occurred for carrier frequencies of 8.67 and 9.16 GHz, but the threshold for ti = 32 μs had a value from 472 to 1240 μJ cm-2.

The first report on the registration of MPA in response to a microwave EMF pulse appeared in 1975 [149]. The fundamental significance of this fact is that the presence of caused MPUs directly and unambiguously indicates the detection of EMF at the periphery of the auditory system, since MPUs arise from mechanical deformation of the hair cells of the organ of Corti due to dynamic processes on the basilar membrane [107, 186, 191, 220]. To reliably register the MPA, a special cylindrical waveguide was designed, in which a traveling wave mode was achieved when an object was introduced. According to the authors, the UPE was an order of magnitude greater than with other irradiation methods. Expand Lowering the frequency range of the registration circuit to 80 kG and reducing the amplitude of the vodkas leading to artefacts made it possible to reliably register (with the accumulation of about 400 clicks) the MPU in the round window of guinea pigs at an EMR carrier frequency of 918 MHz, a pulse duration of 1 ...10 μs, pulse repetition rate 100 Hz and pulse power 10 kW (Fig. 12). The recorded signal had a frequency of about 50 kHz, an amplitude of about 50 μV, and a length of 200 μs. The response to an acoustic click of 10 μs was characterized by the same parameters.



Rice. 12. MPA recordings in the round window of a guinea pig cochlea in response to microwave pulses of duration 1, 5 and 10 μs (figure from [49]).

It was also shown in [150] that microwave acoustic (from a piezocrystal and a loudspeaker mounted on the skull) and laser pulses lead to the appearance of MPUs with identical characteristics for the corresponding stimulus parameters.

The works [154, 155] conclude that for a pulse duration of less than 30 μs, the threshold depends only on the specific absorbed energy (SEA) (proportional to the SEA). The minimum required UPE is 5 mJ kg-1 per pulse.

MPU in cats was recorded in works [148, 152]. They had a frequency of the order of 38 kHz, regardless of orientation, pulse duration (up to 30 μs), carrier frequency (918 and 2450 MHz), field polarization and type of emitter. The authors studied the correlation of the frequency of MPU with ten anatomical parameters of animals. It turned out that this occurs only for a value greater than the axis of the internal cavity of the skull, although a quantitative assessment of this correlation is not given. Based on the results obtained, the authors estimate the frequency of human MPU to be 7...10 kHz.

J. Lin and his colleagues recorded evoked potentials in the brain stem and scalp of cats [205]. It was also shown here that a microwave pulse and an acoustic click lead to responses that are similar in shape.

Works [151, 156] show that the system of ossicles is His ear plays practically no role in the perception of radio sound. In particular, their damping by filling the middle ear cavity with mineral oil did not lead to changes in the responses recorded in the nuclei of the brainstem. Studies

on laboratory animals showed the excitation of mechanical vibrations in the tissues of the head by directly recording them using a piezoceramic sensor inserted into the tissues [221]. In these works on experimental animals, it was shown that the frequency of oscillations of the microphone potential excited by microwave pulses corresponds to the calculated value obtained from the concept of a single-circuit Lin model. Thus, it was shown that resonant oscillations are excited in the tissues of the head with a frequency determined by the radius of the spherical brain and the speed of sound propagation in the tissues.

Thus, it can be assumed that when irradiated with microwave pulses, radio sound is accompanied by mechanical deformation of hair cells and arises as a result of electromechanical interaction initiated at the periphery of the cochlea.

At the same time, publications appeared devoted to the excitation of mechanical vibrations in various media, including liquid ones, when these media are irradiated with pulses of microwave electromagnetic energy.

From the above literature review, several significant generalizing conclusions can be drawn:

1. There is no doubt about the presence of the effect as an objective but existing and occurring at PPM, starting from several tens of mW cm-2. 2.

The quality of perceived radio sound is related to benefits of the auditory system of the perceiver. 3. The connection between the quality of perceived radio sound is obvious with pulse sequence parameters.

4. The subjective volume of radio sound depends on:

a) on the intensity of ambient noise;

b) on the carrier frequency;

c) on energy flux density (EFD) at pulse durations up to 30 μs;

d) on the pulse repetition rate at their constant Duration and MRP;

e) on the duration of pulses at a constant repetition rate and PPM.

5. The primary element where responses to MI EMR are recorded and when destroyed, responses are not recorded anywhere in other parts of the auditory system, is the cochlea of the hearing organ.

6. In terms of their characteristic features, responses to pulsed EMR do not differ from those for pulsed acoustic exposure.

7. The presence of MPU in response to pulsed EMR indicates the conversion of electromagnetic energy into mechanical energy as the primary act of interaction of EMR with the anatomical structures of the head.

8. The correlation of the MPU frequency with the geometric dimensions of the head allows us to consider the head in the process of converting EMF energy into mechanical energy as an acoustic resonator.

9. J. Lin's single-circuit theoretical model demonstrated the energetic possibility of excitation

receptor structures of the cochlea of the organ of hearing by mechanical vibrations during the thermoelastic transformation of EMR energy, but could not explain the experimental data on the spectral composition of radio sound.

10. Attempts to explain the effect of radio sound by the direct effect of EMR on neural structures lack experimental confirmation.

The history of the development of research into the phenomenon of radio sound is presented in detail in [121].

Chapter I

HYPOTHESIS ABOUT THE ACOUSTIC NATURE OF THE MECHANISM OF BIOLOGICAL ACTION OF PULSE MICROWAVE FIELDS

2.1. Basic Prerequisites

Over the course of decades, a completely definite attitude has developed towards microwave radiation as a heat producer. This was mainly the result of the use of microwave energy in industry and medicine as an influencing factor in heating the deep layers of an object.

The development of electronics and the development of powerful pulsed devices and microwave systems have necessitated the study of the effects of pulsed radiation on biological objects.

Research in this area has shown that at sufficiently high pulse powers, effects that were previously unknown under the influence of continuous radiation began to be observed, despite the significantly lower level of the average value of the emitted microwave power in the pulsed mode, which does not lead to any noticeable heating object [89, 91, 171]. Many authors have made assumptions about the existence of subtle mechanisms for converting the energy of pulsed microwave EMR absorbed by a biological object. Moreover, we are talking not only about the impact of strong pulsed fields, but also very weak ones [100, 119, 122, 217]. From the point of view of searching for the mechanisms of the biological action of pulsed microwave EMR based on the observed bioeffects The phenomenon of radio sound is of great interest. The fact of the presence of zero beats between the acoustic signal and the harmonics of the field pulse repetition frequency

Microwave [96] allows us to put forward as a working hypothesis an assumption about the mechanical nature of the observed thermal effects and consider the phenomenon of radio sound as a particular manifestation of a general property inherent in all biological objects, and, in the light of this assumption, consider the experimental data that cannot be explained by thermal theory.

An analysis of the literature data allows us to come to the conclusion that the observed specific microwave effects have much in common with the results of studies on the effects of ultrasound (US) on biological objects [9, 163, 217]. Thus, for further consideration of the issue, it is necessary to accept that part of the electromagnetic energy absorbed by a biological object and converted into heat is transformed into the energy of mechanical vibrations. Let us also assume that the curve of the object's temperature change must have a sharply nonlinear character during the action of the microwave EMR pulse, i.e., a thermal pulse must be formed in the object. It can be assumed that this property should be common to all biological objects capable of absorbing high-frequency electromagnetic energy to one degree or another [105].

It is interesting to compare the hypothesis put forward with the mechanism of propagation of a thermal pulse in solids, which manifests itself in the presence of a heater or a thermal converter and a thermal receiver.

One of the ways to create a thermal pulse is to use the power of a pulsed microwave source by absorbing it in a thin metal film deposited on one surface of a dielectric crystal. In this case, the integral thermal pulse arriving at the receiver corresponds to the input power for small crystal sizes. This indicates that the mechanism of energy transfer is indeed thermal [67]. The use of microwave power pulses as a heat source is also indicated in [131]. It is noted here that the agreement for various substances studied between the velocities corresponding to the observed arrival times thermal pulses, and the predicted rates of propagation of phonon energy clearly shows that the use of the rate of propagation of acoustic energy in describing undissipated thermal energy in dielectric crystals is completely justified. This statement plays a large role in the proposed mechanism, given that a large number of biological objects have an ordered structure, i.e., the front of the thermal pulse in such objects can be quite small.

Consideration of qualitatively adequate observed effects when a biological object is exposed to microwave EMR and ultrasonic pulses makes it possible to identify the physical forces acting on the object under study, the numerical values of which will allow us to proceed to assessing the contribution of mechanical oscillations excited by microwave EMR pulses to the formation of specific effects.

The history of works devoted to the excitation of mechanical vibrations in media by thermal pulses goes back almost a hundred years, but the first works devoted to a serious analysis of the processes occurring during this process appeared only a few decades later [32, 33].

Much later, work [167] appeared, also devoted to the effect of microwave electromagnetic radiation on liquid media in order to excite mechanical vibrations in them. A 0.15 M solution of KSI was used as an object. The liquid, being in a container ($0.3 \times 0.3 \times 0.3$ m^3), was irradiated from above using the open end of a rectangular waveguide with a carrier frequency of 2450 MHz. The radiation intensity was within 5.3 W cm^{-2}. The authors used a special hydrophone with high sensitivity as a receiver of mechanical vibrations. At a microwave pulse duration of 27 μs, the pressure amplitude of excited mechanical vibrations in an aqueous solution of KSI at a temperature of +4 °C, at which the coefficient of linear thermal expansion of water is zero, decreases to zero. From this it was concluded that the process of excitation of mechanical vibrations during pulsed microwave irradiation of liquids is directly dependent on their thermal characteristics.

The range of media in which excited mechanical vibrations were recorded is quite wide: — electrolytes, pure liquids, metals, and coal [181, 237].

Theoretical issues of the processes of excitation of mechanical vibrations in liquid media by microwave EMR pulses are considered in works [141, 179, 183, 207].

Along with the works described, publications appeared on the effect of pulsed laser radiation on liquids. Work [56] describes a simplified thermodynamic model of the effect of a pressure jump in a liquid. It is shown that this model is consistent with experimental data in a wide range of pressure jumps (correspondingly, in a wide range of laser pulse power) and with wide variations in the properties of the liquid.

The results of studies on the conditions for excitation of mechanical vibrations in liquid media created the prerequisites for a qualitatively new approach to studying the effect of radio sound and identifying its nature. At the same time, the analysis of these works showed that it is necessary to determine the very conditions for the excitation of mechanical vibrations, on the one hand, from the parameters of the medium and its geometry, and on the other hand, from the parameters of the influencing microwave pulse.

Revealing the mechanism of radio sound, as we see it, is associated with determining the amplitude-frequency characteristics of excited mechanical vibrations in limited volumes. To do this, it is necessary to solve the following problems:

1. Determination of the dependence of the parameters of excited mechanical oscillations on the parameters of microwave pulses.

2. Determination of the conditions for excitation of various modes of mechanical vibrations and the possibility of focusing the energy of the electromagnetic field in liquid spherical models.

3. Clarification of the nature of radio sound in the perceived frequency band.

This will answer the following questions:

1. Why, when a person's head is irradiated with microwave pulses, the frequency of excited oscillations (or the auditory sensation) is not equal to the pulse repetition frequency?

2. What is the source of excitation of mechanical vibrations and does the frequency of excited mechanical vibrations depend?

fluctuations from the parameters of the absorbing electromagnet the energy of an area that is part of the total volume of the body

3. How to explain the sharp change in the threshold for the perception of radio sound at certain frequencies and the existence of several "types" of radio sound?

It was assumed that the development of such works should lead to the identification of still unclear aspects of the radio sound phenomenon through its modeling.

2.2. Anomalous biological effects of pulsed microwave EMR

Analyzing the literature data, it can be noted that the kinetics of the studied parameters of biological objects under thermal action and under the action of microwave EMR pulses of non-thermal intensities are mutually inverse. Works [90] show that when a frog tibial nerve specimen is irradiated with microwave EMR pulses, the speed of propagation of the excitation wave and the amplitude of the action potential (AP) decrease synchronously with the latent period. At the same time, results were obtained that contradict, on the one hand, ideas about the magnitude of absorbed power and, — on the other hand, data on quantitative and qualitative changes observed in a similar object during thermal exposure [17] and exposure to continuous microwave EMR [40]. According to data [17], when a frog nerve preparation is heated from 0 to +20 °C, the speed of propagation of the excitation wave increases and the dependence of this parameter on temperature is approximately linear. The same picture occurs for the magnitude of the AP amplitude. Work [40] showed the effect of continuous microwave radiation on the speed of propagation of the excitation wave and the amplitude of AP in a frog nerve specimen. At an average power flux density (APMD) of 11 mW cm2, the increase in the speed of propagation of the excitation wave was +16% in 30 minutes, the heating of the drug by the 30th minute was 2 °C. According to data [17], when such preparations are heated by 2 °C, the increase in the speed of propagation of the excitation wave is within +6...+19%. A comparison of the results in this case indicates heat in the action of microwave EMR. In [90], with a field pulse repetition rate of 20 Hz and PMSRR = 100 mW cm-2 for 60 minutes, heating of the nerve preparation was 1 °C, the speed of propagation of the excitation wave decreased by 35...46% , AP amplitude decreased by 93...95%.

It must be emphasized that these data were obtained when the object was irradiated during the latent period throughout the entire irradiation time. When the drug is irradiated with microwave EMR pulses with the same parameters in the post-latent period, the observed effects disappear.

This result cannot in any way be explained from the perspective of thermal theory, since in both cases the amount of absorbed energy was the same. Slight heating of the frog nerve preparation under experimental conditions close to those described is also indicated in [162]. It can be assumed that part of the absorbed energy of microwave EMR pulses triggers an unknown mechanism of inhibition of the propagation of the excitation wave, leading to an anomalous effect. Noteworthy is the fact that the development of recorded changes in the observed parameters is preceded by a certain period of time, during which the values of these parameters are close to normal. This means that such a mechanism of action of microwave EMR pulses should cause local disturbances or damage (microdamage), which, accumulating, result in effects opposite to thermal action. It is obvious that at a certain value of PMSSR, it is possible to compensate for the increase in the speed of propagation of the excitation wave by the accumulation of microdamages. If the released heat does not disrupt the normal functioning of the object, then this state of the object could be considered boundary for dividing the observed effects into non-thermal (anomalous) and combined, in contrast to purely thermal ones. The data presented allow us to draw very important conclusions:

1. The functional state of the object, determined by the temperature during thermal heating, does not correspond to that when it is heated by microwave EMR pulses.

2. The energy of microwave EMR pulses absorbed by the object leads to changes in the recorded parameters, which are the opposite of those caused by thermal exposure.

The revealed contradictions between the amount of absorbed energy of microwave EMR pulses and the observed shifts in the functioning of the object allow us to put forward the main theses for searching for evidence of the proposed hypothesis of the mechanism of action of pulsed microwave EMR.

1. The energy of microwave EMR pulses absorbed by an object is partially converted into heat, and partially transformed into another, undetected type of energy.

2. This type of energy leads to such a disruption in the functioning of the object that the course of the temperature dependences of the main parameters reflecting the functional state of the object does not coincide with those during thermal action.

3. Starting from a certain value of the microwave EMR pulse energy absorbed by the object, the course of the temperature dependences of the main parameters of the object changes sign. The angle of inclination of these dependences to the x-axis reflects the contribution of each type of heat energy to the observed — effect and the unknown.

4. The development of the effect is preceded by a certain period of time, presumably necessary for the accumulation of local changes (possibly disturbances) caused by the presence of an unknown type of energy in the object, representing part of the transformed energy of microwave EMR pulses (presumably mechanical vibrations).

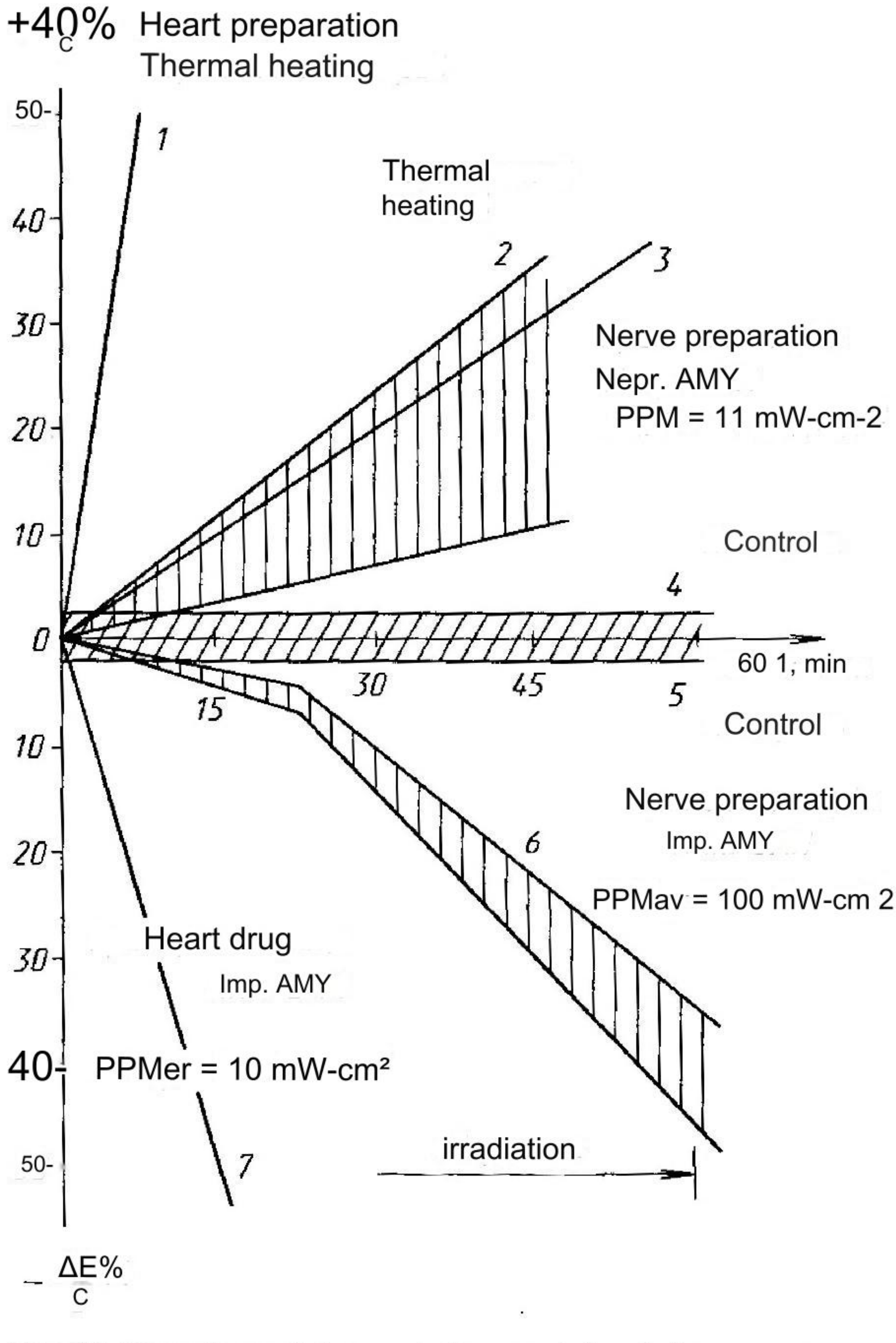
The listed points, naturally, cannot fully characterize the actually existing mechanism of the specific pulsed action of microwave EMR, or the subtleties of the action of this mechanism during irradiation of biological objects of various organizations. But even in this form, these points help to determine the main ways of searching for this mechanism, directions in setting up experiments to identify it.

Before moving on to the search for possible types of transformations of microwave pulse energy absorbed by an object, let's consider a few more experimental examples, which obviously will allow us to speak more confidently in the future in favor of one or another mechanism of action of pulsed microwave EMR.

It is known that with increasing temperature, the speed of propagation of the excitation wave in the cardiac muscle increases [232]. It was shown in [89] that when a whole frog preparation is irradiated with microwave pulses with PPMav = 10 mW cm-2, a decrease in the heart rate and an increase in the P-Q interval are observed. Irradiation was carried out in the Q-wave phase. With the same parameters of microwave EMR pulses, the time shift of these pulses into the phases of the cardiac cycle, characterized by an isoline, did not lead to visible changes. Thus, the amount of energy absorbed by the object remained constant, as in the experiments on the nerve preparation, but in the second case there was no effect, which also cannot be explained from the standpoint of thermal theory. If the irradiation was carried out without synchronization with the cardiac cycle, then the impact of the microwave EMR pulse in the phases of the P-, R- and T-waves caused an instantaneous short-term abrupt increase in the cardiac cycle. And, finally, irradiation with continuous microwave EMR with the same value of PMSSR did not lead to any noticeable changes in cardiac activity. According to [49], with an increase in temperature by 10°C, the speed of propagation of the excitation wave in the cardiac muscle increases by 1.8-1.9 times.

Similar results [91] were obtained on a frog neuromuscular preparation. Synchronization of microwave EMR pulses with the active state of the drug, including propagation of the excitation wave along the nerve, transmission of the signal through synaptic formations and partial propagation of the excitation wave along the muscle fibers, removed the block in the transmission of excitation from the nerve to the muscle. In the control, the block occurred at 7+1 minutes. A shift of the microwave EMR pulse by 50% relative to the stimulus delayed the block, compared to the control, to the 40th minute. These results are also not explained by thermal theory.

In Fig. Figure 13 shows the dependence of the change in the velocity of excitation wave transmission during thermal heating and during irradiation with continuous and pulsed microwave fields of varying intensity in preparations of the isolated tibial sciatic nerve and frog heart.



Rice. 13. Dependence of changes in the speed of excitation wave conduction during thermal heating and irradiation with continuous and pulsed microwave fields of varying intensity in preparations of isolated tibial sciatic nerve and frog heart

2.3. Ultrasonic analogues of anomalous bioeffects of pulsed microwave EMR

Comparison of the results of experiments on the effects of pulsed EMR microwave and ultrasonic oscillations on a nerve preparation leads to the conclusion that it is possible to compare these results and, therefore, to a certain extent, the adequacy of the mechanisms of biological action. According to [8], several studies have shown that exposure to a number of very weak doses of ultrasound, followed at intervals of several minutes, leads to paralysis of the frog's limbs. This means that the accumulation of disturbances under the influence of ultrasound, which separately cause a reversible biological effect, leads to irreversible damage. According to data [90, 162], during the first 20...30 minutes of irradiation with microwave EMR pulses there are no visible changes. In the next 20...30 minutes, the values of the observed parameters of excitation propagation changed sharply, which ultimately led to blocking of excitation propagation.

A very similar picture occurs when an immobilized frog is irradiated with microwave EMR pulses [89]. When an impulse hits one of the ECG waves, an abrupt change in the value of the subsequent cardiac cycle is observed. If the impulse does not re-enter one of the active phases of the cardiocycle, then the ECG is restored. If the hit occurs over several cardiac cycles, then the value of the cardiac cycle after a sudden increase remains at a new level. With a repeated series of hits, the value of the cardiac cycle increases. The picture develops until the onset of a block of the conduction pathways, or before the onset of blockade of the sinus node. It was noted in [163] that when an ultrasound pulse hits systole, the value of the cardiac cycle increases abruptly.

The following comparison is interesting here. Both in experiments on the nerve preparation and on the frog heart preparation, visible disturbances occur only when the preparations are irradiated at the moments of their active state (latent period for the nerve preparation and P, Q, T waves for the heart preparation), i.e., at moments characterized by the redistribution of ion currents through the membranes.

It is extremely interesting to compare the results of exposure of brain tissue to ultrasound and pulsed microwave EMR. The work [8] shows the destruction of brain tissue by single pulses of powerful ultrasound. Starting from a certain point in time (less than 1 s), the cavitation effect of ultrasound, i.e., mechanical damage, begins to introduce into the observed effect.

Thus, with an ultrasound pulse duration of 10 s, the intensity required to destroy brain tissue is about 104 W cm². According to Fraser [110], to inactivate the brain of small animals, he used EMF irradiation with a specific absorbed power per pulse (SAPP) of 1 MW kg, which led to a temperature increase rate of the order of 100 °C s-1,

Changes in the functioning of the neuromuscular drug are indicated in [39]. When exposed to microwave EMR pulses with a power of 1 MW and a duration of 10 ns in the millimeter range, excitation of the neuromuscular drug without noticeable heating was shown. It is also necessary to note the interesting results of the reaction of biological objects to turning on and off microwave EMR [114].

The hypothesis under consideration is presented in more detail in [92]. The excitation of mechanical vibrations, as a factor that can play a leading role in the formation of specific effects of microwave EMR, could explain many observed effects, including radio sound. Indeed, the presence of beats when the human head is irradiated with EMR pulses with the simultaneous supply of a tonal acoustic signal already speaks in favor of a mechanism for the perception of auditory sensation, similar to a physiologically normal one.

On the other hand, calculated data on the magnitude of the sound pressure amplitude [206] and direct experimental measurements using piezoelectric sensors carried out by Rolsen and J. Lin [219] showed that to excite a pressure wave of 1 dyn cm² it is necessary UPM is about 100 mW cm³, i.e. in this case, the effect should be classified as thermal. However, if we do not take into account the attenuation of the sound wave in the tissues, then the pressure amplitude two orders of magnitude greater than the threshold of audibility can be considered sufficient for the perception tia sound. In this case, the effect of radio sound can be classified as non-thermal, since the SMA will not exceed 1 mW cm-3 and can be considered as a possible manifestation of the action of mechanical vibrations.

Thus, the considerations presented here, along with the existing thermoelastic concept of radio sound, determine the need for extensive experiments to study the conditions and processes of excitation of mechanical vibrations in biological media by microwave pulses.

2.4. Brief conclusions

Analyzing the data presented here, we can come to the following conclusions:

1. The effects observed when biological objects of various levels of organization are irradiated by microwave EMR pulses cannot be explained by assessing the total heating of the object within the concept of a nonspecific action of an electromagnetic field.

2. The dynamics of the development of the observed effects when an object is exposed to microwave EMR pulses and cavitation ultrasound pulses is of a similar nature.

3. The question can be raised about the role of the acoustic factor in the formation of the biological effects of pulsed microwave EMR.

Chapter III

PHYSICAL MODELING OF THE RADIO SOUND PHENOMENON

3.1. General provisions and prerequisites for choosing models

An analysis of the literature shows that empirical methods predominate in studies of the effect of radio sound. This has led to the fact that, although we have a fairly large volume of all kinds of specific experimental facts characterizing the phenomenon under study, we do not have a holistic picture of its mechanism. In addition, the results of psychophysical studies related to the study of the characteristics of the emerging auditory image when the human head is irradiated with EMR pulses always depend on the subjective assessment of a particular individual. Considering the fact that, as a rule, a limited number of subjects participate in natural experiments, it is practically impossible to expect accurate quantitative data from them and stable repeatability in different laboratories. It is also important that a full-scale experiment at the EMR power levels necessary for the manifestation of the effect cannot be carried out for a long time, since this is not indifferent to the health of the subjects and, therefore, a systematic study of the characteristics of radio sound in this way is unsafe. Apparently, to construct a holistic concept of the mechanism of radio sound, research of a different nature is needed, which would make it possible to make certain generalizations based on the accumulation of material.

In conditions where, as part of a full-scale experiment, we study study of the mechanisms that form the effect of radio sound, practice virtually impossible or extremely labor-intensive, the only way to

An acceptable direction for deeper studies of this phenomenon seems to be the use of the modeling method [25].

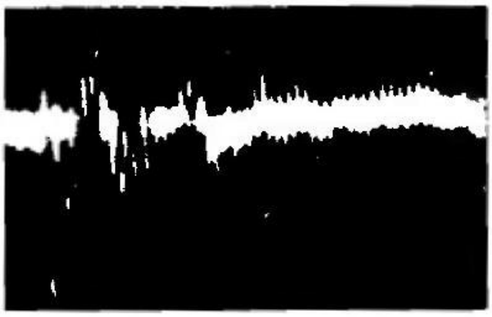
Studying the effect of radio sound using the modeling method makes it possible to analyze certain experimental data within a wide range to understand the entire mechanism of this phenomenon as a whole. It is also important that in model studies there are no restrictions associated with meeting safety requirements within the framework limited only by the properties of the model itself.

At the same time, despite the advantages of the model research method, which allows one to purposefully select from a set of facts the most significant ones for the problem for which the model is being built, the initial set of data that formulate the requirements for the model is inevitably subjective.

By postulating a general algorithm for the performance of certain functions by nature, it is possible, in principle, to determine what set of properties the proposed mechanism of the phenomenon should have. Moreover, the more complex the effect under study, the less definite the task of dividing it into separate mechanisms becomes and the more uncertain the requirements for the characteristics of models of these mechanisms become. The question arises: which of the physical or mathematical models is most advisable to use in each specific case to model the mechanism under study? The first step in modeling the effect of radio sound was made by J. Lin [54, 201-203]. The mathematical model he proposed and developed significantly advanced the understanding of the mechanism of the phenomenon under study, however, as noted above, it was unable to explain some of its essential features. The reason for this was the author's incomplete consideration of experimental data when constructing the model and the unlawful simplification of the real picture of the phenomenon. However, it is important to note that a more complete correspondence of the model to the prototype would inevitably lead to a significant complication of mathematical equations and, accordingly, methods for solving them, or to the impossibility of solving them without formally imposing on them certain conditions that are inadequate to nature. Regardless of the degree of adequacy of the mathematical

A theoretical model in nature would ultimately require an experiment to confirm this model. However, the purely mathematical modeling method does not take into account its physical feasibility. A similar picture is clearly illustrated in work [65], devoted to the study of the mechanisms of the cochlea of the hearing organ using the method of electrical models. Mathematical models of the cochlea of the hearing organ were built, as a rule, with the aim of understanding the processes of frequency analysis of signals in the auditory system. As computer technology developed, the complexity of the equations with which the authors represented oscillatory processes in the cochlea increased significantly. In works devoted to mathematical models of the hydrodynamic system of the cochlea, the latter was considered as a multidimensional oscillatory structure described by a linear and sometimes nonlinear high-order partial differential equation with variable derivatives [65]. This position eventually forced researchers in the field to move toward physically feasible models. In mathematical models used to solve biophysical problems, it is not always possible to introduce conditions characterizing the state of this system in the form of appropriate coefficients or limits of applicability. This leads to the introduction of an additional factor of uncertainty when studying it. Physical modeling in this case seems more appropriate. In a certain sense, this is a more accessible modeling method than the mathematical one, which does not require detailed study of the individual components of each of the intermediate mechanisms of the entire phenomenon as a whole. In fact, there is enough knowledge about the transfer function of each of these mechanisms that it would be possible to build a physical model similar to nature. In this case, the functional state of biological structures, which are links of the whole mechanism, is automatically taken into account. The possibility of implementing individual mechanisms in the form of functional physical blocks is also decided directly during the selection of a specific physical model, naturally, if there is a fundamental possibility of creating a physical analogue.

It is interesting to note that the physical modeling method is widely used in the study of dolphin bioacoustics. One of the main problems in this area of research is the sonar of dolphins. One of the hypotheses regarding the emission of sound by dolphins was proposed by Lilly [200], who believed that echolocation clicks are caused by "impact excitation of resonant frequencies and harmonics in the air-filled cavities of the head" [79]. And although Lilly's hypothesis is disputed, and the direction itself pursues other goals than the study of radio sound, nevertheless, some methodological issues can be successfully borrowed to study the effect of radio sound using the method of physical modeling. Of particular interest in this regard is a model experiment on shock excitation of acoustic vibrations in spherical volumes. In Fig. Figure 14 shows a photograph of emitted mechanical vibrations recorded in a small (200×50×50 cm³) aquarium with water during a pressure surge inside a rubber sphere with a diameter of 3 cm.



Rice. 14. Radiated acoustic vibrations (borrowed from [79])

Two frequencies are emphasized during the emission: approximately 250 Hz and 4.. .6 kHz. The first frequency corresponds to the radiation of the ball as a resonant system with concentrated parameters, the second to the vibrations of the air inside the ball as in a rigid sphere [79].

The fundamental possibility of physical modeling of radio sound is based primarily on experimental data on the excitation of mechanical vibrations in various media—electrolytes, pure liquids, metals [13, 92, 166, 227].

3.2. Excitation of mechanical vibrations by EMR pulses of various durations and repetition rates

Research on the characteristics of excited mechanical vibrations and their relationship with the parameters of microwave pulses and properties of liquids, their goal was, first of all, to study the general patterns of excitation of mechanical vibrations in liquids and to determine the possibility of interpreting the results obtained in the application to radio sound, i.e., the possibility of using the method of physical modeling of radio sound as a research method for searching for the mechanism of this phenomenon. This would make it possible to abandon field studies, which are associated not only with the need to conduct research on humans, but also with a subjective assessment of the research results themselves. Secondly, an explanation of the radio sound threshold curve [234] (Fig. 9) was fundamentally important for understanding the mechanism of radio sound. In accordance with Lin's concept [206], the range of frequency values of the mechanical resonance of the head covers the region 7...10 kHz; in the work of other researchers, this region reaches 18 kHz [145].

On the given threshold curve of radio sound (Fig. 9), this frequency region captures at its boundaries two qualitatively different sections: — the region 7...8 kHz, characterized by high threshold values, and the region 10...12 kHz, which corresponds to the lowest threshold values sensitivity of radio sound perception. This circumstance does not allow us to draw unambiguous conclusions regarding the possibility of treating the region of minimum thresholds as a region corresponding to the resonance frequency of a single-circuit system and, accordingly, to consider the radio sound mechanism as a whole on the basis of this concept. The processes of excitation of mechanical vibrations were studied in single-circuit cylindrical and spherical models.

3.3. Methods and instruments for excitation and recording of mechanical vibrations in liquid media by microwave pulses

Since the full-scale experiment on radio sound consisted of irradiating a human head with microwave pulses, which to a first approximation represents a sphere, the choice of a spherical volume of liquid for studying the conditions for excitation of mechanical vibrations can be considered the most appropriate.

The fundamental possibility of performing these experiments is based on the results of works [92, 94], which show that mechanical vibrations can be excited by microwave pulses in any polar liquid and electrolytes. From this point of view, the choice of liquid filling the sphere is not important, since the data obtained can be transferred to other media with known values of sound speed and attenuation.

Spherical volumes, when mechanical vibrations are excited in them, have a whole spectrum of frequencies [55]. In this regard, to simplify the assessment of the results obtained and to identify the dependence of the parameters of mechanical oscillations excited in a liquid on the parameters of the microwave pulse sequence, a test tube with liquid placed in the action zone of a pulsed EMR was chosen as the simplest model. In this case, the column of liquid filling the test tube has the properties of a quarter-wave resonator with a certain quality factor.

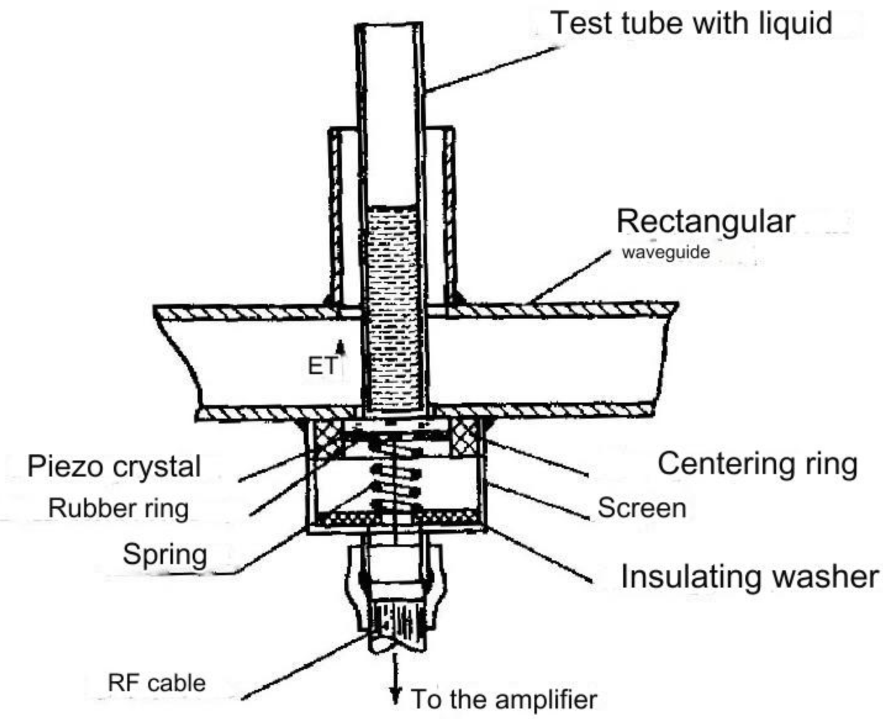
The simplicity and clarity of such a system, as well as complete equivalence with the theoretical model of J. Lin in its main formal characteristics, allow us to consider it as an adequate physical model for studying the effect of radio sound.

To record mechanical vibrations excited in a liquid, piezoceramic transducers with a sensitivity of 106 V dyn cm² in the frequency range 40...2 were used. 104 Hz and uneven amplitude-frequency characteristics ±5 dB. Calibration of the sensors was carried out tod pistonphone [79].

The choice of the irradiator was dictated primarily by the condition of the minimum possible radiation of microwave energy into free space in order to reduce the amplitude of the induced parasitic signal on the input circuits of the recording equipment and safety during operation.

To irradiate physical models with small volumes of liquid, a closed rectangular waveguide with a cross-section of 31×240 mm² with a pulse power flux density (PPD) of up to 2 W cm² in the center plane was used.

In Fig. Figure 15 shows a diagram of the location of the test tube in a closed rectangular waveguide and the recording of mechanical vibrations excited in the liquid using a piezoceramic transducer.



Rice. 15. Irradiation of a test tube in a closed rectangular waveguide with a cross section of 31×240 mm²

Glass flasks and plastic balls filled with an absorbing liquid, which, as a rule, was ethanol, were used as spherical resonators in order to excite more intense mechanical hesitation.

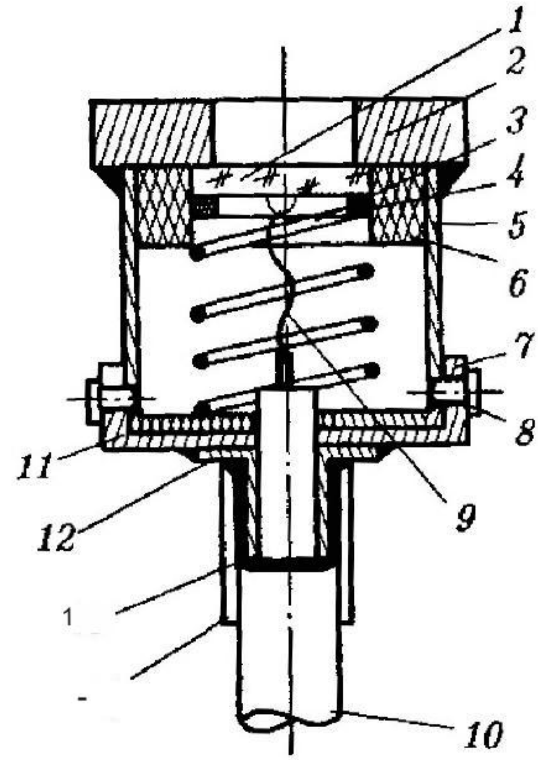
For irradiation of large volumes of liquid (up to 3 l) The irradiators were changed in the form of an open waveguide with a cross-section 10×72 mm² and a rectangular horn with an aperture of 90×120 mm², used at a frequency of 2375 MHz with PPM 140 and 20 W-cm-2, respectively. The source of microwave oscillations was the development microwave pulse generators previously developed by the author based on laboratory generator GS-6 and medical device for microwave therapy "Luch-58-1" [93]. Maximum you- the running power per pulse at a frequency of 800 MHz was 120 W, at a frequency of 2375 MHz - 500 W.

Registration of mechanical vibrations excited in spherical glass resonators is carried out using piezoceramic transducers included in the wall of the flask. To glue the transducer on the side surface of the flask, a hole is made by grinding with a diameter equal to or slightly smaller than the diameter of the transducer. Thin stranded conductors are first soldered to the converter plates. Then, using epoxy glue, the converter is mounted on the walls of the flask.

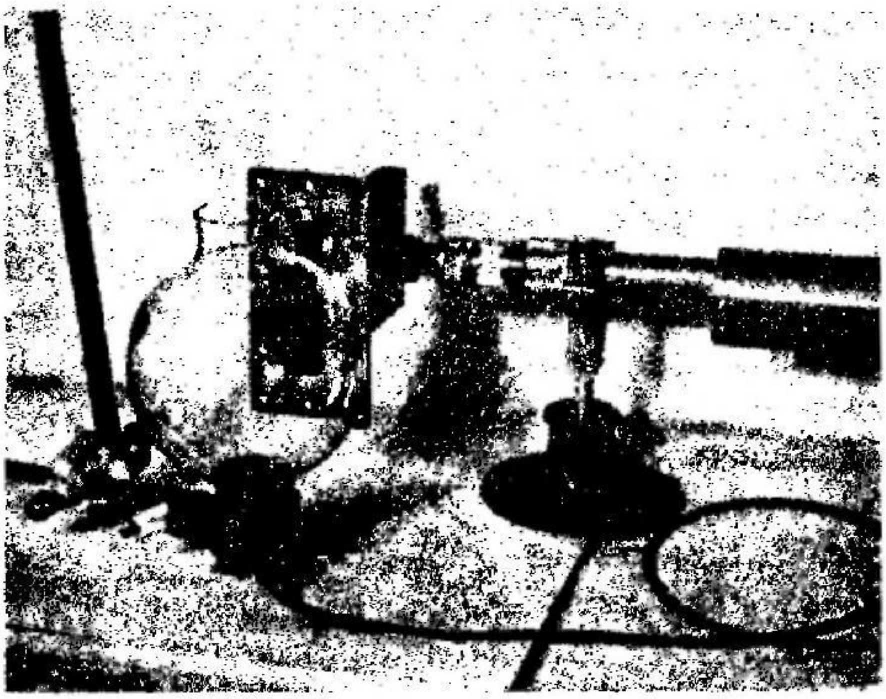
To output internal conductor, a small groove is made at the edge of the hole in the bulb using a diamond file. The output coaxial cable is attached to the wall of the flask using epoxy glue along a length of 15...20 mm. After the glue has hardened, the flexible conductors of the converter are soldered to the cable so that the cable screen is soldered to the inner lining of the converter. The soldering area is also covered with epoxy glue. Registration of oscillations can also be carried out using an autonomous piezoelectric receiver, on which a resonator with liquid is directly installed. Plastic spherical resonators are also installed on the same receiver.

13 14

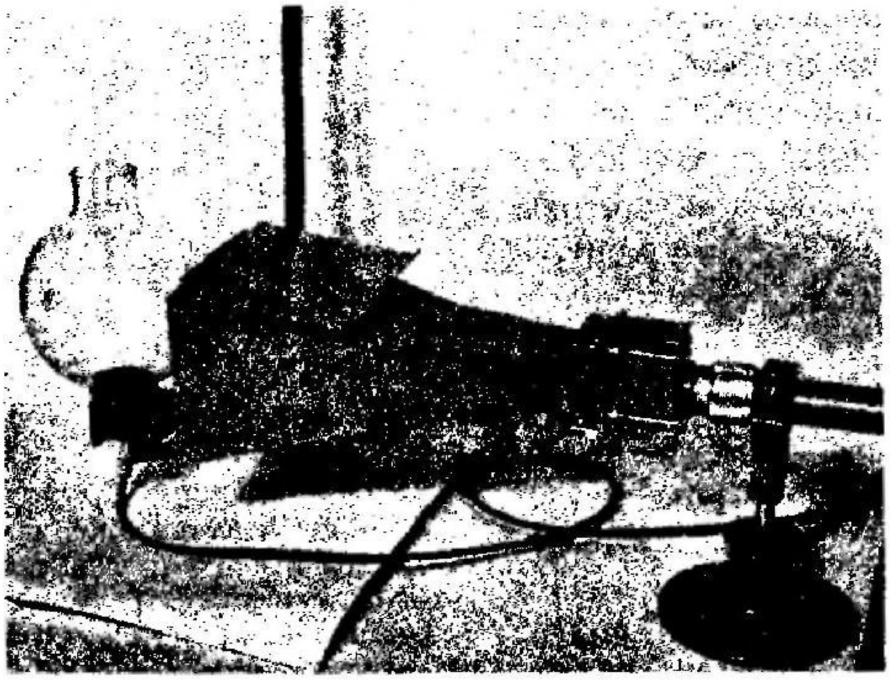
In Fig. Figure 16 shows a cross-section of the design of an autonomous piezoreceiver.



Rice. 16. Section of the design of an autonomous 3 piezoreceiver: piezoelectric transducer; 2 - base (brass); put — pressure spring; 4 — insulating washer (textolite 0.15...0.2 mm thick); 5 — core 10 (brass); 6 centering washer (textolite); 7 removable cover (brass); 8 — pins (brass); 9 - flexible conductor; 0.5 - cable; 11 — insulating gasket (textolite mm thick); 12 glass; 13 - cable screen; 14 — tube (polychloro-vinyl)

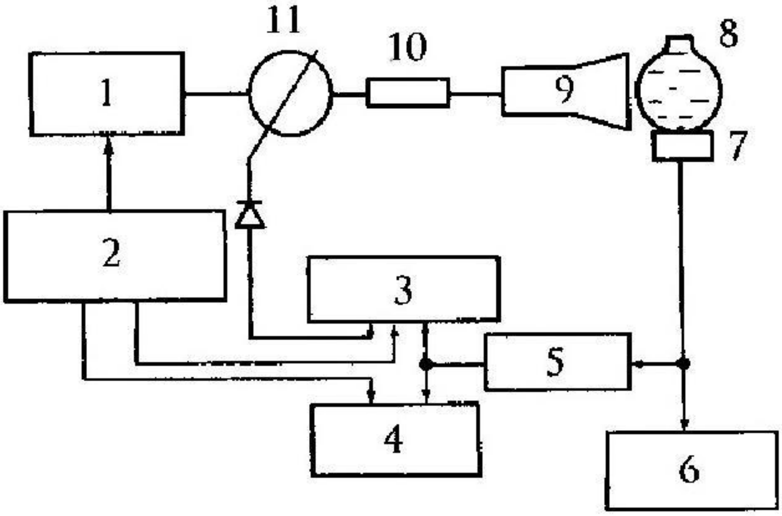


Rice. 17. Irradiation of a sphere with a rectangular waveguide with a cross section of 10x70 mm²



Rice. 18. Irradiation of a sphere with a rectangular horn with a cross section of 90x120 mm²

In Fig. 17 and 18 show methods of irradiating spherical models, in Fig. Figure 19 shows a block diagram of experiments on excitation and recording of mechanical vibrations.



Rice. 19. Block diagram of an experiment on the excitation of mechanical vibrations in liquid spherical models:
1 — microwave generator; 2 square wave generator; 3 — oscilloscope; 4 frequency counter; 5 amplifier; b - millivoltmeter; 7 — piezoelectric transducer; 8 - flask with liquid; 9 irradiator; 10 valve; — 11 directional coupler

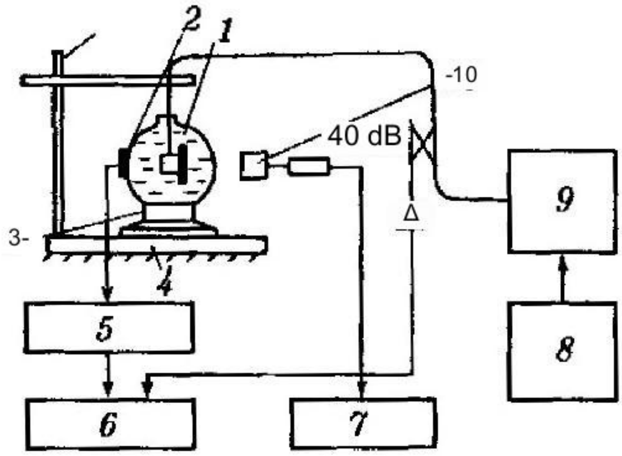
Irradiation of large spherical resonators at a carrier frequency of the order of 0.9 GHz showed that, as a result of diffraction, a parasitic microwave signal is induced on the piezoceramic transducer, making it practically impossible to register mechanical vibrations. To conduct an experiment at these EMR frequencies, a method was developed to excite mechanical vibrations in glass spherical resonators using a microwave applicator with a diameter of 13...15 mm, lowered into ethanol through the neck of the flask.

In all cases, when irradiating spherical resonators, it is necessary to apply all measures that reduce the mechanical vibration of the resonator from external sources. In our ex- In experiments for this purpose, sheets of soft thick rubber on which a tripod with autonomous piezoceramic receiver or plastic bottom from a large-capacity laboratory graduated cylinder to configuration of a spherical resonator.

As a rule, microwave generators are equipped with fans to select the generating heat, which serves as additional source of mechanical vibrations. Measures to reduce the vibration amplitudes are determined by the generator settings for rubber shock absorbers and damping of the HF cable so-using porous rubber, which is wound onto the HF cable in the form of strips.

It is advisable to conduct experiments in shielded, soundproofed rooms. A set of these measures makes it possible to work under conditions of a significant reduction in microwave pulse power (sometimes down to several units of watt) and to record signals taken from the plates of a piezoelectric transducer of the order of 10-5...106 V.

In Fig. Figure 20 shows a diagram of an experiment on excitation of mechanical vibrations in a spherical glass resonator using an applicator operating at a frequency of 915 MHz, with registration of these vibrations using a glued piezoceramic transducer.



Rice. 20. Excitation of mechanical vibrations by EMR pulses in a glass spherical resonator using a microwave applicator: 1 — spherical resonator; 2 - piezoceramic sensor; 3 — plastic mass bottom; 4 rubber gasket; 5 — amplifier; 6 — oscillating logograph; 7 wattmeter; 8 square pulse generator; 9 — microwave generator; 10 frame

Amplification of signals taken from a piezoceramic pre-educator under the influence of EMR, has its own special ness. As can be seen from the above conditions of trans-formation of EMR energy into acoustic, the amplitude of the removal output alternating electrical signal from the piezoelectric plates ceramic converter in order of magnitude can be 10-4... 10-2 V.

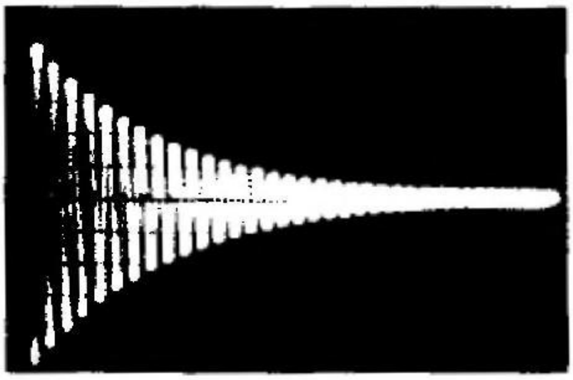
As a rule, amplification of weak signals against a background of noise is carried out using resonant amplifiers. In this

In this case, this could be all the more justified in view of the rather narrow frequency band of excited mechanical vibrations in experiments with a limited set of resonators. However, experience with microwave generators shows that even when operating on a closed load in shielded rooms [93, 98] in a pulsed radiation mode, a negligibly small induced potential from EMR on the input circuits of selective amplification equipment is sufficient to excite it at frequencies close to those recorded. This is natural, since when an induced EMR signal of pulse form is applied to the input of a selective amplifier, the latter is detected and the already isolated video pulse excites the selection circuits of the amplifier, i.e., shock oscillations are excited. And since an identical situation occurs when the energy of an EMR pulse is absorbed in a liquid of a cylindrical or spherical resonance, torus, then the artifact can easily be mistaken for the result. To test the possibility of using amplification equipment with selective properties, a V6-9 selective microvoltmeter was used in the experiment. The G5-54 generator was used as a source of rectangular pulses.

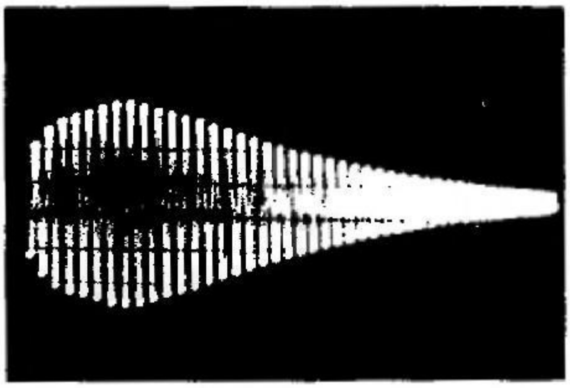
Previously, rectangular pulses with a duration of about 5...25 μs and a repetition frequency of about 100 Hz were supplied to the input of the selective microvoltmeter directly from the output of the G5-54 generator.

In Fig. Figure 21 shows one of the oscillograms of the output signal of a selective microvoltmeter when it is excited by rectangular pulses from a G5-54 generator in a tuning band of 1...20 kHz.

Then they turned on the microwave generator, loaded it onto an open emitter with a cross-section of 10x72 mm^2, and installed a spherical resonator with ethanol in close proximity to it. With the same parameters of the pulse sequence, the EMR pulse modulation mode was carried out at a carrier frequency of 2375 MHz. The selective microvoltmeter was located in a zone with an intensity within the permissible irradiation levels of the — order of 30...50 μW cm-2.



Rice. 21. Artifact of excited mechanical vibrations when a short rectangular pulse is applied to the input of a selective amplifier from a G5-54 generator (V6-9 selective microvoltmeter)

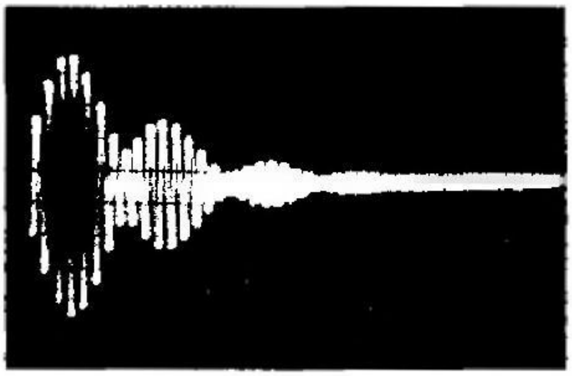


Rice. 22. Artifact of excited mechanical vibrations by a short induced microwave pulse with selective amplification (selective microvoltmeter V6-9)

In Fig. Figure 22 shows an oscillogram of the output signal of a selective microvoltmeter when the input of the device is open. A comparison of oscillograms clearly shows the possibility of an artifact when using selective amplification equipment even under acceptable conditions work.

The next step is to check the possibility of occurrence artifact was the registration of the selective output signal microvoltmeter when applying a signal to its input with pre-educator. Vibrations were excited in a test tube with ethanol according to the diagram shown in Fig. 15, using EMR for cha-800 MHz. Pulse power at the waveguide input — 70...75 W. The measured intensity of EMR in the area of dis-position of the selective microvoltmeter within

10 µW cm-2. The frequency of excited mechanical oscillations in ethanol and the tuning frequency of the selective microvoltmeter were somewhat detuned relative to each other in order to make it possible to observe zero beats between the signal taken from the converter and the one excited in the selective microvoltmeter due to the EMR induced on the input circuits and the detected in the device. In Fig. Figure 23 shows an oscillogram of such beats.



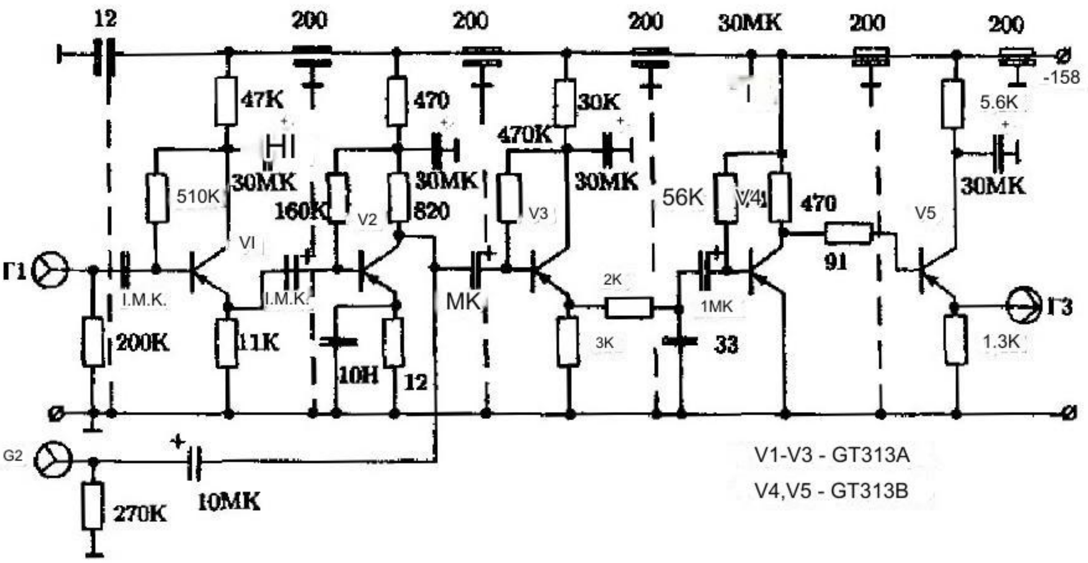
Rice. 23. Artifact of beats of communication frequencies during selective amplification of an induced microwave pulse together with an electrical signal taken from a piezoceramic transducer (selective amplifier V6-9)

The results obtained make it possible to demonstrate the possibility of an artifact occurring when experimenting even with such simple systems and devices under the influence of weak EMR.

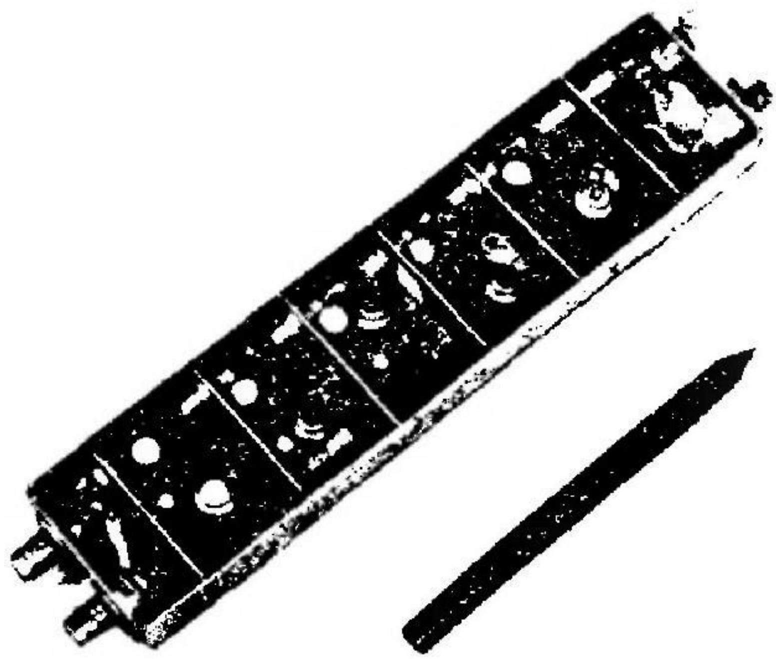
Thus, we can come to the conclusion that under these experimental conditions, eliminating the artifact can be achieved by expanding the amplifier bandwidth. In this case, for undistorted amplification of the video pulse formed on the input circuits of the amplifier, the amplifier bandwidth is determined by the known ratio β = 1/ti. where is the pulse duration. The applied values of Ti in experiments on irradiation of any model or biological systems with EMR in the decimeter range are practically limited from below by a value of 10-6 s, i.e. the value of b should be of the order of 1...3 MHz. The input impedance of the amplifier when working with piezoceramic transducers is ~105 Ohms. The amplitude of the output signal of the amplifier

The voltage can be set within 0.1...1.0 V. Therefore, the gain value can be determined within 500...1000, which is quite enough to observe the signal on the oscilloscope screen and carry out any of the - measurements.

A schematic diagram of the developed amplifier with parameters close to those described is shown in Fig. 24.



Rice. 24. Schematic diagram of a broadband amplifier



Rice. 25. Amplifier design (view with cover removed)

Due to the operation of the amplifier under conditions of a pulsed microwave field, in order to increase its noise immunity and reduce the tendency to self-excitation, the installation of the amplifier is sectioned; the housing and cover have an electrical contact along the entire connector line and are made of brass. The power bus is laid using block containers installed on transverse screens. A photograph of the amplifier installation with the cover removed is shown in Fig. 25.

The amplifier has three CP-50 type connectors, which are used to connect to a piezoceramic transducer and an oscilloscope. In order not to install a special switch when switching from working with a small signal to a large one, connectors ГI, Г2, Г3 (Fig. 24) allow working with the following gain values with different rearrangements of cables:

G. G, Ku = 500

G. - G_2, Ku = 37

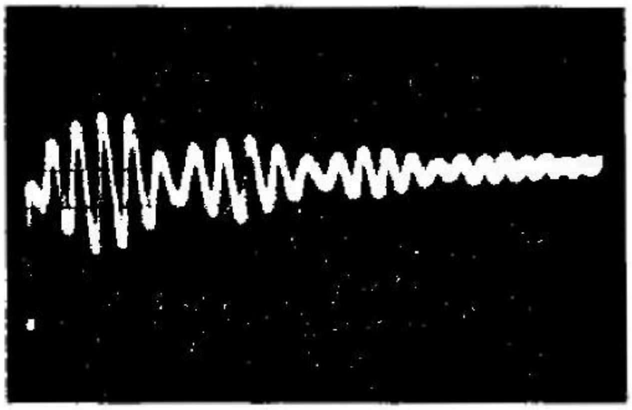
$Г_2 \rightarrow Г_3$, Ky = 13.

The arrows indicate the directions of the signal from input — to output, Ku gain.

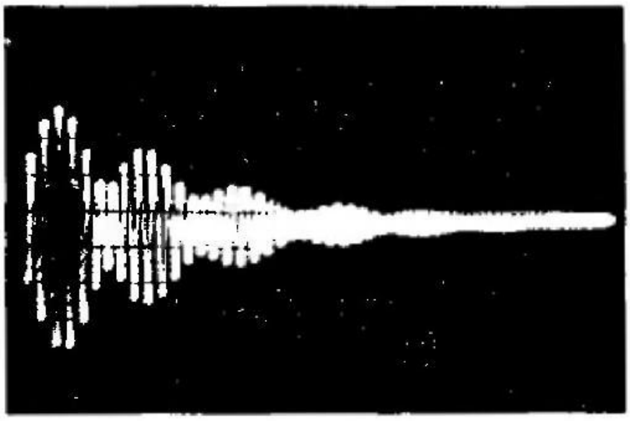
The developed amplifier was tested under the same conditions as the selective microvoltmeter. In this case, beats were observed in a test tube with incomplete filling. If the height of the liquid column and the height of the air column are selected so that their frequencies are close or multiples, then when mechanical vibrations are excited in such a system, beats can be obtained.

Test tubes of the same diameter with a height of 50 and 60 mm were used. The height of the liquid column in both cases was 40 mm. In this way, two systems of resonators were obtained: a liquid one with a height of 40 mm and an air one with a height of 20 mm. Accordingly, the frequency of mechanical oscillations excited in the liquid in both cases is unchanged, and the frequency of oscillations of the air resonator should change by half. This circumstance should appear when recording beats and indicate the absence of an artifact.

In Fig. 26 and 27 show oscillograms of the communication frequency beats for both systems.



Rice. 26. Communication frequency beats: liquid column — 40 mm; height, air column height 10 mm-

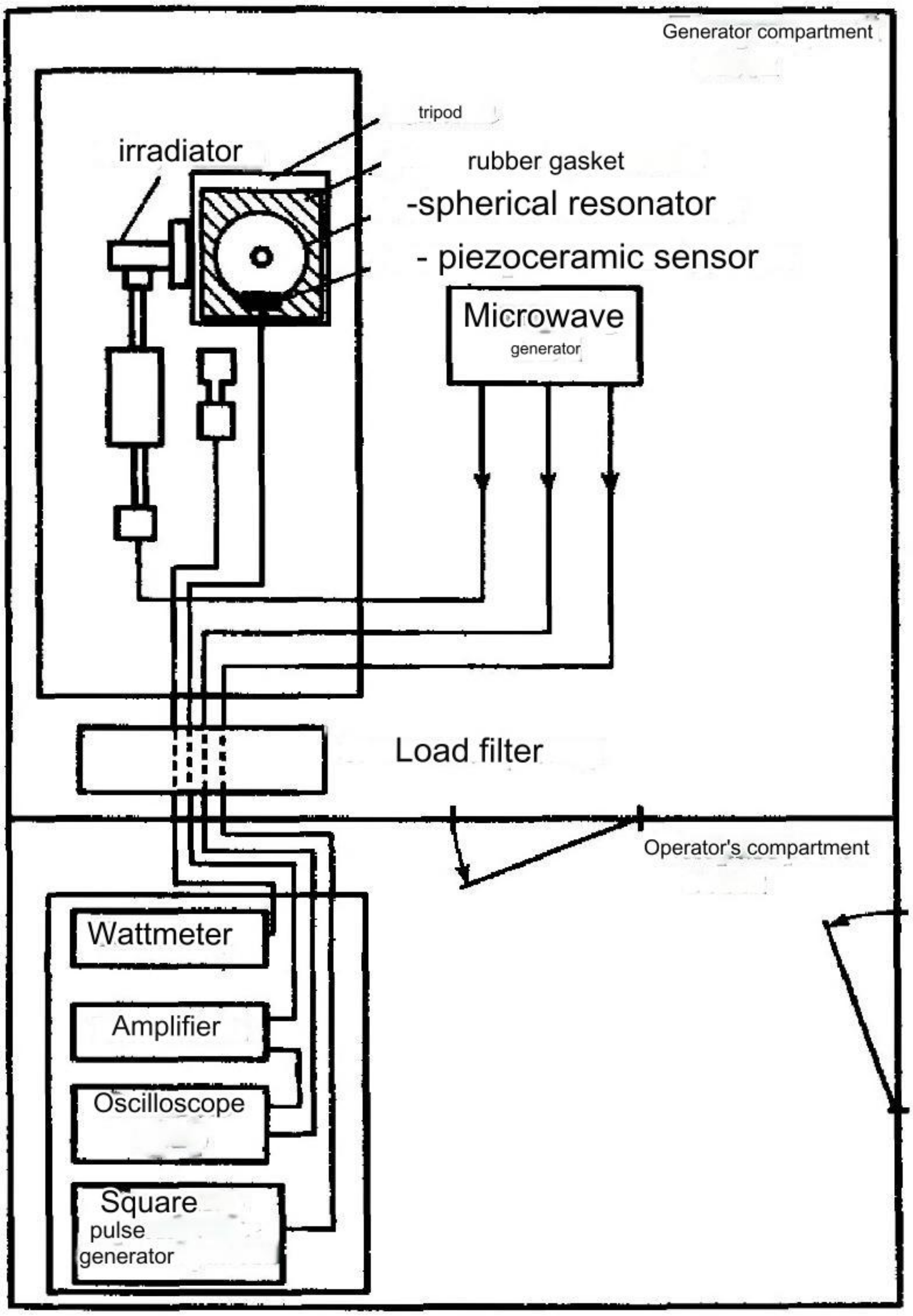


Rice. 27. Communication frequency beats: liquid column height 40 mm; air column height 20 mm

To illustrate the shorter beating process, the oscillogram in Fig. 26 was obtained at a higher sweep speed of the oscilloscope beam. It should be noted that when recording beats in the described resonator system, to obtain the recorded amplitude of the beat signal, the transducer was located inside the test tube in an air resonator due to the weak influence of the air column on the table.

bic of liquid. Bi-
morphic crystal [92].

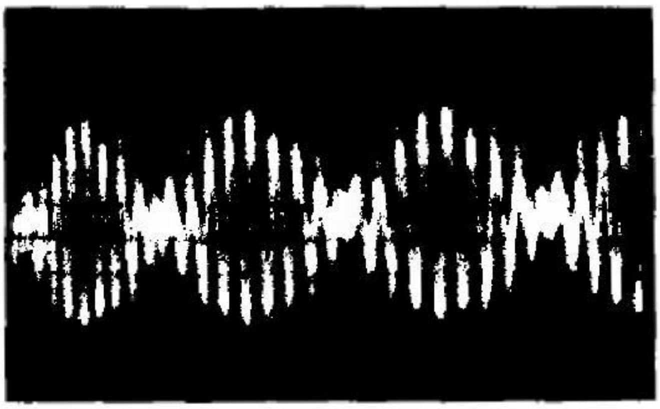
Experiments using physical models of the same should be carried out in shielded rooms with sound insulation, especially when working with open emitters [93]. In Fig. Figure 28 shows a diagram of the equipment layout in such a room.



Rice. 28. Layout of equipment
in a shielded room

In Fig. For comparison, Fig. 29 shows an oscillogram of the beats of communication frequencies when a test tube with ethanol is irradiated according to the diagram in Fig. 15 when exciting resonant oscillations and recording them using the developed amplifier.

The second signal is realized using acoustic electronics. rodinamic head, the radiation axis of which is directed



Rice. 29. Beating of mechanical vibrations excited in a test tube by EMR pulses with an acoustic signal

per test tube. In this case, a piezoceramic transducer serves as a mixer. Thus, we can assume that the use of a broadband amplifier and operation in a shielded room ensures the correct setup of experiments.

3.4. Single-circuit resonant models

J. Lin's single-loop concept of radio sound was studied on single-loop liquid systems.

Cylindrical model of the radio sound effect. The simplest system was a glass test tube with saline solution, which was a quarter-wave acoustic resonator. Irradiation was carried out in a rectangular waveguide at a carrier frequency of 800 MHz. The height of the liquid column in the test tube varied from 30 to 50 mm, the pulse repetition rate was within 10...104 Hz, and the pulse duration was 10-5...10-3 s. For all three columns of liquid (height 30, 40, 50 mm), mechanical vibrations were recorded on the oscilloscope screen. The periods were determined using marks on the screen mechanical vibrations (Table 4). Using the relations ηλ L= [2],

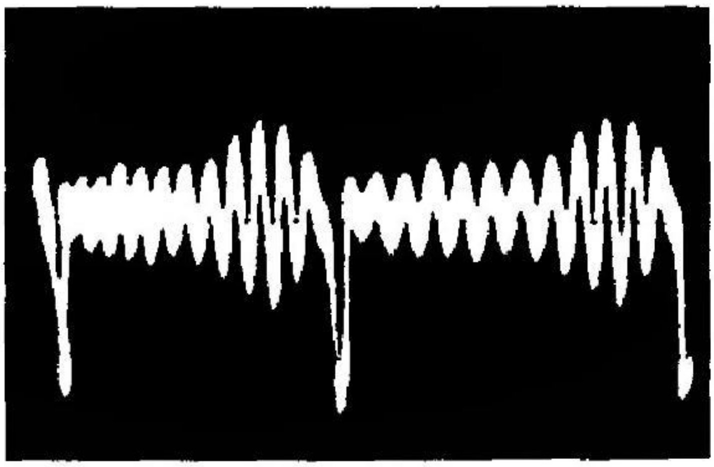
where L is the height of the column; d — wavelength, and C = 2, it is possible to obtain approximate values of the speed of sound in a liquid for three values of the height of the liquid column. A more rigorous expression is given in [103].

Table 4

Liquid column height, mm	Period of mechanical oscillations, μs	Mechanical vibration frequency, kHz	Wavelength, mm	Calculated average speed of sound, cm $^{-1}$
30	80...100	12...10	120	1.44-105
40	100...120	10...8	160	1.45105
50	140...160	7...6	200	1.42105

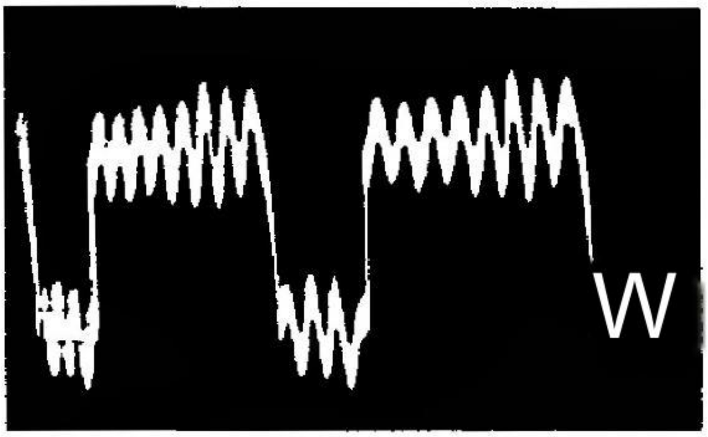
Taking into account the measurement error of the period (up to 10%) and the height of the liquid column (up to 3%), the data obtained are in good agreement with those given in the literature. Similar data were obtained for ethanol.

In Fig. Figure 30 shows an oscillogram of excited mechanical oscillations for one of the pulse repetition frequencies.
In this case, the duration of the microwave pulse is less than the half-period of the mechanical vibrations excited in the liquid.



Rice. 30. Excited mechanical vibrations in a cylindrical resonator by short microwave pulses

When the duration of microwave EMR pulses increases by on the oscilloscope screen, mechanical oscillations excited by the leading and trailing edges of heat physical impulse (Fig. 31). When changing the duration The microwave EMR pulse exhibits an interference pattern, caused by the phase relationship of mechanical vibrations tions excited by the leading and trailing fronts of thermal impulse. As the pulse duration decreases, the interference pattern becomes clearer.



Rice. 31. Excited mechanical vibrations in a cylindrical resonator by microwave pulses of increased duration

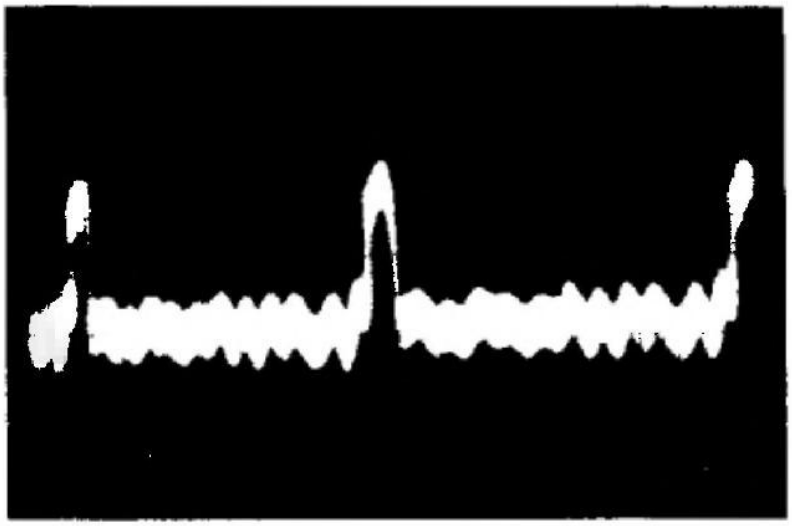
When the pulse duration is less than half the period of excited mechanical oscillations, the latter are observed only from the trailing edge of the thermal pulse. Starting from this moment, the interference pattern is observed with an increase in the pulse repetition rate [98].

Excitation of mechanical vibrations by both fronts where microwave pulse [92, 179] leads to the fact that we actually observe the summation of two damped oscillations, having having the same frequency and shifted in phase by n+ $\frac{2\pi}{T}\tau\eta$,

T is the period of natural vibrations of the mechanical system; Ti is the duration of the microwave pulse. Obviously, the amplitude of the resulting oscillation A will depend on Ti in the following way:

$$A\Sigma = \sqrt{A^2 + A3 + 2A,A, COS\ \pi + \frac{2ДЧ}{T}},$$

where A_1 = Ade-a, A_2 = Abe-alt-tu) amplitudes of damped oscillations baths, excited by the front and rear, respectively fronts of thermal impulse. Thus, A is maximum at ti = 2n+17, where n = 0, 1, 2... and is equal to A_1 + Ar and minimum 2, i.e., equal to A1-A2 at ti-pt. If we take into account that in the system under consideration the calculated value of the quality factor is about 20, and the maximum pulse duration did not exceed several values of T, then the attenuation within the pulse duration can be neglected and considered $A_1 \approx A2 \approx A0$.

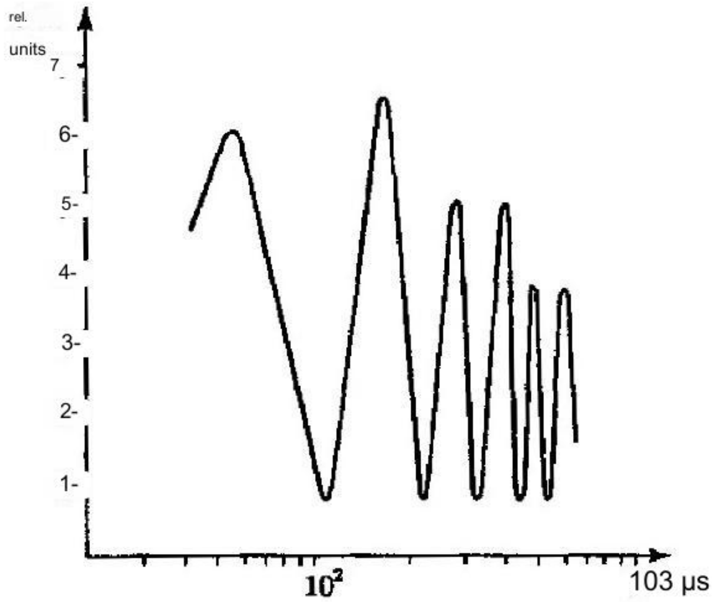


Rice. 32. Damping of excited mechanical vibrations in ethanol

Consequently, by changing the duration of the microwave pulse within the specified limits, it is possible to change the amplitude of excited mechanical oscillations from 240 at ti 2n+1m to complete suppression of oscillations at ti-pt. The minimum value of Ti is determined by the energy required to excite mechanical vibrations in the system.

In Fig. Figure 32 shows an oscillogram of excited mechanical oscillations at the moment of suppression.

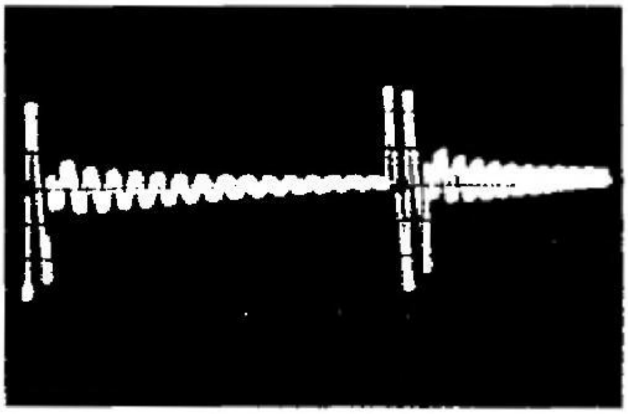
When the repetition rate of EMR pulses changes, the amplitude of mechanical vibrations excited in the liquid is maximum at fu=fo/n, where is the repetition — frequency of EMR pulses; f frequency of mechanical resonance of the column ka liquid; n = 1, 2, 3,... and the higher, the smaller n and is minimal at values and equal to 2f At the $\frac{\text{tracking}}{2n+1}$. frequency pulses sufficient for the damping of excited mechanical oscillations in the liquid in the time intervals between pulses, when the duration of microwave pulses changes, the amplitude of the excited mechanical oscillations periodically changes. The periodicity of the appearance of maxima (minimum) of the amplitude of mechanical vibrations is equal to 1/f, where f is the frequency of mechanical vibrations excited in the liquid. In Fig. Figure 33 shows the experimental dependence of the amplitude of excited mechanical vibrations in a liquid column on the duration of EMR pulses [120].



Rice. 33. Dependence of the amplitude of excited mechanical oscillations on the duration of the microwave pulse

With pulse duration ti≤ 1/4, oscillations from the leading edge are not distinguishable on the oscillogram, but only the total periodic process is visible (see Fig. 30). It is significant that at those moments when the duration of the pulses is such that the amplitude of the excited resonant oscillations decreases (at ti = nm), a lower tone corresponding to the pulse repetition frequency is clearly perceived by ear. The perception of low-frequency oscillations begins with the repetition rate of EMR pulses, at which individual clicks are distinguishable. The tone corresponding to the system's own resonant oscillations is perceived by ear, starting with a pulse repetition frequency of the order of 250...300 Hz. In Fig. Figure 34 shows an oscillogram of excited mechanical vibrations corresponding to the perceived low-frequency tone.

Possibility of direct listening and visual perception visual observation of vibrations on the oscilloscope screen, excited in a liquid during irradiation of a test tube pulse-high microwave EMR, allows us to make the assumption that radio sound is also caused by the transformation of the incident EMF energy into the energy of mechanical vibrations in absorption in the medulla and their conduction into the cochlea of the organ hearing by bone.



Rice. 34. Oscillogram of mechanical vibrations excited in a test tube at a low repetition rate of EMR pulses with a duration equal to pt

From this point of view, the object on which the research was carried out can be considered as a physical model in relation to the study of radio sound, and the results of model experiments can be interpreted as applied to this phenomenon.

The results of the work considered here on radio sound and the generation of mechanical vibrations allow us to make some considerations. The dependence shown in Fig. 33, completely coincides with the theoretically calculated by J. Lin, which confirms the formal analogy of our models. The fundamental difference between the results obtained on this physical model and the results of J. Lin [206] is the identification of the frequency dependence of the amplitude of mechanical vibrations, which puts our model much closer to the real situation, since the dependence of the radio sound effect on the pulse repetition rate has been noted by many researchers. bodies [133, 160, 173, 176, 234]. It is important that such a dependence was obtained both from objective recording on the oscilloscope screen and from subjective listening perception. Particularly interesting and important is the result that it is possible to perceive by ear a low-frequency tone corresponding to the pulse repetition frequency at moments when, with a pulse duration t = nT (n = 1, 2...), oscillations corresponding to the resonant frequency of the model are suppressed and only the generation of bursts of oscillations from leading edge (Fig. 34). This result allows us to dis-consider the so-called low-frequency type of radio sound, described in [104, 105, 113, 195, 196, 234], as the first harmonic of mechanical oscillations, excited inside the skull, perceived by the hearing organ while simultaneously suppressing more intense resonant oscillations with pulse duration , equal to their period. With pulse durations equal to 2n+17, a high-frequency tone is perceived. corresponding to the resonant frequency of the excited oscillations.

The data obtained using the model make it possible to explain the dependence of the threshold for the perception of radio sound on the pulse duration obtained in a full-scale experiment [234] and shown in Fig. 10. If we proceed from the value of the frequency of excited mechanical oscillations, 8 kHz, then with a pulse duration equal to half the period, i.e. 60 μs, a minimum threshold is naturally observed. With a pulse duration equal to the period of excited mechanical oscillations, i.e., 120 μs, there is a complete suppression of the perception of a high-frequency tone and the appearance against the background of this suppression of a lower-frequency tone of a height corresponding to the pulse repetition frequency, as can be assumed based on Fig. . 34. Thus, a fairly simple and visual system allowed us to answer complex questions regarding mechanical nism of radio sound, which gives the right to the object itself on which studies have been conducted, considered as a physical radio sound models. Obviously, to explain the fact it is possible loss of auditory sensation during irradiation of the head human or animal IM EMR is enough to consider as primary the same as in the model, the act of transformation conversion of EMF energy into mechanical energy in an object with some properties of an acoustic resonator [100].

The hypothesis about "two types" of radio sound, due to physiological characteristics, still remains at the level of speculation. At the same time, let us pay attention to the fact that the microphonic potential of the cochlea occurs when the basilar membrane is mechanically displaced [107]. Experiments on recording the MPU of guinea pigs (see Fig. 12) showed that this potential arose when the auditory

Rat as an acoustic signal due to air conduction, and excitation of mechanical vibrations of the skull bones using a radiating piezocrystal due to bone conduction, and under the action of a microwave pulse [147]. Moreover, regardless of the nature of the influencing factor and the type of conductivity, the shape of the microphone potential is approximately the same in general in all cases, i.e., in all three cases there was a mechanical displacement of the basilar membrane.

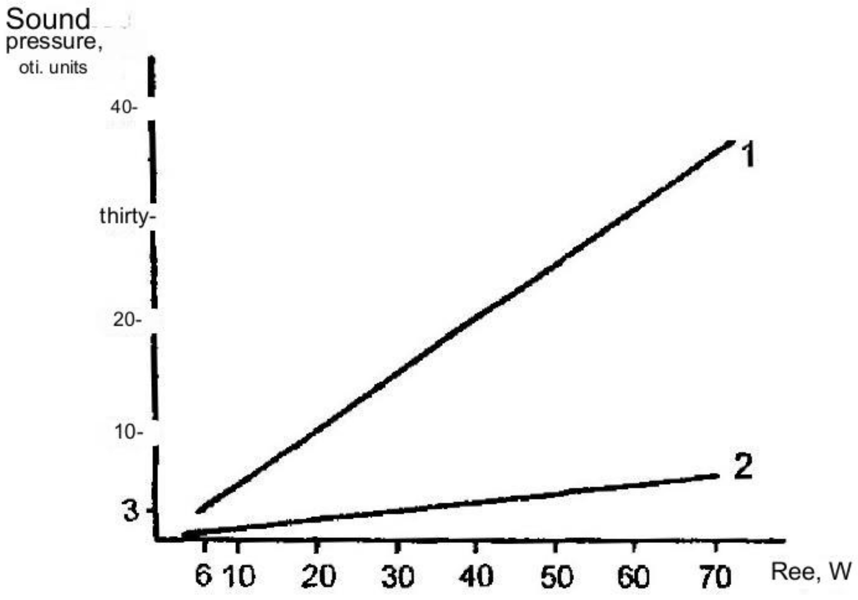
The presence of microphone potentials during mechanical action on the bones of the skull and during microwave irradiation, taking into account the results of irradiation of liquid media with microwave pulses, speaks in favor of a single mechanism for the occurrence of auditory sensation in all described cases.

However, the described model does not explain in any way the complex spectral composition of the excited sound stimulus [226, 241-243], the polytonal nature of radio sound in the frequency range up to 8 kHz, as well as the quantitative relationships on the threshold curves, and, moreover, the dependence of the shape of the threshold curves of radio sound on its own HFGS subjects [104, 234].

One of the fundamentally important issues is the determination of the microwave pulse power required for the occurrence of an auditory sensation in a person under natural conditions. Works [201, 202] present computer-calculated values of the sound pressure amplitude obtained for absorbing models with radii of 3 and 7 cm. However, the lack of consideration of the quality factor of spherical models, data on the size of the absorbing region and the frequency range makes this information clearly insufficient .

Our own studies of these dependencies were carried out both during irradiation of cylindrical and spherical volumes. Irradiation of a cylindrical volume (test tube with liquid) was carried out at pulse repetition frequencies of 10...20 Hz in order to avoid heating the liquid with a pulse duration of 10...20 μs. The carrier frequency is 800 MHz, the feed is a rectangular closed waveguide with a cross-section of 31×240 mm^2, the calculated value of PPM = 2 W cm-2.

In Fig. 35 shows graphs of the dependence of the relative values of the amplitude of sound pressure of excited



Rice. 35. Dependence of the relative amplitude of the sound pressure of excited mechanical vibrations on the power of the microwave pulse: 1 — ethanol; 2 — NaCl solution

mechanical vibrations on pulse power for IM solution of NaCl (2) and ethanol (1) in a test tube.

As can be seen from the presented graphs, the dependence of the amplitude of variable sound pressure of excited mechanical oscillations on the power of the microwave pulse at a fixed pulse duration is linear.

The specific absorbed power (SAP) was determined by the rate of increase in the temperature of the solution. At a pulse repetition rate of 500 Hz and a pulse duration of 100 μs, the temperature increase in the IM NaCl solution in 1 min was 6 °C with a sample volume of about 2 cm³, i.e. DT/D = 0.1 deg s. The power loss in the electrolyte or UPM is determined from relations [111]: $W = \frac{\sigma\varepsilon 2}{2}$ V or $W = stt \frac{}{\Delta t}$.

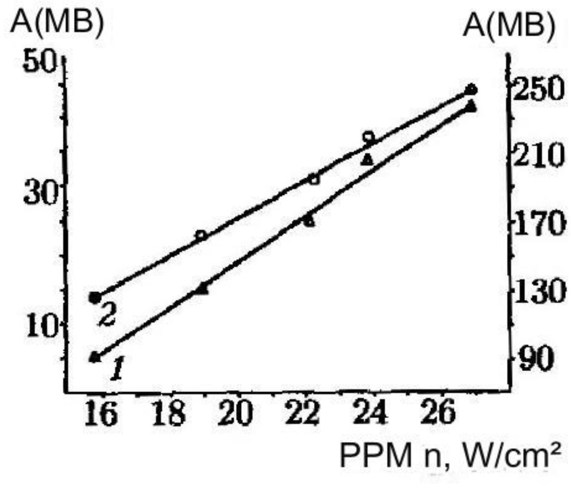
With a duty cycle of 20, the UPM per pulse in terms of per volume of solution was 8.4 W cm³. Calculated at this is the sound pressure amplitude based on the measured value amplitude of the alternating signal taken from the sensor, put the value on the order of 3 102 dyn cm-2. At the resonant frequency nans of the liquid column calculated amplitude of the sound pressure reaches 104 dyne cm-2 at the same MPP value. For a 0.15 M solution of KSI under the same irradiation conditions

The calculated value of the sound pressure amplitude was 2.102 dyn cm2, at the resonance frequency of the liquid column of the order of 3-103 dyn cm-2. When irradiating a sphere with a diameter of 185 mm filled with a 0.15 M NaCl solution, the calculated value of the SMA at a temperature rise rate of 2.10-3 deg s was 8.4 W kg-1. With a duty cycle of 20, UPM = 170 W kg. In this case, the calculated value of the pressure amplitude according to measurements of the amplitude of the electrical alternating signal on the piezoelectric transducer is equal to 20 dyn cm-2.

Spherical models of the effect of radio sound.
At the second stage of studying the role of mechanical vibrations excited by microwave pulses in the formation of sound sensations in persons exposed to irradiation, models that were more responsive to this task were used [245]. Since the human head, to a first approximation, can be represented as a spherical shell filled with a substance with certain mechanical properties [164, 206], glass and plastic spheres were used as a model, filled with the same liquids as the test tubes in the first series of experiments.

Experiments were carried out with glass spherical flasks with a diameter of 105, 120 and 185 mm and a plastic sphere with a diameter of 120 mm, which were filled with ethyl alcohol. In some cases, other models were used to compare results, as will be discussed at the appropriate place.

It is known that the subjectively perceived loudness of radio sound has a logarithmic dependence on the pulse PSD [176]. In the same way, the amplitude of response No. 1 in the auditory nerve and the amplitude of the MPA, recorded in the round window of the cochlea of guinea pigs, depend on the PES [149, 152]. It was also shown in [155] that the dependence on PPE in its pure form occurs only up to a certain pulse duration (30 μs), and at longer durations the amplitude of responses in the brain stem depends only on PPE. Summarizing these experimental data, we can come to the conclusion that subjective loudness radio sound, as well as the threshold of sensation and the amplitude of EP in the auditory pathways, have a logarithmic dependence on the PES. Moreover, this is true only for the pulse duration, no more than a certain maximum, which, as can be seen from the graph in Fig. 33, should be equal to half the period of excited oscillations. It is known that the organ of hearing is a logarithmic device, so it is quite logical to assume that the factor leading to the appearance of an auditory sensation or electrical response in the auditory pathways should linearly depend on the PES or on the PPM at a constant pulse duration. J. Lin theoretically predicted the linear dependence of sound pressure in spheres of various diameters on the incident PPM. No experimental confirmation of this result has been found in the literature, despite its fundamental nature.



Rice. 36. Dependence of the amplitude of mechanical vibrations, excited in a sphere with a diameter of 105 mm, from PPM
1 — for a resonant frequency of 11.8 kHz (y-axis on the right); 2 for resonant frequency 2.6 kHz (y-axis on the left)

In Fig. 36 shows graphs of experimentally obtained calculated dependences of the amplitude of excited mechanical fluctuations from the output pulse power of the generator and, accordingly, the calculated PPM. Dependency 1 was removed for a resonant frequency of 11.8 kHz of a sphere with a diameter of 105 mm with a pulse duration of 20 μs. Dependency 2 removed-was for a resonant frequency of 2.6 kHz of the same sphere for a duration pulse duration 80 μs. Pulse power calculated was based on the measured average and duty cycle. The maximum voltage values of the electrical signal taken from the piezoelectric sensor, measured with a voltmeter, are equal, respectively, to 240 mV for dependence 1 with an amplifier gain equal to Ku = 500 and 43 mV for dependence 2 at Ku = 37.

As can be seen from the graphs presented, the amplitude of mechanical vibrations excited in spherical volumes linearly depends on the PPM (PPE). This fact is a serious argument in favor of the physical mechanism underlying the phenomenon of radio sound, the essence of which is the conversion of EMF energy into mechanical energy.

Since in our experiments the geometric dimensions of model objects were commensurate with the wavelength of the radiation used (2 = 12.6 cm), it seemed important to experimentally study the nature of local field inhomogeneities inside volumes. The possibility of the occurrence of such inhomogeneities due to focusing has been substantiated in a number of works [82, 132, 185, 197], and J. Lin used the EMF focusing condition in his model.

In the "thermoelastic" concept of J. Lin [54, 206], this moment is considered as fundamental and determining the modes of excited mechanical vibrations. And although the results obtained in an experiment on the excitation of mechanical vibrations in a test tube with liquid [94] showed that the vibration modes represent a classical acoustic picture [124], the case of irradiating a sphere with a size mi, comparable to the wavelength, needed verification. To

create regions of electromagnetic energy absorption with different volumes and geometries inside the liquid sphere, the sphere was irradiated in two ways with a rectangular waveguide with a cross-section of 10x72 mm^2 and a rectangular horn with a cross-section of 90x120 mm^2.

The distribution of absorbed electromagnetic energy in a spherical volume was determined by measuring the temperature of the liquid inside the sphere and using a probe method based on the magnitude of the microwave voltage induced on it, followed by its detection.

Registration of the frequencies of excited mechanical vibrations in a sphere with a diameter of 105 mm showed that (with an error within 1-2%) the frequencies of excited vibrations when the sphere is irradiated by a waveguide and a horn coincide. No special determination of the field pattern inside the liquid was carried out, but it is quite obvious that during irradiation under conditions of equality of the values of the power supplied to the irradiator, the horn and waveguide should form different regions of absorption of electromagnetic — energy both in shape (due to different geometry of the end irradiator) and in size (due to different PPM).

Comparing the obtained results of excitation of mechanical oscillations by microwave pulses with equal conditions for their excitation using a laser [56], we can assume that the dimensions of the energy absorption region can serve as determining only if the medium is semi-infinite, i.e., at least not reflected acoustic wave. If the medium is limited (the case we are considering), then the frequency of excited mechanical vibrations will be determined by the size and geometry of the limiting volume, and the region of energy absorption itself can be considered only as a source of external disturbance having a wide spectrum of frequencies. The fact that when a sphere is irradiated by different irradiators, absorbing regions of different sizes and shapes are formed is evidenced by the fact that in the case of irradiation of a sphere by a waveguide having a smaller cross-section compared to the horn and, accordingly, a significantly larger PMD value, the amplitude of the recorded mechanical vibrations was significantly higher. The fact that when a limited volume is irradiated by various irradiators, the resonance frequency of the volume is determined only by its dimensions is indicated in [148, 153].

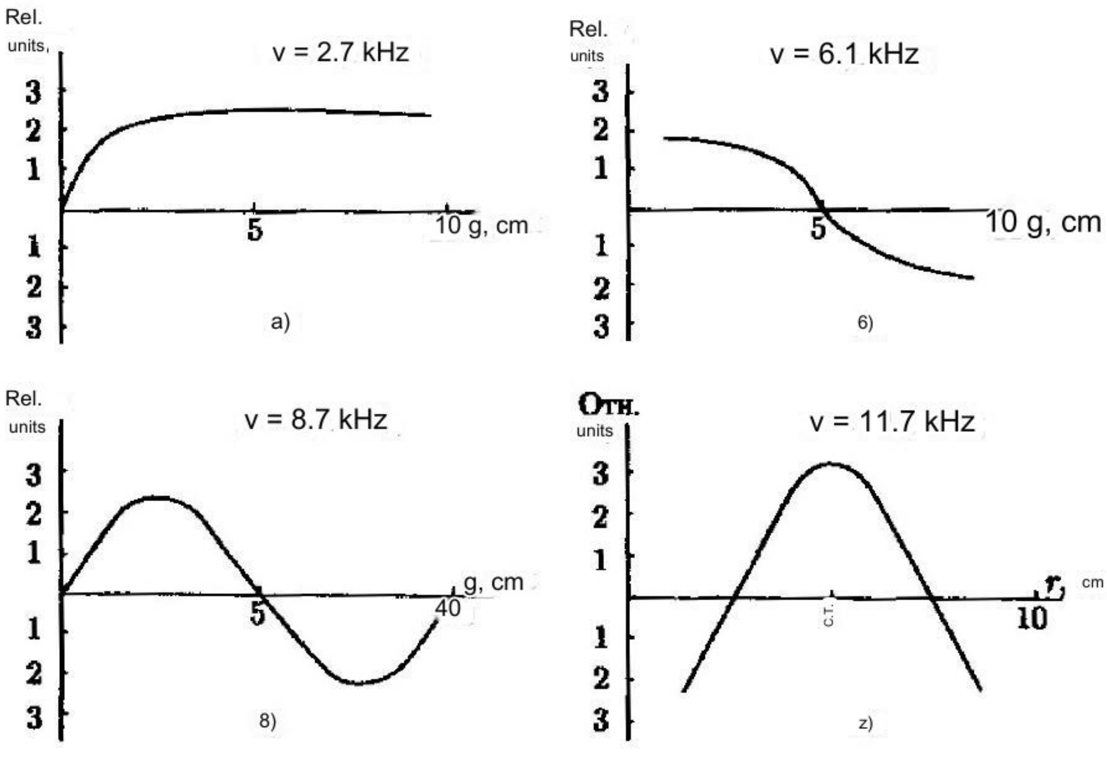
The temperature distribution was measured by irradiating spheres with a diameter of 105 and 185 mm and a cylinder with a diameter of 185 and a height of 65 mm, filled with ethyl alcohol and a 1 M NaCl solution. The irradiation time varied from 15 s to 5 min. Temperature measurements were carried out immediately after turning off the field at three points: in the liquid layer located directly in front of the emitter, in the center and at the point diametrically opposite to the first. To avoid the error associated with temperature equalization throughout the volume during the measurement time (~10 s), the procedure was repeated three times so that each time the sequence of temperature measurements at the selected points was different. It turned out that the uneven heating along the diameter of the spherical volume is of the order of 2.5 °C, with the greatest heating occurring near the emitter and decreasing with distance from it. Thus, in our experiments, no concentration of electromagnetic energy was detected in the center of the spheres of the so-called “hot spots” mentioned in the work of J. Lin [206]. Measuring the distribution of the electromagnetic field voltage inside the liquid filling the sphere showed that the field is maximum near the emitter and decreases exponentially with distance from it. Since we measured the relative change in the electromagnetic field strength, we neglected the disturbance introduced by the probe. The amplitude value of the detected pulses when the antenna is located at the wall of the bulb adjacent to the emitter, in the center of the bulb and at the wall furthest away from the emitter, is in the ratio 1:0.5:0.2. The absence of concentration of electromagnetic energy in the liquid spheres used was confirmed by an experiment with a different method of exciting mechanical vibrations in a cylinder with a diameter of 185 mm and a height of 65 mm. In the first case, the emitter was located on the side of the cylinder. In the second case, irradiation was carried out from above, i.e., focusing conditions were excluded. There were no significant differences in the parameters of the excited mechanical vibrations, i.e., in both cases, the same vibration modes were excited if the EMF parameters coincided.

The same picture occurred when a cylinder with a liquid with a diameter of 60 mm and a height of 200 mm was irradiated from above and from the side by different irradiators and at different frequencies (915 and 2375 MHz). In all cases, the frequencies (modes) of excited mechanical vibrations corresponded to the calculated ones. The measured temperature distribution over the volume of the cylindrical model also did not allow us to identify any characteristic temperature rise associated with the by the radius of the model or the dielectric constant of liquids.

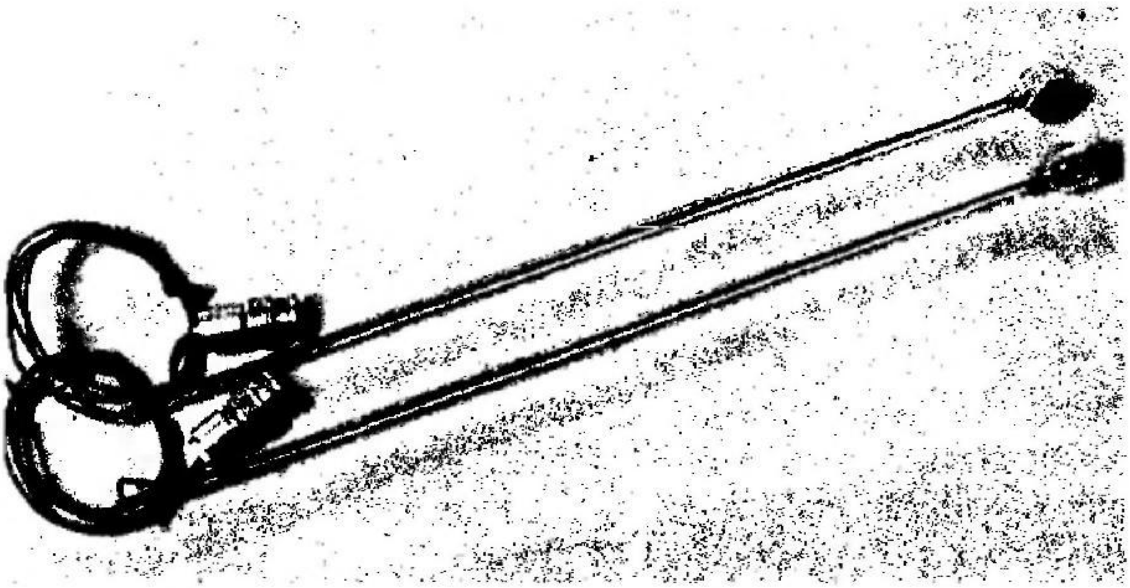
The experimental data obtained allow us to exclude the condition of concentration of electromagnetic energy as necessary for excitation of mechanical oscillations by microwave pulses in a closed volume. In accordance with this, it does not seem necessary to consider the center of the sphere as the source of mechanical vibrations excited in the liquid. The location of an antinode or a pressure node in the center of the sphere depends on the degree of connection of the sphere with the external environment, i.e., on the boundary conditions.

Thus, in our experiments, as well as in work [58] carried out on the heads of animals, a predominant concentration of electromagnetic energy in the center of the irradiated objects was not found, which gives us the right to believe that the use of the focusing condition is unjustified in J. Lin's model.

In Fig. Figure 37a-c shows the distribution of pressure amplitudes in glass spherical flasks filled with ethanol, obtained using acoustic probes.



Rice. 37. Amplitude dependences of acoustic pressure in a spherical ical flasks with ethanol for different frequencies:
a - f = 2.7 kHz; 6 - f = 6.1 kHz; c - f = 8.7 kHz; g - f = 11.7 kHz



Rice. 38. Acoustic probes

Acoustic probes (Fig. 38) are a hollow glass tube, open at the top. The lower end of the tube is expanded. A piezoelectric transducer with a diameter of 10...12 mm is attached to the end of the tube using glue. The coaxial cable connecting the converter to the amplifier is routed through a glass tube. The sound field pattern is determined by measuring the amplitude of excited mechanical vibrations along the diameter of the bulb from the base of the neck to the bottom. The measurements were carried out in a flask with a diameter of 105 mm with a step of 5 mm.

The graphs are plotted for four frequencies of excited mechanical vibrations -3; 6; 8.5; 11.3 kHz.

The results obtained are in good agreement with the calculations for the wavelengths of mechanical vibrations excited in the flask. Thus, for a frequency of 6.1 kHz at a speed of sound in ethanol equal to 1.18-105 cms, the wavelength is 20 cm, i.e., half the wave should fit in the flask. The resulting graphs show that, regardless of the irradiation method, both an antinode and a pressure node can occur in the center of the flask. The validity of this conclusion is indirectly confirmed in [148, 153]. To calculate the maximum pressure occurring in liquid when it absorbs pulsed electromagnetic energy, we use the expressions obtained by L. Garney [179]:

$$P_{max} = \frac{C\beta I_0}{2JS}\left(1 - e^{-\alpha C\tau_и}\right) \quad (1)$$

for a free border and

$$P_{max} = \frac{CB}{2JS} 1(1\text{-e-C}/2) \quad (2):$$

for a fixed boundary, where C is the speed of sound in a given liquid in m s; B is the coefficient of linear thermal expansion in degrees; I. — PPM in W cm-2; J — mechanical heat heat equivalent equal to 4.19 J cal; S — capacity of the medium in Jkg-deg-; a is the absorption coefficient of EMF in the medium, defined as a=2πε"/√e, where e' and є" are the real and imaginary parts of the dielectric constant; λ — wavelength of EMR in air.

Since both extreme cases are mathematical idealizations, and real physical objects can be assigned to one or the other only with varying degrees of accuracy, it is advisable to carry out calculations using both formulas, thereby obtaining boundary values.

If we denote the expressions for 1 in formula (1) as Кс, and in formula (2) as Кз, then, accordingly:

Pax = CL. and Pax = K310.

For alcohol under the conditions under consideration — and Ti 20 μs Ko = 9.1 dyn W¹, K3 = 8.0 dyn. Tue. The simultaneous use of CGS and SI units is explained by the fact that for convenience in calculations, given the pattern [10] = W cm2, we need to obtain the dimension [Pmax] in dyn cm-2. In the absolute majority, the PPM, taking into account 50% reflection, ranged from 15 to 70 W cm-2. Consequently, the pressure arising inside the spheres filled with alcohol should reach values ranging from 120 to 650 dyne cm2. These values are calculated similarly for aqueous solutions of NaCl, based on the acoustic and electrical characteristics close to those of the brain [218].

For a concentration of 0.125 M, at which a = 63 m [239], Kc = 1.0 dyn. W, and K3 = 0.73 dyne W and for the same PPM, pressure values will range from 10 to 70 dyne cm-2. These values are in good agreement with our experimental data. Indeed, the signals we had to work with had amplitudes of tens to hundreds of millivolts and up to 1...2 V in some cases. Taking into account the sensitivity of the recording system (10-5 V dyn^{-1} cm^2), the resonant characteristics of the spheres and K = 37 or 500 depending on the amplitude of mechanical vibrations and the type of recording device, a fairly good agreement in orders of magnitude is obtained. Let us demonstrate this with a specific example related to an experiment to determine the dependence of the amplitude of excited mechanical vibrations on the PPMI.

When a glass bulb with a diameter of 105 mm was irradiated at a natural resonance frequency of 11.8 kHz at Ku = 500, ti = 20 μs and a measured supply PPPi = 26.8 W cm-2, the voltmeter reading was 240 mV. The voltage amplitude on the sensor is therefore equal to 1344 μV and the pressure is 1344 --- dyn cm-2, and taking into account the quality factor (~10), the pressure from a single pulse should be about 130 dyn cm-2. For a resonant frequency of 2.6 kHz from the same example - Ku = 37, voltage according to the voltmeter 43 mV, we find that the pressure on the sensor at the same PPM and quality factor will be an order of magnitude lower, which agrees well with the data of J. Lin, calculated for a single pulse.

When determining the resonant frequencies of specific spherical volumes, we proceeded from preliminary calculations using formulas for spherical resonators [79] and a Helmholtz resonator [48].

Calculation using the formula for a Helmholtz resonator:

$$f_p = \frac{c}{2\pi}\sqrt{S/lV},$$

where p is the resonant frequency; — speed of sound in the medium, With filling resonator; ½ — cross-sectional area of the throat; 1 - throat height; - the volume of the resonating medium, which has the lowest frequency value, for a sphere with a diameter of 105 mm, a neck height of 20 mm and a diameter of 30 mm, filled with ethyl alcohol, gives a value of the order of 1.4 kHz.

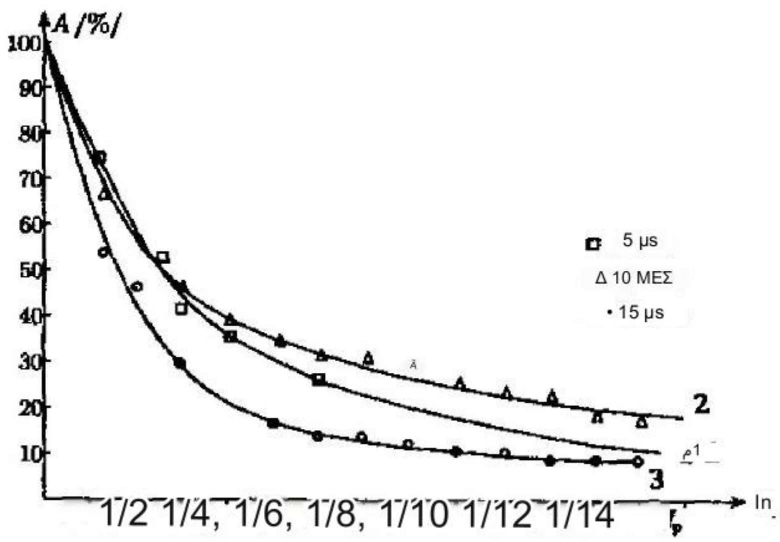
Table 5

Frequency values of excited mechanical vibrations at different parameters of microwave pulses

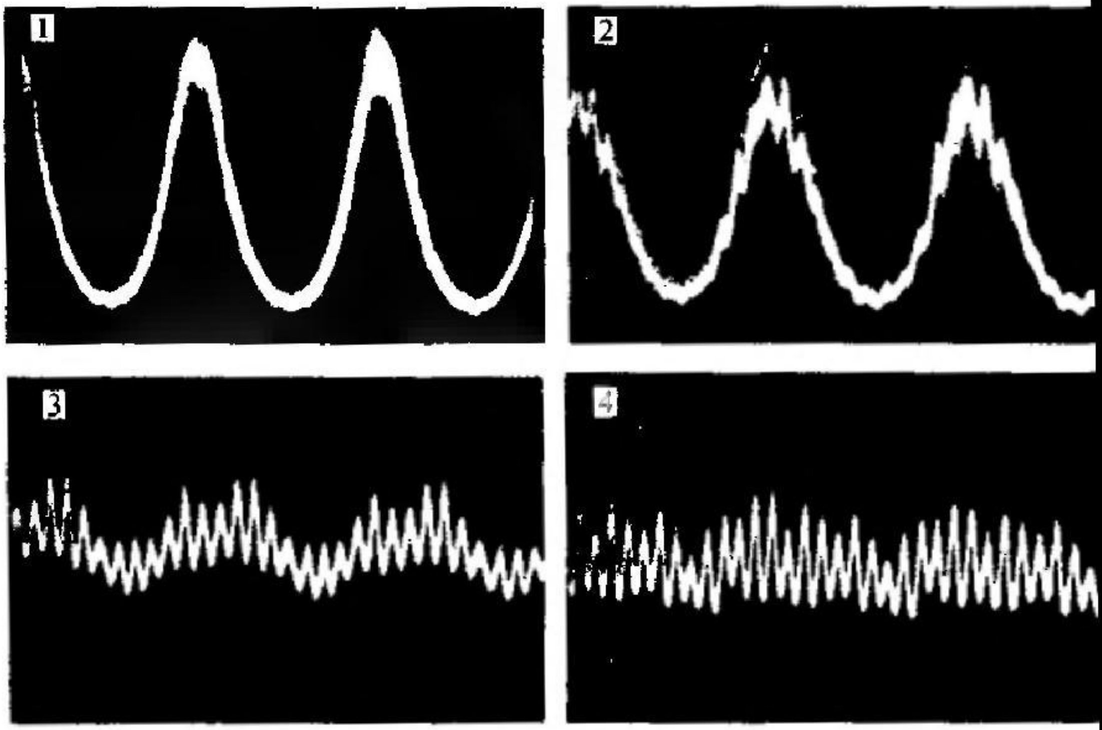
EMR pulse repetition rate, Hz	Frequency Hz excited of mechanical oscillations,	Duration of EMR pulses, microseconds	EMR pulse repetition rate, Hz	Frequency of excited mechanical vibrations, Hz	Duration of EMR pulses, μs
23	1238	400	8270	8270	
24	1238	Same	9030	9030	25
			9190	9190	
			9310	18620	
54	1238	Same	9640	19280	
56	1238	Same	10050	10050	
			10700	10700	
80	1238	Same	11020	11020	
95	1238	Same	11140	22280	
			11220	11220	
177	1238		11490	11980	
206	1238		11820	11820	
			12030	12030	
619	1238		12900	12900	
1238	1238		13100	26200	
1710	3420	300	13130	52520	
1750	5250	100	14070	28140	
2280	6840		14650	29300	
2625	5250		14660	29320	
2925	5850		16670	16670	
3160	6320		16940	16940	
3420	3420	70	17170	17170	
4460	4460		19280	19280	
4600	4600		19810	19810	
5250	5250		20040	20040	15
5850	5850		20450	20450	
5920	5920		20960	20960	
6320	6320	50	21340	21340	
6410	6410		21930	21930	
6610	6610		22280	22280	
6840	6840		22440	22440	
7290	7290	40	22980	22980	
7410	7410		23120	23120	
7560	7560		25380	25380	
8060	8060				

In the experiment, the minimum frequency for the flask at different fillings of the neck (from the level of the sphere to the cut of the neck) changed accordingly from 1735 to 913 Hz, which indeed indicates a strong dependence of the resonance properties on the degree of filling of the neck of the flask.

As indicated earlier, the amplitude of excited mechanical oscillations is maximum at a pulse duration equal to half the oscillation period of a given frequency. However, the limits within which the pulse duration can be varied are determined by the achievement of the meander mode. Based on the above conditions, the initial pulse duration (about 400 μs) and the search range for the low resonant frequency were selected. For a sphere with a diameter of 105 mm, the resonant frequency was 1238 Hz. With an increase in the repetition rate of microwave pulses at the moment of occurrence of mechanical oscillations in the sphere, both the frequency of exciting pulses and the frequency of excited oscillations were recorded by a frequency meter. The data from this experiment are summarized in table. 5. It is significant that oscillations arose not only in the case of equality of frequencies, but also when the pulse repetition frequency was equal to a subharmonic of the resonant frequency of the sphere. The dependence of the amplitude of excited mechanical oscillations on the pulse repetition frequency, equal to the numbers of subharmonics, is shown in Fig. 39.



Rice. 39. Dependence of the amplitude of excited mechanical vibrations nii from the pulse repetition rate: 5 μs:
I — 2 = //n, — 10 μs; 3 - 15 μs. Pulse repetition frequency
f where n — subharmonic number of resonance frequency



Rice. 40. Change in the frequency of excited mechanical vibrations in ethanol with a change in the duration of the microwave — pulse. 1-4 decrease in microwave pulse duration. Oscillograms were obtained at the same sweep speed of the oscilloscope beam

A comparison of the data we obtained on determining the resonant frequencies of mechanical vibrations in ideal spherical resonators shows that the presence of a nonharmonic series of frequencies that we recorded in the experiment is the result of the inconsistency of our model with an ideal resonator. It should be noted that when extrapolating the obtained experimental data to the natural effect of radio sound, it is necessary to take into account the more complex geometry of the human head and the presence of inhomogeneities. Obviously, in real conditions this should lead to an even denser range of frequencies, the perception of which should be limited above by the high-frequency hearing limit of each individual.

In Fig. 40 shows oscillograms of excited me mechanical vibrations in a spherical resonator, demonstrating transforming the frequency of these oscillations when changing changing the duration of EMR pulses.

The results obtained suggest that the factor mi, defining the range of excited in the sphere (heads human) and recorded (perceived by the organ of hearing) mechanical vibrations, primarily the duration of microwave pulses and their repetition frequency. This explains the reason why the subjects experienced a sensation of sound higher in frequency than the pulse repetition rate in early works on radio sound, in which experimenters used short pulses to modulate microwave radiation. Thus, we can come to the conclusion that the mechanism of excitation of both low-frequency and high-frequency mechanical vibrations has a single physical nature associated with the absorption of electromagnetic energy by the tissues of the head or working fluid, and manifests itself in one form or another depending on on the parameters of external influence. The formation of an auditory image in a person proceeds in the same way as ordinary sound is perceived in case of defects of the middle ear (otosclerosis) or as under water, i.e. through bone conduction.

One of the main issues when studying the mechanism of radio sound is determining the resonant frequency of the head as an acoustic resonator.

Unlike a cylindrical system, in spherical volumes the conditions for excitation of mechanical vibrations are more complex [55], which leads to a larger range of resonant frequencies. The presence of a neck in the flask leads to the formation of a system of two connected resonant circuits with different and significantly separated values of the resonant frequencies,

In accordance with the Helmholtz formula [48] for calculating resonant frequency $f_{PE3}=\sqrt{\hat{S}/lV}$, 2π, c where — is the speed of sound in the medium filling the resonator; S - throat area; 1 - neck height and V - volume of the resonating medium, for a flask with a diameter of 105 mm, a neck height of 20 mm and a neck diameter of 30 mm, extreme values of this frequency of 913...1735 Hz were obtained at different levels of liquid in the throat (for eta-nola). At the same time, oscillations with a frequency determined by the Helmholtz formula are excited only if the duration of the microwave pulse is equal to half the period of these oscillations.

With an increase in the repetition rate of microwave pulses, a large range of values of this parameter is observed, which correspond to the moments of excitation of mechanical oscillations. In this case, resonant oscillations, starting from a certain value of the pulse repetition frequency, are “modulated”. The envelope of resonant oscillations is an exponential and reflects the quality factor of the oscillatory system.

The measured value of the quality factor of the spherical systems used is in the range of 300...500. Therefore, the above-mentioned “modulation” of excited mechanical oscillations appears only at sufficiently low pulse repetition frequencies of the order of 102 Hz.

The high quality factor of the spheres leads to an almost instantaneous decrease in the amplitude of the first harmonic at pulse repetition rates only slightly higher than the resonant frequency. More like re- The results of these studies are presented in [120].

3.5. Excitation of mechanical vibrations microwave pulses in spherical liquid models c small tc quality factor

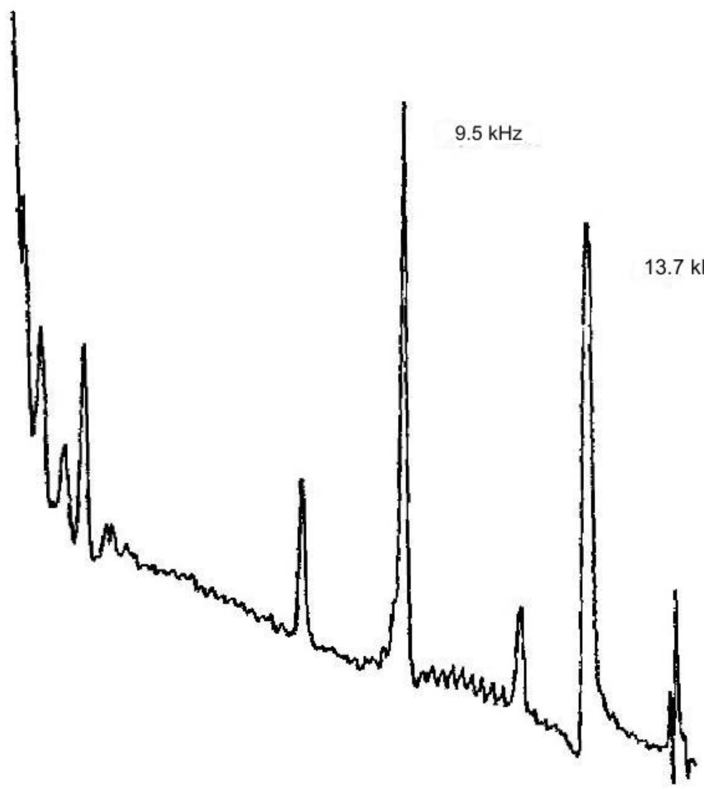
The question of the possible value of the frequency and quality factor of the mechanical resonator of the head as an acoustic resonator when mechanical vibrations are excited in its tissues by EMR pulses still remains open. The ratios C/2a and 1.44C/2a given in the works of J. Lin to determine the possible frequency values of the mechanical resonator of the head cover the frequency range of the order of 7.5...10.8 kHz for a sound speed of 1.44- 105 cm.s and -1 a = 9 cm, where a is the radius of the head. On the radio sound threshold curve, the indicated frequency range is limited below by the region of the maximum sensitivity threshold, and above by the minimum. That is, if we move on to a curve equal to the volume of radio sound and consider it as an amplitude-frequency response (AFC) of a certain resonant system, then these areas will have diametrically opposite properties - minimum and maximum coefficients signal transmission. Such inconsistency does not allow us to accept such a wide range of possible values of the mechanical resonance frequency of the head. On the other hand, a wide range of mechanical vibrations excited in spherical resonators with a high quality factor (about 300...500) does not allow us to determine any frequency as the fundamental one and compare it with one or another characteristic frequency at the threshold radio sound curve. Based on the data from [2, 79], it can be assumed that the quality factor of the head as an acoustic resonator should be low.

Using a working hypothesis, we can roughly estimate the quality factor of such a "resonant circuit" on the radio sound loudness curve for a frequency of 10 kHz to be of the order of 2.5. A more precise definition of the quality factor of this "circuit" will be given below. Thus, the spectral analysis of excited mechanical vibrations in spherical resonators with low quality factor is of practical interest. As liquid spherical models, a plastic ball with a diameter of 120 mm and glass round-bottomed flasks with a diameter of 100 and 120 mm with porous rubber lining were used. Ethanol was used as the working fluid. The ball was installed on an autonomous piezoceramic receiver. Registration of mechanical vibrations in glass flasks was carried out using piezoceramic receivers with a diameter of 20 and a thickness of 0.5 mm, glued into the wall of the flask. Irradiation was carried out using an open rectangular waveguide with a cross section of 10x72 mm^2 at a carrier frequency of 2375 MHz, pulse power up to 500 W. Frequency spectra of excited mechanical vibrations were recorded using a SK4-26 spectrum analyzer and a RA-2 two-coordinate recorder. The quality factor of spherical models, calculated from spectral data, is in the range of 8...78, depending on the material and configuration of the sphere.

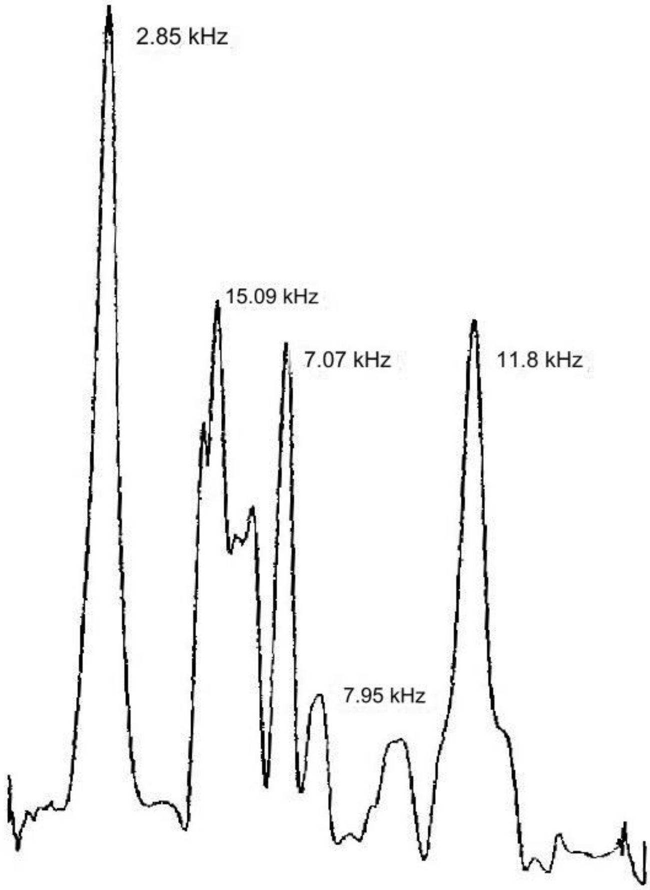
The frequency spectra of excited mechanical vibrations in spherical models are shown in Fig. 41-43.

All spectra contain a frequency component corresponding to the first mode of the oscillatory sphere with a free boundary and determined by the relation f = c/2a [206], C the speed — of sound in ethanol is equal to 1.18-105 cm s-1 at

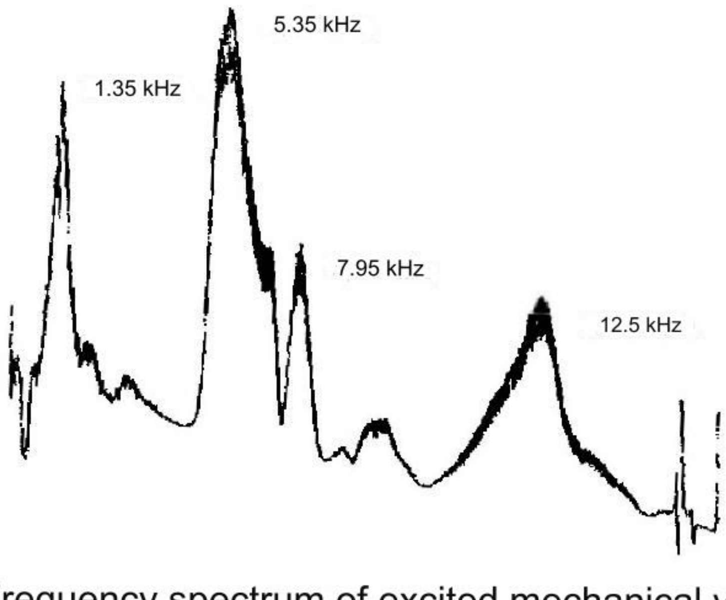
20°C; a — is the radius of the sphere, as well as other frequencies that can be identified as vibration modes f'm, n, corresponding to a sphere with fixed boundaries, where m MO — vibrations. and the overtone number. In addition, in spheres with a throat the following are clearly visible: the frequency corresponding to the Helmholtz cutoff frequency fa=S/IV, where the sound speed is 2π in the liquid filling the resonator; And - volume of the resonator 1nS height and area of the neck of the resonator [48] and frequencies close in value to the oscillation frequency of the liquid column as a quarter-wave resonator f = c/8a. The presence of other frequency components is more difficult to identify, but they may well be overtones of the described frequencies. The possibility of the existence of shell resonators (resonator walls) cannot be completely excluded [164, 194]. In table Figure 6 presents data on the frequencies excited in the spheres and gives their tentative identification, as well as the quality factor of the resonators for the frequency f = c/2a.



Rice. 41. Frequency spectrum of excited mechanical vibrations in the spherical model. Plastic sphere, diameter 120 mm, lobroth 78, fp = 9.5 kHz, repetition frequency 100 Hz, duration pulse duration 10 μs



Rice. 42. Frequency spectrum of excited mechanical vibrations in a spherical model. Glass sphere, diameter 100 mm, quality factor 19. p = 11.8 kHz, repetition frequency 100 Hz, pulse duration 30 μs



Rice. 43. Frequency spectrum of excited mechanical vibrations в of the spherical model. Glass sphere, diameter 100 mm, quality factor 11, f = 12.5 kHz, repetition frequency 100 Hz, pulse duration 5 μs

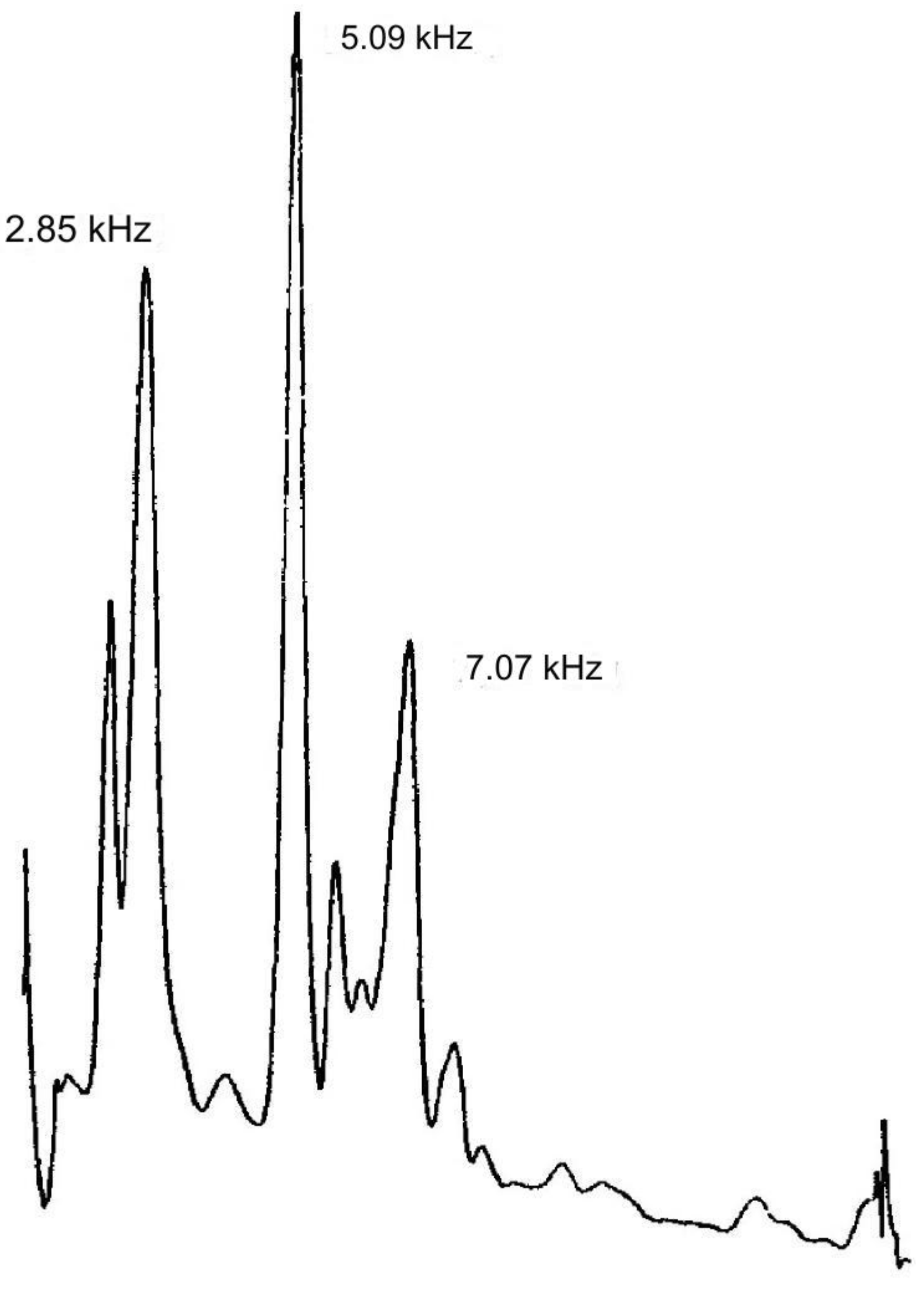
Table 6

Excited mechanical vibrations in spherical volumes

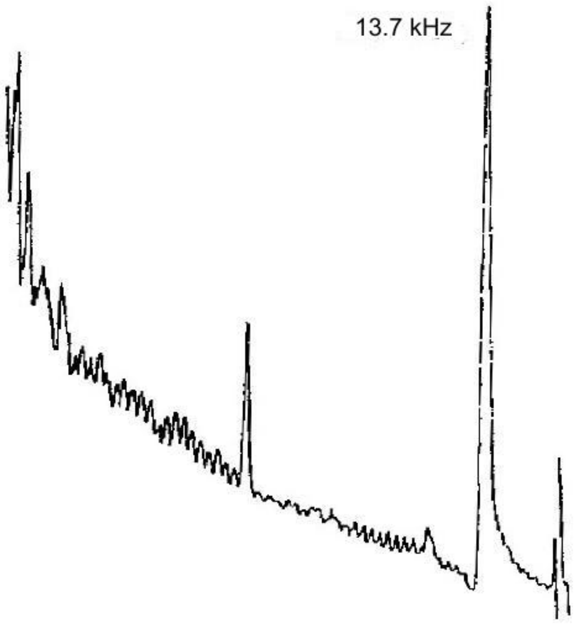
No.	Spherical model type	Diameter, mm	Sphere with free border fyes = d2a kHz	Helmholtz resonator, kHz кГц	Quarter-wave resonator kHz	Sphere with fixed border kHz	kHz	kHz	Resonator quality factor at frequency PF = 2a kHz
1	Glass round-bottomed flask with the neck cut off to the base and lining the outside with porous rubber 10 mm thick	105	Experiment						
			11.8	1.95	2.58	16.8	7.07 7.85	—	19
			Calculation						
			11.4	1.75	2.86	16.3	7.5	21.5	19
2	Round-bottomed glass flask with a neck 30 mm high, lined on the outside with porous rubber 10 mm thick	120	Experiment						
			10	1.15	2.53	13.9	6.3	16.85 17.4	8
			Calculation						
			10	1.43	2.3	14.3	6.6	18.9	8
3	Plastic sphere	120	Experiment						
			9.5	—	—	13.7	—	17.8	78
			Calculation						
			10	—	—	14.3	6.3	18.9	78

By varying the pulse duration, it is possible to suppress or enhance the fundamental frequency of the resonator c/2a in spherical resonators. In Fig. 44-46 show the spectra of excited mechanical vibrations in glass and plastic spherical resonators. In Fig. Figure 47 shows the noise spectrum of one of the spherical models.

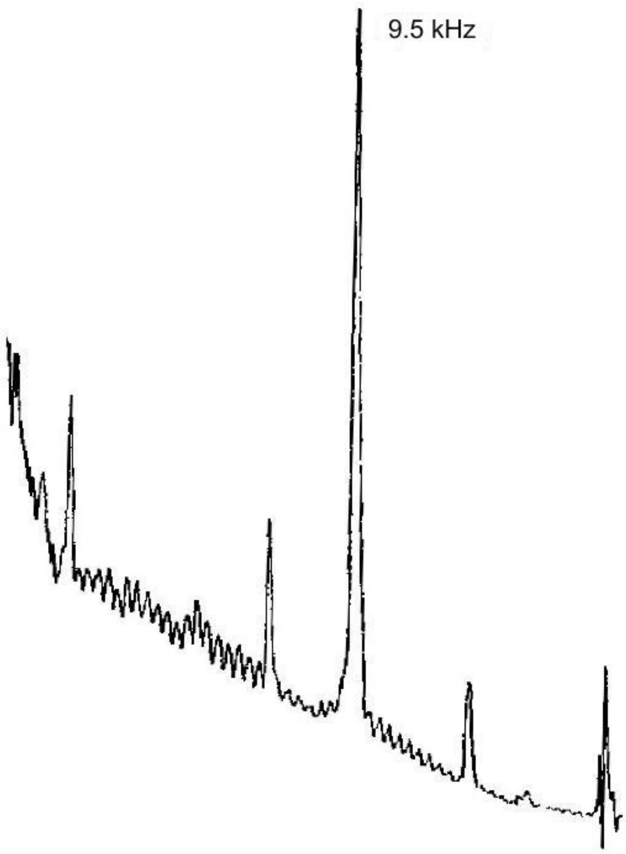
The results of these studies are presented in [102].



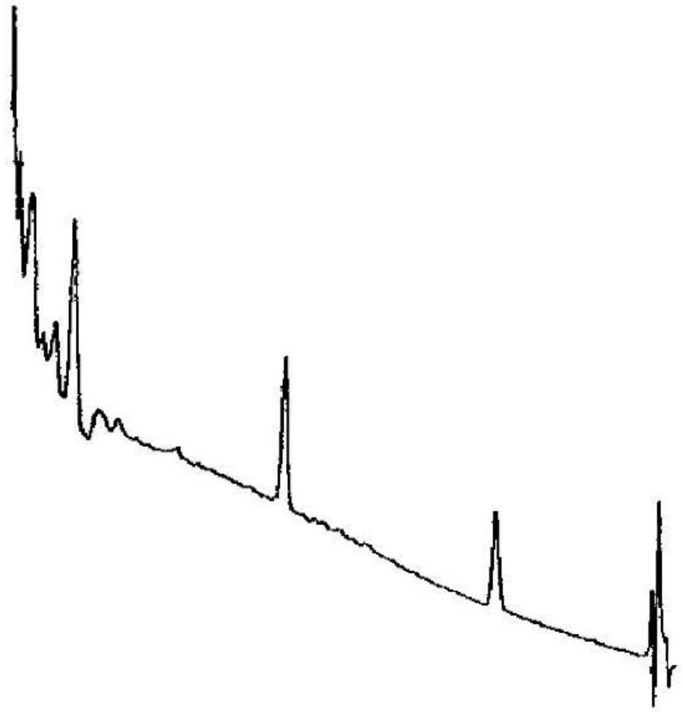
Rice. 44. Suppression of the resonant frequency in the frequency spectrum of excited mechanical vibrations. Glass sphere, diameter 100 — mm, quality factor 19, f = 12.5 kHz, repetition frequency 100 Hz, suppressed frequency f = c/2a



Rice. 45. Suppression of the resonant frequency in the frequency spectrum of excited mechanical vibrations. Plastic sphere, diameter 120 mm, Q factor — 78, p = 9.5 kHz, repetition frequency 100 suppressed, frequency f = c/2a



Rice. 46. Strengthening the resonant frequency in the frequency spectrum of excited mechanical vibrations. Plastic sphere, diameter 120 mm, quality factor 78, p = 9.5 kHz, repetition frequency 10 Pulse duration 72 μs, frequency amplified f = c/2a



Rice. 47. Noise spectrum of a spherical resonator. Plastic sphere, diameter — 120 mm, noise spectrum

A study of the conditions for excitation of mechanical vibrations in liquid media, carried out on cylindrical and spherical models, showed their direct dependence on microwave parameters.

The dependence of the emerging auditory sensation on the parameters of microwave pulses, noted in full-scale experiments on radio sound, can be understood by analyzing the data obtained in model experiments.

The presence of certain boundary conditions in experiments on irradiation of spherical liquid volumes with microwave pulses, approaching the natural conditions of the supposed generation of mechanical vibrations in the tissues of the head, allows us to consider this point as a fundamental possibility of modeling the effect of radio sound in limited liquid volumes. In this case, a volume of spherical liquid can be considered as a resonant model, and the process of excitation of mechanical vibrations in them and their recording by a piezoceramic receiver with further analysis of the vibration parameters as a model of radio sound. In order to provide a more objective interpretation of the obtained experimental data, the parameters of the microwave pulse sequence and the frequency characteristics of the irradiated liquid volumes should approach those in natural experiments.

Works [195, 196] show that with a microwave EMR pulse duration of 100...120 μs, in a full-scale experiment, a lower-frequency auditory sensation was noted than with a pulse duration of 5...25 μs, causing a high-frequency sensation of radio sound. The authors of this work note that when the duration of the microwave pulse is reduced to a value of the order of 60 μs (Fig. 10), the sensation of sound again becomes high-frequency. From what is shown in Fig. 10 of the graph shows that the pulse duration value of 100...120 μs corresponds to the period of excited mechanical oscillations in the tissues of the head in accordance with the value of the resonant frequency determined earlier in Lin's works (8...10 kHz). Consequently, a pulse duration of 60 μs corresponds to half the period of these oscillations. Correlating the obtained experimental results on the excitation of mechanical vibrations in a liquid resonator with the graph in Fig. 30 you can see that resonant oscillations with maximum amplitude corresponds to the values of ti 2n+17 and represents the process of generating sinusoidal oscillations and, with sufficient power, should create the sensation of a high-frequency tone. At values of Tipt, the oscillations excited by the fronts of the thermal pulse compensate each other outside the interval ti 21 and, as a result, the process of generating mechanical oscillations is represented by packs of oscillations that follow with a frequency equal to the pulse repetition rate (Fig. 34). Such a process should cause the sensation of a low-frequency tone, i.e., in this case, the envelope of resonant oscillations is perceived. When the pulse duration changes, the amplitude of the sound pressure of mechanical vibrations excited in the liquid changes periodically (Fig. 33), which is similar to the graph in Fig. 10.

The indicated features of the occurrence of auditory sensations. tion or during irradiation of test tubes with ethanol do occur.

Thus, it can be assumed that the mechanical vibrations excited in the liquid resonator and the tissues of the head obey the same laws, and the identity of the results obtained on the model and the original allows for the presence of the same mechanism of excitation of both low-frequency and high-frequency radio sound .

Shown in Fig. 45-46, the-spectra obtained on spherical models also quite convincingly demonstrate the possibility of enhancing or suppressing one or another component by changing the duration of the EMR pulse and thereby confirms the direct dependence of the nature of the perceived sound on this parameter.

The results obtained on liquid models also make it possible to understand that the sensation of high-frequency radio sound, noted in early works when using only short (5...25 μs) pulses and a repetition frequency of the order of 103 Hz and higher, arose due to continuity of the process of generating mechanical vibrations in the tissues of the head and did not correspond in pitch to the pulse repetition frequency. The “humming” nature of the perceived radio sound, noted in all field experiments, indicates the presence of low-frequency components in the perceived auditory sensation. The damped nature of mechanical oscillations excited by microwave pulses in a liquid resonator, noted in the form of “modulation” of resonant oscillations, leads to the release of a component to the auditory analyzers corresponding to a temporary change in the amplitude of resonant oscillations, which is perceived simultaneously with resonant oscillations. As a result, combination frequencies arise, creating a feeling of “impurity” to the pure tone.

Thus, it can be assumed that the mechanism of excitation of both low-frequency and high-frequency radio sound has a single physical nature associated with the absorption of electromagnetic energy by the tissues of the head and manifests itself in one form or another depending on the parameters of the external influence. The formation of the auditory sensation in a person proceeds in the same way as ordinary sound is perceived in case of defects of the middle ear (otosclerosis) or under water, i.e. through bone conduction.

By analogy with the experimental data obtained, taking into account the large difference in the impedances of the head tissues when mechanical vibrations and air are excited in them (as well as for the liquids used in the experiment), the human head can be considered as a low-Q acoustic resonator with a boundary close to free , and the frequency of mechanical resonance, determined by the ratio hrez = c/2a or the ratio hrez = ps/R, proposed by Lin, where R is the size of the head. In this case, with a head size within the range of 55...60 cm, the value of the resonant frequency will vary within the range of 8.54...7.83 kHz at a speed of sound in tissues of the order of 1.5-105 cm s-1. This leads to a fundamentally important conclusion. On the threshold curve of radio sound, the indicated frequency band corresponds to the region of the maximum threshold, which cannot be explained by the single-circuit Lin model, since it is in this frequency region that the signal amplitude transfer coefficient for the parallel resonant circuit is maximum, which should have been would lead to the presence of a region of minimum sensitivity threshold hearing loss.

The obtained experimental material created the prerequisites for discussing the question of the fundamental possibility of physical modeling of the functions and interrelationships of the anatomical structures of the head and the mechanisms of the auditory system involved in the formation of the auditory sensation of the head by EMR pulses.

At the same time, the results obtained make it possible for the first time to raise the question of the degree of influence of the resonant properties of the head on the processes of formation of the frequency-threshold curve of hearing in the case of inadequate perception of the information signal. It should be noted that even in simple homogeneous systems max, which are the resonators considered here, the presence of a throat in spherical flasks leads to the formation of a system of two resonators of the volume of liquid located in the throat and representing the first acoustic resonator and the volume of liquid in the spherical part of the flask, representing the second acoustic resonator. It is obvious that a whole series of resonant frequencies is the result of superpositions of several simultaneously excited mode in these resonators. This circumstance is also clearly demonstrated by the spectra obtained on spherical models.

In both cylindrical and spherical resonators, mechanical oscillations are excited at a certain pulse repetition frequency, corresponding to such a frequency of excited mechanical oscillations that a further increase in the pulse repetition frequency leads to the release of only the first harmonic.

Here it is necessary to emphasize that a test tube with liquid can be considered as a single-circuit resonant system only under certain conditions. A column of air located in a test tube above the liquid level can also be considered as a quarter-wave resonator due to the different conditions for "fixing" it at the top and bottom. Consequently, the single-circuit condition for a test tube with liquid is satisfied only if the resonant frequencies of these resonators are so separated that a sufficiently noticeable connection cannot arise between them (usually the transfer of no more than 1% of the power). In this case, with heights of ethanol and air columns of 30 and 60 mm, respectively, the resonant frequencies are 10 and 1.4 kHz.

In none of the experiments was the amplitude envelope of excited mechanical oscillations qualitatively adequate to the mirror image of the threshold curve of radio sound realized, which once again confirms the inconsistency of the single-loop concept of radio sound proposed by Lin. As the quality factor of spherical liquid models decreases, it is experimentally shown that in this case a wave acoustic resonator with a boundary close to free is realized.

3.6. Brief conclusions

As a result of the analysis of the issues discussed in this chapter, we can come to the following conclusions:

1. The amplitude, phase and frequency characteristics of mechanical vibrations excited in liquids depend on the parameters of the model liquids and the pulse sequence.

2. By varying the repetition frequency and duration of the pulses, it is possible to generate mechanical vibrations in the liquid in a wide — range from individual damped trains to a continuous sinusoidal signal.

3. In liquid volumes of various configurations, a large number of oscillation modes can be excited depending on the parameters of the pulse sequence.

4. The excitation of one or another mode of oscillations in spherical volumes depends on the value of the quality factor of the sphere as an acoustic resonator.

5. Single-circuit liquid systems, regardless of the quality factor of the acoustic resonator being implemented, do not explain the amplitude-frequency dependence of the radio sound threshold curve.

6. A single-circuit spherical liquid model with a low quality factor is characterized by a resonant frequency equal to c/2a.

7. The identity of the main results obtained from radio sound and in studies on the excitation of mechanical vibrations by microwave pulses in liquid limited volumes allows us to consider this circumstance as a possibility of modeling the effect of radio sound.

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Chapter IV

RADIO SOUND MECHANISM

From the considered concept of radio sound, it follows that when another physical factor acts on the tissues of the head, capable of leading to the excitation of pressure waves, a similar auditory sensation should be formed, i.e., this model should "work" when excitation of the bones and soft tissues of the skull an ordinary acoustic signal of the same shape and intensity as the pressure waves excited by microwave pulses.

The task of determining the resonant characteristics of the human head arises from the need to introduce a finite value of the mechanical figure of merit into the thermoelastic concept and experimentally find the value of the resonant frequency of the head as an acoustic resonator, or show the possibility of the existence of a multimode system. The author of the thermoelastic model himself, apparently, proceeded from his own general ideas regarding the resonant properties of the head, although there are both theoretical [164, 211, 238] and experimental works on this issue [193, 194]. A serious disadvantage of both is their remoteness from the real object. In theoretical works, as a rule, spherical shells of varying degrees of rigidity filled with liquid are considered as models, and in experimental studies, the resonance characteristics were studied on dry skulls. There are also audiometric studies in which the detected resonances had the meaning of some anomalies in the speed of propagation of the sound wave (deviation from a linear dependence), but they were carried out at frequencies not exceeding 4 kHz. Work [219], mentioned in the literature review, was carried out on animals and cannot claim generality, since it was carried out under unusual conditions.

An analysis of the literature devoted to studies of bone-tissue conductivity [12, 45, 47, 209] showed that almost all measurements in this area are limited in frequency to 3...4 kHz.

A significant part of the research is limited to a frequency not exceeding 5...6 kHz [47, 161, 193, 237], or is devoted to the ultrasonic range (well-known works by B. M. Sagalovich). The same works, which in one way or another presented the range of interest to us (4...12 kHz) [6, 7, 83, 159,215, 246], could not provide the necessary information, since traditionally bone-tissue audiograms were taken using points spaced from each other either by an octave or by a value not less than 1...2 kHz, under conditions of asymmetrical sound supply to the mastoid. We needed to have a threshold curve for the frequency range 4...12 kHz, taken in steps of no more than 200 Hz. This condition was dictated by the fact that on the radio sound threshold curve (see Fig. 9) the threshold slope in the frequency range 6...8 kHz reaches 60...90 dB oct.

An analysis of the technical literature in this area also showed that the capabilities of existing methods and devices for bone-tissue audiometry are mainly limited to an upper frequency of about 4 kHz. In this regard, the task arose of developing our own methods and devices for audiometry of bone-tissue conduction and conducting experiments to test the proposed concept of radio sound, which also represents modeling of irradiation conditions in a full-scale radio sound experiment.

For this purpose, bone-tissue conduction audiometry has been developed by transmitting vibrations to the skull tissue through water and air.

4.1. Audiometry of bone-tissue conduction in the high-frequency region

•Water immersion method. Six people participated in experiments to study bone-tissue conduction thresholds using the method of immersing the head in water.

First of all, we checked the presence of a high threshold in the frequency range 6...8 kHz corresponding to that in full-scale radio sound experiments.

In a glass anechoic aquarium with dimensions of 35x45x70 cm, acoustic vibrations were excited using an electrodynamic emitter. The electrodynamic emitter 4GD-8E was covered with a thin (thickness 0.15...0.2 mm) rubber shell. On the front part of the emitter, the rubber was stretched and, thus, represented a tense membrane through which sound vibrations were transmitted to the water. The parietal region of the subject's head was immersed in water. First, using a measuring microphone, the frequency response of the emitter was recorded along with the membrane.

The threshold curve was measured by measuring the magnitude of the effective voltage at the terminals of the emitter, necessary for the appearance or disappearance of the auditory sensation. The subject's ears were covered with special anti-noise headphones, and the auditory canals with cotton wool. To excite acoustic vibrations, a GS-100I laboratory measuring generator with high stability of the output signal amplitude over the entire audio frequency range was used. The signal frequency in the experiment was varied smoothly. The subject, bending down, immersed his head so that the water level reached the ears.

All subjects clearly recorded a significant increase in the sensitivity threshold in this area. Moreover, the region of increasing the threshold is quite narrow and is recorded only with a smooth, slow change in the sound frequency.

The nature of the threshold curve was quite strongly influenced by the degree of immersion of the subject's head in the water. If the frontal part was involved, then the increase in the threshold was more clearly manifested. It can be assumed that the frontal sinuses play a certain role in the formation of auditory sensation.

Experiments carried out using the method of immersing a person’s head in water showed that in order to obtain unambiguous results it is necessary to work in an environment practically free from reflections, i.e., it is necessary to have a sufficiently large pool with a special sound-absorbing material.

terial. Under our conditions, the possibility of conducting such an experiment was practically excluded.

The presence of the applied sound-absorbing material and the size of the aquarium were insufficient, which led to the occurrence of standing waves for a number of frequencies. In this case, a change in the position of the subject's head relative to the walls of the aquarium led to a change in the threshold value.

Despite the imperfection of this technique, a series of experiments has confirmed the presence of a high threshold region (up to 20 dB) in the frequency range correlating with the size of the head when excitation of acoustic vibrations in bone tissue formations without the use of pulsed microwave radiation.

Contact method. Audiometry of bone-tissue conduction in modern studies is mainly carried out by contact using various bone telephones-vibrators. However, to date there are no GOST standards either for the vibrator itself or for the methods of its application. Therefore, we investigated the possibility of using various headphones as a vibrator.

Measurements of the frequency response of the emitters showed that some types of small-sized telephones with a round hole in the center of the cover up to frequencies of 12...14 kHz can be used as a source of sound vibrations.

Our method uses the TK-67-N telephone. The measurements were carried out in a quiet room with dimensions of 2.8x2.8x2.8 m. The noise level in the room was not higher than 25 dB. The noise level was determined by the signal value at the output of the measuring microphone (12 μV), taking into account its own sensitivity (2.5 mV/Pa) and its own noise (24 dB). The frequency response of the telephone was measured using an MKE-2A measuring electret microphone at distances from 15 cm to 1.5 m between the phone and the microphone. The identity of the obtained frequency response suggests the absence of standing waves in the room.

Obviously, to obtain the correct result, in-phase excitation of both cochleae is necessary, i.e., point the overlay must be in the sagittal plane. Otherwise, the phases of pressure waves excited in the brain tissue and activating the cochlea will not coincide. This method of excitation of snails is close to a natural experiment with in-phase excitation of pressure waves by microwave pulses simultaneously throughout the entire volume of brain tissue.

The junction of the frontal part of the skull with the septum of the frontal sinuses was chosen as such a point, located in the sagittal plane. Subsequently, the septum of the frontal sinuses is connected to the main bone of the skull, on which the tubercle (crista galli) is located, separating the orbital surfaces of the frontal bone. Directly from the front The membranes of the brain are in contact with the bone. Thus, the transmission of vibrations from the emitter to the cochlea can be carried out by excitation of the listed bone formations, partly through the meninges.

Using a rubber strap, the phone is pressed tightly to a selected point on the frontal part of the subject's head. The subject's ears are covered with anti-noise headphones - mi VTSNIIOT-2M (NP 45x7). In the frequency range 1...8 kHz The dampening ability of these headphones is in the pre- cases 22...45 dB.

Tone mode. Three subjects took part in the experiment. Using the described method, bone-tissue conduction threshold curves were constructed for each of the subjects using three threshold measurements for each set value of the sound signal frequency in the range of 2...13 kHz with a step of 0.2 kHz. In the frequency range 7...8 kHz, a smooth change in the signal frequency was used, since in the same frequency range on the radio sound threshold curve the slope curve reaches 90 dB/oct.

In the region of 7...8 kHz there is a sharp increase in the threshold relative to 10 kHz. Comparison of the obtained threshold curves of bone-tissue conductivity with the threshold curve of radiosound shows that the course of the curves is qualitatively the same. The difference between the obtained curves and the threshold curve of radio sound in the region of 3...6 kHz (a significantly more pronounced increase in the threshold in this region) cannot be explained by comparing them due to the large difference in the selection of frequency points for measurements (2 kHz interval when constructing the radio sound threshold curve and 0.2 kHz in our experiments). However, an increase in the sensitivity threshold in this area is explained by the Flanagan model of the middle ear [108].

During the experiments, a change in the recorded sensitivity thresholds was noted, corresponding to a change in the signal frequency within ±2...4% and caused by a change in the pressure value of pressing the phone to the frontal bone.

Shock vibration mode. Imitation of mechanical vibrations excited in the tissues of the head by microwave pulses was carried out by a special electronic unit containing a shock excitation circuit with a natural frequency of oscillations of the order of 7 kHz with a quality factor of the circuit equal to the calculated quality factor of the equivalent head circuit. The electronic unit was triggered by rectangular pulses with a repetition frequency of 1...14 kHz. The signal at the output of the block is a series of damped oscillations up to pulse repetition frequencies lower than the resonance frequency of the shock excitation circuit. When the frequency of the triggering pulses is equal to or higher than the resonance frequency of the shock excitation circuit, the signal at the output of this block has a sinusoidal shape. In this case, the signal frequency is equal to the frequency of the first harmonic of the pulse sequence.

Three subjects took part in the experiment. In the mode of shock mechanical vibrations, threshold curves of hearing sensitivity were recorded with a trigger pulse duration of 15 μs with a pulse frequency step of 200 Hz. This model is closest to the real experimental conditions in which the radio sound threshold curve was recorded.

Data from three measurements for each subject were averaged, and the average threshold curve of bone-tissue conduction hearing sensitivity was constructed from the data obtained. At a frequency close to 7 kHz for all subjects, a sharp rise in the threshold of 8...9 dB relative to 10 kHz is also observed, which practically coincides with the same value on the threshold curve of radio sound.

The results of these series of experiments are presented in [95].

Bone-tissue audiometry using a vibrator with a rigid membrane. The phenomenon of a sharp increase in the hearing sensitivity threshold during bone-tissue conduction audiometry in the high-frequency region was discovered for the first time thanks to the applied technique of smoothly changing the sound frequency. At the same time, the applied method of contact excitation of mechanical vibrations in the tissues of the head using a vibrator with a soft membrane differs from the generally accepted method using vibrators with a hard membrane [87, 157].

Therefore, a new series of experiments was carried out using a vibrator with a rigid membrane based on a Rochelle salt emitter. In order to identify the detailed structure of the hearing sensitivity threshold curves, the frequency step did not exceed 200 Hz.

The vibrator is made in the form of a duralumin glass with a flat bottom. The outer diameter of the glass is 30 mm, height 50 mm. Inside the glass there is a package of Rochelle salt crystals connected in series and filled with epoxy glue. Mechanical vibrations from the battery of crystals are transmitted through the bottom of the glass to the tissue of the subject's head. The AHF of the vibrator was measured using acoustic control and measuring equipment from Brühl and Kjaer (measuring microphone No. 4145 and measuring amplifier No. 2606) in a silenced box at a voltage at the vibrator terminals equal to 1.5 V. The experimental conditions remained the same. .

Six subjects participated in the experiments, five of whom did not have any significant deviations from normal hearing. The sixth subject showed a noticeable decrease in hearing sensitivity in the frequency range above 7 kHz.

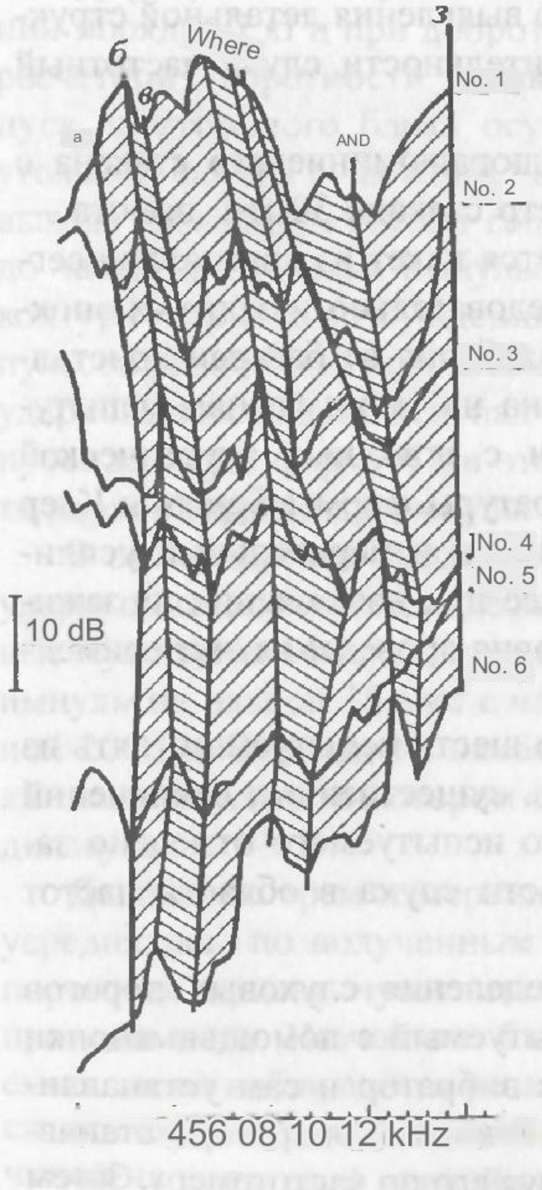
In order to more accurately determine auditory thresholds in this series of experiments, the subject used a button to interrupt the signal supplied to the vibrator and set its level himself. With the button open, the operator set the signal frequency, monitoring it using a frequency meter. Then the subject gradually increased the signal level, starting from zero level until the moment the auditory

Feel. At the same time, for greater reliability of recording the presence of sound [127], the subject interrupted the signal using a button. At the moment the auditory sensation appeared, the subject gave a signal to the operator, who recorded the voltmeter readings and adjusted the frequency. The procedure was repeated and in one session in the frequency range 4...12 kHz, 41 points were taken with a step of 200 Hz. Audiograms were constructed from 3-5 tests after preliminary averaging at each point, taking into account the characteristics of the vibrator.

In Fig. 48 all six audiograms are presented under the number frames that were assigned to the subjects. It can be noted that, despite the pronounced individuality of audiograms, all audiograms have an unconditional similarity, such as similarity of shape, manifested in the presence of alternating rises and falls in sensitivity. The position of these extrema on the frequency axis and their relative magnitude determine the individuality of each audiogram.

For greater clarity, the zones of rises and falls are highlighted with oblique shading and designated as.

As can be seen from Fig. 48, using the described technique for measuring hearing sensitivity thresholds, with bone-tissue conduction it is possible to identify sharp changes in thresholds not only in the frequency range correlating with the mechanical resonance frequency of the head, but also in other areas. - low frequencies of the audio signal [122] S



Rice. 48. Audiograms with small frequency steps (200 Hz)

Simulation of full-scale radio sound experiments using acoustic signals. The results of audiometry of hearing sensitivity thresholds and bone-tissue conduction showed good agreement of the obtained curves with the radiosound threshold curve. This demonstrates the possibility of explaining the effect of radio sound by excitation of mechanical vibrations in the tissues of the head by microwave pulses and their conduction into the cochlea due to bone-tissue conduction. At the same time, for a more complete characterization of radio sound as a phenomenon presumably associated with the excitation of mechanical vibrations, it is of interest to realize the psychoacoustic effects that take place in full-scale radio sound experiments using acoustic signals.

Pulsed microwave radiation was replaced directly by excitation of mechanical vibrations in the tissues of the subject's head using a bone vibrator mounted on the frontal part in the sagittal plane according to the method described above.

The bone vibrator was excited from an electronic unit by a signal representing a series of damped oscillations with a natural frequency of about 7 kHz and a repetition frequency in the range of 1...14 kHz. At the same time, a tone signal was also sent to the headphones in the frequency range 1...14 kHz. Five subjects took part in the experiment. No preliminary measurements of hearing sensitivity thresholds by air or bone conduction were made. All subjects noted beats at tone signal frequencies close to the frequency of the series of shock-excited oscillations or multiples of it.

Using the developed bone-tissue conduction audiometry in the shock vibration excitation mode, the possibility of suppressing high-frequency oscillations (7 kHz) was investigated by changing the duration of the trigger pulses within (0.5... 1.0) T, i.e. from 70 to 140 μs. At a low repetition rate of pulses with a duration equal to the period of high-frequency oscillations in the series, suppression of the sensation of high-frequency sound is observed. With a smooth change in the height of a low-frequency tone, corresponding

corresponding to the repetition frequency of the triggering pulses, upon transition to a pulse duration equal to half the period of the excited high-frequency oscillations, the sensation of a low-frequency tone decreases and a high-frequency sound is perceived, corresponding to the frequency of oscillations in the series. According to the subjective assessment of the subjects, the high-frequency sound has a "humming" character, as in a full-scale experiment on radio sound.

4.2. The mechanism of formation of bone-tissue audiogram in humans and animals

Until now, many processes associated with the analysis and processing of sounds are the subject of research due to the lack of a unified established idea about the role of certain parts of the auditory system in recognizing incoming information, as well as the recognition mechanisms themselves.

One of the effective methods for studying the central mechanisms of analyzer activity is electrophysiological, which is most often used to study the auditory system of animals. The study of the human auditory system is carried out mainly by psychophysiological methods, which represent a certain set of methodological and instrumental approaches for studying the integral activity of the entire brain during the perception of sound information.

The known similarity of some characteristics of the frequency analysis of the auditory system, observed in electrophysiological and psychoacoustic studies, allows, to some extent, to carry out a comparative assessment of data obtained on humans and animals, in the direction of searching for mechanisms for the formation of frequency-threshold curves as a form of manifestation of the frequency properties of the auditory analyzer . This issue is touched upon in modern literature only when trying to explain some particular aspects of reflection. changing the shape of the stimulus by one or another neural structure. Some studies have shown that the formation of certain types of responses of neurons at different levels of auditory system is possibly associated with the resonant properties of the cochlea of the hearing organ [83].

Based on the results of our own research and analysis of literature data, a model of the mechanism of formation of the reflection of the stimulus shape by neurons, associated with the resonant properties of the anatomical structures of the head, is considered.

The search for a possible mechanism for the formation of an audiogram during bone-tissue sound conduction is relevant in itself. This issue is of particular importance due to the close connection between the method of isolating a useful signal and its analysis in the auditory system in the case of inadequate perception of sensory information with the determination of the principles of modulation of non-ionizing radiation.

As a methodological technique, we used the method of comparing the responses of neural structures at different levels of the auditory system and the characteristics of the output signal of an equivalent resonant oscillatory system when they are excited by a stimulus of the same shape. todo

A comparative assessment of the responses of both systems is carried out on the basis of electrophysiological, psychoacoustic and model studies. Electrophysiological data are borrowed from the literature and presented by the results of studies of frequency-threshold curves of dolphins using the method of evoked potentials (EP) and cochlear potentials guinea pigs. By

Psychoacoustic data are presented by the results of our own studies of bone conduction of sound in humans in a wide frequency range.

The dependence of the amplitude of the response of the auditory system on the value of the interpulse interval as a possible manifestation of the interference of oscillations from two unit functions. The work [70] studied the responses of the auditory cortex of the bottlenose dolphin to stimulation with sound pulses when changing the intervals in pairs of sound pulses. With an increase in the initial interval between pulses, which is less than the duration of the wave of the recorded response, a significant increase in its amplitude is observed. ANRONIDO

A similar picture can be obtained by increasing the duration of a rectangular pulse acting on a resonant oscillatory system, considering the pulse fronts in the form of two unit functions of short duration. In this case, a change in the duration of the pulse itself is equivalent to a change in the interpulse interval during stimulation of a biological object.

It is noted in [14] that the basilar membrane, which plays the role of a resonator, has a certain effect on the properties of the auditory frequency analyzer. There, with reference to /Meller/, the influence of the resonant system with extremely small changes in interpulse intervals is noted. It was also noted /Kiang/ the presence of discharges in the nerve fibers of the auditory nerve, synchronized with the beat frequency in response to two tones of equal intensity, and the beat frequency is equal to the difference in the frequencies of the exciting signals.

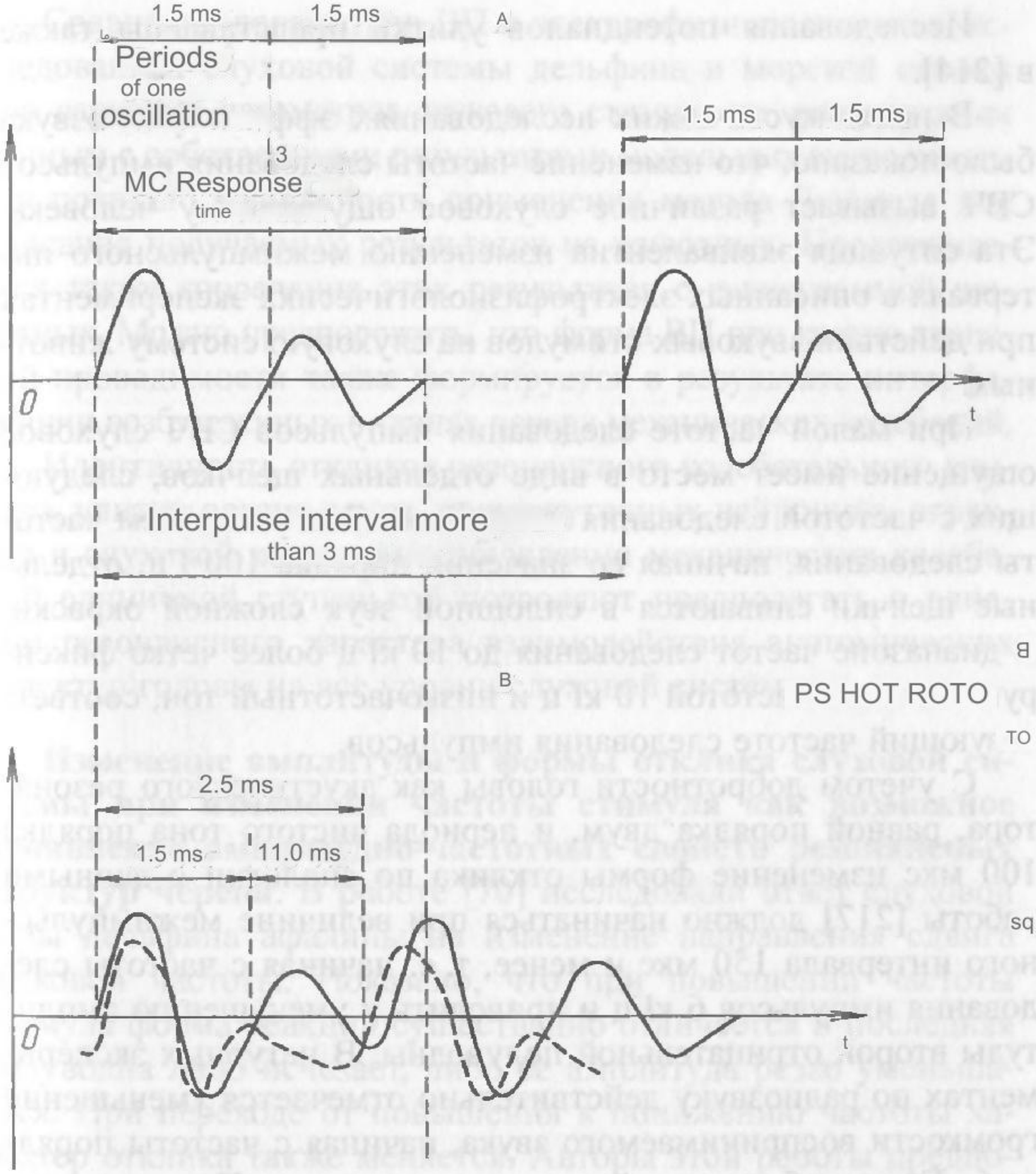
A more pronounced picture with changes in the interpulse interval is observed when ultrasound pulses act directly on the bone and tissue formations of the guinea pig's head [217].

With a pulse duration of 0.5 ms, the interpulse interval was reduced from 200 to 2.5 ms. In this case, the potential in the round window of the cochlea significantly changed its shape. This change was manifested in a decrease in the amplitude of the last negative half-wave of the response by 50...60%.

From the samples of documentary recording of responses given in this work, it follows that with a duration of the entire response of 3 ms, a decrease in the interpulse interval to 2.5 ms leads to the summation of the last negative half-wave of the previous oscillatory process with the first positive half-wave of the subsequent oscillatory process.

This change in the response shape can be explained if we assume that the ultrasonic pulse excites mechanical vibrations in the tissues of the guinea pig's skull with a period of 1.5 ms, which interfere with each other.

In Fig. Figure 49 schematically represents the process of excitation of a series of periodic damped oscillations by short single pulses in a resonant oscillatory system.



Rice. 49. Total oscillatory process excited by ultrasound pulses

When the duration of the excitation process is significantly less than the interpulse interval, the oscillatory process ends before the next series of oscillations (A) is excited. When the interpulse interval is less than the duration of the series of excited oscillations, as a result of interference, the total oscillatory process differs from a single one (B). The dotted line shows the shape of the potential in the round window of the guinea pig cochlea [216] with an interpulse interval of less longer response time.

Studies of cochlear potentials are also presented in [214].

In psychoacoustic studies of the effect of radio sound, it was shown that changing the frequency of microwave pulses causes different auditory sensations in humans. This situation is equivalent to a change in the interpulse interval in the described electrophysiological experiments during the action of sound stimuli on the auditory system of animals.

At a low microwave pulse repetition rate, the auditory sensation takes place in the form of individual clicks that follow at the same pulse repetition rate. With increasing repetition frequency, starting from values of the order of 100 Hz, individual clicks merge into a continuous sound of complex color. In the range of repetition frequencies up to 10 kHz, a tone with a frequency of 10 kHz and a low-frequency tone corresponding to the pulse repetition frequency are more clearly recorded.

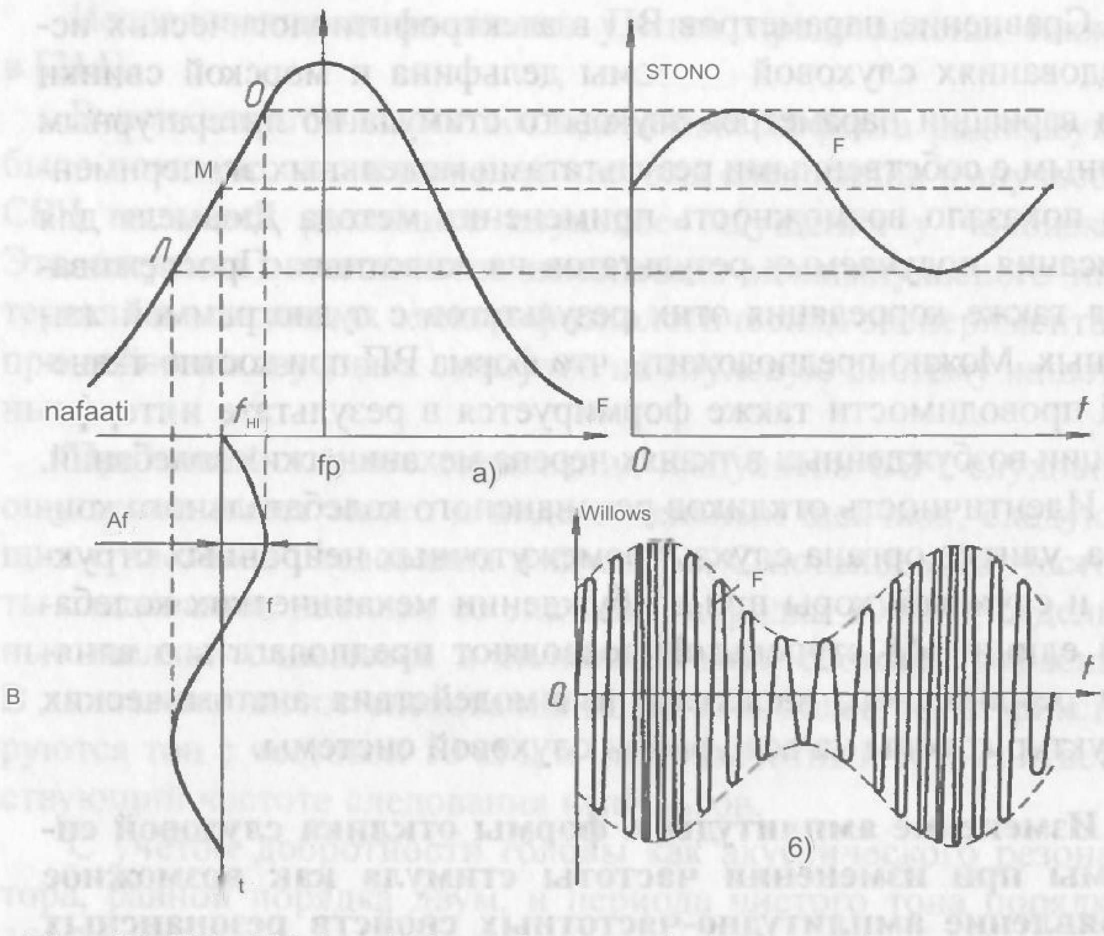
Taking into account the quality factor of the head as an acoustic resonator, equal to the order of two, and the period of the pure tone of the order of 100 μs, the change in the response shape, by analogy with the data in [217], should begin at an interpulse interval of 150 μs or less, i.e., starting from a pulse repetition frequency of 6 kHz and lead to a decrease in the amplitude of the second negative half-wave. In full-scale radio sound experiments, there is indeed a decrease in the volume of perceived sound, starting from a frequency of about 6 kHz, according to the subjective assessment of the subjects. When the interpulse interval is reduced to 125 μs, the response amplitude should have a minimum value, since in this case the amplitudes of already two half-waves are subtracted, which in a natural experiment manifests itself in the form of a maximum decrease in the intensity of the auditory sensation at frequencies of the order of 7.5 kHz. Finally, when the interpulse interval is equal to 100 μs, the amplitudes of two oscillatory processes are summed up, which is marked on the radio sound threshold curve by the region of the minimum sensitivity threshold at approximately 10.3 kHz.

Similar results were obtained on liquid models excited by microwave pulses [120].

Comparison of EP parameters in electrophysiological studies of the auditory system of a dolphin and guinea pig when varying the parameters of a sound stimulus according to literature data with our own results of model experiments showed the possibility of using Duhamel's method to describe the results obtained in animals. There is also a correlation between these results and the audiogram of animals. It can be assumed that the shape of the VP during bone-tissue conduction is also formed as a result of the interference of mechanical vibrations excited in the tissues of the skull. The identity of the responses of the resonant oscillatory contur, cochlea of the organ of hearing, intermediate neural structures and auditory cortex when excitation of mechanical vibrations by a single step suggests the influence of the resonant nature of the interaction of anatomical structures of the head on all levels of the auditory system.

Changes in the amplitude and shape of the response of the auditory system when the frequency of the stimulus changes as a possible manifestation of the amplitude-frequency properties of the resonant structures of the skull. In [70], the response of the auditory cortex of the bottlenose dolphin to a change in the direction of the sound frequency shift was studied. It has been shown that as the stimulus frequency increases, the shape of the response differs significantly and the last half-wave either disappears or its amplitude sharply decreases. When moving from increasing to decreasing frequency, the nature of the response also changes. The authors of this work suggest the presence in the dolphin's auditory cortex of elements that are selective to the direction of the stimulus frequency shift.

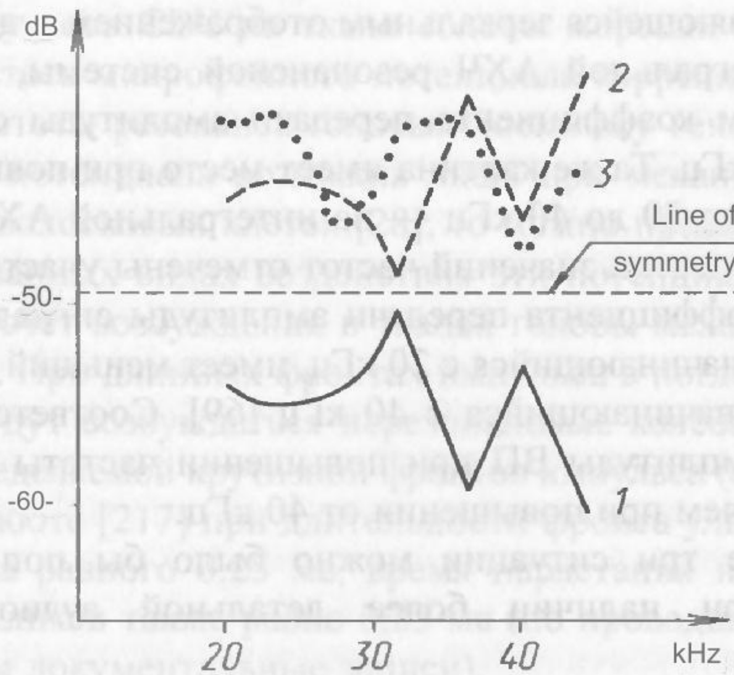
Let's analyze the response shapes of the dolphin's auditory cortex, using the known reaction of a resonant oscillatory circuit when the frequency of the input signal changes. In Fig. 50 schematically shows the dependence of the amplitude transmission coefficient of the circuit signal when changing changing the frequency of the input signal. It can be seen from the figure that if the resonant circuit is detuned relative to the carrier signal, then with a deviation in the frequency of the carrier arriving at the input of the resonant circuit, due to a change in the detuning of the circuit, the amplitude of oscillations on the circuit will change proportionally.



Rice. 50. FM - AM signal conversion on a single resonant circuit

Depending on the location of the operating point (point M), i.e., the value of the signal frequency relative to the resonance frequency of the circuit p, when the input signal deviates by the same value Yes, the shape of the output signal will be different. The lower the quality factor of the circuit, the less distortion the function of changing the frequency of the input signal will be converted into a function of changing the amplitude. In this case, a frequency-modulated (FM) signal is converted into an amplitude-modulated (AM) signal using a detuned oscillatory circuit.

Let's use a detailed audiogram of a dolphin [188], borrowed from [107]. At the audiogram site (Fig. 51) in the frequency range 20...40 kHz we will apply its mirror image display equivalent to the amplitude of the excited auditory vogo sensation (dashed line) and the response of the auditory cortex dolphin when changing the frequency of the tonal sound signal signal in the same frequency range (dashed line [70]).



Rice. 51. Correlation of the response of the auditory cortex with changes in the amplitude of the auditory sensation

In this case, the tone frequency increases abruptly over 50 ms from 20 to 40 kHz and decreases from 40 to 20 kHz over the same period of time.

From Fig. 51 shows that the recorded responses of the auditory cortex correlate quite well with the curve of the amplitude of the auditory sensation, constructed on the audiogram of the dolphin. If we proceed from the assumption that in this case, the resonant properties of the anatomical structures of the dolphin's head form its audiogram, then the shape of the responses of the auditory cortex can be explained by the processes of converting the FM signal into an AM signal.

In [71], when studying EPs in the auditory cortex of a dolphin to a change in tone frequency, an increase in the amplitude of EPs was noted when the tone frequency changed by just a fraction of a percent at frequencies in the range 5...40 kHz. A comparison of these results and a detailed audiogram of a bottlenose dolphin [186] shows that in five cases out of the eight situations presented in [69], the dependence of the EP amplitude with an absolute change in tone frequency and the direction of change in tone frequency is explained by the resonance model.

Thus, with an increase in tone frequency from 10 kHz, an increase in the EP amplitude is observed, which can be explained by the presence on the curve, which is a mirror image of the audiogram, i.e., the integrated AHF resonant system, a section with an increase in the signal amplitude transmission coefficient, starting from 10 kHz. The same picture occurs when the tone frequency increases from 20 to 40 kHz on the integral AHF of the dolphin; starting from these frequency values, areas with an increase in the signal amplitude transmission coefficient are noted. Moreover, the section starting at 20 kHz has a smaller slope than the section starting at 40 kHz [69]. Accordingly, the increase in EP amplitude when the tone frequency increases from 20 kHz is lower than when it increases from 40 kHz.

The remaining three situations could be explained by having a more detailed audiogram of the dolphin.

A comparison of the audiograms from [66] and [188] clearly demonstrates the difference between both curves. It can be assumed, based on audiometric data on human bone conduction, obtained using a standard technique and with a slow gradual change in stimulus frequency, that the dolphin audiograms in these studies were also obtained at different frequency increments of the stimulus.

It should be noted that the presence of a high threshold in the frequency range 7...8 kHz on the threshold curve of human hearing sensitivity by bone conduction was first discovered only when the measured frequency step in this region was less than 10 Hz, which is 0.12%. This figure is comparable with the tone frequency measurements given in [69], and it is possible that a detailed study of the dolphin's audiogram will reveal a more subtle structure of the threshold change.

The work [150], as well as the works of J. Lin, showed a significant similarity in the responses of the primary auditory cortex of cats excited by microwave and acoustic impulses, as well as in the round window of the cochlea.

Works [154, 155, 157, 167] demonstrated the presence of a microphone potential in cats and guinea pigs when applying an audible click, a pulse of microwave electromagnetic energy, and using a piezoceramic emitter through the skull bones. These works also show that under the action of short-of high microwave pulses on the head tissue of guinea pigs and cats, the frequency of the microphone potential correlates with the value of the head resonance frequency. Since the generation of membrane potential is possible only with mechanical displacements of hair cells [28], it can be assumed that with these types of effects these potentials are generated due to the excitation of mechanical vibrations in the tissues of the head. With long pulse fronts, non-resonant oscillations will be excited in the absorbing system with a frequency determined by the steepness of the pulse (stimulus) fronts [26]. Thus, in work [217], with the duration of the front of the ultrasonic pulse equal to 0.25 ms, the rise and fall time of the response half-waves is also equal to 0.25 ms (documentary records based on the samples carried out in the work).

These data allow us to consider the response form not as a co-consisting of individual positive and negative half-waves produced by individual systems or elements, but by a single oscillatory electrical process that repeats the picture of mechanical vibrations excited by one or another physical factor.

The considered mechanism of formation of a bone-tissue audiogram is presented in [99].

4.3. Human head as a multimode acoustic resonator

The work [80] shows that when mechanical vibrations are excited in the bones of the skull, the measured values of the speed of sound in different bones of the skull and even at different points within the same bone vary greatly and vary within 943.8...1440.5 m /s and are determined by the thickness of the bone at the measurement point and the air content of the bones. Since this value determines the frequency of mechanical resonance for each bone of the skull, then, with a certain degree of connection, the individual bones that make up the skull can be considered as independent resonators.

It can be assumed that when mechanical vibrations are excited in the tissues of the head by microwave pulses, the mechanism for the formation of various vibration modes is close to that described, since after the initial detection of EMR energy by the tissues of the head, the pressure surge is equivalent to a mechanical pulse effect. Similar problems are considered in works [1, 37, 52, 238] on the study of frequency properties of spherical models with various boundary conditions. Gender However, it is also necessary to take into account the fact that the process of excitation of mechanical vibrations in the tissues of the head by EMR pulses differs from that described in [194] in the number and order of anatomical structures of the head captured by the primary pressure wave. This cannot but affect the formation of the ratios of resonant peaks and their number, i.e., the formation of one or another vibration mode.

Thus, a combination of such resonators leads to the formation of a multi-circuit or multi-resonant system, forming an integral AFC in the studied (or perceived) frequency range. This conclusion can be confirmed by the results of our own research (audiograms in Fig. 48) and the data presented in works [164, 193, 194].

The authors of these works studied various modes of sound vibrations on natural skulls and plastic models in response to a mechanical blow using a special device with a striker that struck the bone. The study of propagating sound vibrations was carried out using strain gauges glued at various points of the model or skull. The phase characteristics of mechanical vibrations were used to determine the modes of excited mechanical vibrations. It is very important that when the hollow sphere was filled with liquid, no significant shift in the resonant frequencies was observed.

The data from these works also indicate that when the Young's moduli of the shell material of the spherical models and the skull bones of an adult male are equal, the recorded resonant frequencies of various modes in the models are 50% higher than for the skull.

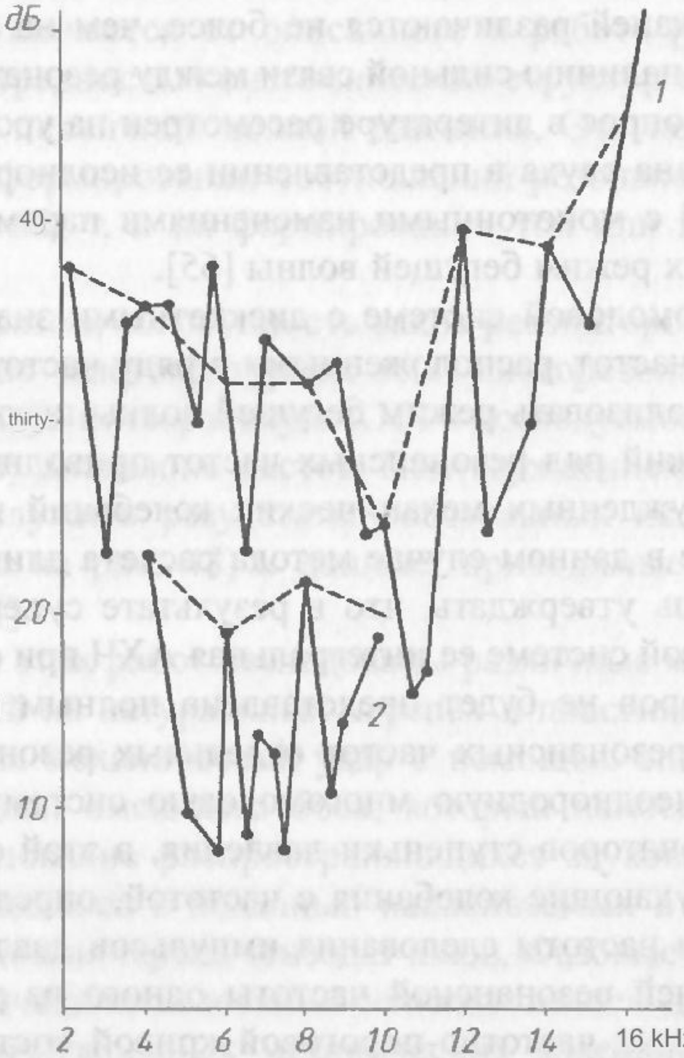
Thus, the human head, when mechanical vibrations are excited in its tissues, can be considered as multihomode resonator. The connection of individual resonators with each other can be determined by the ratio of their acoustic impedances Disp/rtst, where R is the density of the medium and the speed of sound in this medium, respectively; pit indices of the n-th and t-th resonators.

Due to the small difference in the densities of various biological media and the speed of sound in them, the impedances of biological tissues differ by no more than 8...12%, which leads to the presence of a strong coupling between the resonators. A similar issue in the literature is considered at the level of models of the cochlea of the hearing organ, represented by its inhomogeneous long line with monotonic changes in the parameters that ensure the traveling wave mode [65].

In a multimode system with discrete values of resonant frequencies randomly located in a series of frequencies, it is impossible to implement the traveling wave mode. A non-harmonic series of resonant frequencies leads to a superposition of excited mechanical vibrations and excludes the use of the method of calculating long lines in this case. We can only say that as a result of superposition on a multimode system, its integral AFC with strong coupling between the resonators will not be represented by the full set of initial resonant frequencies of individual resonators. When a pressure step is applied to an inhomogeneous multimode system with a strong coupling of resonators, damped oscillations will be excited in this system with a frequency determined by the ratio of the repetition rate of pressure pulses and the closest resonant frequency of one of the resonators.

The explanation of the frequency-threshold curve of bone conduction of sound by the resonant properties of the anatomical structures of the head became possible thanks to the applied technique for measuring hearing sensitivity thresholds with a small frequency step.

In Fig. Figure 52 shows audiograms of auditory thresholds by bone-tissue conduction of two subjects 1 and 2, recorded using the developed (solid line) and standard (dashed line) techniques [12]. From the audiograms presented it is clear that the traditional method of assessing hearing not only leads to the loss of a large amount of information and distortion of the actual state of hearing, according to existing approaches in audiometry of bone conduction of sound, changes in hearing sensitivity within 5 dB in the frequency band of 8 kHz are considered normal, but do not allow us to express at least general considerations regarding the mechanism of formation of the frequency-threshold curve.



Rice. 52. Audiograms of auditory thresholds by bone-tissue conduction taken using the developed method (solid lines) and standard (dashed lines)

Explanation of the frequency-threshold curve of hearing in bone-tissue conductivity resonant properties of anatomy

ical structures of the head predetermines the dependence of position on the frequency axis of areas with a sharp change in the sensitivity threshold

reality, interpreted as mechanical resonances from separate resonators, on the characteristics of these resonators

The speed of sound and the dimensions of individual resonators can be used as such characteristics. However, the complexity of identifying the entire set of anatomical structures of the head that can play the role of resonators and the number of acoustic contacts between them makes it impossible at this stage of research to fully analyze the frequency response of such a system. We can only try to identify some of the structures, the connection between which is most clearly manifested in the frequency response of the system and give a description in terms and categories of four-terminal networks of the structures themselves and the type of connections with parameters that ensure the maximum approximation of the analogues to the structures under consideration.

A series of experiments to identify auditory sensations caused by irradiation of the head with EMR pulses and directly with a bone vibrator, as well as the correlation of the acoustic and geometric parameters of the anatomical structures of the head with the frequency of the mechanical resonance of the head confirmed the validity of the hypothesis put forward about the possibility of considering the head as a multimode resonant system and the formation of a frequency-threshold curve of bone-tissue conductivity as a mirror image of the frequency response of this system. A good agreement is shown between the values of the mechanical resonance frequency of the head, following from the relationship proposed by Lin obtained (RES =) and R in the experiment on subjects 8.54...7.83 kHz (according to Lin) and 8.59...7 .24 kHz (own results) for head sizes in the range of 55...60 cm (s = 1.5-105 cm-s-1).

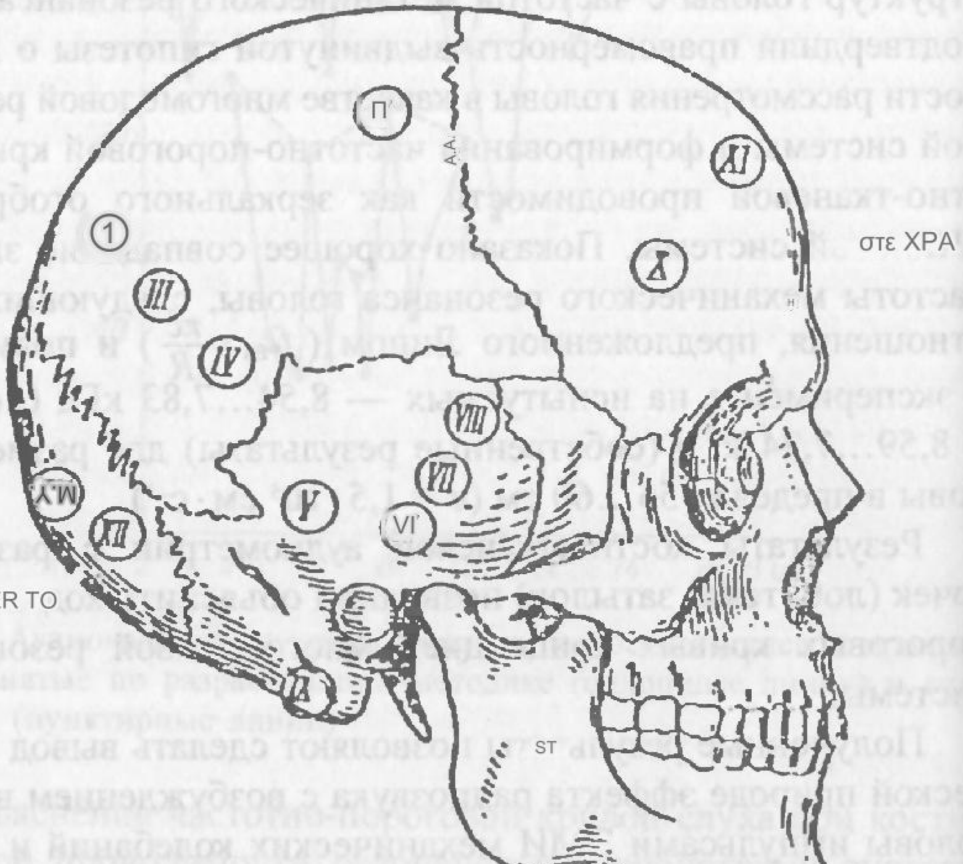
The results of bone-tissue audiometry from various points (forehead, crown, back of the head) made it possible to explain the course of frequency-threshold curves with the concept of a multimode resonance system.

The results obtained allow us to draw a conclusion about the physical nature of the effect of radio sound with the excitation of mechanical vibrations in the tissues of the head by EMR pulses and the formation of a frequency-threshold curve by the anatomical structures of the head, which have resonant properties.

Analysis of literature data on the electrophysiology of sensory systems of animals and their comparison with the obtained ex-

experimental material suggests the existence of a single mechanism for inadequate perception of a stimulus during the action of pulses of non-ionizing radiation on the tissue of the head.

Dependence of the mechanical resonance frequency of the head on the speed of sound in various anatomical structures of the skull. In Fig. Figure 53 shows the location of points on the skull bones at which the speed of sound was measured [80]. From the considered mechanism of formation of the frequency-threshold curve during bone-tissue conduction, it follows that since the marked points are characterized by different values of the speed of sound, the excitation of mechanical vibrations by a bone vibrator at these points should lead to a shift in the frequencies of the resonators of the multimode systems.



Rice. 53. Points of measured values of the speed of sound (borrowed from [80])

Table 7

The speed of sound in the bones of the skull and the resonance frequency of the maximum threshold point on the radio sound threshold curve

Parameter	Points of application of the bone vibrator corresponding to Fig. 53												
	V	VII	VI	VIII	III	IV	I	II	IX	XII	XIII	X	XI
*Sound speed, MC^{-1}	1448.5	1440.5	1428.9	1423.0	1270.0	1260.0	1186.6	1178.4	1098.6	1066.2	1066.2	998.3	943.8
**Resonance frequency, kHz	7, 52	7.43	7.46	7.37	7.10	7.08	7.03	6.99	7.43	7.06	7.06	6.72	6.59

* — from [80].
** — own results.

To solve the problem under consideration, the region on the threshold curve of radio sound, characterized by the highest value of the sensitivity threshold within the frequency range of 6...8 kHz, is of practical interest.

Three subjects took part in the experiment. The experimental procedure is described in paragraph 4.1 (p. 112). The difference was that the subject himself smoothly adjusted the frequency of the tone signal within the range of 6...8 kHz when searching for the point of the maximum threshold.

In table Figure 7 shows the averaged data of the measured values of the resonance frequency of the maximum threshold region.

In general, there is a fairly proportional dependence of the resonance frequency on the speed of sound at the measured points. At the same time, a violation of the monotonicity of the increase in the value of the resonance frequency with increasing sound speed is obvious, which is explained by the proposed model of a multimode resonant system when it is excited at different points. The correlation coefficient calculated on the Iskra-226 computer is 0.818.

Dependence of the mechanical resonance frequency of the head on the size of the head. In accordance with the considered model of a multimode resonant system and the data of works [54, 154-157, 202], there should be a dependence of the mechanical resonance frequency of the head on the size of the head.

15 subjects took part in the experiment. The size of the subjects' heads varied within the range of 54...60 cm. Since the value of the mechanical resonance frequency of the head is characterized by the region of the maximum threshold in the frequency range 6...8 kHz, then each subject, according to the method described here, determined the value of the resonance frequency based on the maximum threshold in this frequency range. The maximum threshold point for each subject was determined twice when the frequency increased from 6 to 8 kHz and then when the frequency decreased from 8 to 6 kHz. The data were averaged and recorded (Table 8).

In general, there is a fairly good correlation between the input and output values; as the size of the subject's head increases, the value of the mechanical resonance frequency decreases. The correlation coefficient calculated on the Iskra-226 computer is 0.77.

Table 8

Dependence of head mechanical resonance frequency on head size

Subject's serial number	Head size, cm	Average resonance frequency, kHz
1	54	8.59
2	54	8.17
3	55	7.59
4	55	7.89
5	56	7.66
6	56	7.64
7	56	7.87
8	56	8.11
9	56	7.71
10	57	7.56
11	57	8.06
12	58	7.04
13	58	6.52
14	60	7.39
15	60	7.24

Frequency response of a multimode resonant system when it is excited at various points. The model of a multimode resonant system assumes a shift in the extreme points of hearing sensitivity (frequency maxima) when it is excited at different points by the presence of a superposition of different oscillation modes. Moreover, a shift in frequency maxima should occur both on individual audiograms when mechanical vibrations are excited at different points of the head due to the difference in the path length of displacement waves from the vibrator to the cochlea and the participation of resonators with different characteristics in their conduction, and for individuals when placement of the vibrator on the same points due to different head sizes.

The experiments involved 24 subjects aged from 24 to 64 years. Points on the frontal, parietal and occipital regions lying in the sagittal plane were chosen as points for excitation of mechanical vibrations. This choice of points ensures in-phase excitation of the basilar membranes

branes of both snails, which ensures a more correct setup of the experiment by reducing the influence of the oscillation phases on the perception of the stimulus. A vibrator with a rigid membrane was used, the frequency range was 3...20 kHz with a frequency step of 1 kHz. The resulting bone-tissue conduction audiograms were corrected taking into account the frequency response of the vibrator and processed on an IBM PC-401 personal computer.

Analysis of the audiograms obtained showed that, according to age, all data can be divided into two groups: normal and pathological, with a difference in the average audiogram threshold levels of 15...20 dB.

In the “norm” group, all 14 subjects showed a shift in frequency maxima on individual audiograms taken from the forehead, crown and back of the head.

In table Figure 9 shows the values of the frequency maxima of three audiograms from the forehead, crown and back of the head for each of the subjects aged 25-55 years.

Table 9

Frequency maxima on individual audiograms from the forehead, crown and back of the head of the subjects are normal, kHz

Serial number of the subject	Vibrator application area														
	Back of the head					Forehead					crown				
	Serial number of the frequency maximum														
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	5	7	10	13	15.5	5	8	10.5	—	16	5	8.5	11	15	18
2	4	7	10.5	—	—	4	6	8.5	13	—	4	9	11	14	16
3	6	9	—	13	—	5	9	—	—	—	5	7	10	12	14
4	4	6	11	—	—	4	—	9	11	—	—	9	—	—	—
5	4	6	10	—	—	6	6.5	9	—	—	6	—	11	—	—
6	4	6	—	—	—	4	6	8	—	—	4	6	8	—	—
7	4	6	10	13	—	4	6	—	—	—	4	8	11	—	—
8	4	7.5	10.5	—	—	4	—	—	—	—	4	7.5	—	13	—
9	4	9	—	—	—	—	9	—	—	—	4	8	11	—	—
10	6	8	—	—	—	4	8	—	—	—	4	6	9	—	—
11	5	8	11	—	—	4	6	8	11	—	6	9	12	—	—
12	5	7	10	—	—	4	6	10	—	—	4	6	9	—	—
13	5	8	12	13	—	4	7	13	—	—	5	—	—	13	—
14	4	6	8	10	—	4	6	8	11	—	4	6	10	—	—

According to the table. 9, you can also trace the displacement of the frequency maxima of individual audiograms relative to each other for each of the points of application of the vibrator. In table Figure 10 shows the frequency regions within which the frequency maxima change for three points of vibrator application.

The results of audiometric studies in the “pathology” group, consisting of 10 subjects aged 24-64 years, are presented in table. 11 and 12.

Table 10

The limits of displacement of frequency maxima on audiograms from the forehead, crown and back of the head in subjects are normal, kHz

Serial number of the frequency maximum	Frequency peak shift limits		
	Vibrator application area		
	Back of the head	crown	Forehead
1	4...6	4...5	4...6
2	6...9	6...9	6...9
3	8...12	8...13	8...12
4	10...13	11...13	12...15
5	0	0	14...18

Table 11

Frequency maxima on individual audiograms from the forehead, crown and back of the head in pathological subjects, kHz

Serial number of the subject	Vibrator application area														
	Back of the head					Forehead					crown				
	Serial number of the frequency maximum														
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	4	6.5	9	—	—	5	7	10	—	—	5	7	11	15.5	—
2	—	7	11	13	15	6	—	—	14	—	4	7	10	14	17
3	5	7	10	—	15	5	7	9	11	15	5	7	10	13	15
4	4.5	7.5	—	—	—	5	7	—	—	—	4	8	—	—	—
5	5	—	—	—	—	4	6	—	—	—	5	8	12	—	—
6	4	6.5	10	—	—	—	—	—	—	—	No data available				
7	5	7	9	—	—	5	7	9	—	—	4	7	10	12	—
8	4	—	—	—	—	4	6	—	—	—	4	6	—	—	—
9	5	6	8.5	—	—	—	8	—	—	—	4	7	9	—	—
10	4	8	10	—	—	4	8	10	—	—	—	8	10	—	—

Table 12

Limits of displacement of frequency maxima on audiograms from the forehead, crown and back of the head in pathological subjects, kHz

Serial number of the frequency maximum	Frequency peak shift limits		
	Vibrator application area		
	Back of the head	crown	Forehead
1	4...5	4...6	4...5
2	6...8	6...8	6...8
3	8.5...11	9...10	9...12
4	0	11...14	12...15.5
5	0	0	15...17

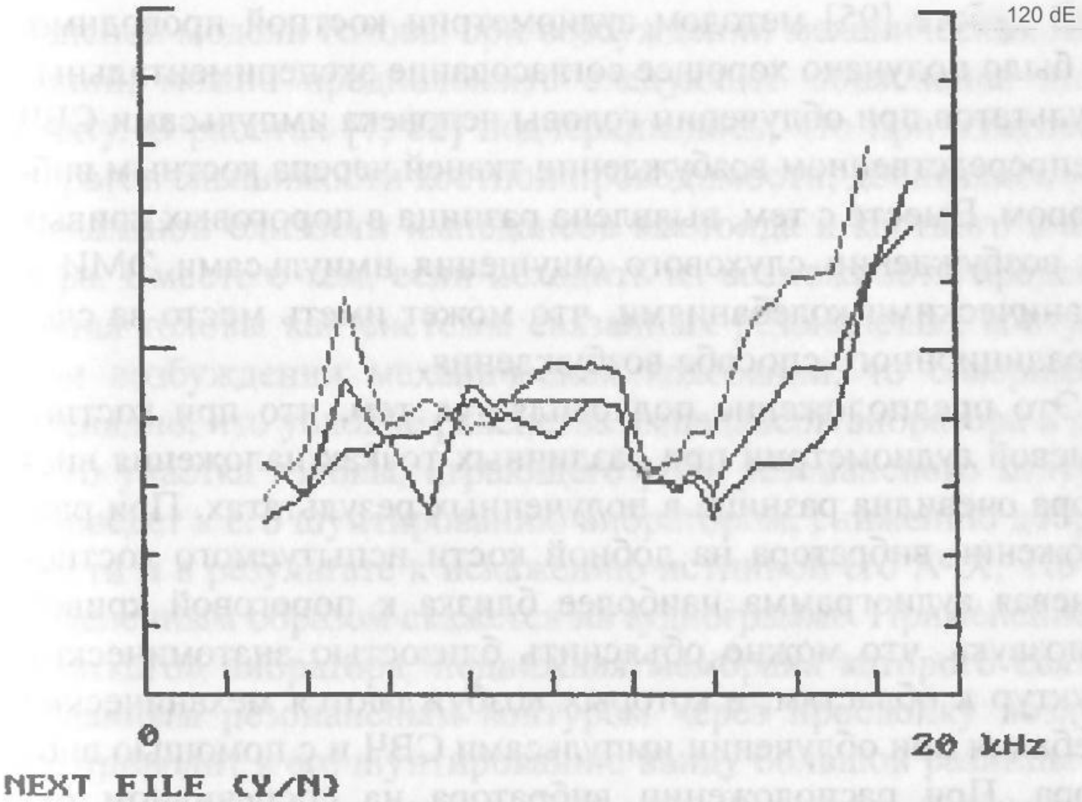
In Fig. 54, 55 as an example, individual audiograms of two subjects are given, obtained on a personal computer IBM RS-401 after processing the original data,

The results of these studies are presented in [101, 122].

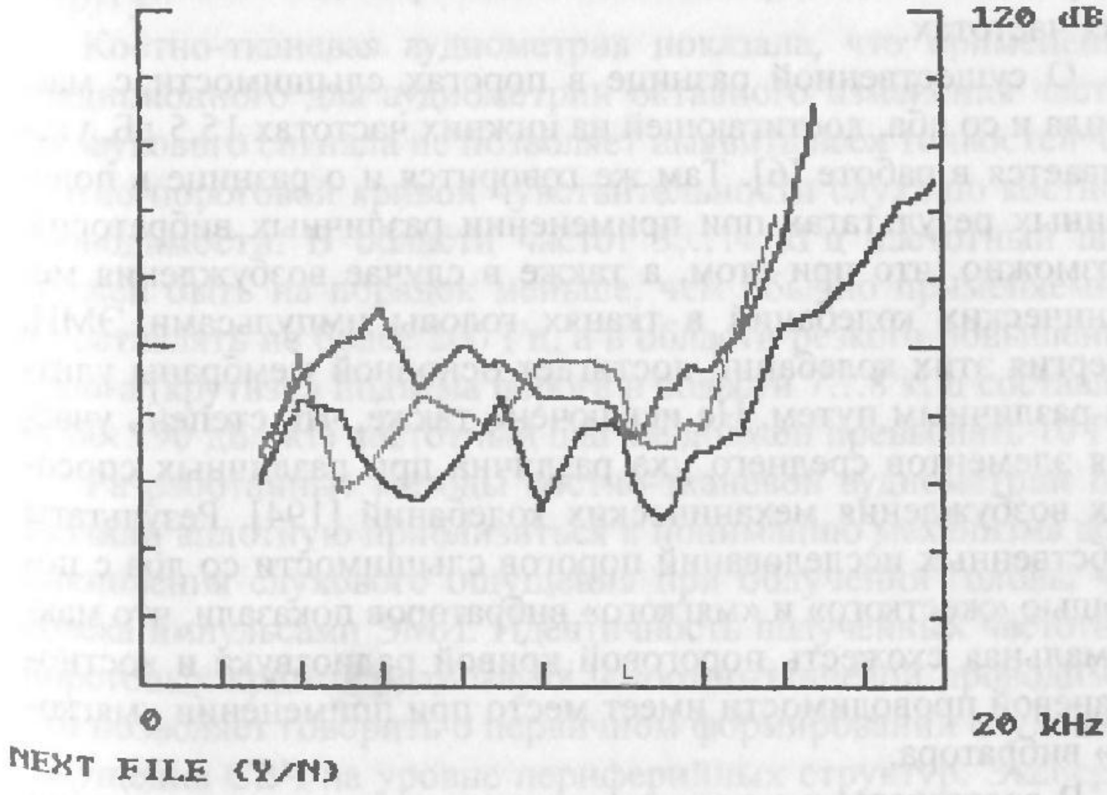
An electrodynamic emitter can serve as a model of the considered multimode system with an inharmonious and non-monotonic range of resonant frequencies.

The conversion coefficient of the supplied electrical energy by the emitter into acoustic energy is different at different frequencies, which manifests itself in its frequency response in the form of "peaks" and "dips" [128], indicating the presence of several resonant frequencies and being the result of stored energy under the action of an impulse in the masses of a moving system, suspension, air volume pushed by a diffuser, etc. That is, such a system as a radiator can serve as an example of a system of connected oscillatory circuits tuned to different frequencies.

Early studies on the mechanism of radio sound [202] indicated the possibility of an auditory sensation occurring in humans when irradiated with EMR pulses due to the excitation of mechanical vibrations in the tissues of the head and their subsequent transmission to the main membrane of the cochlea by the bone route. og Of



Rice. 54. Processed audiograms of subject No. 1



Rice. 55. Processed audiograms of subject No. 2

In [95], using bone conduction audiometry, good agreement was obtained between experimental results when the human head was irradiated with microwave pulses and directly excited the skull tissue with a bone vibrator. At the same time, a difference in the threshold curves was revealed when the auditory sensation is excited by EMR pulses and mechanical vibrations, which may occur due to an unconventional method of excitation.

This assumption is supported by the fact that during bone-tissue audiometry, at different points of application of the vibrator, a difference in the results obtained is obvious. When the vibrator is located on the frontal bone of the subject, the bone tissue audiogram is closest to the threshold curve of radio sound, which can be explained by the proximity of anatomical structures to the areas in which mechanical vibrations are excited when irradiated with microwave pulses and with the help of a vibrator. When the vibrator is located on the mastoid process, which is practically not captured when microwave energy penetrates into the tissue of the head, the proposed system of resonators is excited in a different way, which leads to a sharp decrease in bone conduction thresholds at high frequencies.

A significant difference in the hearing thresholds from the mastoid and from the forehead, reaching 15.5 dB at lower frequencies, is indicated in [6]. It also talks about the difference in the results obtained when using different vibrators. It is possible that in this case, as well as in the case of excitation of mechanical vibrations in the tissues of the head by EMR pulses, the energy of these vibrations reaches the main membrane of the cochlea in a different way. It is also possible that the degree of participation of the elements of the middle ear is different with different methods of excitation of mechanical vibrations [194]. The results of our own studies of hearing thresholds from the forehead using “hard” and “soft” vibrators showed that the maximum similarity of the threshold curve of radio sound and bone-tissue conduction occurs when using a “soft” vibrator.

In accordance with the latest results of our own research and the concept of multimode res-nance model of the head during excitation of mechanical vibrations, we can assume the following explanation for this fact. The works [7, 82] emphasized that when changing the hearing thresholds of bone conduction, they achieved maximum proximity of the impedances of the mastoid and the bone vibrator. At the same time, if we proceed from the possibility of representing the head as a system of connected resonant circuits when excitation of mechanical vibrations, then it is quite obvious that the condition of equality of the impedances of the vibrator and this section of the head, playing the role of a resonant circuit, will lead to its shunting by the vibrator, reducing quality factor and, as a result, distortion of its true frequency response, which will in a certain way affect the audiogram. The use of a "soft" vibrator, the movable membrane of which is connected to this resonant circuit through a layer of air, does not lead to its shunting due to the large difference in the impedances of the tissue and air. Thus, the conditions for excitation of mechanical vibrations in the tissues of the head using a "soft" vibrator and EMR pulses are closer and, as a result, the audiograms obtained under these conditions are closer to each other. to friend.

Bone-tissue audiometry has shown that the use of an octave change in the frequency of the sound signal, traditional for audiometry, does not reveal all the subtleties of the frequency-threshold curve of hearing sensitivity by bone conduction. In the frequency range of 3...11 kHz, the frequency step should be an order of magnitude smaller than usually used and amount to no more than 200 Hz, and in the region of a sharp increase in the threshold (the steepness of the threshold rise in the range of 7...8 kHz is 60. ..90 dB/oct) frequency step should not exceed 10 Hz.

The developed methods of bone-tissue audiometry have made it possible to come close to understanding the mechanism of the occurrence of auditory sensations when the human head is irradiated with EMR pulses. The identity of the obtained frequency-threshold curves of radio sound and bone-tissue conduction allows us to speak about the primary formation of the auditory sensation of microwave frequencies at the level of peripheral structures. An experimental test of the possibility of obtaining acoustic analogues of radio sound showed the identity of the auditory sensations.

tions with direct stimulation of the skull tissues using a bone vibrator and EMR pulses.

The most significant result is the first discovered area of a sharp increase in the bone conduction threshold within the frequency range of 6...9 kHz of external stimulus, which correlates with the mechanical resonance frequency of the head and is determined by its size.

Thus, the previously expressed idea about the acoustic nature of radio sound [92] was experimentally confirmed and for the first time a characteristic feature of a bone-tissue audiogram was discovered in the frequency range, the central frequency of which can be estimated by the ratio c/2a.

The results of experiments on the excitation of mechanical vibrations in limited volumes of various configurations by microwave EMR pulses showed that the modes of mechanical vibrations excited in liquid systems represent a classical picture. At the same time, the availability of recording the parameters of mechanical vibrations excited in a liquid with a wide variability of the parameters of pulsed microwave EMR practically does not impose any restrictions on the duration of the experiment, which is a great advantage compared to full-scale experiments. On the other hand, when mechanical vibrations are excited in liquid volumes, the question of the maximum permissible power levels of microwave EMR pulses is removed, which makes it possible to increase the measurement accuracy, which is impossible in a full-scale experiment, not to mention the subjective assessment of the values of the observed parameters of the effect by volunteers.

The liquid volumes used in the experiment, both cylindrical and spherical, make it possible to operate with parameters of excited mechanical vibrations similar to those observed in the natural experiment, which is fundamentally important from the point of view of identifying the observed dependencies.

The possibility of instrumental measurement of the parameters of mechanical vibrations excited in liquid models, their visualization and perception “by ear” showed the fundamental possibility of modeling the effect of radio sound using physical models due to the identity of the experiment.

experimental results of subjective assessment of perceived radio sound by subjects.

The obtained similar dependences of the pitch of excited mechanical vibrations on the parameters of microwave pulses in model and full-scale experiments allow us to speak about a single mechanism for the occurrence of both low-frequency and high-frequency sound sensations associated with the interference of sound vibrations excited by the fronts of a thermal pulse .

We can come to the conclusion that in the case of bone-tissue conduction, the audiogram can be described by the integral frequency response of the resonant circuits represented by the anatomical structures of the head. The separation of the envelope when irradiating the head of a person and animals with pulses of non-ionizing radiation at a carrier frequency exceeding the HFGS by several orders of magnitude indicates an inadequate mechanism for the perception of information, at the same time also about the fundamental possibility of transmitting information to a person or animal at a distance without the use of technical means reception.

The identity of the results in model and full-scale experiments during irradiation with pulsed EMR, as well as the identity of the auditory sensations that arise when the human head is irradiated with EMR and direct stimulation of the head tissue with a bone vibrator showed not only the fundamental possibility of modeling auditory sensations with using externally introduced mechanical vibrations that are safe for humans, but also the legitimacy of transferring the results obtained in this case to the conditions of irradiation with pulsed EMR. Thus, the method of physical modeling of radio sound with its acoustic analogues makes it possible to predict the nature of auditory sensations in humans using pulsed EMR.

The question of the possibility of the participation of neural structures in the formation of one of the “types” of radio sound due to the direct influence of EMR on them can practically be resolved by the results of bone conduction audiometry. If we assume that the action of pulsed EMR is capable of causing a change in spontaneous activity neurons, then this should manifest itself in a change in the pitch of the perceived radio sound and its intensity during irradiation due to tissue heating. However, in none of the works devoted to the description of the results of natural experiments, such a phenomenon was noted. Moreover, in [11] it is noted that when very low doses of EMR, modulated at frequencies of 16 and 100 Hz, are applied to the spontaneous electrical activity of an identified pond snail neuron, recorded changes in the discharge frequency are observed only after 2-5 minutes of irradiation. According to subjective assessment, radio sound appears instantly when the EMR is turned on. The direct action of mechanical vibrations ator on neural structures can also be excluded. The authors of [15] note that when focused ultrasound acts on the structures of the midbrain of a frog, no changes in the microphone potentials of the sacculus are observed up to intensities of the order of 240 W/cm². Moreover, electrical responses to sound were recorded before, during, and after exposure to ultrasound, focused into the zone of those structures of the center from which electrical responses to sound stimulation were removed. According to the same authors, cell activation is possible at ultrasound intensities of the order of 900 W/cm² in the center of the focal region, and for certain structures. The intensity value for excitation of receptors of the auditory labyrinth of animals and humans is less than 1 W cm2, for excitation of the nerve endings of the auditory nerve in conditions of damage to the hydrodynamic system of the labyrinth or destruction of receptor cells 80...120 W cm2 — [15]. In a full-scale experiment, the order of magnitude of the pressure wave is estimated to be 10-2 dyn cm -2.

Thus, the data from the results of psychophysical and electrophysiological studies have shown that the formation of frequency-threshold curves in humans and animals during bone-tissue conduction can primarily be associated with the resonant properties of the anatomical structures of the head, in particular, the bones of the skull and air flows. - elements forming a multimode resonant system with strong coupling of circuits. NME

4.4. The concept of a two-circuit resonant model of radio sound

To describe the physical characteristics of the anatomical structures of the head and their interactions during the excitation of mechanical vibrations in terms and categories of quadripoles, we will operate with a mirror image of the radio sound threshold curve (Fig. 5), i.e., we will consider the radio sound loudness curve.

Based on the concept of a multi-circuit resonant system discussed in section 4.3, the radio sound volume level curve can be represented in the form of the frequency response of a certain complex resonant system. In this case, the frequency response has two frequency maxima, which can be considered as mechanical resonances of the tissues of the skull, occurring at a pulse repetition frequency equal to the frequency of natural oscillations of various resonators.

The formation of such an frequency response can be realized in the following ways:

1. The presence of one resonant circuit operating at the fundamental frequency and subharmonic.

2. The presence of two resonant circuits with the ratio resonance frequencies 1:2. In this case, the connection between the resonant the contours are weak.

3. The presence of two circuits with equal resonant frequencies with strong coupling.

Analysis of the radio sound threshold curve by pulse duration shows that if we take a frequency equal to 10 kHz as the resonance frequency, then the maximum threshold on this curve should correspond to a pulse duration equal to the period of excited mechanical oscillations, i.e. 100 μs. Meanwhile, it is clear from the graph (Fig. 10) that the maximum of the threshold is shifted to 120 μs, i.e., the value of the resonant frequency is closer to 8 kHz. The same can be said about the minimum threshold on this curve, corresponding to a pulse duration of 60 μs and equal to half the period of excited mechanical oscillations. At the same time, the region of the minimum threshold on the radio sound threshold curve corresponds to a pulse repetition frequency of 10.5 kHz, which naturally leads to the assumption of resonance at this frequency.

The approximate correspondence of the resonant frequencies of liquid models in model experiments (Chapter III) to the expected frequency of the mechanical resonance of the head creates certain convenience when setting up the experiment. At the same time, as noted above, despite the adequacy of some results obtained in full-scale and model experiments, the effect of radio sound is not explained by the single-circuit resonant model.

Analysis of the amplitude dependences of sound pressure in the range of applied microwave pulse repetition frequencies showed that at the resonance frequency of the liquid column equal to 10 kHz, the ratio of sound pressure amplitudes at pulse repetition frequencies of 5 and 10 kHz in the model experiment is significantly greater than for these the same frequency values on the radio sound threshold curve. In this case, the frequency of 5 kHz is considered as a subharmonic of the resonant frequency equal to 10 kHz for the model. The steep (up to several hundred dB/oct) drop in the sound pressure amplitude at a pulse repetition frequency of 7.5...8 kHz can be explained by the presence of a high quality factor of all models used in the experiment, both cylindrical and spherical, the value of which varies. ranges from 50...500. The presence of such a figure of merit in a natural experiment is unlikely to occur, if only because of the large values of viscosity and attenuation in the tissues of the head compared to the liquids used in the experiments: 0.1 M NaCl solution and ethanol.

Let us more strictly determine the quality factor of the acoustic resonator, using a section of the radio sound volume curve as the frequency response of a resonant circuit with a maximum value of the signal transmission coefficient at a frequency of 10 kHz (the resonance frequency of this section). Let us use the well-known relation [60]:

$$X = \frac{K}{Ko} = \frac{1}{\sqrt{1+Q^2\,(\omega/\omega - \omega/\omega')}}$$

where K is the gain coefficient of the oscillatory circuit at frequency o; Ko is the gain of the oscillatory circuit at the resonant frequency; 2 - quality factor. donnag

Assuming that the point of the lowest threshold on the radio sound threshold curve corresponds to the value X = 1, i.e., resonance occurs at this point, we determine the quality factor of such an oscillatory circuit. For the selected values o = 10 kHz and o = 13 kHz X = 0.55. Accordingly, from the expression for the quality factor Q2 = X2[1-(0/0)] we obtain Q=2.3. If at the same time assume that a pulse repetition rate of 5 kHz corresponds to a subharmonic, then, taking into account the obtained value of the quality factor of the equivalent circuit, the ratio of signal amplitudes at the resonance frequency and at the frequency of the first subharmonic should be 1.8 dB. Meanwhile, it is clear that this ratio is within 4 dB.

In [15], for the head of a dolphin as an oscillatory system with lumped parameters, the given value of the quality factor is 2...3, which is in good agreement with the result obtained. On the other hand, the slope of the threshold increase on the radio sound threshold curve in the frequency range 7.5...8 kHz is 60...90 dB/oct, which indicates the high quality factor of the resonant system under consideration.

The value of the resonant frequency proposed in [82] for a single-circuit homogeneous model, determined by the ratio 0.72 s/a in the case of a fixed surface and 0.5 s/a in the case of a free surface, covers the frequency range 7.5...10 kHz for the head of an adult, if we consider a spherical resonator consisting of soft tissues, for which the speed of sound is approximately equal to 1.5.105 cm s. In this case, the question of the possibility of resonance of a spherical shell consisting of hard tissues is not considered.

Natural vibrations of a homogeneous spherical volume are determined by the general equation of sound waves [55]:

$$ν α φ + K α φ = 0$$

satisfying the condition on the walls of the sphere

$$\frac{dφ}{di} = 0,$$

i.e., in the absence of a normal velocity component at the boundary, which corresponds to an absolutely rigid wall. Here f speed potential; Laplace , ∇ — operator; frequency; 2f C/where, f — c is the speed of sound. K =

The solution of the general equation of sound dφ waves at di = 0 is possible only for certain values of K, i.e., only certain types of oscillations can be excited in the sphere [55]. In the case of radially symmetric oscillations (pulsating sphere), the value of the velocity potential is determined by the expression

$$\varphi = c\frac{\sin kr}{r}.$$

The condition equality dφ 2=0 requires the of dp to 0 at r = a, where a is the radius of the cavity. From here we obtain the transcendental equation tanKa = Ka, the roots of which determine the natural frequencies of the oscillating sphere.

Approximately ka = m + 1/where n, where m = 1, 2, 3... from the values of the resonant frequencies will be determined by the relation f = Apa, where An = 1.4303; 2.4590; 3.4709 values of the first three roots of the transcendental equation. With an oscillating sphere, the velocity potential is given by φ the relation =C(sinkr) cose, which leads to another set of oscillations in the sphere. To satisfy the condition eth normal =0 at r = a, it is necessary to satisfy the equality

$$tgka = \frac{2ka}{2 - k^2a^2}.$$

In this case, the values of natural frequencies are determined by the dependence fm = W, where W — m 2a are the values of the first few roots, asymptotically tending to the form m-B = 0.6625; 1.891; 2.930; 3.948; 4.959.

A comparison of the values of frequencies f" and fm for a sphere with a = 5 cm and the experimentally obtained series of frequencies for a sphere of the same radius shows that in real conditions it is possible to

It is not possible to describe this or that case of a fixed sphere in its "pure form". Both sets of frequency values f. and fm do not contain components with the values A„ = 1 and W = 1, which are present in the experimentally obtained series of frequencies for a sphere with a high quality factor and described by the ratio c/2a [98].

As the quality factor of the spheres decreases, components f" and fm are noted in the recorded spectra with values of coefficients An≈ 1.44 and W≈ 0.66 (see Fig. 11-14). Moreover, depending on the boundary conditions, i.e., for different ratios of PC of air, sphere material and liquid, one or another model can be implemented.

Based on the data obtained, it can be assumed that in both full-scale and model experiments, boundary conditions are realized under which the degree of fixation of the surface of the irradiated object represents an intermediate case between the free and fixed boundaries, leading to the excitation of mechanical vibrations in the object with a resonant frequency determined by the relation fp = c/2a and the formation of a wave vibrator.

The case of a sphere with rigid walls presented in [55] is convenient from the point of view of the simplicity of the mathematical apparatus involved. In a real situation, an absolutely rigid wall does not exist, since this would exclude any possibility of radiation, which is confirmed here in the experiment.

Thus, the human head, when mechanical vibrations are excited in its tissues, can be considered as an acoustic wave resonator very weakly loaded by the external environment.

In all works [94, 95, 202] devoted to the study of one or another mechanism of radio sound, the authors discuss issues related to the resonant properties of the head as an acoustic resonator. That is, thereby implicitly discussing the question of the level of sound sensation depending on the pulse repetition rate.

In this case, the working hypothesis is the process of activation of the cochlea of the hearing organ by mechanical vibrations excited in tissues, the amplitude of which has a frequency dependence. In an equivalent acoustic resonator

When mechanical vibrations in a liquid are excited by a thermal pulse, the amplitude of the vibrations at a constant peak power in the pulse depends on the pulse repetition rate. Since the equivalent acoustic resonator is a linear system, it can be described by an nth order differential equation with constant coefficients

$$a_n\frac{d^n y}{dt^n}+a_{n-1}\frac{d^{n-1}y}{dt^{n-1}}+\ldots+a_1\frac{dy}{dt}+a_0 y=X(t),$$

the solution of which using the Fourier integral method is given in the form

$$y(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}k(\omega)S_x e^{j\omega t}d\omega,$$

-TOL

where K(o) is the ratio of complex amplitudes at the output and input of the system for a sinusoidal signal.

When pulsed excitation of a linear system

$$k(\omega)=\int_{0}^{\infty}g(t)e^{-j\omega t}dt,$$

where — g(t) is the response of the linear system to a unit impulse. Thus, the complex frequency response of a linear system is the spectrum of the time response of the system. Consequently, when exciting an acoustic resonator with short pulses, we obtain a frequency response in the form of an envelope of the amplitudes of excited mechanical oscillations for different pulse repetition rates. At a constant pulse repetition rate, the frequency response is obtained in the form of a line spectrum, and the envelope of the spectral components is the frequency response of the system.

In accordance with the working hypothesis, the mirror image of the threshold curve of radio sound corresponds to the frequency response of a certain frequency-selective system, which determines the frequency spectrum of the auditory sensation perceived by a person when it is excited by thermal pulses formed in the tissues of the head when energy is absorbed in them microwave pulses.

Errors introduced in the analysis of linear systems by the Fourier integral method are due to the fact that when excitation

tion of a linear system with rectangular pulses, the spectrum of such a periodic function with period T is determined by the formula [112]:

$$C_k = \frac{1}{T}\int_{-T/2}^{+T/2} e^{-j2\pi k\tau_u/T} f(t)dt,$$

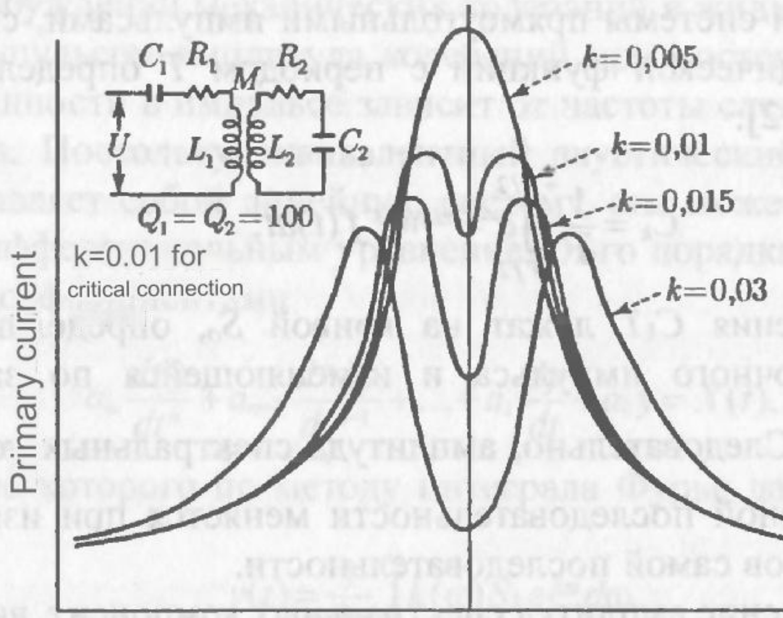
and the values of SkT lie on the So curve, which determines spectrum of a single pulse and varying according to the law

sin X X [112]. Consequently, the amplitude of the spectral components of the pulse sequence changes when the parameters of the sequence itself change.

The distribution of the amplitudes of the spectral components, carried out on the Iskra-226 computer, showed that for the most typical pulse sequence parameters in radio sound research, the error introduced when constructing the threshold curve does not exceed 7% within 14 kHz.

When applying the Fourier integral method for the single-loop concept of radio sound, the threshold curve of this effect should have the classic form of a single-humped curve with a resonance frequency determined by the ratio c/2a and equal to an average of 8 kHz depending on the size of the head, which does not correspond to the mirror display of the experimentally obtained threshold curve of radio sound. It is at the expected resonance frequency that the value of the hearing sensitivity threshold increases sharply, which corresponds to the same sharp reducing the signal amplitude on the frequency response of the oscillatory system. Thus, neither the previously obtained experimental material on spherical liquid models, nor the spectral analysis make it possible to accept the concept of a single-circuit resonant model of radio sound.

The possibility of the existence of two acoustic resonators with resonant frequencies ʃ and 2 with weak coupling is difficult to assume, firstly, as already mentioned, due to the closeness of the acoustic resistances of all biological structures. Secondly, analysis of the anatomical structures of the human head does not allow us to identify a certain area of it as a second resonator with a resonance frequency twice as high as that of the head as a whole. TOTS



Rice. 56. (borrowed from [85]). Family of frequency response of two coupled circuits with equal quality factor and different values of the coupling coefficient

Let us consider a system of two coupled oscillatory circuits having equal frequencies of natural oscillations. It is known that the shape of the frequency response of a single circuit is determined by its quality factor, and the shape of the frequency response of connected circuits is also determined by the coupling coefficient.

In Fig. 56 [85] shows a family of frequency responses of two coupled circuits with equal quality factors and different values of the coupling coefficient. As can be seen from the figure, with strong coupling, i.e. at K > Kcr, the frequency response has two frequency maxima, called communication frequencies and defined by the relation f1.2

$$\frac{1}{f_{рез}} \quad \sqrt{\left[\frac{2K2}{Q2} = \left(\frac{Q_1}{Q_2} + \frac{Q_2}{Q_1}\right)\right]^{1+K1}}$$

where K is the actual coupling coefficient; Kkr - critical coupling coefficient determined by the relation Kcr = $\frac{1}{\sqrt{Q_1 \cdot Q_2}}$, 21 and 22 - quality factors of resonant circuits.

If a system of two coupled circuits with a degree of coupling above the critical one is excited by a short pulse, then free damped oscillations with two different frequencies close to the coupling frequencies will arise in this system fi and 2. As a result of transient processes in such a system, beats also arise, which continue even after the external excitation is removed. Thus, the frequency spectrum of oscillations generated by the system itself of two coupled circuits when they are excited by a short rectangular pulse is significantly richer compared to a single circuit.

When the coupling is equal to the critical one, the bandwidth of the double-circuit system at the level of 0.707 is more than three times wider than that of a single circuit with the same quality factor, i.e. A2K = 3.1f/Q, where ƒ and Q are the resonance frequency and quality factor of a single circuit. With a further increase in the coupling coefficient between the resonant circuits, signal transmission at the resonance frequency decreases and the resulting double-humped curve is characterized by two transmission bands, i.e., the total bandwidth of transmitted frequencies is even wider. The main advantage of a dual-circuit system is an increase in the quality factor when expanding the bandwidth, which helps to increase the steepness of the frequency response slopes.

A qualitative comparison of the frequency response of a two-circuit system with a coupling coefficient K > Kcr with the radio sound loudness curve leads to the assumption of the existence of a real two-circuit system. However, this comparison allows us to draw the following conclusion. The symmetry of the shape of the frequency response relative to the resonance frequency is due to the equality of the quality factors of both circuits and their resonant frequencies. This means that the asymmetry of the radio sound threshold curve, and, accordingly, the radio sound loudness curve, interpreted as the frequency response of a double-circuit oscillatory system, is the result of the presence of two connected circuits with different quality factors and different values of resonant frequencies [85].

To prove the possibility of the existence of a two-circuit system that explains the effect of radio sound, assessing the quality factor of both circuits is of paramount importance. To a greater extent, this concerns the determination of the value of the coupling coefficient. We will evaluate this characteristic based on information about the amplitude-frequency properties of the hearing organs and the threshold curve of radio sound.

It is first necessary to consider the possibility of a particular structure of the human head capable of playing the role of an equivalent second circuit. The resonant model of J. Lin with the resonance frequency ΓRES = c/2a was taken as the first circuit. It can be immediately noted that due to the close values of the impedances of biological tissues, any structure chosen as the second resonator will be quite strongly coupled with the first resonator. However, this situation leads to a paradox - it is impossible to isolate within a certain volume a smaller volume with a sound speed value equal to or close to the same value for a larger volume and having a frequency equal to the frequency of the larger volume. It is assumed that the densities of the substance of both volumes are close or equal to each other.

A way out of this situation can be found if we assume the presence inside the skull of a structure that meets one of the following conditions:

1. The speed of sound in the structure differs from the speed of sound for other brain tissues due to the presence of certain specific features of the selected structure. In this case, the value of the resonant frequency of the structure is not determined by its geometric

2. The speed of sound in the structure differs from the speed of sound for the rest of the volume so that the ratio c/2a for the selected structure has the same numerical value as the entire volume absorbing electromagnetic energy as a whole.

An analysis of the literature shows that at least two anatomical structures of the skull, the cochlea and the frontal sinuses, can be identified as a structure that meets one of these requirements. The cochlea of the hearing organ is characterized by a variable elastic modulus along its length. Considering that the speed of sound is determined by the ratio

sion C= where and is the modulus of elasticity; — ρ density. $\sqrt{r}$

and the fact that the compliance of the cochlea membrane (the reciprocal of the elastic modulus) along its length varies 100...1000 times [65], it is possible, within the rather small size of the cochlea (length about 35 mm), to obtain points with the value - the speed of sound, sharply different from the value of this the same values for other brain tissues. If we consider certain air cavities as the second resonator, for which the speed of sound is almost 4 times less than for biological tissues (0.33-105 cms-1), then with equal resonant frequencies of the head of an adult and the air cavity, the radius of the air cavity will be approximately 2.2 cm, which is close to the size of the frontal sinuses.

From modern ideas about the amplitude-frequency properties of the cochlea of the hearing organ, it follows that when a monofrequency signal is applied to it, the displacement localization point has a characteristic frequency, and the response of the displacement localization point itself allows us to imagine it as an oscillatory circuit.

Using this position, as a second oscillatory circuit that takes part in the formation of an auditory image when the human head is irradiated with microwave pulses, it is possible to advance the cochlea of the auditory organ with displacement localization points on the main membrane with characteristic frequencies f and 2. At close values of the impedance of the tissues of the skull and cochlea, the pressure wave excited by the microwave pulse in the tissues of the skull will reach the cochlea without any special reflections. Thus, we can assume that the tissues of the skull, collectively representing the first resonator, and the region of the cochlea, which responds to a periodic pressure wave as the second resonator, are quite strongly connected.

Since the cochlea of the organ of hearing is the last link that transmits and forms displacements with certain amplitude-frequency properties, i.e., it is the location of information collection points, we must assume, in the case of excitation of shock acoustic waves in the tissues of the skull, the presence two displacement localization points. In this case, we obtain a maximum signal transmission at communication frequencies and 12, which arise at two f_1 points of localization of displacements and a minimum signal transmission coefficient at the excitation frequency of the cochlea HRES, i.e., at the frequency of the excitatory cells excited in the tissues. turnip of shock vibrations.

According to [65], the quality factor of the amplitude-frequency characteristics of the cochlear septum varies within 1...6 when the observation point moves from apical to basal part of the cochlea. By constructing a graph of the linear dependence of the quality factor of displacement localization points on frequency, we find that the equivalent circuit of the cochlea of the hearing organ at the resonance frequency of the head will have a quality factor of the order of 2.5. We will also determine the quality factor of the primary circuit from the threshold curve of radio sound.

Previously, when calculating the quality factor of the head as an acoustic resonator, we proceeded from the assumption of the presence of a single resonant circuit. In a two-circuit system, when the second circuit shunts the first circuit at the resonance frequency, the quality factor of the first circuit should be characterized by the parameters of the first hump on the radio sound threshold curve. Using the same relationship to determine the quality factor

$$Q^2 = \frac{1 - X^2 f^2}{X^2 (f - f^2)^2}$$

provided XMAX = 1 for f = fres and at point f = fPE3, REZ = 1, from the threshold curve of radio sound for points p = 5.5 kHz and f = 1 kHz (selected arbitrarily) we find that the amplitude of oscillations at this point is (6.8...1.4) dB is less than at point f = fPE3, i.e. X = 0.53. In this case, f = 0.18 (fp = 1). Substituting the value of these quantities into the expression for the quality factor of the circuit. we obtain the value of this value for the first circuit equal to 1.8. Substituting the found values of the quality factor of both circuits into the expression for Kcr, we obtain Kcr = 0.46.

These data were published in [95, 97]. Issues related to the influence of the quality factor of the head as a resonator on the course of the threshold curve of radio sound are also considered in [113].

Since in the system of coupled circuits we are considering, the values of the quality factor of the circuits are small, the communication frequencies will be determined by the relations [85]:

$$f = \frac{fp}{\sqrt{1+K}}, \quad f2 = \frac{fp}{\sqrt{1-K}}.$$

With the values f_1 = 5.5 kHz, f2 = 11.3 kHz and p = 7.4 kHz obtained from the radio sound threshold curve (Fig. 9), we obtain a coupling coefficient value close to 0.6.

Thus, the condition K > Kcr for the system of contours under consideration is satisfied. Thus, the assumption about the magnitude of the coupling coefficient between the circuits is higher than the critical one and the quality factor of the first circuit is lower can be considered legitimate.

The above assessment of the values of the quality factor of the circuits and their coupling coefficient is naturally possible under certain assumptions and reflects only the formal side of the phenomena necessary to demonstrate the methodological approach proposed here to the study of the very mechanism of these phenomena. The lack of not just some data, but finally formed ideas about the mechanisms of hearing does not allow for a detailed and complete calculation of the equivalent parameters of such circuits. For example, according to modern concepts, the elasticity of the main membrane along its length can vary within 102...103, which leads to an acceptable change in the speed of sound in the cochlea from 10 to 30 times. But it is precisely this value that determines the impedance of the cochlea and, accordingly, the coefficient of its connection with other tissue structures. On the other hand, at small values of the quality factor of the equivalent circuits, changing these values by several times practically does not lead to a significant change in the ratio of the coupling frequencies to the resonance frequency. And from this point of view, apparently, compliance with the basic physical laws when formally transferring physical concepts to physiological structures should be considered paramount.

Analysis of sections of the threshold curve of radio sound and bone tissue audiogram using the terms and categories of quadripoles showed that the most complete explanation of the minimum signal transmission at frequencies correlating with the frequency of the mechanical resonance of the head is achieved by invoking the idea of the existence of a two-circuit resonant system with a strong connection of the circuits formed by the bone and tissue formations of the skull. A formalized calculation of such a system, consisting of anatomical structures of the head, described by the characteristics of resonant oscillatory systems, showed the validity of this approach for a qualitative explanation of the formation mechanism bone tissue audiogram. The finer structure of the bone-tissue audiogram revealed using a “hard” vibrator can presumably be described by a set of dual-circuit systems forming a multimode (multi-resonant) oscillatory system.

Using a two-circuit resonant model, you can Xia explanation is very interesting, but the result is incomprehensible full-scale experiments given in [113]. Etc By changing the duration of the EMR pulses, according to the subjective assessment of the subjects, the high-frequency, low-intensity auditory sensation was replaced by a very powerful radio sound, more low-frequency. The authors of this work suggest that a similar phenomenon is associated with the possible participation of neuron structures due to their direct interaction with EM pulses. As has already been shown above, the obtained value of the mechanical resonance of the head is in good agreement with the data of the threshold curve of radio sound in terms of pulse duration when at a value of pulse duration close to 120 m (the oscillation period is close to 8 kHz) marks a low-frequency tone in a full-scale experiment, i.e., packets of oscillations are generated filled with oscillations with a frequency close to 8 kHz and the following ones with a frequency. equal to the frequency of microwave pulses. When the pulse duration is 57...60 μs, i.e., close to half the oscillation period with a frequency of 8 kHz, a high-frequency tone with a frequency close to 8 kHz is observed, since this generates resonant oscillations that are weakly attenuated in the pause between pulses The sharp suppression of high-frequency tone, noted by the authors of [113], by at least 20 dB upon the transition from 60 μs to 120 μs, can be explained by a change in the described nature of the excited mechanical oscillations. At the same time, in accordance with Schouten’s concept, a person perceives the frequency of repetition of bursts of oscillations.

The attenuation at the resonance frequency when excitation of oscillations by pulses with a duration of about 60 μs can be estimated at 18 dB (when both branches of the radio sound threshold curve are prolonged until they merge) relative to the signal level at 10 kHz, taken as the reference point. Relative to the same level, a signal with a frequency of 800 Hz (often pulse sequence) is weakened by 7.5 dB. With a difference of 10.5 dB, the resonant oscillations are completely masked by the signal, which is the envelope of packets of damped resonant oscillations with a pulse duration of 120 μs and is perceived by the subject in the form of a low-frequency sound sensation. That is, in this situation, residual sound is realized. Under these conditions, an increase in duration from 60 to 120 μs should indeed lead to a rather sharp change from a weak high-frequency sensation to a low-frequency one.

Thus, a sharp decrease in the threshold of low-frequency tone at a pulse repetition frequency of 0.8 kHz (far from the resonance frequency) and an increase in the threshold at frequencies close to 8 kHz (head resonance frequency), according to the subjective assessment of subjects in a full-scale experiment, can be explained by the presence a system of two resonant circuits with initial resonance frequencies close to 8 kHz, providing a significant reduction in the signal amplitude transfer coefficient at the resonance frequency when the connection between the circuits is above the critical one.

4.5. Brief conclusions

1. Using the developed method of bone-tissue conduction audiometry with a small frequency step up to a smooth change in the frequency of the testing signal, an area of sharp increase in the threshold, correlating with the frequency of mechanical resonance of the head, was discovered for the first time.

2. The identity of the threshold curves during excitation is shown the formation of auditory sensation by microwave pulses and direct acoustic influence through bone conduction of sound, which confirms the assumption that radio sound is formed at the level of peripheral structures.

3. The anatomical organization of the human head, which from a physical point of view is a set of resonators with strong coupling, leads to the formation of a multimode resonant system.

4. Subjective assessment of the level of perceived radio sound and its frequency spectrum using the zero beat method is

implementation of the Fourier integral method in an auditory analyzer, which is confirmed by literary data on neurophysiology. This analysis shows that when a low-Q multimode system such as a human head is excited by EMR pulses, the main contribution to the frequency response of such a system is made by two resonators with equal resonance frequencies and with strong coupling, which leads to the formation of a two-circuit resonance system.

5. When excited in the tissues of the human head and living mechanical vibrations, the multimode resonant system forms the integral AHF of the auditory system, determines the nature of the reaction of the auditory system to external stimulus.

6. The results of model experiments on irradiation of spherical liquid models and their comparison with data from natural experiments allow us to consider radio waves as a physical phenomenon, the mechanism of which can be represented by the processes of absorption of electromagnetic energy by microwave pulses by the tissues of the head, its transformation into the energy of mechanical vibrations and their conduction in cochlea or hearing through the bone-tissue route.

7. The considered mechanism of inadequate stimulation of the hearing aid by pulse-modulated non-ionizing radiation (microwave, ultrasound) allows us to say that it is fundamentally possible to receive information to humans and animals at a distance without the use of technical means of reception.

Konalno z

Chapter V

PHYSICAL MODELING OF RADIO SOUND USING THE METHOD OF ELECTRONIC MODELS

The proposed mathematical two-circuit resonant model of radio sound, based on the idea of the thermoelastic nature of the excitation of resonant mechanical vibrations in the tissues of the head, can most fully be verified by the method of physical models.

The fundamental possibility of physical modeling of radio sound is based, first of all, on experimental data on the excitation of acoustic vibrations in liquid media and biological objects under the influence of microwave pulses [92, 94, 100].

5.1. Electronic model structure

Based on literature data [149, 152, 198, 199] on various methods of excitation of the membrane potential, the generation of which is possible only with mechanical displacement of hair cells [22, 23, 117], we assume that the physical model should contain analogues of the peripheral auditory organs systems and anatomical structures of the head, which determine its frequency-selective properties.

Threshold curves of radio sound [234] for persons with different upper hearing limit (UHL) show that the physical model should contain a low-pass filter with an adjustable upper cutoff limit, and the slope of these curves to the abscissa axis and standard audiograms can be used to estimating the quality factor of the model. The last characteristic seems to be the most important, since it is it that should determine the boundaries of what is perceived in natural experiment.

ryment of the frequency range and, as a consequence, the formation of the auditory sensation. According to [50, 51, 61], the main contribution to the frequency selection of signals at the periphery of the auditory system is made by the mechanisms of the cochlea.

Thus, the basis of the physical model of radio sound can be the following provisions, reflecting the individual mechanisms of the entire effect of radio sound as a whole:

1. Resonant excitation of acoustic vibrations in the tissues of the head due to their thermoelastic expansion upon absorption of the energy of a microwave radiation pulse.

2. Formation of the amplitude-frequency characteristics of the perceived radio sound by the amplitude-frequency characteristics of the periphery of the auditory system and associated anatomical structures of the head.

Based on these provisions, the basic requirements that the physical model of radio sound must meet are formulated:

1. The ability to use various analogies when designing various elements of the model. 2. The presence of a certain correspondence of elements and wearing the model to the elements and relationships of the original. 3. Adequacy of terms for describing the object and model. 4. High degree of existence of the largest possible co- number of common properties of the model and the original. 5. Logical correspondence of the elements and relations of the model to the elements and relations of the original.

The considered physical model of radio sound does not include the paths of transmission, formation and processing of the signal in the higher departments. However, since the periphery of the hearing organ includes additional (after the cochlea of the hearing organ) aggravation of the frequency response of the auditory analyzer with the help of neural structures, it is necessary to take into account some specifics adopted when modeling various forms of nervous activity - the creation of models that implement particularly effective principles of nervous regulation for the needs of control in technology bionic aspect of modeling. Thus, the second task, bionic modeling, is solved especially by bringing the model to technical reality.

lization. In this case, the sequence of operations to successfully solve both problems can be represented by the following program:

1. Initial experiments that allow us to formulate the basic principles of constructing the model.
2. Creation of a formalized mathematical and technical model of the system under study.
3. Study of the model using sufficiently diverse input signals in order to:
   a) checking the correctness of the model;
   b) determining the degree of generalization achieved in the model;
   c) clarifying the system parameters;
   d) detection of effects on the model that have not yet been obtained in experience.
4. Testing the effects predicted by the model in real life.
5. Refinement of the model based on its comparison with the object.
6. Transition to a structural model of the system through experimentation mental study of individual elements of the system and connections (change of level of consideration).

According to modern concepts [61, 65], resonant the curve at the point of localization of the displacement on the cochlea of the hearing organ has an asymmetric shape relative to the resonance frequency with a slope of decline towards high frequencies of 90...150 dB/oct for characteristic frequencies of 5...7 kHz and a slope of rise in characteristics in the low frequency region of about 6 dB /oct, and near resonance 12 dB/oct [189, 221].

In [65] it is indicated that the quality factor of the oscillatory system that forms the exciting effect on the neuron in question is 7...10.

From experimental data [189, 239] it follows that the considered slope of the decline in the amplitude-frequency characteristic increases monotonically with increasing characteristic frequency. An additional aggravation of the frequency response also occurs with a strong connection of the circuits.

Since these exacerbation mechanisms perform the same function without affecting other signal parameters, the model can be limited to one functional frequency response aggravation block. An exception will be the block that forms the decline in the upper limit of the frequency response, which should provide the ability to set different cutoff frequencies at the upper limit of the range of the transmitted signal.

The rise and fall of tissue temperature during pulsed irradiation of the human head, i.e., the formation of a thermal pulse cannot occur with times equal to the duration of the leading and trailing edges of the irradiating pulse due to the finite value of the thermal conductivity of the tissue. In this regard, the model must also contain a block that performs the function of delaying the fronts of the pulse that excites oscillations in the model, i.e., an integrator.

In order for the radio sound model to allow setting up an experiment to identify the frequency band perceived by humans, i.e., using the zero beat method, it must contain blocks with frequency response close to those for the auditory canal of the ear. ringing sound

Thus, the physical model of radio sound should contain the following main functional blocks, reflecting the mechanisms of the entire phenomenon as a whole:

1. A system of coupled oscillatory circuits with a coefficient the connection rate is higher than critical.
2. Integrator.
3. Frequency response aggravation system.
4. Low-pass filter with adjustable upper cutoff frequency.
5. Low-pass filter with middle ear frequency response.
6. Output signal indicating device.

The listed points allow us to imagine the model only in general form. To make it more specific, it is necessary to move on to possible technical implementations.

Based on the provisions included in the physical model of radio sound, it is easy to come to the conclusion that in order to bring this model as close as possible to the original, the oscillatory circuits must be made in a shape that is close to the anatomical structure of the original. This desire, however, will lead to significant complications when constructing such a model and can hardly be justified.

Based on the results obtained in experiments with spherical models and taking into account the above-considered estimates of the quality factors of the first and second circuits, a system of two spheres, the cavities of which are connected through a common hole in the walls of the spheres, can be proposed as a double-circuit system. The sizes of the spheres are selected based on the equality of their resonant frequencies when the spheres are filled with liquids. In this case, one of the spheres must be filled with a liquid that absorbs electromagnetic energy in order to ensure the possibility of excitation of mechanical vibrations in it by microwave pulses. The second sphere is filled with a nonpolar liquid.

The selection of parameters of the spherical model under such irradiation conditions presents certain difficulties. Therefore, it is advisable to replace the spherical model with an electric one while maintaining the transfer function.

In the literature [127], the analogy between mechanical and electrical oscillatory systems described by the same differential equations is quite fully covered. However, since in this case we are talking about the possibility of an analogy not just between electrical and mechanical systems, but about the possibility of an analogy of the total effect, including the absorption of electromagnetic energy and its conversion into mechanical and electrical analogue of this effect, additional information is needed to in this case talk about this possibility. Such information can be obtained by comparing data from field experiments and conducted model studies (Table 13). Let us add that those noted in the table. 13, some qualitative analogues are also confirmed by the functional dependencies of some parameters of these circuits.

A system of two coupled radio-technical oscillatory circuits containing capacitance and inductance was chosen as a physical electrical model. An analogue of losses in a real system is represented by a series resonant circuit that has minimal resistance at the resonance frequency.

Table 13

Comparative assessment of the results
of full-scale and model experiments

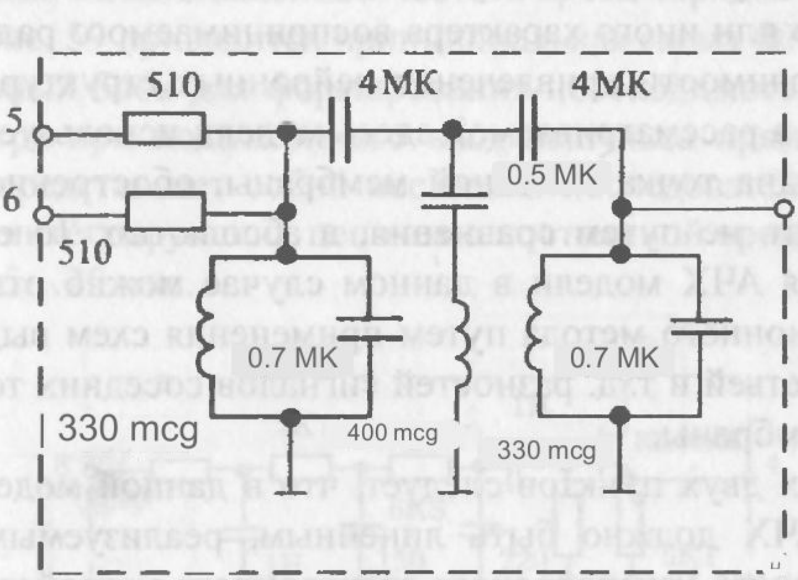
Original	Model
1. Linear dependence of the radio sound level on pulse power. tone	Linear dependence of sound pressure amplitude on pulse power.
2. Lack of radio sound with pulse duration ≤0.5 μs	Excitation of mechanical vibrations with small amplitude by short pulses Pa
3. Perception of radio sound in the form of individual clicks at a pulse repetition rate of <100 Hz	Perception of shock vibrations excited in a liquid "by ear" in the form of individual clicks
4. High-frequency nature of radio sound when modulated by EMR pulses with t = 5...25 μs at frequencies 1...17 kHz 4a. Excitation of recorded mechanical vibrations in the tissues of the animal's head by an EMR pulse	Excitation of resonant mechanical vibrations in spherical and cylindrical volumes when irradiated with short EMR pulses
5. Zero beats perceived by a person when the first harmonic of the EMR pulse sequence and the acoustic signal are equal.	Zero beats with equal frequencies of excited mechanical vibrations and acoustic signal
6. Low-frequency nature of radio sound when modulated by EMR pulses with Ti = 100... 120 μs	Residual sound when irradiating a liquid resonator with EMR pulses with ti - T, where T is the period of excited mechanical oscillations
7. Correspondence of the frequency of mechanical vibrations excited in the tissues of the animal's head to the size of the head. 7a. Frequency dependence fi; 12; RESULT on bone-tissue audiogram depending on head size	Dependence of the frequency of excited mechanical vibrations in a liquid resonator by EMR pulses on the size of the resonator

5.2. Technical implementation of the electronic model

The task of selecting and implementing the main link of the radio sound model is significantly simplified, since in accordance with the possible mechanism of formation of the auditory sensation discussed above when a person's head is irradiated with microwave pulses, it is necessary to simulate only one point of the main membrane and its connection with the first resonator. An analysis of the electrical circuits of the cochlea model [51] showed that the traditional circuit of a series resonant circuit as a separate link is not optimal in the case of modeling the excitation of one point of the cochlea. Therefore, a system of two parallel resonant circuits with capacitive coupling, tuned to the resonance frequency determined from the radio sound threshold curve, was chosen. A series resonant circuit is tuned to the same frequency, simulating losses during the propagation of a pressure wave in the cochlea and connected in parallel to the first two circuits.

The contours were calculated in accordance with the values of the quality factors of the cochlea and head tissues obtained above by calculation.

In Fig. Figure 57 shows a schematic diagram of a two-circuit resonant system for implementing an frequency response that qualitatively coincides with the radio sound volume curve, taking into account losses in the cochlea.



Rice. 57. Double-circuit resonant system with an frequency response that qualitatively coincides with the radio sound volume curve

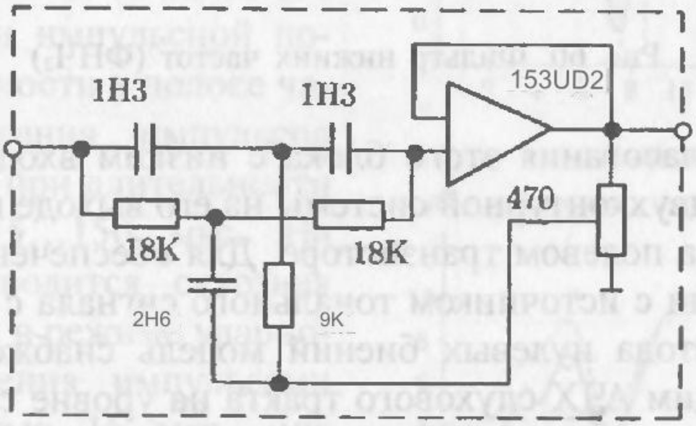
Quantitative coincidence of the frequency response of the system of two connected circuits with the radio sound volume curve is achieved by using a sharpening circuit.

From the literature data it follows that the equivalent quality factor of the resonance curves of individual points of the main membrane of the cochlea is very — low, on the order of unity. At the same time, psychoacoustic studies indicate a very high selectivity of the hearing organ of humans and mammals. The exacerbation hypotheses, based on the nature of the physical mechanisms, are divided into two groups. The first includes hypotheses about the mechanical nature of the process of sharpening frequency characteristics. The first group of hypotheses assumes a linear nature of exacerbation. The second group of hypotheses explains the process of sharpening resonance curves by mechanisms of information processing in a neural network. These hypotheses use ideas about both the linear and nonlinear nature of the processes of signal transmission through nerve elements. The principle common to all hypotheses is exacerbation by comparing the intensities of vibrations of neighboring points of the main membrane [50, 51].

In preliminary experiments on liquid models, it was shown that the low-frequency or high-frequency nature of mechanical oscillations excited in a liquid depends on the parameters of the exciting pulse and there is no need to involve neural structures to explain one or another nature of the perceived radio sound. Further, since the model considered here uses only one point of the main membrane, exacerbation can occur not by comparison, but absolutely. That is, to sharpen the frequency response of the model in this case, you can abandon the traditional method by using schemes for isolating the second, third, etc. differences in signals from neighboring points of the main membrane.

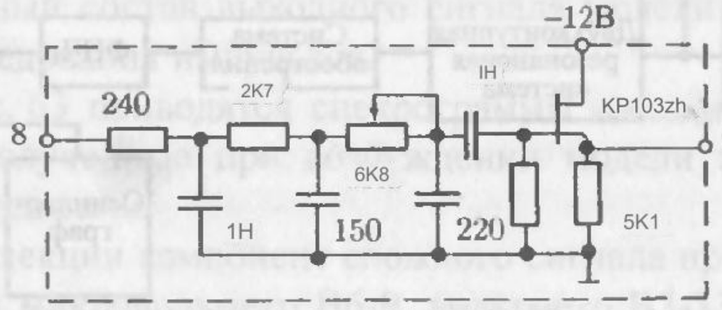
From these two points it follows that in this model the sharpening of the frequency response should be linear, implemented using any narrow-band electronic device with parameters determined by the radio sound threshold curve. Intensification of the frequency response of a two-circuit circuit to values determined

The steepening of the slopes of the cochlea and the slopes of the threshold curve of radio sound is achieved by using two functional blocks. The first of them (Fig. 58) is a stop filter tuned to the resonance frequency and contains an operational amplifier with a double T-bridge in the feedback circuit. Using this block, it is possible to increase the slope of the frequency maxima of the model's frequency response near the resonance frequency to the required value.

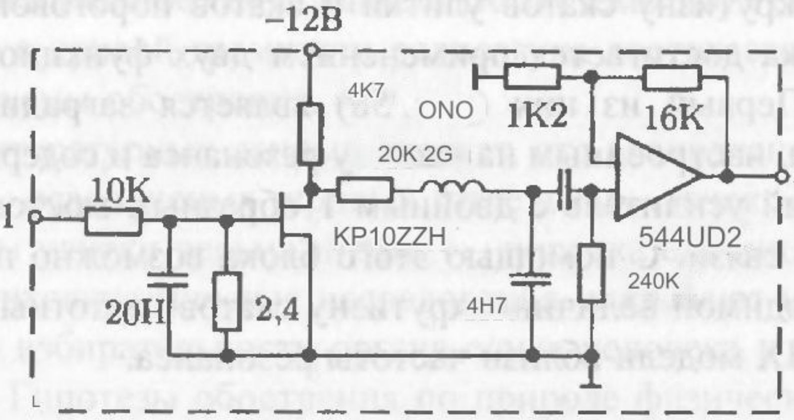


Rice. 58. Barrier filter tuned to resonance frequency

Additional sharpening of the frequency response slope towards higher frequencies is achieved by using a low-pass filter (LPF_1) with a discretely variable upper limit of the cutoff frequency and attenuation at the set cutoff frequency of about 40 dB/oct. In Fig. 59 shows a schematic diagram of the low-pass filter. The functional block for forming the required frequency spectrum when a rectangular pulse is applied to its input consists of several series-connected integrating chains with a time constant much greater than 5...25 μs.



Rice. 59. Low pass filter (LPF)

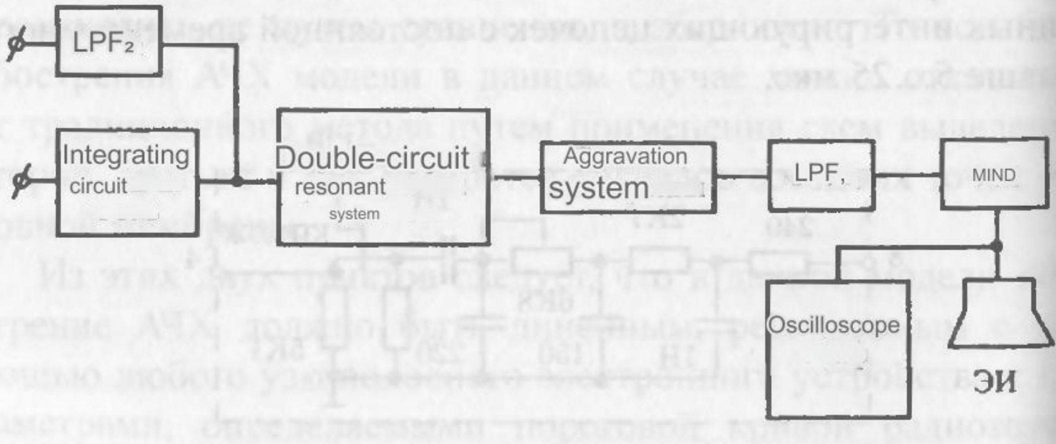


Rice. 60. Low pass filter (LPF_2)

To match this block with the low input resistance of a dual-circuit system, a field-effect transistor repeater is switched on at its output. To ensure the coordination of the model with the source of the tone signal in order to apply the zero beat method, the model is equipped with a block that simulates the frequency response of the auditory tract at the level of the middle ear (Fig. 60). This block is based on the Flanagan model for the middle ear and provides a low-pass filter (LPF2) with a cutoff frequency of 4 kHz.

The output signal of the model is indicated on the oscilloscope screen. Listening is provided by headphones after preliminary amplification of the signal in terms of power. The block diagram of the electronic model of radio sound is shown in Fig. 61.

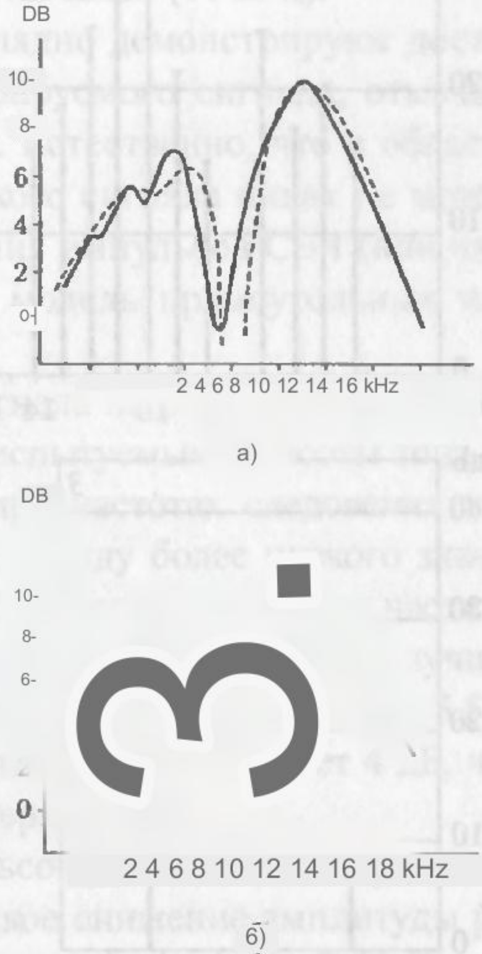
A more detailed description of the two-circuit resonant model of radio sound is given in [97, 98].



Rice. 61. Block diagram of an electronic model of radio sound

5.3. Physical modeling of full-scale radio sound experiments using an electronic model

Study of the output characteristics of a two-circuit resonant model. The study of the output characteristics of the model was carried out in the modes of exposure to a tone signal in the frequency band 1...18 kHz and a pulse sequence in the pulse repetition frequency band 0.8...18 kHz with a pulse duration of 5. ..150 μs. Ha fig. Figure 62 shows the end-to-end frequency response of the model in the mode of shock excitation by pulses with a duration of 15 μs. For comparison, the radio sound level curve is plotted with a dotted line.



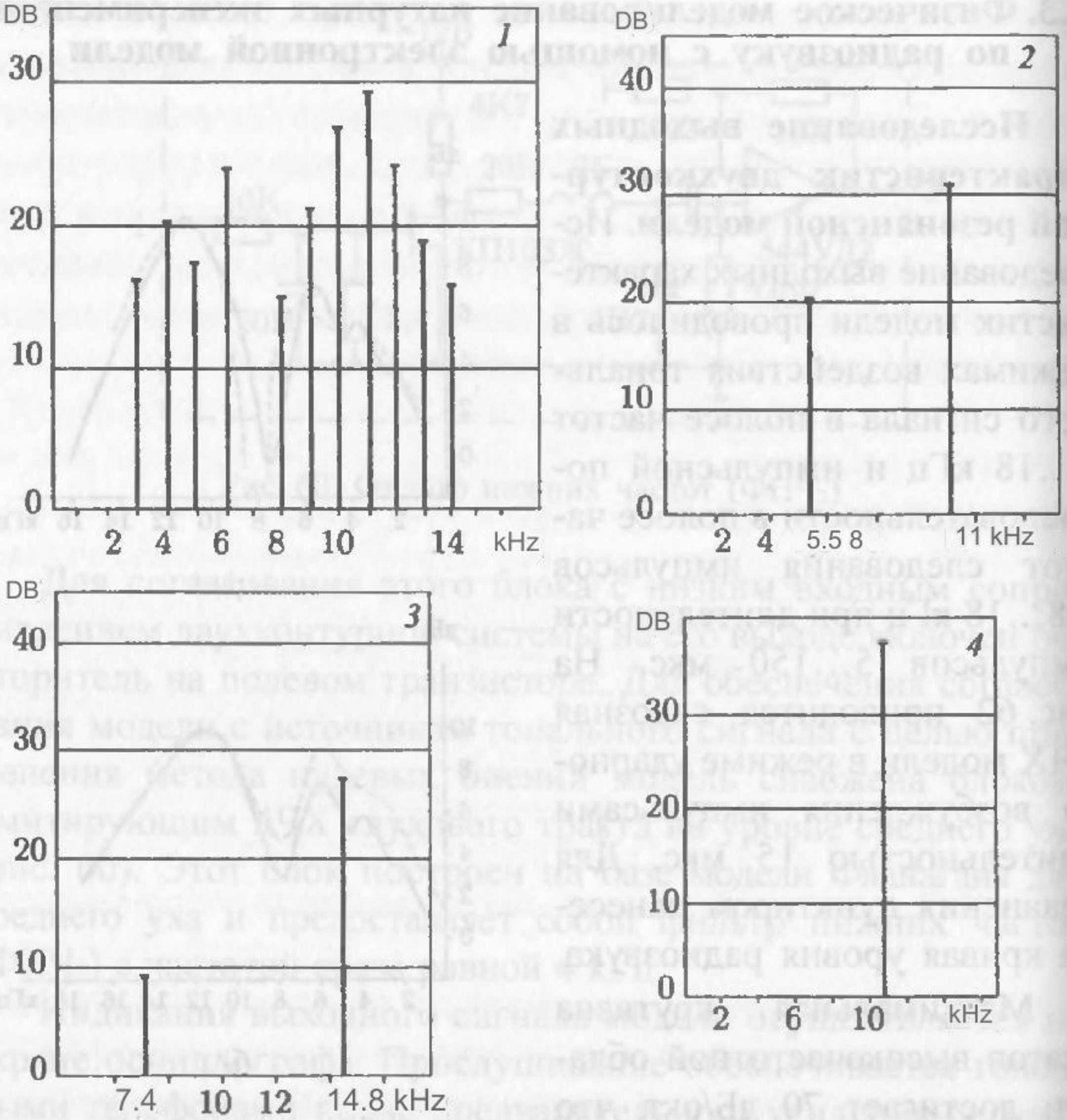
Rice. 62. End-to-end frequency response of a two-kong resonant model in the shock excitation mode (the dotted line is the radio sound level curve (and the — band is 14 kHz, 6 - the band is 17 kHz)

The maximum steepness of the slopes of the high-frequency region reaches 70 dB/oct, which is within the measured values for the steepness of the resonance curves of localization points of displacement of the cochlea of the hearing organ given in the literature [65].

With a pulse duration of 15 μs, the spectral composition of the model output signal was studied at different pulse repetition rates.

In Fig. Figure 63 shows snapshots of the model's output signal, obtained by exciting the model with rectangular pulses.

To select components of a complex signal, a V6-9 selective microvoltmeter, a V3-33 voltmeter and a 43-34 frequency meter were used.



Rice. 63. Spectrograms of the output signal of the double-circuit resonant model:

1 — pulse repetition frequency spectrum 1 kHz; 2 spectrum of the first communication frequency (5.5 kHz); 3 resonance frequency spectrum (7.4 kHz); 4 spectrum of the second communication frequency (11 kHz)

The obtained experimental material allows us to objectively observe changes in the spectral composition of the model's output signal with a changing pulse repetition rate.

It is interesting to compare the obtained data with the results of a subjective assessment of the auditory sensation by subjects in real life. tour experiment on radio sound.

In Fig. 63(1) shows the spectrum of the output signal of the mode- or at a repetition rate of exciting pulses equal to

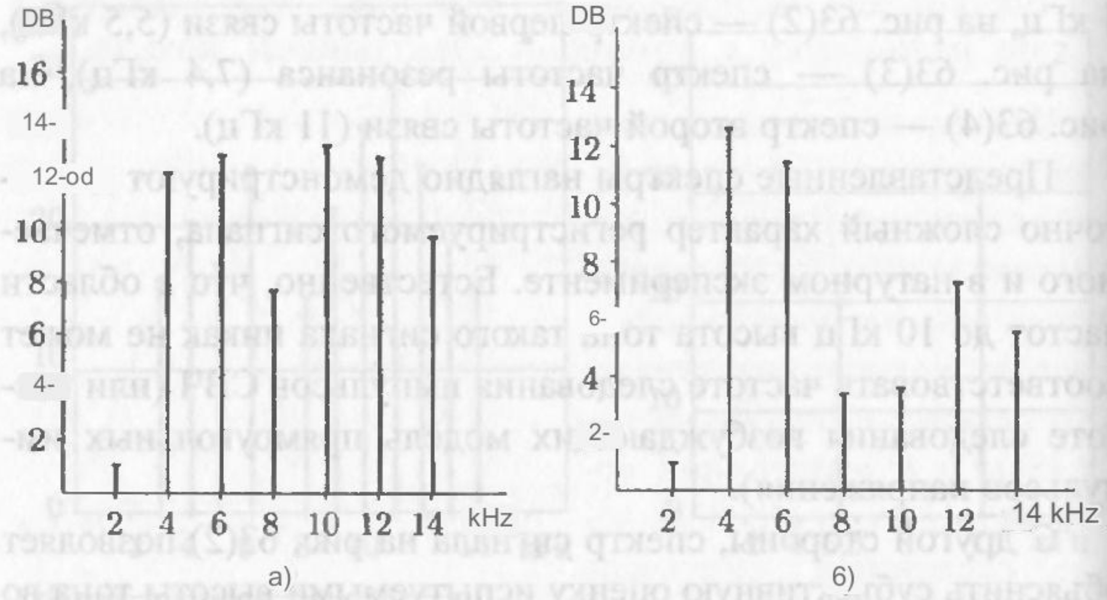
1 kHz, in Fig. 63(2) - spectrum of the first communication frequency (5.5 kHz), in Fig. 63(3) - resonance frequency spectrum (7.4 kHz), in Fig. 63(4) - spectrum of the second communication frequency (11 kHz).

The presented spectra clearly demonstrate the rather complex nature of the recorded signal, which was also observed in the field experiment. Naturally, in the frequency range up to 10 kHz, the pitch of such a signal cannot in any way correspond to the repetition rate of microwave pulses (or the repetition rate of rectangular voltage pulses exciting the model).

On the other hand, the signal spectrum in Fig. 63(2) makes it possible to explain the subjects' subjective assessment of pitch during full-scale experiments at microwave pulse repetition rates of the order of 5...5.5 kHz. Due to the lower threshold value at frequencies 10...11 kHz, the second harmonic of the repetition frequency is perceived by humans significantly better than the — first difference in threshold levels at frequencies 5.5 and 11.0 kHz on the radio sound threshold curve is 4 dB, which is was noted in natural experiments.

At a pulse repetition frequency equal to the resonance frequency of the system, there is also a sharp decrease in the amplitude of the recorded suppression — signal at a frequency of 7.4 kHz of the order of 20 dB, which corresponds to the high threshold region in the full-scale experiment. Moreover, in a full-scale experiment, the test subject, who has a high-frequency hearing limit above 14 kHz, perceives a complex signal consisting of two frequencies - 7.4 and 14.8 kHz. At the same time, due to the lower threshold at a frequency of 14.8 kHz compared to the threshold at a resonance frequency of 7.4 kHz (minimum 6 dB on the radio sound threshold curve), the subject subjectively perceives a higher frequency signal.

At pulse repetition frequencies lying above the second communication frequency, the signal becomes monotonal, its physical spectrum corresponds to the first harmonic of the pulse repetition frequency, which in a full-scale experiment leads to the correspondence of the pitch of the perceived radio sound to the microwave pulse repetition frequency.



Rice. 64. Spectra of the output signal of a double-circuit resonant mode - whether with the same pulse repetition rate:
a — excitation of the model with short pulses; — excitation
b models with long pulses

In Fig. Figure 64 shows the spectra of the model's output signal when it is excited by rectangular pulses of different durations at the same repetition rate. A comparison of these spectra clearly shows that the sensation of "high-frequency type" radio sound that occurs in natural experiments at pulse durations of the order of 15 μs (ti <<T) is explained by the presence of high-intensity high-frequency components. As the pulse duration increases, the output signal is enriched in low-frequency components.

The amplitude of shock-excited oscillations at the output of the model at a fixed pulse frequency in the range of 0.8...18 kHz linearly depends on the amplitude of the exciting pulses.

Simulation of full-scale radio sound experiments using an electronic model. The signal at the output of the model in the shock excitation mode by pulses with a duration of 15 μs was perceived "by ear." The perceived signal is equivalent to the auditory sensation in natural experiments - it is subjectively perceived in the form of a high-frequency "ringing" or "buzzing" at the pulse repetition rate

1...7 kHz. In the frequency range 8...18 kHz there is a gradual change in the nature of the perceived signal; a smooth change in the frequency of the model's output signal when listening.

At various pulse repetition frequencies, the possibility of obtaining a "low-frequency type" analogue of radio sound was tested. With a pulse duration Ti = 1/5 RES = 135 μs, the output signal of the model is perceived in the form of a low-frequency tone corresponding to the pulse repetition frequency. With a decrease in the pulse duration to a value of 67...70 μs, i.e., to a value equal to the half-cycle of excited oscillations, a higher frequency tone is perceived.

Since the question of the width of the frequency range of the auditory sensation excited in humans by microwave pulses is fundamental and, in fact, determines the possibility of constructing a bionic communication channel, testing this characteristic on a model is the most important and responsible point.

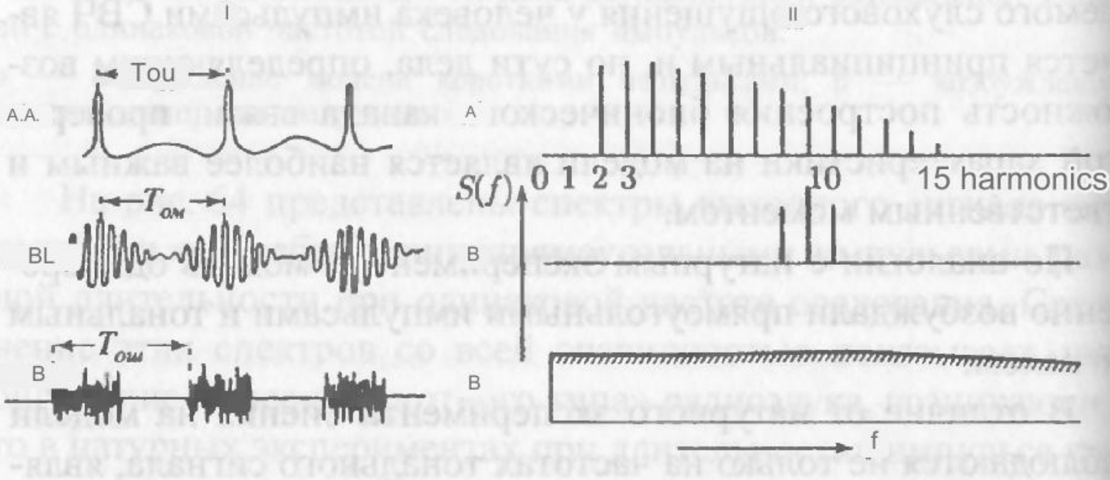
By analogy with the full-scale experiment, the model was simultaneously excited by rectangular pulses and a tone signal.

In contrast to the full-scale experiment, beats in the model are observed not only at frequencies of the tone signal, which are overtones of the pulse repetition rate and lying in the frequency range above 8 kHz, but also at frequencies below 8 kHz and at a frequency equal to the pulse repetition frequency.

Thus, using the zero beat method in a model experiment, the fundamental possibility of human perception of the sound frequency range, perceived by him physiologically in a natural way, was demonstrated for the first time. It is noted that at a given higher frequency of the tonal signal, the average value of the beat frequency amplitude (intensity) increases in proportion to the increase in the repetition rate of the exciting pulses. As the pulse repetition rate decreases, the amplitude of the beat frequency decreases.

We can try to explain the result obtained using the model as follows. Schouten [222-224] expressed

It has been suggested that the perception of the pitch of periodic sounds with the missing first harmonic can be explained using a mechanism for measuring the period of oscillation of a sound wave. According to Schouten's hypothesis, the auditory system should be considered not as a purely spectral, but as a spectral-temporal analyzer, in which, along with the Fourier series expansion, the temporal shape of exciting oscillations is analyzed. Schouten called the sound corresponding to the first harmonic not contained in the signal residual. Schouten's hypothesis is confirmed by neurophysiological observations up to frequencies of the order of 3...5 kHz [107].



Rice. 65. Shapes of sound waves and their spectra (borrowed from [107]: - A - the pitch corresponds to the pulse repetition rate 1/Tone; B the pitch corresponds to the modulation frequency 1/7OM; B — 1/Tone pitch corresponds to the noise interruption frequency

In Fig. Figure 65 shows some forms of sound wave signals, the perception of pitch of which cannot be explained from the point of view of spectral analysis, since they do not contain a component with a frequency corresponding to the pitch of the perceived tone [107].

From a perceptual point of view, all three types of signals have the same pitch, despite the fact that the spectra of these sounds differ significantly from each other. It was experimentally shown that in the first case (A) the pitch corresponds to the pulse repetition frequency 1/Tone [125], in the second — (B) the modulation frequency is 1/Tom [115], in the-third (B) - the noise interruption frequency is 1/Tom [116]. Moreover, the physical spectra of these sounds do not contain components corresponding to the indicated frequencies. The main property that determines the perception of their height is periodic changes in the amplitude of the sound wave.

Comparison of oscillograms of excited mechanical oscillations by microwave pulses (Fig. 30) and damped oscillations at the output of an electrical model excited by voltage pulses (Fig. 66) with those shown in Fig. 65 shows that in this case their spectral characteristics are close and also do not contain the first harmonic. However, as already mentioned, in contrast to a full-scale experiment, the model makes it possible to record the missing component (pulse repetition frequency) using the beat method.

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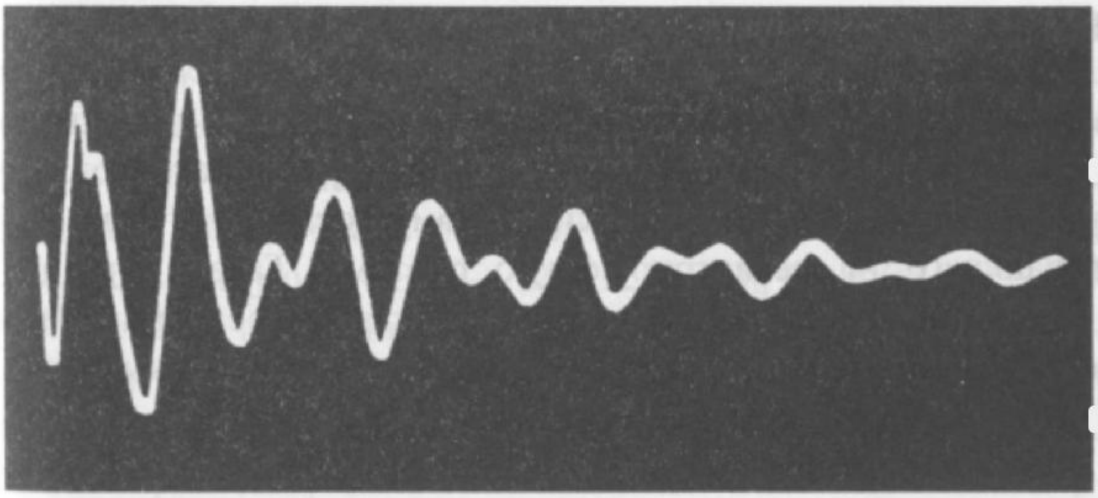

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Rice. 66. Damped oscillations at the output of a double-circuit resonant model

If we were talking about the perception of an ordinary acoustic signal, one could immediately assume the presence of an artifact in the experiment, since in this case beats would necessarily have taken place. And although the concept of the model assumes the absence of participation of structures responsible for signal processing in the formation of the radio effect, sound, however, no definite conclusion can be drawn here.

In this regard, the following interpretation of the results obtained seems possible.

The proposed two-circuit resonant model quite fully reflects the hearing mechanisms involved in the perception of radio sound and, in accordance with the existing analogues of these mechanisms, identifies the first harmonic that is missing in the signal, thereby not contradicting physiological and neurophysiological data. If this is so, then the absence of residual sound in the frequency range below 8 kHz in previously conducted natural experiments, noted by the subjects, apparently can be explained by the following reasons:

1. Insufficient attention of the subjects during the experiment to detect the presence of beats at low frequencies.

2. High noise level in the room where the full-scale experiment was carried out, comparable to the level of excited pressure in the tissues of the skull.

3. Low amplitude of the beat frequency signal at the average level at low microwave pulse repetition rates.

4. Discrepancy between the model and the full-scale experiment transfer function when excitation of the model and the original by a pulse of external influence, which as a result should lead to a different spectral composition of the signal arriving at the recording system. This situation is possible in principle if the critical band of the original is less than the value f - F, where f is the frequency of the resonant oscillations - ny, F is — the modulation frequency, and in the -is greater.

model According to [234], the noise level in the room where the wire The full-scale experiment was carried out and amounted to 40...60 dB at a frequency of 1 kHz. At the same time, according to the data of [206], at close values of the energy density in the pulse, the displacement of the tissues of the human head is of the order of 10-11 cm, which provides a pressure of the order of 10-2 dyn cm-2 at a signal frequency of 1 kHz, i.e. i.e. the signal level above the threshold is also about 40 dB.

An attempt to eliminate residual sound (when received "by ear") in the model by changing the spectral composition of the signal by varying the parameters of the integrating unit did not lead to tangible results. Since in all other respects the model describes a full-scale experiment, then, taking into account the comparability of noise levels and excited pressure (in natural conditions), in a natural experiment) and the physiological features of spectral-temporal analysis of signals by hearing mechanisms, we can conclude that it is necessary to have residual sound in the frequency range below 8 kHz in a natural experiment. Thus, there was a need to re-setting up a full-scale experiment with the participation of volunteers in order to determine the possibility of perceiving beats at sound signal frequencies below 8 kHz. In the case of a positive result, the predictive nature of the electronic model would be simultaneously demonstrated, i.e., the correctness of the provisions underlying it and compliance with the bionic principles of modeling.

5.4. Frequency range of radio sound (full-scale experiment)

A full-scale experiment to detect beats in the frequency range 1...7 kHz was carried out under conditions of a significantly lower level of external noise of less than 20 dB. Carrier frequency is 0.8 GHz. For irradiation, a section of a rectangular waveguide with a cross section of 150x270 mm² was used, the microwave pulse power was 120 W, PPMi = 0.6 W-cm-2. The parietal region of the head was irradiated, as in early experiments, as it has the lowest threshold value for excitation of auditory sensation. The duration of the microwave pulses was selected within 25 μs. A tone signal was supplied to the test subject through headphones from a GS-100I generator. The microwave pulse repetition rate was set in the range 1...7 kHz. The change in the tonal acoustic signal was also within the range of 1...7 kHz. The pulse repetition rate and tone signal frequency were controlled using frequency meters 43-34.

Three volunteers took part in the experiment. At pulse repetition frequencies of 1...3 kHz, radio sound is difficult to perceive. Starting from 3 kHz the sensation of sound intensifies. With a further increase in the pulse repetition rate, microwave radio sound was reliably perceived in the entire range under study. Ima

In order to reduce the exposure time, the presence of beats with an acoustic tone signal was checked at the points where the perception, according to the subjects, was most clear. For the first subject these frequencies were: 3.58; 4.21; 5.23 and 6.99 kHz. For the second subject, the frequencies at which zero beats were observed had values of 4.01; 5.33 and 6.99 kHz. The third subject noted zero beats with pulse repetition rates of 3.80; 4.74 and 4.97 kHz.

It is known that irradiation of metallic (conductive) formations with microwave pulses leads to the excitation of mechanical vibrations in them. Testing the possibility of the presence of an artifact consisted of introducing headphones into the irradiation zone without irradiating volunteers. At the same time, it was not possible to register any additional acoustic effects. The perception of the acoustic signal by volunteers both with headphones on and when they were located outside the irradiation zone (while simultaneously irradiating the volunteer's head with microwave pulses) did not lead to a change in the results of the experiment.

The full-scale experiment confirmed the conclusion about the need for the presence of the first harmonic of the microwave pulse repetition rate in the low-frequency region, which followed from Schouten's concept and the data obtained on the electronic model.

The detected zero beats in the low-frequency region make it possible to significantly shift the lower limit of perceived radio sound towards lower frequencies, at least to 3.6 kHz.

This experimental fact is of fundamental importance not only for understanding the mechanism of the radio sound phenomenon itself, but also from the point of view of its practical application.

Previous data on the limitation from below of the frequency band of perceived radio sound at 8 kHz practically eliminated the question of the possibility of using the auditory microwave effect to transmit information to a person. It is quite obvious that in order to detect zero beats in the frequency range below 3.6 kHz it is necessary to increase the pulse power. In accordance with the threshold curve diosound at a microwave pulse repetition rate of 1 kHz, the peak power in the pulse can be estimated at 360...500 W, i.e., under the same irradiation conditions, the energy flux density in the pulse will be 1.8...2.5 W/cm². These provisions are also consistent with the data of the model experiment, where to increase the amplitude of the beat signal it is necessary to increase the amplitude of the exciting pulses.

Its electronic analogue, created in accordance with the concept of a two-circuit resonant model of radio sound, made it possible to obtain quite convincing data on the possibility of interpreting the effect of radio sound as a physical phenomenon.

The proposed concept of a two-circuit resonant model of radio sound, implemented by electronic models, made it possible for the first time to objectively observe the spectral composition of the model's output signal, which is an analogue of the auditory sensation in a full-scale experiment. The obtained characteristics showed the unified nature of the "two types of radio sound" observed in the field experiment: — low-frequency and high-frequency as a result of the interference of two sources of mechanical vibrations.

The obtained value of the resonant frequency for a sphere with a low quality factor makes it possible not only to confirm the validity of the put forward concept of a two-circuit model of radio sound as a special case of a multimode model implemented with bone conduction of sound, but also to finally clarify the understanding of some essential points related to characterizing the very phenomenon of radio sound, shit

Model experiments confirmed the presence of resonance at frequencies close to those indicated for the head of an adult, which, however, in the case of a single-circuit model of Lin radio sound does not give the expected increase in the signal amplitude at this frequency; on the contrary, it is characterized by a region of maximum the maximum sensitivity threshold on the radio sound threshold curve, i.e. the minimum value of the signal amplitude. The equivalent acoustic resonator has a maximum signal transmission. 08

The introduction of the idea of the possibility of forming a threshold curve of radio sound using a two-circuit resonant model eliminates the noted contradictions. At the same time, according to

By analogy with an equivalent double-circuit resonant system with a strong coupling between the circuits, the region of a high sensitivity threshold is explained by the shunting of the first circuit by the second at the resonance frequency, which leads to a decrease in the signal transmission coefficient at the resonance frequency and an increase in the sensitivity threshold at this frequency. Signal amplification at communication frequencies leads to the formation of areas with minimum sensitivity threshold values at frequencies of 5.5 and 10.5 kHz. At the same time, the greater steepness of the slopes on the threshold curve of radio sound is explained by an equivalent increase in the quality factor ы of the systems due to the expansion of the passband and the introduction of attenuation when the pressure wave propagates along the cochlea (oscillatory system with distributed parameters).

The predictive nature of the two-circuit resonant system in electronic design is manifested in the possibility of isolating the signal of the first harmonic of the repetition frequency of the exciting pulses. Further field experiments confirmed this thesis. Thus, for the first time, the fundamental possibility of human perception of the entire sound range is demonstrated when mechanical vibrations are excited in the tissues of the head by EMR pulses, and the prerequisites are created for the implementation of a bionic communication channel.

5.5. Brief conclusions

1. A structural diagram of the physical model of the interaction of pulsed EMR with the anatomical structures of the head has been determined, forming the spectrum of the signal influencing the auditory analyzer by analogues of peripheral structures auditory system.

2. An electronic two-circuit resonant model of radio sound has been developed and constructed, generating an output signal available for instrumental recording and analysis and human perception by air or bone conduction as an acoustic analogue of radio sound.

3. The frequency response of the two-circuit resonant model corresponds to the radio sound volume curve with equal parameters of the exciting signal.

4. It is shown that when changing the parameters of the exciting signal at the input of the model, similar to changing the parameters of EMR pulses in natural experiments, the output signal of the model creates an imitation of high- or low-frequency radio sound.

5. Spectral analysis of the model's output signal objectively showed a change in the amplitudes of frequency components when changing the parameters of the input signal, corresponding to a subjective assessment of the auditory sensation caused by this signal.

6. The model obtained zero beats in the region of pulse repetition frequencies below 8 kHz up to 100 Hz between the sinusoidal signal and the pulse sequence.

7. For the first time, a full-scale experiment demonstrated the possibility of human perception of the first harmonic of a microwave EMR pulse sequence in the entire audio range perceived by humans. This demonstrates the fundamental possibility of human perception of speech information transmitted by complexly modulated EMR without the use of technical means of reception.

8. Developed on the basis of ideas about the formation of the radio sound effect by peripheral structures, the electronic model confirmed the correctness of the provisions and ideas about this effect underlying it and created the prerequisites for the physical substantiation of the possibility of the existence of a communication channel based on bionics.

Chapter VI

JUSTIFICATION OF THE POSSIBILITY OF CREATING A BIONIC COMMUNICATION CHANNEL BASED ON PULSE ELECTROMAGNETIC RADIATION MICROWAVE

6.1. Physical basis of a bionic microwave communication channel

General provisions. The considered mechanism of radio sound formation and the characteristics of this effect obtained in model and natural experiments create the prerequisites for justifying the possibility of creating a communication channel based on bionics. That is, the question may be raised about developing methods for modulating microwave electromagnetic energy and technical devices that implement these methods in order to transmit the message function and its objective perception by a person in the form of useful information without the use of technical means of reception.

Human perception of part of the spectrum of the pulsed microwave radiation envelope indicates the possibility of detecting non-ionizing radiation by biological structures.

When creating a bionic communication channel, first of all, the question arises about the method of modulating non-ionizing radiation. The solution to this issue is impossible without ideas about the nature of the nonlinear properties of biological structures, the values of equivalent parameters of the elements that make up the decoding structures, and finally, without ideas about the very structural organization of the equivalent detector.

Thus, the task arises of constructing block diagrams of a receiver with equivalent parameters, the values of which can be determined from data obtained in tour and model experiments on radio sound and taking into account the physiological characteristics of hearing mechanisms, and a transmitter that encodes and transmits a signal accessible for its perception by an equivalent receiver. c Available literature data, mainly of a theoretical nature, on a pressure jump during thermoelastic expansion of a medium indicate the presence of sufficiently high rates of temperature rise and fall as a necessary condition for the generation of mechanical vibrations. That is, we can talk about the formation of a thermal pulse, the shape approaching rectangular, and consider this function as a result of formalized detection of the microwave carrier by biological structures.

In the most general case, the mechanism for excitation of mechanical oscillations in the tissues of the head can be represented by an equivalent circuit containing an input circuit with a very low quality factor (since the excitation of mechanical oscillations is observed in a wide frequency band of the carrier), loaded on a pulse detector (formation thermal pulse) and a system that forms the frequency band of the information signal (double-circuit resonant model).

If the question of formalized detection of a microwave carrier can be presented unambiguously, based on the provisions of thermoelastic theory, then an idea of the structure of the second detector, and, accordingly, the choice of the necessary mode of modulation of pulsed microwave radiation, is possible only after analyzing data from full-scale and model experiments on radio sound taking into account the principles of processing sensory information in the auditory analyzer.

According to Schouten's concept, the auditory system is considered not as a purely spectral, but as a spectral-temporal analyzer, in which, along with the Fourier series expansion, the temporal shape of excited oscillations is analyzed.

Since the amplitude of excited mechanical oscillations linearly depends on the peak power of the microwave pulse [95], and the data obtained in natural experiments indicate the possibility of conducting these oscillations into the cochlea of the hearing organ by bone conduction, then, in accordance with the con-

According to the Schouten concept, there should be a temporary change in the amplitude of EMR pulses according to the law of the modulating function. Absorption of the amplitude of EMR pulses with different peak powers will cause the excitation of mechanical vibrations in the tissues of the head with an amplitude that repeats the modulation law, i.e., mechanical vibrations will be modulated in amplitude.

On the other hand, the ability of the auditory analyzer to measure the period of an irritating stimulus indicates the possibility of perceiving a periodic signal, the oscillation frequency of which varies over time, i.e., frequency or time modulation of EMR is also possible, leading to frequency or time modulation of the excited mechanism - logical hesitation. In all cases, the auditory analyzer will receive an acoustic signal modulated by one or another parameter, which represents excited mechanical vibrations and plays the role of a carrier.

Thus, according to the principle of organization, a bionic communication channel is similar to technical communication systems that transmit information according to the scheme: modulating — signal information carrier transmitting — medium receiving a modulated information — detective carrier torus - dedicated modulating signal.

Type of EMR modulation. By periodically changing the amplitude of EMR pulses, the mode of amplitude-pulse modulation (APM) is achieved. The restoration of the modulating function in the auditory analyzer can be formally represented as a detection process by analogy with technical systems, where the detector performs the same function of forming a frequency component that is absent in the spectrum of the output signal due to its nonlinear transformation.

Let us analyze the course of the radio sound volume curve and determine in general terms the possibilities of using AIM. On the radio sound volume curve, three regions of maximum signal amplitude values can be distinguished, which correspond to central pulse repetition frequencies of 3.5; 5.5 and 10.5 kHz. These frequency values can be considered as pseudo-resonant, i.e. at these points the first harmonic of the pulse repetition frequency has the greatest amplitude (Fig. 67).109 con

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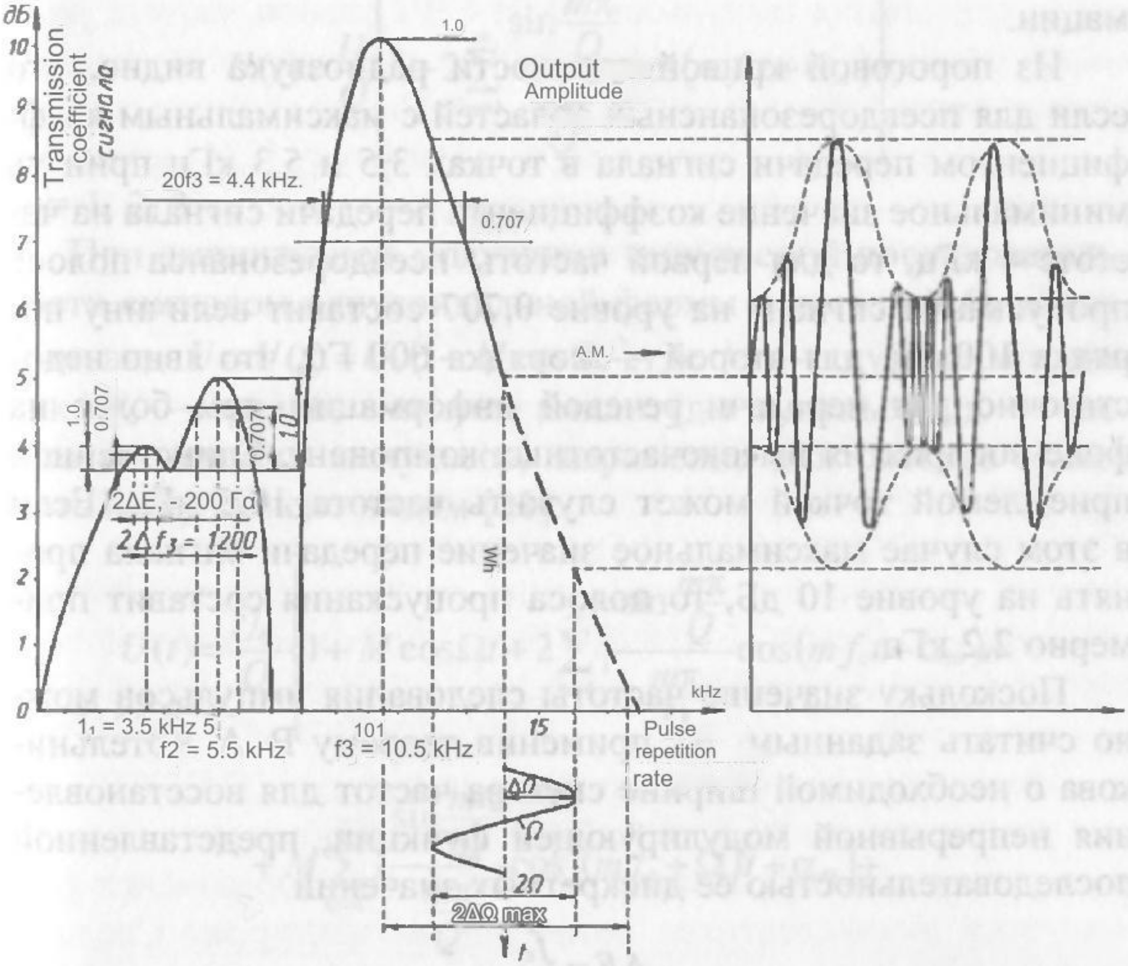


Rice. 67. Areas of pseudo-resonances on the radio sound volume curve

The term "pseudo-resonance frequency" was introduced to differentiate limitations of the concept of true resonance frequency of individual contours and resulting from multimode power systems of individual zones on the integrated frequency response, having high signal transmission coefficient for individual hours - gotah, i.e. frequency selectivity. If the frequency follows select pulses equal to one of the central hours - then it can be represented as a carrier (in this case, tea subcarrier, so as not to be confused with the microwave carrier), i.e. re- carrier of information, and the law of change in the amplitude of these pulses, i.e. a modulating function, as a function tions of the message. During subsequent detection, the spectrum

Such a signal will have information capacity and, due to bone conduction during activation of the cochlea of the organ of hearing and subsequent processing at neural levels, should be perceived by a person in the form of useful information.

From the threshold curve of radio sound volume it is clear that if for pseudo-resonance areas with a maximum signal transmission coefficient at points 3.5 and 5.3 kHz we take the minimum value of the signal transmission coefficient at a frequency of 4 kHz, then for the first pseudo-resonance frequency the signal bandwidth at the level of 0.707 will be a value of the order of 100 Hz, for the second order 600 Hz, which is clearly insufficient for the transmission of speech information, especially against the background of the perception of high-frequency components. The only acceptable point would be 10.5 kHz. If in this case the maximum signal transmission value is taken to be 10 dB, then the bandwidth will be approximately 2.2 kHz.

Since the value of the pulse repetition rate can be considered given, then, using the theorem of V. A. Kotelnikov on the necessary width of the frequency spectrum to restore the continuous modulating function, represented by a sequence of its discrete values

$$AF=f_{\mu},$$

where AF is the width of the required frequency spectrum; fe - pulse repetition frequency; and - the pulse repetition rate is 2.5-5 times higher than the theoretical limit, we obtain the value DElin = 10.5/5 = 2.1 kHz, which indicates the correct choice of the bandwidth on the radio sound threshold curve.

It is customary to distinguish between two types of AIM. In type I AIM, the modulated voltage during the duration of the entire pulse follows a change in the modulating function. Both types of AIM are considered in the technical literature [31]. Here we only point out that the technical implementation of the AIM mode of the 1st kind is simpler and consideration of this mode will be adopted in the future to determine all the parameters of the bionic communication channel (for simplicity, in the future we will use the notation AIM). a ton of cinemadobo

The spectrum of an unmodulated periodic sequence of rectangular pulses is described by the well-known expression:

$$U(t)=\frac{U}{Q}\left[1+2\sum_{mal}^{\infty}\frac{\sin mn\,Q}{\frac{M\pi}{Q}}\cos(m f_c t+\alpha_m)\right],$$

m = 1, 2, 3...

With amplitude modulation of a pulse sequence with a sinusoidal signal and frequency 2, having the form U=U(t)=Uo (1+M cost), where M is the — modulation depth; o is the average value of the pulse amplitude; fo is — the pulse repetition frequency, the expression for the spectrum can be represented as [31]:

$$U(t)=\frac{Uo}{Q}\left\{1+M\cos\Omega t+2\sum_{m=1}^{\infty}\frac{\sin\frac{m\pi}{Q}}{\frac{M\pi}{Q}}\cos(m f_c t+\alpha_m)+\right.$$

$$+M\Sigma\, 2\sum_{m=1}^{\infty}\frac{\sin m\pi\,Q}{\frac{M\pi}{Q}}\cos[(m f_c+\Omega)t+\alpha_m]+$$

$$\left.+M\Sigma_{3\, m=1}\frac{\sin m\pi\,Q}{\frac{M\pi}{Q}}\cos[(mfc-\Omega)t+am]\right],$$

where 2 is the duty cycle; t = 1, 2, 3...; am is the initial phase of the th harmonic of the spectrum. The resulting expression is the spectrum of the AIM signal, which consists of the amplitude-modulated spectrum bath (AM) and its harmonics along the carrier and side. Let's consider the course of the radio sound volume curve in the region of pulse repetition frequencies of 11... 18 kHz. Since in the full-scale experiment the threshold curve of radio sound was taken at a maximum pulse repetition rate of 14 kHz, the missing section of 14...18 kHz may be constructed in accordance with the data of threshold bone conduction curves in this range.

The results of experiments on pulsed irradiation of spherical liquid models [120] showed that when the microwave EMR pulse repetition rate is equal to the resonance frequency of the sphere and higher, a signal of the first harmonic of the pulse repetition rate is released in the spherical resonator.

In field experiments on radio sound [234], all subjects noted the monotonality of the perceived auditory sensation, starting with a repetition frequency in the region of 10 kHz and higher, i.e., from the frequency corresponding to the second communication frequency.

Thus, if the initial EMR pulse repetition frequency is set equal to 14 kHz, which will correspond to the middle of the slope of the section of the pseudoresonance curve, then, in accordance with the data obtained in model and natural experiments, the change in the pulse repetition frequency is within 11. ..18 kHz will lead to the release of the first harmonic signal in a shape approaching sinusoidal.

A change in the repetition rate of microwave EMR pulses will lead to a change in the amplitude of excited mechanical oscillations, since the pseudoresonance section is formed by an equivalent resonant circuit. Consequently, at the initial repetition rate of microwave EMR pulses corresponding to the average frequency value on the high-frequency slope of the pseudoresonance section and its subsequent deviation, there is an inversely proportional change in the amplitude of the excited mechanical oscillations. If there is an amplitude detector at the output of the resonant system, a change in the amplitude of the sinusoidal subcarrier signal in time, caused by the deviation of the microwave EMR pulse repetition rate, will lead to the detector identifying the law of this change.

By performing pulse frequency modulation (PFM) at the transmitting end, we obtain the ability to convert a pulse sequence into a frequency modulated (FM) signal and further convert it into an AM signal with a bandwidth of 4 kHz (Fig. 67).n for Monan

The signal spectrum for PFM radiation can be obtained from the spectrum of an unmodulated pulse sequence of the form

U(t)=1+2) 1+2Σ basin mn / Q cos (m.fct+am),
Q Mπ m=1 / Q

m = 1, 2, 3... by substituting the expression fc = @co + Dot coset,

where co = ω_0 / fo — 2π is the central (subcarrier) frequency of the

Co Afmy spectrum; A = \f fo — 2π max amplitude of deviation relative

= Ho — Ω subcarrier frequency deviation; F =- to / 2π — frequency modulation.

Since FM is an angular modulation, it is more convenient to consider not the instantaneous value of the subcarrier, but the instantaneous value of the phase of these oscillations:

$$\varphi(t)=\int \omega dt=\omega_0 t+m_f \sin\Omega t,$$

where m = Δωm / Afm = Ω — F is the modulation index, which has the dimension of phase [31]. In this case, for simplicity, we assume φ = 0. We substitute the obtained phase value instead of the subcarrier frequency into the expression for the spectrum of the pulse unmodulated sequence, we obtain

U(t)= U / Q {1+2Σ sin Mπ / Q / Mπ m=1 / Q cos [mp(t)] =

$$=\frac{U}{Q}\left\{1+2\sum_{m=1}^{\infty}\frac{\sin\frac{m\pi}{Q}}{\frac{m\pi}{Q}}\cos\left[m(\omega_0 t+m_f\sin\Omega t)\right]\right\}.$$

Let's transform the expression in square brackets:

cos [m(wot+ms sint)]= cos (mwot+mm; sinot)=

= cosmoot cosmm, sin Ωt - sin mot sinmm, sinot.

Using series expansion in Bessel functions of the 1st kind

$$\cos(x\sin y)=J_0(x)+2\sum_{n=1}^{\infty}J_{2n}(x)\cos 2ny,$$

$$\sin(x\sin y)=2\sum_{n=0}^{\infty}J_{2n+1}(x)\sin(2n+1)y,$$

Let's transform the resulting expression to the form

cosmeat Jo(Mm)+2Jn(Mm)cos2not] -

n=1

-sinmod [222 (Mm)sin(2n+1)],

from here

$$U(t)=\frac{U}{Q}\left[\left[1+2\sum_{n=1}^{\infty}\frac{\sin\frac{m\pi}{Q}}{\frac{M\pi}{Q}}\left\{\cos m\omega_0 t\left[J_0(Mm_f)+2\sum_{n=1}^{\infty}J_{2n}(Mm_f)\cos 2n\Omega t\right]-\right.\right.\right.$$

$$\left.\left.\left.-\sin m\omega_0 t\left[2\sum_{n=0}^{\infty}J_{2n+1}(Mm_f)\sin(2n+1)\Omega t\right]\right\}\right]\right]=$$

$$=\frac{U}{Q}\left\{1+2\sum_{k=1}^{\infty}\frac{\sin\frac{K\pi}{Q}}{\frac{K\pi}{Q}}\left[J_0(Mm_f)\cos m\omega_0 t+2\cos m\omega_0 t\sum_{n=1}^{\infty}J_{2n}(Mm_f)\cos 2n\Omega t-\right.\right.$$

- 2sinmontĖJan-1 (Mm)sin(2n+1)]-

$$=\frac{U}{Q}\left\{1+2\sum_{k=1}^{\infty}\frac{\sin\frac{K\pi}{Q}}{\frac{K\pi}{Q}}\right.$$ [Jo(Mm) cosmoot-J(Mm)sin mot sinot +

+2ΣΣ[J2n (Mmf)cosmost cos2net-J2n+1 (Mmf)sinmootsin(2n+1)Ω 1)Ω]}=

$$\frac{U}{Q}\left[\left[1+2\sum_{k=1}\frac{\sin\frac{K\pi}{Q}}{\frac{K\pi}{Q}}\{J_0(Mm_f)\cos m\omega_0 t-2J_1(Mm_f)\sin m\omega_0 t\sin\Omega t+\right.\right.$$

$$\left.\left.+2\sum_{n=1}^{\infty}[J_{2n}(Mm_f)\cos m\omega_0 t\cos 2n\Omega t-J_{2n+1}(Mm_f)\sin m\omega_0 t\sin(2n+1)\Omega t]\}\right]\right]=$$

$$=\frac{U}{Q}\left[\left[1+2\sum_{k=1}^{\infty}\frac{\sin\frac{K\pi}{Q}}{\frac{K\pi}{Q}}\{J_0(Mm_f)\cos m\omega_0 t-J_1(Mm_f)[\cos(m\omega_0 t-\Omega t)-\right.\right.$$

$$-\cos(m\omega_0 t+\Omega t)]+\sum_{n=1}^{N}[J_{2n}(Mm_f)\cos(m\omega_0 t-2n\Omega t)+$$

$$+J_{2n}(Mm_f)\cos(m\omega_0 t+2n\Omega t)-J_{2n+1}(Mm_f)\cos[m\omega_0 t-(2n+1)\Omega t]+$$

$$\left.\left.+J_{2n+1}(Mm_f)\cos[m\omega_0 t+(2n+1)\Omega t]]\}\right]\right]$$

Let's consider the possibility of isolating a modulating function in the frequency range 6...9 kHz on the threshold curve of radio sound. Hour

By setting the microwave EMR pulse repetition rate equal to the mechanical resonance frequency of the head, i.e., about 7.5 kHz at the point of maximum threshold (see Fig. 5), FM is possible on a pseudo-resonant system, equivalent to a system of two detuned resonant circuits at the initial nom PFM radiation. However, the bandwidth of the useful signal does not exceed 1.5 kHz. The main disadvantage of such FM is the presence of overtones and subharmonics that lie in the band of physiologically perceived frequencies and lead to an increase in the amplitudes of interfering signals, i.e., to a decrease in the signal-to-noise ratio.

Analysis of the spectra of AIM and PFM radiation will be carried out after determining the values of the modulation coefficient and index.

The previously defined fundamental possibility of transmitting useful information using microwave EMR in the form of a code is also of great practical interest. The considered mechanism of radio sound and the threshold characteristics of this effect create the prerequisites for assessing the possibility of implementing such a communication channel and its characteristics.

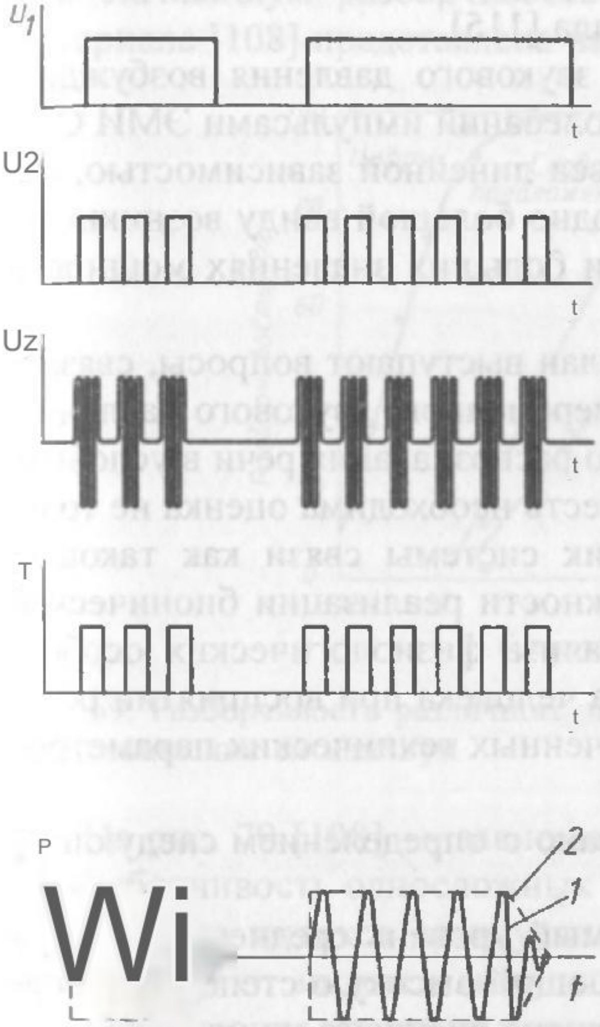
Due to the fact that, as shown above, with any type of modulation of the EMR pulse sequence, the microwave signal entering the auditory analyzer is characterized by three frequency components representing the spectrum of the AM signal, as well as the independence of the frequency of excited mechanical vibrations in the tissues of the head from the frequency of the trace - microwave pulses, it can be considered optimal to form a code using burst-pulse modulation (PPM). Short and long bursts of pulses correspond to different periods of time, during which mechanical vibrations will be excited, i.e., a perceptible acoustic signal of different durations will be realized, which is an analogue of amplitude telegraphy (AT) [31].

In this implementation, the issue of choosing pulse parameters is not fundamental from the point of view of the implementation of the bionic communication channel itself. However, due to the damped nature of excited mechanical oscillations, with an arbitrary choice of the pulse repetition rate in a burst and their duration, residual sound will be observed, i.e., the superposition of the envelope of excited mechanical oscillations in the form of an exponential on the very process of generating these oscillations, which in will ultimately lead to a decrease in the probability of correct signal recognition. Therefore, the pulse repetition rate in the burst must be set equal to the second communication frequency (~10 kHz), which will allow obtaining a pure tone signal with maximum sensitivity of the auditory system. The pulse duration can be selected from the condition ti < 1/2, i.e., within 50 μs.

Since when receiving a code “by ear” the frequency band of the signal is obviously smaller than when receiving a “telephone” signal [31], the bandwidth of the pseudo-resonant section at the level of 0.707 satisfies the conditions for undistorted reception of the AT signal.

Codes are developed taking into account the physiological characteristics of the auditory analyzer (in particular, Morse code) and issues such as the choice of the duration of a short and long burst are resolved in accordance with existing ГОСТ.

In Fig. 68 schematically depicts the process of transmitting and receiving an AT signal bionically.



U — message function — primary modulation

U2 - pulse code modulation secondary modulation

From - PIM EMR microwave

T - formalized detection function release of a thermal impulse in tissue - primary detection

1 tone
2 — communication — function co-envelope
P — excitation of mechanical vibrations with a frequency equal to the frequency of pseudo-resonance 01. Secondary detection in the auditory analyzer - restoration of the message function

Rice. 68. The process of forming the AT signal in the auditory analyzer

6.2. Justification for the choice of the main parameters of the bionic communication channel

The physical foundations of the bionic system discussed above communication systems reveal the essence of information transfer trapper using pulse-modulated electromagnetic nit radiation without the use of technical means ema and determine the basic principles of EMR modulation and nits of the frequency range of the message function.

Compared to any other technical communication system zi bionic can be realized only under the condition fulfillment of some additional requirements related to the sensitivity of the auditory analyzer for bone conduction and the threshold sensitivity of the AM signal for various signal levels [115].

The amplitude of variable sound pressure of mechanical vibrations excited in tissues by microwave EMR pulses is related to the pulse power by a linear dependence, but cannot be arbitrarily large due to the occurrence of thermal overloads at high values of the pulse power.

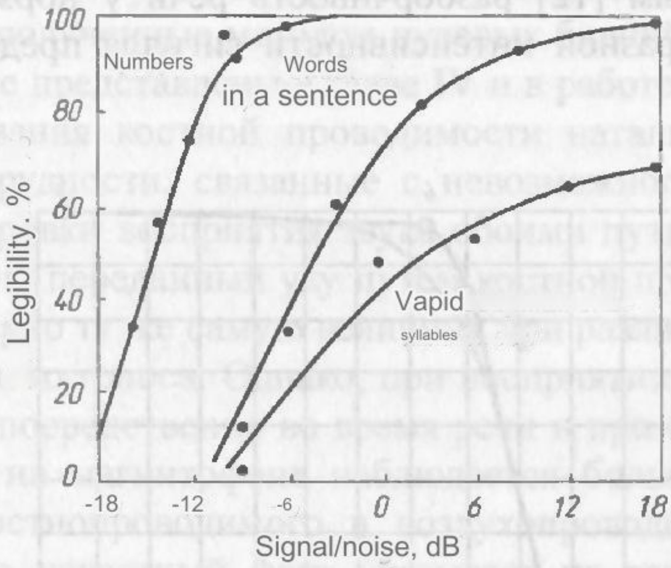
In this regard, issues related to ensuring a level of variable sound pressure sufficient for correct speech recognition in conditions of external noise come to the fore. That is, it is necessary to assess not only the technical characteristics of the communication system as such, but also the fundamental possibility of implementing a bionic communication system based on an analysis of the physiological characteristics of the human auditory analyzer when perceiving a speech signal and taking into account the obtained technical parameters of the communication system itself.

Solving this problem involves determining the following parameters of the communication system:

1. The minimum required level of average pressure of the speech signal, ensuring a high degree of speech intelligibility at a given level of external noise.
2. Coefficient (index) of modulation of the carrier signal, taking into account the frequency-threshold dependence when perceiving information in the frequency range of the modulating signal.
3. Pulse duration.
4. Pulse power.
5. Thermal loads.

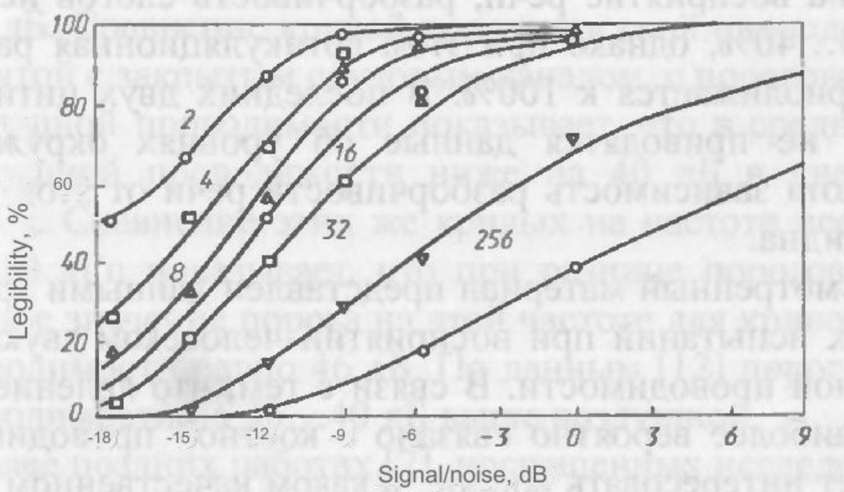
Pressure level and speech intelligibility. According to [35], to ensure high speech intelligibility, the average pressure level of the speech signal must be 40...50 dB above the threshold value of 2-104 dyn cm-2. The percentage of correct perception of the material reaches 80...100%.

The results of studies of articulation tests with three types of words [87] show that 80...100% correct of the perceived material are realized at a relative intensity of the speech signal of 25...50 dB. As a function of the signal-to-noise ratio, the intelligibility of material with different contents [108] is presented in Fig. 69.



Rice. 69. Intelligibility of different contents of material as a function of the signal-to-noise ratio

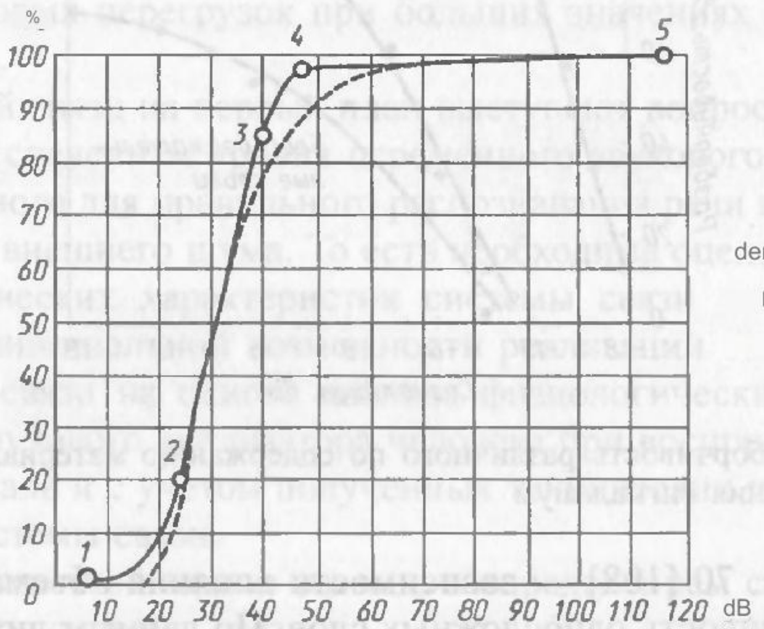
In Fig. 70 [108] dependence of the influence of vocabulary size on the intelligibility of monosyllabic words. According to these diagrams for calculating the articulation index and the dependences of speech intelligibility on the modulation index given in [108] for an average speech signal pressure level of 40...50 dB, the articulation index is about 0.8, which gives from 92 to 100% speech intelligibility depending on the dictionary.



Rice. 70. Dependence of the influence of vocabulary volume on the intelligibility of monosyllabic words

Thus, for a sufficiently high level of speech recognition (80% and above), the average sound pressure level of a speech signal during air transmission should be about 6.3 10-2 dyn cm-2.

According to [12], speech intelligibility in people with normal hearing at different signal intensities is shown in Fig. 71.



denka not 101

how soORO

bionic

Rice. 71. Speech intelligibility in normal hearing people at different signal intensities

According to research results [127], in conditions of loss of hearing sensitivity of no more than 10...20 dB, which practically does not affect speech perception, syllable intelligibility does not exceed 30...40%, however, articulatory intelligibility approaches 100%. The last two cited works do not provide data on ambient noise levels, although the dependence of speech intelligibility on this value is obvious.

The material considered is presented by data from articulation tests on human perception of sound by air conduction. Due to the fact that the phenomenon of radio sound is most likely associated with bone conduction, we will be interested in the question of what qualitative and quantitative relationship these data have with the results of bone conduction studies.

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According to data [136, 137, 209], for both types of audibility, an identical vibration pattern of the cochlear septum of the hearing organ is formed, which was demonstrated by the neutralization of the tone perceived by bone conduction by the tone perceived by air conduction. The same results obtained by the zero beat method in a full-scale experiment are presented in Chapter IV and in work [96].

Bone conduction studies encounter serious difficulties associated with the impossibility of completely differentiating the perception of sound in both ways. According to data [87], the sound transmitted to the ear by bone conduction has approximately the same value when distinguishing our own voice. However, when perceiving one's own voice directly during speech and when listening to a recording on a tape recorder, a large difference in the timbre of bone-conducted and air-conducted sound is observed. This well-known fact indicates a different course of the frequency-threshold curves for bone and air conduction.

Ultimately, bone conduction thresholds will determine the level of pressure of excited mechanical vibrations in the tissues of the head, necessary for a person to perceive auditory sensations in an inadequate way.

Measuring bone conduction thresholds has its own characteristics. Thus, with a closed auditory canal, the bone conduction threshold decreases by approximately 10 dB for frequencies below 2 kHz [138], at a frequency of 125 kHz the threshold decreases by 24 dB. Comparison of the bone conduction threshold curve [138], taken with a closed ear canal, with the air conduction threshold curve shows that, on average, the air conduction threshold is 40 dB lower in the range of 50...104 Hz. Comparison of the same curves at a pseudoresonance frequency of 10 kHz shows that with a threshold difference of 36 dB, the absolute value of the threshold at this frequency for the bone conduction curve is 46 dB. According to [12], bone conduction thresholds are 30...40 dB higher than air conduction.

In later works [7], devoted to the study of hearing thresholds during bone and air conduction of sounds, it was shown that there is a rather nonlinear dependence

The relationship between the thresholds for bone and air conduction of sounds depends on frequency. Thus, at a frequency of 0.125 kHz, the excess of the threshold during bone conduction is only 9 dB and reaches 39 dB at a frequency of 0.5 kHz. At a frequency of 13 kHz, the threshold values are the same.

Comparison of the threshold curve of radio sound with the threshold curve of bone conduction of sound shows their good qualitative, and in some areas, quantitative, approximation.

The difference in the quantitative characteristics of the threshold curve of radio sound, which are mainly of an amplitude nature, from the threshold curve of bone conduction of sound [87], obviously, can be explained by the difference in the methods of excitation of the skull bones and soft tissues of the head.

Masking of the useful signal by external noise has a significant impact on the required level of pressure of the speech signal. Data on masking thresholds for various noises are reviewed in the literature [87, 107, 115].

We will use here the main results of these studies - the equality — of the masker and masked signal levels when determining masking thresholds. This circumstance is one of the main criteria for determining the threshold value of the sound pressure level when excitation of mechanical vibrations by microwave EMR pulses and hereinafter - threshold values of pulse power. According to data [104, 234], in a natural experiment when a human head was irradiated with microwave EMR pulses, the resulting auditory sensation was masked by external noise with a level of up to 60 dB, and the masker was perceived by air no conductivity.

The brief analysis carried out allows us to highlight the following basic principles for determining the required sound pressure level of a speech signal when perceiving sound by bone-tissue conduction:

1. The identity of the vibration model of the main membrane of the cochlea during bone and air conduction allows us to transfer the fundamental features of the effects of masking acoustic stimuli to stimuli excited by microwave EMR. ONBEBNOY

2. The identity of the vibration models of the main membrane of the cochlea with bone and air conduction allows us to apply the main dependences of speech signal intelligibility on the signal-to-noise ratio and the intensity of the external stimulus with air conduction to bone conduction, taking into account the difference in sensitivity thresholds in a given range of stimulus frequencies.

3. The need to take into account the threshold curve of radio sound and the frequency-threshold curve of bone-tissue conduction in the mode of shock acoustic vibrations when determining the threshold values of bone conduction of sound in a given stimulus frequency range.

The considered acoustic and audiometric data allow us to proceed to the selection of the main technical parameters of the bionic communication channel.

Modulation coefficient and spectrum of the perceived signal in the AIM radiation mode. Increasing the coefficient The modulation element helps to increase the communication range, which is equivalent to an increase in transmitter power. On the other hand, this increases the amplitude of the useful signal in the receiver, which is equivalent to increasing its sensitivity.

These known provisions do not undergo changes for the bionic communication channel, i.e., in this case, it is necessary to strive to achieve the maximum possible value of the modulation coefficient.

On the other hand, due to the nonlinearity of the modulation characteristics of the functional blocks of the transmitter, the modulation coefficient in AM mode is always significantly less than unity.

According to data from [93], when AM modulation of tube microwave generators with a sinusoidal signal with a carrier power in a matched load of up to 220 W, the nonlinearity of the signal taken from the detector does not exceed 5% with a modulation coefficient M = 0.8. At M = 0.95, the nonlinearity at individual points in the carrier wavelength range 9...100 cm reaches 12%. Taking into account the large spread of parameters of electron tubes used in microwave generators, the value M = 0.8 mo-can be selected as implementable with small deviations for a sufficiently large number of lamps. In addition, achieving values of M close to 1 leads to unjustified complication of modulation blocks and, as will be shown below, in all cases does not completely solve the problem. According to [127], nonlinear distortions in hearing aids are 4...6%.

For the selected value of M, we determine the signal spectrum for AIM radiation.

The component corresponding to the maximum value $\Omega\mu$ = 2.2 kHz has an amplitude equal to $\frac{}{Q}$ UOM and is attenuated in accordance with the radio sound threshold curve by 7 dB. For M = 0.8, the value of the constant level No. can be chosen equal to 0.5 to maximize the use of the dynamic range of the useful signal. The duty cycle, based on the commonly used pulse duration values in full-scale radio sound experiments, is about 10 μs and the pseudoresonance frequency is 10 kHz, has a value of 10. In this case, the $\frac{UOM\ Q}{}$ component will be attenuated by an additional 28 dB, i.e. its total attenuation is 35 dB.

Let us write down the condition for the formation of the signal spectrum in the AIM mode: at M = 0.8,

$$\lim_{\frac{\pi}{Q}\to\infty;\ \frac{\pi}{Q}\to 0} \frac{\sin\frac{M\pi}{Q}}{\frac{m\pi}{Q}} = 1,$$

which is true for sufficiently large values of O. The condition f = f'RES, where 'RES is the pseudoresonance frequency or the second coupling frequency, ensures the selection of the first harmonic of the pulse sequence.

It is known that in order to isolate the useful signal, i.e., the modulating function, the detector must contain a low-pass filter (LPF). Due to the fact that in the case under consideration, the range of frequencies perceived by a person in the form of useful information and the selected subcarrier are within the limits of physiologically perceived sound frequencies and cannot differ by more than an order of magnitude, then it is quite obvious that only the overtones of the subcarrier will be suppressed. The subcarrier itself must be “listened to” simultaneously with the perception of the modulating signal.

The process of filtering overtones can be represented by a decrease in the sensitivity of the auditory analyzer in the high-frequency region. Taking into account the limitation of the useful signal bandwidth, the 2fc, 2fc – 2, 2f + 2 components are attenuated by at least 40 dB (according to the radio sound threshold curve). Thus, questions related to the occurrence of combination frequencies, their assessment and determination of possible distortions during speech reception disappear.

In the presence of strong attenuation of the components of the spectrum of the AIM signal at t = 2, 3... due to the presence of HFGS through bone conduction, which formally plays the role of a low-pass filter [16], the spectrum of the AIM signal degenerates into the spectrum of the AM signal, which has the form:

$$U(1) = \frac{}{2}[0.5+ \cos fot +0.4\cos (fo +2)+0.4\cos (fo -\Omega)],$$

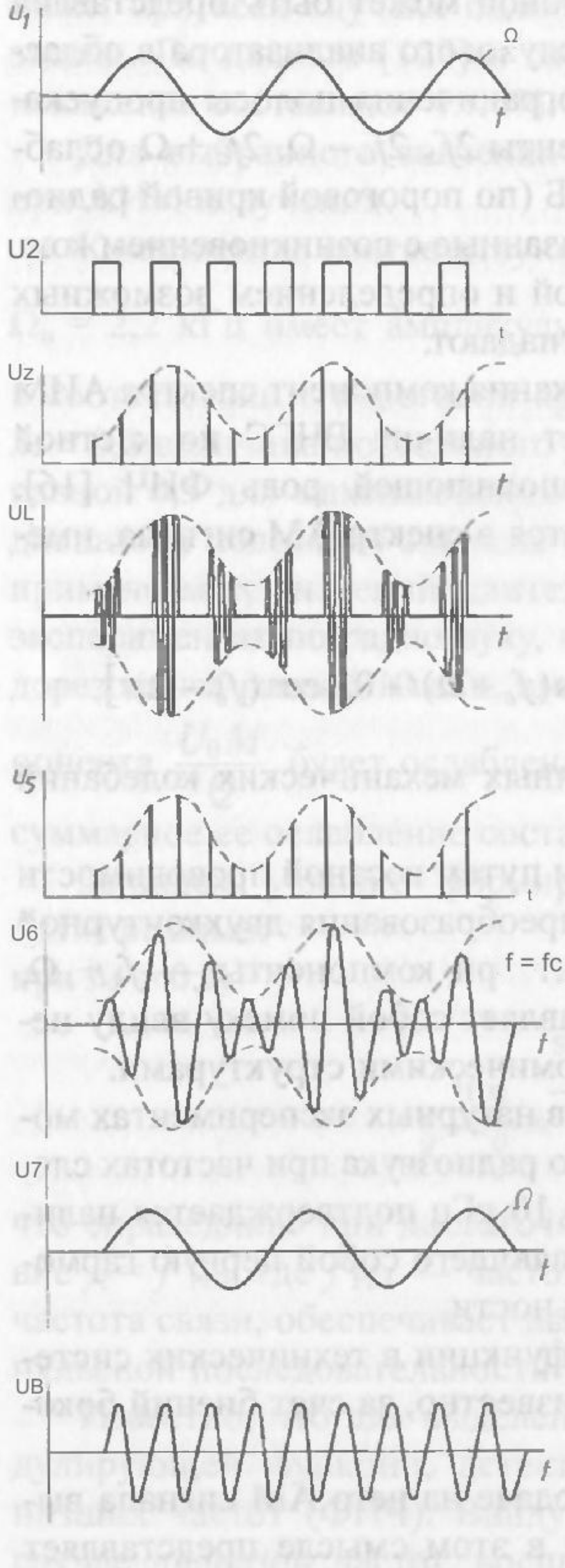
where f —— = fo frequency of excited mechanical vibrations at the pseudoresonance point.

The spectrum of AIM radiation perceived by a person through bone conduction after conversion by a two-circuit resonant system contains three components fe —+ Ω, fe - Ω, 6. Component b represents interference due to the impossibility of its rejection by anatomical structures.

Thus, the monotonality of perceived radio sound observed in field experiments at microwave pulse repetition rates above 10 kHz is confirmed by the presence of the Uocoswot term, which represents the first harmonic of the pulse sequence.

Isolation of the modulating function in technical communication systems is carried out, as is known, due to the beats of the side frequencies.

An auditory analyzer, when supplied with an AM signal, performs the same function [14] and in this sense is an analogue of an amplitude detector. This means that the presence in the signal spectrum of frequency components fe + 2, fe-2 will lead to the formation of a useful signal by the auditory analyzer, which is a modulating function. In Fig. 72 schematically shows the process of transmitting and receiving a message function in AIM mode.



U — message function — primary modulation

U2 - repetition rate of modulating pulses equal to the pseudo-resonance frequency - secondary modulation

U — pulse-amplitude modulating signal

U4 - AIM EMR microwave

Us — formalized detection function for the formation of thermal pulses in tissue

U_6 - excitation of amplitude-modulated mechanical oscillations in a double-circuit system with a frequency equal to the frequency of the EMR pulse sequence foc

U — of amplitude-time analysis — restoration of message function

Ia - frequency analysis - highlighting tone signal decreases with frequency frequency equal to the mechanical frequency ical fluctuations

Rice. 72. The process of formation of a modulating function in the auditory analyzer in AIM mode

Modulation index and spectrum of the perceived signal in PFM radiation mode. An increase in the bone conduction threshold in the high-frequency region also affects the formation of an FM signal; in the PFM mode, the amplitudes of the subcarrier and side overtones are attenuated by 40 dB or more in accordance with the radio sound threshold curve. This leads to a narrowing of the spectrum of frequencies perceived by radio sound and makes it pointless to expand the bandwidth of the useful signal.

Indeed, by using a low-pass filter with a cutoff frequency Fc < Ωμ at the transmitting end, one can ultimately obtain wideband D/FM with modulation indices tr = - -> 1, where Dc max Ω (s max, maximum) subcarrier deviation equal to 4 kHz; Ω - modulation frequency less than 2μ = 4 kHz. Such a solution to the issue, in addition to unused spectrum expansion, will lead to a narrowing of the useful signal band, i.e., as a result, to a deterioration in the characteristics of the entire communication channel as a whole. Therefore, it is advisable to take tr = 1, i.e. Afc max = Ωμ.

According to the graphs of the dependence of the Bessel functions on the modulation index [31] at tr = 1, we obtain: № = 0.77; J_1 = 0.44; J2 = 0.1; J = 0.02.

At 2000=00, Ω sin =1. $\frac{\pi}{\Omega}\to\infty;\ \frac{\pi}{\Omega}\to 0$ Kπ Q Kπ Q lim Q

and for M = 0.8 the resulting PFM radiation spectrum takes the form:

$$U(t)=U_0\left[1+1{,}23\cos f_c t-0{,}7\cos(f_c-\Omega)t-0{,}7\cos(f_c+\Omega)t+\right.$$
$$+0{,}08\cos(f_c-2\Omega)t+0{,}08\cos(f_c+2\Omega)t-0{,}016\cos(f_c-3\Omega)t+$$
$$\left.+0{,}016\cos(f_c+3\Omega)t\right].$$

Having normalized the amplitudes of the components relative to the component c, we obtain an expression for the PFM spectrum in the form:

$$U(t)=U_0\left[1+\cos f_c t-0{,}57\cos(f_c-\Omega)t-0{,}57\cos(f_c+\Omega)t+\right.$$
$$+0{,}065\cos(f_c-2\Omega)t+0{,}065\cos(f_c+2\Omega)t-0{,}013\cos(f_c-3\Omega)t+$$
$$\left.+0{,}013\cos(f_c+3\Omega)t\right].$$

The amplitudes of the last two terms are less than 5% of the amplitude and can be neglected. The o +22 πo- component is pressurized by more than 40 dB due to the presence of HFGS, the power of the fc-22 component is less than 1% of the subcarrier power.

As a result, we obtain a spectrum in the

form: U(t)=Uo [1+cosfet-0.57 cos (fc2)1-0.57cos (fc+2)], which is the spectrum of the AM signal.

Because in this expression, the subcarrier also represents the frequency of the excited mechanical vibrations. then we write the expression for the spectrum of the perceived AM signal in the form:

U(1)=Uo [1+cos fet-0.57cos (f. -Ω)1-0.57cos (f+2)].

As follows from this expression, in the absence of FM, the first harmonic of the pulse sequence is also isolated, i.e., a monotonal signal.

The introduction of additional FM pulses leads to the appearance of side components that form the useful signal.

The output AM spectrum, taking into account the frequency response K(1) of the pseudo-resonant section, will be described by the expression:

U(t)=K(fe)cosfet-0.57 K(fc2)cos(f-2)1-0.57 K(fc+2)cos(f+2)t.

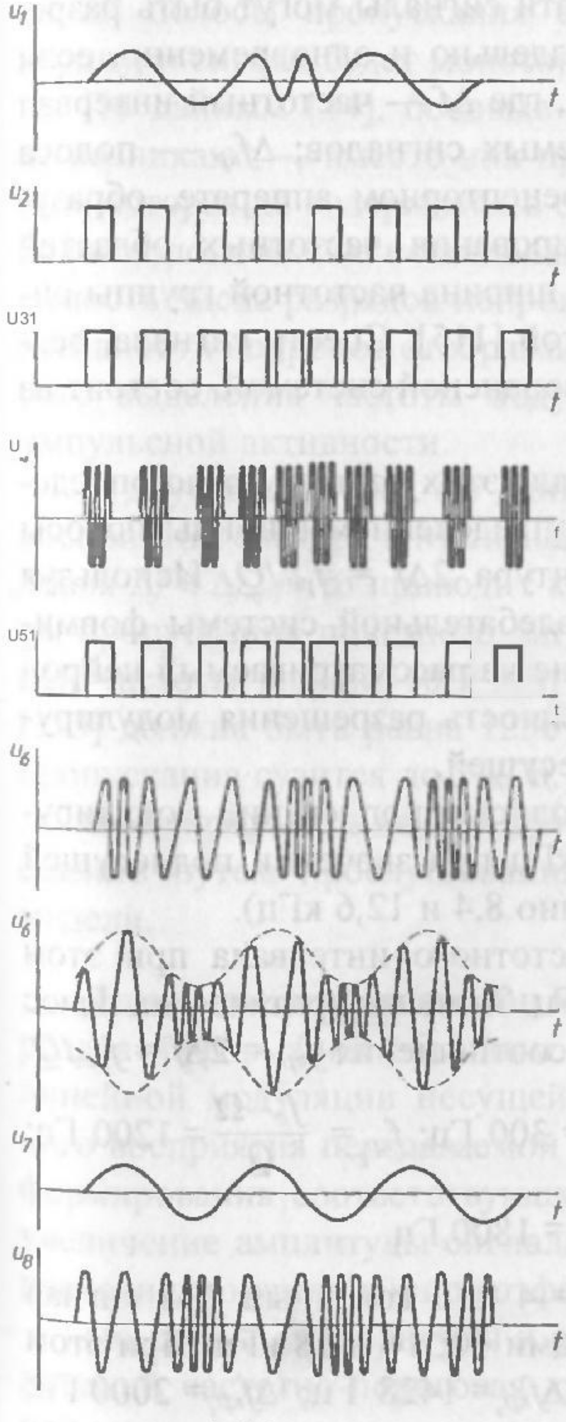
To determine the value of K for the components fo, fo - Ω H fc + 2, we determine the dynamic range of the modulation coefficient using data on the minimum audible AM signal [115]. For the above minimum required level of average pressure of the speech signal of the order of 40...50 dB, the required minimum value of M is determined by a value in the range of 0.055...0.045 at a frequency of 1 kHz. Taking M = 0.8 for the upper region of low frequencies (Imax/ min = 9), for the high frequency region for M = 0.045... ...0.05 we obtain Imax/U/min = 1.1. Hence, K(f) = 0.5, K(f - Ω) = 0.9 and K(f + 2) = 0.11 for 2 = Ωmax

The spectrum components will have the following amplitudes:

- subcarrier 0.5;
- first side - 0.513;
- second side —0.0627.

A similar type of conversion of a modulated FM- mixed — AM signal is considered in [29] and is called amplitude-frequency modulation.

In Fig. 73 schematically shows the process of transmitting, receiving and analyzing a message function in PFM mode.



U — message function — primary modulation

U2 — initial repetition frequency of modulating pulses equal to the frequency of the middle of the high-frequency slope of the pseudo-resonant section

From - pulse-frequency modulating signal

U4 - CHIM EMI

Us — formalized detection function for the formation of thermal pulses in tissue

U6; 6'- excitation of frequency-modulated mechanical oscillations in a double-circuit system with an average frequency equal to the initial repetition frequency of microwave pulses From the beginning conversion of FMAM on the high-frequency slope of the pseudo-resonance section

secondary detection in the auditory analyzer:

U — amplitude-time analysis - restoration of the message function

OV - frequency analysis, FM signal extraction

conductivity

Rice. 73. The process of formation of a modulating function in the auditory analyzer in PFM mode

Frequency resolution of the modulating signal and subcarrier. The presence of an unfiltered subcarrier signal in the resulting auditory sensation leads to the formation of a two-tone signal consisting of two sinusoidal oscillations of — subcarrier and modulating signal the signal.

According to [3, 14, 63, 64], these signals can be resolved, i.e., perceived separately and simultaneously, if the condition Af > Ducr is met, where Df is the frequency interval between the frequencies of the perceived signals; D/R — band of narrow-band "filters" in the receptor apparatus, formed as a result of the integration of frequency regions into frequency groups. In this case, the width of the frequency group is determined by the central frequency [115]. The spectrum of the signal realized by the equivalent resonant system consists of components №, fc, fc - Q u fo + Ω.

The excitation regions [64] for these frequencies can be determined using the classical definition of the bandwidth of the resonant circuit 24f = fpes/Q. Using the data [65] on the quality factor of the oscillatory system that forms the exciting effect on the neuron under consideration (Q = 7...10), we determine the possibility of resolving the modulating signal and the subcarrier signal.

In the AIM mode, the bandwidth of the modulating signal was 2.1 kHz with a subcarrier value of 10.5 kHz (side carriers were 8.4 and 12.6 kHz, respectively).

The minimum value of the frequency interval is equal to min = (f – Ω) – Ω = 6.3 kHz. The value of the critical bands at the level of 0.707 is determined from the relation vcr = 24f = fpe3/Q.

For Q = 7 we obtain kr, = 2/Q = 300 Hz; kr, = f- $\frac{\Omega}{Q}$ = 1200 Hz;

fxp=fc/Q = 1500 Hz; cr. = $\frac{fc+\Omega}{Q}$ = 1800 Hz.

For PFM mode at Df = 4 kHz, the final AM signal contains components with frequencies of 10; 14 and 18 kHz. In this case, D/min = 6 kHz; Dukr = 571 Hz; Dar = 1428 Hz; Dukr = 2000 Hz; Acre = 2570 Hz.

Comparing the obtained values of frequency groups with those given in [115], it can be noted that the use of physical

It is quite acceptable to use the Russian approach to determine this value. The resulting values of frequency groups are smaller than those given in [23]. This circumstance can be explained by the asymmetry of the resonance curves of the localization points of displacements of the main membrane of the cochlea.

Thus, the signal bandwidths determined from physical representations form a frequency group; and the signal will be monotonic.

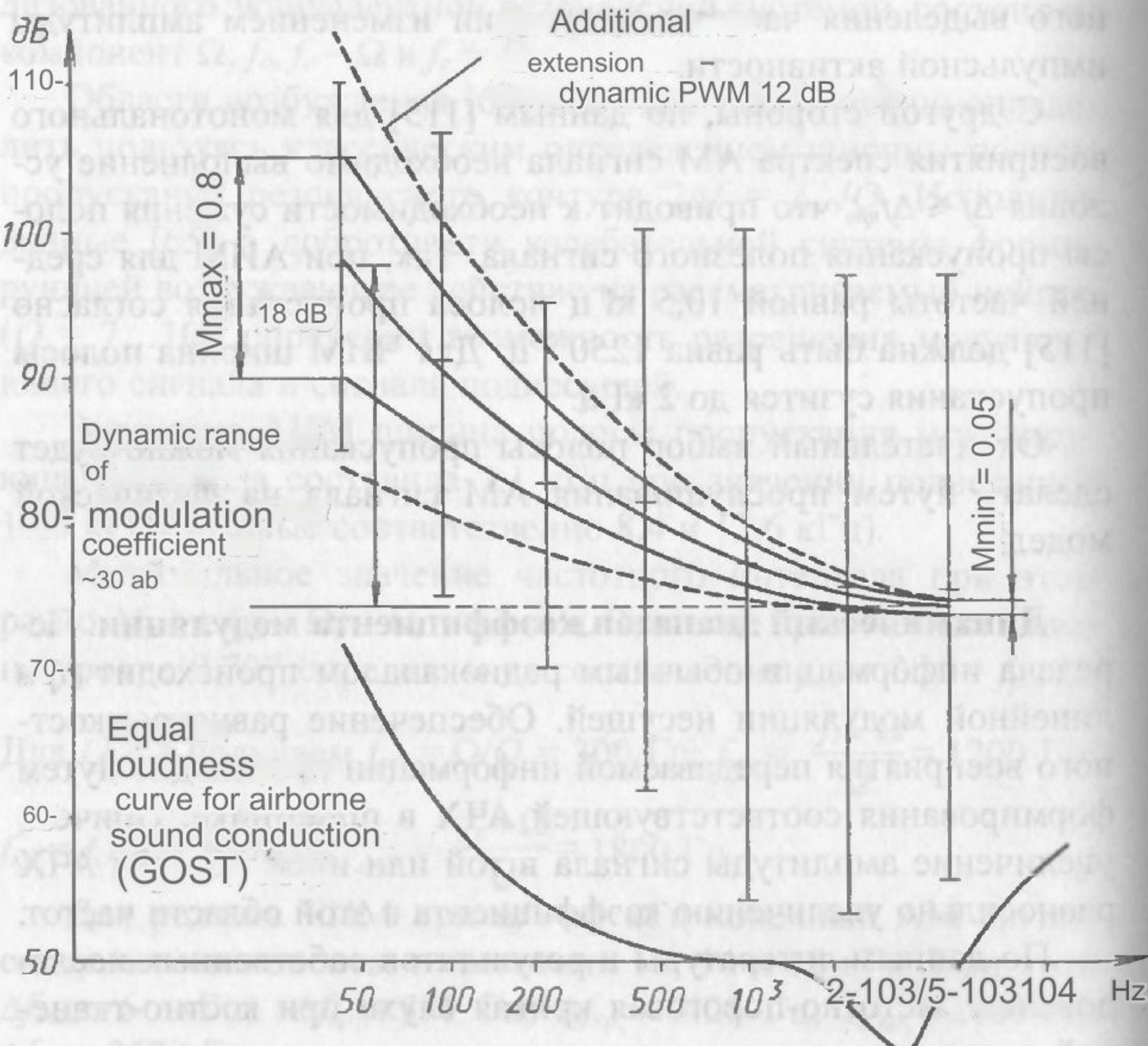
According to [14], side spectral bands never appear; instead, the — modulation frequency is traced, which is not contained in the signal spectrum. Data from electrophysiological studies show a direct dependence of the number of neuron discharges on the carrier frequency, and the pattern of neuron activity reflects the possibility of directly identifying the modulation frequency by changing the amplitude of impulse activity.

On the other hand, according to [115], for monotonal perception of the spectrum of an AM signal, the condition Af / kr must be met, which leads to the need to narrow the bandwidth of the useful signal. Thus, with AIM for an average frequency of 10.5 kHz, the passband according to [115] should be equal to 1250 Hz. For PFM, the bandwidth will narrow to 2 kHz.

The final choice of bandwidth can be made by listening to the AM signal on a physical model.

Dynamic range of modulation coefficient. The transmission of information via a conventional radio channel occurs with linear modulation of the carrier. Ensuring equal-loudness perception of the transmitted information occurs by forming the appropriate frequency response in the receiver. Moreover, an increase in the signal amplitude in one or another frequency response region is equivalent to an increase in the coefficient in this frequency region.

According to the literature and the results of our own research, the frequency-threshold hearing curve for bone-tissue conduction is also uneven, i.e., in this case, correction of the frequency response of the receiver is necessary. In case of excitation of the auditory sensation when absorbed by the tissues of the head energy of pulse-modulated microwave EMR, i.e., with the formalized reception of information by the anatomical structures of the head, the structure of such a receiver is rigidly specified. Consequently, equal-loudness reception of information through bone-tissue sound conduction during bionic reception is possible only by forming an appropriate frequency response in the modulation path of the transmitter, i.e., there is a need to implement a frequency-dependent modulation coefficient. In this case, the dynamic range of the modulation coefficient is set by the magnitude of the rise in the perceived signal in the transmitted frequency band relative to the minimum threshold point on the equal loudness curve for bone-tissue conduction.



Rice. 74. Averaged curve of equal volume during bone-tissue conduction

In accordance with defined in paragraphs. 6.2.2 and 6.2.3. the maximum value of the frequency band of the transmitted signal is equal to 4.4 kHz and using the data [7, 62, 82, 95, 129, 134, 180] it is possible to determine by calculation the averaged curve of equal loudness for bone-tissue sound conduction (Fig. 74).

The maximum rise in the low-frequency region of this curve relative to the frequency of 4.4 kHz is approximately 30 dB.

Using the data [115] on the curves of the minimum audible AM signal and their parallelism to the curve of equal loudness during air conduction of sound, as well as the unified mechanism of vibration of the cochlea during air and bone conduction of sound [138], the resulting curve of equal loudness during bone-tissue conduction can be considered as curve of the minimum audible AM signal.

According to the values of Mmin and Mmax defined in paragraph 6.2.3, the dynamics The mic range of M is only 18 dB, which does not allow the implementation of an equal-loudness curve of the final AM signal.

An additional increase in the modulation depth at lower frequencies can be achieved using either the dependence p = f(Pu) [92], i.e., by selectively increasing the pulse power, or the dependence p = f(Ti) [92, 206] - by increasing the duration of EMR pulses, where p is the variable sound pressure developed by mechanical vibrations excited in the tissues of the head.

The first solution is technically simpler, but it is not applicable in PFM mode. With an increase in the pulse duration within 0 < ω < 1/2, where the period of excitation of mechanical vibrations is observed, an increase in the amplitude of sound pressure is observed to a certain maximum value. Character this dependence is determined by the relation Ax = 2sin $\frac{\Delta\varphi}{Ao}$ [37], where Ax is the amplitude of the resulting oscillation; — 2 is the oscillation amplitude of the thermal pulse developed by the fronts; DF is the phase shift between oscillations excited by the leading and trailing edges of the thermal pulse and is proportional to the pulse duration. The solution of this Equation for the value of the phase shift, expressed in do-

For the period of excited oscillations in the range of 0...1/2, the dependence is close to linear, which is confirmed in [135], indicating that the relation Ti Pu = const is preserved within the range 0 < Ti < 1/2. The additional expansion of microwave EMR pulses for low-frequency components of the AM signal should be about 12 dB.

Duration of EMR pulses. As shown above, the frequency of resonant oscillations in real conditions can vary from approximately 7.5 to 10 kHz, i.e., the maximum pulse duration during AIM cannot exceed 50 μs. In

PFM mode at f=14 kHz (pulse repetition period is 70 μs), the maximum possible value of the pulse duration is 35 μs. With tu = 1 and subcarrier deviation equal to 4 kHz, the maximum pulse repetition frequency reaches 18 kHz (Tsl = 55 μs) and the pulse duration pulses cannot exceed 27.5 μs.

Having determined the upper limit of the pulse duration for both types of modulation, we can consider a single method for implementing an equal-loudness AM signal curve. butt

As a measure to form an equal-loudness curve, it is possible to introduce additional pulse-width modulation (PWM) in both radiation modes. In this case, it is necessary to consider the conditions for choosing the initial pulse duration. In accordance with the AM audibility threshold curves, the minimum value of the pulse duration must correspond to the frequency range 1...4 kHz.

The choice of the microwave pulse duration at a given repetition rate should be dictated by the following considerations:

1. The cost-effectiveness of the communication channel transmitter, which requires the minimum possible pulse duration values realized by technical means to achieve high duty cycle values and, accordingly, low values of the average level of power consumption.

2. A sufficient amount of pulse energy necessary to excite mechanical vibrations in the anatomical structures of the human head with an amplitude sufficient for their perception.

3. The need to provide more or less safe radiation doses determined by low values of the average level of absorbed power by the tissues of the human head.

4. The width of the emitted frequency spectrum and, accordingly, the choice of values of the carrier frequency of the communication channel.

Points 1 and 3 predetermine radiation with a minimum duration. On the other hand, as shown in [160], short pulses of the order of fractions and units of microseconds lead in full-scale experiments to the absence of the perception of radio sound at a given pulse power. In the model experiment, the amplitude of the sound pressure drops almost proportionally to the decrease in the pulse duration. In this case, to restore the perception of the effect, an increase in the pulse power is required in inverse proportion to a decrease in its duration.

In a full-scale experiment, the choice of pulse duration is also related to the level of ambient noise, masking the effect of radio sound.

Thus, the first three points are quite contradictory. Point 4 in this case has virtually no effect on the choice of communication channel parameters due to the low value of the quality factor.

ity of the primary circuit.

Taking into account the dependence $A_1 = f(ti)$, the choice of the initial value of the pulse duration will be determined by the dynamic range of the modulating signal.

In this regard, in order to create a single functional block for the formation of microwave pulse duration for both types of modulation, it is possible to take Timax = 25 μs, taking into account possible distortions in the pulse signal conversion paths. In accordance with the need for additional signal boost in the lower frequency region of the order of 12 dB, the minimum or initial value of the pulse duration is 6.5 μs when PWM is turned on. Without PWM, the Pulse Duration value for the AIM and PFM modes is assumed to be 10 μs. In the PIM mode, due to the absence of restrictions on the minimum required sound pressure level and in order to reduce the average PPM value, the pulse duration is chosen to be 5 μs.

EMR pulse power. It was shown in [95, 96] that the minimum threshold for the occurrence of the radio sound effect was 0.3...0.6 W cm2 at a pulse repetition rate of 3.5 kHz with a pulse duration of 10 μs and an ambient noise level of 40...60 dB. To reduce noise, anti-noise inserts “Earplugs” were used, which made it possible to reduce the bone conduction threshold by 10 dB and had an anti-noise efficiency of about 20 dB in a frequency band of 8 kHz. It can be assumed that the equivalent masker level is 40 dB (with an initial level of 60 dB).

From Fig. 74 it can be seen that at a stimulus frequency of 3.5 kHz, the threshold for bone-tissue conduction is 30 dB higher than the threshold for air conduction, i.e., the sound pressure level of oscillations excited by microwave pulses in the tissues of the head, compensated by the masker, should be 70 dB (6.32-10-dyne cm² relative to the threshold of 210-4 dyne cm-2). Since information is transmitted at a subcarrier frequency of 10 kHz, at which the hearing sensitivity threshold by bone conduction is 5 dB lower relative to the threshold at a frequency of 3.5 kHz, then the threshold value of the sound pressure level of excited mechanical vibrations at a frequency of 10 kHz will be 60 dB (2-10-1 dyne cm 2) at a threshold PPMi = 0.1 W cm 2.

Studies of auditory sensations in a full-scale experiment during irradiation of the human head with microwave EMR pulses with a duration of 5...20 μs and a frequency of 4...1000 Hz showed an increase in the threshold at lower frequencies relative to a frequency of 10 kHz of the order of 14 dB.

Taking into account the reduction of the threshold by 10 dB as a result of the use of earbuds, one can note a very good agreement between the rise in the threshold in the LF region for radio sound (24 dB) and for the calculated curve of equal loudness of bone-tissue conduction (23 dB). On average, the increase in the threshold of the resulting calculated equal loudness curve over a similar curve for air conduction in the 4 kHz baseband is 28 ± 4 dB.

In accordance with the required minimum value of the sound pressure level of the speech signal required for its perception by air conduction it is equal to 40...50 dB, with bone-tissue conduction this value can be taken on the order of 70...80 dB. Thus, to obtain a sound pressure of up to 2 dyn cm² at a pulse repetition frequency of 10 kHz, the required value of PPMi = 1 W cm-2.

The obtained value of sound pressure at a given value of PPM agrees well with the data of [201] - - the calculated value of sound pressure is 2 dyn cm 2 at an irradiation intensity of 1 W cm carrier 918 MHz.

Comparison of the obtained sound pressure levels of the speech signal during bone-tissue conduction with the data presented in Fig. 69-71 allows one to estimate speech intelligibility during bionic reception within the range of 57...90% at a sound pressure level of 70...80 dB.

According to [132], when a sphere with parameters close to the parameters of brain tissue is irradiated by a plane wave, focusing of electromagnetic energy by the sphere is possible under the condition a ≤ 0.3a, where — a is the radius of the sphere; d wavelength. For the frequency range 915...2400 MHz (= 33...12 cm) considered here, this condition is not met, i.e., there is no focusing at a = 9 cm. Under these conditions, the irradiation cross-sectional area will be determined by the cross-sectional area of the sphere.

With the cross-sectional area of an adult's head at the level of the forehead on average equal to 250 cm², the power per pulse will be 250 W [132]. When ultrasonic signals act on head tissue, the signal level required for perception is determined to be 87 dB [159].

Thermal loads. The issues of microwave EMR absorption and the distribution of thermal fields in biological structures represent an independent problem and are considered in the literature using the example of various models [34, 46] and experimental data [73, 74]. The data on the electrical and thermal characteristics of biological objects presented in [21, 118, 132] indicate the extreme difficulty of correctly solving this problem due to the rather large scatter of parameter values for different biological tissues, on the one hand, and, on the other hand, due to the presence of a large number of tissue layers with different characteristics. Therefore, when solving such problems, as a rule, some layers are not taken into account due to their insignificant contribution to the overall picture of heat distribution, or due to their high thermal conductivity. For example, when calculating the absorption of microwave EMR energy in [74], absorption in subcutaneous adipose tissue is not taken into account due to its small thickness on the skull, and in the bones of the skull, due to the fact that the thermal conductivity of bone is almost an order of magnitude higher than the thermal conductivity of fat [21]. In [46], a flat two-layer model containing fat and muscle tissue is considered.

The work [118] shows that in the absence of taking into account the skin, with increasing thickness of the subcutaneous adipose tissue, the proportion of microwave EMR energy absorbed by tissues varies widely. At the same time, with a small thickness of the layer of subcutaneous adipose tissue, which is the case in our case, failure to take into account the presence of skin leads to an error in determining the absorbed EMR energy within the range of 5...20% at frequencies 1...3 GHz.

An analysis of these works shows that with a thickness of subcutaneous adipose tissue on the skull of about 1 mm, about 5% is absorbed in the skin and 1% in adipose tissue — of the total heat generated during irradiation of a multilayer structure. The remaining 94% of heat is generated in muscle tissue. As a result, in the case considered here, due to the small thickness of the intermediate layers between the skin and brain structures and the weak absorption of EMR energy in them, for a rough assessment of the absorption pattern it could be assumed that with the exception of 6% of of all the absorbed power, all the heat is released in the structures of the brain. According to [165], the wavelengths in brain tissue and adipose tissue at frequencies of 1...3 GHz are almost the same (12.63 and 12.42 cm at a frequency of 1 GHz, 3.97 and 3.79 cm at a frequency 3 GHz), which indicates that the values of ϵ are close for these types of tissues. That is, it can be assumed that when EMR energy propagates through these layers, there will be no significant reflection of energy. At the same time, due to the difference in electrical and thermal

Due to the physical characteristics of adipose and muscle tissue, a large amount of heat is released at their boundary.

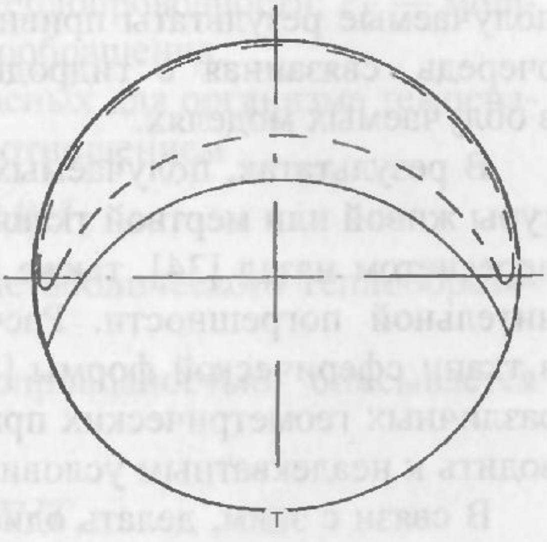
Thus, the pattern of heat distribution in a multilayer absorbing structure depends not only on the absorbing properties of each layer, but also on the ratio of these properties in different layers. Therefore, to determine the field distribution pattern, the method of various models is often used—both disassembled [34, 109] and integral phantoms [58, 59].

If we neglect the absorption of energy in thin layers of skin and subcutaneous fat, we obtain a homogeneous model with cooling of the heated area due to blood flow, since the brain is penetrated by a dense network of blood vessels.

The possibility of representing this particular multilayer structure using a homogeneous spherical model is supported by a comparison of the data obtained in [103] on the distribution of the electric field in a homogeneous spherical liquid model with the data from [58, 59].

According to data [132], in the case under consideration there should be no focusing of electromagnetic energy, which is confirmed by the results of research and data from works [58, 59]. Calculations performed on a computer [142] showed that when simulating irradiation of a multilayer spherical model of a human head with microwave EMR with a frequency of 1 GHz, no focusing is observed when a plane wave is incident on the front part. That is, in these cases, the absorbing volume can be approximately determined by the isotherm method, provided that the absorbing cross section is equal to the geometric tric section of the head. In Fig.

Figure 75 shows the microwave EMR absorption region in the sphere, constructed taking into account the data from [34, 109, 132]. The dotted line shows the EMR absorption region obtained



Rice. 75. Determination of absorbing volume using the isotherm method

calculated using a computer calculation method [109]. This work emphasizes that absorption at the center of the sphere is very small. Qualitatively, both absorption regions coincide. The quantitative difference can be attributed to the difference in taking into account the dielectric properties of the tissue layers captured during the absorption of EMR.

Similar results were obtained in works [58, 59] on phantoms (sawdust moistened with saline solution) and on living animals and corpses. When irradiating the heads of rabbits and dogs in the temporo-parietal region, the temperature under the skin and in the muscle layer and in the brain was measured. Irradiation was carried out at a frequency of 460 MHz. With increasing depth of the layer in which the temperature was measured, the tissue heating decreases exponentially.

The power flux density used by the authors of these works is in the range of 0.4...2.0 W cm-2. Thus, the effect of microwave EMR on a multilayer anatomical system, such as the head, can be quite well described by the effect on a homogeneous spherical system.

At the same time, work [34] provides thermograms of artificial brain tissue, from which it follows that in a sphere with a radius of 7 cm at microwave EMR frequencies equal to 918 and 2450 MHz, focusing takes place, which naturally should be taken into account when calculating thermal characteristics. However, in this case, as in all those described earlier, it can be noted that an error is introduced into the results obtained, primarily associated with hydrodynamic instability in the irradiated models.

In the results obtained by direct measurement of the temperature of living or dead tissue after irradiation and then recalculating it back [34], the presence of additional error is also inevitable. Calculations of the electric field in spherical tissue [88] are based on the consideration of various geometric approximations and can also lead to inadequate conditions for heat distribution.

In this regard, it is not possible to draw an unambiguous conclusion about the heat distribution pattern in the original at the level of the results of modern research.

The determination of thermal loads was carried out on the basis of ideas about the distribution of absorbed microwave EMR energy in the tissue volume obtained using isotherms (Fig. 75).

According to data [9, 43, 123], the diameter of capillaries in the cerebral cortex is 6...8 μm, the total length is 1120 km [96, 208] with an average capillary density of 1400 mm per 1 mm³ of the medulla [57, 158, 208]. The total volume of blood in the capillaries, taking into account the volume of blood in the veins, is approximately 150 ml. With a total blood flow velocity through the vertebral and carotid arteries of about 750 ml [9], the second blood flow rate will be 12.5 ml. Thus, it takes 12 s to renew the entire volume occupied by blood.

Taking into account reflections, the average value of specific absorption Noal power (UPM) will be determined by the value UPMSR = $\frac{K\ Fig}{VQ}$ provided there is no leakage of released heat, where K = 0.5±0.1 [41]; — volume in which electromagnetic energy is absorbed; 2 — duty cycle.

In the general case, the temperature rise in the tissue is determined by the expression [21]:

$$\frac{\Delta T}{\Delta t} = \frac{1}{4200}(\text{UPMSR} + \text{RM-R-Rk}),$$

where is the absorbed power, taking into account the duty — cycle; PM metabolic heat generation power; PT — power dissipated due to thermal conductivity; RK — power-waste removed by the circulatory system.

Within the range of temperatures safe for the body, the value of Pm is described by the relation

$$\text{RM=P(1,1)47},$$

where Ro is the initial power of metabolic heat generation.

The term due to thermal conductivity is described by the expression:

$$P_T = \frac{K_T}{P}\nabla^2 T,$$

where Kt is the thermal conductivity of the fabric; ∇ gradient operator.

If blood enters the heated area at temperature T, and leaves it at temperature T2> T1, then the value

$$P_K = K\frac{mC_K}{\rho_K}\Delta T,$$

where — K is a constant equal to 0.689; m blood flow speed; Sk - specific heat capacity of blood; pk - blood density.

Since a noticeable expansion of blood vessels occurs at a temperature of 42...44 °C, which leads to an increase in blood flow velocity, the introduction of a quadratic term into the heat conduction equation [46] can be considered justified only at large exposures (naturally, within the limit - lah safe doses of microwave EMR energy). This point is reflected by a linear section on the temperature dependence of the irradiated tissue area on time [21] for exposures not exceeding 3 minutes (within the limits of microwave EMR energy doses 50 <.UPL < 170 W kg-¹).

For a linear section, the following expression is valid:

$$\frac{DTUPMCP}{\Delta t} = \frac{}{4200}.$$

For the pseudoresonance point in the AIM mode, the repetition frequency is 10 kHz. With an average pulse duration of 10 μs (with a weight ratio of frequency components in the transmitted frequency band of the order of 3:1 [108]), the duty cycle is 10.

Taking into account the penetration depth of microwave EMR at a frequency of 1 GHz [34] and constructing the absorption cross section of microwave EMR in tissues according to the described model, we can estimate the absorbing volume as 500 cm 3. In this case, the calculated average value of the UMSSR will be 25 W kg-1. From here

$$\frac{AT}{\Delta t} \text{-=6-10-3 deg-s.}$$

According to [108], with single-channel communication, taking into account pauses between words and sentences, the subscriber occupies the channel on average for 75% of the total transmission time, i.e. for intermittent AIM UPMSR = 18.75 W kg-1 and DTIΔI = 4 .5-103 deg-s-1. The average value of the thermal load is determined from the correspondence wearing:

PMSSR = K Risr,
S.Q.

where K-is the reflection coefficient equal to 0.5±1; Risr is the peak power value of the microwave EMR pulse equal to 250 W; — S absorbing cross-sectional area equal to 250 cm²; 2 - duty cycle equal to 10.

For the first and second AIM modes, the thermal loads will be 50 mW-cm2 and 37.5 mW-cm-2, respectively.

In PFM mode with a duty cycle of 7, UMSP = 35.7 W. kg-¹, AT/A1 = 8.5·10-3 deg and PMSSR = 70 mW- cm 2.

In the code transmission mode at Ti= 5 μs at a pulse repetition frequency of 10 kHz, taking into account the threshold value of pulse power at this frequency equal to 0.1 W cm-2 with an external noise level of 40...60 dB, using 75 % of the total operating time of the communication channel, we obtain UPMSR = = 0.93 W. kg-¹, AT/A = 0.22-10-3 deg-s and PPMSr = 1.7 mW-cm-2.

In the code transmission mode, the need to ensure a high sound pressure level is reduced, and the probability of correct signal recognition is entirely determined by the level of the interference signal, i.e., external noise. In the limiting case (No. 2=0), according to [176], the pulse threshold power is reduced to 3 μW cm2, i.e., the total power of the incident wave will be 750 μW. This circumstance in some cases may become decisive when choosing the type of information transmitted.

Extremely small values of the MPP are also given in [81]. In the USSR, according to GOST 12.1.006-84, in the frequency range 300 MHz...300 GHz, with total irradiation of the human body, the permissible energy load is 200 μWh. cm-2 or 12 mW-min cm 2, which corresponds to a UMSR of 0.4 W. kg-1. The given value of absorbed power is considered safe and is taken with a 10-fold margin [30, 109].

According to the same work, in the USA, starting from 1982, a new standard for maximum permissible exposure levels (MALs) introduced by the American National Institute of Standards (ANIS) has been in force, according to which in the frequency range 0.3... The 1.8 GHz PMSSR increases linearly from 10 to 50 W cm-2 and then remains at this level up to a frequency of 100 GHz. OBORSE

Thus, according to ANIS standards, the values of PMSSR obtained here for irradiation of the head can be considered close to safe. Moreover, it must be remembered that both ANIS standards and GOST 12.1.006–84 provide for total body irradiation. If a part of the body is irradiated, a higher rate is considered acceptable.

The old ANIS standard, adopted in 1966 and in force until 1982, provided for PMSSR = 100 mW cm2. In this case, heating of the irradiated body area did not exceed 1 °C [109]. Based on the given figures, it is possible to determine the safety long time of irradiation of the human head with the following values: ◇ AIM mode without pauses - - PPMSR = 50 —mW. cm-2 2.4 min; ◇ AIM mode with pause - PMSSR = 37.5 mW-cm² - 3.2 min;
◇ PFM mode - PMSSR = 70 mW cm-2 — 1.7 min;
+ PIM mode - PMSSR = 1.7 mW cm-2 —70 min.

According to the given MRLs, the danger of thermal damage to the body during total irradiation begins at 4 W. kg-1. The given calculated value of the UMSSR for irradiation of the human head is:

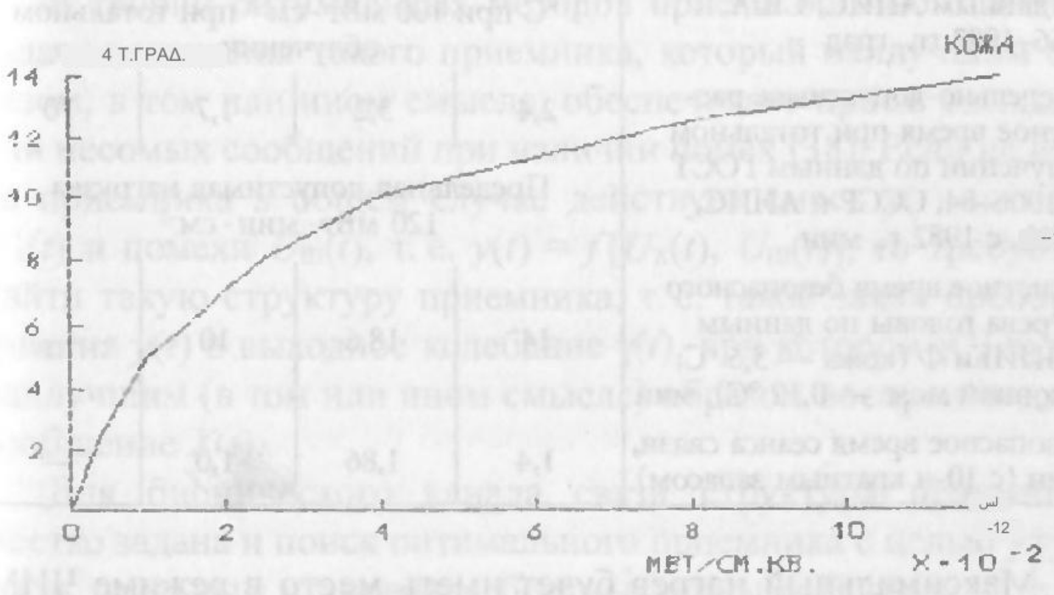
◇ AIM mode without pauses - 25 W - kg-1.
◇ AIM mode with pause - 18.75 W kg.
◇ PFM mode - 35.7 W kg.
◇ code mode - 0.93 W. kg.

With the exception of the last mode, the remaining three numerical values of the UMSSR are several times higher than the maximum permissible level for total body irradiation. We can assume that the value is 4 W. kg - obtained taking into account the heat production of the whole body and exceeding it can lead to thermal overload of the body. And although the works [109, 206] indicate the use of PPMs of up to 40 and 50 W cm³ in full-scale radiosound experiments, the obtained calculated values of the SPMSR apparently cannot be considered absolutely safe even when individual parts of the body are irradiated. On the other hand, if at 100 mW-cm-2 the heating of the irradiated area reaches 1 °C, then with the calculated values of PMSSR heating of head tissues during irradiation with microwave EMR pulses even in the most unfavorable case (CHM mode, PMSSR = 70 mW cm-2 2) should lead to tissue heating by 0.7 °C, which cannot be considered dangerous to humans. 11 001 totals od plant mote in some ass

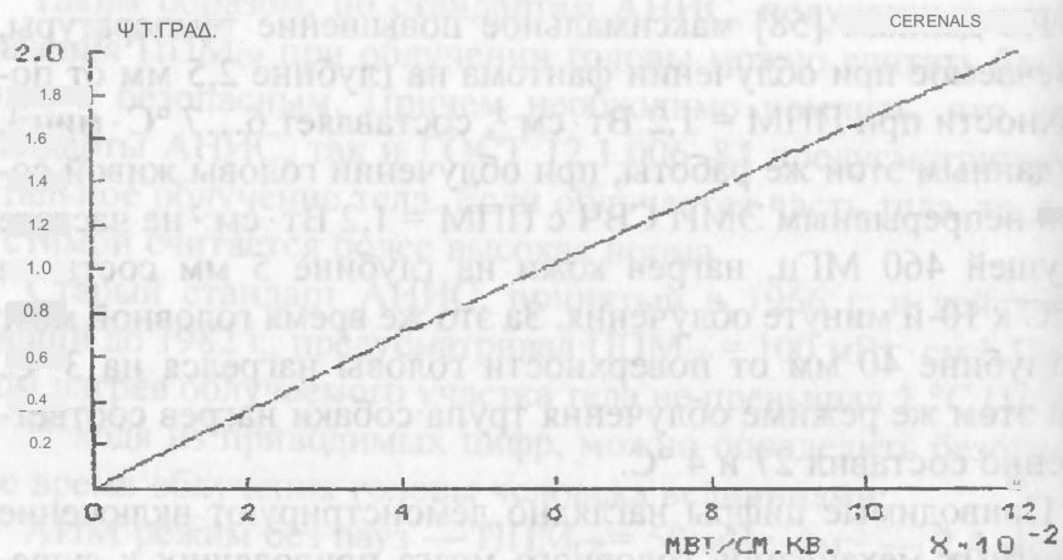
According to [58], the maximum temperature increase observed when the phantom is irradiated at a depth of 2.5 mm from the surface at PPM = 1.2 W cm2 is 6...7 °C min-1. According to the same work, when the head of a living dog was irradiated with continuous microwave EMR with PPM = 1.2 W cm2 at a carrier frequency of 460 MHz, heating of the skin at a depth of 5 mm was 14 °C by the 10th minute of irradiation. During the same time, the brain at a depth of 40 mm from the surface of the head warmed up by 3 °C. With the same irradiation mode of the dog's corpse, the heating was 27 and 4 °C, respectively.

The given figures clearly demonstrate the activation of the protective mechanisms of the brain leading to a significant inhibition of the rate of increase in the temperature of the head tissues. Moreover, this inhibition is carried out not only due to the functioning of the blood — flow by increasing the speed of local blood flow, but also by the inclusion of an additional heat removal system [135]. It can be assumed that such specific points may not have been reflected in the PDU standards.

According to the data of [58], using the interpolation method on the Iskra-226 computer, the dependences of the temperature increase on the PPM for an exposure of 10 minutes were constructed (Fig. 76, 77), using which it is possible to determine the heating of the skin and brain for the calculated PPM values in different irradiation modes.



Rice. 76. Dependence of temperature increase on MRP in 10 minutes (scalp) tavdaliyah mote



Rice. 77. Dependence of temperature increase on MRP in 10 minutes (brain).

Table 14

Thermal loads

Load / Mode	AIM without pauses	AIM with pause	ЧИМ	Pim
UPM, W - kg $^{-1}$	**25**	18.75	35.7	0.93
AT/D, hail from 10-3	6.0	4.5	8.5	0.22
PPM, mW cm $^{-2}$	**50**	37.5	**70**	1.7
Heating of the body surface according to ANIS data, USA, 1966-1982, degrees	0.5	0.7	0.017	0.375
	1 °C at 100 mW cm² with total irradiation			
Maximum permissible estimated time for total irradiation	2.4	3.2	1.7	**70**
according to GOST 12.1006-84, USSR and ANIS, USA, since 1982, min	Maximum permissible load 120 mW min cm $^{-2}$			
Estimated time for safe heating of the head according to TsNIIKI F — (skin 3.6 °C, brain - 0.12 °C), min	**14**	18.6	**10**	—
Safe communication session time, min (with a 10-fold margin)	1.4	1.86	1.0	—

The maximum heating that will occur in the PFM mode will be 3.6 °C for the skin, 0.1...0.12 °C for the brain. At the same time, the increase in skin temperature at the initial temperature of a normally functioning organism, taken to be 36.6 °C, does not yet lead to protein denaturation.

The obtained safe communication session time does not take into account the possible heating of local areas, the temperature of which may be significantly higher than the given values. In addition, the effect of pulsed microwave EMR on brain structures has not been sufficiently studied. The calculated values of thermal loads are summarized in table. 14.

6.3. Noise immunity of the bionic communication channel

The noise immunity of a communication channel is generally determined by the modulation coefficient and the power levels of the information carrier and ambient noise. When calculating the noise immunity of a bionic communication system, additional properties of the auditory analyzer such as masking, two-tone suppression [146] and the dependence of speech recognition on observation time and signal level must be taken into account.

One of the main tasks when assessing the noise immunity of a bionic communication channel is the correct determination of the nature and intensity of interference, both external and internal.

In the theory of optimal reception methods, the problem is usually set of finding a receiver that best, in one sense or another, ensures the reception of signals or carried messages in the presence of interference [38]. If at the receiver input in the general case there is a mixture y(t) of the signal Ux(t) and interference Ush(t), i.e. y(t) = f[Ux(t), Um(t)], then it is required to find such a structure of the receiver, i.e., such a law of transformation y(1) into the output oscillation γ(1), in which y(1) will best (in one sense or another) reproduce the message X(t).

For a bionic communication channel, the structure of the receiver is rigidly specified and the search for an optimal receiver in order to improve the real one becomes pointless. In this regard, we can only talk about assessing its parameters during AIM and PIM and comparing them.

The high pulse power at the receiving end makes it unlikely that interference may arise as a result of modulation of the pulse amplitude by an external signal [31].

When calculating the noise immunity of receiving devices with two demodulation stages, it is advisable to present the overall gain factor as a product of two coefficients, each of which characterizes the noise immunity of one of the stages. For a bionic communication channel, at a high level of the signal acting on the equivalent input circuit, the interference power is many orders of magnitude lower and therefore we will consider only interference to the second demodulator. Moreover, since both with AIM and PFM radiation an AM signal is isolated at the output of the second demodulator, the noise immunity calculation must be carried out for the AM signal.

An analysis of modern ideas about the mechanisms of hearing shows that the transfer of criteria for assessing the noise immunity of technical communication channels to an auditory analyzer without a corresponding transformation of these criteria is impossible. The fundamental difference between filtering the frequency components of a signal by hearing mechanisms is the simultaneous perception of signals with different frequencies and their further processing in various equivalent filters with different critical bands. Moreover, to highlight components that are not present in the signal spectrum. The auditory analyzer carries out preliminary amplitude-time analysis of the signal and then simultaneous time analysis of the two-tone signal, i.e., the frequency components of the signal according to this model are isolated as a result of the current autocorrelation analysis of the signal at the periphery of the auditory system [3].

Work [3] considers the issue of noise immunity when determining the azimuth of a signal source and qualitatively assesses the nature of signal and noise transformations by the periphery of the auditory tract. In this case, the sum of the signal and external additive noise is presented in the form of a nonstationary random function of time, which describes the change in the volumetric displacement of the base of the stapes - p(-1-). Under certain conditions, this function has the form:

R.2(1,0) = S(1,0) + 1,2 (1) + nî,2(t),

where 1, 2 are indices indicating the right and left halves of the auditory tract; — S1,2(1, 0) signal component of pressure (completely deterministic function); 71.2(t)— external noise component of pressure (broadband random process with zero mathematical expectation); ท.2(t) own noise of the stapes, caused by fluctuation tensions of the muscles of the middle ear. This expression echoes the generally accepted one for the case of additive noise in the theory of noise immunity:

$$y(t) = U_x(t) + U_ш(t),$$

where Ux(t) is a useful signal that carries a message and is known exactly; Um(t) is interference.

But the auditory analyzer, unlike a conventional receiver, performs a spectral transformation over a mixture of signal and noise, and the signal S(1) equivalent to Ux(t) and carrying a message, in the general case, should be considered as noise after filtering the message X(1) in the amplitude-time analyzer.

In the general case, the integral effect of all interfering noise sources is characterized by suprathreshold intensity, but it will not yet correspond to a sound image localized in a certain area of the “displaying space”. In this particular case, the total noise will consist of the sum of terms U(1) + n(t), where U(t) is the — subcarrier signal, considered in the form of interference localized within the subjective sound space and together with the transmitted message X (t) representing a fused sound image, and n(t) is the result of the influence of a sum of independent interfering sources randomly distributed in space. Here, apparently, the task of localizing a subjectively perceived sound complex image, consisting of two signals U(t) and X(t) and noise (1), should be considered, i.e., it is necessary to consider the processes of isolating components from a complex sound signal and the formation by neural networks of two independent (incoherent) signals, creating a complex subjective image of the “displaying space”. The noise background (1), evenly distributed in subjective space, is apparently not perceived by a person due to adaptation. The intrinsic noise of the stapes (1) is neglected in comparison with the intrinsic noise of the cochlea n(1), caused by fluctuations of membrane currents in hair cells and neurons of the spiral ganglion. Noise n(1) is normal white noise [3].

Thus, the function p(1) can be written as:

$$p(t) = U(t) + X(t) + n(t) + \eta(t).$$

Since the time of observation of the signal is significantly less than the time interval during which the noise is active (r), this quantity can be represented as stationary, and the process (1) itself as a sum of narrow-band random processes. The decomposition of the signal S(1) has actually already been carried out.

Bekesy showed (cited from [3]). that the presence of certain properties of the cochlea leads to a decrease in the signal transmission coefficient, starting from 1000 Hz. Because of this, the decomposition of process (1) for the range 600...1000 Hz is considered. Below 600 Hz there is a differentiating influence of the general high-pass filter, above 1200 Hz - the influence of the high-frequency part of the main membrane of the cochlea [108], which leads to the decomposition not of the p(t) process itself, but of its derivative dpldt. Due to the fact that the stapes response is 1.3 ms, decomposition is possible with filters with a bandwidth of 800 Hz. In this case, the noise components (1) at the output of neighboring equivalent filters will be statically independent. However, there is no direct experimental confirmation of the presence of such filters.

Based on experimental and model studies of the functioning of neural structures and cochlear nuclei, the following conclusions were made [3]:

1. The neural structures of the spiral ganglion and cochlear nuclei realize the current amplitude-phase spectrum of the decomposition of the p(1) process (above 800 Hz) in a short signal observation time (1.3 ms), due to the time of amplitude establishment vibrations of the membrane, and the phase spectrum

is obtained implicitly in the ratio of the amplitudes in the cosine and sine components.

2. Neural structures implement an assessment of the power of the above narrow-band random processes, i.e., the current energy spectrum of the process p(1) is realized in an averaging time equal to 1-2 periods of the lowest audible frequency - 50... 100 Hz for the problem we are considering. The formal recording of the considered provisions is given in the terms and notations of [3].

Due to the accepted restrictions regarding process 7(1), it is represented as a sequence of random processes of the form

$$\eta v\,(1) = \sum_{k=l}^{N} \alpha\mu\,(\omega,\,1)\,coswt + \beta x\,(\omega,\,1)sinot,$$

where ak, vk are real random processes with uncorrelated increments. In this case, the process p(1) can be approximated over the observation interval T by the expression:

$$p(t) \equiv \sum_{k=1}^{N}{}' A\text{т}.\kappa\,(0,\,1)\,coswit + Crk\,(w,\,t)sinot,$$

where At.k = at,k +CTk; CT,k=CT.k+BT,k .

Since AF >= 800 Hz, as shown above (то = то = 1.3 ms), noise coordinates (1) at,k and ut,k are uncorrelated. Thus, frequencies ok and ok+1 in expression No. (1) have the meaning of extreme frequencies of bandpass filters; ω′ k is — the harmonic component of the signal S(t). If S(t) has a continuous spectrum within the band, then the frequencies will coincide with the central frequencies of equivalent filters. When T = then, where T is the observation time, a "fast" analysis takes place and only the frequency o is assessed according to the "place principle". This means that in the case of AM, when transmitting a short message, the function X(1) will be lost and the signal U(t) —subcarrier—will be subjectively perceived. It follows that the observation time should be significantly longer than the reaction of the stapes, i.e. T>> then. This condition is necessary for the perception of the function X(1). At the lowest frequency, given function X(1) both during AIM and PFM and in accordance with [28], the observation time should be at least 0.251, where the period of oscillation with the lowest frequency, i.e. Tmin ≥ 0.25-10 ms = 2.5 ms.

More precisely, the minimum observation time can be determined from the following considerations. In the theory of hearing, the problems of recognizing individual speech segments, which are separate continuous sound parcels with different durations and different time intervals between them, are considered [87]. A separate task is the study of the conditions of perception of a vowel sound [10, 87] due to its high information content compared to consonants.

Analyzing these tasks, we can highlight the following main points that determine the choice of the minimum observation time:

◇ the minimum time for distinguishing a syllable is about 65 ms [36] and does not exceed 100 ms [27, 106];

◇ interval between syllables 60...70 ms [10];

◇ a person can carry out phonemic recognition of a sound without waiting for the end of this sound, as shown in experiments on rapid vowel imitation; the average value of hidden periods of vowel imitation does not exceed 200 ms and averages 130...170 ms [116].

If we accept the maximum duration of a continuous sound transmission of the order of 1...2 s, then the range of possible values of observation time can be determined by the boundaries of 0.25...2.0 s.

From the analysis of these provisions it follows that when transmitting a message X(1), "slow" analysis takes place

(1) 12 2 will not be filtered out. Since (1) >> (1)², the function p(1) can be written as:

$$p(t) = U(t) + X(t) + \eta(t),$$

where U(t) is a subcarrier signal with a given frequency (10 kHz for AIM and 14 kHz for PFM); η(1) white noise.

Since the functions U(t) and X(1) are implemented according to the "place principle", their analysis is uncorrelated and the power of these signals will be assessed against the background of noise.

Until now, we have considered in general terms the total signal arriving at the auditory analyzer and have not taken into account some physiological features of the auditory analyzer associated with masking a low-frequency signal with a high-frequency one and the presence of an intermittent signal when implementing one of the AIM modes. Filtering the low-frequency region of the speech range also cannot but affect the quality of information perception.

Since the subcarrier and side carriers are in different critical bands, the concepts and results of research into the effects of masking and suppression of two-tone signals can be applied to the implemented AM signal.

According to [212], speech masking with pure tones decreases with increasing masker frequency. So, with an average speech level of 95 dB and a masker intensity of 95 dB, with a masker frequency of 3...4 kHz, the articulation of perceived words reaches 80%, with a masker frequency of 900...1500 Hz - 60%. Studies of speech masking with pure and complex tones have shown [229] that both pure and complex tones at high frequencies cannot cause speech masking.

According to [107], at a masked signal level of 15 to 30 dB in a frequency band of 3200 Hz and a masker frequency of 10 kHz, the shift of the masking threshold reaches 60 dB. Analysis of masking data with pure tones in [87] shows that at a masker level of 40...50 dB, which corresponds to the subcarrier signal level and the minimum ratio of masker and masked tone frequencies of the order of 2.5...5 (subcarrier frequency ratio carrier and upper boundaries of the modulating signal during PFM and AIM), the threshold shift is close to zero, i.e., masking does not take place.

Thus, the presence of a subcarrier signal during the perception of an auditory sensation caused by the excitation of mechanical vibrations in the tissues of the head by EMR pulses does not lead to a decrease in the intelligibility of the useful signal.

In the intermittent AIM mode with the pulsed radiation switched off during pauses, the case of periodic switching off of the masking noise is realized. It was shown in [213] that depending on the noise interruption frequency, its masking effect changes. With an interruption frequency of 1...200 Hz, it is possible to connect speech excerpts - masking is effective

The noise level is low. At very slow interruption rates, entire words or groups of words are masked and perception will be on an all-or-nothing basis [212]. The maximum percentage of articulation of monosyllabic words at an average level of 90 dB and masking with random noise of various intensities is observed at a masker interruption frequency of 10 Hz - 75...90% depending on the noise intensity. In the interruption band of 1...40 Hz, the articulation of words varies within the range of 60...95%.

Comparison of the interruption period with the observation time allows us to come to the conclusion that if these values are commensurate, the discontinuity of the signal in the AIM mode will not lead to an additional decrease in speech intelligibility compared to the calculated value. Moreover, interruption of radiation in the AIM mode is carried out by control pulses generated by the beginning and end of fragments of transmitted information, i.e., synchronously with pronounced syllables, words, etc.

Speech filtering caused by a narrow band of the pseudoresonance portion of the radio sound threshold curve leads to a decrease in speech power by approximately 80% for frequencies below 1 kHz, but the quality of articulation with AIM (bandwidth 2 kHz) is 71%, with PFM, when the upper limit The frequency range of the useful signal reaches 4 kHz — 92%.

From the given table. 15 [127] it is clear that, despite the suppression of a rather large portion of the range of frequency components of the speech signal, the realized bandwidth is sufficient for satisfactory speech perception.

Table 15

The importance of individual frequencies for speech perception

frequency Hz	500	1000	2000	4000
Importance, %	7...15	20...40	30...40	10...26

Thus, filtering the speech signal leads to a slight decrease in speech intelligibility during its perception. Data on the technical characteristics of hearing aids from various brands and models are also provided in [127].

On average, with a hearing loss of 65 dB, the devices provide an excess of 45 to 65 dB above the perception threshold. For a hearing loss of 90 dB, the minimum possible level of excess is 40 dB. The bandwidth in the devices varies from 125...500 Hz to 4000 Hz. Comparison of these data with the capabilities of the bionic principle for receiving sound information determined in this chapter indicates their sufficiency for speech perception.

The analysis of factors influencing the amount of correctly received information and taking into account the physiological characteristics of the auditory system during the perception and analysis of complex sounds allows us to write a new expression for the function p(1).

Since there is no masking of the useful signal by a subcarrier signal, the task posed can be represented as recognizing a binary signal consisting of a useful signal and external noise. At the same time, the solution to this problem is possible if we use uniformly masking noise as noise, i.e., consider the auditory analogue lyser as an optimal receiver. For these

conditions, the signal arriving at the input of the analyzer can be represented by the generally accepted expression y(t) = = Ux(t) + η(τ), where Ux(t) is a useful signal carrying information (message function or modulating signal);
(1) - additive noise.

The error probability of the optimal receiver when analyzing incoming information is determined by the expression

$$Roche = P(X = 0)Rlt + P(X \neq 0)RPR,$$

where P(X = 0) is the probability of no signal; P(X ≠ 0) is the probability of the presence of a signal.

Since P(X=0) and P(X ≠ 0) are known a priori, it is necessary to determine Rlt and RPR - the probabilities of a false alarm and missing a signal, respectively, determined by the expression [31]:

$$P_{лт} = \frac{1}{2}\,\frac{}{\sqrt{2\pi}}\int_{a_1} e^{-\frac{z^2}{2}}\,dz, \quad \text{where } a_1 = \frac{\ln \frac{P(X=C)}{P(XC)} + \frac{Q}{NoAf}}{NOA};$$

$$PUP = \frac{1}{\sqrt{2\pi a_1}} Se^{\frac{22}{2}} dz, \text{ where } a_2 = \frac{\frac{Q}{N_0\Delta f} - \ln\frac{P(X=C)}{P(X\neq C)}}{\sqrt{\frac{Q}{NoAf}}},$$

where is the signal power; — No. noise power spectral density; Df - masker frequency band.

The probabilities RIt and RPR are Laplace functions - PIt = Φ(αι); PΠP = Φ(2). The probability of correct recognition will be determined by the expression PPRAV = 1 - Roche. If the limits of integration are [0, 0], then

$$\Phi(\alpha)=0.5-\int_0^{\alpha} e\, dz,$$

P = 0.5 – Φ(αι); RPR = 0.5 – Φ(α2).

Considering that the prior probabilities P(X=0)=P(X≠ 0) = 1, we obtain a = α_2= a and RPRAV = 2Φ(α); $\alpha = \sqrt{\frac{Q}{NoAf}}$.

For an AM signal, the expression for 2 is: T

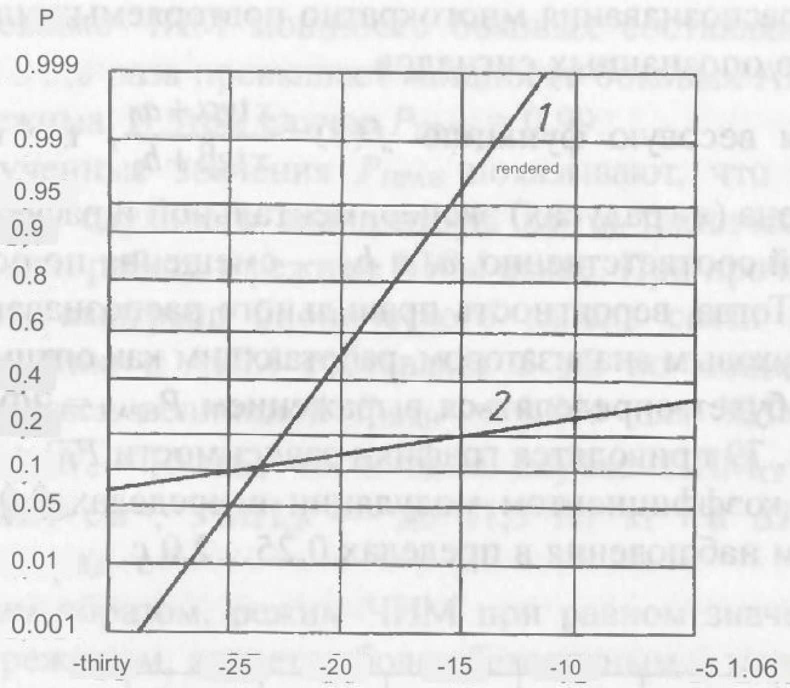
$$= + [[U_\circ (1 + M \cos t)\cos wot\, fdt = Uz\, (1+M^2)\ 0$$

where M is the modulation depth; 2 — modulation frequency; — ωo subcarrier frequency; U average subcarrier level. AM signal energy in the interval [0; T] can be estimated by the expression

$$E=QT=U3T1+ M2 \left(\frac{2}{U}\right) \text{ и } \alpha = \frac{0}{\sqrt{N_0}}\sqrt{T\left(1+\frac{M^2}{}\right)}.$$

The expression for signal energy includes the power of the subcarrier signal and the power of the sidecarriers. But since the subcarrier signal does not mask the modulating signal, and the selection of both signals in the auditory analyzer occurs simultaneously, i.e., the detection and selection of the AM signal is formally carried out, then the expression for the argument of the Laplace function will have the form: α

$$= M \frac{UT}{V2No}.$$



Rice. 78. Graphs of the dependence of RPR on the signal-to-noise ratio at an observation time of 1 s

Let us determine the possibility of describing an auditory analyzer in terms of the categories of an optimal receiver by comparing the values obtained here for the probability of correct recognition of a subcarrier signal in the absence of modulation with the experimental data given in the literature.

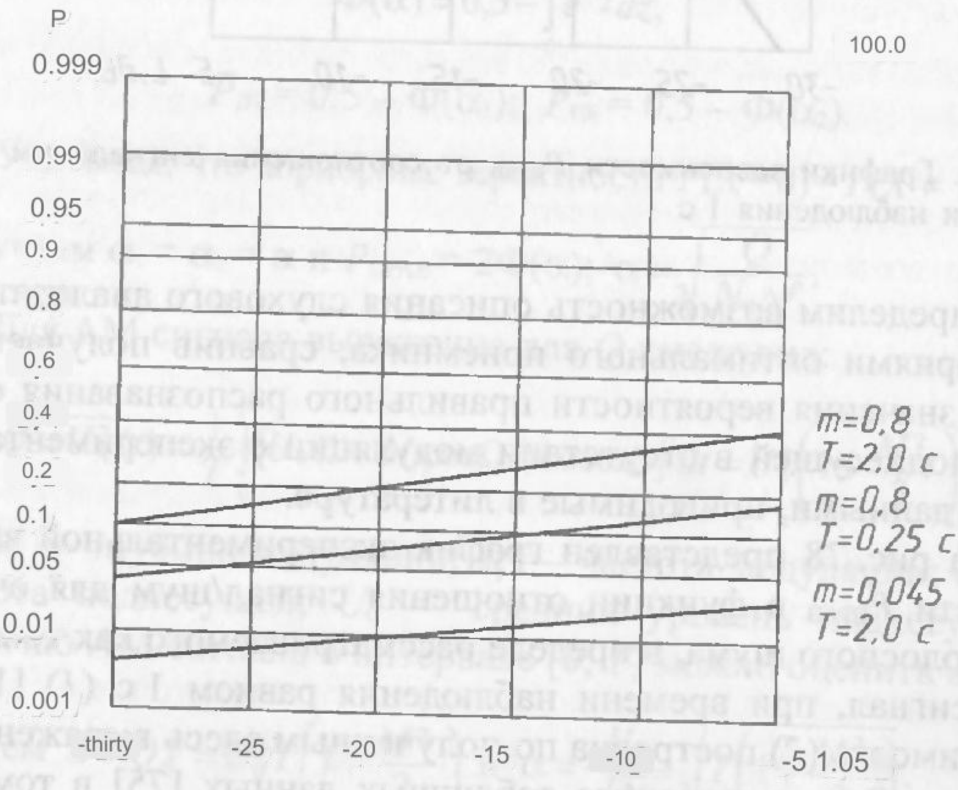
In Fig. Figure 78 shows a graph of the experimental dependence of RPR as a function of the signal-to-noise ratio for very narrow-band noise, in the limit considered as a tone signal, with an observation time equal to 1 s (1) [115]. Dependence (2) is constructed using the expressions obtained here for a and RPR USING tabular data [75] in the same range of signal/noise values and for T = 1 s.

The qualitative course of both dependencies is the same, which indicates that it is fundamentally possible to evaluate the auditory analyzer as an optimal receiver. The general nature of the calculated and experimental dependences indicates the identity of the signal processing mechanisms. The different slope of these dependencies can be attributed to the psychophysiological characteristics of hearing, such as associative memory, numerous correlation processing, etc., which subjectively increase the likelihood of

reliable recognition of repeatedly repeated
or pre-identified signals.

Let us introduce the weight function f(x) = xtg□+bo' — xtga + ao,

where a, in the angles of inclination (in degrees) of the experimental and calculated dependences, respectively, — ao and in the displacements along the probability axis. Then, the probability of correct recognition of an AM signal by an auditory analyzer operating as an optimal receiver will be determined by the expression RPRAV = 2Φ(α) f(x). In Fig. 79 shows graphs of the dependence of RPR for an AM signal with a modulation coefficient in the range of 0.045...0.8 and observation time in the range of 0.25...2.0 s.



Rice. 79. RPR dependence for AM signal

To estimate the parameters of the bionic communication channel, the external noise level is assumed to be 40 dB. Taking the minimum average level of the speech signal required for perception to be 50 dB, we determine the probability of RPR AT M = 0.8 and T = 2.0 s for the AIM and PFM modes and for the AM signal at the detector output. Substituting the values of M and Tv into the expression for the argument of the Laplace function for the AM signal, we obtain the value RPRAV = 0.844 for the AIM mode.

In PFM mode, the power of the side components of the AAM signal is 3.3 times higher than the power of the side AM signal of the AIM mode. In this case, RPR = 0.99.ɔ

The obtained RPR values show that the noise immunity of an auditory analyzer, as well as a technical receiver, when operating in PFM mode is higher. All other things being equal, the gain of the bionic communication channel with PFM compared to PIM is 5 dB in power, i.e., if you set the value RPR = 0.844 for the PFM mode with Uo/No = 10 dB, then in this case the PMSSR will decrease to 22 mW-cm-2, UMPSR 2.67-10-3 — W. kg and DT/Di up — to deg s. up to 11.3

Thus, the PFM mode, with an equal value of RPR with the AIM mode, is safer and less energy-intensive - the minimum microwave pulse power to ensure a sound pressure level of 80 dB in the head tissue can be estimated at about 80 W.

6.4. Audiometry of age-related changes in bone-tissue conduction

In the physiology of hearing, modern bone tissue audiometry mainly covers the frequency range from approximately 250 to 4000 Hz. The upper limit is determined by technical capabilities, primarily by the bandwidth of the vibrators. Functionally, the upper limit of auditory perception reaches 225 kHz [81].

Since the equivalent circuits of the amplitude detector and low-pass filter discussed above determine the spectrum of the signal perceived by the auditory system and are related to the HFGS by bone conduction, there is a need to study hearing sensitivity thresholds in the high-frequency region.

It is known that with age there is an increase in hearing sensitivity thresholds and a decrease in HFGS in air conduction [12, 53, 87, 127]. Age-related changes in hearing, depending both on the functional state of the receptor-horn-nervous apparatus of the auditory system, and on the acoustic characteristics of bones and soft tissues of the head, for high-frequency bone-tissue audiometry have been practically not studied. Meanwhile, due to the supposed strong connection of the resonant circuits formed by the anatomical structures of the head, changes in the characteristics of these structures should lead to quite significant redistributions of phase relationships in the overall system, which cannot but affect the integral frequency response. As a result, these age-related changes can lead to various kinds of anomalies in the perception of radio sound and even to the loss of the ability to perceive this kind of auditory sensation. Thus, high-frequency bone-tissue audiometry makes it possible to determine the age limit for individuals capable of perceiving information bionically.

Methodology. A bone telephone (vibrator) was used in the frequency range from 4 to 20 kHz. In this range, hearing thresholds were measured stepwise with a frequency step of 1 kHz. The magnitude of auditory thresholds was measured by the voltage of the electrical signal supplied to the vibrator from the GZ-102 laboratory sound generator in millivolts. The vibrator was fixed on the frontal bone of the subject in the sagittal plane.

Control threshold measurements showed the constancy of the energy output of the mechanical vibrations of the vibrator at different amounts of pressure from the vibrator on the subject's head.

The external auditory canals of the subjects were tightly covered with cotton wool and petroleum jelly. It is known that obstruction of the auditory canals in normally hearing people or in patients with receptor-nervous hearing impairment causes a decrease in bone-tissue hearing thresholds. At the same time, when the sound conduction apparatus is impaired, the thresholds do not change [44, 45, 228]. Obturation of the auditory canals made it possible to conduct research under more uniform conditions, excluding possible changes in auditory thresholds associated with individually different resonant properties of the external auditory canal [68]. onoar

All subjects underwent pure-tone audiometry using an MA-31 audiometer (GDR). Bone telephone dis-was assumed according to the method described above. Audiometry was carried out in a special soundproofed acoustic chamber.

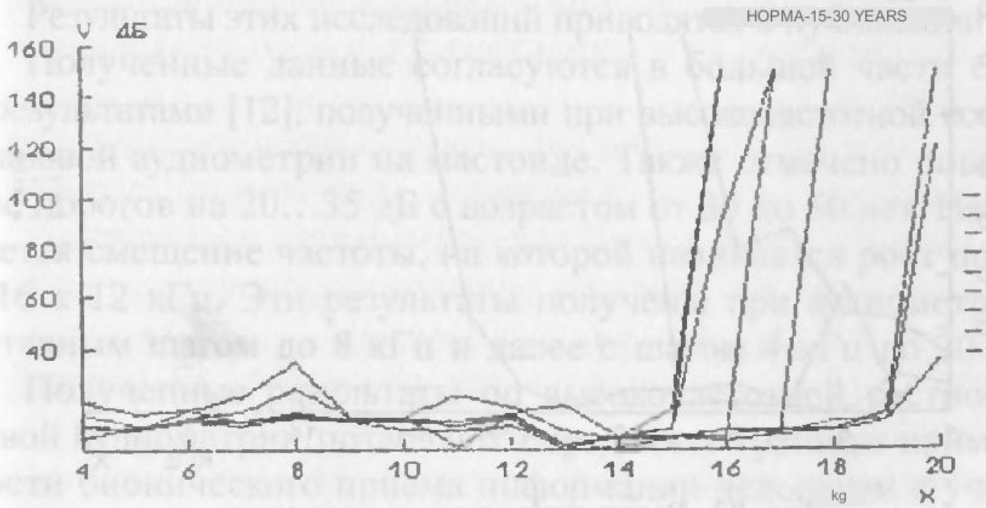
Results. 42 healthy people without any complaints of hearing loss were examined. According to age, all subjects were divided into 4 groups:

1) 15-30 years — old 14 women, 4 men.
2) 31-40 years — old: 5 women, 3 men.
3) 41-49 years — old: 6 women, 5 men.
4) Over 50 years — old: 4 women,1 man.

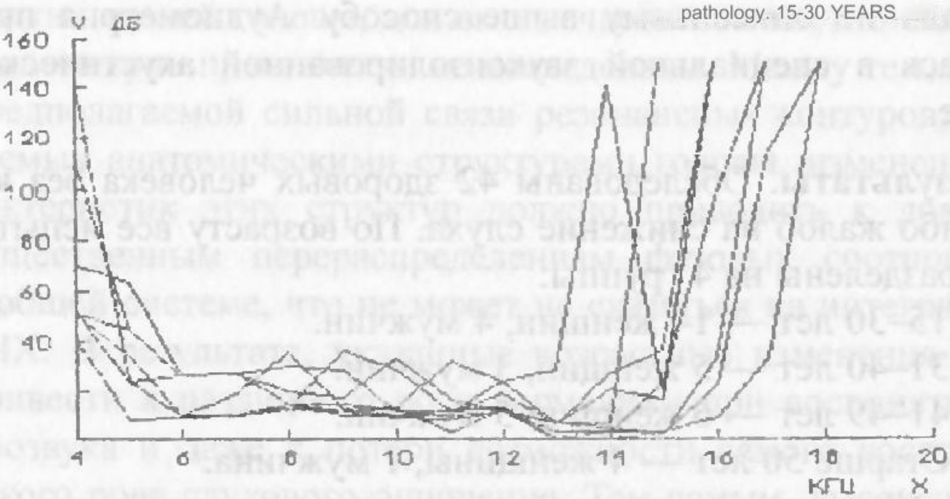
Based on the results of pure-tone audiometry, in each age group, people with deviations from the norm were — identified: 10, 3, 5 and 3 people, respectively, who made up the "pathology" group, in contrast to the rest of the subjects who made up the "norm" group.

It has been established that the high-frequency limit for auditory sensations using this technique is 20 kHz. With age, the cutoff frequency decreases to 10 kHz in the "norm" group and to 7...8 kHz in the "pathology" group. The "pathology" group is also characterized by higher auditory thresholds, and for subjects under the age of 30 the increase in thresholds is most pronounced for frequencies of 4...5 kHz, in older age — for different frequencies.

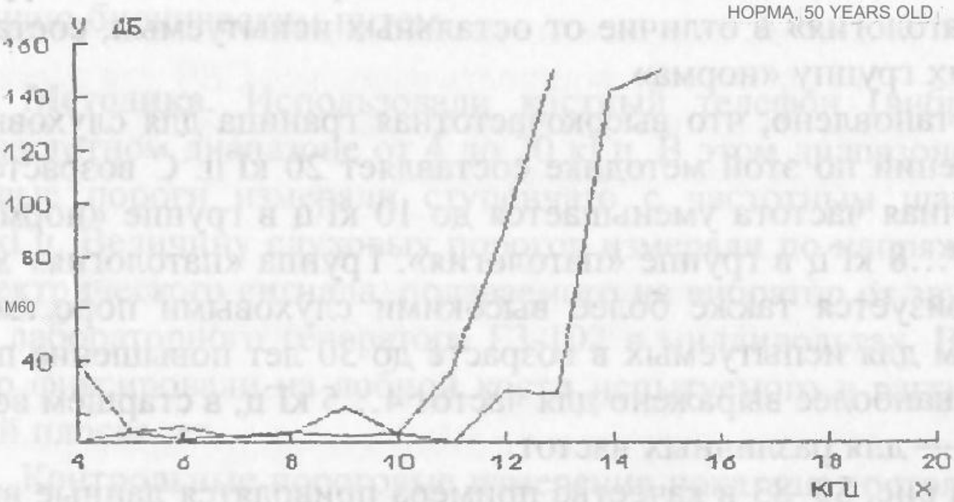
In Fig. 80-83, as an example, high-frequency audiometry data of both groups are given. The graphs were constructed taking into account the frequency response of the bone vibrator and processed on the Iskra-226 computer.



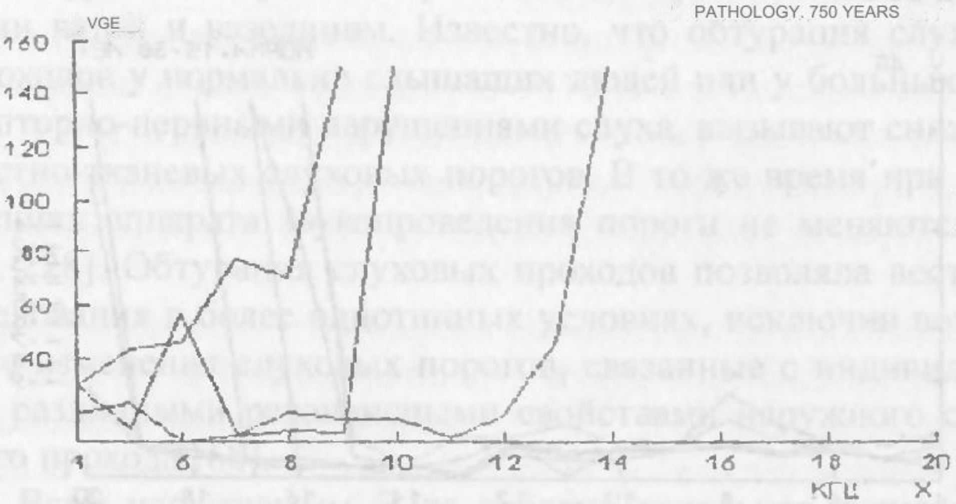
Rice. 80. High frequency audiometry



Rice. 81. High frequency audiometry



Rice. 82. High frequency audiometry



Rice. 83. High frequency audiometry

Taking into account the data obtained from measurements from the mastoid process [12, 82, 159], an increase in ear sensitivity with increasing frequency would be expected. However, the measurement results showed the opposite — picture in both groups; for all subjects, a very sharp increase in thresholds in the high-frequency region was observed.

The identification of the "pathology" group based on the results of pure-tone audiometry is undoubtedly arbitrary, and in people with normal hearing there are no clear boundaries on the audiogram between normal and pathology. Conditional criteria for inclusion in the "pathology" group were: an increase in air conduction thresholds at frequencies 125...4000 Hz by more than 10 dB for all age groups and at a frequency of 8000 Hz by more than 10 dB for persons under 30 years old, more than 15 dB - up to 40 years, more than 20 dB - up — to 50 years, more than 25 dB over 50 years. During bone audiometry, fluctuations in thresholds within ±20 dB relative to the zero level were regarded as normal; if this value was exceeded, the subject was assigned to the "pathology" group.

Despite the rather arbitrary division of all subjects into two groups, it turned out to be useful for assessing the results of high-frequency bone-tissue audiometry, which were clearly different in the "norm" group from the "pathology" group.

Studies have shown that high-frequency bone-tissue audiometry clearly records age-related changes in both normal and pathological conditions. Common to all subjects in both groups is an increase in thresholds and a decrease in the upper limit of hearing with age.

The results of these studies are presented in publication [16].

The data obtained are consistent for the most part with the results [12] obtained with high-frequency bone-tissue audiometry on the mastoid. An increase in thresholds by 20...35 dB with age from 30 to 50 years was also noted. There is a frequency shift at which the threshold begins to increase from 16 to 12 kHz. These results were obtained with audiometry with octave steps up to 8 kHz and then with steps of 4 kHz up to 20 kHz. The results obtained from high-frequency bone-tissue audiometry make it possible to determine the limits of applicability of bionic information reception in humans, taking into account age-related changes in the auditory system.

A prerequisite for the implementation of a bionic communication channel is the presence of pronounced areas of change in the threshold sensitivity for bone conduction, forming a pseudo-resonance characteristic.

In a real situation, some of the considered parameters of an ideal bionic communication channel will undergo changes. This is primarily determined by HFGS. The norm is considered to be the range of sound frequencies perceived by humans within the range of 16...2-104 Hz. However, in the vast majority of people, the HFHS ranges from 14 to 16 kHz, and this range, as research results have shown, can be narrowed by half with age.

These results, first of all, limit the possibilities the ability to perceive information bionically, i.e. bio- the communication channel when transmitting a speech signal is not mo- can be considered as a means of communication accessible to all. To determine the limits of applicability of bionic information reception, it is of interest to study the possibility of perception of radio sound by people with various forms of hearing impairment conducted by A. Frey [168].

Volunteers with various forms of hearing impairment were selected for the study. Irradiation was carried out at carrier frequencies of 1310 and 2982 MHz with pulse repetition rates of 244 and 400 Hz and pulse durations of 6 and 1 μs. The "hearing" threshold varied among individual subjects within the range of 0.4...2.0 mW cm2 at the average level.

The experiments revealed the following features of the occurrence or absence of auditory sensation during irradiation:

◇ when removing the mastoid process, radio sound is not perceived even at 30 times the density power necessary for normal perception;

◇ in the presence of otosclerosis, radio sound is perceived in the same way as by normal hearing people;

◇ with atrophy of the auditory nerve, radio sound is not perceived;

◇ despite normal acoustic hearing, one of the subjects did not perceive radio sound from Toeges knives

The results of the experiments and the availability of audiograms of the subjects allowed the author of the cited work to come to the following conclusions:

1. To perceive radio sound, it is necessary for a person to perceive an acoustic signal with a frequency above 5 kHz through bone conduction.

2. To perceive radio sound there is no need for the ability to perceive sound due to air conduction.

The results obtained can be commented on based on the latest data from full-scale and model experiments. Indeed, as model studies have shown, the mechanical resonance frequency of a human head with a size of 57 cm should correspond to 7.8 kHz, and with a size of 53 cm it should be about 10 kHz. Such a strong deviation of the upper limit of the radio sound range determined in [168] from the model results can be explained as follows. Field experiments on bone conduction [95] showed the presence of a region of high threshold values in addition to the region of mechanical resonance (also with an increase in the threshold), which was not noted in field experiments on radio sound. The technique for recording the threshold curve of bone conduction allows us to assume the absence of this area on the threshold curve of radio sound (5...6 kHz) due to the large gradation of the pulse repetition frequency. At the same time, in a full-scale experiment on radio sound, all subjects noted the perception of a signal with a frequency close in pitch to 10 kHz at a pulse repetition rate of about 5 kHz. Moreover, the threshold at a signal frequency of 10 kHz relative to the threshold at 5 kHz on the radio sound threshold curve is below 4 dB, on the bone conduction threshold curve by 5 dB. In this regard, audiometric data on age-related loss of hearing sensitivity are also of interest [12, 87]. Interestingly, according to [87], at frequencies of 5...6 kHz there is an increase in the threshold by 5...6 dB relative to the threshold at a frequency of 10 kHz, which also coincides with the data of our own studies of bone conduction.

The similar values of the ratios of sensitivity thresholds at the same frequencies suggest the presence of the same mechanism of sound perception in bone the initiation of mechanical vibrations in the tissues of the head and during irradiation with microwave pulses.

At the same time, a decrease in the repetition frequency from 5 kHz with short pulse durations (6 and 1 μs) and insufficient power in the pulse should lead to the fact that the amplitude of the first harmonic will be insufficient for its clear perception due to an increase in the threshold as the frequency decreases , and the second harmonic falls into the region of increasing the threshold at frequencies below 10 kHz. All this leads to a sharp decrease in the sound pressure level at microwave EMR pulse repetition rates below 5 kHz and is subjectively manifested in the absence of auditory sensation. Obviously, this can explain the minimum value of HFGS determined by A. Frey for the perception of radio sound.

6.5. Structure of a bionic communication channel

Determining the structure of a bionic communication channel is primarily associated with the need for its physical modeling for quantitative and qualitative assessments of the put forward provisions and confirmation of their validity.

That is, the question is raised about the development of technical means for receiving and transmitting information with the ability to flexibly change the parameters of functional blocks and their connections in a model experiment in order to check the acceptability of the quantitative indicators of the bionic communication channel, clarify them and determine their applicability.

Under natural conditions, the formation of the auditory sensation occurs with the direct participation of the auditory analyzer and the anatomical structures of the head, the resonant properties of which and their relationship determine the presence of pseudo-resonance areas on the frequency-threshold curve of bone-tissue sound conduction. Let's call this complex of structures bionic receiver. In

physical modeling, a bionic receiver can be represented by two functionally connected blocks; an equivalent receiver, which is a technical analogue of a set of anatomical structures of the head interacting with microwave EMR pulses and detecting an AM signal in the audio range, and a second detector, represented by physiologically natural mechanisms of the auditory analyzer that form an auditory sensation adequate to the modulating function against the background of interference. The connection between these two functional blocks is carried out using a bone telephone (vibrator).

Using known technical methods, it is naturally possible to model the functions of the auditory analyzer - the second detector, i.e., subcarrier filtering. However, such a solution to the structure of the receiver, providing a filtered modulating signal at the output, would lead to the usual perception by the auditory analyzer of a simple signal, in the limit, monotonal, which would not correspond to the conditions for the perception of an auditory sensation in a full-scale experiment. Therefore, in order to maintain maximum analogy between the signal perceived by the auditory analyzer in natural conditions and during bionic modeling, the functions of detecting and filtering the modulating signal are retained by the auditory analyzer.

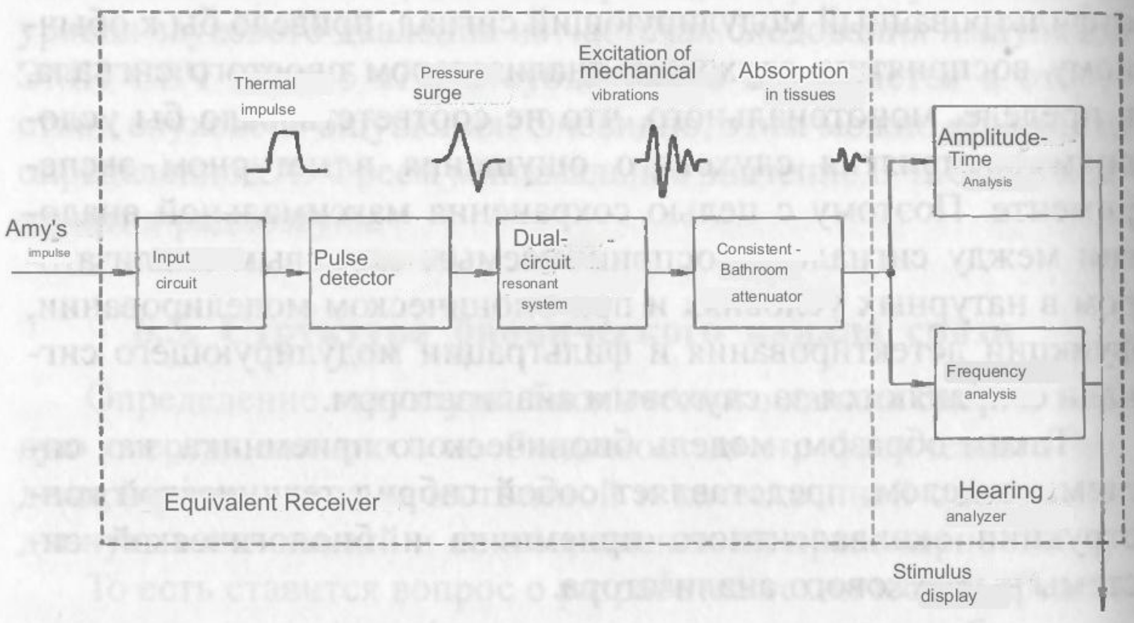
Thus, the model of a bionic receiver, as a system as a whole, is a hybrid of the technical design of an equivalent receiver and the biological system of an auditory analyzer.

Structure of a bionic receiver. The essence of physical processes during the interaction of pulsed microwave EMR with the anatomical structures of the head, discussed in the previous paragraphs, allows us to identify the following functions performed by the bionic receiver:

1. Absorption of EMR pulse energy by head tissues in a wide range of carrier frequencies.
2. Performing a formalized function of primary carrier detection—forming a thermal pulse in the tissues of the head.
3. Formation of a pressure surge leading to expansion and subsequent compression of the tissues of the head, i.e., performing a formalized operation of differentiating the thermal pulse.
4. Excitation of mechanical vibrations in a system formed by anatomical structures with resonant properties.

5. Amplitude-time and frequency analysis of excited mechanical vibrations of — formation of auditory sensation.

The functions listed above were determined from ideas about the thermoelastic nature of radio sound and the concept of a two-circuit resonant model. In general, the block diagram of the bionic receiver model is shown in Fig. 84.



Rice. 84. Block diagram of the bionic receiver model

Structure of the modulating device of the bionic communication channel transmitter. Due to the rigidly specified structure of the bionic receiver, all necessary transformations of the modulating signal when transmitting information are carried out at the transmitting end of the communication system. These transformations Calling boils down to the following operations:

1. Limiting the speech signal to the mid-frequency region.
2. Increase in frequency response in the modulating signal path in the low-frequency region.
3. Expansion of the dynamic range of the modulating signal in the region of lower frequencies by introducing additional PWM.

The first two points do not require special consideration and are implemented using conventional techniques. Before-

An additional condition in this case is a sufficiently high slope of the frequency response slope at cutoff frequencies of the order of 20 dB/oct, which will ensure a small amplitude of the second harmonic power (no more than 1%).

The technical solution of the functional blocks that provide the first two points does not require consideration of any issues related to the physiological characteristics of hearing and does not introduce changes in the values characterizing the perception of useful information. The solution to the last point is associated with isolating the control signal from the complex modulating signal.

Let us consider the possible functions of converting a modulating signal into a control signal and the corresponding coefficients for reducing the intelligibility of the transmitted message.

In general, the pulse duration will be expressed by the dependence ti = (7), where T is the current value of the modulating signal period. This function can be implemented in the following ways:

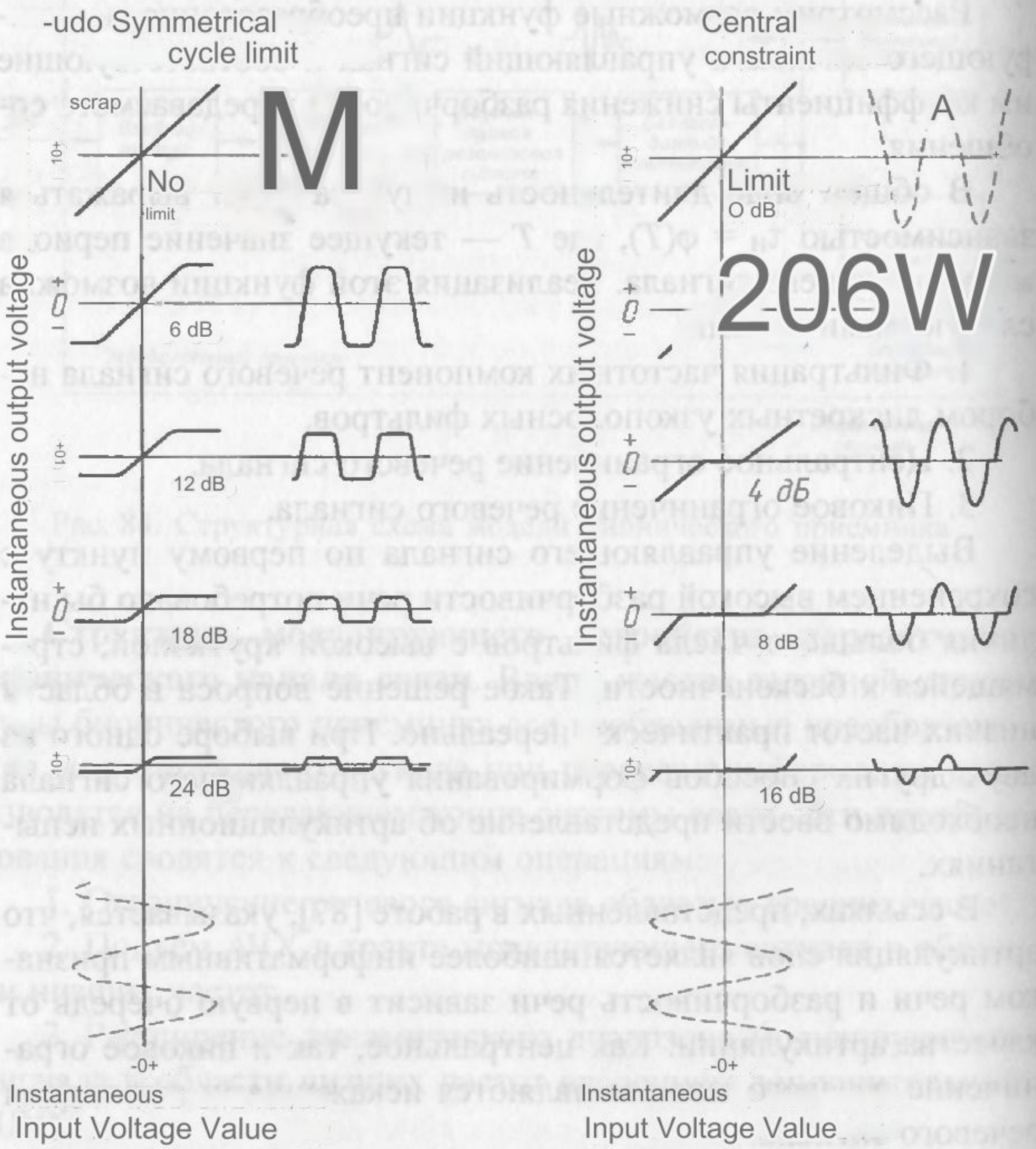
1. Filtering the frequency components of the speech signal with a set of discrete narrow-band filters.
2. Central limitation of the speech signal.
3. Peak limitation of the speech signal.

Isolating the control signal according to the first point while maintaining high speech intelligibility would require the presence of a large number of filters with a high slope tending to infinity. Such a solution to the problem in the low frequency region is practically unrealistic. When choosing one of the other two methods of generating a control signal, it is necessary to introduce an idea of articulation tests.

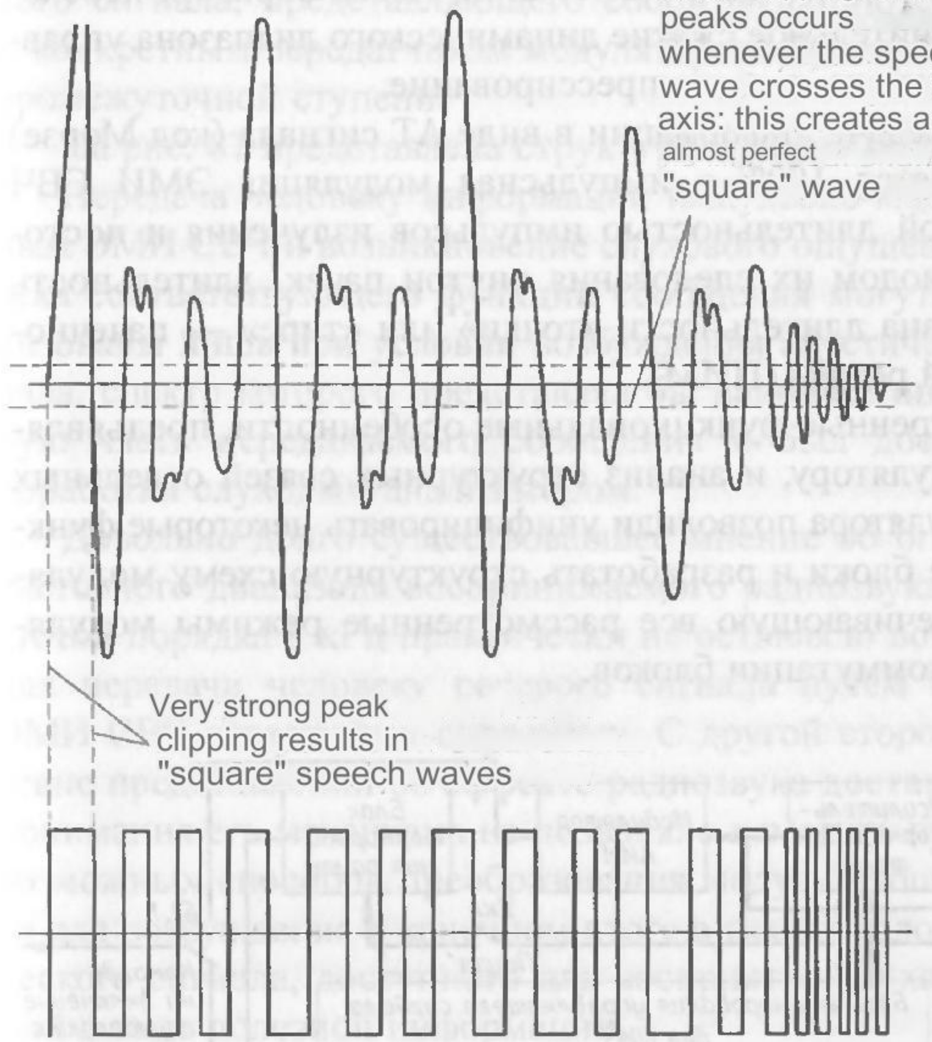
The references presented in [87] indicate that word articulation is the most informative feature of speech and speech intelligibility depends primarily on the quality of articulation. Both center and peak clipping of the speech signal are distortions in the amplitude of the speech signal.

According to [87], the central limitation is associated with a sharp deterioration in speech intelligibility, which, when forming control signal does not allow implementing the function Ti = (7). Peak limiting of signal amplitude allows speech intelligibility to be maintained at 95% at infinity, i.e., with infinitely large limiting, intelligibility drops to only 70% [87].

In Fig. Figure 85 shows the process of generating both types of control signal. Thus, the peak limiting process, called clipping, is the most suitable for generating a control signal. The process of clipping a speech signal is shown in Fig. 86.



Rice. 85. The process of generating control signals (modulating signal conversion function)



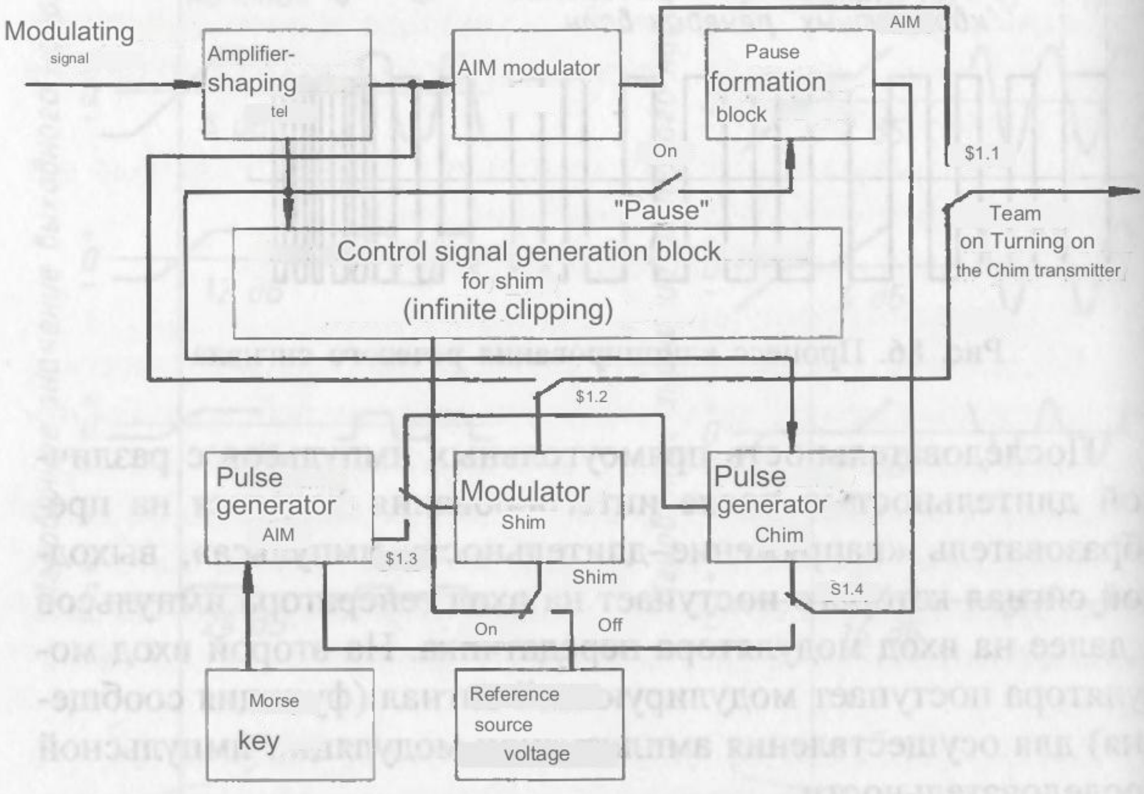
Rice. 86. The process of cluttering a speech signal

A sequence of rectangular pulses with different durations, after integration, is fed to a “voltage-pulse duration” converter, the output signal of which goes to the input of the pulse generator and then to the input of the transmitter modulator. The second input of the modulator receives a modulating signal (message function) to perform amplitude modulation of the pulse sequence.

For AIM with a frequency band of 100...2000 Hz as a result clipping, the duration of the pulses varies within 10 ms 250 μs at required durations microwave pulses 6.5...25 μs. With PFM, clipping ensures prints a change in the duration of rectangular pulses almost within the same limits due to a small change threshold in the frequency range 2...4 kHz. Thus, additional compression of the dynamic range of the control signal is necessary, i.e. compression.

When transmitting information in the form of an AT signal (Morse code), 100% pulse modulation of microwave EMR is carried out with a constant duration of radiation pulses and a constant period of their repetition inside bursts, the duration of which is equal to the duration of the “dot” or “dash” burst-pulse mode (PIM).

The considered functional features required of the modulator and the analysis of the structural connections of individual modulator blocks made it possible to unify some functional blocks and develop a block diagram of the modulator that provides all the considered modulation modes by switching the blocks.



Rice. 87. Modulator block diagram

The modulator is based on controlled self-oscillators of pulses of AIM and PFM modes. Control of both the amplitude and repetition rate of pulses is carried out using control signals generated from the input a significant signal representing a function of the message. The modulator is connected to a specific transmitter using an intermediate stage.

In Fig. 87 shows a block diagram of the modulator.

The transmission of information to a person by pulse-modulated microwave EMR and the emergence of an auditory sensation in a person corresponding to the function of the message can be realized only under the condition of excitation of an acoustic signal, the spectrum of which would represent the most informative part of the transmitted message and would be accessible to processing by an auditory analyzer.

The long-standing opinion about limiting frequency range of perceived radio sound from below cha- with a frequency of about 8 kHz there was practically no possibility for transmitting a speech signal to a person by modulation Microwave EMR using known methods. On the other hand, there is no lack of ideas about the effect of radio sound sufficient for understanding of its mechanism did not allow us to outline search paths possible methods of converting the modulating signal la for excitation ultimately in the tissues of the head acoustic ical signal available for perception by the auditory system mine in the form of useful information.

Human perception of the first harmonic of the modulating signal in the entire audio range in a full-scale experiment and the studied dependences of the parameters of excited oscillations on the parameters of microwave EMR pulses in model experiments made it possible to substantiate the fundamental possibility of solving the problem posed. Using the equivalent resonant circuit method, the most optimal laws of modulation of the pulse sequence of EMR microwave AIM and PFM with additional PWM at low frequencies were determined.

Calculation of signal spectra in modulation modes taking into account the presence of HFGS showed that the auditory system will receive a standard AM signal, corrected by the equal-loudness curve of bone conduction of sound. At the same time, it was necessary to formally introduce the concept of the head tissues performing the process of primary detection of the separation of the envelope of EMR pulses in the form of thermal pulses.

pulses leading to the excitation of acoustic pressure waves.

The AM signal isolated by the auditory system is a two-tone signal consisting of a subcarrier frequency signal and two side frequencies separated by a frequency interval exceeding the boundaries of frequency groups. Simultaneous analysis of a two-tone signal ensures synchronous perception of components in the form of separate auditory sensations of different tones.

The presence of an HFGS ensures filtering of the first harmonics of a two-tone signal and, together with the auditory analyzer, which performs the function of a secondary nonlinear transformation, forms a detector with a low-pass filter that selects a useful signal. The subcarrier signal does not mask the lower-frequency modulating signal and is not an interference. We can say that the noted feature of the bionic detector represents an organic disadvantage mainly for AIM.

Unlike radio low-frequency detectors, when the carrier signal and the modulating signal are separated in frequency by several orders of magnitude, the useful signal is filtered using a simple low-pass filter. In the case of a bionic detector, the subcarrier signal and the modulating signal are in the frequency range available for simultaneous perception; the subcarrier signal — frequency is 10 kHz in the AIM mode and the upper frequency of the useful signal is 2.2 kHz. For PFM mode, the subcarrier signal frequency is 14 kHz with a signal bandwidth of 4.4 kHz.

In AIM mode, the subcarrier signal level is higher than the modulating signal level. With PFM, for most people at 14 kHz the sensitivity threshold is quite high and the modulating signal is more emphasized.

From a technical point of view, the PFM mode is more preferable, and in some cases it may be the only possible one. The power of modern pulsed microwave transmitters is very high and linear modulation of radiation in this case may turn out to be technically impossible. The operation of a transmitter with constant pulse power and repetition frequency deviation is implemented relatively simply (for example, when using a multicavity magnetron as a microwave oscillation generator). NAVE

The point limiting the possibility of a bionic communication channel is the need to ensure a certain minimum level of pressure of the speech signal for its intelligible perception. This circumstance, according to estimates, leads to high levels of radiation and does not allow the use of such a communication channel for transmitting any long-term message.

In the mentioned literature sources, high speech intelligibility - within 70...90% - is ensured at an average speech signal pressure level of 13...53 dB. Such a high scatter of this value, naturally, does not allow us to draw final conclusions regarding the required level of pulsed power of microwave EMR. It is also noted that an increase in the volume of the dictionary leads to a decrease in speech intelligibility, which must be taken into account when transmitting a speech signal.

Comparison of the obtained values with the available literature data, both theoretical and full-scale experiments, shows that the justification of the dependence p = f(Ti) up to the values Ti = 1/2 is consistent with the data of [206], reflecting calculations of pressure amplitudes for spherical models, carried out using EMR, starting from values Ti = 1 μs.

The calculated value of pulsed power for a given carrier frequency (800 MHz) is within the limits of this value, determined by the threshold pulsed power curve for a range of carrier frequencies [169]. 01

The sound pressure level, determined taking into account the properties of masking and suppression of external noise by earbuds inserted into the ear canals with a simultaneous decrease in the threshold of bone conduction of sound, is in good agreement with the data [206]. The required sound pressure level of the speech signal relative to the absolute threshold defined here is 50 dB. The sound pressure level given in the literature, equal to 70 dB for the center of the sphere, at the periphery will be attenuated by 16 dB according to the graphs given in the link and should be additionally reduced by 6 dB to bring the volumetric energy densities into line. As a result, the sound pressure level in the cochlea area can be can be estimated at 48 dB, which is almost equal to the selected value of this value in this work.

The use of the provisions of the masking effect to determine the pressure level from the available values of the threshold pulse power in the case of radio sound does not encounter contradictions in the existing literature and was also used in [168]. The results of a full-scale experiment to determine the frequency range of radio sound, however, showed that the external noise factor plays an important role in the perception of the auditory sensation that occurs during irradiation.

Calculations have shown that the bionic communication channel has a fairly high noise immunity and provides speech intelligibility of at least 80 dB even with a slight excess of signal over noise.

Speech intelligibility could be improved by increasing increasing the modulation index, which is equivalent to increasing transmitter power. However, a significant increase in horns of sensitivity of bone hearing in the region of the lower hours - when excitation of acoustic vibrations by pulses Microwave EMR leads to the need to implement more dynamic range of modulation depth and limits capabilities of this parameter. At the same time, significant spread of values of the minimum speech pressure level signal to ensure high intelligibility needs in verification in a full-scale experiment. Thus, the decrease in average sound pressure level of the speech signal by at least 10 dB relative to the value adopted here of 50 dB would allow reduce the required value of PMSSR to levels close to to safe.

Speech intelligibility is also affected by an age-related decrease in the sensitivity of bone hearing, and therefore this issue should also be taken into account when solving applied problems.

As has been shown, a decrease in HFGS leads to a narrowing of the useful signal bandwidth. However, with HFGS equal to or below a certain value of 10 kHz, when the possibilities of bionic reception with optimal parameters have been exhausted, it is possible to implement PFM on the low-frequency slope of the pseudo-resonant section with maximum bandwidth transmission 1 kHz. The asymmetry of the pre-resonance section relative to the subcarrier frequency in the AIM mode does not allow achieving equality of the side amplitudes, which leads to distortion of the perceived signal.

Changes in threshold values in the pseudoresonance region should lead to the need to revise the above-determined values of M, tu and Ripor for both modulation modes.

The obtained experimental data from model and full-scale studies of radio sound made it possible to propose the structure of a bionic communication channel, determine the functional blocks of the transmitter and receiver, and the relationship between them.

Analysis of the transfer functions of the receiver made it possible to introduce the concept of an equivalent receiver for a quantitative assessment of the processes of converting the energy of EMR pulses into the energy of mechanical vibrations.

The auditory analyzer is an integral part of the bionic receiver and is connected to the equivalent receiver by a bone vibrator. Such a hybrid makes it possible to simulate the conditions for excitation of mechanical vibrations and their analysis under natural conditions.

The specific structure of the bionic communication channel created the conditions for its physical modeling using the method of electronic and liquid spherical models.

6.6. Brief conclusions

1. A method has been proposed for describing the amplitude-frequency characteristics of a bone-tissue audiogram in the categories and terms of quadripoles (the concept of pseudo-resonance areas).

2. The laws of modulation of pulsed EMR were determined, which made it possible to describe the nature of its transformation in the tissues of the head and the formation of an acoustic signal lying in the band of physiologically normally perceived frequencies and accessible for processing by an auditory analyzer.

3. Based on psychoacoustic data, the values of the main parameters of the microwave EMR pulse sequence were calculated to ensure the formation of the necessary auditory sensation in humans.

4. Based on audiometric and acoustic studies, the necessary pressure levels of excited acoustic oscillations and pulse power values were determined to consider microwave EMR modulation modes that ensure high speech intelligibility.

45. An assessment was made of the thermal loads when irradiating the head with pulsed microwave EMR of all defined modulation modes and the possible time of an information transmission session.

6. Based on the studied thresholds of bone-tissue conductivity, the possible limits of applicability of bionic principles of information reception are considered.

7. The structure of the bionic communication channel, the structural organizations of the receiver and transmitter and the main transfer functions are determined.

spread

Chapter VII

PHYSICAL MODELING OF A BIONIC COMMUNICATION CHANNEL

7.1. Choosing a bionic communication channel model

The main goal pursued in the physical modeling of a bionic communication channel is to confirm the validity of the provisions put forward above related to the encoding and decoding of useful information and the possibility of its objective perception by a person during the distant action of modulated microwave EMR on the anatomical structures of the head. In this case, the principles of organization and function of biological structures discussed above must be implemented, forming the threshold curve of radio sound and the patterns of analysis of information received by the auditory analyzer. This goal is achieved by developing technical devices for transmitting and receiving information, the functional blocks of which are logical analogs that have formalized transfer functions of the original structures. Demonstration of the possibility of implementing a real bionic communication channel is ensured by the compliance of the technical parameters of the newly developed functional blocks, as well as the involved serial equipment, with the main quantitative indicators of the bionic communication channel defined above. Thus, a model bionic communication channel must contain an equivalent receiver and transmitter.

The equivalent receiver is based on the block diagram of a two-circuit resonant model, which implements the concept of the formation of a radio sound effect at the periphery of the auditory system by excited mechanical vibrations.

When modeling a bionic communication channel using electronic means, amplification of microwave oscillations is associated with well-known technical difficulties. An assessment of the gain showed that an equivalent receiver should have a voltage gain of the carrier signal of the order of 102, which would entail solving a technically complex problem. At the same time, the issue of choosing a carrier during bionic modeling of a communication channel using electronic means is not fundamental or determines any specific aspects of the modulating signal transfer process itself.

On the other hand, preserving analogues of the main stages physical interaction of biological structures with microwave EMR, i.e. absorption of EMR microwave energy by the medium, the formation of a thermal pulse and a pressure jump, leading in the presence of a resonating volume to the excitation of mechanical vibrations, require the use of a carrier in the model experiment , pulsed microwave radiation.

In this regard, physical modeling of a bionic communication channel is presented here by two approaches:

1. Using one of the radio frequencies as a carrier using an electronic analogue of an equivalent receiver and radio transmitter. This solution of the bionic communication channel circuit, having maximum flexibility, makes it relatively easy to achieve compliance of the parameters of the functional blocks of both the equivalent receiver and the radio transmitter with the calculated ones. This circumstance, in turn, makes it possible to widely vary many structural elements of functional units, achieving an optimal solution, which in turn makes it possible to simulate various real situations when receiving information and evaluate them. The mobility and autonomy of such a communication channel allows it to be used as a working tool in the training of operators and correspondents in order to adapt hearing to the perception of useful information against the background of a subcarrier, as well as for demonstration purposes.

2. Direct use of pulse-modulated microwave EMR as a carrier of information and used

using a spherical liquid resonator as an equivalent receiver. This model of a bionic communication channel is adequate to the real situation when a person's head is irradiated with microwave EMR pulses and implements all the above-described points of transforming the energy of microwave EMR pulses into the energy of mechanical vibrations and forms an acoustic signal spectrum available for amplitude-frequency analysis. Thus, the model of a bionic communication channel WITH microwave EMR as a carrier of information is the closest approximation to the original and the results on this model can be considered decisive.

In general, the implementation of both models of a bionic communication channel can be represented by the following steps:

1. Technical development of an equivalent receiver with the implementation of transfer functions by functional blocks reflecting the structural organization of the processes of absorption of microwave EMR and its primary detection by the tissues of the human head, taking into account the physical essence of the interaction of anatomical structures of the head when carrying out the primary selection of the transmitted message and special - the benefits of the peripheral mechanisms of the auditory system that implement the amplitude-frequency signal in displaying the auditory image.

2. Technical development of a transmitter that provides functional transformation of the useful signal (code, speech) in accordance with the amplitude-frequency properties of the threshold curve of bone conductivity when modulating the radiation power, into a signal whose spectral composition correlates with the resonant properties of the human head and the formation of is present at the receiving end of the frequency response necessary for legible perception of the message function.

3. Instrumental testing of the bionic communication channel, including:

a) checking for compliance of the technical characteristics of the functional blocks of the equivalent receiver and transmitter with the developed technical requirements in the modulation and demodulation mode with a test signal in a given frequency band;

b) verification of the main considered ideas and provisions by spectral analysis of the output signal of an equivalent receiver in the mode of receiving and transmitting a test signal under various modulation modes;

c) performance testing by determining the intelligibility of words and syllables according to existing GOSTs in the reception and transmission mode;

d) adjustment of model parameters based on the obtained new results.

4. Transmission of speech signal and code, including:

a) transmission and reception of free text in Russian with determination of the probability of correct speech recognition;

b) transmitting and receiving Morse code by typing on a typewriter or writing the text of a message by hand.

7.2. Technical development of bionic communication channel models

General provisions. In accordance with the bionic receiver circuit defined in clause 6.5, the implementation of the equivalent receiver circuit is achieved by developing a double-circuit resonant model (clause 4.4) with functional blocks that allow receiving information at a distance.

When developing functional blocks of an equivalent receiver, the main issue was the choice of their technical implementation.

An analysis of technical literature has shown that the implementation of individual functions of such a receiver is possible using available technical techniques, however, the structure of an equivalent receiver as a whole does not obey the structural diagrams of known radio receivers. So, for example, according to the type of carrier signal amplification, the equivalent receiver is a direct amplification receiver. Indeed, when an EMR pulse is absorbed by the tissues of the head, there is no conversion of the carrier frequency, as for example in a superheterodyne receiver, and the use of a selective input circuit will reflect the threshold dependence of the pulse power on the carrier frequency [219].

The presence of a pulse detector in an equivalent receiver reflects the formalized function of detecting microwave EMR — tissue by separating the envelope of a radio pulse in the form of a thermal pulse. However, this receiver is not a highly specialized device for receiving only telegraph signals.

The sequence of thermal pulses released by the tissues of the head is transformed into an AM subcarrier signal with a frequency determined by the resonant properties of the anatomical structures of the human head and the degree of their connection, which is represented by a double-circuit resonant system. In fact, these structures perform the primary Fourier transform. An analogue of such a transformation is the process of excitation of shock oscillations in a resonant circuit by a unit function. There is no data in the literature on the use of this type of information converter in radio receiving devices.

Further transformation of the signal, which is an AM oscillation, occurs in the auditory analyzer.

The solution to some technical issues in the development of an equivalent receiver that are not of fundamental importance can be carried out using traditional methods and mainly bear a purely technical burden.

The quality factor of the input circuit of an equivalent receiver can significantly exceed that if it is determined from the threshold pulse power curve [219], and the presence of a high-frequency amplifier (UHF) will only formally reflect the amplification provided by this circuit. However, the absence of these functional units in an equivalent receiver would lead to the need for a powerful transmitter, which would essentially correspond to the real situation in a full-scale experiment, but would create great technical inconveniences and lead to high energy costs . At the same time, such a solution would not fundamentally change the situation in the model experiment. This could also partially include the need to introduce an automatic gain control (AGC) system into the structure of the equivalent receiver in order to prevent overload of the first UHF stage and ensure constant output signal level at different distances between the receiver and transmitter. However, these measures would also lead to a complication of the receiver circuit, without simultaneously reflecting the essence of the ongoing processes. In this regard, it is more advisable to use manual signal gain adjustment.

The use of one or another method of regulating the gain of the useful signal is primarily dictated by the need to set a certain sound pressure level when transmitting a speech signal. When determining the types of microwave EMR modulation in Chap. VI, it turned out to be sufficient to consider individual sections of the frequency-threshold curve of radio sound. In this regard, in an equivalent receiver one can limit oneself to a single-circuit resonant system in order to simplify the solution of technical problems. ca

As shown in Chap. VI information transfer in the PFM mode is realized when the initial repetition rate of microwave EMR pulses is equal to the average value of the high-frequency slope of the pseudoresonance section and its subsequent deviation. In order to bring the model as close as possible to the original, an equivalent receiver may contain a self-oscillator unit synchronized by transmitter pulses, and the FM-AM conversion will be carried out by the anatomical structures of the head by applying an FM signal using a bone vibrator to the bone-tissue formations of the skull. Isolation of the AM signal in this case will also confirm the dependence of the frequency-threshold curve of bone conduction of sound on the resonant properties of the anatomical formations of the head.

The structural diagram of the transmitter of the model bionic communication channel is determined by those discussed in Chapter. VI questions concerning the choice and justification of the type of modulation and carrier parameters.

When physically modeling a bionic communication channel, the tasks that usually occur when implementing one or another type of radio channel were not set: high stability of the carrier frequency, minimal harmonic content, etc. These issues in this case are not fundamental and are not the main indicators bionic communication channel. Therefore, the transmitter itself can be assembled according to the circuit self-oscillator triggered by control pulses coming from the modulator output. Thus, the transmitter block diagram can contain only two functional blocks: a — modulator and a carrier frequency oscillator. Specific transmitter solutions will be discussed below.

One of the important indicators of a bionic communication system is the high stability of the parameters of the pulse sequence due to the linear dependence of the parameters of the subcarrier oscillations excited in the dual-circuit resonant system of the receiver on the parameters of the radio pulse.

Generalization of the provisions discussed above allows us to develop the following technical requirements for the equivalent receiver and transmitter of the model communication channel:

Frequency band of the modulating signal in AIM mode, Hz .. .. 100...2000

Baseband Bandwidth in PFM mode, Hz...... .... 100...4000

The slope of the frequency response of the modulating signal path at the upper cutoff frequency, dB 20

Increase in frequency response of the modulating signal path in the low-frequency region, dB 18.5

Initial duration of modulation pulses, s... 10-5

Pulse duration variation range modulation, p. .... (6.5...25)-106

Pulse repetition frequency in AIM mode, Hz... 10⁴

Initial pulse repetition rate in PFM mode, Hz 1.4-10

Modulation coefficient in AIM mode at the lowest frequency of the passband 0.8

Dynamic range of modulation ratio output AM signal in the frequency band modulating signal, dB 22

Modulation index in PFM mode at the lowest frequency bandwidth 1.0

Pulse repetition rate in a packet in PIM mode, Hz 104

Pulse burst duration and interval between bursts of pulses in PIM mode, s. .. according From GOST to AT signal

Duration of pulses in a packet in PIM mode, with..	5.106
Quality factor of a single-circuit resonant system equivalent receiver, abs. units	2
Upper low-pass filter cutoff frequency of the receiver, Hz	1.4-10+
Slope of the frequency response of the low-pass filter at the cutoff frequency, dB/oct	40
Range of the communication channel for radio frequency models, M. up	to 15
Communication channel range for the microwave model with an isotropic emitter, m. up	to 0.5

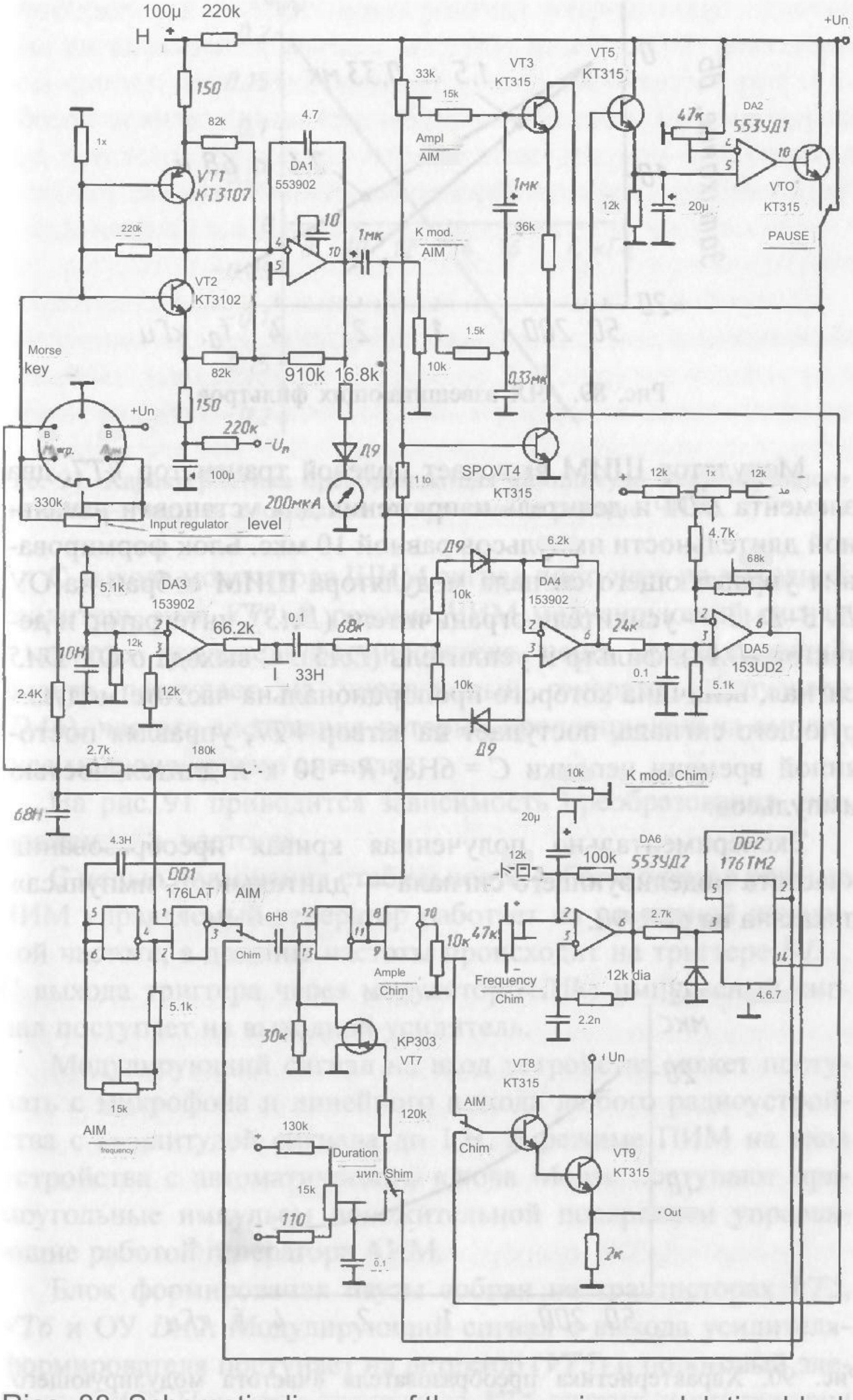
Conversion-modulating block. Defined in Chap. VI parameters of the bionic communication channel signals and the transfer functions of the blocks that convert the input signal and modulate the carrier are universal from the point of view of their applicability in one or another physical model. In this regard, the converter-modulation unit is a complete design and its technical development can be considered independently of the use of a bionic communication channel in a particular model and precede the technical development of these models.

In accordance with the block diagram discussed in clause 6.5.2 and the technical requirements defined in clause 7.2.1, the conversion-modulating block issues a control signal (command) to the transmitter through a buffer device, in the limiting case representing an amplification current and voltage.

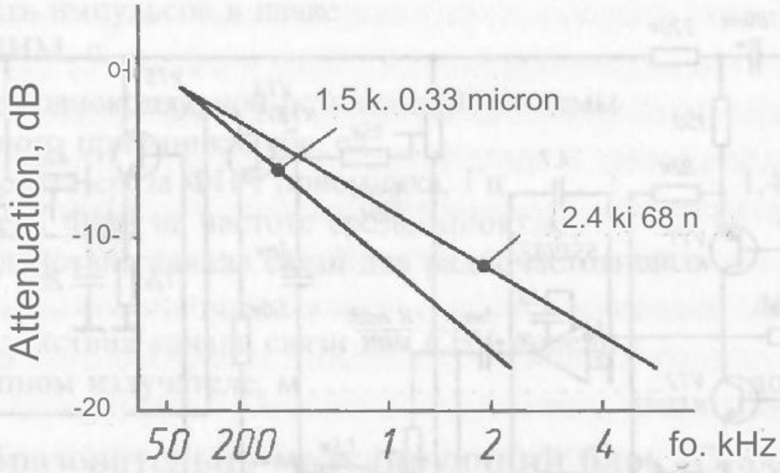
In Fig. 88 shows a schematic diagram. The driver amplifier is made of transistors VT1, VT2 and op-amp DAI. From the output of the amplifier, the signal through weighting filters (R = 1.5 k and C = 0.33 μ in the AIM mode and R = 2.4 k; C = 68N in the PFM mode) goes to the modulators.

In Fig. 89 shows the frequency response of weighting filters that provide the necessary increase in the level of the modulating signal in the low-frequency region.

In the AIM mode, pulses with a repetition frequency of 10 kHz are generated by a generator using two DDI elements and, through a PWM modulator, are supplied to the input of the AIM modulator (VT4). In this case, an amplified modulating signal (VT3) is received at the other input of the modulator.



Rice. 88. Schematic diagram of the conversion-modulating block

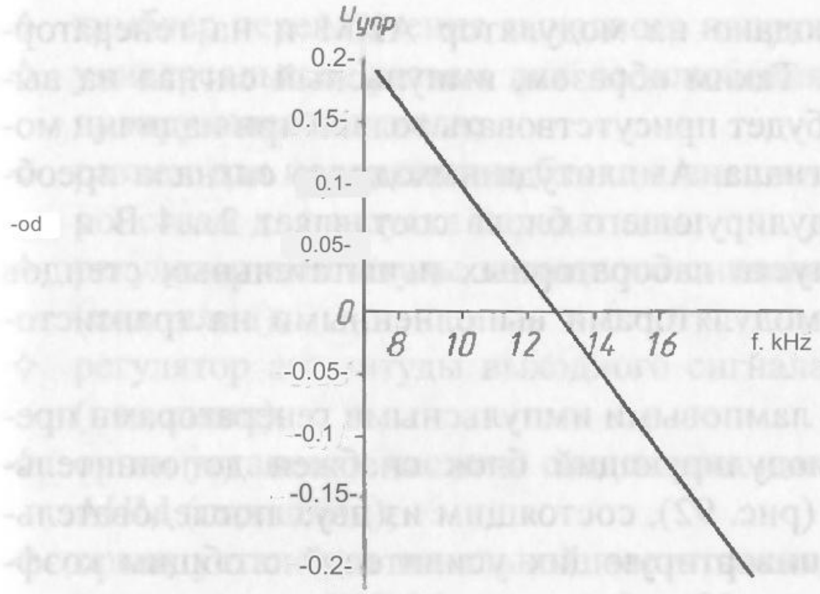


Rice. 89. Frequency response of weighing filters

The PWM modulator includes a field-effect transistor VT7, two DDI elements and a voltage divider to set the initial pulse duration to 10 µs. The block for generating the control signal of the PWM modulator is assembled on the op-amp DA3-DA5 — amplifier-limiter (DA3), integrator and detector (DA4), filter and amplifier (DA5). From output 6 of op-amp DA5, a signal whose value is proportional to the frequency of the modulating signal is supplied to gate VT7, controlling the time constant of the chain C = 6H8; R = 30 k and duration impulses.

The experimentally obtained conversion curve "frequency of the modeling signal is shown in — Fig. 90. Pulse duration"

Rice. 90. Characteristics of the converter "frequency of the modulating signal — pulse duration" of the PWM modulator ofniyaP



Rice. 91. Characteristics of the converter “amplitude of the modulating signal, — pulse repetition rate” in the PIM mode

From the output of the PWM modulator, the signal goes to the output amplifier VT8, VT9. In PFM mode, the modulating signal from the output of the shaper amplifier through the weighing the filter is fed to a controlled pulse generator (DA6), the repetition frequency of which is proportional to the ampli- there is a modulating signal.

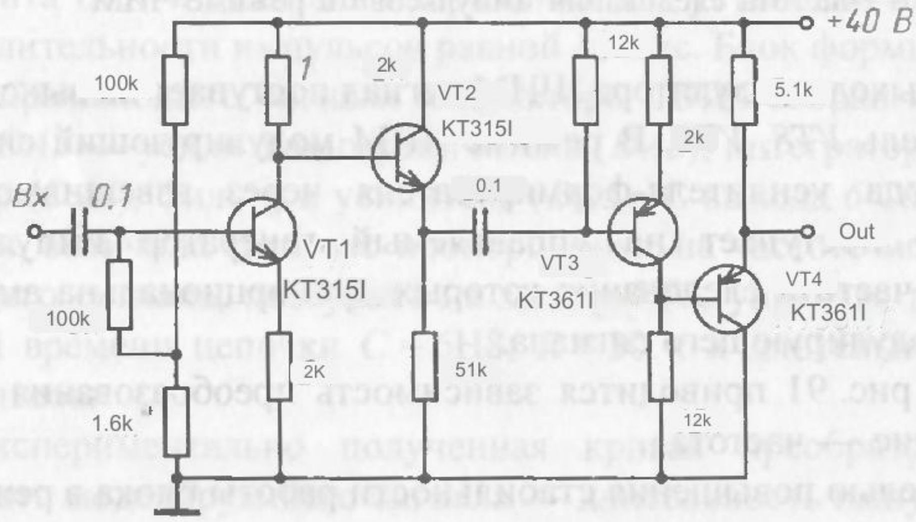
In Fig. 91 shows the dependence of the “voltage-frequency” — conversion.

In order to increase the stability of the unit in PFM mode, the controlled generator operates at double the initial frequency, and frequency division occurs on trigger DD2. From the trigger output, a pulse signal is fed through a PWM modulator to the output amplifier.

The modulating signal to the input of the device can come from a microphone and the linear output of any radio device with a signal amplitude of up to 1 V. In PIM mode, rectangular pulses of positive polarity are received from the automatic Morse key to the input of the device, controlling the operation of the PIM generator.

The pause formation block is assembled using transistors VT5, VT6 and op-amp DA2. The modulating signal from the output of the shaping amplifier is supplied to the detector (VT5) and the threshold element (DA2). In this case, transistor VT6 is open, and the voltage power will be supplied to the AIM modulator and the PFM generator-modulator. Thus, the pulse signal at the output of the device will be present only in the presence of a modulating signal. The amplitude of the output signal of the conversion-modulating unit is 2...4. Sufficient for launching laboratory test benches with pulse modulators made on transistors [93].

To work with tube pulse generators, the conversion-modulating unit is equipped with an additional amplifier (Fig. 92), consisting of two inverting amplifiers connected in series with a total gain of 10.



Rice. 92. Matching inverting amplifier

The conversion-modulation unit is made in two modifications - in the form of a separate universal unit of a desktop design (together with a block power supply) including an additional amplifier and in the form of a printed circuit board organically combined in one housing with a radio transmitter when implementing a model bionic channel communications.

The universal converter-modulation unit contains the following controls: ◇ operating mode toggle switch - AIM-CHIM;

◇ PWM enable toggle switch;

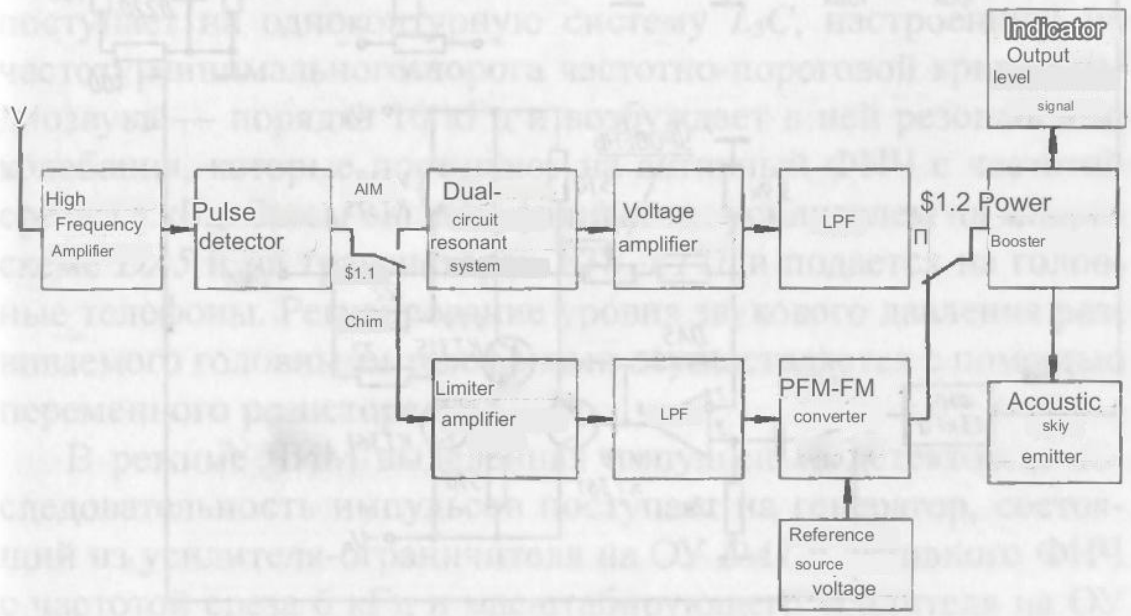
✧ pause switch;

◇ toggle switch for switching output voltage;
◇ universal connector for connecting power sources
blowing signal;
◇ connector for connecting the unit to external buffer devices to start the transmitter;
◇ output signal amplitude regulator in AIM mode (for slot);
◇ output signal amplitude regulator in PFM mode (for slot);
◇ control for setting the pulse repetition rate in the mode AIM (for slot);
◇ control for setting the initial pulse repetition frequency in PFM mode (under the slot);
◇ regulator of constant output signal level.

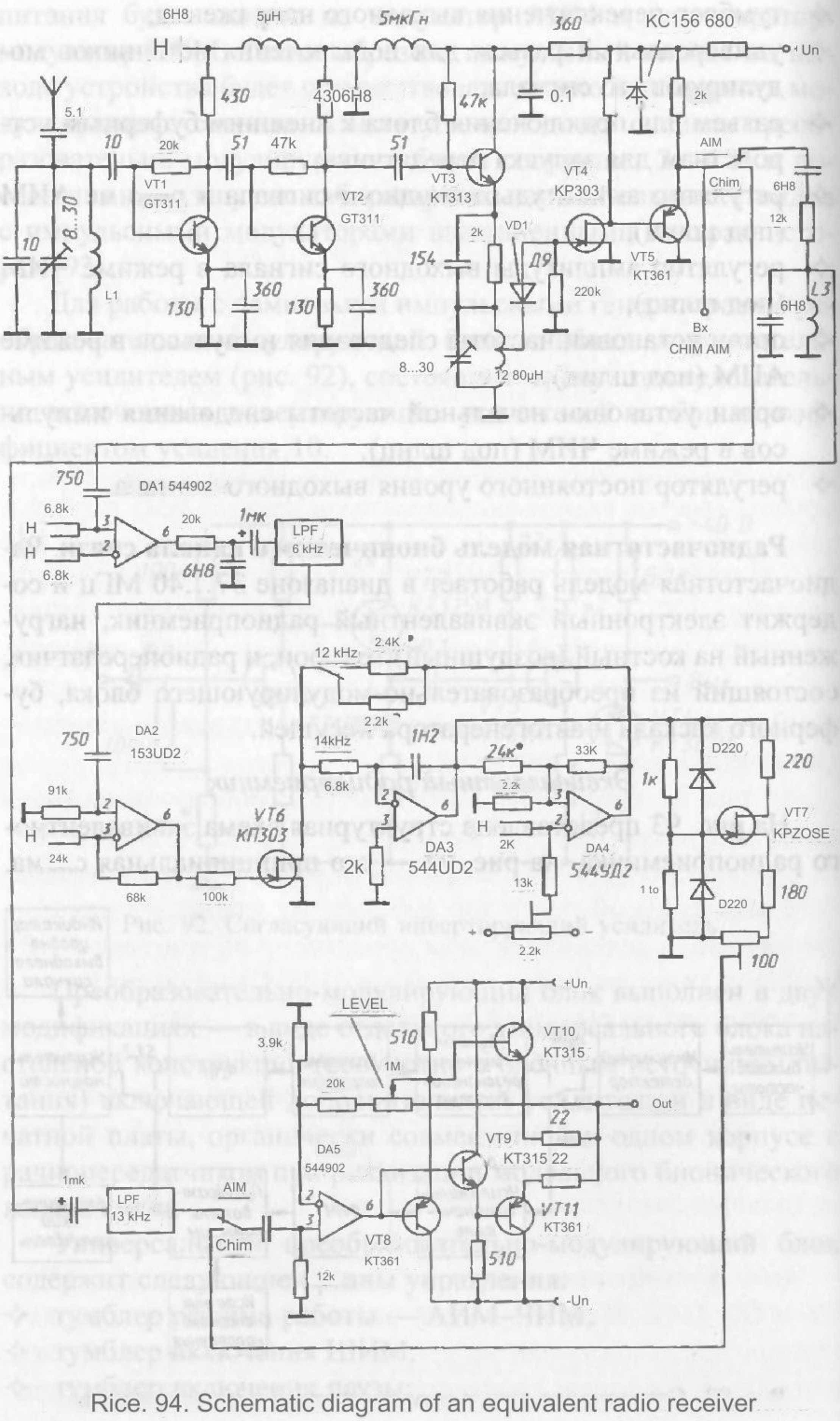
Radio frequency model of a bionic communication channel. Ra- The dia-frequency model operates in the range of 37...40 MHz and contains an electronic equivalent radio receiver loaded on a bone (air) telephone, and a radio transmitter consisting of a converter-modulation unit, a buffer stage and a carrier oscillator.

Equivalent radio receiver

In Fig. 93 shows a block diagram of an equivalent radio receiver, in Fig. — 94 its circuit diagram.



Rice. 93. Block diagram of an equivalent radio receiver



Rice. 94. Schematic diagram of an equivalent radio receiver

The input circuit of an equivalent radio receiver is formed by an antenna and an oscillating circuit tuned to the transmitter carrier frequency. The antenna consists of a telescopic rod and a six-beam star, which makes it possible to obtain an electric quarter-wave rod with a geometric rod length of 955 mm. The connection between the antenna and the circuit is capacitive, which simplifies the circuit of the input circuit and makes it possible to achieve a maximum circuit voltage transfer coefficient of 5. The selective circuit is formed by a constant inductance 11, a trimming capacitance of 8...30 pF and a constant capacitance of 10 pF. The circuit bandwidth is sufficient for the passage of radio pulses without distortion.

The signal from the circuit is fed to a three-stage high-frequency amplifier (UHF), assembled using transistors VT1-— VT3. The cascade on transistor VT3 is assembled according to an emitter follower circuit for matching with the input of a VDI pulse detector. The UHF output stage is connected to the input of the pulse detector using a parallel circuit L2C. This type of connection makes it possible to obtain a higher voltage transfer coefficient of the detector connected to part of the inductance turns of the circuit.

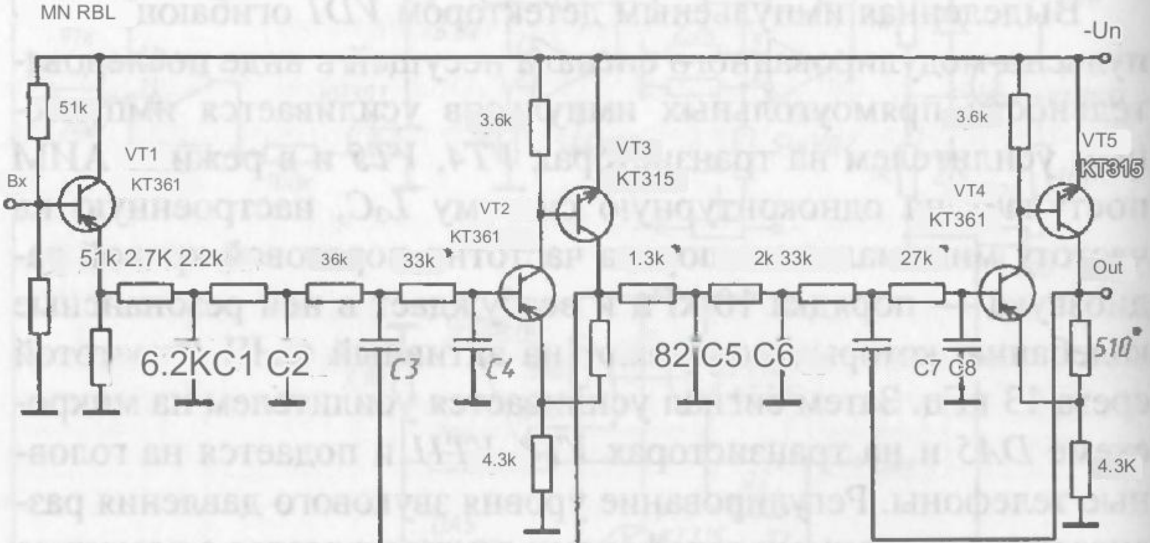
The envelope of the pulse-modulated carrier signal, isolated by the VDI pulse detector, in the form of a sequence of rectangular pulses, is amplified by a pulse amplifier on transistors VT4, VT5 and, in the AIM mode, is supplied to the single-circuit L3C system, tuned to the frequency of the minimum threshold of the frequency-threshold curve of the operation. diosound of the order of 10 kHz and excites resonant oscillations in it, which are fed to an active low-pass filter with a cutoff frequency of 13 kHz. Then the signal is amplified by an amplifier on a DA5 microcircuit and on transistors VT8-VT11 and fed to headphones. The sound pressure level developed by the headphones is regulated using a 1 M variable resistor.

In PFM mode, the pulse sequence selected by the pulse detector is fed to a generator consisting of a limiting amplifier on op-amp DA1 and an active low-pass filter with a cutoff frequency of 6 kHz and a scaling amplifier on op-amp DA2. Output signal representing constant level voltage, proportional to the pulse repetition rate, controls the frequency of a self-oscillator sinusoidal signal with a constant amplitude, consisting of a controlled triangular pulse generator (DA3, DA4, VT6) and a sinusoidal signal shaper on a field-effect transistor VT7.

The controlled oscillator frequency can be set to 12 or 14 kHz using a switch. When the pulse repetition frequency deviates in the PFM mode, the frequency of the self-oscillator is proportionally shifted, and the output signal of the self-oscillator is an FM signal. Thus, the frequency of the self-oscillator is synchronized by the pulse repetition rate of the radio transmitter.

When this signal is applied after amplification to the bone telephone, FM-AM conversion occurs on the high-frequency branch of the pseudo-resonance section, the second

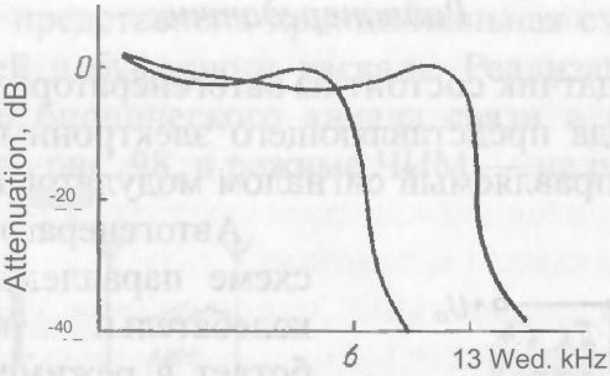
Thus, in the AIM and PFM modes, the auditory analyzer receives an AM signal containing a tone signal with a frequency of 10 kHz (AMM) or 12...14 kHz (PFM) and a signal adequate to the modulating function.



Frequently cut	C1	C2	C3	C4	C5	C6	C7	C8
6 kHz	18H8	5H	10H	500	30H	1H5	1H2	300
РНФ 13 kHz	9N4	2H5	5H	250	15H	770	600	150

VO BH RESTRIK

Rice. 95. Active low-pass filter of an equivalent radio receiver



SNH Rice. 96. Frequency response of active FICs

In Fig. Figure 95 shows a diagram of an active low-pass filter receiver with an attenuation of 40 dB/oct.

In Fig. 96 shows the frequency response of the developed active low-pass filters with the realized attenuation value at cutoff frequencies equal to 40 dB/oct.

The receiver contains the following controls and control:

- power switch; sound
- pressure level regulator;
- toggle switch for switching the type of work in various modulation modes "AIM-CHIM";
- toggle switch for switching the range of the useful signal during PFM - "12...14 kHz";
- connector for connecting headphones;
- connector for monitoring the output signal;
- connector for supplying a modulating signal directly to the receiver in wired communication mode.

RNI

The equivalent radio receiver is powered by four elements of type "3336" connected in series with the middle point.

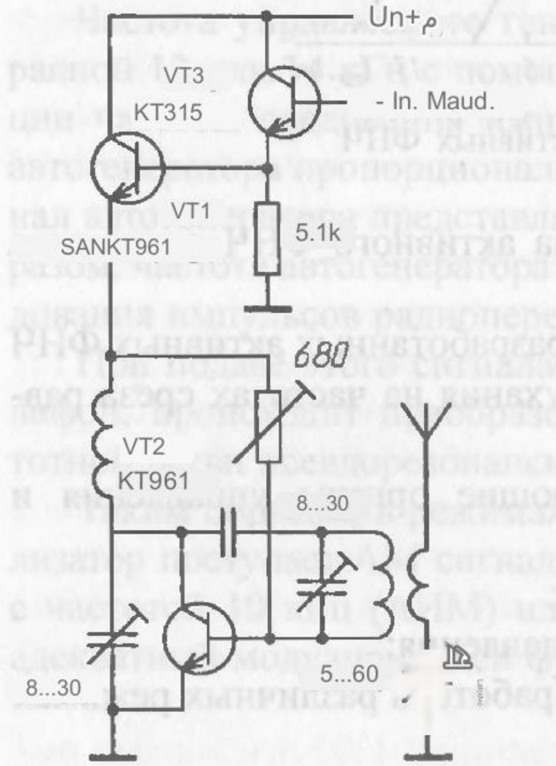
Structurally, the receiver is made in the form of a vertical structure on a duralumin chassis and is closed with a cover made of sheet steel. A telescopic antenna is mounted in an insulator on the top shelf of the chassis. Installation is done by printing. The inductances of the UHF input and output circuits are made of copper wire on polystyrene frames, the inductance of the resonant system is made — in armored of an SB-2a core.

Radio transmitter

The radio transmitter consists of a carrier oscillator and a buffer stage representing an electronic switching key controlled by a modulator signal.

The self-oscillator is assembled using a parallel power supply circuit for an oscillatory circuit and operates in soft excitation mode. This solution to the self-oscillator circuit makes it possible to obtain almost 100% AM analog signal with minimal distortion while simultaneously providing 100% pulse modulation to provide AIM and PFM.

An emitter follower is used as a buffer cascade, the load of which is a self-oscillator. The self-oscillator circuit is inductively coupled to the telescopic antenna. The maximum pulse power in the antenna is about 1 W.



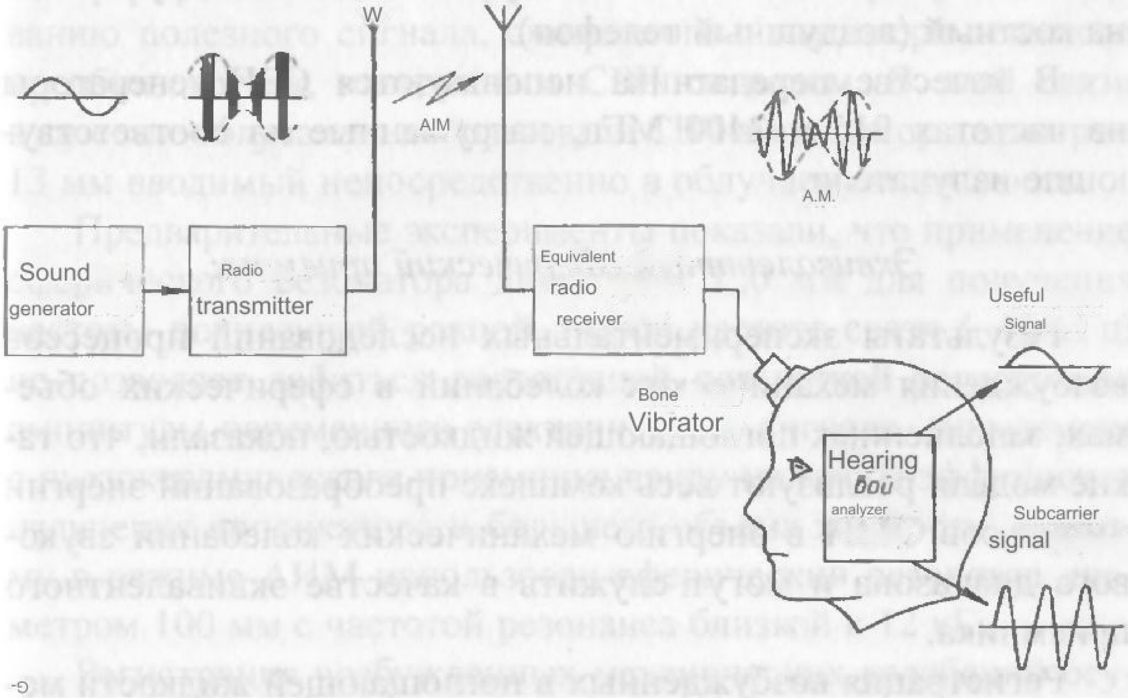
Rice. 97. Radio transmitter

Structurally, the self-generator is made in a duralumin casing of vertical design.

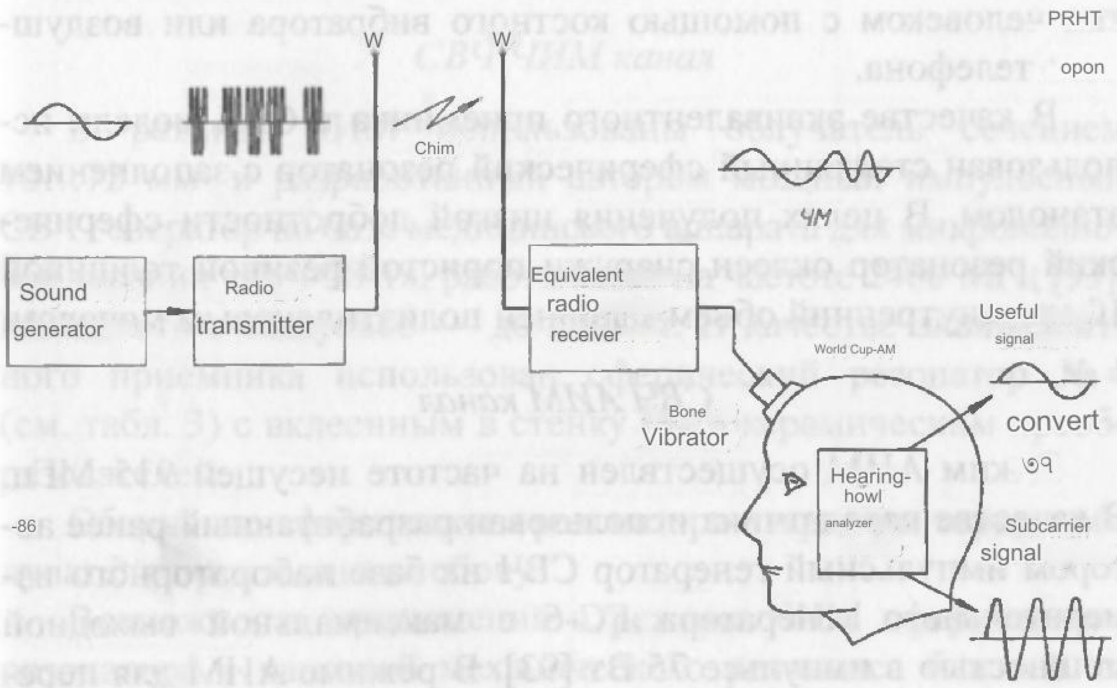
The radio transmitter contains the following controls and control:

- power switch;
- power on indicator light;
- modulation depth regulator;
- pointer device for monitoring modulation depth;
- toggle switch for switching the operating mode - AIM-CHIM;
- pause switch;
- PWM enable toggle switch;
- toggle switch for switching to PIM mode;
- universal connector for connecting mod sources lying signal and automatic Morse key.

In Fig. 97 shows a schematic diagram of a carrier oscillator and a buffer stage. The implementation of the radio frequency model of the bionic communication channel in the AIM mode is shown in Fig. 98, in PFM mode - in Fig. 99.



Rice. 98. Block diagram of the radio frequency model of the bionic communication channel in AIM mode



Rice. 99. Block diagram of the radio frequency model of the bionic communication channel in PFM mode

Microwave model of a bionic communication channel. The microwave model operates in the range 915...2400 MHz and contains a spherical liquid resonator as an equivalent receiver, a piezoceramic sound pressure converter into an electrical signal and a low-frequency amplifier loaded on a bone (air telephone).

Microwave generators at frequencies of 915 and 2400 MHz, loaded onto the corresponding emitters, are used as a transmitter.

Equivalent spherical receiver

The results of experimental studies of the processes of excitation of mechanical vibrations in spherical volumes filled with an absorbing liquid have shown that such models implement the entire complex of transformations of the energy of EMR pulses into the energy of mechanical vibrations in the audio range and can serve as an equivalent receiver.

Registration of mechanical vibrations excited in an absorbing liquid using one of the methods described in Chap. III, allows the use of a signal taken from a piezoceramic transducer for spectral analysis and human perception using a bone vibrator or an air telephone.

A glass spherical resonator filled with ethanol is used as an equivalent receiver in the microwave model. In order to obtain a low quality factor, the spherical resonator is covered on the outside with porous rubber 10 mm thick, and the internal volume is filled with polyethylene bast.

Microwave AIM channel

The AIM mode is implemented at a carrier frequency of 915 MHz. The transmitter used was a microwave pulse generator previously developed by the author based on the GS-6 laboratory measuring generator with a maximum output power per pulse of 75 W [93]. In the AIM mode for transmitting an undistorted analog signal, the maximum power per pulse was 25 W.

The use of this transmitter with subsequent amplification of microwave power to 500 W per pulse when irradiating a spherical model with a rectangular waveguide with a cross-section of 150...270 mm² showed that the presence of strong field diffraction on the spherical model leads to almost complete masking of the useful signal taken from piezoceramic transducer induced by a microwave signal. In this regard, a microwave amplifier with a diameter of 13 mm, inserted directly into the irradiated liquid, was used as an irradiator.

Preliminary experiments have shown that the use of a spherical resonator with a diameter of 120 mm to obtain a subcarrier frequency equal to the second communication frequency (~10 kHz) does not allow achieving an amplitude of the alternating electrical signal taken from the piezoceramic receiver sufficient for clear recording due to the low emissivity of the applicator and the larger volume of liquid. Therefore, in the AIM mode, a spherical resonator with a diameter of 100 mm with a resonance frequency close to 12 kHz is used.

The registration of excited mechanical vibrations was carried out using an autonomous piezoceramic receiver, onto which a spherical resonator was installed directly [98].

Microwave PFM channel

In the PFM mode, an irradiator with a cross-section of 10...72 mm² and a powerful pulse microwave generator developed by the author based on a medical device for microwave therapy "Luch-58-1", operating at a frequency of 2400 MHz, are used [93]. Pulse power up to 500 W. Spherical resonator No. 4 (see Table 3) with a piezoceramic transducer glued into the wall was used as an equivalent receiver.

The spherical resonator is irradiated from the open end of the irradiator from the side.

The possibility of using a spherical resonator in PFM mode with a mechanical resonance frequency close to the second coupling frequency ensured that the model was as close as possible to the original.

Microwave PIM channel

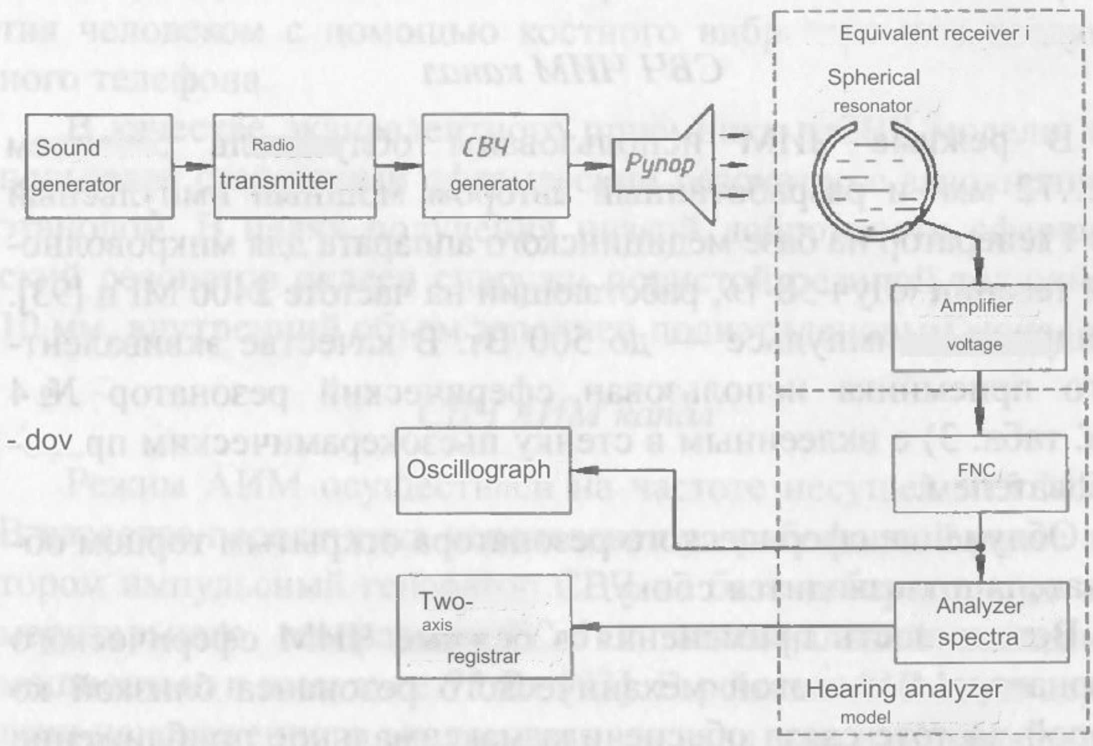
The PIM mode is implemented on a spherical resonator with a diameter of 100 mm. Ethanol irradiation was carried out using an applicator with a diameter of 13 mm, inserted into the liquid. Pulse power up to 100 W, carrier frequency - 915 MHz. The spherical resonator is installed on an autonomous piezoceramic receiver.

The formation of pulse trains is carried out using an automatic Morse key that controls the operation of the converter-modulation unit.

Pulses from the output modulator trigger the microwave generator. The pulse repetition rate was chosen to be 12 kHz, and the pulse duration was up to 20 μs.

7.3. Spectral analysis of the output signal of an equivalent spherical receiver

In the AIM and PFM modes, when modulating a pulsed EMR test signal in the frequency band of an equivalent spherical receiver, the spectrum of mechanical vibrations excited in ethanol was recorded using an SK 4-26 spectrum analyzer and a PA-2 two-coordinate recorder.

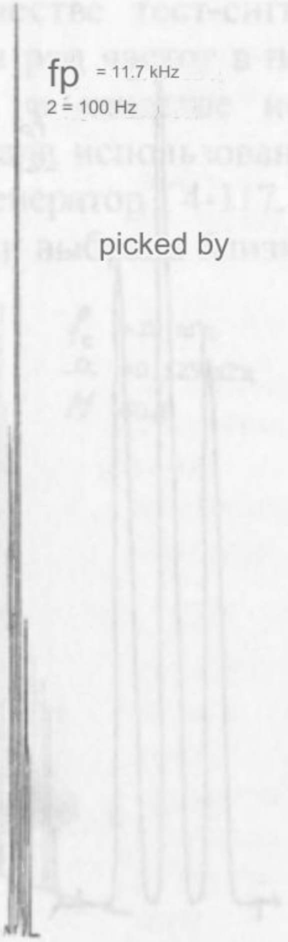


Rice. 100. Microwave model of a bionic communication channel

The passband of the spherical resonator was preliminarily determined at a level of 0.707 of the amplitude of excited mechanical vibrations at the main resonance frequency. Modulation of microwave transmitters was carried out using a developed universal converter-modulation unit. In Fig. Figure 100 shows a block diagram of a microwave model of a bionic communication channel.

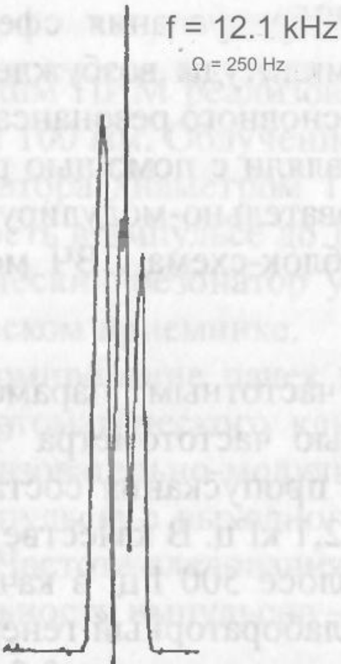
AIM mode. According to the measured frequency parameters of the signals monitored using a frequency meter 43-34, the calculated value of the bandwidth was 500 Hz at a resonance frequency of 12.1 kHz. A number of frequencies in the 500 Hz band were used as a test signal; a G4-117 laboratory generator was used as a test signal source. The modulation depth was varied within 0.3...0.8.

In Fig. 101-107 show samples of recorded spectra, consisting of a subcarrier signal and two side signals.

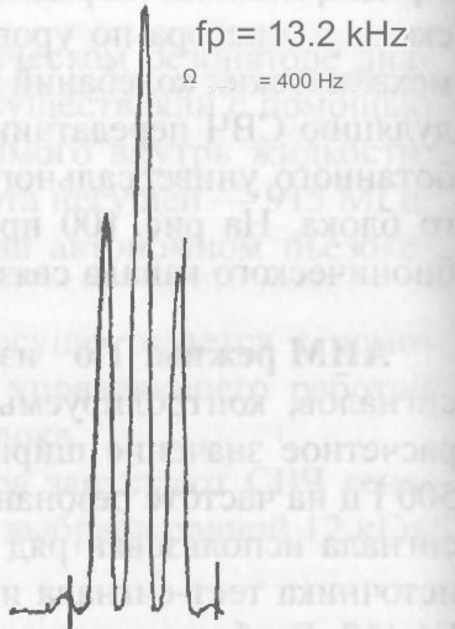


Rice. 101. Spectrum of a spherical model in AIM input mode

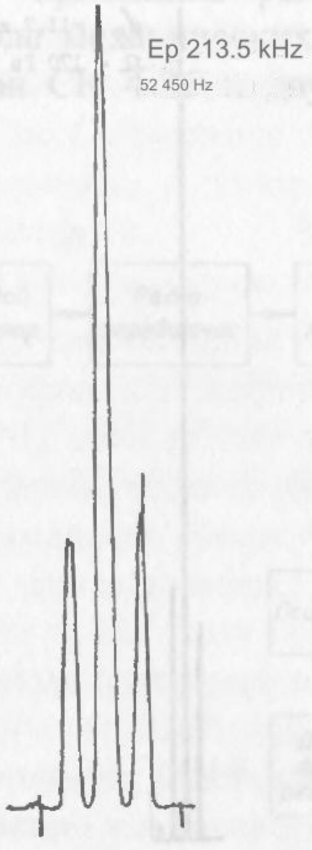
Rice. 102. Spectrum of a spherical model in AIM mode



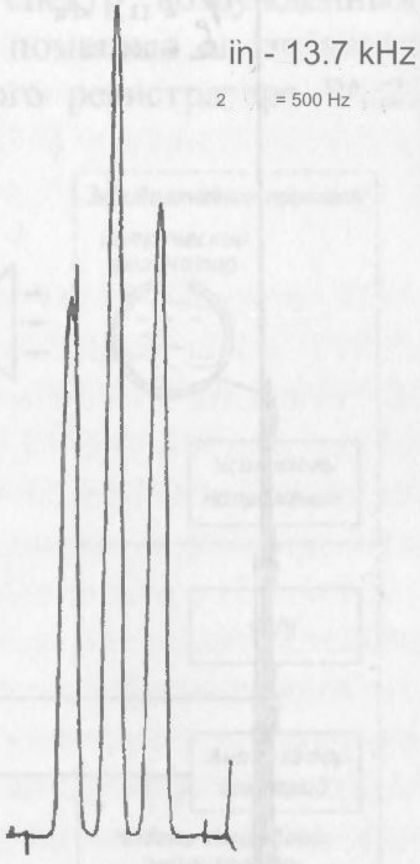
Rice. 103. Spectrum of a spherical model in AIM mode



Rice. 104. Spectrum of a spherical model in AIM mode



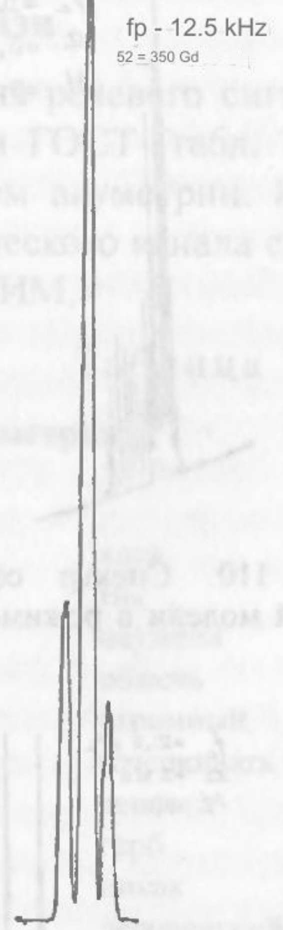
Rice. 105. Spectrum of a spherical model in AIM



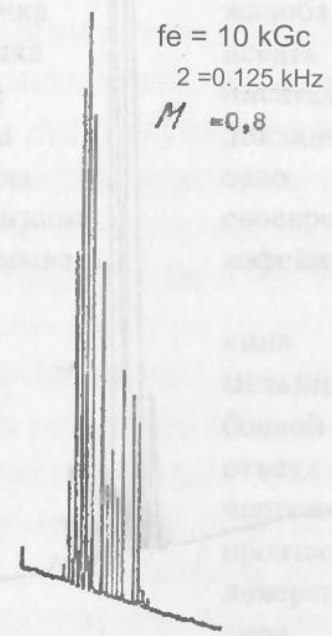
mode Fig. 106. Spectrum of a spherical model in AIMor mode

PFM mode. The frequency of the main resonance and the width of the high-frequency slope of the frequency response of the spherical resonator corresponding to the region of the second coupling frequency of the double-circuit resonant system were determined. Frequency parameters were monitored using a 43-34 frequency meter. According to the measurement data, the initial pulse repetition frequency was set equal to 10.22 + 0.67 = 10.89 kHz using an electronic frequency meter, which corresponds to the middle of the high-frequency slope of the frequency response of the resonator (0.67 kHz half-width of the high-frequency slope in the region of the second communication frequency).

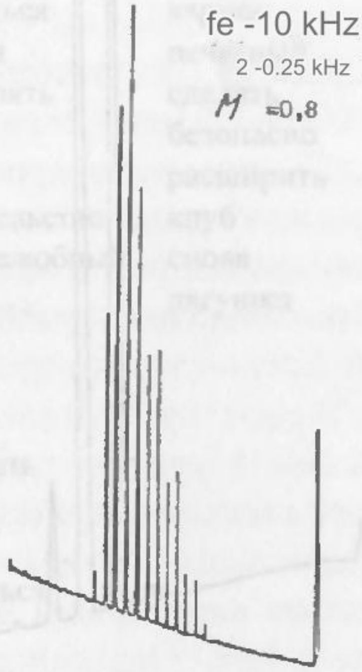
A number of frequencies in a band up to 1000 Hz were used as a test signal; a G4-117 laboratory generator was used as a test signal source. The modulation depth was chosen to be close to 0.8.



Rice. 107. Spectrum of a spherical model in LIM mode



Rice. 108. Spectrum of a spherical model in PFM mode



Rice. 109. Spectrum of a spherical model in PFM mode

Rice. 110. Spectrum of a spherical model in PFM mode

In Fig. 108-112 show samples of recorded spectra consisting of three components, the first side, the amplitude of which is close to the amplitude of the carrier, the carrier signal and the second side and their harmonics in the passband.

It is

NORTH

gov -10.5 kHz

2 -0.5 kHz

M =0,8

-ON BILBHTH-ɔOREA N

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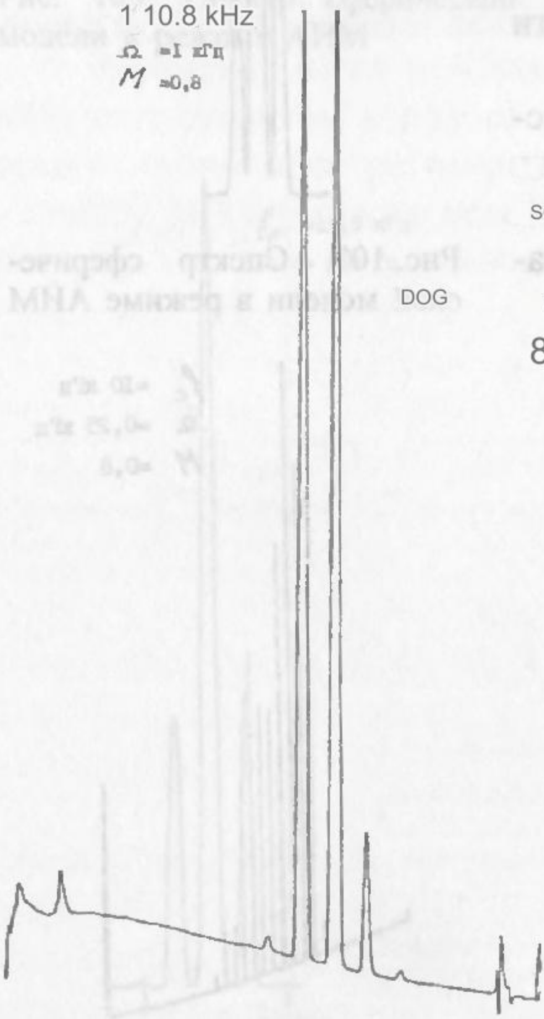
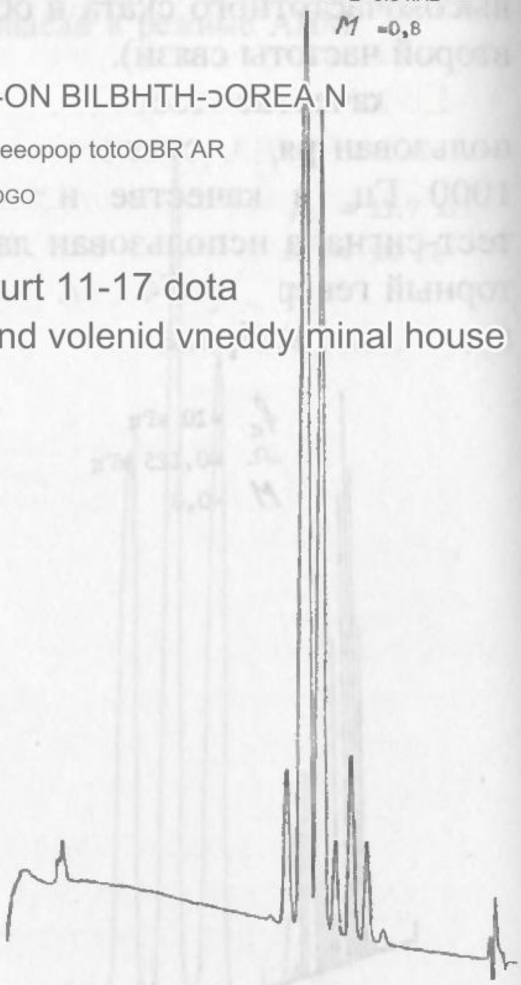
8.0 and volenid vneddy minal house



Rice. 111. Spectrum of a spherical model in PFM mode



Rice. 112. Spectrum of a spherical model in PFM mode

7.4. Acousmetric studies of the bionic communication channel model

The probability of correct recognition of a speech signal when receiving and transmitting words according to GOST tables (Table 16) in Russian [30] was determined by the acumetry method. We used a radio frequency model of a bionic communication channel in the AIM and PFM modes with PWM turned on.

Table 16

List of words for speech audiometry (GOST 12.1.037-82)

demand	from afar	guest	the house
Cute	child	technical College	You
average	old man	clean up	really
scandalous	Goodbye	Language	burn
Adultery	reader	interest	huge
student	quantity	pour over	cross out
eyebrow	sleeve	Fine	warmth
rescue	drunk	such	coat of arms
calm down	machine	throw	no way
sieve	dressing	Hope	rustic
running	tablecloth	ice	fairy tale
refusal	fluffy	Also	hearing
expressive	two	climb	pocket
a jacket	complaint	gait	printed
horse	search	correct	do
except	writer's	kefir	safely
grass	reporter	city	expand
never	village	proof	club
organization	in a timely manner	unfriendly	again
ponder	coffee pot	USA	frog
	Hina	dark	
	mill	taste	
	combat	run out	
	departure	cotton wool	
	draftsman	team	
	performance	fall in love	
	power of attorney	stand	
	crying	rod	
	asks	mode	
	winter	half	

The experiment was carried out in a soundproofed room measuring 2.8x2.8x2.8 m³. The measured noise level in the room is no more than 20 dB. opo

Twenty subjects aged 26-50 years took part in the experiment without any preliminary hearing tests.

The criterion for assessing the performance of the model in the transmission-reception mode was the amount of information received by the test subject divided by the amount of information transmitted.

Experimental technique. The table of words was recorded on a household tape recorder. In the playback mode, the signal from the linear output of the tape recorder was fed to the input of the conversion-modulating unit, the signal from the output of which was fed directly to switch S.1.1 of the radio receiver through a wire connection, i.e. after the pulse detector (see block diagram of equivalent radio receiver in Fig. 93). This was done in order to exclude possible random interference, both high-frequency and low-frequency, when operating a radio channel and thereby identify the direct connection between the parameters of the perceived signal and the parameters of the equivalent receiver.

The receiver's own noise was used as a masker.

Using the passport data of the MKE-2A measuring microphone (self-noise of the measuring microphone 24 dB), the voltage level at its terminals was determined using a V3-33 millivoltmeter with the microphone muffled in a soundproofed room. When the model was operating in AIM mode, the headphones were placed in close proximity to the microphone.

The receiver was turned on and the “signal level” control set the noise signal level to 40 dB according to the readings of the V3-33 millivoltmeter. Then the input of the millivoltmeter was switched to the output connector of the receiver and the voltage level of the noise signal was measured at the headphone terminals. The converter-modulation unit was connected to the receiver and the unit’s controls set the subcarrier level to 50 dB in terms of millivolts.

meters. Thus, a mixed signal consisting of interference and a subcarrier signal was supplied to the headphones.

A signal with a frequency of 100 Hz was supplied to the input of the converter-modulating block from an audio frequency generator, and the modulation depth was set by the block adjustment controls to 0.8. The maximum and minimum values of the subcarrier signal amplitude were determined using the scale of the oscilloscope screen. The audio frequency generator was turned off and a signal from the linear output of the tape recorder was supplied to the input of the converter-modulation unit. By adjusting the output signal level of the tape recorder, a subcarrier modulation depth of 0.8 was achieved. This completed the calibration of the model in the AIM mode.

The subject sat in a comfortable position in a chair and put on headphones. They turned on the recording. The subject, having heard the next word, had to repeat it out loud. At the same time, the experimenter who was nearby marked the correctly pronounced word with a "+" sign in the word table. If the subject reproduced the word incorrectly, the experimenter placed a "-" sign in the table of words against the incorrectly pronounced word. If the subject did not distinguish the next word, he said out loud the phrase "did not understand" and the experimenter also put a "-" sign against the word that the subject did not distinguish. At the end of the recording, the tape recorder was turned off, the film was rewound back and the tape recorder was turned off. The number of correctly perceived test words was counted, their ratio to the total number of words in the table (100) was taken and multiplied by 100%. The percentage of correctly received information was obtained. The level of the total signal supplied to the headphones was adjusted and the entire cycle of operations was repeated with the participation of the next subject.

In the PFM mode, the signal from the receiver output was fed through an additional power amplifier to a bone telephone with a "soft membrane", secured with a rubber belt on the subject's head. The ear canals of the subject were closed with cotton wool pads and Vaseline. Noise suppressors were put on the ears. Previously, the bone telephone was also placed in close proximity to the measurement body microphone and calibrated the millivoltmeter scale as described above.

The voltage level at the clamps of the bone phone was measured. In this case, in the PFM mode, a total signal consisting of the masking noise of the receiver and a tone signal with a frequency of 12 or 14 kHz is supplied to the headset. Using the “signal level” organ of the power amplifier, the signal voltage at the terminals of the bone telephone was increased to a value corresponding to a sound pressure level of 80 dB on the millivoltmeter scale. A converter-modulation unit was connected to the receiver and a signal with a frequency of 100 Hz was applied to its input. The control elements of the unit achieved the deviation of the frequency of the tone signal at the output of the receiver with a modulation index equal to 1. The control was carried out on the scale of the oscilloscope screen. The audio frequency generator was turned off and a signal from the linear output of the tape recorder was supplied to the input of the unit. We turned on the recording and visually achieved the maximum undistorted deviation of the tone signal. This completed the preparation for the experiment in PFM mode.

The subjects who participated in the experiment in the AIM mode were excluded, and the second 10 subjects participated in the PIM mode.

At the end of the series of experiments, the average value of correctly accepted words, expressed as a percentage, was calculated separately for the AIM and PIM modes. The average value of correctly accepted words containing three or more syllables, two-syllable and one-syllable words was calculated separately and also expressed as a percentage.

Research results. In the AIM mode with PWM turned on, according to experiments involving ten subjects at a masker noise level of 40 dB and a useful signal level of 50 dB, word intelligibility was 57.9 ± 10...12%. All subjects accurately accepted 77% of words containing more than three syllables. Two-syllable words were perceived in 40% of cases, one-syllable words in — 27.1% of cases.

In PFM mode without turning on PWM, the noise level was 40 dB, the sound pressure level on the scale of a millivoltmeter calibrated by the noise of the receiver was — 80 dB.

The first experiments showed that the placement of a bone telephone on the subject's forehead in the sagittal plane in the presence of additional noise in the room leads to low word intelligibility. In this regard, all subsequent experiments were carried out with the bone telephone located on the mastoid process.

According to the experimental data, the intelligibility of the received material was 66.6±6%. The number of correctly accepted words containing three or more syllables was 83%, two-syllable and one-syllable words - 52.5% and 32.8%, respectively.

7.5. Transmission and reception of useful information by models

Conducted spectral analysis of demodulated in an equivalent receiver of the transmitted signal, and acoustic studies have shown the validity of the physical approach for analyzing the interaction of head structures and peripheral hearing mechanisms using the quadripole method when solving the problem.

The experimental data obtained showed that the limiting values of the parameters characterizing the functional blocks of the bionic communication channel when processing a useful signal and defined in Chap. VI, are sufficient for confident perception of the transmitted message function without the use of technical means of reception. This confirms the validity and effectiveness of the formalized calculation used to identify the degree of interrelation of equivalent structures and determine transfer functions.

The transmission and reception of useful information of code and speech signals by physical models of a bionic communication channel with human participation is the final stage in testing the formulated principles of information reception based on bionics with the inclusion in the experiment of a complete circuit of a hybrid receiver - an —equivalent receiver and auditory analyzer. This part of the work bears more of a demonstration load, since the fundamental possibility of receiving individual words and quantitative assessment of the parameters of the perceived signal on models of a bionic communication channel in the experiment have already been shown above.

Transmission and reception of useful information by a radio frequency model. The radio frequency model of a bionic communication channel includes a radio transmitter, an equivalent radio receiver and headphones. A random speech signal from the broadcast network was fed to the input of the tape recorder and recorded for one minute. This time was previously determined by calculation as the safe exposure time in a real situation.

In the transmit-receive mode, the signal from the linear output of the tape recorder was fed to the conversion-modulating unit of the radio transmitter to modulate the carrier.

Transmission and reception of speech signal in AIM mode

In the AIM mode, with the help of a modulating signal arriving at the input of the radio transmitter, amplifier frequency modulation of carrier radio pulses. The experiment was carried out in a hall with dimensions of 18x18x8 m. The radio transmitter and radio receiver were located at a distance up to 10...12 m from each other in line of sight.

Six subjects participated in the experiment. With the radio transmitter turned on, each subject subjectively selected the minimum volume level sufficient for legible perception of the text. All subjects fully accepted the transmitted information.

Transmission and reception of speech signal in PFM mode

Using the controls of the radio transmitter and radio receiver, the PFM mode was ensured. In this case, frequency modulation of the carrier radio pulses is carried out using a modulating signal. The location of the experiment and the methodology remained the same. New text from the broadcast network was also recorded randomly onto the tape recorder and then transferred to the subject.

All participants in the experiment fully understood the transmitted text.

Transmitting and receiving Morse code in PIM mode

We used an automatic Morse key filled with rectangular pulses with a frequency of 10 kHz for a long

The duration of the pulses is 5 μs inside the pulses corresponding to the “dot” and “dash” signals. The signal from the output of the automatic Morse key was fed to the input of the converter-modulation unit of the radio transmitter operating in the AIM mode with a pause. Information was received via headphones.

Random combinations of “dots” and “dashes” were transmitted. The subjects had to write down the information they perceived. Previously, the subject listened to a randomly generated transmission to distinguish the duration of the “dot” and “dash” signals.

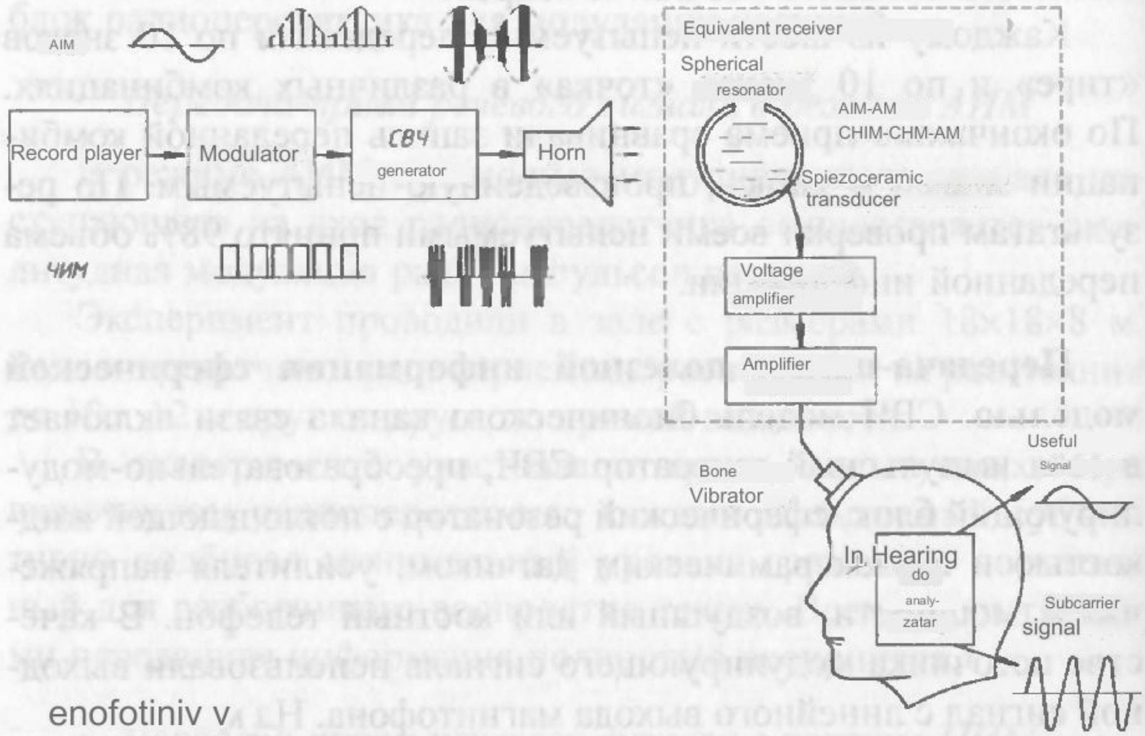
Each of the six subjects was given 10 “dash” characters and 10 “dot” characters in various combinations. At the end of the reception, the recording of the transmitted combination of characters and the recording made by the subject were compared. According to the test results, all subjects accepted 98% of the volume of transmitted information.

Transmission and reception of useful information by a spherical model. The microwave model of a bionic communication channel includes a microwave pulse generator, a conversion modulation unit, a spherical resonator with an absorbing liquid and a piezoceramic sensor, a voltage and power amplifier, an air or bone telephone. The output signal from the linear output of the tape recorder was used as a source of the modulating signal. Random text in Russian was recorded on a tape recorder. The performance of the microwave model was tested in the PIM, AIM and PFM modes. The experiment was carried out in a screened room measuring 2.8x2.8x2.8 m^3 with the participation of six subjects.

In the AIM and PFM modes, the possibility of receiving a speech signal was tested by exciting mechanical vibrations in a spherical resonator filled with ethanol under irradiation with pulse-modulated EMR. The modulating signal, which is free text in Russian, recorded from a microphone on magnetic tape, was taken from the linear output of the Vesna household tape recorder and fed to the input of the converter-modulating unit, the output signal of which controlled the amplitude (AIM mode) or repetition frequency (PFM mode) of microwave pulses. Cont.

The role of the parameters of the microwave pulse sequence was determined using an omnidirectional coupler included in the microwave path and the detector section. The signal from the output of the piezoceramic transducer of the spherical resonator, after amplification, was sent to an air or bone telephone for listening by the subjects.

In Fig. 113 schematically shows a block diagram of an experiment on the perception of speech information in the AIM and PFM modes, indicating the diagrams of the active signals at the output of each functional block.



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Rice. 113. Block diagram of an experiment on the perception of speech information in the AIM and PFM modes with a spherical model

In the PIM mode, the possibility of reception "by ear" was tested with the recording of Morse code characters by subjects unfamiliar with this code.

Using an automatic Morse key and a conversion-modulating unit, mechanical oscillations were excited in the spherical resonator in the form of bursts with different durations, corresponding to the duration of the "dot" and "dash". The oscillations converted into an electrical signal were amplified and suppressed on headphones for listening.

Transmission and reception of speech signal in AIM mode

In the experiment, we used a spherical resonator with a diameter of 100 mm according to clause 7.2.4.2. The power of the microwave pulses in the absence of a modulating signal was 25 W. The perception of the speech signal was carried out using stereo headphones connected in parallel.

With an external noise level in the room of about 20 dB and a signal-to-noise ratio of 2.5 at the telephone terminals, in a frequency band of about 500 Hz, speech intelligibility reaches 60%.

Transmission and reception of speech signal in PFM mode

In the experiment, we used a spherical resonator with a diameter of 120 mm according to clause 7.2.4.3. The microwave pulse power was set within the range of 200...500 W.

Since in the microwave model in the PFM mode there is a direct conversion PFM→FMAM, then in this case the information was received using stereo telephones.

With PWM enabled, the signal-to-noise ratio is 15 and the bandwidth is up to 1000 Hz, speech intelligibility reaches 90%.

Transmitting and receiving Morse code in PIM mode

In the experiment, both types of spherical resonators were used with excitation of mechanical vibrations with frequencies of 10 and 12 kHz. Information was received via stereo headphones. The power of microwave pulses varied within 25...250 W.

With an external noise level in the room of about 30 dB and Morse code transmission with an arbitrary combination of three letters at a transmission rate of one character per second, 100% information reception is ensured.

The justification for the choice of the physical model of the bionic communication channel and its implementation made it possible to experimentally confirm the correctness of the starting premises when developing the principles of bionic information reception and the prospects of a formalized calculation of the physical interactions of anatomical structures using the quadripole method. Govi

Availability of two types of physical models — radio frequency-spherical and spherical made it possible to most fully demonstrate explore the possibilities of a fundamentally new approach when resolving some problems of information transfer based on bionics. Despite the qualitative difference and different structural organization, both models allow you to solve given task, implementing the same methodological approach.

The radio frequency model, containing functional blocks that have analogues in the original and provide formalized transfer functions of the analogues, makes it possible to detail the entire sequence of processes occurring in the original. The completeness and autonomy of the functional blocks of the radio frequency model made it possible to implement all the calculated parameters of the bionic communication channel. This circumstance provides the most flexible and complete study of the characteristics of the bionic communication channel, determining its capabilities when varying certain parameters. In this regard, conducting acoustic studies using a radio frequency model can be considered the most appropriate.

The experimental material obtained on the radio frequency model with the participation of volunteers showed the sufficiency of the theoretically determined values of the main parameters of the bionic communication channel, the bandwidth and sound pressure level of the useful signal for its perception and processing in the auditory analyzer. Refusal of special selection of subjects through preliminary audiometry was aimed at conducting the experiment under more “strict” conditions. Despite this, a fairly high percentage of accepted material was obtained, about 70.

The lack of technical possibility of using uniformly masking noise as interference also obviously led to a decrease in the degree of correct recognition of the speech signal, which was especially evident when determining correctly accepted words of varying complexity. It can be assumed that the actual volume of material received may be greater.

The presence of resonant oscillations with a frequency of 10 kHz in the AIM and a frequency of 12...14 kHz in the PFM mode, as expected from data on the physiology of hearing, does not lead to masking of the transmitted useful signal. Defined in Chap. VI, the need to increase the signal amplitude in the LF region by introducing a frequency-dependent modulation coefficient was confirmed in an experiment on a radio frequency model. When PWM is turned on, the amount of correctly received material increases significantly. Thus, the use of frequency-dependent modulation depth of the subcarrier signal allows for equal-loudness reception of information without increasing the transmitter radiation power.

Despite its advantages associated with the maximum implementation of theoretical calculations and methodological approaches, the radio frequency model does not directly convert the absorbed energy of the carrier signal into a signal perceived by the auditory analyzer. This problem is solved by the spherical model.

When irradiating a spherical liquid volume with complexly modulated pulsed microwave EMR, an analogue of the absorption of electromagnetic microwave energy by the tissues of the head and the release of a modulating signal is realized due to its nonlinear conversion into a thermal pulse and the further formation of a pressure jump, leading to the excitation of mechanical oscillations.

Spectral analysis of the output signal of the spherical model confirmed the presence of three frequency components in the AIM and PFM modes, leading to the formation of an AM signal accessible to frequency resolution.

Thus, on both models, confirmation of one of the fundamental theoretical conclusions was obtained - the need to form a final AM signal during bionic reception of information lying in the audio frequency band.

As in the RF model, the AM signal of the spherical model consists of a subcarrier and a message function. Despite the higher quality factor of the spherical resonator compared to the calculated value of this value for the human head, as an acoustic resonator, leading to a narrowing of the bandwidth, in the PFM mode with PWM turned on, almost complete perception of the transmitted material is ensured.

As shown by the calculations given in Chap. VI, the PFM mode, with equal intelligibility of the perceived material in the AIM mode, can be implemented with significantly lower pulse power, which makes the use of this mode more expedient when transmitting information using a bionic communication channel.

7.6. Brief conclusions

1. The types of physical models that most fully reflect the physical essence of the processes of converting complexly modulated microwave EMR into an auditory sensation during the absorption of electromagnetic energy by the tissues of the head have been determined.

2. Technical requirements have been developed and radio frequency and microwave models of the bionic communication channel have been created.

3. A universal conversion-modulation unit was developed and constructed to encode the message function and control the transmitter in all radiation modes.

4. Using the method of spectral analysis of mechanical vibrations excited in a spherical liquid model, it was shown that the amplitude-frequency characteristics of the recorded spectra correspond to the calculated ones in all modes of irradiation with pulsed microwave EMR.

5. Using the acumetry method according to GOST tables on a radio frequency model, the value of the probability of correct recognition of a speech signal is determined and the sufficiency of the calculated values of the bandwidth and sound pressure of the useful signal for its perception and analysis by an auditory analyzer is shown.

6. On radio frequency and microwave models of the bionic communication channel, the transmission and reception of coded information and free text in Russian was carried out.

7. Using physical models, the validity of the developed principles of bionic reception of information by humans without the use of technical means of reception has been confirmed.

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Chapter VIII

FIELD EXPERIMENT ON TRANSMITTING AND RECEIVING MORSE CODE BY PULSE EMI

8.1. Equipment complex

The results of experimental studies of physical models of a bionic communication channel using the methods of spectral analysis and acumetry and the implementation of code and speech information on models of transmission and reception make it possible to move on to full-scale experiments with the participation of volunteers.

A modernized GS-6 generator with a pulse power of about 30 W was used as a source of microwave oscillations. The feed in the form of a rectangular waveguide with a cross section of 150x240 mm² is connected through a ferrite valve to the output connector of the microwave generator using a coaxial cable. Modulation of the microwave generator with short pulses of 10 μs duration is carried out by a converter-modulation unit. Pulse trains inside the dot and dash signals are formed using an automatic Morse key. Carrier frequency - 915 MHz.

The experiment was carried out in a shielded room with a volume of 5x2.8x2.8 m³, divided into two compartments - generator and operator - connected by a door, providing attenuation of about 25 dB. The generator compartment contained a microwave generator and irradiator, and the subject was also located there. In the operator's compartment there was an experimenter who set the radiation mode using an automatic Morse switch and a converter-modulation unit. The cable connecting this block to the modulator of the microwave generator is passed through a filled filter. The external noise level in the generator compartment is about 25 dB.

During irradiation, the subject was seated in a comfortable position, the subject's ears were covered with cotton wool and Vaseline. The parietal region of the subject's head was irradiated at a distance of 10...20 cm from the open end of the waveguide. The subjects were given telegraph signals corresponding to the letters A, B, C, and the international signal "SOS" in a random sequence.

whop

8.2. Experiment results

The experiment involved three subjects aged 33-45 years, who had no complaints about the auditory system and were not familiar with the telegraph alphabet.

The subject was located in the generator compartment, the subject's eyes were covered with safety glasses. The transfer of information began in any of the first five minutes of the subject's presence in the compartment without any preliminary signal from the experimenter or by applying a pre-modulating signal to the microwave generator. in order to attract the attention of the subject. This was done in order to increase the reliability of reception of transmitted information. The telegraph alphabet was transmitted at a speed of 40-60 characters per minute.

With an average duty cycle of about 20 and calculated values of PPMI = 120 mW cm2 and PPMSR = 6 mW cm-2 of the wave incident on the head, all subjects fully accepted all the material representing sequences of transmitted messages in three different combinations. The transmission time for each of the subjects for one combination of transmitted characters was 30 s. The total irradiation time with 3 min breaks between irradiations was 1.5 min. In this case, the calculated value of the PMSSR for the absorbed power is about 3 mW cm-2.

There were no complaints from the subjects during irradiation and within 5 days after irradiation.

Thus, in a full-scale experiment, the possibility of bionic reception of information by a person during direct reception of pulsed EMR modulated by one of the considered modes of opennet and vmush was confirmed

Chapter IX

ANALYSIS OF THE POSSIBILITIES OF RECEIVING INFORMATION IN THE WATER ENVIRONMENT BY BIONIC WAY

9.1. Assignment of tasks

People are increasingly faced with the need to live in the aquatic environment in connection with its development for their needs. The question inevitably arises about the development of communication means.

The use of traditional methods of organization and technical means for transmitting and receiving information in the aquatic environment can be considered only the initial stage of this problem. It can be assumed that a person's ability to perceive sound information through bone conduction will serve as the basis for the development of fundamentally new means of communication in the aquatic environment.

In this regard, the study of the principles of organization of the auditory system of marine animals and the functions of its individual structures, issues of adaptation to the aquatic environment, methods of encoding and decoding information become particularly relevant. It is these questions that are of great interest when studying human perception of sound information through bone conduction in an aquatic environment.

In the available literature there is practically no information about the development of this direction.

These issues are of particular relevance in connection with solving the problems of communication between underwater and surface objects with scuba divers in modern conditions of their interaction, which in certain situations require extraordinary methods of transmitting and receiving information.

Considering the principles of organizing a communication channel based on bionics using pulsed ultrasonic radiation (US) and applying them to the problems of underwater communication, it would be possible to highlight some advantageous aspects of this method of information transmission, noted in the bionic reception of modulated microwave radiation. readings.

The absence of the need to use technical means of reception when moving a scuba diver increases his mobility and capabilities when performing certain operations. On the other hand, the presence of a dependence of the mechanical resonance frequency of the head on its size can be used to increase the secrecy of information by selecting the pulse repetition rate individually for each scuba diver. The same advantages of a bionic communication channel can be used when exchanging information between scuba divers.

The first stage towards studying the possibility of developing bionic principles for organizing a communication channel can be considered the identification of general patterns and mechanisms of formation of the response of the auditory system to an external stimulus under conditions of functioning in an aquatic environment. In the direction of searching for the optimal temporary change in the parameters of radiation used as a carrier of information, the study of neural activity may turn out to be the most effective.

It is known that various mammals distinguish speech sounds with similar spectral-temporal characteristics if the parameters of these sounds lie within the limits of the perceived frequencies and resolution of the animals' hearing.

The correspondence of the pattern of neural activity to the spectrum of the speech signal used as a testing stimulus will not only allow us to study the capabilities of the auditory system in an aquatic environment under conditions of perception of sound information through bone conduction. By transposing the spectrum of the speech signal into the range of frequencies perceived by one or another marine mammal, it will be possible to significantly expand communicative capabilities when communicating with animals. So, for example, in del-

Finally, hearing sensitivity in air in the region of optimal frequencies is 30 dB lower than in water. In the frequency range of the speech range, the decrease in sensitivity is even greater - an additional 20...40 dB. This means that when a person communicates with a dolphin in the air, only a small part of the transmitted information can be perceived by the dolphin in a form that is completely inadequate to the original testing signal.

Thus, the implementation of a communication channel based on bionics in an aquatic environment can not only significantly increase a person's communicative capabilities, but also solve a number of problems of a fundamentally new nature.

As the first stage of research into the possibility of the existence of a communication channel based on bionics in an aquatic environment, it is necessary to analyze the data on the following points: * theoretical analysis of the conditions for transforming the absorbed energy of ultrasound pulses into a low-frequency signal in a spherical mathematical model;

◇ experimental verification of the results of theoretical analysis on spherical physical models under conditions of wide variability of ultrasound parameters;

◇ assessment of the communicative capabilities of marine animals (dolphins) and search for mechanisms for the formation of frequency-threshold curves of humans and animals during bone conduction of sound in the aquatic environment.

The results of such a study could serve as a basis for determining the characteristics of a bionics-based communication system in an aquatic environment.

9.2. General provisions

The implementation of a bionic communication channel in an aquatic environment, by analogy with a channel based on microwave EMR in air, is possible in the presence of pseudo-resonance sections on the threshold curve of hearing sensitivity during bone conduction of sound (or on the loudness curve).

The possibility of perceiving an auditory sensation when a person is immersed under water under conditions of irradiation of his head with microwave pulses was demonstrated in [234].

According to the subjective assessment of the subjects, the pitch of the emerging auditory sensation did not change when the subject's head was gradually immersed under water. There was only a decrease in sound intensity as the immersion progressed, until its complete disappearance when the subject was completely immersed under water, when the layer of water above the head began to act as a screen for microwave EMR.

This result directly confirms the above-substantiated mechanism for the formation of the auditory sensation when the head tissue is irradiated with microwave EMR pulses through bone conduction of sound. However, fundamentally important from the point of view of the possibility of implementing a bionic communication channel in an aquatic environment is the fact that the height of the perceived tone is constant when the head is immersed in water.

The similarity of the perception of auditory sensation by subjects in air and in water allows us to assume the identity of the conditions for the propagation of mechanical vibrations in the tissues of the head after their excitation by microwave EMR pulses and, to some extent, to assume the existence of the same threshold curve for bone conduction. However, this position needs experimental confirmation.

In the known literature, the question of the possibility of creating a communication channel in an aquatic environment based on bionics has not been discussed. The works [4, 19, 20, 24, 76-78] present the results of studies of the effects of amplitude-modulated and pulse-modulated ultrasound directly on the auditory nerve for the purpose of hearing prosthetics. According to these studies, the constant-sign radiation pressure created by ultrasound in a medium, caused by a high-frequency carrier, changes in the amplitude modulation mode according to the law of the modulating signal and can cause the occurrence of auditory sensations. At focused ultrasound intensities above 100 W. cm 2 its effect on the auditory nerve fibers is manifested. According to these authors, minimum perception thresholds were obtained only by combining focused ultrasound with an ear labyrinth. A high level of intensity of focused ultrasound, reaching up to 240 W cm 2 at the target when modulating ultrasound with a speech signal [15] and the need for local

Such effects make it difficult to use the described method of stimulating the auditory nerve to create a bionic communication channel. It should also be noted that these references do not contain data from clinical observations of long-term exposure to focused ultrasound.

oto At sufficient power levels of ultrasound pulses, heat is generated when they are absorbed in tissue [146]. Based on the data [32, 33, 217], we can assume the presence of unified physical processes leading to the generation of mechanical vibrations and the identity of the mechanisms of excitation of auditory sensations in humans by microwave EMR and ultrasound pulses due to the transformation of the energy of the irradiating field when it is absorbed by the tissues of the head into acoustic energy vibrations of the sound range. However, the fundamental difference in the very mechanisms of absorption of energy from microwave EMR and ultrasound can lead to a significant difference in assessing the required level of absorbed energy to generate a pressure jump sufficient to excite the auditory sensation.

The commensurability of the ultrasound carrier wavelength with individual anatomical structures of the skull and the possibility of its direct perception by an auditory analyzer [81] up to frequencies of 225 kHz during bone conduction of sound lead to the need for experimental verification under natural conditions of the possibility of differentiated human perception of the ultrasound carrier signal and a low-frequency acoustic signal adequate to the modulating one. In this case, one of the main points is the assessment of hearing sensitivity by bone conduction under conditions of loading the human head, as an acoustic resonator, with a denser medium than air.

Modern literature completely lacks any experimental data on the generation of acoustic vibrations by ultrasound pulses in resonant physical models, as well as quantitative estimates and experimental data on the excitation of auditory sensations in humans by ultrasound pulses.

The work [217] presents the results of studies of the effect of ultrasound pulses with a carrier frequency of 98.8 and 143.5 kHz directly on the bone formations of the guinea pig skull.

The data obtained in this work show that in the case of irradiation of the human head with ultrasound pulses, the generation of mechanical vibrations can occur after the absorbing tissues perform a formalized detection function. Just as for microwave EMR, the similarity of the shape of the microphone potential under the action of an ultrasonic pulse and a sound click is shown.

Analyzing the experimental results in [217], we can come to the following conclusions:

1. Based on the given value of the amplitude of the voltage exciting the ultrasonic emitter, one can roughly estimate the maximum intensity of ultrasonic vibrations of 4 W. cm 2.

2. At the indicated voltage amplitude at the emitter, the potential amplitude in the round window of the cochlea reaches 1 mV.

3. A decrease in the voltage amplitude at the emitter by 20...30 dB leads to an almost complete disappearance of the potential in the round window of the cochlea.

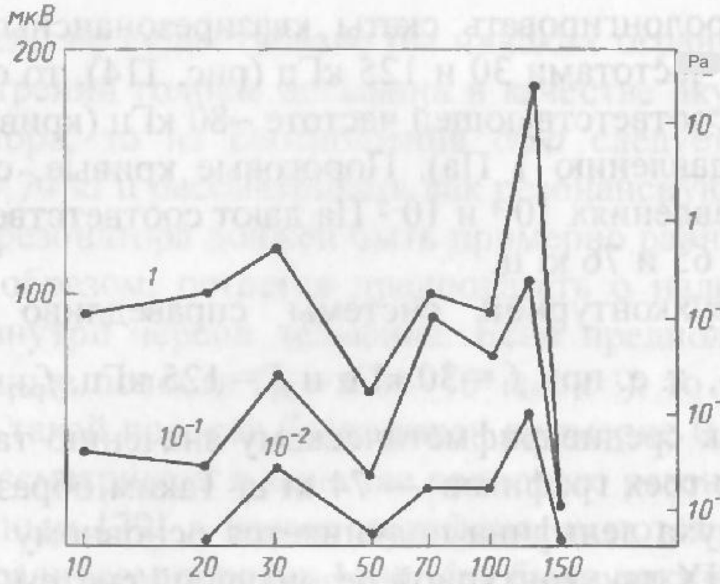
4. The potential in the round window of the cochlea has the form of a damped oscillation.

9.3. Possible mechanism for the formation of the frequency-threshold curve dolphin auditory system

Of particular interest is the transfer of information to marine animals, in particular dolphins, taking into account the features of the bone-tissue audiogram, in order for them to carry out certain commands. This problem can be solved using existing technical means, but in this case a large amount of information is lost due to the narrowing of the frequency range when commands are given by various whistles.

In this regard, it is of interest to analyze some of the results of electrophysiological studies of dolphin hearing depending on the parameters of the acoustic stimulus [126], obtained by the method of evoked potentials (EP) in the auditory cortex.

In Fig. 114 shows the dependence of EPs in the auditory cortex of the dolphin, arising in response to the inclusion of a tonal signal, on the intensity and frequency of the sound [71].



Rice. 114. Dependence of EPs in the auditory cortex of the dolphin that arise in response to the inclusion of a tone signal on the intensity and frequency of the sound

A significant increase in VP, as can be seen from the graph, occurs at frequencies of 30 and 125 kHz. At the same time, as the authors note, with a maximum response to a frequency of 125 kHz, the response to a frequency of 150 kHz is practically absent.

Let us analyze this graph, applying the main provisions of the working hypothesis proposed here about the excitation of resonant oscillations in the anatomical structures of the head.

Considering the selective increase in the EP amplitude at frequencies of 30 and 125 kHz as a manifestation of the resonant properties of certain anatomical structures that play the role of acoustic resonators, and applying the concept of a two-circuit model, we will determine the equivalent parameters of these resonators. The maximum change in the EP amplitude at a frequency of 125 kHz occurs at a sound pressure of 1 Pa. In this case, the bandwidth of the equivalent circuit at a pseudo-resonance frequency of 125 kHz can be determined by the value 20...30 kHz (quality factor 6).

For a pseudoresonance frequency of 30 kHz, the maximum change in the EP amplitude is observed when the sound intensity changes by 10-1 Pa. Drawing the point of “zero” response at a level of 32 µV, we obtain a signal bandwidth of about 11 kHz with a quality factor of 2.7.

If we extend the slopes of the quasi-resonant sections with average frequencies of 30 and 125 kHz (Fig. 114), then they converge at a point corresponding to a frequency of ~80 kHz (the curve corresponding to a pressure of 1 Pa). Threshold curves taken at sound pressures of 10-1 and 10-2 Pa give values equal to 65 and 76 kHz, respectively.

For a two-circuit system, the equality fpes = fi+f2 2 is true, i.e., at f = 30 kHz and f = 125 kHz, thres = 77.5 kHz, which is close to the arithmetic mean value of such a frequency for all three graphs - 74 kHz. Thus, the general course of the frequency response of a dolphin's hearing obeys the basic law of constructing the frequency response of a double-circuit resonant system.

According to the authors, the greatest increase in the amplitude of reactions at signal frequencies of 60...70 kHz, noted in Fig. 114, occurs only in isolated cases. The authors also admit the possibility of directing a response to the recording electrodes from nearby areas of the cortex that respond to signal frequencies that differ greatly from each other (from 10 to 125 kHz). The audiograms of the bottlenose dolphin presented in [66, 188] have the same double-humped character.

- The average frequency value obtained graphically, equal to an average of 74 kHz, should reflect a very significant quality, representing the value of the mechanical resonance frequency of the dolphin's head (by analogy with the mechanical resonance frequency of the human head), or some cavities inside the head. Moreover, according to the concept of the two-circuit resonant model, there should be two cavities. But if the relation cut-in uch = determine is applicable to the frequency of mechanical resonance of the human head, then for a dolphin it could hardly be applied for two reasons:

- ◇ the anatomy of the dolphin's body structure does not allow us to distinguish the head as a more or less pronounced acoustic resonator, but at the same time, the Q-value obtained here graphically equal to 6 indicates a greater "isolation" of such a resonator from the body of the dolphin, in other words, the supposed resonator is less loaded ;

◇ even if there were no restrictions when considering the head of a dolphin as an acoustic resonator, then from the ratio c/2a it follows that if the frequency of 74 kHz is considered as resonant, then the radius of such a resonator should be approximately equal to 1 cm.

Thus, it remains to assume that there are some cavities inside the dolphin's skull. Assuming that these are air cavities (C = 0.34 105 cms-1), then in this case In this case, the radius of such a cavity will be approximately 0.24 cm, if the cavity is considered as a wave resonator. M According to [79], in the head of a dolphin there are air cavities with a radius of about 1 cm. As was shown in Chap. III, in a spherical resonator it is possible to excite a large range of frequencies, which is also noted in [55], depending on the parameters of influencing force.

The lower frequency of such a resonator could be estimated at about 4.5 kHz, if we consider the air cavity as a quarter-wave resonator. Oscillations with such a frequency can be excited at a low speed of air injection into the cavity and a minimum duration of air injection of the order of 220 μs. With increasing speed of air injection, the oscillation frequency increases and in the limit can reach 18 kHz for an air cavity and about 72 kHz for a cavity filled with water or tissue. In this case, excitation of overtones is not excluded, so such a cavity can also be considered as a harmonic generator.

A similar mechanism for excitation of oscillations explains the ability of a dolphin to instantly change the frequency of its location signals.

A brief analysis of the results of some works devoted to the electrophysiology of data on the effect of pulse-modulated ultrasound on the formation of responses of the guinea pig cochlea showed the possibility of using the principles of formation of a useful signal discussed above in the bionic reception of modulated microwave EMR to implement an identical communication channel with guinea pigs. animals. For the previously defined types of modulation, a necessary condition for bionic reception of information is also the presence

linear dependence of the EP amplitude during amplitude modulation of pulses, which actually occurs [72].
For the PIM mode, applied to a pseudo-resonance frequency of 125 kHz, the useful signal bandwidth can be estimated at 10...15 kHz; for PFM with an average pulse frequency of 137.5 kHz, it is about 12.5 kHz.

According to the data given in [217], the threshold pulse power of ultrasound for a guinea pig is 0.13...0.4 W cm 2. This value is in good agreement with the threshold pulse power of EMR in field experiments on radio sound (0.1. ..0.6 W cm-2).

Experimental data [66] make it possible to estimate the threshold pulse power of ultrasound when perceiving acoustic signals from a dolphin.

At an external noise level of about 50...60 dB, the threshold pulse power of radio sound is determined to be 0.1...0.3 W. cm-2. According to [66], the auditory threshold of a dolphin at the same level of external noise is equal to the auditory threshold of a human. According to data [188], the auditory threshold of a dolphin, determined in a soundproofed artificial pool, is 10-18 W cm-2, i.e., two orders of magnitude lower than that of a person. If we take these data as the absolute threshold of hearing sensitivity for a dolphin, then the threshold pulse power of ultrasound for a dolphin can be estimated at about 106 W cm-2. It is also necessary to take into account the fact that the threshold values of pulsed microwave EMR were obtained with a pulse duration of 10 μs. The pulses emitted by the dolphin are significantly longer by one to two orders of magnitude, i.e., they have more energy.

Some of the provisions considered here were published in [99].

According to estimates in [79], the intensity of acoustic vibrations emitted by the dolphin is not lower than 104 W cm-2. The relationship between these quantities, as well as those discussed in Chap. IV correlates, in principle, allow us to make an assumption about the mechanism of auditory perception in dolphins associated with the generation of mechanical vibrations in tissues when absorbing the energy of an emitted acoustic pulse. With this approach, the carrier

Ultrasound can also be considered as a carrier of the message function.

According to [72], the following features of the occurrence of EPs in the auditory cortex can be noted, correlating with the excitation of the signal in the resonant oscillatory system:

◇ linear increase in EP amplitude with increasing duration of the acoustic pulse from 0.5 to 5 ms;

◇ linear dependence of the EP amplitude on sound intensity up to levels of 50...60 dB;

✧ proportional decrease in the EP amplitude with deviation of the signal frequency relative to the pseudoresolution frequency nance;

✧ decrease in the amplitude of VIT with increasing duration of the front of sound bursts.

In table 17 presents for comparison the results of model experiments performed on various physical models, full-scale experiments on radio sound and bone tissue audiometry, and data from electrophysiological studies of the auditory system of dolphins and guinea pigs.

The data presented in this chapter allow us to present the following model of the formation of sensation during bone conduction of sound. When pulsed non-ionizing radiation acts on the bone and tissue formations of the head, due to the absorption of the pulse energy, a pressure jump is formed, leading to tissue expansion and the generation of free vibrations. Due to the presence of resonant properties of the head, oscillations are most intensely excited in the tissues with a frequency determined by the size of the head as a resonator with a free boundary. The pressure wave, spreading through the bones of the skull, activates hair cells through the main membrane of the cochlea. The shape of the pressure wave is determined by the resonant properties of the multimode resonant system, represented by the anatomical structures of the head.

Thus, both in the case of exposure to microwave EMR pulses and when exposed to ultrasonic pulses, the processes of primary conversion of radiation energy into a stimulus-like signal are of a physical nature.

Comparative experiments

No n/p	Model experiments: Double-circuit resonant model	Psychoacoustic studies of human hearing: Subjective assessment of auditory sensation in full-scale radiosound experiments	Audi po n provo u che
1.	At the resonance frequency of the oscillatory circuits there is a significant decrease in the signal amplitude transmission coefficient, and at communication frequencies there is an — increase. In this case, cut = 1 + 2 for circuits with low quality factor	Raising the threshold 10 dB at a microwave pulse repetition rate equal to the mechanical resonance frequency of the head, determined by the ratio cut-in = 0.5c/a. At frequencies 1 and 2, a decrease in the threshold is observed	Rise above 1 per frequent strong hour f_1
2.	Excitation of damped oscillations by individual pulses: a) microwave in liquid mo- Delhi; (6) voltages in the electronic- model; c) perception "by ear" of shock oscillations excited in a liquid model by microwave pulses	Perception of individual clicks at microwave pulse repetition rates below 100 Hz	Perception of the relevant impulse for the signal, f Cut
3.	Linear dependence of the amplitude of sound pressure on pulsed microwave power in liquid models, the amplitude of excited mechanical vibrations on the pulse amplitude in the electronic model	Dependence of the level of perceived radio sound on pulsed microwave power	Depends not resp sound it СИВНОСТИ
4.	Increasing the amplitude of excited mechanical oscillations with increasing pulse duration within 0...0.5T for any models	Reducing the threshold for the perception of radio sound with increasing duration of microwave pulses in the range of 0...50 μs at T-100 μs	

Table 17

mental data vania	Electrophysiological studies on animals	
ometry of human bone susceptibility	Guinea pig	Dolphin
threshold 2...14 dB te tonal signal equal to mekogo resolovy brez otah communication Glitches no threshold	—	The presence on the audiograms of the bottlenose dolphin in the region of stimulus frequencies of 10...150 kHz of areas with frequencies equivalent to frequencies f1, f2 and brez and the course of the threshold curve identical to the threshold curves of radio sound and the human audiogram by bone conduction . The same occurs for the amplitude-frequency dependence VP bridges in the Azov dolphin
from - clicks awakening sound owls with an hour equal to	The presence of potential in the round window of the cochlea in the form of a short damped oscillatory process when the bones are excited by ultrasound pulses	Recording of EPs in the auditory cortex during stimulation with an auditory click

Continuation of the table. 17

vania	Electrophysiological studies in animals	
ometry of ОСТНОЙ the human capacity	Guinea pig	Dolphin
and level of the amplitude of the from inter- incentive	Dependence of the amplitude of the microphone potential of the cochlea on the intensity of the ultrasound pulse	Linear dependence of the logarithm of the EP amplitude on the logarithm of the intensity of sound stimulation
—	—	Direct dependence of the EP amplitude of the auditory cortex on the duration of sound stimulation

End of table. 17

№ n/p	Model experiments	Psychoacoustic studies of human hearing		Electrophysiological studies in animals	
	Double-circuit resonant model	Subjective assessment of auditory sensation in full-scale radiosound experiments	Bone conduction audiometry in humans	Guinea pig	Dolphin
5.	When the time interval between pulses is equal to or less than the decay time of the oscillatory process, with its further decrease, a periodic decrease in the amplitudes of the half-wave of the next oscillation period is observed	—	—	Decrease in the last half-wave of the cochlea's microphone potential when the interpulse interval decreases to a value less than the response decay time	A decrease in the EP amplitude of the auditory cortex with an increase in the interpulse interval by an amount commensurate with the time of action effects of two half-waves
6.	Reducing the amplitude of excited mechanical vibrations in physiological solution by microwave pulses when the temperature of the solution decreases	—	—	Decrease in the amplitude of the microphone potential of the cochlea when the head tissues are cooled	—
7.	Suppression of mechanical vibrations excited in the liquid model by microwave pulses by an external acoustic signal of equal frequency, which is in antiphase with the excited ones mechanical vibrations	Disappearance of the perception of radio sound with the simultaneous application of an acoustic antiphase signal of equal frequency	Disappearance of sound perception during bone conduction with simultaneous application of an antiphase acoustic signal of equal frequency through the auditory canal	—	—

• A comparison of the human bone-tissue audiogram and the dolphin audiogram showed the presence of similar areas that obey the concept of a two-circuit model. The qualitative similarity of the excited oscillations in spherical liquid models by microwave EMR pulses and the recorded acoustic signals emitted by dolphins during shock excitation of mechanical oscillations by blowing air into the cavities formed by the bones of the skull supports the put forward concept of a double-circuit resonant model of radio sound. and allows us to talk about the participation of the anatomical structures of the head in the formation of the spectrum of auditory sensations perceived by a person.

This mechanism of emission of signals by a dolphin also makes it possible to explain the ability of a dolphin to quickly adjust the frequency of emitted signals by changing the speed of the air stream blown into the cavities. A similar picture is observed under the influence of other physical factors when the rate of growth of the disturbing force changes.

The auditory sensation in humans under the action of microwave EMR pulses occurs in the audio range. A similar picture occurs when ultrasonic pulses act on the bone and tissue formations of a guinea pig.

With HFGS of a guinea pig equal to 50 kHz, the potential in the round window of the cochlea occurs at a filling frequency of the ultrasound pulse equal to 98.8 and 143.5 kHz, i.e. at frequencies that are “ultrasonic” for the animal. The presence of the potentials themselves under the influence of factors not directly perceived by the auditory system indicates an inadequate mechanism for their perception.

Thus, when the head of a person and an animal is irradiated with pulses of non-ionizing radiation, the mechanism of inadequate perception of information by the auditory system is realized. In this case, temporary changes in the radiation power must be adequate to the sound stimuli perceived by the auditory system of an animal or a person. The existence of an inadequate nature of the occurrence of auditory sensations is also mentioned in the work on the action of pulsed modulated ultrasound during its direct impact on the tissues of the head of a guinea pig [217].

The similarity of pre-resonance sections of bone-tissue conduction audiograms of humans and dolphins, as well as the manifestation of similar reactions of the dolphin's auditory system and the oscillatory resonance system in response to the same exciting signal indicates the possible unity of the mechanisms for the formation of audiograms in humans and dolphins and their resonant nature. This circumstance allows us to assume the possibility of receiving information by a person and a dolphin in the aquatic environment using a communication channel based on bionics.

9.4. Brief conclusions

1. Pulsed effects of EMR microwave and ultrasound cause auditory sensations identical to an audible click due to an inadequate mechanism of perception of the release of the envelope of the active physical factor in the form of a thermal pulse formed when a pulse of non-ionizing energy is absorbed, the formation of a pressure jump, and the excitation of mechanical vibrations and conducting them to the mechanoreceptors of the auditory system through bone conduction.

2. The similarity of the type of bone conduction audiograms of humans and dolphins and the qualitative coincidence of the characteristics of evoked potentials in a dolphin and a guinea pig with the same variations in stimulus parameters suggest the presence of a single mechanism for the formation of the auditory sensation in humans and animals during the perception of stimuli. mule by bone-tissue conduction.

3. The preservation of the basic parameters of the auditory sensation when mechanical vibrations are excited in the bone-tissue formations of the skull by microwave EMR pulses when a person is immersed in sight suggests the possibility of him perceiving useful information in an aquatic environment in a bionic way.

4. The possibility of explaining the dolphin audiogram using the concept of a double-circuit resonant system is shown.

5. Based on comparative assessments of the responses of the auditory system of humans, dolphins and guinea pigs to a sound stimulus using bone-tissue conduction, the fundamental possibility of the existence of a biionic communication channel in the aquatic environment is shown. NO

CONCLUSION MO EKVONANNI

The conducted studies of the mechanism of radio sound made it possible to reveal the great potential of a new type of interaction between complexly modulated pulsed non-ionizing radiation and a living organism.

The physical modeling method, first used by the author of the book in this area of research, turned out to be very fruitful and largely determined the direction of research into the phenomenon of radio sound.

An assessment of the parameters of microwave EMR during the transmission of information and its reception by bionic means has generally shown the need to ensure high energy densities at the point of reception, which leads to high thermal loads on a living organism. On the one hand, this leads to a sharp reduction in the possible time of information transmission, on the other hand, to the need for radiation with high peak powers per pulse when transmitting information over long distances, which requires large energy costs.

At the same time, according to some literature sources, when the external noise level is reduced to 0 dB, the threshold power of a non-ionizing radiation pulse can be reduced to units of mW cm2 and even to units of μW cm2. However, detailed research in these areas capacity was not carried out by anyone.

The author of the book calculated the parameters of the bionic communication channel based on the traditional idea for the physiology of hearing that the bone conduction thresholds exceed the air conduction thresholds of 30 dB.

According to literature data, this excess varies from 0 to 50 dB, which requires special research in order to clarify some characteristics of the bionic communication channel and increase its efficiency.

In works devoted to the issues of transmitting microwave energy over long distances, in order to achieve high efficiency, a prerequisite is the requirement that all supplied energy be intercepted by the receiving aperture. The problem posed is solved by focusing the beam of the transmitting aperture to a size at the receiving end that does not exceed the area of the receiving aperture.

The use of microwave EMR with a carrier frequency of the order of 1 GHz requires the presence of large transmitting antennas to create narrowly directed radiation, which is a weak spot in the bionic communication system. In this regard, it seems promising to use the centimeter and millimeter microwave range to receive information bionically, especially at long distances. The absence in the literature of any data of both a theoretical and experimental nature on this matter does not allow us to conduct any in-depth analysis and come to unambiguous conclusions about the possibility of using centimeter and millimeter wavelengths to implement a bionic communication channel .

In this regard, of interest are the literature data on the excitation of mechanical vibrations in water using a rectangular waveguide immersed in a vessel with pulses of 2 μs duration at a carrier frequency of 9 GHz and recording these vibrations with a piezaceramic sensor. One of the works indicated that with an increase in the carrier frequency from 3 GHz to 9.5 GHz and a pulse repetition rate of 1 kHz, all subjects noted a decrease in the level of perceived radio sound until it completely disappeared, despite an increase in PPM to 5 W cm 2. Calculations show that at a pulse repetition frequency of 10 kHz at the specified PPM, radio sound will be perceived due to a lower (by 10 dB) sensitivity threshold at a frequency of 10 kHz. In this case, one of the reasons for the lack of perception of radio sound at a frequency of ~ 10 GHz may be an increase in the sensitivity threshold of bone hearing at lower pulse repetition frequencies, but not only.

The use of a complexly modulated carrier signal to transmit the message function and the obtained experimental material allows us to offer the following explanation for the increase in threshold pulse power with increasing carrier frequency noted in published works. With the transition to the region of centimeter and millimeter waves, the depth of penetration of radiation into tissue decreases to units and fractions of millimeters, i.e., mainly a thin layer consisting of several layers with different characteristics is captured.

As is known, a very significant reflection of both electromagnetic and mechanical energy occurs at the interfaces of such layers. As a result, in a multilayer structure, energy pumping can occur due to re-reflections as the wavelength decreases, and the absorbing layer can be considered as a resonator operating at a frequency determined by the boundary conditions. Thus, with a carrier frequency of 10 GHz and a penetration depth of 0.343 cm, depending on the boundary conditions at high pumping rates of electromagnetic energy, the formation of a quarter-wave to half-wave resonator is possible. At a speed of sound in tissues of the order of 1.5-105 cm s-1, the excitation of mechanical vibrations will occur with a frequency determined by the thickness of the layer with the boundary conditions optimal for the excitation of mechanical vibrations and lying outside the HFGS (resonance of the shell of the sphere) . In this case, the energy of mechanical vibrations excited in the multilayer structure increases and the energy of mechanical vibrations excited in deep structures decreases. That is, in the high-frequency region of EMR, the wavelength will determine the frequency of excited mechanical vibrations.

All references given here to works on the study of the perception of radio sound at frequencies of 3...10 GHz used microwave EMR with constant power per pulse without additional modulation in amplitude or pulse repetition frequency. In this case, excited mechanical vibrations with a frequency higher than the HFGS will not be objectively perceived. Obviously, this can explain the increase in threshold pulse power with increasing carrier frequency.

Thus, when mechanical vibrations are excited in tissues with a frequency higher than HFGS and there is a change in the parameters of the microwave pulse sequence, i.e., when using complex modulated pulse EMR, a person will be able to perceive a modulating signal.

The fundamental possibility of the existence of such a mechanism has been demonstrated in literary sources in ex-

experiments on laboratory animals. Issues of human perception of ultrasonic frequencies are covered in [4, 18-20, 24, 76-78, 81, 84]. Despite the fact that in the monograph of model and full-scale experiments carried out by the author, the hypotheses he had previously put forward and the correctness of the methodological approaches to solving the problem of creating a bionic communication channel were fully confirmed, the author does not consider the work completed.

Many questions need clarification or more correct interpretation. This is the case with the study of bone conduction thresholds in a wide range of sound frequencies, the data in which the author of the monograph borrowed from literary sources. It is necessary to study bone hearing thresholds in the frequency band above the HFGS. The question of choosing the duration of microwave pulses needs clarification, which, judging by the published data, is decided arbitrarily or based on the capabilities of the experiment. The fact that the generation of mechanical oscillations occurs at the moments of the action of the front and decline of the thermal pulse is practically not taken into account. An increase in the duration of the pulses only leads to an increase in the temperature of the object and, at certain ratios of Ti and Tesche, and to the complete suppression of mechanical vibrations. Therefore, it is not entirely correct to associate the presence or absence of an effect with the duration of the pulse itself and the expression of its energy in units of SPM (W kg-¹). It would be more correct to use the expression Tfr, where T is the duration of the front (fall) of the pulse, Ri is the peak power of the microwave pulse.

With an increase in the repetition rate of microwave EMR with a transition to the region of centimeter and millimeter waves, it may be necessary to revise the two-circuit concept of radio sound (or its adjustment) for new conditions of excitation of mechanical vibrations. This refers to the need to conduct research on a multilayer spherical model. As for the study of the communicative abilities of humans and animals in the aquatic environment with the direct reception of ultrasound, given the special importance of the problem in solving applied problems, research in this area must be carried out on the broadest front. But

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