MILLIMETER WAVE SENSOR FOR FAR-FIELD STANDOFF VIBROMETRY

Cite as: AIP Conference Proceedings **1096**, 1641 (2009); https://doi.org/10.1063/1.3114155
Published Online: 23 March 2009

S. Bakhtiari, N. Gopalsami, T. W. Elmer, and A. C. Raptis

MILLIMETER WAVE SENSOR FOR FAR-FIELD STANDOFF VIBROMETRY

S. Bakhtiari, N. Gopalsami, T. W. Elmer, and A. C. Raptis

Nuclear Engineering Division, Argonne National Laboratory, Argonne, IL 60439

ABSTRACT. Current state-of-the-art in remote vibrometry is based predominantly on optical technology. Although these systems allow measurement of displacement with high degree of precision, they suffer from known limitations of optics including sensitivity to atmospheric conditions and surface scattering. We have developed a millimeter wave (MMW) counterpart of an optical vibrometer for the detection of acoustic signatures from common man-made structures and at far-field standoff distances. This compact W-band system employs solid-state active and passive components. The comparative studies carried out to date have demonstrated the advantages of the MMW sensor over commercial laser vibrometers with regard to detection range, ease of alignment, and reduced sensitivity to surface condition of the target. Although the system was intended initially for national security applications, it is expected that this technology will be useful for a wide range of applications including structural health monitoring, nondestructive examination of dielectric materials, and for biomedical sensing. Preliminary results are presented on the use of the MMW sensor for standoff detection of biometric signals.

Keywords: Millimeter wave, Vibrometry, Biometric, Sensor, Standoff monitoring
PACS: 84.40.-x, 87.63._d, 43.40.Yq

INTRODUCTION

Electromechanical and optical sensors have been used in the past for monitoring of vibration associated with industrial machinery and minute displacements of civil structures. Examples include strain gauges for measuring deformation, accelerometers for measuring vibration, and laser-based systems that sense the displacement of optically reflecting targets. Such devices, although accurate, require the sensor to be either in direct contact or at close proximity to the object under test. Optical sensors on the other hand require optically reflecting surfaces and precise alignment. For standoff monitoring applications the current state-of-the-art is almost exclusively based on laser doppler vibrometry/velocimetry (heterodyne interferometer) that can measure subtle surface motions collinear with the sensor's line-of-sight. The signal-to-noise-ratio (S/N) of an optical sensor is proportional to the square root of the reflected signal from the surface of a target. With most natural and man-made structures having optically rough surfaces, photon scattering results in very little signal being reflected back to the sensor and thus limits the range of optical systems. In addition, optical signals are strongly affected by a wide range of environmental conditions including atmospheric conditions, target

CP1096, *Review of Quantitative Nondestructive Evaluation Vol. 28,*
edited by D. O. Thompson and D. E. Chimenti

composition and properties, incidence angle, and line-of-sight accessibility. As the direct consequence of operating at longer electromagnetic wavelengths, millimeter-wave (MMW) techniques can be used to overcome certain limitations associated with optical sensors. Both active and passive MMW techniques have been employed in the past for various remote sensing applications [1-4]. Millimeter wave techniques have also been used for nondestructive examination (NDE) of materials at close standoff distances [5,6].

In situations where placement of sensor or reflector on the target is not feasible, microwave interferometric and radar techniques may be the only viable method for standoff monitoring of subtle vibrations. Phase interference of coherent microwave radiation can be used to measure displacement and velocity. At millimeter-wave frequencies, displacement can be measured with micron level resolution using either continuous wave or swept-frequency techniques. Pulsed techniques may be employed to acquire similar information at larger distances. The primary technical challenge with such systems is to deduce the relevant information about the target and eliminate all irrelevant but typically wide-band interfering signals.

THEORY

The basic concept of remote sensing of acoustic vibrations from civil structures or reverberations from nearby objects (e.g., structural as well as seismic vibrations) is to measure the modulation induced on a coherent signal reflected off of the object's surface. Analogous to heterodyne detection of interferometric optical signals, mixing of the backscattered electromagnetic signal with a portion of the reference transmitted signal (i.e., local oscillator) allows recovery of low-frequency modulations induced by the vibrating target. In-plane displacements may be sensed by either measuring the doppler frequency shift or the phase modulation induced by the target on the backscattered carrier signal. In their basic form, these effects may be expressed as:

$$f_d(t) = \frac{2v}{\lambda}\cos\left(\omega_{vib}t + \phi\right) \tag{1}$$

and

$$\varphi(t) = \frac{4\pi}{\lambda}d\left(t\right) \tag{2}$$

in which λ is the carrier wavelength, v is the target velocity, ω_{vib} is the vibration angular frequency, ϕ is the angle between the direction of target motion and the beam, and d is the target displacement. In reference to Eq. (2), phase interference of coherent MMW radiation acquired over a period of time may be used to remotely obtain information about displacement and in turn the vibration frequency of an object.

APPROACH

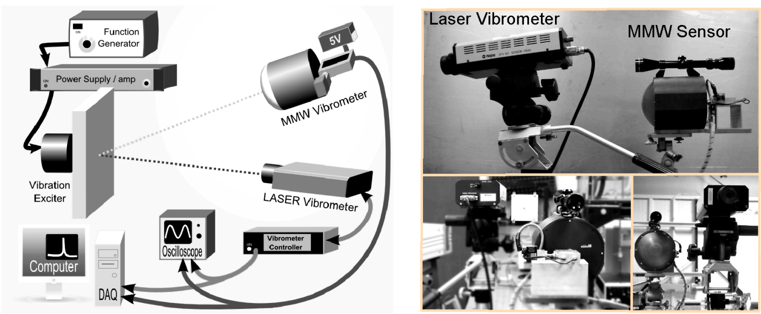
The primary goal of this study was to demonstrate the feasibility of selective detection of acoustic signatures using millimeter-wave (MMW) technology at relatively large standoff distances. Characteristic acoustic signals that may be picked up from a structure or its surrounding objects can be correlated with the operation of a plant or health condition of a structure. A MMW counterpart of an optical vibrometer was developed for such applications. In view of the tradeoff between sensitivity and range, it is expected that millimeter wavelengths, which occupy the band between microwaves and far-infrared frequencies, will provide the optimum operating frequency within the microwave band. In addition to the sensor front end, appropriate data acquisition and analysis hardware and software were also implemented to help detect and isolate faint signal returns in presence of relatively strong interference from background noise. Several frequency and time domain filtering schemes were implemented for on-line and off-line processing of data.

System Configuration

To demonstrate the feasibility of remotely detecting acoustically induced modulations with a MMW sensor, a prototype interferometer was assembled at Argonne. The sensor front-end employs a W-band (94 GHz) solid-state Gunn oscillator that uses a 5-v modulator-regulator as its power supply allowing frequency or amplitude modulation of the source. The transmitter was fitted with a heater unit for better frequency stability. The MMW transceiver uses a homodyne configuration for down-conversion of the modulated carrier signal to acoustic frequency range that is detected by a quadrature mixer. The quadrature mixer was used to simultaneously obtain both the amplitude and the phase information. A six inch Gaussian optic lens antenna was used to focus the beam on the target. The lens was mounted with a telescope for alignment purposes. The electronic block of the MMW sensor consisted of tunable bandpass filters and low-noise amplifiers. Data acquisition and analysis was carried out using computer-based hardware and software employing a four channel, 24-bit data acquisition board. The LabVIEW™ software was used for all data acquisition operations.

Figure 1(a) shows all components of the laboratory setup used to carry out the feasibility studies including a commercial optical vibrometer (class-II helium neon laser) that was employed for verification purposes. Pictures of the MMW sensor and the laser vibrometer from different view angles are shown in Fig. 1(b). Also visible in the background is the mock-up structure made of a cinder block attached to a vibration exciter that was assembled in order to simulate multimode excitation of a target. The cinder block with a porous surface was chosen because it represents typical surface condition of building materials. An arbitrary function generator in conjunction with a power amplifier provided the input signal to the vibration exciter.

A LabVIEW™ virtual instrument (VI) was implemented to allow multi-channel recording and real-time processing and visualization of the sensor output. The VI provides one-dimensional time traces, power spectrum, and two-dimensional time-frequency image displays. A graphical user interface (GUI) has also been developed under the MATLAB™



(a) (b)

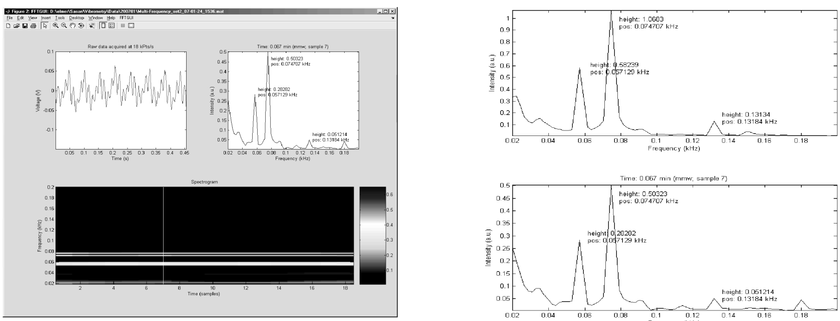
FIGURE 1. (a) Depiction of the apparatus used for evaluation of the MMW sensor for remote detection of acoustic vibrations. Also shown is (b) a picture of the laboratory setup showing (top) the laser vibrometer (left) and MMW sensor (right) and (bottom) the front and back view of the two systems along with the target (white square) shown in the bottom left picture.

environment for post processing of recorded data. The GUI is implemented in a modular fashion and allows one to conveniently update the existing functions (filters) or create and interface for new algorithms under the GUI independent of the source code.

Experimental Observations

For the preliminary evaluations the target was excited with a composite periodic signal simulating two modes of vibration. To verify the MMW sensor readings, the output of the laser vibrometer was simultaneously recorded from a separate channel. Typical display of data in the main GUI window collected with the MMW sensor is shown in Fig. 2(a). Expanded display of the power spectral density plots for both vibration monitoring systems is shown in Fig. 2(b). For the short standoff distance of ~15 m in this case, the data indicates excellent agreement between the output of the optical and the MMW sensor. It is should be noted that for all the test cases the laser beam was pointed at the center of the vibrating plate that was fitted with an optically smooth reflector to obtain maximum signal return. The MMW beam on the other hand was pointed at an arbitrary location away from the center of the target.

Several tests were subsequently carried out to assess the effect of the surface condition of the target (reflectivity) on detection. A representative test case is shown in Fig. 3 in which data was collected at three different spots on the target's surface. The reflector in the center of the block was covered with radar absorbing foam. The MMW signal in this case was clearly detectable from all three locations. As expected, the measurements in this case indicated relative insensitivity of the signal to diffuse scattering from optically rough surfaces. Representative data from another set of experiments on evaluating the effect of incidence angle on detection are shown in Fig. 4(a). The incidence angle was varied between 0 and 35 degrees (limited by the test apparatus). Unlike the optical sensor, the MMW signal was detectable over a wide range of view angles. Similar experiments were also performed to examine the effect of range on detection. Data was collected using both the MMW and the optical vibrometer at incremental distances and up to ~25 m (>70 ft.) standoff distance. A representative trace recorded with the MMW system at a distance of ~25 m is displayed in Fig. 4(b). For the test case here the target



(a) (b)

FIGURE 2. (a) Main data acquisition VI showing time trace (top left), power spectrum (top right), and frequency-time display of MMW signal collected from multimode vibration of a target excited at two specific frequencies. The two main horizontal bands on the image display indicate the two dominant modes of vibration. Also shown are (b) comparison of laser vibrometer (top) with the MMW sensor (bottom) output showing nearly identical response of the two systems to multimode vibrations measured from a target placed ~10 m away.

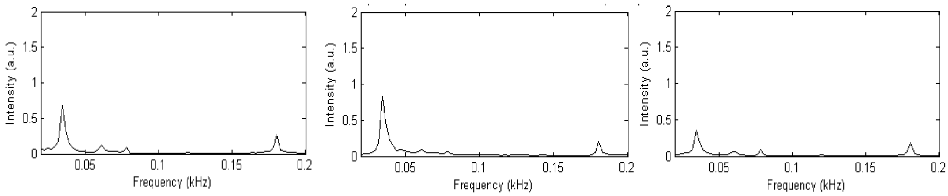
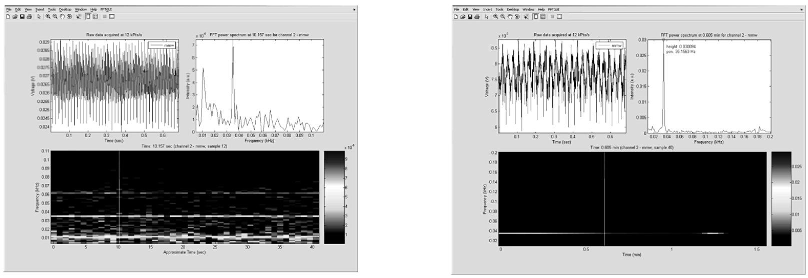


FIGURE 3. MMW sensor data collected from three different locations over the target to assess the effects of target surface reflectivity. The frequency components representing the primary modes of vibrations are detectable from all three locations at different view angles.



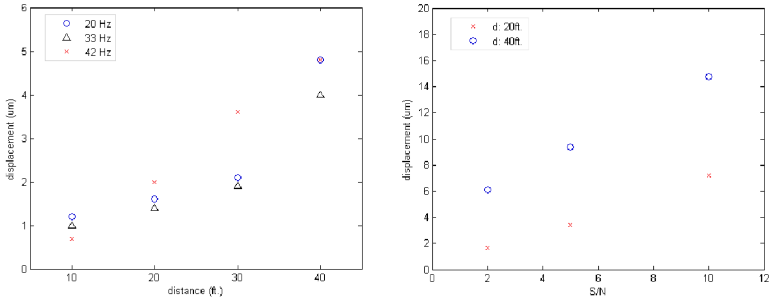
(a) (b)

FIGURE 4. Results of comparative studies on range and alignment of optical and MMW sensor showing data collected with the MMW sensor with single mode excitation of target at 35 Hz at a standoff distance of (a) ~15 m with 35° incidence angle and (b) ~25 m (>70 ft) with oblique incidence (<10°).

was excited at an arbitrarily selected vibration frequency of 35 Hz. While no discernible signal was present in the optical power spectrum, the signal was clearly visible in the MMW data.

A series of tests were later conducted to more quantitatively determine the sensitivity of the low-power MMW system. Once again, the laser vibrometer readings were used to quantify the displacement, which was done by placing an optical reflector on the target. For the first test, the cinder block target was excited at three arbitrarily selected vibration frequencies and detectable displacement was measured as a function of standoff distance. Detection was based on a minimum S/N of around two at which a clear signal above the background could be observed. The results of these tests are plotted in Fig. 5(a). For all three vibration frequencies, a displacement of <5 μm was detectable at the longest standoff distance of ~15 m (>40 ft.). For the second test, the detectable displacement (S/N ~ 2) was recorded as a function of S/N at two standoff distances and at a number of excitation frequencies of the target. The results of this test are plotted in Fig. 5(b). Measurement points on the graph represent the average value of readings at multiple vibration frequencies (all <20 Hz). As expected, the data in this case shows that more decisive detections (higher S/N) are made at higher vibration displacements. Tests carried out so far have demonstrated the ability of the low-power MMW sensor to detect displacement levels of <20 μm at standoff distances of up to 50 m (~150 ft.) using the cinder block target.

In general, the results of experimental studies performed so far indicate the advantages of the MMW system over the optical sensor in terms of increased detection range and ease of alignment that are important criteria for many field applications. While the laser beam in all test cases had to be pointed directly at the optical reflector placed on



(a) (b)

FIGURE 5. (a) Detectable displacement (maintaining a S/N>2) with MMW sensor as a function of standoff distance. Measurements were made at three arbitrarily selected excitation frequency of simulated target (cinder block). (b) Measured displacement as a function of signal-to-noise ratio (S/N) at two standoff distances. Measurement points represent average value of readings at multiple excitation frequencies (<20 Hz) of the simulated target (cinder block). The laser vibrometer readings were used to quantify displacement, which was done by placing an optical reflector on the target.

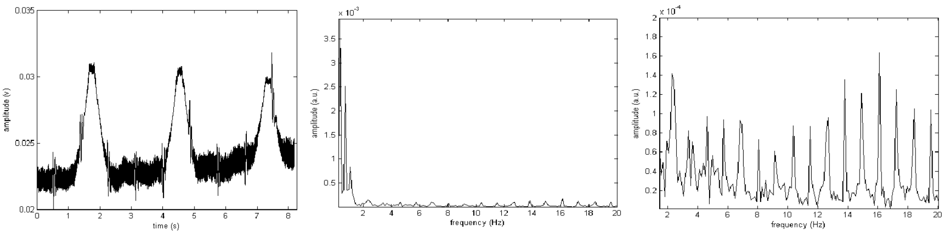
the vibrating plate, the MMW signal could be detected from any arbitrary location on the target and from a wide range of view angles.

Preliminary Investigations on Biometric Sensing

As the direct consequence of operation at longer electromagnetic wavelengths, MMW radiation can penetrate through many optically opaque materials and efficiently reflect off of optically coarse surfaces. The ability of microwave energy to penetrate through clothing with little attenuation and its reflection off of human skin has been exploited to detect concealed objects. Studies have been reported by other researchers in this field on the use of radar techniques for remote detection of human vital signs [7,8]. The majority of those studies have been performed at the microwave or the lower range of the millimeter-wave band. Because of their shorter wavelengths, millimeter waves are expected to provide improved sensitivity over microwave techniques for detection of subtle displacements associated with human vital signs. Under an internal laboratory-directed research and development program at Argonne, other applications of the MMW system described above are currently being explored. In particular, applicability of this sensor for remote monitoring of human vital signs is currently being investigated. Proof-of-principle studies have been carried out to demonstrate the ability of to detect displacements associated with the respiration and heartbeat at tens of meters away from the subject.

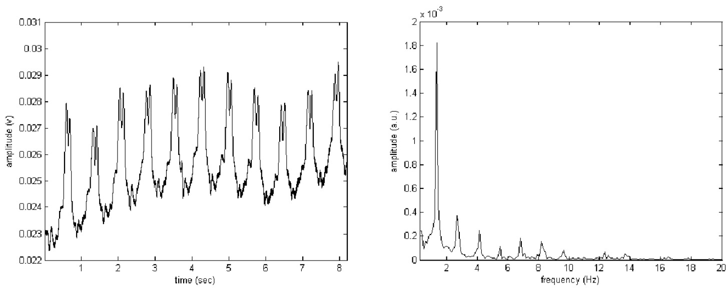
Preliminary results of experimental tests on remote detection of human vital signs are presented here. Movements associated with respiration and heartbeat was first simulated by using the vibration exciter system described above. The surface of the target was covered with a layer of lossy dielectric material (rubber sheet) to better simulate reflection from human body. The arbitrary function generator was used to simulate the biometric signal composed of a tapered-edge pulse and a *Sinc* function that represented the respiration and heart rate (RR and HR), respectively. The RR in this case was set to 0.36 Hz and the HR was set to 1.1 Hz. The selected heartbeat and respiration frequencies are within the normal range of values reported in the literature. With an optical reflector placed on the target, the laser vibrometer readings, used as reference, indicated a total displacement of ~0.04 mm for the respiration function and roughly a third of that for the heart function. It is worth noting that the simulated displacement here is roughly five times smaller than typical displacement associated with chest movement due to the respiration function. Figure 6(a) displays the time trace of the MMW sensor output at a short standoff distance (~5 m), which closely resembles the output of the function generator. Both the RR and the HR signal are clearly visible along the 8-s trace. The power spectrum of the time-domain data is shown in Fig. 6(b). The RR and HR fundamental frequencies in that figure are the dominant components. The same power spectrum for frequencies above 2 Hz is shown in Fig. 6(c). All the higher order harmonics of the simulated HR are clearly visible in this plot.

Experimental data from another test on biometric sensing is presented in Fig. 7. In this case the signal was collected from a stationary human target at a standoff distance of 10 m (~30 ft.). For this proof-of-principle test, the respiration function was suppressed in order to more clearly detect the HR signal. The temporal data for the measured HR signal over an approximately 8-s interval is shown in Fig. 7(a). The periodic heartbeat signal is clearly observable in the time trace. The corresponding power spectrum displayed in Fig. 7(b) shows the fundamental and the harmonics of the HR signal. The results of initial investigations on the use of MMW sensor for remote monitoring of human vital signs have been very encouraging. Further studies in this area are currently being pursued at Argonne. This technology is expected to have a wide range of applications in the biomedical as well as in the homeland security area.



(a) (b) (c)

FIGURE 6. MMW sensor response at a short standoff distance for a simulated biometric signal composed of a respiration rate of ~0.36 Hz and heart rate of ~1.1 Hz. Shown here are the (a) time domain signal over an 8-s interval, (b) the power spectrum, and (c) the power spectrum for frequency components above 2 Hz.



(a) (b)

FIGURE 7. Measured (a) heartbeat signal and (b) its power spectrum using the MMW sensor pointed at the chest area of a human subject and at a standoff distance of 10 m (>30 ft.). The respiration function was suppressed to more clearly detect the much weaker signal associated with the heartbeat.

CONCLUSIONS

A millimeter-wave (MMW) sensor has been developed for remote detection of vibrations associated with common man-made structures at far-field standoff distances. A description of this compact W-band prototype system that employs solid-state active and passive components was presented. Representative data from comparative studies carried out to date have demonstrated the advantages of the MMW sensor over conventional laser vibrometers with regard to detection range, ease of alignment, and reduced sensitivity to surface condition of the target. Sensitivity studies demonstrate the ability of this low-power system to resolve displacements of a few micrometers from fence-line standoff distances. Further increase in range of the MMW sensor may be achieved through either hardware or software modifications. These include employment of solid-state sources with higher output power, incorporation of a low-noise amplifier in the sensor front-end, and more elaborate signal processing and data analysis. Although the system described here was intended originally for national security applications, it is expected that the same technology will be useful for a wide range of applications including structural health monitoring, NDE of dielectric materials, and for biomedical sensing. Preliminary data was presented on the use of the MMW sensor for standoff detection of biometric signals. The results of these investigations have been very encouraging and demonstrate the potential for use of this technology for biomedical and biometric sensing applications.

ACKNOWLEDGEMENTS

Research supported by the U.S. Department of Energy under Contract DE-AC02-06CH11357.

REFERENCES

1. N. Gopalsami, S. Bakhtiari, A. C. Raptis, S. L. Dieckman, and F. C. De Lucia, "Millimeter Wave Measurements of Molecular Spectra with Application to Environmental Monitoring," IEEE Trans. Instr. Meas., Vol. 45 (1996), pp. 225-230.
2. S. Bakhtiari and R. Zoughi, "Backscattering Characteristics of Tall Prairie Grass Canopies at Microwave Frequencies: A Theoretical Approach," Remote Sensing of Environment, Vol. 36, no. 2 (May 1991), pp. 137-147.
3. N. Gopalsami, S. Bakhtiari, T. W. Elmer, and A. C. Raptis, "Application of Millimeter-Wave Radiometry for Remote Chemical Detection," IEEE Trans. Microwave Theo. Tech., Vol. 56, No. 3 (March 2008), pp. 700-709.
4. N. Gopalsami and A. C. Raptis, "Millimeter-Wave Radar Sensing of Airborne Chemicals," *IEEE Trans. Microwave Theory Techniques,* vol. 49 (2001), pp. 646-653.
5. Gopalsami, N., S. Bakhtiari, S. L. Dieckman, A. C. Raptis, and M. J. Lepper, "*Millimeter-Wave Imaging for Nondestructive Evaluation of Materials*," Materials Evaluation., Vol. 52, no. 3 (March 1994).
6. Bakhtiari, S., N. Qaddoumi, S. Ganchev and R. Zoughi, "*Microwave Non-Contact Examination of Disbond and Thickness Variation in Stratified Composite Media,*" IEEE Trans. on Microwave Theory and Tech., Vol. 42, no. 3 (March 1994).
7. J. C. Lin, "Microwave Sensing of Physiological Movement and Volume Change: A Review," Bioelectromagnetics 13:557-565 (1992).
8. C. Li, Y. Xiao, and J. Lin, "Experiment and Spectral Analysis of a Low-Power Ka-Band Heartbeat Detector Measuring From Four Sides of a Human Body," IEEE Trans. Microwave Theo. Tech., Vol. 54, No. 12 (Dec. 2006), pp. 4464-4471.