A Laser Device for Remote Vibration Measurement

JOHN V. FOSTER
NASA, Ames Research Center
Moffett Field, Calif.

Abstract

A laboratory study has been made of concepts that utilize a laser for a vibration measurement device. The laser beam possesses the needed characteristics for a spatially directed carrier capable of detecting and transmitting vibration information to remote data processing equipment; furthermore, such a laser vibration measurement device can accomplish the measurement without mechanical contact with the structure under test. The measurement technique utilizes the Doppler shift produced on a wave reflected from a surface vibrating normal to the beam path. Several techniques are available for detecting the Doppler shift; optical heterodyne or homodyne detection and microwave subcarrier modulation methods are candidates for practical instruments. Preliminary results from laboratory experiments indicate optical heterodyne detection to be the most practical method with present state-of-the-art equipment.

Key Words—Doppler shift, heterodyne, laser, measurement, modulation, transmission, vibration.

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Introduction

Measuring vibration on a structure during testing or operation usually means attaching vibration sensors, such as strain gauges, inertial-type transducers, or similar devices, to the structure so that the vibratory motions can be converted into electrical signals suitable for recording. There has been a need for some method that would allow measurements to be made remotely without the attachment of such devices. Furthermore, a method has been desired that would allow the rapid survey of a particular section of the structure, which might be chosen during the actual test run. Such a survey should be by an operator at a location remote from the structure.

The laser, because of its small beamwidth and high frequency, appears to have the characteristics needed for a spatially directed carrier capable of transmitting the vibration information to remote data processing equipment. The vibrating reflective surface under test will produce a time-varying phase shift on a wave that is reflected from the surface. The phase shift is due to the change in effective pathlength between the source of the wave and the point of reception. There are a number of possible methods of implementing a laser system so as to utilize this phase shift for measuring structural vibration; some methods use the optical carrier itself, others use subcarriers. Some of the aspects of the system and of the associated hardware of several different methods will be discussed. An experimental program has been conducted to examine one method that uses a radio frequency subcarrier modulated onto the optical carrier as the vehicle for measuring the vibration, and another method that uses optical heterodyne detection.

Figures 1 and 2 illustrate two possible system configurations. Figure 1 illustrates a system in which the laser transmitter–receiver is remote from the structure under test. The beam, controlled either manually or automatically, scans the test specimen searching for vibration patterns, and records the vibration amplitude and frequency. Figure 2 illustrates a hand-held device by which the technician places the laser transmitter–receiver near the area of concern.

System Considerations

Vibration Considerations

The amplitudes and frequencies of interest range from the very low frequency and high amplitude of swinging suspension bridges to microinch vibrations of gyros. The vibrations of concern in this particular investigation are those of typical spacecraft structures which are represented by the performance of a typical vibration tester illustrated in Fig. 3. From a practical viewpoint, limitations are imposed by available displacement, maximum velocity, and available force. At low frequencies, the typical vibration test unit will have a displacement limit of ± 0.5 inch as shown in Fig. 3. For intermediate frequencies, maximum velocity limits the performance to the

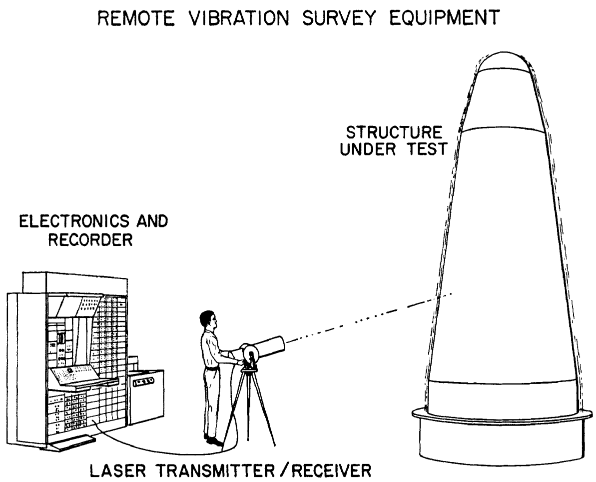


Fig. 1. Remote vibration survey equipment.

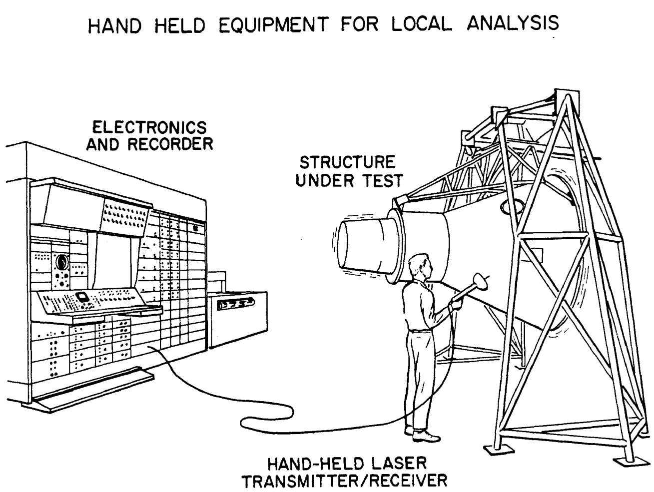
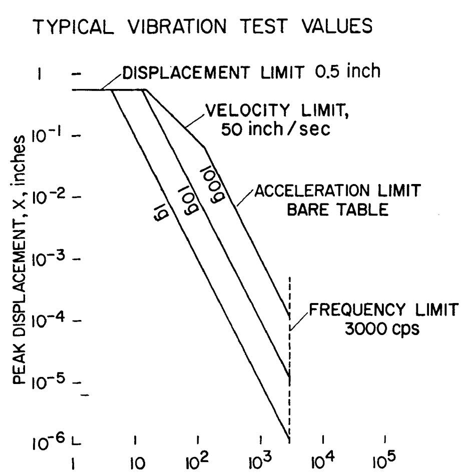


Fig. 2. Hand-held equipment for local analysis.

Fig. 3. Typical vibration test values.



typical 50 inches per second illustrated. At high frequencies, available force, and consequently acceleration limit the amplitude. The maximum achievable acceleration depends on the mass of the object under test as well as the force available. The 100-g limit illustrated in Fig. 3 is representative for small mass loads. The laser vibration study is concerned with vibration limits within the confines of the typical values illustrated by Fig. 3.

Doppler Frequency Shift and Sensitivity Considerations

The Doppler frequency shift caused by a vibrating surface on carriers of different frequencies is pertinent to this study because this Doppler shift is the information-bearing factor in the methods studied. It can be shown that the return signal from a reflecting surface at a distance from a transmitted signal is shifted in frequency by the factor $2\omega V/c$, where ω is the carrier frequency, V is the reflecting surface velocity normal to the beam, and c is the velocity of light. Consequently, the sensitivity of a carrier or subcarrier phase-detecting system can be calculated if the characteristics of the system components are known. Assuming a subcarrier frequency of ω_m and a structural vibration of $x = x_0 \sin \omega_r t$, we obtain a peak phase deviation of $\delta = 2x_0\omega_m/c$, based on the Doppler shift. It is apparent from the Doppler shift equation that, for a given vibration, the phase shift increases linearly with subcarrier frequency. Consequently, it would appear desirable to use as high a subcarrier frequency as practicable since the ease of detection increases with the amount of phase shift. Indeed, the laser optical carrier itself would provide a greater phase shift than any subcarrier. Thus, methods that use no subcarrier modulation but, rather, utilize direct coherent detection of the reflected light beam have maximum sensitivity, and for small-amplitude or low-frequency vibrations, appear to be highly attractive. Nevertheless, for certain applications, this high sensitivity is not essential. Furthermore, the requirement of coherent detection of the optical beam has certain practical problems in a field-use-type instrument. It is for these applications that subcarrier methods may be useful. The detection in this case depends on the shift of the modulation frequency rather than the optical frequency and becomes more a matter of radio frequency techniques than precision optics. For this case the laser optical coherence is used for maintaining the small beamwidth needed to investigate small areas or points on the vibrating surface. It is apparent, however, that the modulation frequency should be as high as practical to achieve adequate sensitivity. The modulation system described in this paper uses a subcarrier of approximately 3000 MHz. As a comparison of the Doppler shifts for a direct optical carrier of 5×10^{14} Hz (the approximate frequency of the helium-neon 6328 Å line) and for a 3000 MHz subcarrier, a vibration of 1 g at 1000 Hz produces about 0.03 Hz deviation at the 3000 MHz subcarrier frequency and 5000 Hz for the helium-neon frequency.

System Concepts

Direct Optical Carrier

There are several more or less obvious approaches to utilizing the coherent optical carrier beam directly; typical of these are systems using heterodyne or homodyne detection techniques. A typical heterodyne system is illustrated in Fig. 4. The components of Doppler frequency shift are generated by the optical frequency. The laser beam is split into two components, one of which is offset in frequency by F_L in the single-sideband suppressed-carrier (SSBSC) modulator. Typical of such modulators are those that pass circularly polarized light through an effective rotating birefringent medium. A frequency component, shifted in frequency by an amount harmonically related to the angular frequency of rotation of the birefringent element, can be separated out and used as the offset frequency.[1-3] In an alternate modulation method, the light beam intercepts a traveling diffraction grating, and a portion of the beam is diffracted into higher-order beams whose frequencies are shifted from that of the main beam by an amount directly related to the effective velocity of the diffraction grating. Typically, the traveling grating consists of moving ultrasonic waves.[4,5] The unmodulated beam is transmitted to and from the vibrating surface to the photodetector, where it is combined with the offset carrier. The photodetector output is a frequency-modulated signal at a center frequency of F_L. The signal is then processed with either a discriminator or a synchronous detector to recover the vibration data. A reference signal from the oscillator is needed if synchronous detection is utilized.

A homodyne detection system is illustrated in Fig. 5. This system is similar to the heterodyne system but does not require the offset frequency. The photodetector determines the Doppler shift by directly detecting the beat frequency between the two beams.

Other optical carrier methods are possible. However, the foregoing described systems are representative of the direct optical methods.

Subcarrier Methods

A system utilizing a laser beam amplitude modulated with a subcarrier at a microwave frequency of about 3000 MHz is illustrated in Fig. 6. In this system the vibration amplitudes are small compared to the microwave wavelength. The laser beam is modulated by a microwave

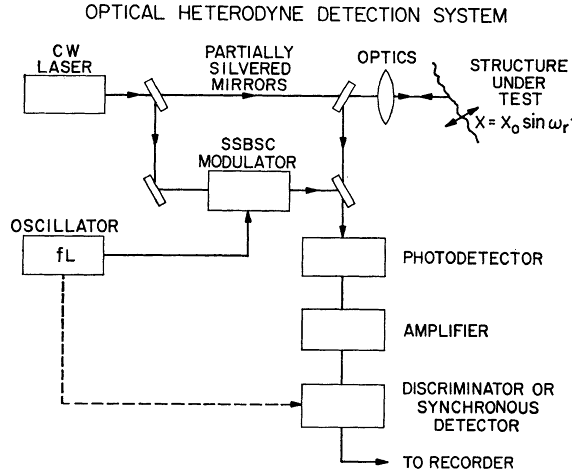


Fig. 4. Optical heterodyne detection system.

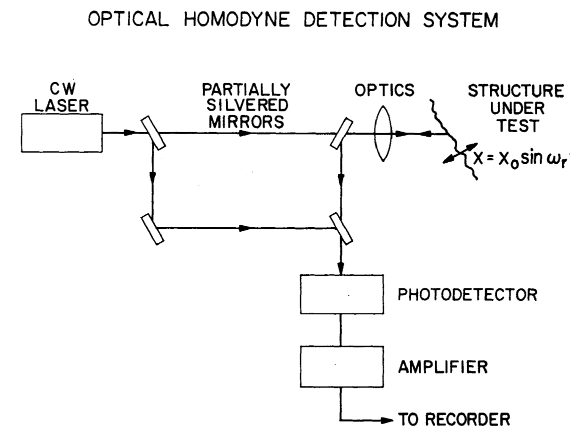
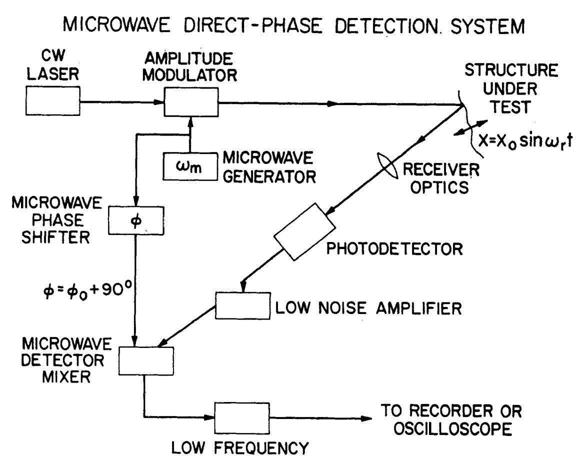


Fig. 5. Optical homodyne detection system.

Fig. 6. Microwave direct phase detection system.



[1] C. F. Buhrer, V. J. Fowler, and L. R. Bloom, "Single-sideband modulation and reception of light at VHF," *Proc. IRE* (*Correspondence*), vol. 50, pp. 1827–1828, August 1962.

[2] C. F. Buhrer and L. R. Bloom, "Single-sideband modulation and reception of light at VHF," *Proc. IRE* (*Correspondence*), vol. 50, p. 2492, December 1962.

[3] C. F. Buhrer, "Single-sideband microwave light modulation," *Proc. IEEE* (*Correspondence*), vol. 52, p. 969–970, August 1964.

[4] H. Cummins, N. Knable, L. Gampel, and Y. Yeh, "Frequency shifts in light diffracted by ultrasonic waves in liquid media," *Appl. Phys. Letters*, vol. 2, p. 62, February 1963.

[5] W. J. Thaler, "Frequency modulation of a He-Ne laser beam via ultrasonic waves in quartz," *Appl. Phys. Letters*, vol. 5, p. 29, July 1964.

electro-optic amplitude modulator. The beam is reflected by the vibrating surface and collected by optics associated with a photodetector. The detector output is a frequency near the modulation frequency with a time-varying phase shift caused by the vibration.

An alternate subcarrier system is illustrated in Fig. 7. The laser is modulated and demodulated as in the above system; however, the photodetector output is not mixed with a phase-shifted signal at the same frequency, but instead with a signal of slightly different frequency. This system is similar to the heterodyne optical system in that the frequency offset mixing signal is produced by a single-sideband modulator to produce a frequency offset. The signals are mixed and the vibration-induced phase shift appears on the intermediate frequency which is then demodulated by a discriminator.

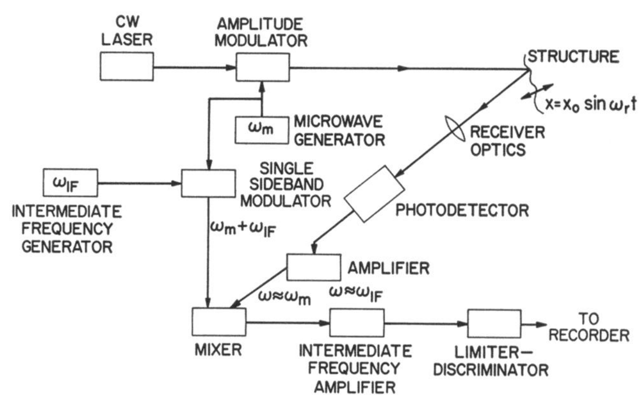


Fig. 7. Microwave heterodyne detection system.

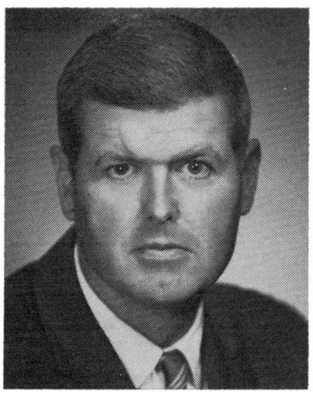
Experimental Results

A laboratory test of a 3000 MHz subcarrier system has been conducted. The test was performed on an optical bench using existing microwave modulators, lasers, detectors, and associated equipment not specifically designed for this application; however, the equipment represented the latest state-of-the-art in the laser modulation field. The results tended to verify analyses which have shown that the very small amount of phase shift produced on a 10-cm modulation wave by the vibration amplitudes would lead to low signal-to-noise ratios. It was found that the noise generated by the laser and mechanical instabilities were sufficient to seriously interfere with the small microwave Doppler shift signal.

Preliminary laboratory tests of an optical heterodyne detection system gave promising results. Work is in progress which is directed toward a more thorough determination of any performance-limiting factors inherent in this technique.

Conclusions

The use of the coherent light from a laser as the medium for detecting structural vibrations appears to be attractive because it requires no mechanical contact with the test object and because it makes rapid vibration surveys possible. Several systems that use either coherent detection at optical frequencies or microwave modulation are available, but preliminary experiments have shown the direct optical carrier methods to be superior. Improvements in laser technology should lead to a workable system in the near future.



John V. Foster was born in Modesto, Calif., in 1921. He received the B.S. degree from the University of California, Berkeley, in 1942.

He is Chief of the Systems Engineering Division, NASA Ames Research Center. While in the U. S. Navy from 1942 to 1946 he served as an Instructor in radar theory and saw action in the Pacific-Aleutian campaigns. He is presently a Lieutenant Commander in the U. S. Navy Reserves. He has specialized in communications, guidance and control, and instrumentation, and is now concentrating in the field of technical management of systems engineering work. He is author or co-author of several technical reports, and has obtained four patents as a result of his work in these fields.