

LASER DETECTION OF ACOUSTIC DISPLACEMENTS BY DESTABILIZING A FREQUENCY
STABILIZED HELIUM NEON LASER

B. A. Barna, D. M. Tow, R. T. Allemeier,
J. G. Rodriguez and J. A. Johnson

Idaho National Engineering Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-2209

A sensor for detecting low-amplitude acoustic displacements is described. This instrument is based on a stabilized helium-neon laser and is capable of measuring submicron displacements of diffuse surfaces at distances of up to 10 m and with a bandwidth between 0.2 and 100 kHz. The potential for extension of the technique to higher frequencies is discussed. The sensor uses the inherent sensitivity of an alternate-mode balanced, frequency-stabilized laser to small amounts of retroreflected light. Applications of the sensor include a study of bonding flaws in complex multilayer materials, such as the thermal protection tiles on the Space Shuttle Orbiter and in graphite epoxy laminar composites.

FREQUENCY STABILIZED LASER PHYSICS [1]

The stabilization is based on the alternate mode balance technique first described by Bennet et al. [2]. The laser, shown schematically in Reference 1, is a helium-neon laser designed to have only two modes, separated by about 680 MHz. In certain discharge tubes the modes are orthogonally polarized, and such a tube was chosen for this laser. Photocells monitor the intensities of the two modes and the length of the laser cavity is adjusted by a transducer attached to the laser tube, to keep the ratio of the intensities constant. Maintaining a constant ratio of intensities ensures that the emission lines are stationary with respect to the center of the gain curve. The control system in the laser detects a deviation from the desired constant ratio, C , of intensities by monitoring the difference $(A_1 - C \cdot A_2)$. This difference is zero when the intensity ratio A_1/A_2 is equal to C . One of the output beams is blocked with a polarizer so that the final output is a single-frequency polarized beam.

The laser can be used as a displacement detector by allowing the backscattered light from an object to reenter the laser cavity. The backscattered light passes through a polarizer before it reenters the cavity so that it has the same polarization as the output beam. This results in modulation of the cavity field of the output beam. The electric field of the orthogonally polarized confined beam is unaffected. Donati [3] shows that the amplitude of the perturbed electric field is

$$E = E_0[1 + G \cdot \cos(2ks)]$$

$$G = \frac{(c/2L) \alpha T^2}{2(g_0 - \Gamma)}$$

where E_0 is the unperturbed field amplitude, c is the speed of light, L is the length of the laser cavity, α is the backscatter attenuation, T is the transmittance of the laser mirror, g_0 is the gain parameter, Γ is the effective cavity bandwidth of the loaded laser, and k is the wave number ($2\pi/\lambda$). The term G varies very slowly with time compared to $\cos(2ks)$ and can be assumed constant. Furthermore, G is much less than unity, with an estimated value of 0.01 for this laser.

The photocells measure intensity. The intensity of the perturbed electric field is

$$I = I_0(1 + 2G\cos 2ks + G^2\cos^2 2ks)$$

Because G is small compared to unity

$$I \approx I_0(1 + 2G\cos 2ks).$$

The photocell difference is

$$\begin{aligned} D &= I_{10}(1 - 2G\cos 2ks) - CI_{20} \\ &= -2I_{10}G\cos 2ks \end{aligned}$$

where C is the desired ratio of intensities.

In the second equation the modes are assumed to be at the set balance in the absence of any backscatter into the cavity. The voltage applied to the servo to vary the laser cavity length is proportional to D . Thus the servo signal is proportional to the cosine of the distance with a period of half a wavelength of the laser light.

If the distance, s , is an integral number of wavelengths plus $1/8$ or $3/8$ of a wavelength, then small variations about this distance would be proportional to D , the difference signal. However, variations which are larger would have a nonlinear relationship to D and the output signal would reverse phase if the variations were larger than $1/8$ wavelength.

As an example, consider a displacement variation which consists of a large amplitude, low frequency oscillation superimposed on a small amplitude, high frequency oscillation as shown in Figure 1. Such a signal is very commonly observed with the low-frequency component being due to ambient vibrations of the system under observation and the high-frequency component being the signal of interest. Figure 1b shows the servo signal which correctly follows the high frequency signal only at the time when the low frequency oscillation centers the displacement at the multiple plus $1/8$ wavelength. The high-frequency signal is exactly out of phase at the multiple plus $3/8$ wavelength and reverses phase between these two distances.

A calibrated piezo element, driven by a high-voltage op amp, provided a means of accurately characterizing the sensor. Signals collected from the element show similar characteristics to those predicted in Figure 1. The data in Figure 2, collected from the piezo element, show the same type of nonlinearity and phase reversal as predicted in the data in Figure 1.

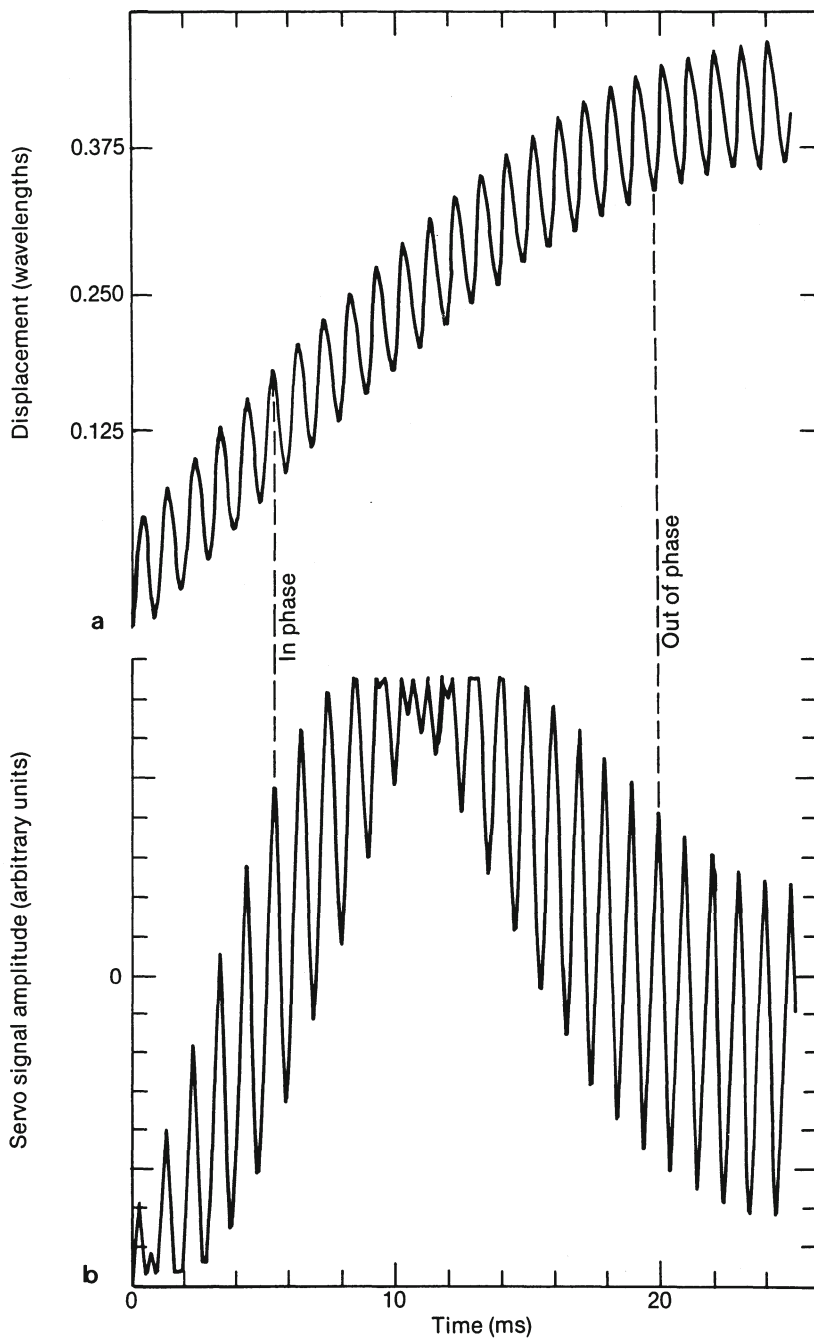


Fig. 1. The calculated effect of large amplitude vibrations on the sensor output. a) Actual signal b) signal as output by laser.

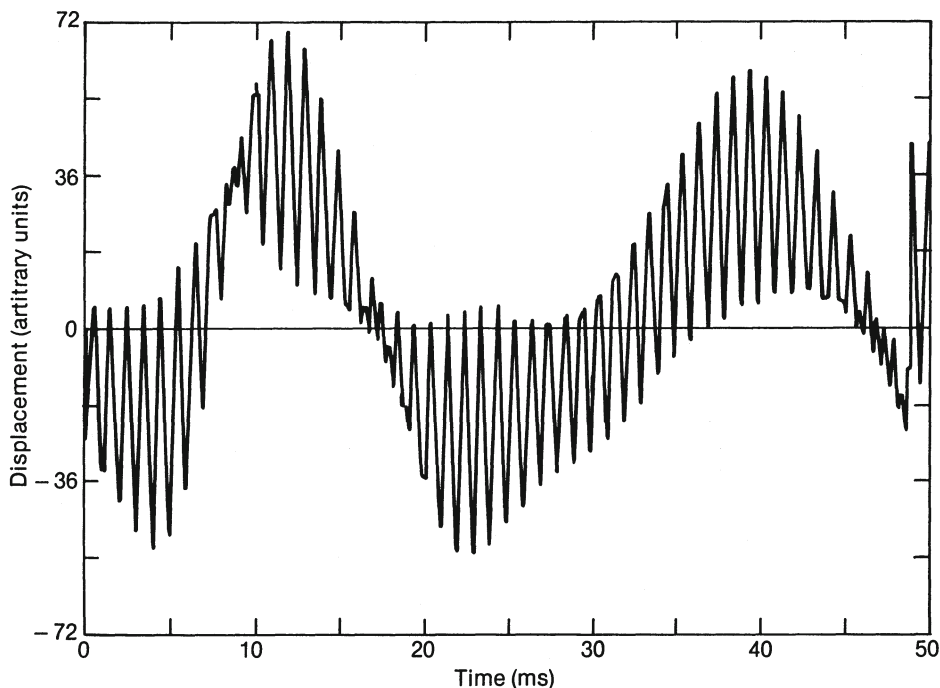


Fig. 2. Actual sensor data showing the phase reversal and nonlinear effects due to large amplitude vibrations.

DATA COLLECTION

The data collection method described in a previous paper [1] uses a gating system which accepts only those displacement signals which are at the correct distance of any ambient low-frequency oscillation of the part being measured, so that the low amplitude high-frequency components can be acquired with the correct phase, without distortion. The hardware is discussed in Reference 1.

The operation of the hardware can be understood by referring to Figures 3 and 4. In Figure 3 three data sets, which were acquired from a Space Shuttle Orbiter thermal protection tile, show the variation without the gating system. The first and third data sets are very similar in both amplitude and phase. The second data set is inverted compared to the others. The gating system works by accepting only data which has a large positive amplitude during a short time interval after excitation of the tile by an acoustic click or by a pulse excitation from an air jet. The positive amplitude guarantees that the phase of all the data sets is the same. The large amplitude requirement guarantees that the low frequency oscillations are at or near the linear portion of the sensor response curve where, as seen in Figure 1b, the response of the sensor is largest. Figure 4 shows four sequential data sets acquired with the gating system; only very small differences can be seen in the data.

Two difficulties still remain. The first is that the absolute phase is not known since the choice of a positive signal is arbitrary. This is not a problem for most analyses. The second is that the low frequency motion may be so large that the data become nonlinear before the time of the data acquisition is completed. This is apparent in small differences in the first and third signals in Figure 3. The amplitude in the later portions of the first signal is smaller than in the later portions of the

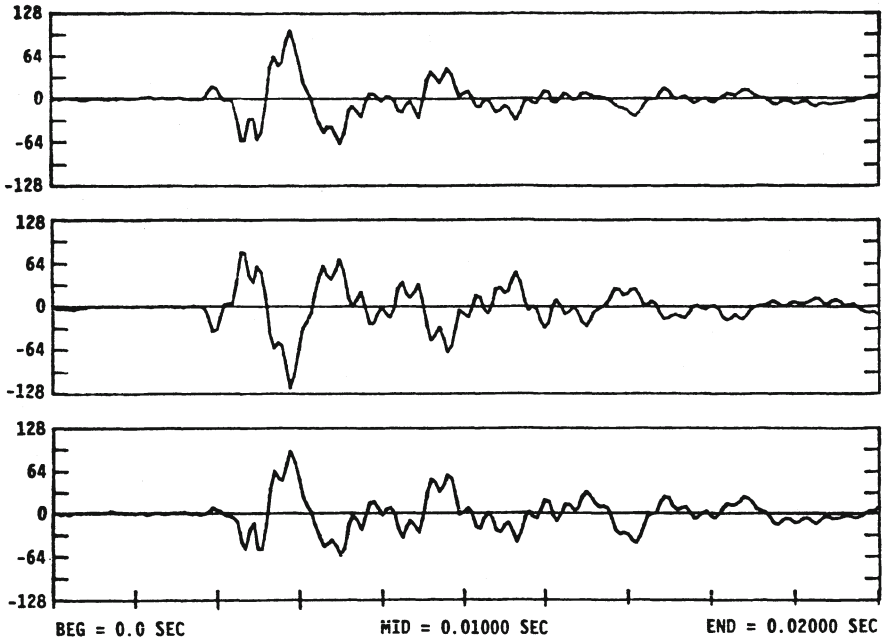


Fig. 3. The variation in the sensor signal without gating and thresholding.

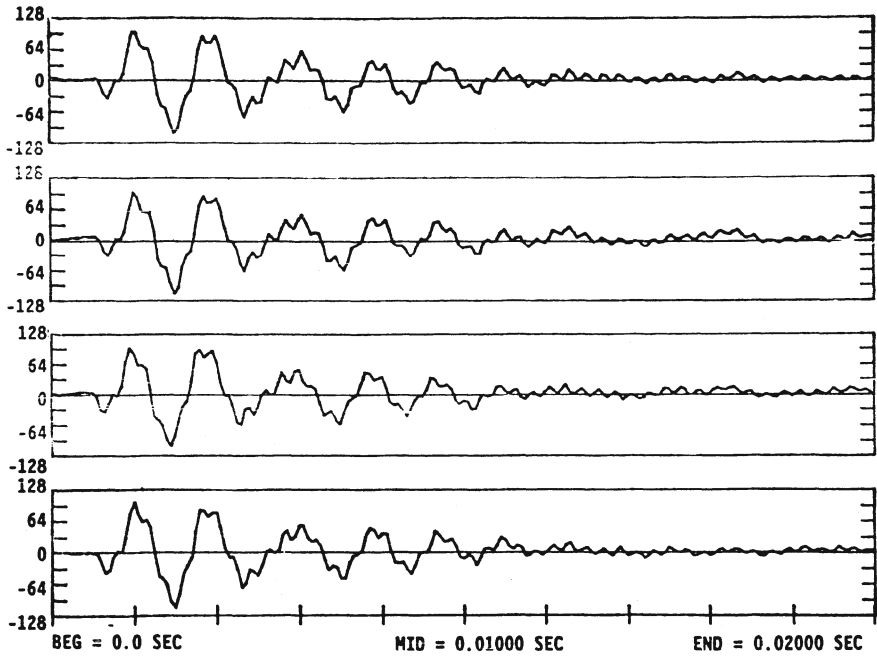


Fig. 4. Sensor signal with gating and thresholding.

third signal. Apparently the low-frequency motion was large enough during the first data acquisition so that the later parts of the signal are reduced in amplitude. In effect this implies that the period for accurate data collection is a function of the ambient vibration and can only occur during the time when the part is at a half-integral multiple number of wavelengths plus $1/8$ wavelength.

IMPROVING THE STANDOFF

One of the most important areas of progress was implementation of an optical system that allows up to 10 m of working distance between the part and the measurement system. This was accomplished by increasing the focal length of the optical system while maintaining equivalent light gathering capabilities. In order to obtain an adequate signal using the frequency stabilized HeNe laser, an adequate amount of light must be collected. In addition, the sensing beam must be focused to a spot size at the tile surface which is small enough to avoid averaging out the displacement over the spot diameter.

The initial data collection was accomplished using a 100 mm focal length lens. This particular lens provided an adequate signal-to-noise ratio and the data collected with it established a baseline optical collection capability. The calculated values of this baseline are a spot size (beam waist) at the part surface of $102 \mu\text{m}$ and a collection capability of $f/125$.

To achieve a long standoff distance, it is important to note that the problem is essentially one of imaging the primary beam waist (located within the lasing cavity) at the tile surface. Therefore, it can be seen that the problem is one of magnification. In evaluating this situation, the previously mentioned criteria for adequate signal production must be kept in mind. The optical configuration for the long standoff, accordingly, uses two elements. First, a -5 mm focal length lens is used which has the effect of producing a virtual beam waist with a $6.5 \mu\text{m}$ diameter and the Rayleigh range of the laser is simultaneously shortened. This allows the beam waist to be imaged at the tile surface with a small diameter. The second element is a 150 mm compound lens. This lens is of high quality and, therefore, has been corrected for aberrations. Using this lens, the virtual beam waist is imaged at the tile surface with a calculated diameter of $124 \mu\text{m}$. The combined effect of the two optical elements is to produce a small spot size at the tile with a collection capability of $f/149$ and a standoff of approximately 2 m. In addition to these properties, this configuration has a variable focal length capability allowing the lens to be used from as close as 1 m to distances greater than 9 m.

There are some slight differences for the calculated spot sizes and f-numbers for the two lens configurations. These differences can be accepted since the calculations are for ideal lenses with the 150 mm compound lens considered a single thin lens for computational ease. Data collected with the long standoff lens at a variety of distances from the tile surface are in excellent agreement with data collected using the 100 mm focal length lens.

IMPACT AND IMPLEMENTATION OF THIS TECHNOLOGY

While the focus of this work is on the Orbiter thermal tile protection system, the capabilities being developed will have application to many other NDE problems. Two key new capabilities are associated with the

research being performed. The first is the ability to make practical noncontacting acoustic measurements with a laser beam. The second key element hinges on using this new sensing capability to form the basis for predictive models of how complex structures resonate and how various flaw conditions perturb the resonances. This is an extension of existing vibration analysis technology to take advantage of the high degree of sensitivity and precision of the acousto-optic sensor. Candidate materials and flaws range from detecting delaminations in carbon-carbon composites to determining the fiber-matrix cohesion in metal matrix composites.

ACKNOWLEDGMENTS

This work is supported by the John F. Kennedy Space Center, NASA, through Department of Energy Contract No. DE-AC07-76ID01570.

REFERENCES

1. B. A. Barna, R. T. Allemeier, and J. G. Rodriguez, "Laser optic vibration sensing for the inspection of bonds in the orbiter thermal protection tiles", Review of Progress in QNDE 7b, D. O. Thompson and D. E. Chimenti, eds., Plenum Press, New York, p. 1227 (1988)
2. S. J. Bennet, R. E. Ward, and D. C. Wilson, "Comments on: Frequency Stabilization of Internal Mirror He-Ne Lasers," Applied Optics, Vol. 12, No. 7, July 1973, p. 1406
3. S. Donati, "Laser Interferometry by Induced Modulation of a Cavity Field," J. Appl. Phys., Vol. 49, No. 2, February 1978, pp. 495-497.