LASER OPTIC VIBRATION SENSING FOR THE INSPECTION OF BONDS IN THE ORBITER THERMAL PROTECTION TILES

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INTRODUCTION

This paper describes the use of a noncontacting acousto-optic sensor for the detection of bonding flaws in complex composite structures. The current area of emphasis for this work is the inspection of the complex, multilayer bond of the silica fiber composite thermal protection tiles for the Space Shuttle Orbiter. This paper describes the approach used to sense submicron vibration displacements of the tile surface using a frequency stabilized helium-neon laser, and the signal processing applied using a computerized NDE workstation. The basic premise is that a bonded structure will exhibit varying dynamic responses to an excitation pulse that depends on the boundary conditions defined by the bonded area. The noncontacting laser acoustic sensor allows a rapid measurement that does not perturb the dynamic response and does not damage the surface of interest. In addition, a coherent light imaging technique for real-time visualization of the tile vibration modes (speckle interferometry) was used to guide the single point vibration measurements and study the vibration mode shapes and their behavior as the bond was degraded.

The results of this research are applicable to many materials characterization problems. The key elements of the new capability discussed here are the laser acoustic point sensor and a detailed understanding of how resonance vibration modes are affected by flaws in typical aerospace structures. Potential applications include the noncontacting detection of delaminations in composites and honeycomb structures and the detection of bond flaws in solid rocket motor components.

A NONCONTACTING ACOUSTO-OPTIC SENSOR

The primary objective of this phase of the research was to develop a noncontacting sensor for use with the diffuse black reflecting surface of a standard thermal protection tile. Since it was not feasible to utilize mirror-like surfaces, laser heterodyne techniques [1-4] were not deemed appropriate and an approach was taken that utilized the frequency stabilization scheme of a low power helium-neon laser. Tests with this laser system had shown a great sensitivity to even the small amounts of light backscattered from the black tile surface. There are also other
potential benefits in this approach in that the technology is well developed, and if it could be successfully adapted to make the desired measurement, significant benefits would result in reduced development time and reliability. A final deciding factor was that comparatively little research had been reported on using this type of system as a vibration detector. By determining the capabilities of the technique in this phase of the project, a more informed decision about the optimum sensor choice could be made in the future. If need be, the heterodyne system could be refined in later phases of the research.

An understanding of this laser stabilization scheme can be obtained from the somewhat stylized diagram in Fig. 1. The stabilization is based on the alternate mode balance technique first described by Bennet et al. [5]. In certain preselected plasma tubes the relative intensity of two orthogonally polarized lasing modes can be used to generate a servo signal that controls the tube length to achieve stabilization. By maintaining the ratio of the two intensities at some fixed value (typically 1.0), thermal and vibrational effects that would normally destabilize the laser can be compensated for with the servo. As can be seen from the figure, the intensities are sensed by two photodiodes with appropriate polarizers mounted on the end of the lasing tube. In addition, an output polarizer can be used to allow the transmission of one or both beams out of the laser.

In the normally anticipated use of this type of laser, one would try to minimize the reentry into the cavity of any backscattered light (retroreflection) from outside of the cavity. In this way, the stabilization servo can maintain a very constant light frequency by detecting and compensating for temperature and small vibrational drifts. Operating in this fashion, frequency stability on the order of 500 kHz out of 474 terahertz can be obtained over periods of an hour or more. If, however, retroreflection is allowed to enter the cavity, it will disturb the mode of similar polarization and contribute to its destabilization. A retroreflection of less than 1% can cause power fluctuations in the mode of ±20%. It is this fact which makes this device a potential vibration detector.

Fig. 1. Stabilized laser--concept of operation.
When the output beam of the laser impinges on a vibrating surface, the retroreflected light is modulated in phase or Doppler shifted by the vibration of the surface. When this reflection reenters the lasing cavity, it is superimposed on the existing lasing mode and vectorially sums to produce an amplitude variation that is dependent on the relative phase between the stabilized and retroreflected beam. This variation is detected by the photodiode whose signal is fed to an operation amplifier for comparison to the second mode of orthogonal polarization with the resulting error signal being used to drive the tube length servo transducer. Essentially this is an autodyne detection scheme in which the reflected signal containing the vibration information is beat with the unperturbed original signal. The technique has an inherent limitation when the displacement of the vibrating object is greater than one-half of the optical wavelength. In this case the phase of the retroreflected signal cannot be distinguished from a displacement that is smaller in amplitude by one-half wavelength. As is shown in the results that follow, however, this was not an insurmountable problem in the measurement of the tile vibrations even though it does cause a time dependent variation in the servo output signal.

**Implementation of the Stabilized Laser as a Sensor**

In practice, data are collected by focusing the laser output beam on the surface of the tile which, for these experiments, was bonded to a strain isolation pad which in turn was bonded to an aluminum plate. The plate was bolted to a heavy aluminum block to simulate the effect of mounting on a large rigid structure. The tile was driven into oscillation with a standard audio loudspeaker placed from 0.5 to 2.0 m from the tile. In order to excite a broad band of resonance modes in the tile simultaneously, the audio signal was a square wave pulse of 100-μs duration. Such a pulse (which sounds like a brief "click") has a Fourier transform with frequency components from 40 to 10,000 Hz after amplification. This bandwidth was more than adequate to excite all the modes observed on the tiles. When the tile is excited by this "click", it undergoes a transient oscillation with a peak amplitude on the order of 0.1 to 3.0 μm which damps out in less than 50 ms depending on the amplitude of the excitation and the characteristics of the tile, strain isolation pad (SIP), and mounting configuration. This transient oscillation causes a phase shift in the scattered light off the tile surface which is collected by the lens and directed back into the lasing cavity.

The signal which contains the vibration information is the servo error signal which is applied to the tube length transducer. In addition to the bandpass response of the servo circuits, this signal is also bandpass filtered with a separate active filter before being processed on the INEL NDE Workstation [6], a PDP 11/73 based real-time data acquisition and analysis workstation. If the raw data are collected as-is with no further processing or discrimination, the variations caused by the servo response and low frequency displacements greater than one-half wavelength of light are observed as phase inversions and amplitude variations in the digitized signal. Fig. 2, which shows three digitized signals from the laser spaced at one-second intervals, illustrates this quite clearly. The top and middle traces are phase inverted while the bottom trace shows reduced amplitude compared to the other two traces.

Obviously, a means was required to account for the potential signal variations if repeatable data were to be obtained. This was accomplished by using the capabilities of the NDE Workstation and associated electronics to only capture a signal when the servo system was at its...
midrange operating point and the path length between tile and laser head was at a repeatable position compared to previous data sets. This is not as difficult to do as it sounds. In the scheme finally devised, a threshold condition was imposed in that the computer would not accept a signal unless it had a peak which crossed a given threshold within a tightly defined time gate. In simplified terms, this translates to only accepting signals that are of similar amplitude and phase. The hardware implementation of this is shown in Fig. 3. The digitizer is told by the software to begin digitizing and wait for a stop trigger to mark the occurrence of an acceptable signal. A specified pretrigger sampling range is defined so that the beginning of the event (which occurs before the stop trigger is generated) can also be collected. After the system is armed and waiting for acceptable events, subsequent clicks of the speaker resulting in a signal that meets the selection criteria are digitzed and stored. With an excitation rate of 10 pulses per second and computer response time of better than 60 ms, data acquisition can proceed rapidly.

Fig. 4 shows four representative data sets collected with this technique. The phase inversion and large amplitude variations are no longer evident. However to ensure maximum accuracy for the subsequent experiments, an additional step of averaging 25 separate acquisitions was taken. That is, the software averaged the data from 25 separate events or "clicks" before storing the data. The effects of this enhancement are shown in Fig. 5 where two different data sets from the same tile taken at different times are overlaid on the same plot. As can be seen, there is virtually no significant difference between the sets, demonstrating the repeatability of the data.

Another feature of this data collection scheme which might have introduced some variability was the effect of the threshold selection. To examine this in more detail a number of data sets were collected at different thresholds. The results of two of these plots are shown in
Fig. 3. Acousto-optic vibration measurement.

Fig. 4. Four sets of unaveraged laser data files.

Fig. 6. The correspondence is again quite good with the main difference being a slight timing offset which is exactly what is to be expected when the stop trigger threshold is changed.

Once the basic repeatability of the stabilized laser noncontacting measurement was established, additional experiments were undertaken to compare the sensor's response to more conventional devices such as the accelerometer mounted on the tile surface. To accomplish this, an accelerometer was glued to the center of the tile surface and signals
Fig. 5. Overlay of two averaged sets (25 averages).

Fig. 6. Overlay of two data sets with differing thresholds.
were digitized from both the accelerometer and the laser sensor which was focused onto the back of the accelerometer housing. The time series data were then Fourier transformed; the two resulting spectra are compared in Fig. 7. Since the accelerometer is an acceleration sensor and the laser sensor measures displacement, it is necessary to divide the accelerometer spectra by the square of the frequency. This plot clearly verifies that the laser sensor is measuring displacement and is in good agreement with a known and calibrated source.

Application of the Sensor

After it was determined that the laser sensing technique was viable, a large number of tests were conducted to study the effect of the degree of bonding on the tile's dynamic response. The results presented below are only a brief summary of these tests to illustrate the capabilities of the technique. A more complete description of the experimental technique and an analysis are given in an EG&G report [7].

A representative set of data from a tile is shown in Fig. 8 [8]. During these tests factors such as acoustic source location and energy, mounting configuration of the tile, and measurement points were kept constant. Data were collected with the laser sensor as described earlier. Data sets were collected with no unbond, 20% unbond, and 47% unbond (0, 1, and 2 UB). Fig. 8 shows the spectra measured at a point located at the top center of a tile with 0 UB as the uppermost plot. There are obvious differences in the spectra as the tile is unbonded. The peaks below 1250 Hz show an increase in the energy at lower frequencies and the peaks above 1250 Hz show somewhat more complex changes.

In addition to the point measurements, real-time speckle interferometry was used to visualize the effects on resonance behavior as the bond was degraded. Fig. 9 shows the effect of the three bond

Fig. 7. Accelerometer-laser data comparison after omega squared correction.
Fig. 8. Tile 8122 TC point--spectra during unbonding. Top spectrum, 0 UB; center, 20% UB; bottom, 47% UB.

Fig. 9. Tile 8491 modes at 209 Hz.

conditions on a resonance mode that occurred at 209 Hz on a given tile. The lighter shaded linear areas are vibration nodes on the tile surface. The nodal area rotates and changes in width as the bond is degraded.

These two figures give a general idea of how the technique was applied to the study of bonding for this particular material. The effect of the bond on the dynamic response of the tiles is, as mentioned before, a complex phenomenon. The current research effort is concentrating on developing a more complete understanding of the physics of the vibrations and why certain resonance modes are affected by a degradation of the bond. In addition the sensor is being modified to be portable to enable field measurements.
CONCLUSIONS

A noncontacting laser acoustic sensor has been shown to be feasible for use on diffusely reflecting surfaces. Comparisons between the laser acoustic sensor system and a standard accelerometer have shown good agreement in the range from 200 to 5000 Hz. Extensions of this bandwidth, if necessary, are also feasible. The system as configured, while capable of field use, can be refined and modified to improve its capabilities. There are no apparent problems in sensing directly off of a normal tile surface. In addition the resonance vibrations of the tiles studied are affected by disbands.

The capability provided by this sensing technology may be the basis for predictive models of how complex structures resonate and how various flaw conditions perturb the resonances. In a sense, 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 applications for this technique range from detecting delaminations in carbon-carbon composites delaminations to determining the fiber-matrix cohesion in metal matrix composites.

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REFERENCES


