APPLIED HOLOGRAPHIC INTERFEROMETRY AS A NONDESTRUCTIVE METHOD FOR THE DYNAMIC AND MODAL ANALYSIS OF AN ADVANCED GRAPHITE-EPOXY COMPOSITE STRUCTURE

Howard Fein
Polaris Research Group
24400 Highland Road, Richmond Heights, Ohio 44143

INTRODUCTION

Holographic Interferometry methods have been successfully employed to characterize the materials and behavior of diverse types of structures under stress [1,2,3]. Specialized variations of this technology have also been applied to define dynamic and vibration related structural behavior[4]. Such applications of holographic technique offer some of the most effective methods of modal and dynamic analysis available. Structures and processed materials can be analyzed with very low amplitude excitation and the resultant data can be used to adjust the accuracy of mathematically derived structural models.

Holographic nondestructive test techniques have offered a powerful tool to aid in the the primary engineering and development of advanced complex composite materials. One such material is a graphite-epoxy fiber reinforced polymer matrix composite, now finding increased use in advanced aerodynamic, automotive, and other highly mobile platforms. Avionic and undersea applications especially must consider environments where extremes in vibration and mechanical stresses can affect both operation and structural stability. These are ideal requisites for analysis using advanced time-average holographic methods in the initial design and subsequent test of such advanced structures and materials. Holographic methods are non-destructive, real-time, and definitive in allowing the identification of vibrational modes, displacements, and motion geometries. Such information is often crucial to the determination of mechanical configurations and designs as well as operational parameters of structures composed of advanced engineering materials.

METHODS

The applications and methods of holographic interferometry to vibration and modal analysis are mature and well understood. The usefulness and value of these analytical tools have also been greatly enhanced by new technology developments in Lasers and holographic instrumentation.

The methods of interest to this discussion are called "real-time" and "time-average" holography. The first term refers to the superposition of a hologram of an object over the object itself while being subjected to some small stress[5]. This enables observation of the effects of minute changes in displacement on, or in, the structure of the object as stress affects it in real time. The second term defines a hologram that is created while the object under study is subjected to some type of periodic displacement[5]. Both techniques reveal different aspects of the geometry and magnitude of vibration induced displacements in a structure or its components.

Time average holograms generate fringe patterns of bright and dark lines which appear superimposed on the object under study. These interference fringes define isobars of stress or vibration induced displacement. Specific geometries and symmetries in the holographic fringe patterns map the behavior of the structure by defining characteristics of motion and displacement. Such "maps" can readily show distortions resulting from material, structural, or processing anomalies. Data has shown that mass loading, substrate thickness and homogeneity, and other factors have great effect on the vibrational mode shapes and frequencies. Modal analysis using real-time holographic analysis allows visual identification of structural resonances, while time-average methods are employed to map these resonant modal geometries.

Structures composed of advanced materials such as metal and epoxy-matrix composite substrates are especially suited to this type of analysis. Extremely small stresses and displacements can be induced without damaging the structures themselves through low level vibration from either attached transducers or transmitted acoustic excitation. Modal geometry, resonant behavior, structural and material defects, as well as other considerations, are observable employing holographic techniques.

A diagram of the holographic system employed in this work is illustrated in Figure 1. The system incorporates an Argon-ion laser operating at a single mode and single frequency. Holograms were recorded with a photo-thermoplastic based "instant holocamera"[7]. The optical system was configured to produce off-axis holograms which were imaged by a high resolution television camera and monitor. Hard copy of the holographic data was made from the video record on the monitor screen using direct video print-out. The holographic recording procedure generally required less than one minute per image due to the unique capabilities of the holocamera device employed.

Holographic techniques were applied to characterize the dynamic behavior and structure of an advanced graphite-epoxy composite part and its ancillary mounting geometry. It was determined that such information would be essential since the part would be subjected to extreme mechanical stress and vibration in normal use. The method employed depends on introducing low level, non-destructive vibration and stress which propagate to induce corresponding resonances and minute displacements at the surface of the structure. This was accomplished using acoustic energy transmitted from an audio source positioned close to the composite part under test. The resonant modes produced by this uncoupled, low amplitude excitation were holographically recorded.

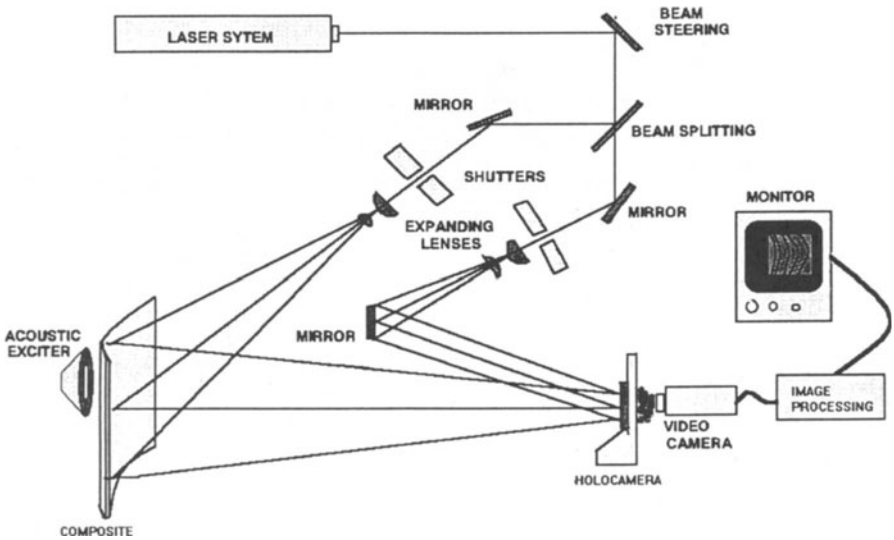

Figure 1. Holographic interferometry system.

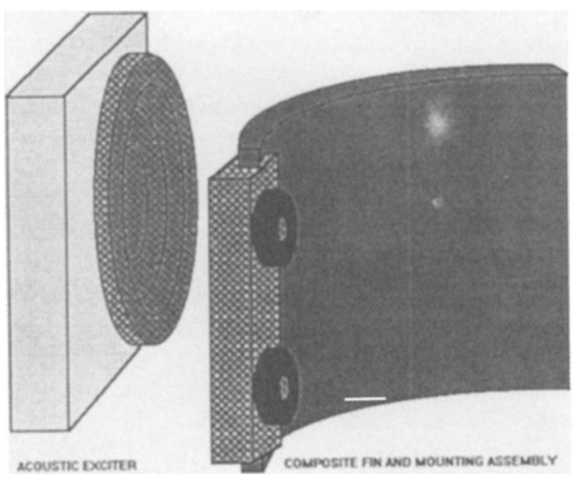

Figure 2. Graphite-epoxy composite structure assembly configuration.

Time average holograms of the vibrational modes of this structure were used to identify the resonant frequencies and accurately map the nodes, maxima, minima, and geometry of the induced motion. Such "maps" can be readily compared to the noise spectra of the operational and test environment to allow the true real-world behavior of the structure to govern its subsequent optimum design and engineering.

Holograms were made at .5145 microns wavelength with exposures controlled radiometrically by measuring the energy density at the holographic plate. This method insured the high contrast ratios and resolutions desired in the interferograms. The object beam was configured to illuminate the structure under study while the reference beam illuminated the holographic plate directly. Either real-time or time-average holograms of the composite structure assembly were possible in this configuration.

RESULTS

Data has been taken for an advanced polymer matrix composite structure assembly. Mass loading, composite thickness, shape, as well as material density, homogeneity, and constraint have great effect on the vibrational mode shapes and frequencies. A schematic representation of the graphite-epoxy composite structure and it's mounting and excitation geometry is illustrated in figure 2. Different constraint and stress geometries were applied to this assembly in order to develop an understandable characterization of it's dynamics from the resulting modal data.

The composite structure assembly under test was mounted and a holographic exposure made while it was in an "undisturbed" state (isolated from any induced vibrations or stresses). The resulting superimposed real-time holographic image was displayed on the monitor. The interference fringes produced mapped the displacement and shape of the resonant modes in as the composite structure assembly was excited through a range of acoustic frequencies.

These real-time holographic images are observed while the fringe patterns are optimized to negate rigid body motion, and frequencies are recorded for the modal patterns of most significant interest. Time-average holograms which map these mode shapes are subsequently created and recorded so that complete motion geometries of the assemblies are easily defined. An essential advantage of these methods is that the magnitude of the displacements represented by the holographic fringes is very small and thus non-destructive to the assembly under test. Each fringe in the real-time holographic image denotes an isobar of displacement of one half wavelength of the illuminating light. This corresponds to a displacement of 0.2573 microns (10.1 micro-inches). Each fringe in the time-average hologram represents displacement isobars of the same order whose absolute magnitudes are determined by the previous value modified by a factor proportional to the coefficients of the zeros of a Bessel function.

The simple modal analysis of a homogeneous, symmetrically mounted composite structure assembly presents primary modal maps like those shown in figure 3. These geometries vary with the frequency of the induced excitation. The mode shapes of fundamental resonances are generally very distinctively developed. This figure shows holograms of the very strong first bending and first torsional modal geometries, of the composite structure. The mode shapes are not distorted or modified by constraint or mass loading effects. The excitation of these modes results from very high sensitivity to their respective resonant frequencies.

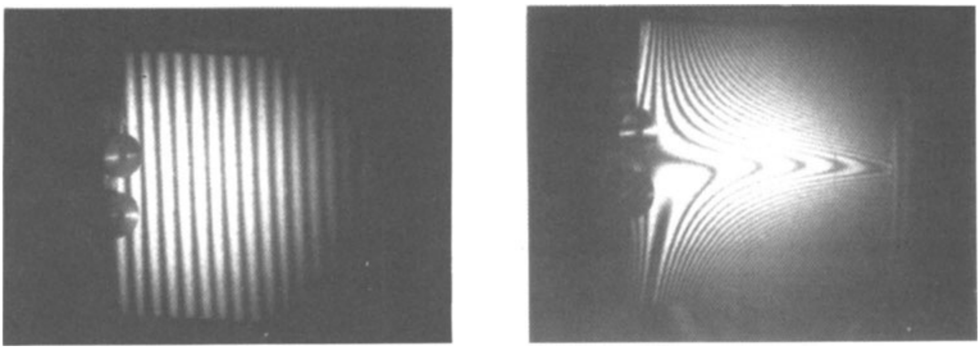

Figure 3. Fringe patterns showing first bending and first torsional modal geometries.

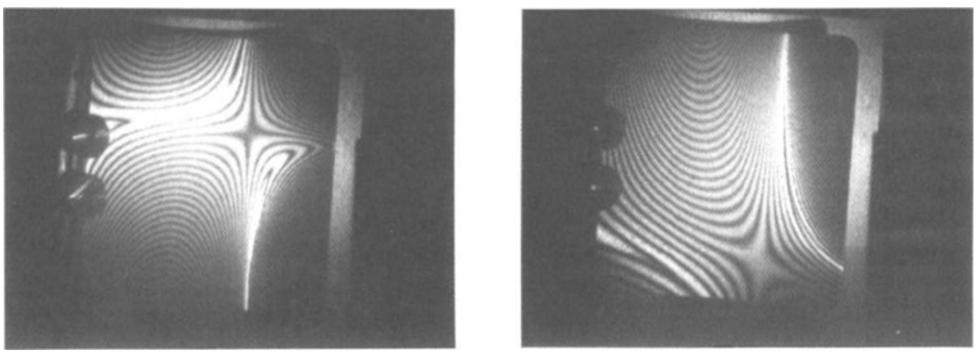

Figure 4. Holograms of bending/torsional conjugate modes.

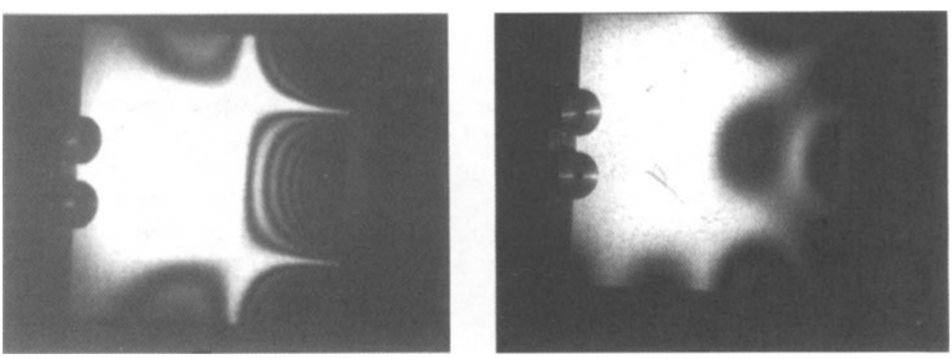

Figure 5. Holograms of higher order complex mode shapes.

The first holographic fringe pattern shown in figure 3 defines the bending of the structure as a displacement phenomenon whose amplitude increases linearly from the mounting assembly of the component. The fringe geometry in the second hologram depicts a strong torsional displacement pattern. The nodal "ridge" dividing the high amplitude fringe groups denotes that a phase change occurs between them. This defines a high stress point which could result if the inherent noise spectrum of the structure in its operational configuration includes a component at this frequency.

Examples of higher frequency mode shapes are these are shown in figure 4. Nodal geometries are progressively more complex as the frequency increases and displacement phase changes across the nodes induce localized cyclic stress in the substrate at nodal locations indicated by the highly visible bright nodal fringe. It is noted that mode shapes can be modified by the inclusion of various constraint parameters such as material and mounting anomalies. Both bending and torsional modes can be selectively modified by changes in the substrate as well. Figure 4 illustrates holograms of bending/torsional conjugate modes whose fundamental geometries have been distorted by nonisotropic mounting constraints. The modes shown in each hologram are modified patterns at slightly different frequencies of the same geometry with opposite nodal phase distributions. The distortion of the strong geometry is amplitude independent and defines the effect of constraint and loading on the structure.

Figure 5 shows holograms of higher order complex mode shapes. The fringe patterns show superpositions of the higher order bending and torsional modes which define broad areas of zero motion at the excitation amplitudes employed in these experiments. The well defined nodal distributions and displacement fringe geometries define multiple phase change points whose excitation generates highly localized stress.

The first holographic fringe pattern in figure 5 denotes the second bending/second torsional mode (N = 2,2). The regular geometry undistorted by mounting or loading and the sharp, bright nodal fringes are seen to extend from the broad zero-motion bright nodal center which could also be induced to generate high displacement levels resulting in extremely sharp nodal fringes. The corresponding phase changes of the alternating displacement fringe groups contribute to very high stress at this resonant frequency. The accompanying hologram shows the fringe pattern of a higher order complex modal geometry with low amplitude fringes and complex nodes. The superposition of modes results in complex patterns such as this as the excitation frequency increases.

Final structural analysis and development depends on a direct comparison of the of the actual composite structure assembly configuration with associated noise spectrum of the entire system of which it is a component. This comparison shows the true effect that the vibration environment contributes to the complete mechanical system. If the spectrum does not contribute significant energy at the frequencies of excitable modes then the system should exhibit mechanical stability and the components of the assembly will experience minimal stress in the operational environment. If the converse is seen, then modal analysis enables the identification of the appropriate geometry for application of stiffening or dampening constraints to change the mode shapes or strengths and shift or prevent their excitation. The holographic data could ultimately define parameters for finite element modeling and modification of the substrate material itself or its processing to eliminate anomalous behavior.

CONCLUSIONS

It has been demonstrated that holographic interferometry can be successfully employed to characterize the vibration induced behavior of an advanced grahite-epoxy composite structure. The frequency dependent characteristics of the structure are shown to be highly dependent on the substrate materials, processing, and mechanical geometry.

Since mobile platforms of any type present uniquely stressful environments, understanding the effects of vibration and noise by correlating spectra and mode shapes can insure the stability and integrity of the system and its component parts in operation. Holographic techniques were included in ongoing development and subsequent production testing of the assemblies illustrated and have proven to be the most effective method of evaluating their critical dynamic characteristics.

ACKNOWLEDGMENTS

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REFERENCES

1. Fein, H., "The Application of Holographic Interferometry to the Characterization of the Dynamics of a Complex Bonded Structure; *Proceedings of the SPIE Symposium on Optics, Imaging, and Instrumentation*, July, 1993
2. Fein, H., "Holographic Evaluation of the Material and Dynamic Characteristics of Bonded Compliant Structures"; *Proceedings of International Conference on the Applications of Lasers and Electro-Optics, (ICALEO)* October, 1993
3. Fein, H., "Holographic Interferometry Applied to Evaluate the Material Characteristics and Dynamics of Cast Compliant Structures", *Proceedings of International Congress on the Applications of Lasers and Electro-Optics (ICALEO)*, October, 1994
4. Fein, H. "Holographic Inteferometry Applied to the Characterization and Analysis of the Dynamic and Modal Behavior of Complex Circuit Board Structures", *Proceedings of the SPIE Symposium on Holography and Imaging Science and Technology*, February, 1994
5. Vest, C. M. (1979), *Holographic Interferometry*, John Wiley and Sons, Inc., New York. pp. 179-183
6. Ibid.
7. Newport Corp., *Instant Holocamera*, (1981), Fountain Valley, Ca.