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Testing for Material Flaws and Thermal Design Defects Using Holographic Interferometry

BDX-613-812

December, 1972

Project Leader:
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Department 445

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MASTER

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**Kansas City
Division**

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Prepared by M. C. Collins, M. P. Schoeppner, and C. E. Watterson

The feasibility of using holographic interferometry as a technique for nondestructive evaluation of internal voids and defects in Bendix materials and products has been established by Bendix Kansas City Division.

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THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission

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SUMMARY

A three-year development project has resulted in Bendix capability to perform nondestructive holographic testing on various products and materials. This report describes the principles of holographic interferometry, its implementation in the laboratory and illustrates the usefulness of holographic interferometry in detecting internal voids and defects in laminated and composite structures.

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DISCUSSION

SCOPE AND PURPOSE

Holographic interferometry is used as a technique for nondestructive evaluation of internal voids and defects in materials, such as laminated and composite structures. The intent of this project was to determine the feasibility of using this new technique at Bendix Kansas City and to develop the knowledge to perform holographic analysis in the laboratory. A facility was assembled for performing experimental work. The experiments were designed to attain proficiency in all techniques used for holographic testing.

It is not the intent of this paper to present a detailed mathematical theory of holography, since the principles can be explained in purely physical terms.

ACTIVITY

Principles of Holographic Interferometry

Holography is the science of recording the object wave of a scene and of recreating an image of that scene by wavefront reconstruction. The resultant holographic recording is not an optical image of the object, but the interferometric fringe pattern caused by the object. This pattern is recorded in such a way that a subsequent illumination of the recording serves to reconstruct an image of the original object. A visual observation of this reconstructed image yields a view of the scene which is practically indiscernible from the original.

Holographic interferometry (HI) is a technique of superimposing two slightly different images in a manner that causes the differences to be apparent because of interference patterns superimposed on the image.

Figure 1 shows a typical working setup for making the hologram of an object. The beam of coherent light from the laser, by reflection of mirrors, is positioned so that the light can be divided by a beam splitter mirror. Part of the light (the reference beam) is focused and spread out by a lens, and directed to a photographic plate which will become the hologram. The reference beam alone causes a uniform illumination of the hologram plate. The rest of the light (the object beam) is directed, focused, and spread to illuminate an object. The light striking the object is scattered (reflected diffusely) so that some of this light also strikes the hologram plate.

Figure 1. Typical Working Setup for Holography

Figure 2. Reconstruction of the Object Wavefront From a Hologram

Since the light originating from the laser is coherent, the reference beam arrives at the hologram plate with a constant phase wavefront. The light arriving at the hologram plate from the object has a wavefront which corresponds to the shape of the object. The two wavefronts of light interfere to form a minute pattern of light and dark areas. This pattern, called the interferometric fringe pattern, is recorded by the holographic plate. When developed, the plate contains, not an image as in ordinary photography, but a recording of the complex interference pattern. The interference pattern appears random but actually has all the information contained in the light reflected from the object.

Figure 2 illustrates how a hologram is used to create an image of the original object. The configuration is similar to Figure 1 except that the object has been removed, the hologram plate has been developed, and only the reference beam is used for illumination. Light from the laser is directed to fall upon the hologram and illuminate it in the manner shown. Light striking the minute patterns on the plate is diffracted in a manner similar to a diffraction grating but in a complex, irregular manner so that a new wavefront traveling toward the viewing point is formed. This wavefront, being a function of the information recorded on the hologram plate, assumes the shape of the original object wavefront. Observation of this wavefront at the viewing point reveals a virtual image in the original location of the object. This virtual image possesses all the characteristics of the original object. The image is three-dimensional and appears in space in a position corresponding to the original object location. True parallax exists, that is, a slight movement of the viewing point causes a change in the perspective of the object. Except for the monochromatic illumination from the laser, an observer would be unable to differentiate between the virtual image and the real object.

If a developed hologram is placed in the reference beam (Figure 2), and the object is replaced and illuminated by the object beam (Figure 1), the virtual image will be exactly superimposed upon the real object when viewed from the viewing point. Because the virtual image is realistic, the viewer is unable to discern that he is viewing both the image and the superimposed object. Figure 3 illustrates the application of a mechanical load to the real object, a fundamental application of HI. The load causes a deformation of the object so that different areas of the object are displaced different amounts. In an area where the object is moved $1/4$ wavelength nearer to the hologram plate, the light from the object and the light from the virtual image will interfere so that the image is blanked out. Where the object is moved $1/2$ wavelength closer to the hologram plate, light from the object and the virtual image will again be in phase and will reinforce, causing the image to be visible. Therefore, the viewed image will contain superimposed blanked out areas which correspond to odd multiples of $1/4$ wavelength movements of the object. For a complex object, this superimposed pattern (interferogram) will be complex and resemble a contour map of the displacements of the object.

Figure 3. Real Time Holographic Interferometry

The proposed use of holographic interferometry is based upon the idea that an object with areas of relative strength and weakness will deflect in a manner that represents those strengths and weaknesses. Therefore, the interference contour patterns will illustrate strengths and weaknesses. Analysis of the fringe pattern produces a point-to-point mapping of local surface displacements of the object. The surface behavior of an ideal test specimen is predicted from a theoretical stress analysis for a given stress loading. Differences between the results of fringe analysis and stress analysis may indicate internal flaws in the test specimen. Illustrations of holographic interferograms will be presented following a description of the implementation of the working arrangements.

Laboratory Implementation

Because a hologram is formed by interference of light waves, the optical components must be mechanically held in position with close tolerance. These components, and other details described in this section are critical to the implementation of holographic interferometry (Figure 4).

illuminating Source

A 2-watt, Coherent Model 52 argon laser with a minimum output of 1 watt at 514.5 nanometers was used as the illuminating source. This laser produces a beam of coherent monochromatic light of sufficient intensity for the photographic process. The coherence length (purity) exceeds 10 meters. The light must be coherent so that all light waves arriving at the hologram plate have a constant phase relationship that is determined by the object and not by spurious, non-coherent causes. The source must be monochromatic so that different wavelengths do not interfere with each other, and so that the displacements obtained in HI are a function of a known wavelength. The power output of the source must be sufficient to expose holographic plates in a reasonable amount of time and for viewing the virtual images. The source must be stable and have no random phase shifts over long periods of time. Instability causes degradation of the hologram images.

Mirrors and Beam Splitters

The optical components used in holographic setups must be of high quality and be rigidly mounted. The beam splitter reflectivity must be variable to adjust the relative intensity of the object and reference beams. Any small movement (including vibration) of these mirrors during the exposure or reconstruction of a hologram will shift the wavefront of the beams, producing hologram failure.

Figure 4. Typical HI Equipment Setup

Spatial Filters

The lens pinhole systems shown in Figures 1, 2, and 3 eliminate optical noise from the laser beams. Each beam is focused to a diffraction-limited spot at the pinhole. Unwanted optical noise not focused at the pinhole will not be allowed to pass. The emerging higher purity beams yield better quality holographic images.

Test Object

For this project, the test object consisted of various piece-parts which were to be tested for defects. In each case, a rigid mounting fixture was designed to hold the object rigidly in a precise location and to allow precise control of the distorting stress load.

Hologram Plate

Glass photographic plates are customarily used in holography. At the start of the project, the optimum photographic emulsion for holography was Kodak 649-F because of its higher resolution and good sensitivity to the laser wavelength. Emulsion 649-F was originally developed for spectrographic work. Glass plates are used for rigidity, where the hologram must be exposed, developed, and then replaced precisely in order to view the interferogram. Recently developed Agfa-Gevaert 10E56 plates have proven more sensitive with negligible loss of resolution for this application.

It is possible to make simple holograms on ordinary film by using short exposure times or by contact printing the plate onto the film. Such prints are adequate for viewing holographic images but not for forming interference stress patterns on the object.

Photographic Plate Techniques

A small change in the dimensions of the hologram emulsion during developing will physically displace the hologram image, creating an apparent distortion in the test specimen. In this project, methods have been perfected to minimize the effects of emulsion shrinkage.

Determination of the best exposure conditions is a fundamental problem in holography. Exposure conditions directly affect the quality of the image, but are not directly measurable on the photographic plate. From the experimental work, the data for optimum exposure of the plate was determined and a servo-actuated shutter which automatically gives the right exposure was constructed.

Figure 5. End View of Complete HI System [Code:
1. Granite Surface Plate (4 by 8 feet); 2.
Air Suspension Support Legs; 3. Air
Suspension Reservoir Tanks; 4. Atmos-
pheric Enclosure With Removable Panels;
5. Argon Laser.]

A technique for bleaching the developed hologram was perfected. After bleaching, a dielectric transparency, rather than a dark negative results. This transparency is a more efficient hologram and, therefore, yields brighter images.

Vibration Isolation

Because the interference pattern being recorded is a minute pattern of light and dark areas, any movement of the light beams because of floor or table vibration transmitted to the optical component obscures the interference pattern. Because the floor vibration level in the test laboratory was intolerable for HI, extensive design and testing of a stable platform was included in the system design. The stable platform shown in Figure 5 consists of a 1-ton granite surface plate supported by four concrete-based air suspension systems, with a natural resonant frequency below 2 Hz. This system provides adequate damping of floor vibration.

Some holographic systems use a pulse laser to make instantaneous flash holograms in order to minimize the effects of vibration. These systems, however, do not allow real time observation of stress contours.

Atmospheric Problems

Thermal distortions in the object and in the mounting hardware also cause changes in the optical path lengths which, in turn, cause undesirable shifts in the interferograms. Therefore, the system must be placed in a constant temperature environment and the components must be shielded from heat sources, such as the laser power supply.

Masses of warmer or cooler air drifting across the laser beams cause small changes in the index of refraction of the air, and result in a phase shift of the light. In practice, the amount of turbulence near air conditioning outlets is sufficient to cause phase shift and, therefore, blurring of the interference patterns. These problems were alleviated by construction of a container around the work area. A typical plywood enclosure can be seen in Figure 5.

Testing in Real Time Mode

Cantilever Beam Calibration Fixture

Initially a 1-inch wide steel bar was used to derive data for small displacements in a stressed cantilever configuration. The complete experiment

Figure 6. Cantilever Beam Calibration Fixture
[Code: 1. Rigid Base; 2. Cantilever Beam; 3. Transducer for Force and Displacement.]

Figure 7. Cantilever Interferogram
[Code: 1. Base; 2. Cantilever Beam.]

included mathematical analysis of the curvature of the cantilever, design of a cantilever and holding fixture, and holographic analysis to correlate with the mathematical model.

Figures 6 and 7 show the experimental cantilever and the interferogram of the cantilever in a stressed condition. The cantilever is a steel bar about 2-1/2 cm wide, 15 cm long and 3 mm thick. It is clamped at the bottom, and the top is flexed outward. The dark bands visible in Figure 7 immediately left of the ruler are the interference fringes showing contour lines of uniform displacement. Each dark band represents an area where the cantilever has been displaced toward the viewer by an odd multiple of 1/4 wavelength. Therefore, as in a contour map, each dark line represents another half-wavelength or $0.25\text{ }\mu\text{m}$ (10 microinches). A quick qualitative analysis of Figure 7 shows that the cantilever has not merely moved forward on the top as expected, but that the clamped bottom has twisted somewhat in the clamp. When the original photo of Figure 7 was taken, it was possible to vary the bending force and view the changes in fringe pattern.

A more conventional method of analyzing the cantilever displacement would have been by attaching several small strain gages to the surface. However, a glance at the holographic photo reveals more about the unexpected movement than would a whole array of strain gages.

The mathematical analysis was concluded and compared with a photo similar to Figure 7. Tabulated data shows that the behavior of the cantilever, and thus the location of the holographic interference fringes can be predicted. Conversely, it has been shown that the behavior of the cantilever can be measured from the location of the interference fringes.

Filament Wound Domes

The first major benefit from the project was a test using real time interferometry, and gas pressure as a stressing medium. The specimen parts are basically a 25-cm diameter dome of filament wound fiberglass, coated with epoxy about 0.5 cm thick. When this part is clamped in a suitable fixture and stressed by increasing the internal pressure slightly, holographic interference patterns are formed which show contours of uniform extension. For dome-shaped parts, deviations from circular patterns indicate non-uniformities. Because of the sensitivity of HI, extremely small uneven expansion displacements can be detected. Figure 8 is a polar view of a normal pattern. In this test of a hollow fiberglass dome, the internal air pressure was varied by 3 psi (2.1 N/cm^2) to cause specimen expansion. The fringes shown in Figure 8 are contour lines of uniform displacement (approximately $0.25\text{ }\mu\text{m}$ or 10 microinches per fringe). Perfectly homogeneous material would yield circular rings, but this part shows normal deviations.

Figure 8. Polar View Interferogram of Fiberglass Dome. Perturbation (Arrow) Indicates severed Fiberglass strand.

Figure 9. Oblique View Interferogram of Fiberglass Dome

Figure 10. Encapsulated Module
Approximately 350 cm Wide

Figure 11: Interferogram of the Illuminated
Area in Figure 10. Arrow indicates
Sinking Area.

The small fringe perturbation, designated by the arrow, indicates a weakness. Microscopic examination revealed that several fiberglass strands had been severed during manufacture.

Figure 9 is an oblique view of a similar fiberglass part. A high modulus (stiffer) ring extends around the area where the filament wrap pattern changes from spherical to cylindrical. In one area (arrow) the high modulus band is wider than it should be. Also visible is the strength pattern of the wrap on the cylindrical portion. Obviously, some parts are more uniformly made than others--a desirable characteristic. Since these photographs were taken in a real time situation, the pressure could be varied to directly observe the results in the stress pattern. The pressure range for this test was 2 to 5 psi (1.4 to 3.5 N/cm²).

Thermal Stressing in Double Exposure Mode

Double exposure HI is performed in a manner similar to real time interferometry, except that two exposures are made on the same hologram plate: one with the object unstressed, and one with the object stressed. The interference patterns, instead of being formed between hologram image and real object, are formed between the two holographic images. This record is permanent and can be viewed any time without the actual object. Double exposure is used primarily in situations where the unstressed and stressed conditions cannot be held in a steady state for casual observation. Double exposure is particularly useful where thermal, rather than mechanical stressing is used.

Encapsulated Electronic Modules

A series of tests has been completed on an encapsulated module. This unit is a complex assembly of electronic components, circuit boards, and structural hardware. The assembly is completely encapsulated with a rigid potting material. During the design and redesign stages, severe cracking of the potting material during temperature cycling occurred. The cracking resulted from the different coefficients of thermal expansion of the internal components. HI was used to predict areas of high stress concentrations in the potting material that would cause cracking.

The test is carried out by first soaking the part at a nondestructive 35°C. Double exposure holograms shot at 10-minute intervals are taken while the part cools normally back to room temperature. The resulting differential expansion stress patterns recorded on the interferogram are studied to determine localization of stresses. In Figure 10, the test surface

is illuminated with ordinary light. In Figure 11, the double exposure interferogram shows displacement contours on the surface caused by internal components when the unit is cooled about 1°C. Detailed analysis of the resulting pattern reveals areas of critical stress which may crack in higher temperature excursions. Just above the "sinking area" (arrow) is a horizontal stress line caused by the edge of an internal printed circuit board. Areas of close fringe spacing indicate areas of high differential slope.

Figures 12 and 13 show interferograms of a mockup which contained enough stress to cause a crack to appear on the surface. The interferogram shown in Figure 13 was made after the unit had been subjected to a thermal cycle D-test. The potting material has cracked completely through the surface along the horizontal line shown in Figure 12. At this stage the fringes are completely discontinuous, indicating that both sides of the crack are moving independently.

This investigation proved feasible enough to result in a testing program on a special order for these modules. Because of the promising outcome of the work in this area, a separate special order has been received for testing other potted assemblies.

ACCOMPLISHMENTS

As a result of this project Bendix Kansas City has developed a testing technique not formerly available. At the start, HI was an art that was available only in the research laboratory. HI is now in use at Bendix for diagnostic and production testing. The theory of holography and holographic interferometry has been studied and understood, as applicable to practical use. The mathematical analysis of expected results for many test configurations has been carried as far as possible. A holographic test facility has been assembled in the Bendix test laboratory and includes a large number of mechanical, electrical and optical components. Practical problems such as temperature, vibration, photographic processing, illumination levels, optical alignment, mechanical stressing, thermal stressing and photography were systematically resolved in Bendix holographic studies.

Holographic tests have been performed on calibration fixtures, which allow correlation of results with theoretical expectations. Also, several Bendix products have been tested before shipment to the customer and the holographic results have been provided as part of their quality certification.

Figure 12: Interferogram of Mockup Thermally Induced Stresses (1.1°C) [Code: 1. Valleys Caused by Internal Vertical Steel Posts; 2. Area of High Differential Slope; 3. Severe Horizontal Stress Line.]

Figure 13: Interferogram of Mockup After Temperature Cycle Testing. Encapsulated Material Cracked Through to Surface at Horizontal Stress Line (Fringes Now Discontinuous at Crack).