Displacement Analysis Using Holographic Interferometry

by

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Abstract

Laboratory experiments are described which demonstrate the process of holographic recording and the use of holographic interferometry for displacement analysis. The material is designed to be used as a portion of an advanced undergraduate or graduate level course in experimental stress analysis.

Introduction

The holographic process is now more that three decades old, having been proposed by Dennis Gabor in 1948 as a possible means of improving the resolving power of the electron microscope[1]. It was not until the early 1960's, when Leith and Upatnieks produced the first high quality holographic image using a strong coherent source[2], that widespread attention was given to holography. The exactness of the holographic image made it invaluable for detecting faults, and the holographic recording process has since become an important diagnostic tool for stress analysis.

In many ways, holography has grown in parallel with electronic information processing. Some of that technology has been incorporated into the proposed holographic experiments. For example, individual singlemode fibers (initially developed for the communications industry) have been used to guide light for the reference and object beams. Phase modulation is demonstrated in some experiments, paving the way for more advanced laboratory sessions designed to digitize, automatically analyze, and couple holographically recorded displacements with sophisticated finite element routines.

It is assumed that the instructor is somewhat familiar with holography and holographic interferometry and that students taking this course in experimental stress analysis have an engineering background but are not specialists in optics. Little attempt has been made to cover the background material required to conduct experiments. However, guidelines are suggested and a few references are cited to aid the instructor in preparation of this preliminary material.

Experiments involve a relatively large class of twenty students and have been designed with consideration for the typical instructor, limited by a tight budget and faced with the problem that several students must use the same equipment.

Preliminary Material

Each student must be exposed to a basic understanding of the nature of light, including interference and diffraction, in order to design or effectively use a holographic system. Introductory lectures for this laboratory experiment should stress the basic requirements for making a hologram, namely, pathlength matching, polarization, and stability[3-5]. Lectures should also cover photography and photographic processing, holographic construction and reconstruction, and an introduction to holographic/fiber optic recording[6,7].

A knowledge of the theory and equations of holography is essential in order to quantitatively interpret holographic fringes obtained by interferometry. Consequently, additional material must be covered including displacement recording by double-exposure and real-time techniques, the basic phase-displacement equations, and a description of time-average recording and associated equations[8-11]. Superposition of holographic interferograms is important for isolating certain displacement components and can be introduced by covering the holographic-moire technique[12,13].

Laboratory Set-Up

One week prior to the laboratory session, the instructor divides the class of twenty students into four groups of five students. Each group chooses a group leader who assumes his/her own responsibilities and assigns tasks to other members of the group as follows:

- The group leader initially serves as a member of the launch team, coordinates the experiments performed by his/her group, and delivers the final report.
- The second member of the group is designated as a designer. He/she is responsible for planning the experiment and discussing the proposed set-up with the group and the instructor.
- The third member of the group is responsible for implementing the design. He/she sets up the optics, measures pathlengths, and checks for proper polarization and stability.
- The fourth member of the group actually records and photographically processes the hologram.
- The fifth member of the group reconstructs the hologram and is responsible for developing prints and slides required for the final report.

Each group is assigned approximately one-quarter of the available working space. Figure 1, for example, shows the top of a 4' x 10' vibration isolated surface table partitioned into five segments. The laser and launch optics have been centrally located to provide easy access to each of the four 2' x 4' work areas. This configuration allows each group to work over their own corner of the optical bench.

The four members of the launch team (the group leaders) are responsible for providing the two fiber optic illuminators used by each group (for illuminating the object and as the reference wavefront). The instructor assigns tasks to each of the four members of the launch team as follows:

- The first member prepares two monomode fibers of equal length (approximately 10' each). The protective coating is removed from each end of the fiber (approximately 1") using acid, or by burning the coating with a match. Ends are prepared by initially scoring the fiber over a conventional tool bit (approximately 1/2" from the end) and then initiating a fracture by bending the tip. Differences in length between the fibers should be noted so that they can be taken into consideration when matching the pathlengths of the object and reference beams. It is important to remember that the equivalent pathlength in air is obtained by multiplying the length of the fiber by the index of refraction of the fiber core.

- The second member of the launch team is responsible for designing the configuration for launching laser light into the optical fibers. Nearly all spatial filter devices can be modified to accommodate an optical fiber. For example, a pinhole can be replaced with a magnet having a hole drilled through its center. The fiber can be fed through the hole and held in place using some epoxy or adhesive tape. A suitable alternative is to use a low power microscope objective (5X objectives will produce good results; higher powers tend to launch light outside of the numerical aperture of the fiber) and a three axis positioner. The fiber can be anchored to the positioner using a magnet coated with felt.

- The third member sets up the beam splitter and launch devices as shown in Figure 1. Of course, one could get fancy and buy specially made fiber launch devices, use vacuum chucks to hold the fiber, or use a directional coupler to eliminate the beam splitter, but this approach minimizes learning content of the laboratory from a design standpoint and limits opportunity for hands-on experience.

- The fourth member of the team launches light into the fibers. The procedure for the configuration shown in Figure 1 is analogous to that used to align the pinhole in a spatial filter.

The exit ends of the two fibers can now be anchored to posts or other optical mounts (using small magnets coated with felt), providing diverging sources of coherent light that can be easily positioned throughout the working space. The advantage is that the same fibers serve each group, eliminating the need for multiple beamsplitters, spatial filters, mirrors, and lenses.

Two sets of four experiments (eight in all) are now suggested. An instructor should choose four of these if time or equipment is limited. For example, choosing experiment numbers 1, 2, 5, and 6 or 8, cover the basics of holography and holographic interferometry. Such an approach requires a minimal amount of hardware (especially if one chooses experiment 6 instead of 8) and eliminates the need to cover multiplexing and the holographic-moire technique.

Holographic Experiments

Holography is a technique for recording the three-dimensional information of an object on a two-dimensional film plane such that when the hologram is reconstructed or "played back" the original object can be viewed in its original three-dimensional form. Unlike ordinary photography where only the amplitude of the light intensity is recorded, the holographic process records both the phase and amplitude of the light scattered from the object. A good hologram can be recorded provided that the holographic system is properly isolated from unwanted vibrations, the object and reference beams are approximately equal in length (to within the coherence length of the laser), and that the reference and object wavefronts have common directions of polarization at the hologram (preferably perpendicular to the plane formed by their respective propagation vectors).

Figure 1 shows a typical configuration for the first set of four experiments. None of these involve interferometry but are designed to illustrate different methods for holographic construction and superposition.

The instructor should keep in mind that most of the holograms recorded in the laboratory sessions can be used for public display and perhaps more importantly, to attract potential students to his/her research program. Each group should be encouraged to be imaginative in choosing their subject and conscientious in their work (care should be taken to avoid unwanted reflections and uneven illumination, an extra effort might be made to bleach the plate, etc.).

Experiment No. 1 demonstrates that a hologram can be generated when a coherent light source is split into two beams. One beam is used as an object wavefront to illuminate the object surface. Light is diffused to the photographic plate. A reference wavefront, split from the main source, is directly impingent on the plate. Mutual interference between these two highly coherent wavefronts is recorded. The developed plate is called a hologram.

Experiment No. 2 demonstrates that a lens can be inserted between the object and the photographic plate. This decreases the coherent requirements during reconstruction and allows the developed hologram to be reconstructed in white light. An imaging bundle can be used in place of the lens in order to demonstrate that optical fibers allow for remote access. In this case, the object could be submerged underwater[14].

Experiment No. 3 demonstrates that two (or more) holograms can be recorded on the same photographic plate without changing the angle of illumination of the reference beam. This process is called multiplexing and can be accomplished by inserting a relatively coarse grating (10 lines/in) in the reference beam. The grating is translated through one-half the pitch between holographic recordings. Depending upon the position of the grating during reconstruction, either one of the images or both of them can be viewed through the developed hologram. The image of the grating will not show up on a photographic recording as long as the grating is outside the depth of field of the imaging system.

Experiment No. 4 demonstrates that two (or more) different holograms can be recorded on the same photographic plate by changing the angle of illumination of the reference beam. Both objects can be simultaneously reconstructed after processing using both fiber optics.

Holographic Interferometric Experiments

There are at least three different approaches to doing holographic interferometry, beginning with the time-averaged technique developed by Powell and Stetson [15,16] to reveal contours of constant amplitude on the surface of a vibrating object. In this technique a holo-interferogram is produced by exposing a hologram for a period of time during which the test object executes many cycles of steady vibration. Quantative analysis and interpretation of the resulting fringe fields revealed that the vibratory nodes correspond to the square of the zero-order Bessel function evaluated at zero, Jo(0); the dark holographic fringes to the zeros of Jo(Z), and the light holographic fringes to its maxima and minima. A second technique, usually referred to as double exposure holographic interferometry, generates a high contrast fringe field by interfering two object wavefronts reconstructed from the same doubly exposed hologram. In this case dark cosine fringes appear in space around the test object. These fringes are associated with the changes in optical pathlength (resulting from changes in the test object occurring between exposures) which in turn induce changes in phase. As such, double exposure holographic interferometry provides a permanent record of the changes which occurred between exposures, but no history of information describing the changes over time as they actually occurred. Real time holographic interferometry, on the other hand, provides a cosine fringe field which changes as the test object changes. Real-time fringes are generated directly by interfering the actual coherent wavefront from the object with a reconstructed holographic "reference" wavefront. In order to generate high contrast real-time fringes, this approach requires that the object illumination and reconstructing reference beams be adjusted to yield object wavefronts of nearly equal intensity and that both beams and the hologram be located in exactly their original positions relative to the test object during reconstruction of the reference wavefront. This latter (most critical) requirement can be met, though often with some difficulty, by precise repositioning of the hologram after its removal for processing elsewhere, or, more effectively, by processing the hologram in place (in situ processing). In recent years the development of so-called "instant" holographic recording systems has greatly facilitated the latter approach.

In general, the holographic-interference-fringe field can be related to the deformation of the surface by the simple vector expression,

$$n\lambda = \underline{g} \cdot \underline{d} \qquad (1)$$

where n is the fringe order number, λ is the wavelength of coherent light used to record and reconstruct the hologram, $\underline{g}$ is the sensitivity vector ($\underline{e}_2 - \underline{e}_1$) where $\underline{e}_1$ and $\underline{e}_2$ are unit vectors in the illumination and observation directions respectively, and $\underline{d}$ is the displacement vector at the point of observation on the surface of the sample. If a relatively flat surface is intentionally oriented normal to the angle bisector of $\underline{e}_1$ and $\underline{e}_2$, the interferometer senses only the out-of-plane displacement component, W, and Equation (1) becomes,

$$n\lambda = 2W \cos \beta \qquad (2)$$

where 2β is the angle between the propagation vectors in the directions of illumination and observation.

Holographic interferograms can also be optically superimposed to isolate specific displacement components. The holographic-moire method is one approach for obtaining such results. In particular, when the object is illuminated by two beams oriented symmetrically with respect to the surface normal (say each at an angle α), two holo-interferometric fringe patterns result. These are often referred to as component patterns. The fringe orders can be numerically subtracted or the component patterns can be optically superimposed to produce a moire[12,13]. The superposition is characterized by the equation,

$$n\lambda = 2U \sin \alpha \qquad (3)$$

where n is the difference between the fringe order numbers in the component patterns, λ is the wavelength used to record and reconstruct the holo-interferograms, and U is the displacement component measured in the plane formed by the propagation vectors from the two sources and oriented perpendicular to their angle bisector.

Figure 2 shows the second set of four experiments proposed for this laboratory. All of these involve interferometry and are designed to illustrate various methods of holographic superposition for stress analysis. Each of the following experiments has been paired with one from the initial set in an effort to minimize reorganization of the set-up, and to evenly distribute the work load between the various groups.

Experiment No. 5 (done in conjunction with Experiment No. 1) demonstrates that real-time holographic interferometry can be accomplished by making a single holographic recording of a test piece in its rest position; the hologram is processed and replaced in its original exposed position with respect to the test piece; then the holographic image is observed to be superimposed on the object. Any subsequent movement of the test piece will produce real-time fringes. Students should be encouraged to move the hologram, the reference beam, the illumination, or the object to illustrate that the resulting phase changes superimpose with the deformation and change fringe localization. This exercise serves as background for understanding the holographic-moire method, and visually demonstrates the principle of phase modulation which is currently used in systems for automated processing of holographic interferograms[17,18]. Digital processing can be demonstrated in a higher level stress analysis course, or in another laboratory session.

A more elaborate set-up for this experiment involves placing a linear polarizer between the object and hologram, and a linear polarizer followed by a half wave plate mounted in a rotation stage in the reference beam. The undeformed state of the object is recorded with the polarizations of both beams aligned. Real-time holographic fringes will be observed when the object is loaded, but only the undeformed state is reconstructed (the holographic interference fringes vanish) when the polarization of the reference beam is rotated through 90 degrees. This approach has been used to holographically store information in real-time studies involving speckle photography[19], and moire interferometry[20].

Experiment No. 6 (done in conjunction with Experiment No. 2) demonstrates that double-exposure holographic interferometry can be accomplished when holograms of an object in its undeformed and deformed states are superimposed. Interferometric fringes can be analyzed using phase-displacement equations.

Experiment No. 7 (done in conjunction with Experiment No. 3) demonstrates that a single component of displacement can be isolated using a holographic-moire method. The model can be mounted on a rotation stage along with a mirror positioned so that the object can be illuminated from two different directions. An initial holographic recording is made with the object illuminated by the direct beam and the indirect (from the mirror) beam. The object is deformed and rotated. The interference fringes produced by each illumination superimpose to form a moire pattern indicative of the displacement component measured perpendicular to the angle bisector of the illumination in a direction parallel to the plane formed by the propagation vectors from the source to the object, and from the object to the hologram. Multiplexing (see Experiment No. 4) can be used to separately record the interference pattern produced by the direct and indirect beams if an appropriate shutter system is used to block the corresponding portion of the object beam. The moire pattern can be viewed when the grating in the reference beam is in an intermediate position, or completely removed.

Experiment No. 8 (done in conjunction with Experiment No. 4) demonstrates time-average holographic interferometry can be accomplished by recording a hologram over a period of time when the object undergoes a periodic vibratory motion. Two (or more) different modes of vibration of an object (vibrated at different frequencies) can be captured on the same plate by changing the angle of the reference beam.

Each group should be asked to prepare a written report on their findings, and the group leader should report his group's activities to the entire class in a five to ten minute oral presentation.

Conclusion

Eight laboratory experiments have been suggested to illustrate the holographic recording process and some of its applications in experimental stress analysis. These relatively simple experiments can be used as background for a more advanced session on holographic interferometry, possibly involving digital processing and hybrid analysis.

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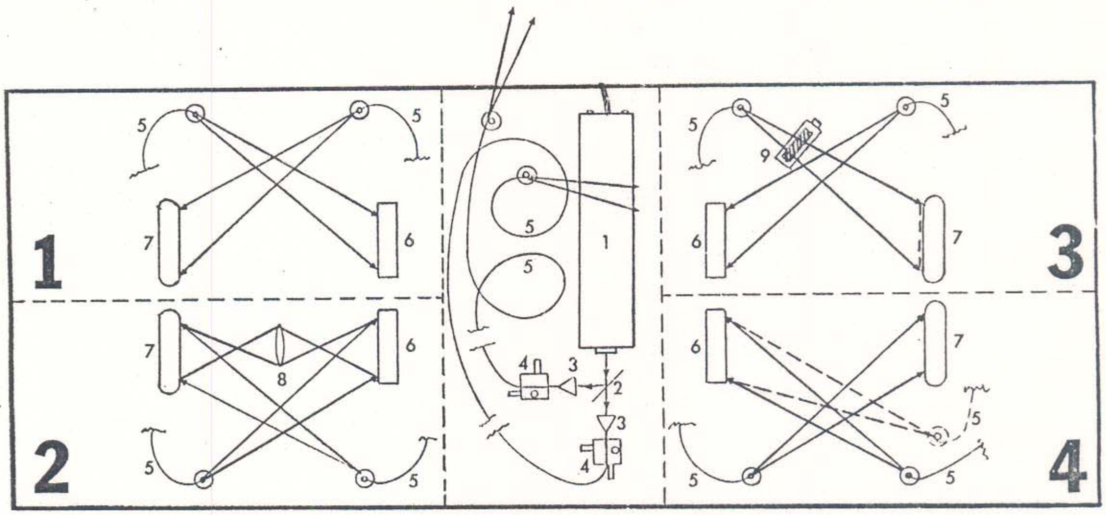

Figure 1 - Experimental layout for holographic recording experiments.

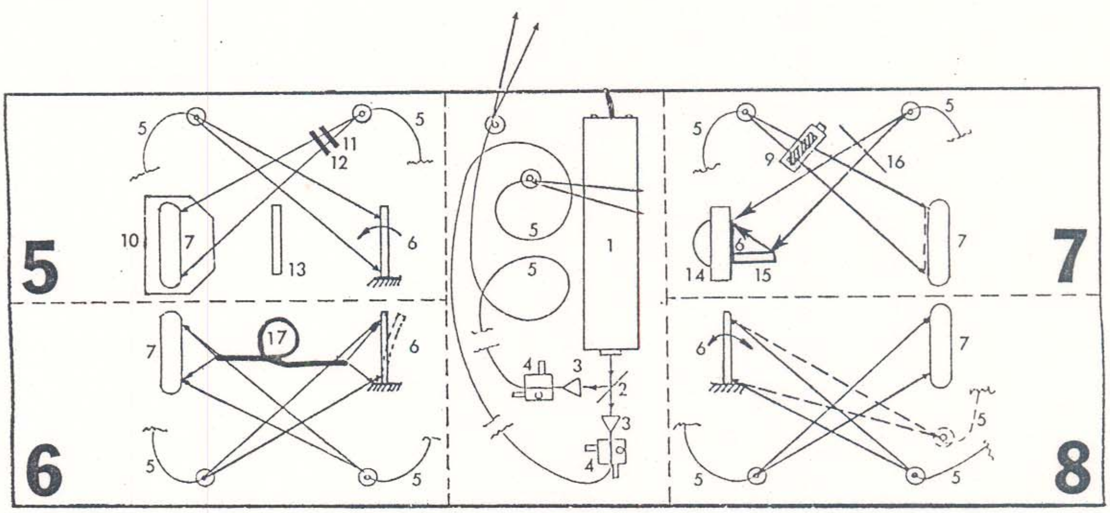

Figure 2 - Experimental layout for holo-interferometric experiments.

Key to Figures 1 and 2

1. laser
2. beam splitter
3. microscope objective
4. three-axis positioner
5. monomode fiber
6. test object
7. hologram
8. lens
9. grating on translation stage
10. real-time device
11. adjustable half-wave plate
12. polarizer in rotation mount
13. linear polarizer
14. rotation stage
15. mirror
16. shutter
17. coherent imaging bundle