Remote deformation field measurement through different media using fiber optics

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Abstract. This series of tests demonstrates the feasibility of recording deformation holograms of reflecting subjects that are not mounted on an optical bench and vibration-isolated and that, in fact, can even be submerged in a transparent liquid. This represents an important extension of research into the use of fiber optics in holography. Various considerations for the ultimate development of a practical fiber optic device for making in-situ or "production environment" deformation field measurements by continuous wave holographic interferometry are also discussed.

Subject terms: holographic interferometry; fiber optics in holography; continuous wave holographic interferometry; production environment measurements; submerged objects; stress analysis; deformation measurement.

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1. INTRODUCTION

Fiber optics, which were originally developed for communications networks, are finding new applications in other areas. Individual fibers are now being used in transducers to measure displacement, pressure, torque, etc. Fiber bundles, on the other hand, have proven invaluable in medicine when used as tools for inspection in devices like cystoscopes and endoscopes. Boroscopes are used in industrial applications to view remote or otherwise inaccessible regions of structures. Other applications are even more unique; for example, optical fiber bundles are used as "eyes" in robots as part of their closed-loop feedback system. In short, fiber optic technology is rapidly being incorporated into a variety of practical devices.

Many more sophisticated instruments use combinations of individual fibers and fiber bundles to transmit light amplitude. These include the laserscope, which is being designed to burn passageways through clogged arteries and uses some fibers to conduct the main laser beam, a fiber bundle for inspection, and still other fibers for illumination. Other fiber-based systems rely on the transmission of both amplitude and phase. For example, two of the authors have recently established the feasibility of measuring deformation fields on remote surfaces by applying the techniques of holographic interferometry through fiber optics. An individual fiber is used to illuminate the test subject while a coherent fiber bundle transmits image amplitude and phase information back from the object to the hologram. This paper expands the scope of this prior holographic/fiber optic research and outlines some of the steps required for the potential subsequent development of a practical device designed to make production-related or in-situ holographic deformation measurements.

2. PRIOR RELATED RESEARCH

Fiber optics were first used in holography as the reference wave in recording a hologram or as the illuminating wave in reconstructing it. Although fibers were used in the object beam to illuminate the test surface, scattered wavefronts recorded on the hologram were not captured through fiber optics, and direct optical access to the test surface was required. These studies established basic feasibility for holographic recording with fiber optics but did not take deformation measurement into account.

Prior research in scattered light and image plane holography led one of the authors to develop a holographic technique in which a coherent bundle was inserted between the object and the photographic plate. Amplitude and phase information could then be conveyed to the hologram for subsequent displacement analysis in cases where optical access was limited. These concepts were expanded, and displacement was measured over the full field using coherent multimode bundles (MMBs) made up from individual step index fibers. Unfortunately, these fibers transmitted more than one wavefront, and adequate stability could only be assured when fiber elements were rigidly mounted throughout their length. Since then, considerable effort has been directed toward understanding the light propagation characteristics of optical fibers and developing techniques to ensure that both amplitude and phase information remains stable during holographic recordings. A significant breakthrough was made by two of the authors using monomode (single-mode at \( \lambda = 633 \text{ nm} \)) optical fiber designed and manufactured by AT&T Bell Laboratories. Results showed that single-mode fibers (SMFs) provided a means of transmitting stable coherent illumination to the vicinity of the object surface and/or hologram and requiring only

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that the ends of each fiber be rigidly anchored.

In these pioneer deformation studies, fiber optics were used to increase the flexibility of the holographic setup and to decrease the number of required optical components. Optical fiber could easily be arranged to provide the close matching of path lengths needed to satisfy coherence requirements and to gain access to remote areas of the test subject. The position of the fibers in the system could be quickly modified (1) to change the location of the source or the point of observation in order to record different scalar displacement components or (2) to vary the spatial frequency content of the hologram.

The achievement of low spatial frequency is of fundamental importance in another holographic/fiber optic stability study by the authors. In that work the object and reference beams were first combined at a remote location following transmission through paired SMFs. The resulting standing wave intensity pattern was then transmitted back through an MMB to the recording site. This technique is also being applied to deformation measurement, although its potential is somewhat limited because such holograms are of relatively poor resolution. Its major advantage, however, is that the stability requirements on the recording system are decreased since the SMFs are used for amplitude (as opposed to phase) transmission.

So far, all holographic testing with fiber optics has been carried out under laboratory conditions in uncirculating room air and on a vibration-isolated optical bench—the same stringent laboratory conditions required for conventional holographic testing. There is, however, a growing desire to apply holography and holographic interferometry in production-related or in-situ environments, many of which require testing on nonisolated, remote surfaces located in media different from air. Watson and Britton, for example, have demonstrated an approach to performing optical holography underwater for purposes of inspection and archiving. Their system was fairly complicated and did not involve the use of fiber optic elements. The successful development of holographic/fiber optic deformation recording systems, on the other hand, should further such efforts and lead to the development of new systems with many unique practical applications since fiber optics provide reasonably flexible and environmentally insensitive light guides. For example, a fiber network could be used to monitor deformation at several test sites located throughout an industrial test floor, while the holographic patterns could be recorded and analyzed at a central processing location. A device, similar to the laserscope, could be developed to make holographic deformation measurements on human organs for diagnostic purposes. Other applications might include testing in nuclear environments and deformation analysis on ship hulls and submarines.

This paper demonstrates that holographic interferograms can be recorded through fiber optics from surfaces located off the vibration-isolated optical bench and, in some cases, underwater. These investigations constitute a portion of the fundamental research that must be performed before holographic techniques can be applied in the types of practical problems described above.

3. EXPERIMENTS

Several tests were conducted to demonstrate the feasibility of recording deformation through fiber optics from nonisolated test surfaces that may be submerged in water.

Figure 1 shows the experimental setup used to record the displacement field of the object. All optical components were vibration-isolated except for optical fibers in tests conducted on models located off the optical bench. A HeNe laser ($\lambda = 632.8$ nm) was used as a coherent light source. Light from the laser was launched through a $5 \times L$ microscope objective into a single-mode fiber having a numerical aperture (NA) equal to 0.1159 and a core diameter of 7.3 $\mu$m. Light emerging from the exit end of the fiber illuminated a portion of the cantilever beam (length $L = 23.8$ cm) shown in Figs. 2 and 3. The size of the illuminated area was dependent upon the index of refraction of the test environment. The regions $0 \leq X/L \leq 0.21$ and $0 \leq X/L \leq 0.16$ were illuminated in tests conducted in air and underwater, respectively.

A coherent multimode fiber bundle (MMB of 4 mm diameter, having a resolution of 27 lines/mm and composed of individual 12-$\mu$m-diameter multimode fibers) was used to transmit the image of the test subject from the test site to the photographic plate. A Selloc microlens was used to image the illuminated surface onto the entrance end of the MMB (the acceptance angle of the lens also depends upon the index of refraction of the surrounding medium and is smaller in water than in air). The real image transmitted through the MMB was focused on the photographic plate and combined with a collimated reference beam to form an image plane hologram. A second SMF could have been used to generate the reference beam. In the present study, however, this would be of little advantage except, perhaps, as a convenient means of equalizing object and reference beam path lengths.

For small beam deflections, the significant displacement component lies parallel to the Z-axis, and for a concentrated intermediate loading $W$, this deflection $w$ at a distance $X$ from the fixed end is given by

$$w = \frac{WX^2}{6EI} (3b - X) \quad \text{for } 0 \leq X \leq b,$$

(1)

$$w = \frac{Wb^2}{6EI} (3X - b) \quad \text{for } b \leq X \leq L,$$

where $E$ is Young's modulus, $I$ is the moment of inertia, and $b$ is the X-coordinate at which the load is applied.

A double-exposure holographic technique was used to record holograms. First, a hologram of the undeformed surface was taken during an initial exposure. After a displacement of $25.4 \times 10^{-4}$ cm was applied at $X/L = 0.75$, a second hologram was recorded on the
same photographic plate so that the deformed state was superimposed on the undeformed state. The photographic plate was then developed and reconstructed using white light to reveal the interference fringe or deformation pattern. This test was repeated for four different situations, namely, with the cantilever beam located (1) on a vibration isolation table and in air, (2) off a vibration isolation table and in air, (3) on a vibration isolation table and underwater, and (4) off a vibration isolation table and underwater. Holograms were recorded on Kodak 131 high speed holographic plates and were bleached using bromine. In all cases the exposure time was 12 s per exposure, and in cases (3) and (4) the temperature of the water was 23°C.

The interference patterns obtained from these experiments are shown in Fig. 4. The w component of the displacement vector \( \mathbf{d} \) was analyzed using the vector equation

\[
- (\hat{e}_1 - \hat{e}_2) \cdot \mathbf{d} = \frac{N \lambda}{n},
\]

where \( \hat{e}_1 \) and \( \hat{e}_2 \) are unit vectors drawn from the source to the model and from the model to the observation point, respectively; \( N \) is the fringe order number; and \( \lambda \) is the wavelength. The index of refraction \( n \) was taken to be 1.0 for air and 1.33 for water. The quantity \( (\hat{e}_1 - \hat{e}_2) \) is often referred to as the sensitivity vector along which \( \mathbf{d} \) is projected.

Figures 5 and 6 show the experimental data obtained from Eqs. (1) and (2), respectively, compared with the theoretical solution for an elastic cantilever beam of the same dimensions and loading.

4. DISCUSSION

The diverging wavefront emerging from the SMF illuminates each model point from a slightly different direction. In addition, the propagation vector from a point on the subject to the MMB changes direction across the illuminated area. Therefore, displacement is projected along a slightly different sensitivity vector at each point such that some curvature is observable in each of the fringe patterns shown in Fig. 4.

A comparison of the four holographic deformation patterns indicates that fringe quality not only depends on the stability of the recording system but is affected by the medium surrounding the test specimen. The deformation hologram recorded in air and using vibration isolation definitely has the best overall fringe contrast. The two deformation holograms recorded in air and underwater with the object on the isolated optical bench both have fringes of relatively good contrast when compared to those taken through a comparable medium in tests conducted off the bench. It does appear, however, that there is less deterioration in fringe contrast between the isolated and nonisolated deformation patterns for the tests conducted underwater as compared to that observed between those conducted in air. This suggests that in the absence of vibration isolation, water serves as a damping mechanism that increases stability.

In this study, experimental results agreed well with theory. In general, however, there are two fundamental sources of error in extracting data from holographic patterns: inaccurate measurement of fringe order number and inaccurate evaluation of the illumination.
and observation directions. Errors in fringe order are usually due to a lack of precision in interpolating between fringes and can be minimized using a microdensitometer. Errors in the measurement of the positions of the source, object, and observation points increase with increasing source-to-object and object-to-hologram distances. Fiber optics can help to reduce these errors since the NAs are small and the exit end of the SMF and the entrance end of the MMB can be accurately placed in optimum proximity to the subject.

In all of the tests carried out in this investigation, the exit and entrance ends of the SMF and MMB, respectively, were rigidly fixed to portions of the test subject holding frame (see Fig. 3). The use of optical fibers allowed the test subject to be located on or off the table and in or out of the water without significantly changing the optical path lengths. More importantly, displacement of the cantilever beam was measured with respect to the position at which the fiber ends were fixed on the frame, and deformation was measured independently of the rigid body motion of the holding frame itself. This is unique to holographic/fiber optic systems and would not have been the case if a conventional holographic setup had been used. In general, holographic interferometry measures absolute displacement. Consequently, changes in optical path length caused by rigid body motion often take up a substantial portion of the usable range of the technique when used (without fiber optics) to measure deformation.

All existing flexible coherent imaging bundles (including the one used for this study and those used in boroscopes, endoscopes, etc.) are made up of thousands of coherently arrayed multimode optical fibers. Unfortunately, each multimode fiber in an MMB transmits many coherent wavefronts (called modes) that interact. This interaction can be extremely complicated and varies when the fiber is disturbed. Such modal interaction can be very detrimental during holographic recording since random phase changes take place. Therefore, adequate stability cannot be assured with multimode fibers unless all fiber elements are carefully mounted to avoid any and all movements that might produce bending and alter their modal propagation characteristics during and between holographic recordings. At present this places a somewhat rigid stability constraint on the technique but should be significantly relaxed by the development of a coherent single-mode fiber bundle. Careful attention may still have to be paid to other transmission characteristics such as polarization and temperature-related phenomena, which may influence holographic recordings.

5. CONCLUSIONS

The present series of tests has demonstrated that it is possible to record deformation holograms through fiber optics from remote surfaces that are not vibration-isolated and/or are, in some cases, submerged underwater. Even though the present required use of multimode fibers places some undesirable constraints on stability, these tests constitute a portion of the research required for the potential subsequent application of holographic/fiber optic systems to problems that involve production-related or in-situ testing.

In short, optical fibers not only provide convenient, flexible, and environmentally insensitive light guides, but they also allow holographic deformation measurements to be made on test specimens that are located on or off a vibration-isolated table and in or out of water. The model can be moved quite easily without changing the optical path length of the object beam, provided that the ends of the fiber optics that access the surface are rigidly attached to the test frame. Furthermore, relative deformation can be measured between the test subject and the fixed fiber ends and independently of the rigid body motion of the test frame itself.

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7. REFERENCES