Holographic Displacement Analysis with Multimode-fiber Optics

Multimode-fiber optics are used to record deformation in remote areas of a structure

by J.A. Gilbert and J.W. Herrick

ABSTRACT—Multimode-fiber optics are used to holographically record surface deformation in remote areas of a structure. Displacement patterns agree well with theory, indicating that the proposed technique is feasible. Inherent difficulties encountered with multimode fibers are discussed and guidelines are established for further studies, designed to improve holographic displacement recording using monomode fibers.

List of Symbols

- a = fiber diameter
- $\mathbf{d}$ = displacement vector
- d_i = inner diameter of pipe
- $\hat{\mathbf{e}}_i$ = unit vector
- n = fringe-order number
- w = scalar-displacement component
- D = distance from fiber exit
- L = length of pipe
- M_t = applied torque
- R = radius of plate
- X, Y, Z = axes system
- λ = wavelength

Introduction

Holographic interferometry can be used for nondestructive and noncontact experimental stress analysis to measure full-field displacement and/or strain with high sensitivity provided that one has optical access to the surface under consideration. This investigation explores the potential of using a combination of incoherent and coherent fiber optics to make holographic measurements in remote areas of a structure.

Fiber optics offer many distinct advantages when used to record deformation, especially when one realizes that to date, there are relatively few practical applications of holography in hostile environments using the present state of art. This is partially due to the needed alignment of all the necessary optical components, a lengthy and tedious process, which requires a high level of skill. Even the simplest of arrangements involves the use of a beam splitter, spatial filters and mirrors mounted on a stable optical bench; in practice, the situation is often more complicated by the addition of collimating lenses and extra mirrors to orient the beams. Environmental factors, such as mechanical vibrations or air turbulence, often make holographic recordings difficult, if not impossible. The results of this investigation indicate that the use of optical fibers in a holographic system leads to a drastic reduction in the number of optical components to be adjusted, allows deformation to be monitored in remote areas of a structure, and can ultimately help to ease environmental requirements.

Light emitted from the exit end of an optical fiber has been used as the reference wave in recording a hologram and/or the illuminating wave in reconstructing it.[1] Mechanical flexibility of fibers has added a new degree of freedom to holographic reconstruction; for example, a fiber has been used to scan a small hologram array.[2] Fiber optics have also been used in both the object and reference beams to record and reconstruct holograms with a negligible reduction in diffraction efficiency.[3] These techniques have been applied in the medical field where fiber optics have been used to holographically capture specimens which are stored for subsequent examination and/or inspection.[4] These authors, however, have not been concerned with interferometric applications to record deformation.

This paper explores the potential of using multimode fibers to holographically record deformation in remote areas of a structure. Displacement patterns agree well with theory, indicating that the proposed technique is feasible. Inherent difficulties encountered with multimode fibers are discussed and guidelines are established to improve holographic displacement recording using monomode fibers.

Discussion

A great deal of work has been done with fiber optics, usually classified as monomode or multimode depending upon their radiation characteristics. Consider light launched from the exit end of a fiber, illuminated with coherent light of wavelength λ. If a point is observed at a distance,

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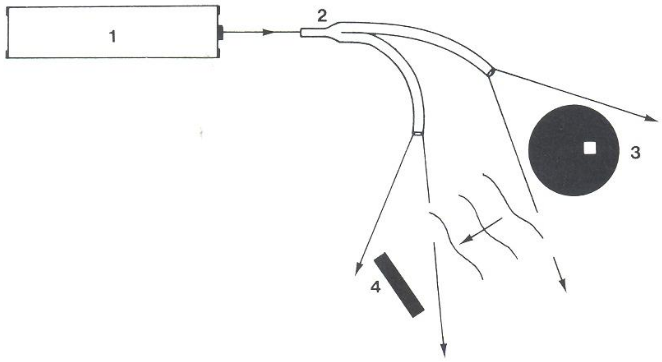


Fig. 1—Holographic recording using incoherent fiber optics

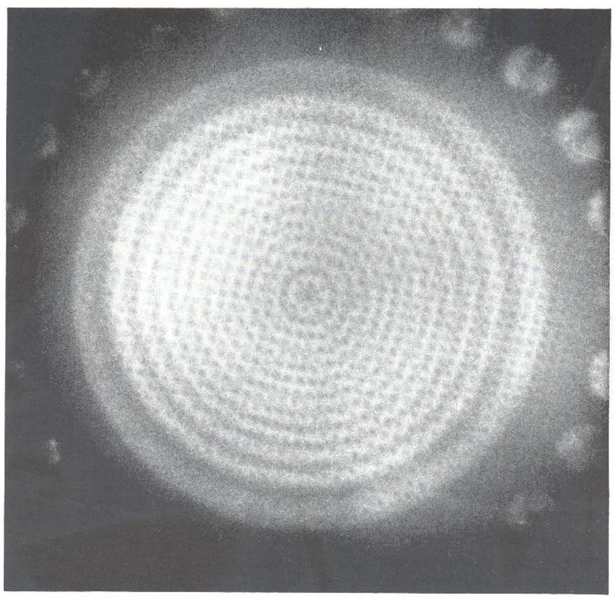


Fig. 2—Displacement pattern for a centrally loaded circularly clamped plate

D, from the fiber tip; such that,

$$D >> \frac{2a^2}{\lambda} \quad (1)$$

where a is the core diameter of the fiber, it lies in the Fraunhofer region. The right hand side of eq (1) is on the order of several millimeters for a typical fiber of a = 60 μ with λ = 5145 Å.

The complex amplitude of light in the far field is that of a spherical wave, modulated by a factor representing the effect due to the inclination of the light emergence with respect to the optical axis of the fiber; and a 'mode function' representing the effect due to the character of the modes within the fiber.[1] Light directed straight through the fiber generates the lowest, azimuth-independent mode for which the amplitude is uniform within the core and zero out of the core. Other modes can be generated by light rays which trace relatively coarse zigzag paths down the fiber. These waves take longer to traverse the wave guide and give rise to more dispersion than would be present if only one mode were transmitted. Mode conversion may also occur among the guided modes due to both refractive-index inhomogeneities of the core and boundary irregularities between the core and the cladding. These effects become more pronounced as the length of the fiber is increased.[5] Fibers which transmit more than one mode are classified as multimode. This study concentrates on using multimode fibers to record deformation.

Experimental

An initial experiment was performed with the setup shown in Fig. 1. Mirrors, spatial filters, lenses and even beam splitters (one can use a bifurcated-fiber optic) can be eliminated during the test. The fiber bundles shown in the figure are called incoherent. They transmit light along their length; however, as opposed to coherent fiber bundles, the orientation of individual fibers is not maintained throughout the bundles and images cannot be transmitted. The main 3.2-mm-diam fiber bundle is bifurcated into two equal-diameter legs. Each leg consists of individual 60-μdiam fibers which are multimode and of the step-index type. The refractive index of each step-index fiber in the bundle is uniform throughout the core but undergoes an abrupt change at the point where the cladding meets the core. Fiber ends are potted in a stable epoxy, then ground and hand polished on a felt lap to produce a high-grade optical surface. The fibers are randomly distributed in each leg so that the surface distribution is uniform at all tips.

The laser was carefully aligned with the main fiber-optic bundle. Launching efficiency was determined to be approximately 40 percent when reflection loss at the fiber end was neglected. This value agrees with that specified by the manufacturer. The object and reference beams were collimated by placing a lens at a focal distance from the end of each fiber bundle. The photographic plate was used to record the reference and object wavefronts before and after model deformation. Figure 2 shows the fringe pattern corresponding to the displacement for the centrally loaded, circularly clamped plate used for this test. The specimen was illuminated and observed along the normal to the plate with the aid of a partially reflecting mirror. Displacement was analyzed using

$$(\hat{\mathbf{e}}_1 - \hat{\mathbf{e}}_2) \cdot \mathbf{d} = n\lambda \qquad (2)$$

where **d** is the displacement vector, n the fringe-order number, λ the wavelength; and $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$ are unit vectors along the directions of propagation from the source and to the observation point, respectively, drawn to/from the point under consideration. Equation (2) is the conventional linear phase-displacement equation used for holographic analysis of deformation for points located on a diffuse surface.[6] In our case, the illumination is collimated and the object is viewed from a large distance; consequently, eq (2) reduces to

$$w = \frac{n\lambda}{2} \qquad (3)$$

where w is the displacement measured normal to the plane of the clamped plate.

The tip of each fiber bundle can be regarded as a collection of point sources which are highly coherent. In general, every fiber in the bundle illuminates each model point from a different direction and produces a hologram with a fringe pattern which is unique. The result is a superposition of as many displacement patterns as sources. This may be complicated, especially if the tip of the bundle is placed close to the object. In this case, the propagation vectors from each source are significantly different for a particular model point. A collimated illumination, however, generates propagation vectors which are parallel to one another, and the correlation of multiple holograms forms an interpretable displacement pattern.

A comparison of experimental results obtained from the centrally loaded circularly clamped plate with the predicted elasticity solution[7] is shown in Fig. 3.

Each individual fiber in the bundle has a relatively large numerical aperture. Some rays or modes trace coarse zigzag paths down the guide and take longer to reach the exit end than those traveling along the axis. Consequently, each fiber is classified as multimode, exhibits dispersion and has a radiation pattern in the far field which resembles a speckle pattern due to the overlap of light corresponding to the many guided modes usually present. The particular radiation pattern for each individual fiber depends on the excitation conditions and the fiber itself. The latter determines the guided modes excited by the input beam as well as the mode conversion along the fiber. The mean speckle size, however, is inversely proportional to the waveguide-core diameter.[8]

When the reference beam is created with a multimode-fiber optic, effective reconstruction is obtained only when the reference and the illuminating wave used for reconstruction are of the same mode.[1] Unfortunately, the radiation-speckle pattern in each fiber is very sensitive to external conditions, such as stress and temperature, which may change during exposure; or, when the plate is being developed, ultimately destroying the hologram recording. In addition, the superposition of wavefronts emerging from the many fibers in the bundles used to illuminate both the test surface and the hologram results in a significant amount of speckle noise. This leads to an uneven intensity distribution in both the object and reference illumination. Both of these factors contribute to a degradation of image quality and details of the object and/or

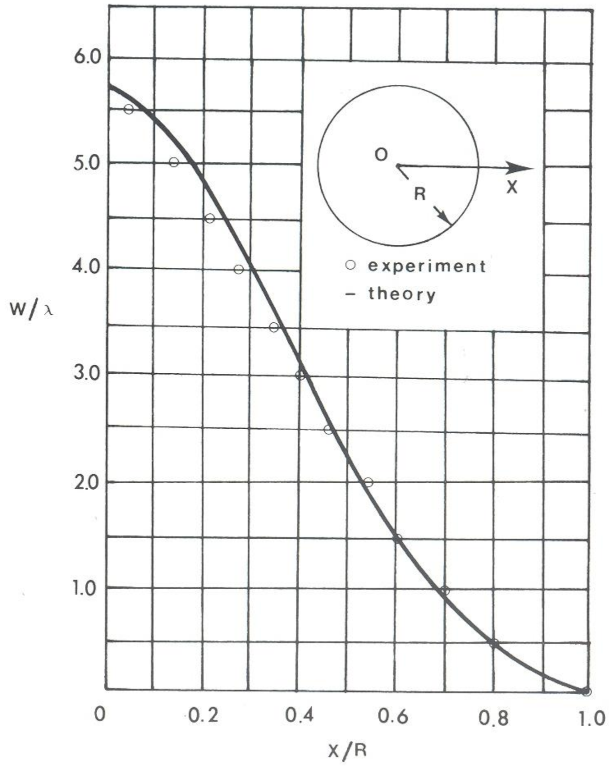


Fig. 3—A comparison of results for the centrally loaded circularly clamped plate

fringe pattern are absent from the holographic recording. The important observation, however, is that although the reconstruction of the interference fringes produced by wave fronts of coherent light passing through multimode fibers has many speckle patterns, spatial coherence is practically preserved in each wavefront recorded by the photographic plate.

The basic characteristics of the radiation relevant to holography are coherence, the form of the wavefronts and the polarization. Polarization of coherent light passing through monomode-fiber wave guides has been studied by several investigators.[9-11] In multimode fibers, however, the polarization is distributed at random throughout the radiation pattern due to scattering within the fiber and to the fact that each guided mode has its own polarization state. It has been shown that a holographic reconstruction becomes brightest when the object and reference wavefronts are linearly polarized perpendicular to the plane containing their axes of propagation.[12] Consequently, the random polarization in both the object and reference wavefronts, produced by the multimode fibers, has resulted in a further degradation of fringe contrast and reconstruction efficiency.

The setup shown in Fig. 1 was modified in an effort to minimize speckle noise when using multimode fibers and, more importantly, to gain optical access to remote areas of a structure. As shown in Fig. 4, a coherent-fiber optic bundle is used to transmit the image of the undeformed and deformed object to the photographic plate.

Holograms recorded with the object or image of the object close to the recording plane are called image-plane holograms.[13-18] Recent investigations in experimental mechanics have incorporated image-plane techniques to record deformation.[19,20] These investigators have reported significant improvements in fringe contrast over conventional holographic interferometric methods. The apparent proximity of the object to the plate decreases the coherence requirement of the source during reconstruction and allows a real image to be viewed in white light.

Fiber optics have been eliminated in the reference beam of the modified setup to reduce speckle noise and modal dependence. The illumination has been collimated and an imaging system incorporated between the coherent fiber tip and the photographic plate.

Figure 5 shows a cylindrical pipe subjected to an applied

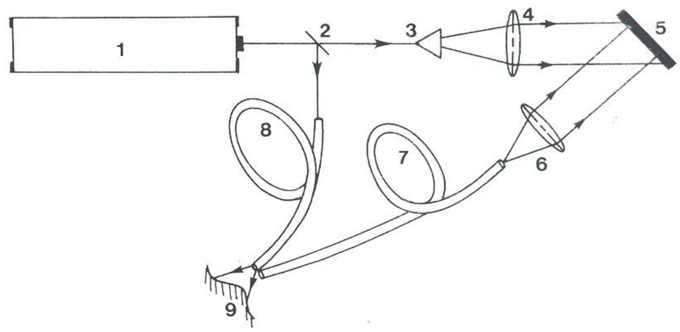


Fig. 4—Holographic recording using incoherent and coherent fiber optics

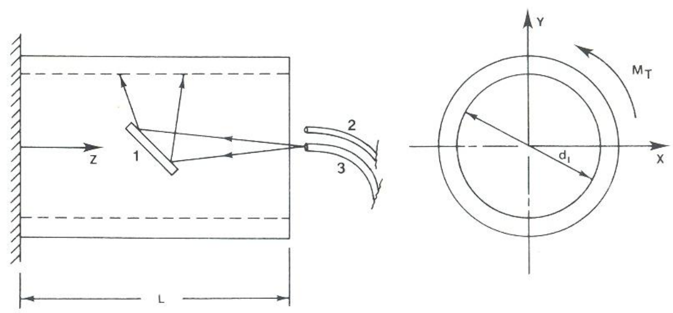
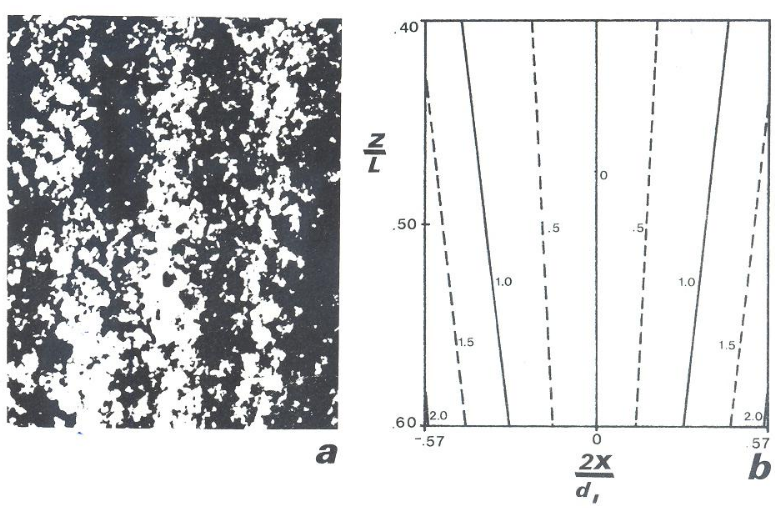


Fig. 5—A cylindrical pipe subjected to pure torsion



(a) Displacement pattern for a pipe subjected to pure torsion
(b) Theoretical fringe loci for a pipe subjected to pure torsion

Fig. 6—A comparison of results

torque, M_t, which produces a state of pure torsion. An incoherent fiber bundle and a mirror positioned at 45 deg with respect to the Z axis were used to illuminate the interior surface of the pipe in the region $0.40 \le \frac{Z}{L} \le 0.60$; $-0.57 \le \frac{2x}{d_i} \le 0.57$; where L is the length and d_i the interior diameter of the pipe. The incoherent and coherent fiber bundles were situated side by side to previde the illumination and observation, respectively. Figure 6(a) shows the fringe pattern reconstructed in white light in the region of interest. Displacement was analyzed with eq (2). The theoretical fringe loci are plotted in Fig. 6(b) and a comparison of experimental results with theory[21] is shown in Fig. 7 for $\frac{Z}{L} = 0.5$.

The coherent optical bundle used in this investigation was 2.5 mm in diameter, made up of individual 50-μdiam multimode fibers. Two significant characteristics of coherent fibers when used to generate holograms are their resolution and image transmission. For a given test surface, the number of fibers and optical configuration in the bundle defines how clearly the image is transmitted. For a given object size and optical fibers of equal quality, a better image is obtained when more fibers are used to record the image. This effect can be simulated by recording an object at different distances from a fiber-bundle entrance. Figure 8 shows two photographs taken through the same coherent-fiber-optic bundle of a test surface positioned at different locations with respect to the fiber entrance. Laser light was used to illuminate the surface. In Fig. 8(a) the 'B' is not clearly defined; however, Fig. 8(b) shows more definition. This verifies the previous observation that, when more optical fibers image the test specimen, more definition or resolution is obtained.

Broken fibers do not transmit an image and result in

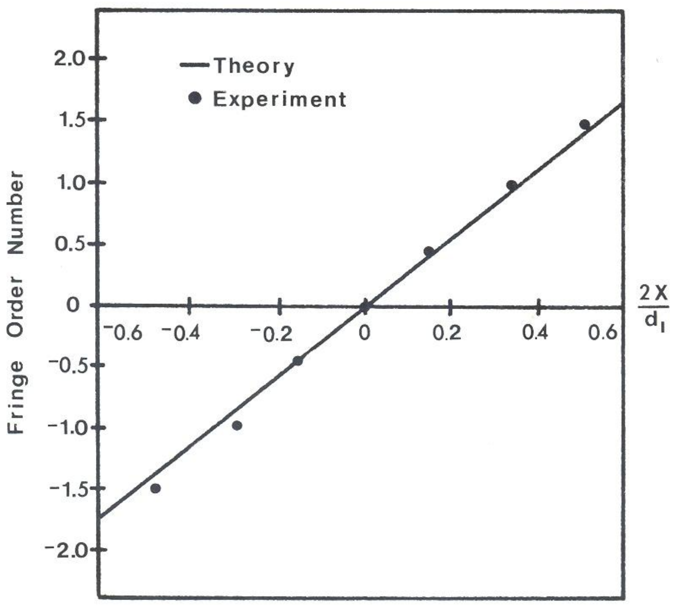
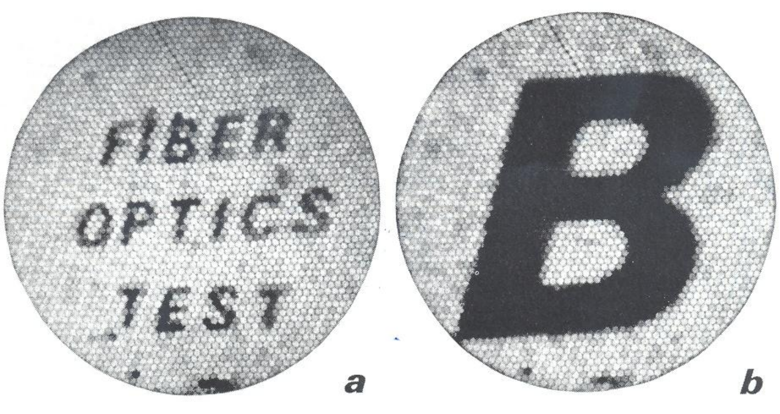


Fig. 7—Theoretical and experimental fringe orders for a pipe subjected to pure torsion along $Z/L = 0.5$



(a) Photograph taken through a coherent fiber bundle of the test surface
(b) Photograph taken through a coherent fiber bundle with the test surface close to the fiber entrance

Fig. 8—Resolution of a laser-illuminated test surface

black spots in the recording, leading to a degradation of image quality. This effect is also enhanced when fewer fibers are used to record the image.

Discussion and Conclusion

This study has shown that deformation holograms can be recorded using multimode-fiber optics of the step-index type. Results indicate that the object should be imaged through a coherent fiber bundle of high resolution; and that the test surface should be illuminated with as few fibers as possible to reduce the number of holograms generated by the individual fibers in the bundle. One other possibility which is currently under investigation is to image the tip of the illuminating bundle on the test surface so that each fiber acts as a source for a different region.

Both of the experiments performed recorded displacement primarily along the line of sight. To make three-dimensional-displacement analysis feasible with the setup shown in Fig. 4, the authors have devised a wave-front modulation technique which simultaneously records displacement along and normal to the line of sight.[22] Implementation of this technique with fiber optics will eventually require fiber tips to be modified to produce a dual-beam illumination. The ends of the fibers may have to be prepared by controlled breaking, polishing or other suitable techniques to successfully record and describe the displacement/strain patterns. The possibility of incorporating a lens head or microlens to obtain a collimated beam from the incoherent-fiber optic which illuminates the specimen will be explored. Compound lenses will be positioned between the coherent-fiber-optic bundle and the hologram for telecentric imaging.[20]

Monomode fibers may offer distinct advantages over the multimode fibers used in this study. This conclusion is based on preliminary tests which are currently being carried out on individual multimode and monomode fibers. For example, when laser light is launched into a fiber whose ends have been constrained, the fiber can be moved to observe the effect on an illuminated test surface. For the same perturbation, the surface speckle is substantially more stable for a monomode, as compared to a multimode fiber. This test will also be performed on a coherent bundle of monomode fibers as soon as one becomes available. This may present unique problems; for instance, when the bundle is moved, light transmitted through each fiber may experience a different phase change, resulting in a variable phase shift across the image. Factors such as this will have to be taken into account to make the proposed technique feasible, say, in a hostile industrial environment. Coherence, the form of the wavefronts and polarization will depend upon the type of monomode fibers used in future studies. For example, in a monomode fiber the sole guided mode really corresponds to two modes having the same configuration but with orthogonal polarizations.[23] When the fiber is illuminated with linearly polarized light from the laser, coupling occurs between these degenerate modes of propagation and the fiber produces an output which is elliptically polarized. The state of polarization is directly dependent on environmental factors, such as temperature, and/or geometrical configuration, such as the twist in the fiber. This phenomenon will require us to evaluate the effect of using elliptically polarized light during recording and/or reconstruction, or to devise schemes to eliminate these effects.

A more complete understanding of the radiation in monomode optical fibers will help to establish limitations on resolution, magnification, depth of focus and field of view. It will also lay a foundation on which to build theories which govern displacement fringes and their properties, such as localization.

In short, further research in the area of holographic interferometry with fiber optics will require the use of newly devised techniques and more efficient fibers in order to reduce or eliminate adverse effects inherent in this process.

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