OPTICS AND LASERS IN ENGINEERING

An International Journal

Edited by
J. N. BUTTERS

Ultra Low Frequency Holographic Interferometry Using Fiber Optics

J. A. Gilbert

Department of Civil Engineering, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA

T. D. Dudderar

Bell Laboratories, Murray Hill, New Jersey 07974, USA

A. J. Boehnlein

Department of Civil Engineering, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA

(Received: 30 August 1983)

ABSTRACT

Earlier studies have shown that stable ultra low frequency (ULF) holograms can be transmitted through flexible multimode optical fiber image bundles, with potential for recording interferometric quality images of remote or significantly obscured (but appropriately illuminated) subjects. This report describes the first successful demonstration of the use of doubly exposed ULF holography for the interferometric measurement of deformation fields through a fiber optic image bundle, and defines some of the capabilities and limitations of this approach to the application of coherent metrology to remote subjects.

1. INTRODUCTION

The fundamental concepts of wavefront reconstruction, or holography as it is now called, were explained more than thirty years ago by Dennis Gabor.[1,2,3] The subsequent development of the laser accelerated the pace of holographic research and led to new techniques which are now being used to record and store data. An

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interesting outgrowth of this work was the development of various techniques of holographic interferometry which could be used to make non-contacting and non-destructive deformation measurements on the surface of objects under applied loads. At first, the potential practical applications for this technique seemed limitless, especially those associated with industrial testing. So far, however, industry has proven reluctant to employ holographic interferometry to any significant extent, largely due to the many stringent requirements that are inherent to both holography and interferometry. The most limiting of these requirements is the need to isolate all optical components from vibration. The present research demonstrates the potential of fiber optics to meet these stability requirements even under conditions which exist in a typical industrial environment.

Recent advances in technology have led to the development of optical fibers and optical fiber bundles. These fiber optic elements have enabled us to illuminate and view scenes never before observed and have proven invaluable when used to gain access to objects located in remote and/or hostile environments. The laserscope, for example, which is being developed to burn passageways through clogged arteries, uses some optical fibers to conduct the intense main laser beam, a coherent optical fiber bundle for inspection and still other optical fibers for remote area illumination. Fiber optics have now been combined with holographic interferometry to measure deformation fields. Initial feasibility studies[4,5] demonstrated that the use of commercially available multimode fiber optics provides additional degrees of freedom and reduces some of the strict vibration isolation constraints imposed on holographic systems, but not to the extent that they could be applied in a typical industrial environment.

More recent holographic/fiber optics research[6,7] and applications,[8] however, have shown that an individual singlemode optical fiber (SMF) can act as an environmentally insensitive light guide when used to transport coherent light for illumination of test objects. Unfortunately, a flexible SMF cannot transmit an image and a coherent multimode imaging bundle (MMB) must be used to transmit amplitude and phase information from the illuminated object back to an appropriate media for holographic recording. Laser light passing through each optical fiber in the MMB involves many modes propagating along different paths which are significantly influenced by bending losses. Consequently, if the bundle is flexed during or

between exposures, modal propagation effects make phase transmission time-dependent and interferometry impossible. This problem could be eliminated if SMFs were used in the imaging bundle. Unfortunately, singlemode imaging bundles (SMBs) are not yet available. Until they are, it is desirable to search for alternate techniques for transmitting holographic information through fiber optics under field conditions.

It has been shown in related fiber optic studies of laser objective speckle[9,10] that MMBs can transmit amplitude information with little distortion even when vigorously agitated, provided that the spatial frequency content of the speckle image is within the resolution capabilities of the bundle. These findings were recently incorporated into holographic/fiber optic research[11] when the complex diffraction pattern corresponding to an ultra low frequency (ULF) hologram was transmitted through an MMB for subsequent playback at a remote location. The present study expands the scope of this prior research and demonstrates that ULF holographic/fiber optic techniques can be used to transmit stable interference fringe patterns from test objects (potentially situated throughout an industrial test floor) to a remote location (for example, to a central holographic processing laboratory) for interferometric applications. No special precautions need be taken to isolate fiber elements from vibration other than rigidly fixing their ends.

2. THEORY

In holography, laser light is divided by a beam splitter so that a portion of the light follows a path to the recording plane and is called the reference beam. The other portion of the light, called the object beam, illuminates and reflects off the test object towards the recording plane. These beams superimpose on the recording plane to form a standing wave interference fringe pattern which is usually captured directly on a high resolution photographic plate. The developed plate (called a hologram) is then illuminated with the reference beam so as to reconstruct (by diffraction) a virtual image of the test object. Interferometry may then be accomplished by recording two images of a test object which has been very slightly perturbed between exposures. Reconstruction of this doubly exposed hologram then produces

another interference pattern whose light and dark fringes represent loci of constant differences in optical path length related to constructive or destructive interference between the two reconstructed wavefronts.

In general, both reference and object beams are spatially modulated plane or spherical waves and the hologram itself may be regarded as a complicated diffraction grating with interference fringes of variable orientation and spacing. This paper explores the possibility of transmitting superimposed holograms corresponding to different states of deformation of a test surface through an MMB for recording, subsequent reconstruction, and analysis at a remote location.

The simplest hologram is formed by two plane waves (corresponding to the object and reference beams) which intersect at an angle 2θ. In this case, the resulting interference pattern is a system of parallel light and dark fringes with spacing d, given in terms of the wavelength λ, as,

$$d = \frac{\lambda}{2 \sin \theta} \tag{1}$$

The spatial frequency corresponding to this or any more complex hologram fringe spacing must be within the resolution capability of the MMB used for transmission. The 10 mm diameter coherent bundle consisting of individual $12 \, \mu$m diameter multimode fibers used for the present experiments can be expected to resolve fringes spaced at a minimum distance of $33 \, \mu$m; or, around 3 times the diameter of the individual fibers of which the bundle is composed. This requires that holograms which are recorded at $\lambda = 0.633 \, \mu$m be generated with θ equal to 1 degree or less between the object and reference beams at the entrance end of the MMB. This information is of extremely low frequency when compared to that recorded using most conventional holographic techniques; therefore, the resulting diffraction fringe pattern will be referred to as a ULF (Ultra Low Frequency) hologram.

3. EXPERIMENT AND RESULTS

The experimental set-up shown in Fig. 1 was used to conduct these feasibility tests. The object beam was expanded to illuminate a
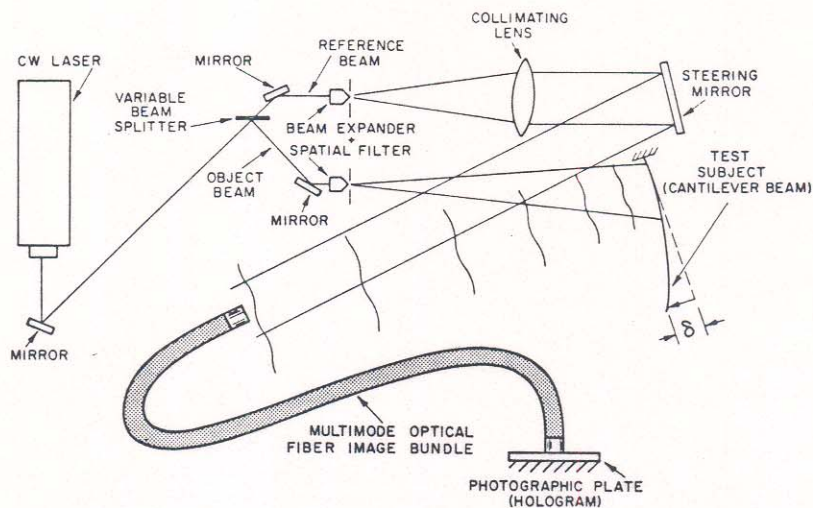
Fig. 1. Schematic of the configuration used to record ULF holograms transmitted through a 10 mm MMB.

portion of the cantilever beam used for a model, Fig. 2. The object beam was expanded to illuminate a small portion of its surface. A collimated reference beam was reflected off a front surface mirror located immediately above and behind the object and directed so as to combine with light reflected from the model and form a complex interference fringe pattern at the entrance end of the MMB.
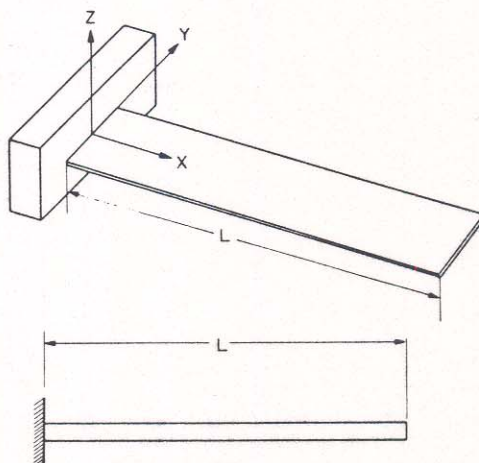

Fig. 2. Cantilever beam test subject.

Whenever the end of the cantilever beam was displaced, changes in this ULF fringe pattern could be observed through a microscope focused on the exit end of the bundle. The real images of these complex interference fringe patterns corresponding to the unloaded and loaded beam positions were transmitted through the MMB and recorded using the double exposure technique by contact copying from the exit end of the MMB directly onto a photographic plate. The only requirement necessary for transmitting stable holographic fringe information through the MMB was to rigidly fix its ends with respect to the model and the hologram plate. When this condition was satisfied, no changes were observed in the interference fringe patterns of either image, and the MMB, with its ends fixed, could be vigorously agitated along its length during or between exposures without effect.

The cantilever beam (of length, $L = 181 \cdot 1$ mm and width, $W = 25 \cdot 4$ mm) was illuminated with laser light ($\lambda = 6328 \times 10^{-7}$ mm) directed along propagation vectors parallel to the XZ plane and making angles of approximately 6° with respect to the X axis. Only a small portion of the beam was illuminated ($0 \cdot 02 \leq X/L \; 0 \cdot 21; \; -0 \cdot 21 \leq Y/W \leq 0 \cdot 21$) so as to reduce the complexity of the standing wave interference pattern produced at the recording plane. The observation point was located at a sufficiently large distance to keep the angles between the object and reference beams small enough so that most of the spatial frequency content of the complex interference fringe pattern was within the resolution limit of the MMB.
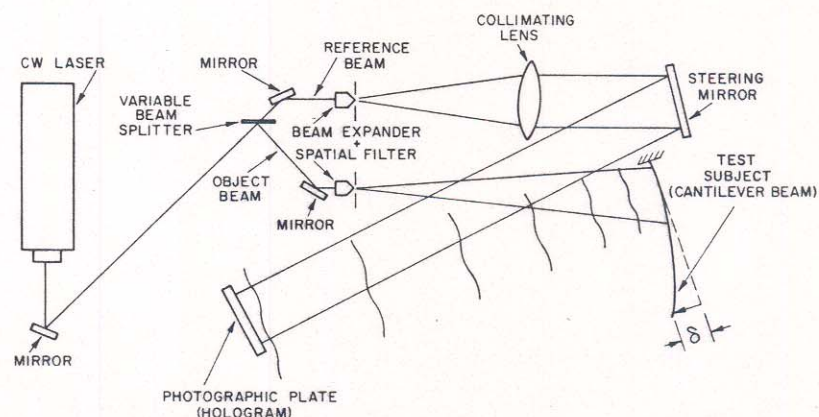

Fig. 3. Schematic of the configuration used to record ULF holograms directly.

The experimental set-up was designed so that a second photographic plate could be located in the same plane as the entrance end of the MMB to produce direct holograms for comparison purposes (Fig. 3.) In each test, both direct and through the MMB, the initial hologram exposure was made with no imposed deformation. Then the end of the cantilever was displaced an amount δ, and the second
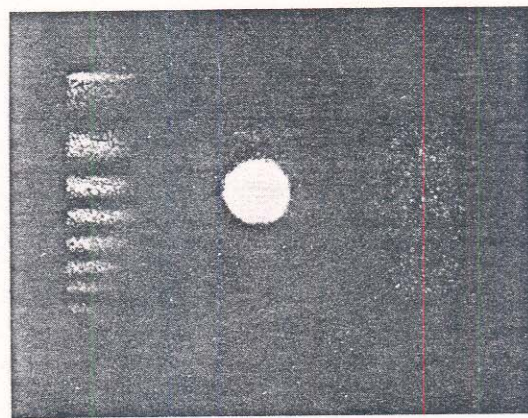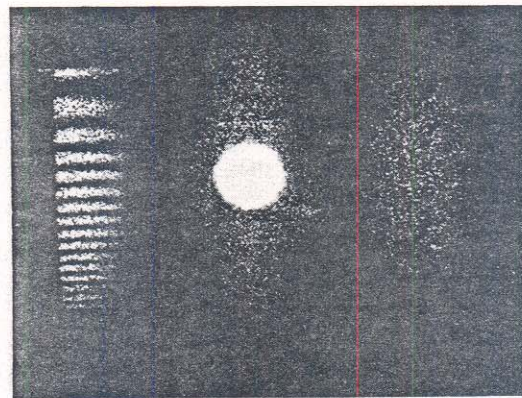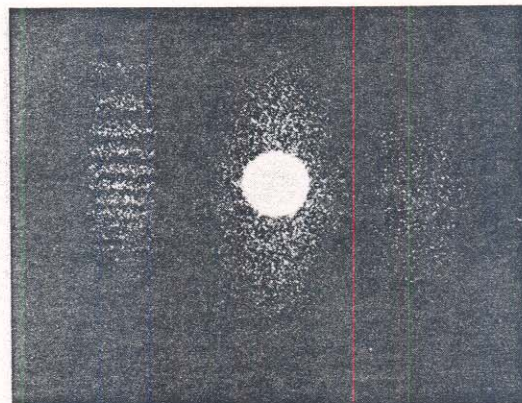

(a)
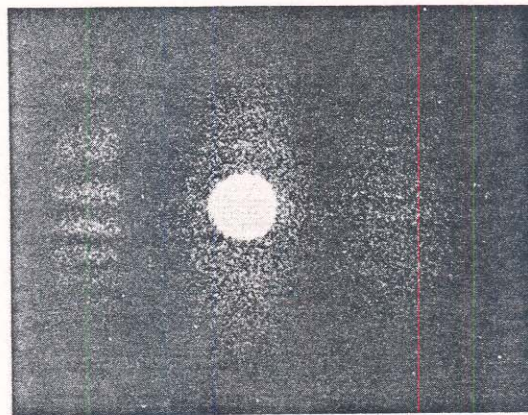
(b)

Fig. 4.   Holographic interferograms showing the displacement fringe field formed on the top surface of the cantilever beam displaced $0·0254$ mm at $X = L$ (out of view) as recorded: (a) directly, and (b) through a 10 mm MMB.

exposure was recorded. Two end displacements, $\delta = 0.0254$ mm and $\delta = 0.0508$ mm, were used, each with and without the MMB. In all cases the ULF diffraction fringe patterns were recorded on Kodak 131 plates and the processed holograms were bleached in bromine. The resulting double-exposure holograms were reconstructed using a conjugate reference beam which yielded the real images shown in Figs 4 and 5. These holographic interferograms were recorded on

(a)

(b)

Fig. 5. Holographic interferograms showing the displacement fringe fields formed on the top surface of the cantilever beam displaced 0·0508 mm at $X = L$ (out of view) as recorded: (a) directly, and (b) through a 10 mm MMB.

photographic film located at a distance equal to that between the object and entrance end of the MMB, or the photographic plate used to record the direct holograms, whichever was appropriate.

The reconstructed deformation patterns shown in Figs 4 and 5 were analyzed using the relation

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

Here $(\hat{\mathbf{e}}_1)$ and $(\hat{\mathbf{e}}_2)$ 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 λ is the wavelength. The quantity $-(\hat{\mathbf{e}}_1 - \hat{\mathbf{e}}_2)$ is often referred to as the sensitivity vector along which the displacement vector $(\hat{\mathbf{d}})$ is projected.

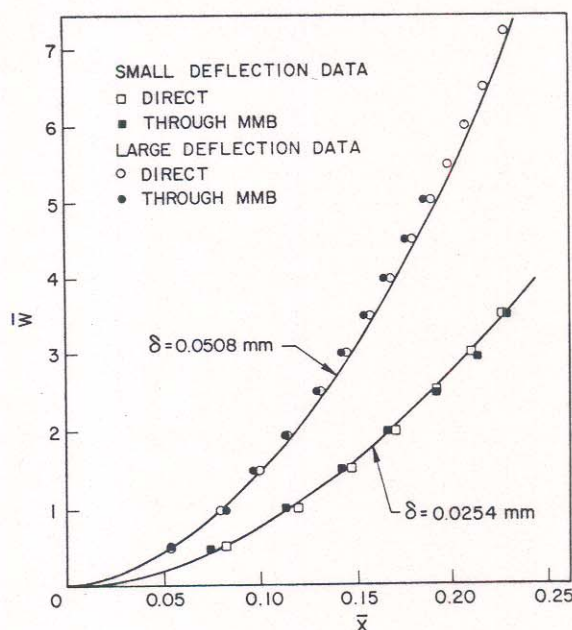Figure 6 shows a plot of these results in the form of normalized

Fig. 6. Plots of normalized beam deflection, $\bar{W} = W/\delta$, versus normalized position along the cantilever beam, $\bar{X} = X/L$, for end displacements of $\delta = 0\cdot0254$ mm (open squares represent interferometric data recorded directly and filled squares represent data recorded through the MMB) and $\delta = 0\cdot0508$ mm (open circles represent interferometric data recorded directly, and filled circles represent data recorded through the MMB). The solid line represents the normalized deflection distribution calculated from the theoretical solution for an elastic cantilever beam (eqn 3).

beam deflection $\bar{W}(X) = W(X)/\lambda$ versus normalized axial location along the beam, $\bar{X} = X/L$, as determined by the interferometric fringe data. This figure also shows the theoretical beam deflection distribution as computed from the normalized displacement relation

$$\bar{W}(\bar{X}) = \frac{\delta}{2}\lambda(3\bar{X}^2 - \bar{X}^3) \tag{3}$$

derived for a linear elastic cantilever beam displaced an amount δ at the $\bar{X} = 1$ end.

4. DISCUSSION

As can be seen in Fig. 6, the agreement between theory and the experimental results is reasonable in every case. This demonstrates that ULF holograms, recorded either directly or through a flexible coherent bundle of flexible multimode optical fibers, can be used to make interferometric measurements of deformation fields. Moreover, while there is some unavoidable loss of resolution and contrast associated with the use of an MMB, no vibration isolation of this component was required to achieve usable results. This is significant for potential remote applications.

However, the restriction on bandwidth imposed by the very limited resolution ($\approx 33\ \mu m$) of the present MMB does represent a handicap. This component acts as a low pass filter, cutting off the higher frequency fringes in the standing wave interference pattern and thereby effectively restricting the range of possible propagation directions of any wavefronts to be diffracted by fringe patterns recorded at the MMB output. This in turn limits both the size and complexity of any test subject to be recorded holographically, and the range and complexity of any associated deformation field to be measured interferometrically. Real time observations of standing wave interference fringe patterns made through a low power microscope revealed visually that increases in either (a) the deflection of the beam, or (b) the area of illumination of its surface, act to increase the complexity of the pattern itself. With such an increase in complexity there is inevitably an associated increase in the proportion of higher frequency components which will exceed the resolution limit of, and consequently not be transmitted through, the MMB. Such information does not contribute to the formation of a hologram and cannot appear in the reconstructed wavefront or image.

Moreover, as described in the earlier study of ULF holography per se, a relatively small hologram area combined with the necessarily large reconstruction/viewing distance can result in the formation of significant objective speckle noise in the reconstructed image and an associated loss of resolution. In the present study this problem is significantly reduced by the use of an unusually large diameter (10 mm) MMB, although this same objective might also be achieved through the use of a coherent array of smaller MMBs.

Consequently, the optimization of fiber optic ULF holographic interferometry for remote applications will require both maximized MMB area for the suppression of speckle noise and significantly improved MMB resolution to reduce the deleterious effects of band-pass aperturing.

5. CONCLUSIONS

In this study using a large 10 mm diameter MMB (with a $33 \mu m$ resolution limit), it has been successfully demonstrated that multimode fiber optic ULF holography is stable enough for interferometric applications. Such applications are presently restricted to studies of quasi-planar subjects of limited size and subjected to simple deformations. However, practical applications to larger, more complex subjects and deformations can be accomplished using MMBs of greater resolution, perhaps configured in coherent arrays to provide the hologram area required to suppress speckle noise.

6. ACKNOWLEDGEMENTS

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