Application of Fiber Optics to Speckle Metrology—a Feasibility Study

The application of monomode and multimode fiber optics to laser-speckle metrology is evaluated using numerical- and optical-correlation techniques

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ABSTRACT—The development of fiber optics provides a potential means of simplifying coherent-light-metrology techniques and, simultaneously, increasing their realms of applicability by suppressing the negative effects of hostile mechanical and thermal environments. This report describes a series of experiments which explore some of the possibilities for applying fiber optics to speckle metrology, and, at the same time, demonstrates the use of both photoelectronic-numerical and conventional optical systems for recording and correlating the resulting speckle fields.

List of Symbols

BD = bundle diameter
CW = continuous wave
D = diameter of laser beam
FD = fiber diameter
LSP = laser-speckle photography
MMB = coherent-multimode (fiber) bundle
NA = numerical aperture
R = displacement to speckle-size ratio, x/σ
S = normalized speckle size, σ/FD
SMF = a single-mode fiber
d = diameter of illuminated area on test surface
l = distance from end of SMF to illuminated area on test surface
n_i = core index of refraction
n_0 = cladding index of refraction
x = displacement of the test surface
z = distance from test surface to the input end of the MMB
Δ = index difference, $n_i - n_0$
λ = wavelength
σ = objective speckle size
θ = SMF-propagation cone angle

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Introduction

In recent years a variety of coherent-optical-metrology techniques (holographic interferometry, speckle interferometry and speckle photography)[1-4] have been developed, largely in response to the development of the laser as an efficient source of coherent illumination. A similar increase in interest in the use of light in communications, likewise stimulated by the development of the laser, has led to the development of sophisticated fiber optics.[5,6] This report describes an initial application of fiber optics to one of these coherent optical techniques, laser-speckle photography (LSP), using both monomode- and multimode-fiber optics. This investigation also explores the use of a vidicon-camera/digitizer system as a means of recording the speckle images and the application of simple numerical-correlation techniques for determining displacements.

There are two obvious applications for fiber optics in speckle metrology. The first is as a flexible but environmentally insensitive element used to guide the coherent light from its source, the laser, to a potentially remote object. The second application is as another flexible but environmentally insensitive element used to transmit the speckle-field images from the vicinity of that remote test object back to some location where they can be recorded, either on film or photoelectronically, and analyzed or correlated. Naturally, either application may be of use by itself, but the greatest advantages lie in the use of both together. For reasons which shall be explained, the currently most appropriate choices of fiber types are an individual single-mode fiber, or SMF, as the illumination fiber, and a coherent bundle of multimode fibers, or MMB, as an image fiber. (When used to describe an optical-fiber bundle, the word 'coherent' refers to the cross-sectional fiber array in the bundle, specifically at the ends, and not to properties of the light passing through the bundle. Such an array of fibers is arranged at either end of the bundle so that the end of each individual fiber at one end of the bundle occupies a mirror position at the other end. If this were not the case then the individual contributions to the image entering the bundle would not emerge in the appropriate places so as to reproduce the image.)

To date a few investigators[7-10] have reported on the application of optical-fiber elements to the recording and/or reconstruction of holograms, but without reference to metrology or interferometry. Several of the present authors have recently reported on the first successful demonstrations of the use of multimode-fiber optics in incoherent or 'white-light' speckle metrology[11,12] and the use of multimode[13] and multimode with single-mode[14] fiber optics in holographic interferometry. This work showed that the propagation characteristics of the multimode fibers are extremely sensitive to the effects of mechanical vibration along the fiber length, while the single-mode fiber is far less so. This is because single-mode fibers transmit only one mode. Consequently, motion which might give rise to bending effects which alter the propagation of higher modes has little effect because there are no such higher modes. Unfortunately, while it provides an excellent means of transmitting light to the test object, an individual single-mode fiber cannot readily be made to transmit an image. Image transmission requires a coherent fiber bundle and, unfortunately, coherent single-mode fiber bundles (SMB's) do not exist. Until they do, interferometric applications of fiber optics will require careful mounting along the entire length of any MMB used to transmit an image in order to assure stability and avoid the deleterious effects of vibration, etc. For the most part the same might be expected to be true of speckle applications. Fortunately, commonly available MMB's can be used for point-wise speckle metrology without being subject to such restrictions. This is the case so long as the speckle size is greater than the size of the individual fibers in the bundle, as will be demonstrated in this study.

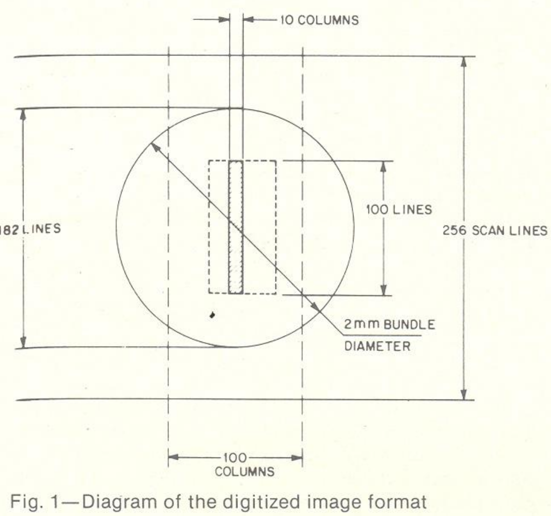


Fig. 1—Diagram of the digitized image format

Experimental Equipment

In the first three experiments an MMB (manufactured by American ACMI, Stamford, CT), BD = 2 mm and length = 230 mm, was used to transmit the speckle images via a 10× microscope objective to a vidicon-camera/digitizer system. This system consisted of the Hamamatsu Model C-1000-01 (E5001) camera control and head, with an M1003 intensity monitor, an M1004 video A/D converter, an M1005 video slicer and an M999 C1000 to LSI-11 interface. This system was controlled by an LSI-11 microcomputer which in turn transmitted the resulting data to a PDP-11/45 minicomputer for processing. With multiple-scan interlacing this system is capable of digitizing a 1024 × 1024 array of image points at 256 intensity levels, albeit rather slowly. Because of real-time and space limitations the interlace was not used, reducing the operating capacity to a 256 × 1024 array. On the TV monitor the 2-mm MMB appears as a nearly circular field approximately 180 scan lines in diameter located in the center of the screen. At the magnification used, each scan-line spacing represents a real object spacing of about 11 μm, the same as the size of the fibers in the MMB. This system scans along the 256 horizontal scan lines, but digitizes along the vertical columns indicated by a cursor as it moves across the field from left to right as directed by the LSI-11. In the interest of efficiency only every fourth such column was digitized, reducing the full field to a 256 × 256 array. A further reduction to a more manageable 256 × 100 point array was achieved by recording only the central 100 such columns (that is, every fourth of the central 400 columns of the maximum 1024 columns). This scheme recovers most of the significant data in the image, as shown in Fig. 1, while requiring the storage of less than 30000 bytes per digitized picture file.

Illumination of the test surface was provided either directly or through an individual single-mode telecommunications fiber of 4-m length with a numerical aperture, NA, of 0.1143 at a λ of 0.633 μm. [For an individual single-mode step-index fiber of the type used in these experiments, $NA = n_i(2\Delta)^{1/2}$ where n_i is the core index of refraction and Δ is the normalized step difference in index between the core and the cladding, $(n_i - n_0)/n_i$.] Coherent illumination at that wavelength was provided by a He-Ne CW laser.

The Experiments

Speckle Size

This series of tests was conducted in order to examine the effect of varying the speckle size, σ. Initial investigation revealed that if the speckle size was smaller than an individual fiber such that a single fiber contributed to the formation of several speckles, even a small displacement

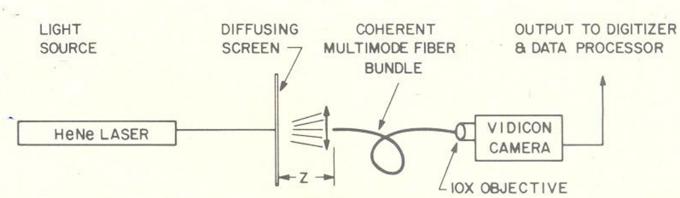


Fig. 2—Schematic of the forward-scattered objective-speckle experimental setup with a MMB used to transmit the speckle image to the vidicon camera-digitizer system

of the fiber bundle at any point along its length would so alter the modal propagation through the bundle that the resulting speckle field would be greatly changed and correlation between successive speckle images would be lost or severely degraded. In fact, fine speckle fields transmitted through such multimode fiber bundles generally appeared to be more susceptible to the effects of minor displacements of the bundle along its length than they were to the displacements of the test surface supposedly being monitored. Consequently, the first series of experiments involved a study of the effective range of suitable speckle sizes at or above the individual fiber size (which is, not coincidentally, the resolution limit of the vidicon-camera/digitizer system). These objective speckle images were generated in free space (without lenses) by illuminating a frosted glass from behind with an unspread laser beam and picking up the forward scattered light at a distance, z, using the lensless input end of the MMB as shown in Fig. 2. This approach (using objective speckle images rather than 'imaging' full subjective speckle fields into the MMB using a lens) was chosen because it provided a practical means of generating bright speckle of the size needed to render the images insensitive to any movements of the MMB which might occur along its length. A

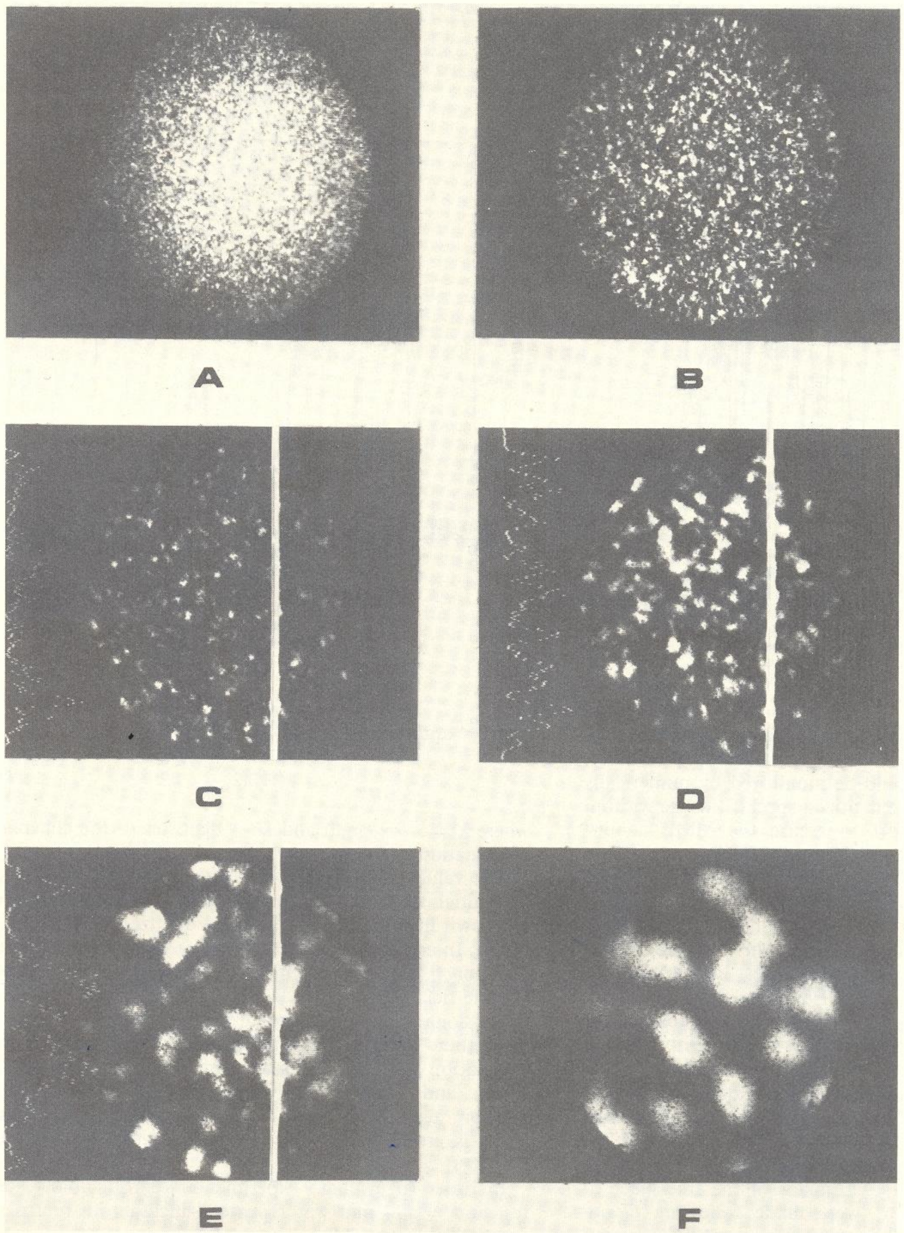
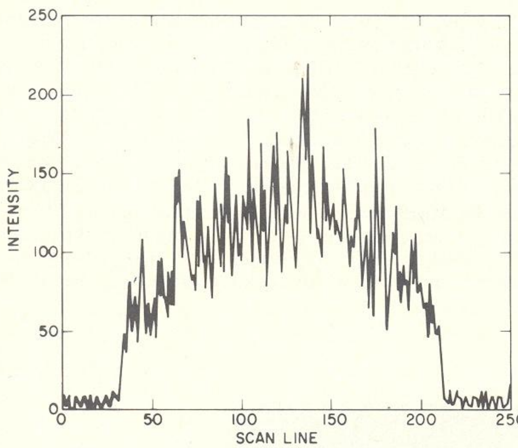
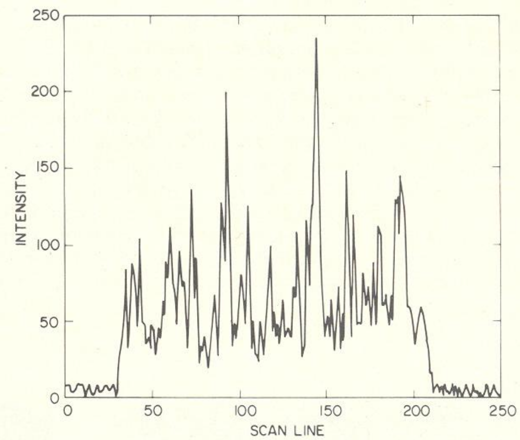


Fig. 3—Photographs of MMB speckle fields on the TV monitor with CW laser illumination on a glass diffuser (approximately 1-mm diam spot) and MMB distance, z, of (a) 10.9 mm, (b) 43.4 mm, (c) 87.0 mm, (d) 174.0 mm, (e) 348.0 mm, (f) 696.0 mm



(a)



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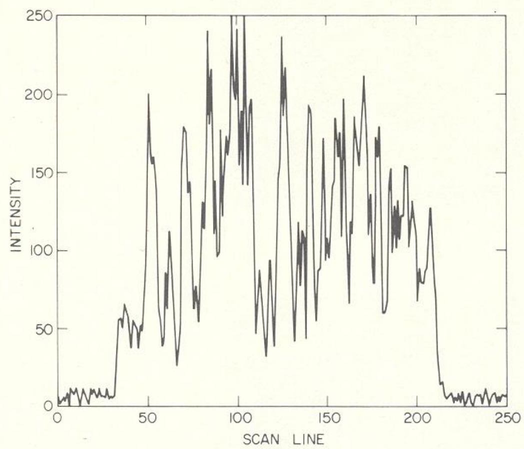

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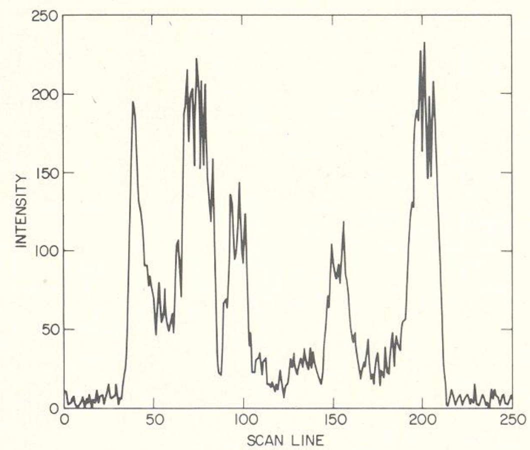


(e)

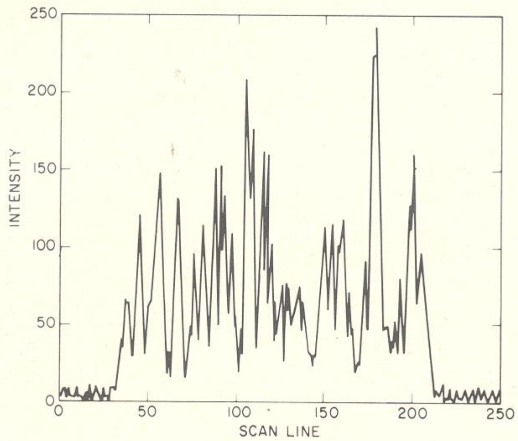
second intended purpose of this experiment was to demonstrate that, as a result of having achieved such stability, in-plane displacement could be monitored by numerically correlating two successive digitized speckle images without making any special effort to secure the MMB against unwanted movement except (naturally) as its ends. These experiments were conducted by digitizing an initial image, displacing the end of the MMB enough to shift the speckle field about 10 data scan lines or columns, and recording a second digitized speckle image. This procedure was repeated for a range of speckle sizes by varying the distance, z, between the diffuser and the input end of the MMB. At no time was any effort made to restrict the movement of the MMB along its length. Only its end positions were controlled, and at times the intermediate portion of the bundle was moved about quite freely. The resulting speckle images are shown in Figs. 3(a)–(f) as they appeared on the television monitor, and Table 1 shows the estimated average free-space speckle sizes, σ, for each of the six distances. These estimates of the free-space or objective speckle size, σ, were made following Goodman[15,16] and the relation given by Ennos[17]

$$\sigma \simeq 1.22 \frac{\lambda z}{D} \tag{1}$$

where λ = wavelength and D = diameter of the coherent-illumination beam.

The values of σ vary from a little below the size of an individual fiber to one-quarter of the bundle diameter, as shown in Fig. 3 and the typical digitized data plots of Fig. 4. In each case a translation of approximately 10 data lines or 0.11 mm was imposed between each of two speckle-field recordings. Figures 5(a)–(f) show the one-dimensional numerical-correlation distributions obtained from these data. (For a mathematical description of the correlation used in this study the reader is referred to Dixon and Massey.[18] A discussion of numerical-correlation techniques for two-dimensional displacement fields is given by Peters and Ranson *et al.* in Refs. 19 and 20.)

In order to evaluate experimental reproducibility, the test at z = 174 mm was repeated—including a return to



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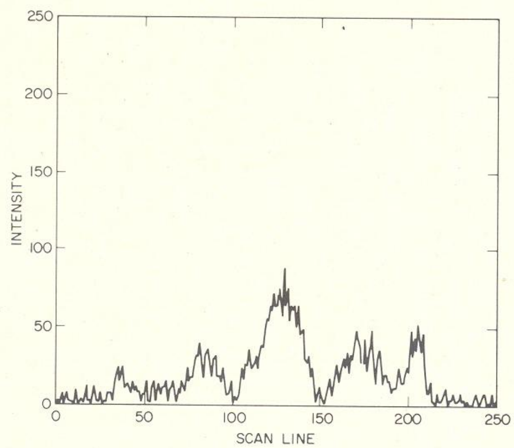

(f)

Fig. 4—Plots of the initial digitized intensity distributions from top to bottom across the center of the field (column 50) taken for MMB distances, *z*, of: (a) 10.9 mm, (b) 43.4 mm, (c) 87.0 mm, (d) 174.0 mm, (e) 348.0 mm, (f) 696.0 mm

and re-recording of the initial position after the displaced speckle image was recorded—and all three speckle images were compared and correlated.

Illumination and Imaging with Fiber Optics

In this experiment the full potential of fiber optics to facilitate remote measurements was demonstrated by using both an SMF to illuminate a test surface and an MMB to transmit the generated speckle field back to the vidicon-camera/digitizer system (Fig. 6). To do this a small spot on a flat, diffusely reflecting surface was illuminated with coherent light from the SMF situated at a distance, ℓ, from that surface, and the objective speckle field that resulted was input to the MMB at a distance, z, from the test surface. The diameter of the coherently illuminated spot, d, varies with the stand-off distance, l, as $d = l \tan\theta$. Here θ is the propagation cone angle which also defines the numerical aperture, NA, of the SMF, e.g., $NA = \sin\theta$. Since θ is normally small, $\tan\theta$ may be replaced by the NA and the relation for the objective speckle size, σ, becomes

$$\sigma \simeq 1.22 \frac{\lambda z}{NA\, l} \tag{2}$$

In the present experiment $NA = 0.1143$; so for $l = 6.35$ mm and $z = 178$ mm the estimated speckle size was around 0.189 mm. Figure 7 shows the correlation distribution for a horizontal translation of the test surface of 10 lines or 0.11 mm.

Numerical Analysis of the Digitized-speckle Data

Initial numerical correlations for data taken from digitized-speckle images were found to be somewhat unreliable when correlated column by column because of the effects of variations along any single rather narrow ($\sim$11 μm wide) column of 180 or fewer significant data points. However, it was found that intensity values over a 10-column × 98-line array gave a much better sampling of the speckle field. As an example, a 10 × 98 array of intensity values was selected from the center of the

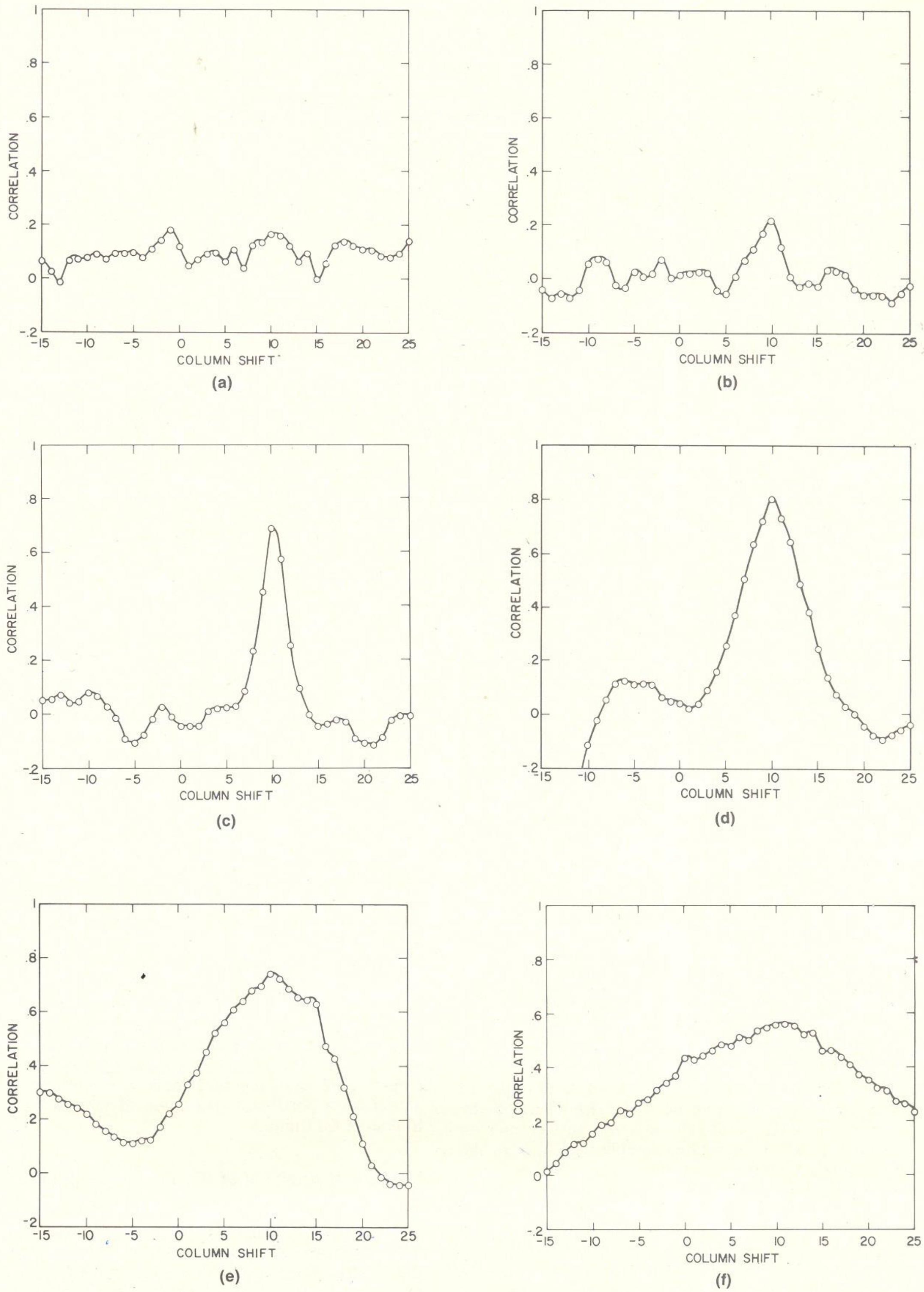

Fig. 5—Plots of correlations vs. the horizontal line shifts for MMB distances, z, of: (a) 10.9 mm—no significant peak, (b) 43.4 mm—peak at −99.9 lines, (c) 87.0 mm—peak at −10.2 lines, (d) 174.0 mm—peak at −10.0 lines, (e) 348.0 mm—peak at −10.2 lines, (f) 686.0 mm—peak at −10.6 lines

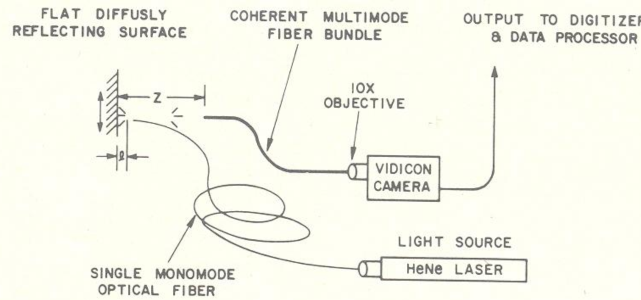

Fig. 6—Schematic of the experimental setup with a SMF used to illuminate the test plane and a MMB used to transmit the resulting speckle image to the vidicon camera-digitizer system

digitized-speckle image and correlated with a progressive succession of similar 980-point arrays taken from a 50 × 98 strip of intensity values taken from the initially digitized speckle image as shown by, respectively, the shaded and chain-dotted regions in Fig. 1. This progression of correlations was computed for integer line shifts from left to right for every experiment and provided all the correlation distributions evaluated in this study and shown in Fig. 5 for the speckle-size experiments and Fig. 7 for the reflected-speckle experiment using two fiber-optic elements. In all these figures the calculated correlations are represented by circles. These data were spline fit (the continuous line connecting the circles) and the maximum value thus produced was used to estimate the measured line shift.

The Use of Optical (Young's Fringes) Techniques

In its present form, the application of numerical-correlation techniques to LSP using fiber optics is confined to analyzing simple in-plane motion in a known direction, and has not as yet been applied to making measurements of two-dimensional in-plane motions and/or rotations as described by Chu and Peters *et al.*[20] On the other hand, conventional optical techniques (such as generating Young's fringes by interrogating a doubly exposed LSP specklegram or photograph with an unspread laser beam) can readily deal with such two-dimensional displacements and rotations, as has been demonstrated many times.[3,4] However, it remains to be shown that such photographic optical techniques of recording and analysis will be effective for stabilized LSP applications involving fiber optics.

Conventional LSP optical analysis requires that the motion be greater than the size of the speckle, σ, yet not so large as to generate unresolvable fringe densities or otherwise lose correlation (perhaps around 20 σ). As it happens, the requirement that the speckle size be greater than the individual fiber size in order to assure transmission of a stable speckle image through the MMB does not necessarily rule out the use of an optical technique for analyzing the resulting specklegrams, although it does place a significant limitation on its use. At the very least, this means that it is confined to the measurement of motions greater than the size of the optical fibers used to make up the MMB, around 11 μm. Furthermore, because of the inverse relationship between speckle size and the size of the diffraction halo in which the Young's fringes are to be observed, only a restricted range of such motions may be measurable. In other words, if the speckle size is too small, modal propagation problems may arise to disturb the image, while if it is too large the associated diffraction halo may itself be too small to allow for the observation of many Young's fringes.

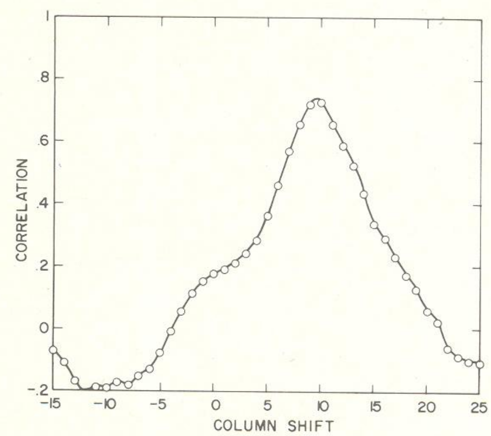

Fig. 7—Plot of the correlation vs. horizontal line shift for SMF (NA = 0.143) at 6.35 mm and MMB at z = 178 mm

In order to verify the use of the photographic technique for the recording and correlation of stabilized LSP images transmitted through an MMB, experiments were conducted using mostly the same equipment as before but with photographic film (rather than the vidicon-camera/digitizer computer system) used to record the speckle fields, as shown schematically in Fig. 8. A speckle size, σ, of around 35 μm was obtained by using a SMF illumination distance, l, of 14.5 and an MMB distance, z, of 76 mm. In these tests the emulsion side of the film was placed in direct contact with the output end of the MMB and exposed to two successive speckle patterns separated by an imposed surface displacement. The resulting Young's fringe fields are shown in Figs. 9(a) and (b) for effective displacements of 70 μm and 98 μm respectively.

Discussion

The initial series of experiments demonstrated that it is possible to transmit correlatable speckle images derived from surface displacements through a coherent-multimode fiber bundle or MMB without the need to rigidly stabilize the MMB along its entire length. However, in order to do this it is necessary to assure speckle sizes larger than the size, *FD*, of the optical fibers in the MMB, which is typically around 11 μm. Table 1 gives the results for objective speckle experiments with the normalized speckle size, $S = \sigma/FD$, running from less than one to over 45 (almost 25 percent of the MMB diameter), and the associated maximum correlations from which the line shifts were determined. These correlation peaks vary from none at $S = 0.73$ to a maximum of 0.81 at $S = 12.2$. As shown in Fig. 5 these correlation peaks are very sharp for speckle sizes up to $\sigma = 0.134$ mm (the same $S = 12.2$), but broaden significantly above that with some associated loss in accuracy. This broadening might be reduced a bit by a significant widening of the reference correlation window from a 10 × 98 array to a square 31 × 31 array so as to include more of the larger speckle, but such an approach would probably be of limited effect (after all, the speckle is already approaching the MMB diameter in size). Moreover, it would also lead to a significant (around 63-percent) reduction in the potential range of measurement.*

The repeated experiment at $z = 174$ mm showed significantly lower correlations, 0.65 and 0.67, with only a three-percent variation in line shift between trials. This result was at least partially a consequence of having used significantly lower levels of illumination in these tests. The repeat of the initial position yielded a maximum correlation of around 0.7 at a line shift of 0.1, which illustrates a probable repeat error for this system comparable to the magnitude of the errors shown in Table 1. In this series of tests meaningful correlations (>0.5) were obtained for displacement to speckle-size ratios, *R*, ranging from 0.20 to almost 14.00.

Objective speckle was chosen because it represents the most practical means of obtaining the large speckle needed, and not so as to rule out full-field applications. It just turns out to be rather difficult to propagate stable full-field subjective-speckle fields (of sufficient intensity and speckle size) through the MMB using lenses. However, the use of objective speckle *per se* does limit the application of such a system to the measurement of displacement at just that point on the surface whose illumination contributes to the formation of the objective-speckle image

**With the present correlation configuration, line shifts from −45 to +45 can be accommodated without biasing the reference window—a range of 90 lines or almost 1 mm of motion with an accuracy on the order of two percent, and nearly twice that with biasing. Changing to a square 31 × 31 array would reduce the range to only 34 lines without biasing, and a maximum of less than twice that with biasing. Biasing refers to locating the reference window either to the right or to the left of the center of the full-digitized-speckle image, depending on conditions. For example, correlations might be run first with a full-right reference window, and then with a full-left reference window, with the resulting maximum correlation peak used to define the shift accordingly.*

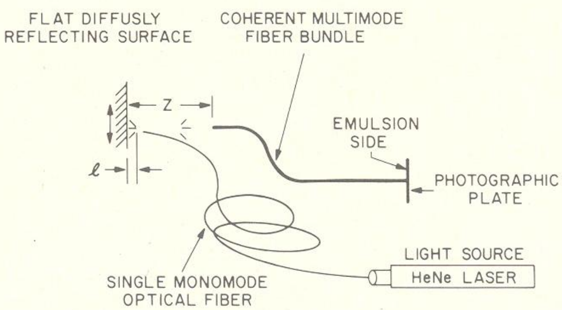

Fig. 8—Schematic of the experimental arrangement with a SMF used to illuminate the test plane and a MMB used to transmit the resulting speckle image to a photographic film

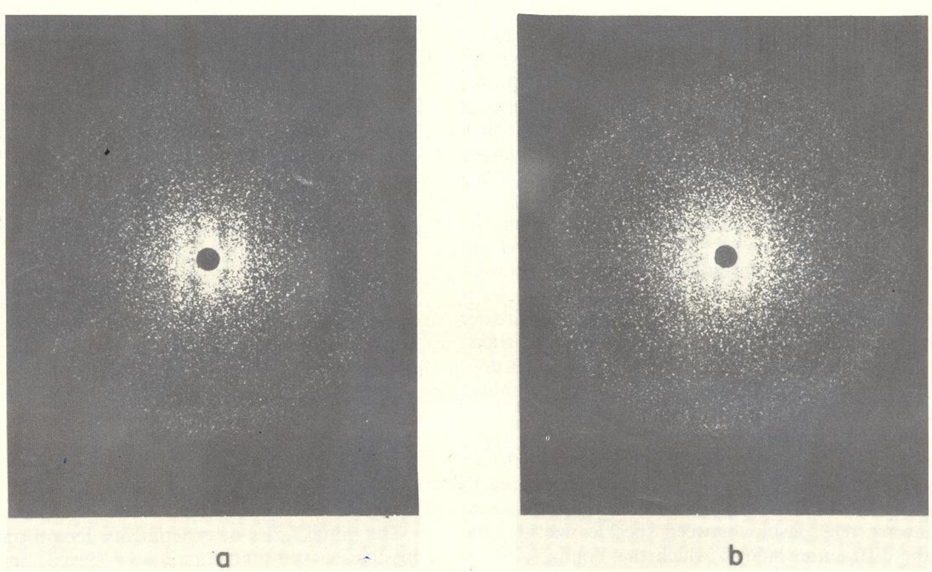

Fig. 9—Photographs of the resulting Young's fringe fields representing effective displacements of (a) 72 μm and (b) 108 μm from specklegrams recorded through the MMB at $z = 68.6$ cm

at the input end of the MMB. No information about adjacent regions on the test surface will be available unless, of course, other points on the surface are illuminated, perhaps by other SMF's. In this case the associated objective-speckle fields might be transmitted through the MMB in sequence, perhaps by sequentially illuminating the various points on the surface as desired, or perhaps by some manner of multiplexing at multiple wavelengths or polarizations. Certainly 'rosette' arrangements might be operated in this way so as to determine local displacements gradients, etc.

Finally, the application of an individual single-mode fiber to the coherent illumination of a surface, together with the use of a coherent-multimode fiber bundle for the return of correlatable-objective-speckle images, Figs. 6 and 7, demonstrates a direct application of flexible fiber optics to remote LSP. Moreover, the use of a vidicon-camera/digitizer system and the numerical-correlation technique permits the analysis of one-dimensional motion over a range of displacements both larger and smaller than the speckle size, in contrast to such optical techniques as the Young's fringes method which requires displacements greater than the speckle size in order to work. On the other hand, the experiments with LSP specklegrams recorded by contact printing from the end of the MMB directly on to photographic film demonstrated that this conventional 'two-dimensional' optical-correlation technique can be made to generate viable fringes from such specklegrams, albeit within a necessarily small diffraction halo. The rather larger outer halo visible in Figs. 9(a) and (b) is associated with the characteristic size, 11 μm, of the individual fibers in the bundle which are smaller than the effective speckle size of 35 μm. Consequently, and fortunately, this diffraction halo lies well outside the diffraction halo associated with the displaced speckle.] At the same time this small speckle-diffraction halo, associated with the relatively large speckle size required to assure image stability through the MMB, limits the separation and visibility of fringes to be seen within it and, unfortunately, restricts the potential range of remote displacements to be measured by this technique, especially when compared to the potential range of the photoelectronic-numerical method of analysis.

Acknowledgment

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TABLE 1—CORRELATIONS AT VARIOUS SPECKLE SIZES

Distance z mm	$\sigma = 1.22 \frac{\lambda z}{D}$ mm	S*	$R = x/\sigma$	Maximum Correlation	Est. Shift (lines)	Error** Magnitude
10.9	0.008	0.73	13.75	none	—	—
43.4	0.033	3.0	3.30	0.22	9.9	−0.1
87.0	0.067	6.1	1.64	0.71	10.2	+0.2
174.0	0.134	12.2	0.82	0.81	10.0	+0.0
348.0	0.268	24.4	0.41	0.75	10.2	+0.2
696.0	0.504	45.0	0.20	0.57	10.6	+0.6

**S is the normalized speckle size, obtained by dividing the estimated speckle size, σ, by 11 μm, the diameter of an individual fiber in the MMB*
***Based on an applied shift of 10 lines which represents a displacement, x, of 0.11 mm*