Objective Speckle Measurement

by

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ABSTRACT

Studies using fiber optics to make objective speckle measurements of [illegible] in-plane surface displacements show that the sensitivity can be increased by increasing the distance at which the speckle field is sampled, decreasing the illuminated surface area, or increasing the divergence of the coherent illumination from the fiber.

1. Introduction

When a small surface area is illuminated with coherent laser light, interference effects generate an observable three-dimensional speckle field in the surrounding region[1]. Figure 1 shows a speckle pattern which has been captured on photographic film positioned in front of the illuminated surface. The random areas of light and dark are caused by the superposition of coherent wavefronts emanating from all points in the illuminated area. This pattern is classified as "objective", as opposed to "subjective" speckle, because no lenses were used to image the speckles onto the film. Surface displacement in the area of illumination will cause changes in this objective speckle field. Successive speckle patterns recorded from such changing fields may be correlated[2] numerically or optically to determine this displacement. A single pair of objective speckle patterns cannot measure complex deformations over the field, but can provide averaged information about the displacement across the area of illumination so long as the patterns correlate.

Earlier studies by the authors have demonstrated the feasibility of using fiber optics for both speckle and holographic metrology[3-9]. In the present system, the laser light is launched into an individual single mode fiber optic (SMF) and then transmitted through it to the test surface. The resulting objective speckle field is then captured by a coherent multimode fiber bundle (MMB) and transmitted to the recording medium.

There are several advantages in using fiber optics with objective speckle photography. From an experimental standpoint, fiber optics reduce the number of optical components (mirrors, lenses, etc.) needed, thereby simplifying the laboratory set-up. The flexibility of optical fibers allows an investigator to change points of illumination and observation quickly and easily. From a practical standpoint, the application of fiber optics allows investigation of remote areas on surfaces that are not otherwise optically accessible. Individual fibers and most fiber bundles are relatively small in diameter and quite flexible. They can easily be inserted into many areas of an enclosed structure where access via conventional optical components would be impossible.

In earlier investigations, the authors also described the use of a vidicon camera digitizer and computer (see Figure 2) for speckle applications[7-9]. Objective speckle patterns are digitized, transferred to a computer, and then numerically correlated. The major advantage of using photoelectronic data acquisition and numerical analysis lies in the potential for much greater speed. In addition, they are much more precise at determining displacements than optical techniques which leave evaluation of fringe spacing up to the judgement of the investigator. Numerical speckle fields can be enhanced or otherwise altered before correlation, whereas a specklegram, or doubly exposed photograph, cannot readily be changed. Moreover, numerical correlation permits the evaluation of differential displacements. In other words, rather than being restricted to

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comparisons between the two states represented by the initial and final speckle patterns on a given specklegram, the present approach permits the recording of a succession of speckle patterns during the history of an event. These may then be correlated numerically in pairs to evaluate the associated incremental displacements. Finally, the combination of fiber optics for scanning a test surface and photoelectronic-numerical techniques for rapid data acquisition and analysis raises the potential for making field measurements using objective speckle.

2. Photoelectronic Recording, Numerical Digitization and Correlation

The vidicon camera system is capable of digitizing a rectangular array of image points which is 256 scanlines (rows) high by 1024 columns wide. At each image point, a number between zero and 255 is assigned proportional to the light intensity encountered at that point. In the interest of saving both space in the memory and processing time, only the central 100 of the 256 total horizontal scanlines and every fourth of the central 800 vertical columns are digitized in this study. This results in a speckle pattern 100 scanlines high by 200 columns wide which requires only 19.5K of memory and can be digitized in 7 seconds. After digitization, the designated initial and final objective speckle patterns can readily be correlated numerically on the VAX. In this study the displacements and speckle movements were always imposed along the same direction because the present correlation software is essentially one dimensional.

Once all the correlations have been computed, the correlation coefficients vs. data shifts are spline fitted. The computer then searches along the spline fit and finds the highest positive correlation which corresponds to a measured data shift.

3. The Effects of Various Geometrical Parameters on Sensitivity

Initial experiments demonstrated that varying the illumination angle between 90° and 30° had little effect on the numerical correlation. On the other hand, qualitative observations revealed that three geometrical parameters significantly influenced sensitivity. The first parameter is the distance from the test surface to the MMB , or "observation" distance, z. The second is the area of illumination, which can be characterized by a spot size diameter, D. The third is the degree of divergence or convergence of the illuminating beam emanating from the optical fiber, which can be characterized by its numerical aperture, NA.

Various combinations of these three parameters were investigated to determine their affect on sensitivity. The experimental set-up shown in Figure 2 was modified by inserting different lenses between the SMF and the test surface to provide illumination at five different effective NA's; two diverging beams (NA=0.101 and 0.031), a collimated beam (NA=0), and two converging beams (NA=-0.018 and -0.042). Combinations of three different spot sizes (3.175mm, 1.588mm, and 0.794mm) and three different observation distances (z = 5.06cm, 20.32cm, and 50.8cm) were evaluated for each of these NA's. The results are shown in the Table. This data demonstrates that the sensitivity of the speckle pattern increases as z becomes larger and the speckle size grows. This behavior can be modeled by a speckle field which grows and "fans out" as one moves away from the test surface, i.e., the speckle field "rotates." Therefore, for a given object motion, the corresponding speckle pattern is more sensitive far from the surface than near the surface.

The Table also shows that an increase in D decreases the sensitivity. Increases in D allow more surface points to contribute to the formation of the objective speckle field; thereby introducing higher frequency information which results in speckles of smaller width. This also reduces the rate of growth and "fan out" of the objective speckles in the field which effectively reduces sensitivity such that the column shift becomes smaller at any given z. Changes in spot size, D, also effect the stability of a speckle pattern, defined as the ability of speckles to retain their shape and correlatability, during surface displacement. From qualitative observations, speckle patterns associated with a large illuminated spot are more stable than those associated with a small illuminated spot. Consider, for example, two speckle patterns of identical z and NA but with different D's. Assume that the first speckle pattern spot size is of a D_1 = 1 mm, while the second is of a D_2 = 0.125 mm. If the test surface is translated by 0.125 mm, the spot of size D_2 will now illuminate an entirely new portion of the surface. This new surface information will cause the speckles in the shifted pattern to change completely; thus destroying correlation. On the other hand, the spot of size D_1 will introduce only 12.5% of new information from the surface and retain 87.5% of the old information. In this case, the speckles in the shifted pattern will change shape only slightly; thereby preserving correlation with the initial pattern.

Results in the Table also show that the speckle pattern becomes more sensitive when the numerical aperture of a diverging illumination (NA>0) is increased while D and z are held constant. This may be explained as follows. Figure 3 shows two diverging beams illuminating a test surface with differing numerical apertures of NA_1 and NA_2. The more divergent beam, with higher numerical aperture, NA_1, must originate closer to the surface than that with NA_2 in order to illuminate the same spot size, D. Each of the diverging beams illuminates a surface which is not perfectly diffuse, and many of the illuminating rays tend to scatter in directions close to the reflection angle. Consequently, points in the outer region of the illuminated area contribute significantly less light to speckle formation in the plane of observation. The speckle pattern captured by the MMB is due to the interference from surface points which are primarily in the inner region of the illuminating spot. The diameter of this region, referred to as the effective spot size, is denoted on Figure 3 as D_1 and D_2 for illuminations NA_1 and NA_2, respectively. Since the more divergent illumination of NA_1 originates closer to the surface, the rays captured by the MMB appear to reflect from within an effective spot size D_1 which is smaller than the D_2 resulting from NA_2. Therefore, the sensitivity of the speckle pattern formed by NA_1 is greater than that formed by NA_2. In general, then, the sensitivity increases as the NA of the diverging beam is increased.

A more complicated situation exists for a convergent illumination (NA>0). Here, the sensitivity of the speckle pattern increases or decreases depending upon z. Consider Figure 4 which shows two converging beams illuminating a test surface with numerical apertures NA_3 and NA_4. Since the test surface is not perfectly diffuse, many of the reflected rays converge at the reflection angle. Both beams illuminate a spot of size D, but the reflected rays from points in the illuminated area associated with NA_4 (the more rapidly convergent beam) focus to a point closer to the surface than do those associated with NA_3. Suppose then that the MMB is positioned between the surface and point of focus in the converging reflection at station a-a. As discussed for the diverging beams, the speckle pattern formed at a-a is constructed, almost entirely, from surface points which are in the inner region of the illuminating spot. At station a-a, illumination NA_3 has an effective spot size of D_3 while NA_4 has an effective spot size of D_4. Since D_4 is larger then D_3, the speckle pattern formed by NA_4 will be less sensitive than that formed by NA_3. Therefore, in the converging reflection, an increase in convergence of the illuminating beam decreases the sensitivity of the resulting speckle pattern. Now, consider the MMB positioned beyond the point of focus inside the diverging reflection at line c-c. At this observation position, illumination NA_3 has an effective spot size of D_3', while NA_4 has an effective spot size of D_4'. Since D_4' is smaller than D_3', the speckle pattern formed by NA_4 will be more sensitive than that formed by NA_3. Consequently, in the diverging reflection, an increase in convergence of the illuminating beam leads to an increase in sensitivity of the resulting speckle pattern.

It is important to note that the objective speckles in the converging reflection move in the opposite direction to those in the diverging reflection for the same surface translation. For example, the data in the Table was generated by moving the surface in question from left to right with respect to the observation position. Speckles in the converging reflection moved in this direction; however, speckles in the diverging reflection moved right to left. This reversed motion is represented by negative sensitivity values in the Table. This phenomena is caused by the convergent nature of the illumination, but should present no problem for measurement of in-plane displacement provided that the point of transition from convergence to divergence, station b-b, is known.

When the MMB is positioned at, or near, station b-b in Figure 4(a) and a displacement is given to the test surface, the speckle pattern displays a random motion. This behavior is referred to as boiling because it resembles bubbles reaching the surface of boiling water.

4. Summary

This series of experiments has uncovered techniques which can be used to change the sensitivity of the objective speckle measurement system. Measurement of small displacements will probably best be achieved by speckle patterns of high sensitivity which can be created by diverging the illumination, decreasing D, or increasing z. Conversely, measurement of large displacements could be facilitated by converging the illumination, increasing D, or decreasing z.

5. Acknowledgements

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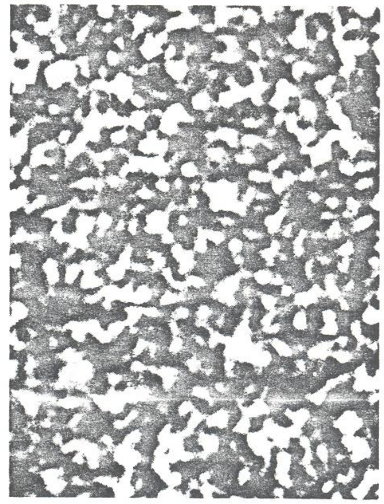
Table - Sensitivities of Different Speckle Patterns for Various D, z, and NA values

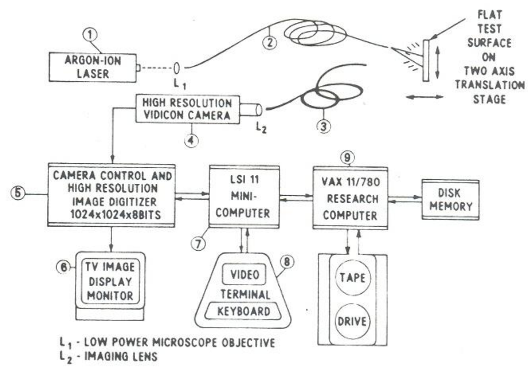
S = Sensitivity in column shift/mm of motion
z = Observation Distance in mm
D = Spot size in mm (diameter)
NA = Numerical Aperture in radians

NA	D	z		
		51	203	508
0.101	3.175	S=184	S=665	S=1575
	1.588	S=294	S=984	S=2460
	0.794	S=1008	S=3579	S=9843
0.031	3.175	S=109	S=339	S=803
	1.588	S=165	S=689	S=1457
	0.794	S=433	S=1272	S=2811
0.000	3.175	NM	S=58	S=65
	1.588	NM	S=63	S=72
	0.794	S=73	S=80	NM
-0.018	3.175	S=16	S=-109	S=-307
	1.588	NM	S=-261	S=-677
	0.794	S=-382	S=-1232	S=-231
-0.042	3.175	S=-38	S=-264	S=-781
	1.588	S=-107	S=-472	S=-1232
	0.794	S=-433	S=-1791	S=-5630

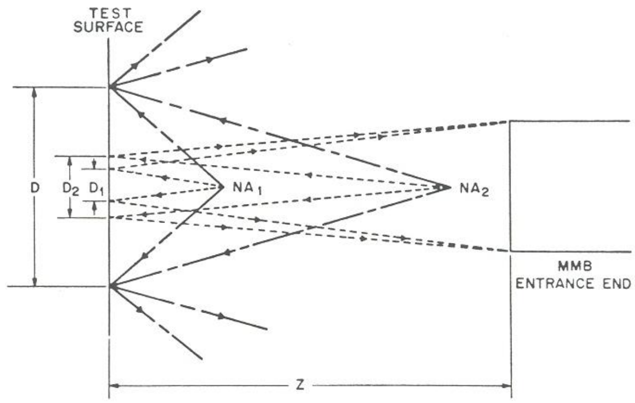
NM = Not measurable



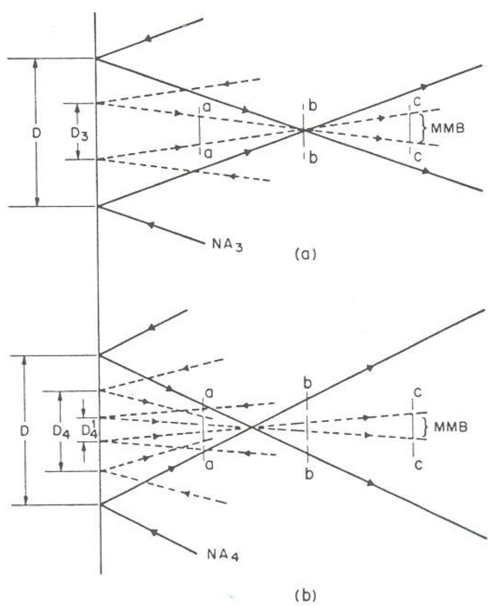
1. Objective Speckle Pattern



2. Hardware Schematic of Objective Speckle Measurement System



3. Comparison of the Effective Diameters of Two Diverging Illumination Beams



4. Comparison of the Effective Diameters of Two Converging Illumination Beams