REMOTE SHADOW SPECKLE METROLOGY

by

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Abstract

A computer-based method has been developed that applies speckle correlation techniques to measure out-of-plane surface motion. Incorporation of fiber optics demonstrates the potential of applying this technique to monitor deformations in hazardous locations or in remote areas of structural components.

Introduction

In general, speckle patterns are produced when light with sufficient spatial and temporal coherence is scattered by a medium or surface that introduces random optical path fluctuations comparable to the optical wavelength[1]. For example, when a small area of a test surface is illuminated with coherent laser light, a three-dimensional interference effect or speckle field is formed on the object and in the region surrounding it. These laser speckles are classified depending upon the manner in which they are recorded[2]. Objective speckles generally form in front of the illuminated surface and can be captured directly on a photographic plate or other medium positioned at a selected distance from the object. Subjective speckles, on the other hand, are obtained with a lens system by focusing the scattering surface onto the recording medium.

This nomenclature can also be applied to artificial speckles. For example, subjective speckles can be generated on an object by splattering paint on its surface. Objective speckles, on the other hand, can be produced by projecting a real image of a random pattern into a localized region of space (for example, using a 35mm projector and a clear glass slide splattered with black paint). Projected speckles form the basis for remote shadow speckle metrology.

Whether generated by a laser or artificially produced, random speckle patterns can be used to measure displacement and strain[3]. One approach for making these measurements is to use speckle photography[4]. Procedures for analyzing speckle patterns recorded using this technique can be divided into methods that use fringes[5] and methods that utilize digital correlation techniques[6-9]. The method of fringes has the advantage of simplicity but at the same time the disadvantage that displacements must be larger than the speckle size. In general, only a few fringes can be obtained using this approach and because the specklegram must be interrogated with a laser, fringes are modulated by secondary speckles, making precise measurements difficult even with automated analysis[10-14]. The technique can be improved when speckle patterns are captured directly with a photoelectronic-numerical processing system. In this case, photographic processing is not required and displacements can be quickly evaluated over the full-field. More importantly, the displacements to be measured can be smaller than the speckle size[6].

The basic approach in digital speckle photography is to correlate systematic pairings of intensity samples extracted from digitized speckle patterns separately recorded at different times in a load cycle. Earlier studies concentrated on the development of basic numerical algorithms for extracting speckle motion. Many of these algorithms have been improved, for example, to perform sub-pixel interpolation using Lagrangian weight functions[15], or to analyze relatively complex deformations using surface fits and bilinear interpolation techniques[16].

Most prior research involving digital speckle photography dealt with subjective speckles either produced by a laser, painted on the test surface, or occurring as a result of natural surface texture. Some of these studies reported that digital analysis could be applied to speckle patterns recorded through fiber optic systems, demonstrating the potential for making displacement measurements in remote locations[6,8,15,17]. In contrast to these investigations involving subjective speckles, the authors recently developed a technique called shadow speckle metrology in which speckles are projected on a test surface using a 35mm slide projector equipped with a clear glass slide splattered with black paint[18]. The present work incorporates fiber optics into this approach, to introduce a new technique called remote shadow speckle metrology.

Shadow Speckle Metrology

The name shadow speckle metrology was derived as a result of an analogy drawn between that technique and the shadow moire method[19,20]. In one approach to shadow moire, a reference grating, illuminated at oblique incidence, is positioned in front of an object. The shadow cast on the specimen produces a second grating which deforms as the elevation of the surface changes with respect to the reference plane. A moire pattern (representing the topology of the surface) is created when the two gratings are observed by eye or recorded with a camera.

The shadow moire method has been used to evaluate the flexure of thin plates, for contouring, and to solve torsion problems using membrane analogies. The method can be applied (using point illumination and point receiving) to an area of a structure as large as a grating can be manufactured. This makes the method useful, for example, in studying buckling phenomenon of large panels. Sensitivity, however, is somewhat limited once a grating pitch has been established. A composite grating (consisting of two parallel superimposed gratings with two discretely different pitches) has been used to circumvent this dilemma[21], but the approach requires a customized grating, and sensitivity is still limited. In addition, it is a rather challenging task to arrive at the proper orders in the moire fringe pattern. For example, a centrally loaded plate clamped around its boundary would display the same moire pattern for deflection toward or away from the observer. In simple cases, boundary conditions are usually sufficient to render proper ordering of the fringes. In others, they are often inadequate, and linear or rotational mismatches must be introduced[22]. In many cases, optical filtering is required to enhance fringe contrast.

All of these disadvantages (fixed sensitivity, customized gratings, sign ambiguities, and the need for optical filtering) are circumvented in shadow speckle metrology.

Analysis

The standard analysis used for shadow moire[22] can be applied to the present work as follows. Figure 1 shows a light source and camera located at equal distances from a structure. A speckle pattern is projected from point S onto its undeformed surface (AB). When the surface deforms or changes its location (to A'B') speckles appear to shift in the x direction. The corresponding displacement, u, is related to the out-of-plane displacement, w, by[18],

$$w = \frac{-u}{\tan\alpha + \tan\beta} \qquad (1)$$

Although both α and β vary from point to point, the sum of their tangents is constant, and w is linearly proportional to u over the full field.

In shadow speckle metrology, the original and displaced speckle patterns are separately recorded. When digital methods are applied to correlate these patterns both the magnitude and direction of $\underline{w}$ can be computed from Equation (1), since one measures the vector displacement $\underline{u}$ (as opposed to shadow moire, or optical processing of a doubly-exposed specklegram, where the moire and Young's fringes, respectively, establish the magnitude but not the sign of the out-of-plane displacement vector).

Remote Shadow Speckle Metrology

In the case of remote shadow speckle metrology speckles are projected and recorded through fiber optics. These tools can be used to transmit both amplitude and phase information, and are beginning to play an important role in experimental mechanics[17,23,24].

In general, light can be forced to travel through a thin glass fiber whose cross section and optical properties are designed based on the phenomenon of total internal reflection. Individual fibers cannot transmit images but several thousand fibers can be collected into a bundle. A real image, focused on the entrance end of the bundle, can be transmitted provided that the relative orientation of each fiber in the bundle is maintained throughout its length. In this case, the bundle is classified as coherent (i.e. "coherent" refers only to the ability of a bundle to transmit an image and not to the property of the light transmitted through it). Each fiber transmits a different amount of light and the image at the exit end is composed of discrete components of varying intensity.

There are two obvious advantages of using fiber optics in shadow speckle metrology. The first is that optical fibers are flexible and environmentally less-sensitive elements that can be used to project speckles onto a potentially remote test surface. The second advantage is the capability of transmitting images of the initial and displaced speckle patterns from the vicinity of that object back to another location where they can be photoelectronically recorded and analyzed for deflection.

Experimental

Figure 2 shows one method for implementing remote shadow speckle metrology. An unexpanded laser beam is directed through a lens to illuminate a diffuser. This produces an objective speckle pattern on the entrance end of a 10 mm diameter coherent bundle (composed from hundreds of thousands of individual 12 micron diameter step-index fibers).

Speckles could have been produced on the end of the fiber in many different ways, for example, using a 35mm slide splattered with black paint, by lightly spraypainting and illuminating the end of the bundle, or backlighting a transparency covered with speckles in direct contact with the end of the bundle. The method using objective laser speckles, however, allows speckle size to be easily changed by moving the entrance end of the bundle relative to the diffuser. More importantly, the surface is illuminated with coherent light which can be used to make other types of measurements (using holographic interferometry, in-plane speckle photography, etc.). The potential of such combinations are currently under investigation and will be reported in the future.

The image of the speckle pattern is transmitted to the exit end of the bundle where a microlens is used to project speckles onto the object. Each of the projected speckle contains secondary speckle patterns caused by laser illumination and modal interaction created within each fiber of the bundle.

A second microlens is used to focus a real image of the test surface (covered by the projected speckles) onto the entrance end of the imaging bundle. The image is transmitted to the exit end which is rotated until the movements observed in the object plane correspond to those observed directly on the exit end of the bundle. In the present study, the smaller secondary speckles produced by the coherent illumination (as opposed to the larger speckles projected on the surface) are below the resolution limit of the bundle and will not be transmitted to the recording system. Prior research indicates that speckles must be at least three times the diameter of the individual fibers in the bundle[6]; in this case, speckles would have to be at least 33 microns in diameter. Images can be transmitted without concern for the mechanical stability of the bundle, since only amplitude information is of interest (as opposed to holographic recording, for example, where phase is required).

To illustrate this approach, a 7.62 cm diameter circular disk loaded at the center and clamped around its boundary was positioned in the optical set-up shown in Figure 2 so that speckles were projected at approximately 45 degrees with respect to the surface normal. Observations were made normal to the surface using an imaging bundle. The advantage of this optical configuration is that the magnitude and sign determined for $\underline{u}$ is equal to that of $\underline{w}$ [α and β are equal to -45 and 0 degrees, respectively in Equation (1)].

Two images were individually digitized and stored using the photoelectronic-numerical system shown in Figure 3. These corresponded to the initial flat surface (undeformed) and its displaced counterpart deformed by loading the disk so that the center point moved 1.103 mm toward the observer.

Each image was stored in an LSI 11/23 computer as a digital array of 256x256 pixels, each of which was assigned a grey level ranging from 0 to 255. Ordinary correlation techniques (with Lagrangian weighting for interpixel interpolation) were applied to selected subsets of the pattern to measure the apparent in-plane displacement 'u' (parallel to the x direction) in terms of column shift. The latter was converted to milimeters using a calibration factor of 0.481 columns/mm (the system magnification), and Equation (1) was applied to determine the out-of-plane displacement 'w'. Figure 4 shows the experimentally measured values (labeled as x's) obtained along the horizontal centerline of the disk (extending from column 50 to 208). These values are in excellent agreement with the theoretical solution shown by the solid line on Figure 4.

Conclusion

This work has demonstrated the potential for measuring deflections on a remote object by projecting a random speckle pattern onto its surface and recording that pattern through a fiber optic system. Digital image processing and computer analysis determine both the magnitude and sign of the out-of-plane displacement, the method relies on a relatively simple set-up, and tests can be conducted in ambient light.

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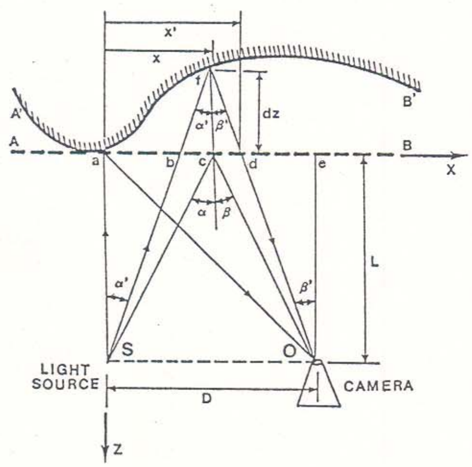


Figure 1 - Analysis of shadow speckle metrology.

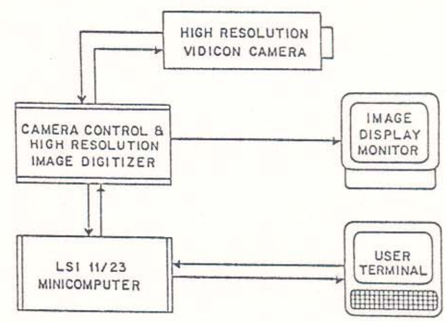
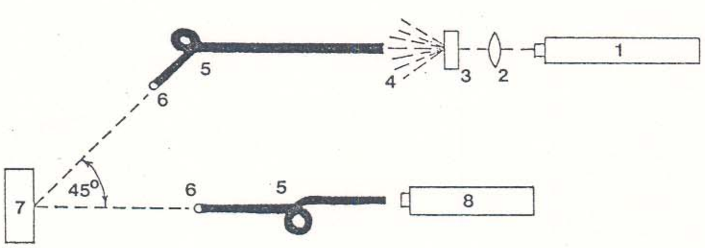


Figure 2 - Photoelectronic-numerical processing system.



1. laser
2. lens
3. diffuser
4. objective speckle
5. coherent bundle
6. microlens
7. specimen
8. vidicon camera

Figure 3 - Remote shadow speckle set-up.

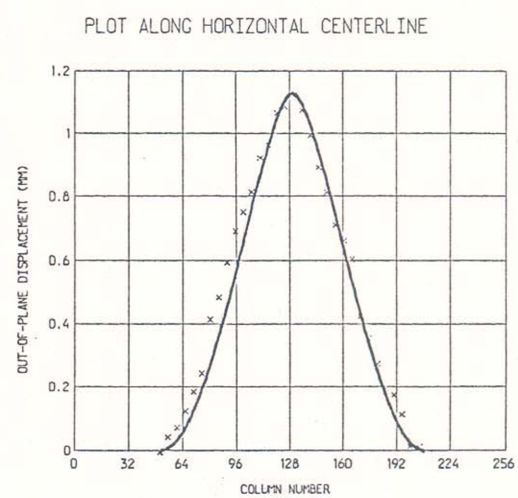


Figure 4 - Displacement for a circular disk loaded at the center and clamped around its boundary (x's represent experimental values; the solid line is the theoretical solution).