Shadow speckle metrology

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A computer-based method is developed to measure the out-of-plane motion of a surface which might arise, for example, from the deflection of a structural component or as a result of contouring a 3-D surface with respect to a reference plane. Artificial speckles are projected onto the test surface using an ordinary 35-mm projector equipped with a clear glass slide sprayed with black paint. Speckle patterns are digitally recorded as the surface changes its shape, and the apparent in-plane movements of the projected speckle are computed over the full field by numerically correlating small subsets extracted from each pattern. These shifts are related to the deflection of the surface with respect to its initial location.

I. Introduction

A. General

Prior research in speckle metrology has demonstrated that artificial speckles (generated by spraying white paint on a dark surface or dark paint on a white surface) can be recorded in discrete form by sampling the light intensity of the image as one of many grey levels (usually from 0 to 255). These subjective speckles (as opposed to objective laser speckles cast into 3-D space) are localized on the surface and move along with it when the surface is deformed. Small subsets taken from the speckle field can be compared before and after deformation to establish surface displacement. For example, Gilbert et al. and Dudderar and Gilbert have used ordinary correlations of systematic pairings of intensity samples from correlatable digitized speckle patterns to make remote measurements (through fiber-optic systems as opposed to direct recording using a vidicon camera system) of simple motions to within pixel accuracy. More recent applications to hybrid analysis by Matthys et al. incorporate Lagrangian weight functions for interpolating between pixels. Peters and Ranson and Chu et al. have also developed numerical correlation routines for speckle metrology. They have evaluated complex deformation fields for directly recorded and digitized subjective speckle data using a surface fit and bilinear interpolation techniques. Subsequent improvements were made with the help of Wolters and McNeil.

Prior investigations involving photoelectronic-numerical data processing of artificial speckles dealt with subjective speckles either painted on the surface or generated by natural surface texture. Speckle movements were directly related to the in-plane displacement of the test surface. In the present study, however, speckles are projected onto the surface using an ordinary 35-mm projector equipped with a clear glass slide spray painted with black paint. The dark spots (or shadows) cast on the surface create a speckle pattern which shifts as the surface moves away from its reference position, and these shifts are related to the deflection.

In an earlier paper one of the authors noted that each area of an artificial speckle pattern is equivalent to a collection of linear gratings of random orientation whose spacings depend on speckle density. A similar analogy can be drawn between shadow speckle and shadow moire.

The shadow moire method is one of the simplest optical techniques to measure out-of-plane displacement. In general, 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 moiré pattern (representing the topology of the surface) is created when the two gratings are observed by eye and/or recorded with a camera. Shadow moire 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, 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 and 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 and/or rotational mismatches must be introduced. In many cases, optical filtering is required to enhance fringe contrast.

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

B. Nomenclature

dx, dz lateral shifts parallel to x and z, respectively;
n fringe-order number;
p pitch;
x, y Cartesian coordinates;
x', y' apparent coordinates (including perspective effects);
u, w displacement components along x and z, respectively;
D distance between light source and camera;
L distance between recording system and surface;
α, β' sensitivity angles.

II. Analysis

The standard analysis used for shadow moire 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 an initial surface (AB) using a 35-mm projector equipped with a clear glass slide sprayed with black paint. Without loss of generality, we can assume that point a remains stationary when the surface deforms or changes its location (to A'B'). In this case, the projected speckle remains in the same location when viewed from point O. Points between a and f, however, experience an out-of-plane movement dz (measured parallel to the z axis shown in Fig. 1). The projected speckle pattern appears to shift along the x axis as it falls on the displaced surface. The lateral shift dx can be determined by digitally correlating the speckles contained in region ad of the initial pattern with those in region ab, as projected onto af. That is, a speckle originally located at point b moves through an apparent in-plane displacement dx to point d. From geometry,

\[ dx = dz (\tan \alpha' + \tan \beta') \]  

The quantities dx and dz can be related to the scalar components of displacement u and w (measured along the positive x and z directions) as follows:

\[ u = dx \text{ and } w = -dz. \]  

Substituting Eq. (2) into Eq. (1),

\[ w = \frac{-u}{\tan \alpha' + \tan \beta'}. \]  

But

\[ dz = \frac{dx}{L + dx} = \frac{dx(L + dz)}{D}, \]  

where D is the distance separating the light source and camera, and L is the distance from the initial position of the surface. Equation (4) can be simplified to

\[ dz = \frac{dx}{L}. \]  

If the experimental arrangement is such that

\[ D \gg dx \]  

and noting that

\[ D/L = \tan \alpha + \tan \beta, \]  

where α and β are as shown in Fig. 1, Eq. (5) can be simplified to

\[ dx = \frac{dx}{\tan \alpha + \tan \beta}. \]  

Using Eq. (2)

\[ w = \frac{-u}{\tan \alpha + \tan \beta}. \]  

Although both α and β vary form point to point, the sum of their tangents is constant [see Eq. (7)], and w is linearly proportional to u over the full field.

The perspective effect of the coordinates can be corrected for a large structure by noting that

\[ \frac{x' - x}{dz} = \frac{D - x'}{L} \]  

or
Fig. 2. Shadow moire: (a) grating projected on a circular disk; (b) moire pattern for rotation around the vertical center line.

\[ x = x' + \frac{w}{L} (D - x'), \]

where \( x' \) and \( x \) are the apparent and real coordinates, respectively. Similarly,

\[ y = y' + (w/L)(D - y'). \]

III. Experimental

The flat surface of a 9.05-cm diam circular disk was illuminated at 26.5° (\( \alpha \)) with respect to its normal using a 35-mm projector and two slides, one having a linear grating with a pitch \( p \) equal to 0.085 mm, the other sprayed with different size black spots. Figures 2(a) and 3(a) show the initial grating and speckle pattern, respectively, as observed normal to the surface at \( \beta = 0 \). The disk was rotated 14° around its vertical center line (parallel to the y axis of the system shown in Fig. 1). The moire pattern shown in Fig. 2(b) (generated by projecting the line grating) resulted when the deformed grating was superimposed on the reference grating. This pattern was optically filtered and analyzed using

\[ w = \frac{np}{\tan \alpha + \tan \beta}, \]

where angles \( \alpha \) and \( \beta \) are defined in Fig. 1 (\( \alpha = 26.5°, \beta = 0 \) in this investigation), \( p \) is the pitch of the reference grating as projected onto the surface (0.86 mm), and \( n \) is the fringe-order number. Since both the direction of rotation and location of the rotation axis were known, absolute fringe orders were determined.

Figure 3(b), on the other hand, shows the superposition of the initial and deformed speckle patterns. This specklegram could be analyzed by passing a thin ray of coherent light through selected points. The speckle in the illuminated area of the specklegram causes light to be diffracted into a halo about the primary ray, and provided that movement is greater than one speckle diameter and that the speckles remain correlated with one another, interference effects between the first and second exposures create parallel equispaced fringes in the halo. The diffraction pattern is the product of the diffraction halo due to a single speckle pattern and the intensity distribution generated by two point sources spread at the same distance as the image shift. Fringes are oriented perpendicular to the direction of motion of the image and have a spacing inversely proportional to the magnitude of the displacement. The authors plan to apply this pointwise analysis to shadow specklegrams using digitization methods developed in Ref. 12. It should be stressed, however, that movement between exposures must be greater than one speckle diameter to obtain fringes in the diffraction halo. This restriction imposes a limitation on the sensitivity of the method. However, it has been demonstrated that a photoelectronic-numerical system can be used to measure surface displacements of less than one speckle diameter if the intensity distributions of the initial and deformed speckle patterns are individually recorded using a system similar to that shown in Fig. 4. This approach has been applied in the present study.

Each image was stored in an LSI 11/23 computer as a digital array of 256 × 256 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 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 millimeters using a...
calibration factor of 1.625 columns/mm (the system magnification), and Eq. (9) was applied to determine the corresponding out-of-plane motion \( w \). Both the magnitude and direction of \( w \) can be computed from Eq. (9), since absolute values are known for \( u \). Although the test surface extended from columns 59 through 203, the eleven-pixel wide window used for the interpolation gave results for \( u \) to within five pixels of these boundaries. Thus Fig. 5 shows the results obtained from the shadow speckle technique for columns 64 through 198 (established using digital correlation and labeled X) along with those from the shadow moire pattern (recorded by double exposure and labeled O). The solid line represents the theoretical solution.

The shadow speckle technique was used to contour the test object shown in Fig. 6. A flat surface (used as a reference and located along plane AB in Fig. 6) was positioned in the optical setup shown in Fig. 1 with its normal along the angle bisector of the illumination and observation directions (\( \alpha \) and \( \beta \) equal to 13.5\(^\circ\)). The speckle pattern projected on this reference plane was recorded using the system shown in Fig. 4 with a system magnification of 1.36 columns/mm. The flat surface was replaced by the test surface, and the displaced speckle pattern was recorded. Figure 7 shows the theoretical and test results for the deflection plotted as a function of column position. Overall, a close match is obtained between the theoretical and test results. However, the data seem to indicate that the test surface was inaccurately positioned with respect to the reference plane. Moreover, the approach is suspect between columns 112 and 140 (as compared to the rest of the results). This is attributed to the fact that speckles become very distorted in this region (the test surface rapidly recedes) and that the intensity of light scattered from this deformed section is very low. Fortunately, the computer gives an indication that it has trouble in that region. Figure 8 shows a plot of the maximum correlation coefficients evaluated for subsets centered at various column locations (displacements are based on this number; a value of 1.0 represents a perfect match). Relatively low values are observed between columns 112 and 140.
Future work will expand the capabilities of the shadow speckle technique by incorporating fiber-optic components into the recording system. This approach could be used to monitor deflections from a remote site in air-, land-, and sea-based vehicles under in situ conditions or to measure displacements in inaccessible locations, perhaps within the human body.

IV. Conclusion

A computer-based method has been developed to measure both the magnitude and direction of the out-of-plane displacement vector associated with surface movement. The method relies on a relatively simple setup, and tests can be conducted in ambient light.

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References


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dynamic laws can often be deduced in some detail, and they exhibit practically the entire gamut of possible nonlinear behavior, e.g., temporal oscillation, multistability, hysteresis, spatial pattern formation, and aperiodic behavior that is likely deterministic chaos. All of this is done in a way often interpretable using basic ideas from the theory of bifurcations in nonlinear differential equations.

This volume reports the Proceedings of the Third Conference on Nonlinear Dynamics in Chemical Systems ably organized by the CNRS laboratory and Paul Pascal-Domain University in Bordeaux. The preceding two conferences and their published proceedings have contributed heavily to the recognition of the importance of nonlinear dynamics in chemistry, its relationship to other fields, and understanding the chemical systems themselves. This third volume will continue that tradition.

Its contents are organized into seven logical sections: (1) General Introduction; (2) Oscillating Reactions and Modeling Problems; (3) Spatial Structures and Chemical Waves; (4) Chemical Chaos; (5) Noise Effects; (6) Stochastic Analysis; and (7) Posters. The last section contains short descriptions of a large variety of ongoing research activity on problems in nonlinear dynamics. Each of the sections is introduced by a 10-15-page plenary lecture, all of which are remarkably successful in giving a good overview of the subject. Each plenary lecture is followed by 3-9 shorter reports (5-6 pages) of specific research results. The coverage is about evenly divided between theory and experiment.

This book is highly recommended (especially at the low price resulting from the use of a camera-ready format) to any person with an interest in any of the areas in which nonlinear dynamics plays a fundamental role.

RICHARD J. FIELD


This is an excellent book. It is about graphing in science and engineering and contains graphic methods and principles that can be powerful tools for showing the structure of data. Thus it helps the analyst to understand the data and to communicate those data to others. The author, at AT&T Bell Laboratories, has had the advice of colleagues and the help of the scientific literature in providing useful illustrative graphs as examples and subjects for improvement. The information in the graphs is interesting enough itself, ranging from a predicted model’s drop in temperature following a nuclear exchange, to speakers of the various world languages, to the fraction of space devoted to graphs in 57 scientific journals, to the number of compositions of 45 composers played on WCN over 2-month period, to a comparison of stocks, private bonds, and public bonds values with time.

A few comments from the text. A divided bar chart always can be replaced by a graphic method that requires only position judgments . . . Area, volume, and angle judgments are subject to bias . . . Acuter angles are underestimated, and obtuse angles are overestimated . . . Should the zero always be shown in the scales? Often not when differences are important . . . Scales do not have to be linear; showing data on a logarithmic scale can improve resolution.

There was a controversy in the 1920s between the advocates of pie and divided bar charts. The author comments that it was a tie; other graphs perform far better than either.

The author makes his greatest contribution in trying to analyze various kinds of data to find the best method of presenting that data graphically for the most meaningful form, that is, to tailoring the graph to fit the data. In short, this is a well-organized and useful book for anyone who would like to present data in useful graphic form.

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