Numerical Correlation of Remote Objective Speckle Patterns for Displacement Measurement

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ABSTRACT

Remote objective speckle photography utilizes a single mode optical fiber to illuminate a small surface area with laser light. This coherent illumination creates a three dimensional speckle field, a sample of which is transmitted through a coherent multimode optical fiber bundle into a vidicon camera system where it is digitized and stored in the computer as numerical data. Surface displacements are measured by numerically comparing digitized speckle patterns which correspond to different positions of the surface. In this study, the effect of changes in various operating parameters on the numerical correlation routine are described.

1. Introduction

In the conventional ROS (or remote objective speckle) measurement system a single mode optical fiber (SMF) is used to illuminate a small area of the test surface with light from a laser. This coherent illumination creates a three dimensional speckle field in the region surrounding the illuminated surface area. A portion of this speckle field is captured by and transmitted through a coherent multimode fiber bundle (MMB) from which it is then focused into a vidicon camera/digitizer system. This system digitizes the speckle pattern intensity distribution and stores it in a computer as numerical data. Since the objective speckle field moves in response to surface motions, digitized original and displaced speckle patterns are then correlated numerically to measure surface displacement. Previous publications describe these processes of numerical digitization[1–3] and correlation.[4]

Recently, many other investigators have also begun to apply photo-electronic digitization systems and numerical correlation techniques to experimental mechanics. For example, Voloshin and Burger[5] have synthesized photoelasticity and image analysis procedures to evaluate the stress intensity factors for near surface cracks. In this technique, the isochromatic fringe field surrounding the crack is digitized in real time, and its intensity distribution is used to determine the fractional fringe orders at points near the crack. Using this information, stress intensity factors are readily computed. Another application by Nutting, Peters, and Ranson[6] utilizes a computer-based data acquisition system to record data associated with the slow crack growth phenomena in plexiglass. In this system, video images of a slowly advancing crack are digitized and stored in a computer at set increments of time. The digitized images yield crack speed-time data and the subsequent incorporation of load data produces a stress intensity factor - crack speed curve. Finally, Chu, Peters, Ranson, and Sutton[7,8] have developed a digital correlation method for rigid body mechanics. This technique is significant because it allows the measurement of two-dimensional displacements of a body. In this method, white light speckle photographs record different positions of a moving body and are subsequently digitized. These digital images are then correlated using the "least squares" method, and bilinear interpolation is employed to increase accuracy. The resulting correlation coefficients are used to determine the two-dimensional rigid body motion.

In the present study, emphasis is placed on investigating the use of a conventional numerical correlation routine for use with fiber optic objective speckle. These include studies of the effects of variations in the size, distribution and resolution (of both intensity and position) of the correlation data samples taken from the digitized speckle fields.

2. The Effect of Varying the Spacing of the Vertical Columns Digitized and Analyzed

The vidicon camera/digitizer system used in these experiments is capable of digitizing a rectangular array 256 scanlines (rows) high by 1024 columns wide. In real space, the rectangular array is approximately square, such that one scanline

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width approximates four column widths. The effect of varying the spacing of the digitized columns, which partially determines the spatial resolution of the system, was investigated using the simplified experimental set-up shown in Figure 1a with the MMB observation distance fixed at $z = 457.2$mm. A normally incident collimated laser beam was used to illuminate an approximately 3mm diameter spot on the test surface. Every column of the central 400 columns was digitized for five horizontal positions of the test surface ranging from 0.000mm to 1.270mm. These 100 scanline by 400 column (every column digitized) files formed the full data base for this initial investigation. Subsets of these files were taken by selecting every second column to produce the 100 scanline by 200 column (every second column digitized) files. This process was repeated twice more to produce the 100 scanline by 100 column (every fourth column digitized) files and the 100 scanline by 50 column (every eighth column digitized) files.

The size of the correlation sample or window was also varied in order to keep the real space size of the correlation window the same for all trials. The height of the correlation window was fixed at 21 scanlines, while the width of the correlation window was varied to include fewer columns in the window at the lower digitizing densities. This kept the physical view of all windows the same, but involved more detail in the higher density trials. A 21 by 80 correlation window should have been used for trial A, but was reduced to 21 by 45 to keep the number of window elements from exceeding the limit of 1000 required by the correlation routine.

For all four trials, the differential displacements were correlated in various combinations to measure four in-plane displacements ranging from 0.127mm to 1.270mm. Using the appropriate field calibration, column shifts were converted to measured displacements. These results indicated that the spacing of the digitized columns should be chosen as every second or every fourth of the available columns. Surprisingly, when every column was digitized and analyzed to yield high correlation values the displacement measurements were the least accurate! Apparently this was so because the associated correlation curves were very rough, exhibiting large local variations in correlation coefficient (see Figure 2a) and frequently yielding inaccurate numerical correlation maxima. The large amount of detail in this trial appears to render the correlation routine overly sensitive to slight differences between the initial and final speckle pattern, thereby enhancing any noise or filter effects. A 21 scanline by 80 column correlation window might improve the displacement measurement accuracy at high column densities, but the time required to perform the correlation would become significant. As the digitized column density was decreased, the maximum correlation values also decreased while the correlation curves became smoother (see Figure 2b). This effect is beneficial in the trials at 2 and 4 columns spacing as they both produced accurate displacement measurements at all but the largest displacements. In the final trial, however, the further decrease in column density yielded further decreases in the correlation maxima and inaccurate displacement measurements which were probably due to a broadening of the correlation peak, while the loss of detail associated with digitizing only every eighth column resulted in a direct loss of resolution.

3. The Effects of Varying the Characteristic Speckle Width

The characteristic speckle width, $\hat{\sigma}$,* is a measure of the speckle width of greatest occurrence in the speckle pattern. The effect of various $\hat{\sigma}$'s on numerical correlation were investigated using the experimental set-up shown in Figure 1b. Lenses positioned between the SMF and the test surface provided collimated illumination beams of various diameters giving a range of illuminated spot sizes. By combining various spot sizes, D, and observation distances, z, five different $\hat{\sigma}$'s ranging from less than 0.01mm to almost 0.36mm were evaluated. For all five trials, speckle patterns for various horizontal positions of the test surface from 0.0mm to 1.524mm were digitized. These were correlated in various combinations to yield differential displacements from 0.127mm to 1.270mm. Using the appropriate field calibration for each trial, the measured column shifts were converted to displacements, averaged, and are shown, along with the averaged maximum correlation values, in Table 1.

It is evident from Table 1 that the value of $\hat{\sigma}$ does affect the measuring accuracy. For the smallest speckle, $\hat{\sigma} = 0.0099$, $S = 0.90$,** the displacement measurements were frequently wrong and the numerical correlations were characterized by consistently low maximum coefficients. In this case, $\hat{\sigma}$ was smaller than the diameter of the individual fibers in the MMB and, therefore, the resolution limit of the MMB. This contributed significantly to the errors found in this run. The runs at $S = 1.8$ also yielded low correlation maxima but produced accurate displacement measurements between 0.127mm and

* $\hat{\sigma} \cong \frac{1.2\lambda z}{D}$

** S the normalized characteristic speckle width, computed by dividing $\hat{\sigma}$ by individual fiber diameter, 0.011mm.

0.762mm. The next series of runs produced accurate displacement measurements over the full range using a $\hat{\sigma}$ which was roughly eight times the diameter of a fiber in the MMB. Displacements between 0.254mm to 1.270mm were measured with a less than one-percent error. The runs at S = 16.2 also yielded high maximum correlation values and accurate displacement measurements ranging from 0.254mm to 1.016mm. Finally, the runs at S = 32.4 also gave high correlation maxima, but significantly less accurate displacement measurements. In conclusion, it would appear that for the present system $\hat{\sigma}$ should be kept between two and 16 times the diameter of a single fiber in the MMB, but as close to eight fiber diameters as possible for the most accurate measurement over the greatest range of displacement.

4. The Effects of Varying the Resolution of Illumination Intensity

One of the strengths of the ordinary correlation technique is that it is very robust. This robustness was demonstrated by examining what happens to the correlation distribution when the intensity resolution is reduced. The vidicon camera digitizes the light intensity at each point in terms of an integer number between 0 and 255, so that the speckle patterns contain up to 256 total intensity levels and have high intensity resolution. A reduction in this resolution would decrease the memory needed for storage, which would be advantageous so long as the measured line shift at maximum correlation remained unaffected.

In order to numerically correlate comparable speckle patterns with more limited intensity levels, a set of speckle patterns was chosen from a single "bright" data set at $\hat{\sigma} \cong 0.148$mm, S = 13.5 which correlated well using all 256 intensity levels. Other data sets, with smaller ranges in intensity, were then created from the original patterns by compacting the original data using a simple software routine. This procedure insured that the only variable in the experiment was the resolution of illumination intensities used to describe the speckle pattern. Five different ranges of intensity levels, (256, 16, 8, 4 and 2) were generated for these trials and the resulting speckle pattern pairs were correlated over a range of displacements from 0.127mm to 1.016mm. Using a calibration factor of 0.02072mm/column, the measured column shifts were converted to displacements and compared with the imposed values. Averaged values of the numerical correlation maxima and the error magnitudes, taken from these trials, are shown in Table 2.

As might be expected, decreases in the resolution of intensities caused decreases in the values of the averaged correlation maxima, which fell from 0.661 to 0.431 as the resolution was decreased. However, the accuracy remained well within ±2% right down to 8 levels, and only at the minimum displacement (0.127mm) did the 4 level trial error exceed that range. The reduction to two levels, however, reduced the range of accurate measurements by about half.

If the number of intensity levels were reduced to 4, for which little loss in accuracy would be experienced, two major benefits could be expected. On one hand the cost of system hardware might be reduced by choosing a camera/digitizer system of significantly lower intensity resolution and sophistication, while significantly reducing the number of bits of memory needed to store a speckle pattern. A 256 level intensity scale (from 0 to 255) requires eight bits or one byte of memory to store all possible numbers ($255_{10} = 11111111_2$), whereas a 4 level intensity scale (from 0 to 3) requires only two bits of memory ($3_{10} = 11_2$). Therefore, in a strict sense, the memory requirement needed to digitize with a resolution of 4 intensity levels is one quarter of that needed when 256 levels are used. This reduction in required memory could be implemented using a "two-bit" microcomputer. A more practical scheme, however, would be to store four digitized points of any 4 level intensity pattern in each eight bit memory location and then transfer to the VAX for decomposition and analysis.

5. The Effects of Varying the Absolute Illumination Intensity of the Speckle Pattern

In order to determine the effect that absolute illumination intensity has on the correlateability of the speckle patterns, an experimental set-up similar to Figure 1b was constructed with the MMB oriented normal to the surface at a distance of 203.2mm. An unlensed SMF (NA = 0.101) was used to illuminate a spot of diameter D = 1.600mm. Five different illumination intensities were investigated. On a numerical scale of zero to 255, average intensities varied from 29.5 to 202.2. The average values for all trials appear in Table 3.

For each trial, three different speckle patterns were digitized corresponding to surface positions at 0.0000mm, 0.0254mm, and 0.0000mm again. These patterns were then correlated to measure three displacements of 0.0000mm, 0.0254mm, and -0.0245mm. The displacement -0.0254mm was measured by correlating the 0.0254mm final pattern with the second 0.0000 pattern. For all trials, a calibration factor of 0.000770mm/column was used to convert column shifts to measured displacements, and the results are also shown in Table 3.

It appears that changing the absolute illumination intensity has little effect on the accuracy of displacement measurements. As shown in Table 5, the displacement measurements were reasonably accurate for almost all the trials. The most accurate measurements were made in the third trial at an average intensity of 90.4. All other trials also produced acceptable results, though the maximum correlation values found in trials at the maximum and minimum average intensities were somewhat lower.

Other differential displacements were correlated to simulate the effect of a change in absolute illumination intensity between the final and initial speckle pattern. In this experiment, 0.000mm displacements from all the trials were correlated with the 0.000mm displacement of the third trial. Also, the 0.000mm displacements of the brightest and darkest trials were correlated. In every case the results fell within 0.0016mm or better for all trials, which was quite acceptable.

6. Conclusions

1. Varying the spacing of the vertical columns digitized has limited effect on the accuracy of displacement measurements. The past practice of digitizing every fourth column is acceptable.
2. Speckle patterns of medium speckle size correlate most accurately. The shape of the correlation curve varies with the size of the predominant speckle width in the patterns correlated.
3. The range, or resolution, of intensity levels used in the digitizing process could be reduced to 4 without significant loss of measuring accuracy. This would reduce both the sensitivity requirements of the digitizing hardware, and the file size needed to store the digitized speckle patterns.
4. Varying the absolute intensity of a speckle pattern has little effect on the accuracy of displacement measurement, although the most accurate results are obtained by using a medium intensity.
5. Substantial (~four fold) differences in absolute intensity between two speckle patterns to be correlated will not significantly decrease the accuracy of the measured displacement.

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Table 1 - Numerical Correlations and Measuring Errors for Various Characteristic Speckle Widths Averaged Over Six Displacements*

Speckle Size $\hat{\sigma}$ mm	S**	Averaged Correlation Maxima	Averaged Error Magnitude %	Percent of Range With ±2.5% Error
0.0099	0.9	0.179	161.6	17
0.0199	1.8	0.245	7.8	66
0.0892	8.1	0.539	0.9	100
0.1784	16.2	0.718	16.0	66
0.3568	32.36	0.5925	28.9	17

* The imposed displacements were 0.127mm, 0.254mm, 0.508mm, 1.016mm and 1.270mm.

** S is the normalized characteristic speckle width computed by dividing $\hat{\sigma}$ by the individual fiber diameter, 0.011mm.

Table 2 - Numerical Correlations and Measuring Errors for Various Resolutions of Illumination Intensity Averaged Over Eight Displacements*

Number of Intensity Levels	Averaged Correlation Maxima	Averaged Error Magnitude %	Percent of Range Within ±2% Error
256	0.661	0.76	100%
16	0.650	0.85	100%
8	0.620	0.86	100%
4	0.542	1.24	88%
2	0.431	9.22	50%

* The imposed displacements were 0.127mm, 0.254mm, 0.381mm, 0.508mm, 0.635mm, 0.762mm, 0.889mm and 1.016mm.

Table 3 - Numerical Correlations for Various Absolute Illumination Intensities

Averaged Intensity	Given Disp. (mm)	Meas. Disp. (mm)	Error (%)	Correlation Maxima
202.2	0.0000 0.0254 -0.0254	0.0000 0.0250 (-)0.0554	0.00 1.53 118.50	0.679 0.472 0.403
148.2	0.0000 0.0254 -0.0254	0.0000770 0.0267 (-)0.0264	- 5.74 4.23	0.920 0.746 0.711
90.4	0.0000 0.0254 -0.0254	0.0000 0.0252 (-)0.0252	0.00 0.62 0.62	0.901 0.712 0.709
63.3	0.0000 0.0254 -0.0254	0.000154 0.0262 (-)0.0267	- 2.72 5.14	0.723 0.724 0.745
29.5	0.0000 0.0254 -0.0254	0.0000 0.0269 (-)0.0264	0.00 5.75 3.63	0.825 0.704 0.624

For all trials: $z = 203.2$mm, $D = 1.600$mm, and $NA = 0.101$

Calibration = 0.000770mm/column

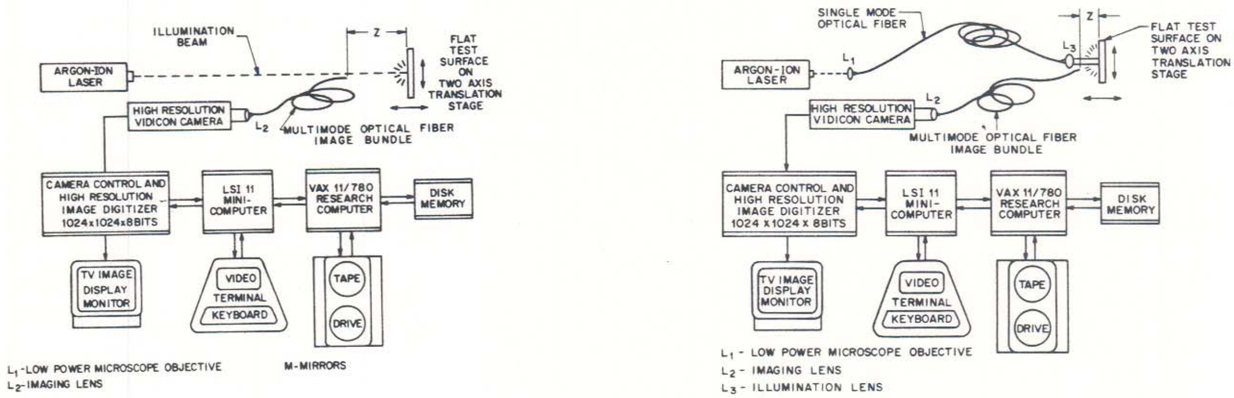

Fig. 1. Experimental set-up using:
a) collimated illumination
b) SMF illumination

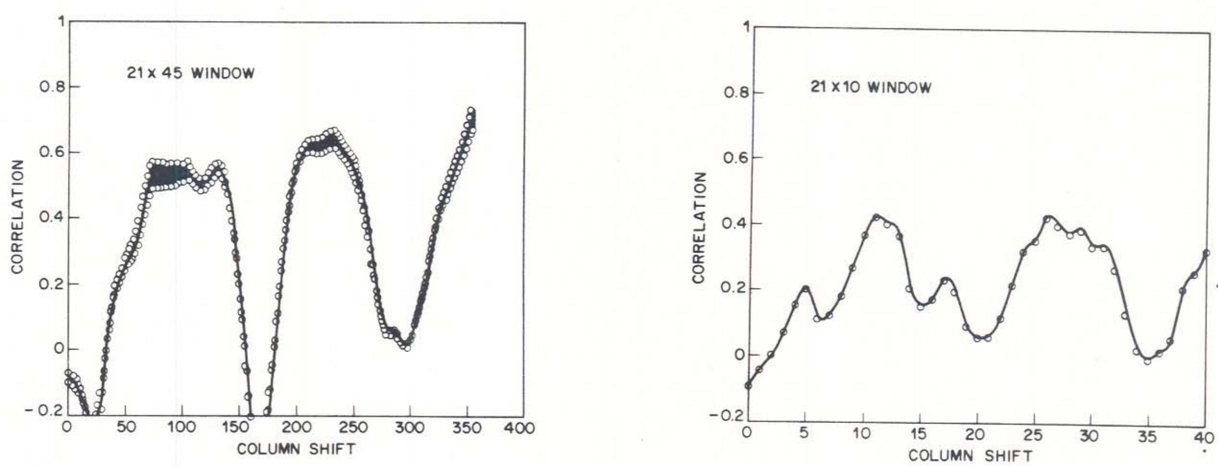

Fig. 2. Correlation plots for a displacement of 0.381mm where;
a) every column digitized is correlated
b) every eighth column digitized is correlated