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Measurement of Out-of-plane Dynamic Deformations by Digital Speckle Pattern Interferometry

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ABSTRACT

In this paper, measurement of dynamic deformations in a rectangular plate fixed at one end, using digital speckle pattern interferometry (DSPI), has been presented. To improve the measurement accuracy, a new filtering scheme has been developed. This scheme is based on the combination of average/median filtering and Symlet wavelet filtering which enhances the signal-to-noise ratio in the speckle interferogram obtained from the DSPI. Experimental results show that this filtering scheme is quite effective in improving signal-to-noise ratio of the speckle interferogram. The measurements by DSPI and accelerometer are in good agreement. The DSPI technique can be implemented for measuring the large deformations as well.

Keywords: Digital speckle pattern interferometry, dynamic deformations, large deformations, signal-to-noise ratio, histogram equalisation, Symlet wavelet, Daubechies wavelet, phase filter, wavelet filter, minimum-phase filter

NOMENCLATURE

I_o	Intensity of object wavefront
I_r	Intensity of reference wavefront
$I_1(x,y,t)$	Time-dependent intensity in the first frame
$I_1(x,y)$	Time-average intensity recorded in the first frame
$I_2(x,y)$	Time-average intensity recorded in the second frame
$I(x,y)$	$I_1(x,y) - I_2(x,y)$
ϕ_r	Phase of reference beam
ϕ_o	Phase of the object beam
w_o	Amplitude of vibration
γ	Geometric factor
τ	Frame period
ω	Frequency of vibration
$\Delta\phi$	Additional phase difference introduced between the two frames
J_0	Zero-order Bessel function
ξ	Periodicity
$m_0(\xi)$	Moment
h_n	Scaling filter
W	Wavelet coefficient

1. INTRODUCTION

Analysis of vibrations by theoretical methods[1,2] for complex profile components made of an anisotropic material is time-consuming and difficult. Also, theoretical results differ significantly from actual experimental results in the cases where boundary conditions are not clearly defined. Under these circumstances,

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one has to rely on measurement tools. Accelerometers are commonly used for measuring frequency and amplitude of vibrations at a point of interest, but the main disadvantage of using accelerometer is that it has to be in contact with the component adds weight on the component and sometimes there is noticeable change in stiffness of the component. Digital speckle-pattern interferometry (DSPI)[3-9] has emerged as a powerful non-contact-type, full-field inspection tool for measuring/monitoring of vibrations in the laboratory as well as in the industry. In DSPI, a speckle pattern is formed by illuminating the surface of the object by a laser beam. The object wave is imaged on the photosensitive part of the CCD camera, where it is made to interfere with an in-line reference light wave. The interferograms of two different states of the object are grabbed and subtracted. The speckle correlation fringes are displayed on the computer, using digital techniques. The subtraction process eliminates the constant speckle noise introduced due to environment which improves the signal-to-noise ratio (SNR) in the fringe pattern. The high frequency speckle noise, however, cannot be removed by mere subtraction. Several methods have been employed to reduce the high frequency speckle noise to further enhance the SNR in the speckle interferogram[10-17]. Recently, it has been investigated that Symlet wavelet filtering in combination with average/median filtering substantially improves the SNR in DSPI interferograms[18-21]. Also, it preserves details of the object and is more effective at the edges of the fringes.

In this paper, a filtering scheme has been presented for processing DSPI fringes and implementing the same to measure the out-of-plane dynamic deformations in a rectangular plate fixed at one end and free at the other end.

2. THEORY

2.1 Out-of-plane Dynamic Deformation Analysis

A schematic of DSPI setup for measurement of out-of-plane or transverse vibrations is shown in Fig. 1. Let one assume that the frequency of vibration of the plate is much more than the frame rate of the CCD camera used to record image of the object. Under this assumption, in a single exposure, the intensity is averaged over the frame period[7] τ and is given by

$$I_o(x,y,t) = I_o + I_r + 2\sqrt{I_o I_r} \times \frac{1}{\tau}\int_\tau \cos\left[\left(\frac{2\pi}{\lambda}\right)\gamma\, w_o + (\phi_o - \phi_r) \right] dt \tag{1}$$

where I_o and I_r are the intensities of object and reference wavefront, respectively, ϕ_r is the phase of reference beam, ϕ_o is the phase of the object beam, w_o is the amplitude of vibration of the object, and γ is geometric factor which depends both on the angle of illumination and the angle of observation.

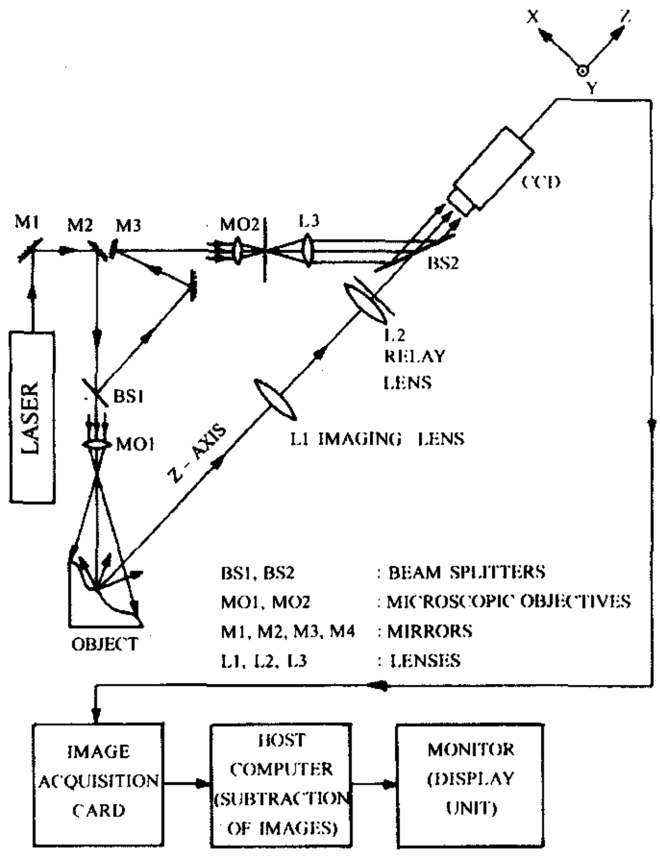

Figure 1. Experimental setup of digital speckle pattern interferometry for measuring out-of-plane dynamic deformations/vibrations.

Assuming the object is vibrating harmonically with a frequency ω, the time-average intensity is given as

$$I_1(x,y) = I_o + I_r + 2\sqrt{I_o I_r}\cos(\phi_o - \phi_r) \times J_0[(2\pi/\lambda)\gamma\, w_o] \quad (2)$$

where, J_0 is a zero-order Bessel function. If in the second exposure an additional phase difference of $\Delta\phi$ is introduced between the object and reference wave fronts, the intensity in the second recording is written as

$$I_2(x,y) = I_o + I_r + 2\sqrt{I_o I_r}\cos[(\phi_o - \phi_r) + \Delta\phi] \times J_0[(2\pi/\lambda)\gamma\, w_o] \quad (3)$$

If two time-averaged speckle interferograms are subtracted, the intensity is given by

$$I(x,y) = I_2(x,y) - I_1(x,y) = 2\sqrt{I_o I_r}\,|\,J_0[(2\pi/\lambda)\gamma\, w_o]\,| \times |\cos[(\phi_o - \phi_r) + \Delta\phi] - \cos(\phi_o - \phi_r)| \quad (4)$$

If the phase difference between two successive frames is π, the above equation is modified to

$$I(x,y) = 4\sqrt{I_o I_r}\,|\,J_0[(2\pi/\lambda)\gamma\, w_o]\,| \times |\cos(\phi_o - \phi_r)| \quad (5)$$

The term $|\cos(\phi_o - \phi_r)|$ represents phase-dependent high frequency speckle information[8,9]. The Bessel function J_0 spatially modulates brightness of the speckle pattern.

2.2 Filtering Scheme

The DSPI fringe pattern has inherent speckle noise. Presence of undesired bright speckles in the area of dark fringes, and similarly, the dark speckles in the area of bright fringes bring inaccuracy in measurement from speckle interferogram. Depending on the level of speckle noise present in the speckle interferogram, preprocessing is done by the average or median filtering to remove some of the speckle noise and to make the speckle interferogram smoother.

To further improve the SNR, wavelet filtering is implemented. Wavelets are new families of orthonormal basis functions, which do not require to have infinite duration. When wavelet decomposition function is dilated, it accesses lower-frequency information, and when contracted, it accesses higher-frequency information. It is computationally efficient and provides significant speckle reduction while maintaining the sharp features in the image[17,22,23]. Daubechies analysed[22] the phase of the haar wavelet. The phase of the haar wavelet has discontinuity at π. The Daubechies wavelet (dbN) is a minimum-phase filter. However, more symmetric wavelet filters make it easier to deal with the boundaries of the image. The phase introduced by Symlet wavelet filter is closer to linear phase than that of the dbN. The Symlets are compactly supported wavelets with least asymmetry and higher number of vanishing moments for a given support width. Associated scaling filters are near-linear phase filters having support width $2N$-1 and filter length $2N$. To make a filter close to symmetric, the idea is then to juggle with its phase so that it is almost linear. The idea consists of reusing the function m_0(where, $m_0 = \frac{1}{\sqrt{2}}\sum_n h_n e^{-in\xi}$, h being the kernel filter) introduced in the wavelet dbN, considering the $|m_0(\xi)|^2$ as function of W of $z = e^{i\xi}$. One can factor W in several ways in the form of $W(z) = U(z)\overline{U(1/z)}$. The roots of W with modulus not equal to one, goes in pairs. If one is z, then $1/z$ is also a root. By selecting U such that the modulus of all its roots is strictly less than one, dbN are built. The U filter is a minimum phase filter. By making another choice, one can obtain more symmetrical filters[20,22,23]. These symmetrical filters are Symlets.

3. EXPERIMENT & RESULTS

The DSPI setup for recording the fringe patterns of the out-of-plane dynamic deformations of the rectangular plate is shown in Fig. 1. A beam of 30 mW

He-Ne laser of wavelength 632.8 nm was split into two beams by a beam splitter (BS1). One of the beams illuminated the surface of the rectangular plate under study and the other beam was used as the reference beam. The value of γ for the experimental setup was 1.938. The object beam was combined with the reference beam to form a speckle interferogram that was converted into a video signal by the CCD camera. The video analog output from HTC-550B/W CCD camera was fed to the PC-based image processing system developed using National Instrument's IMAQ PCI-1408 card. LabVIEW 5.0-based program[24] in graphical programming language was developed to acquire, process, and display the speckle interferogram. The program implements the accumulated linear histogram equalisation after subtraction of the interferograms. The histogram equalisation alters the gray-level value of the pixels. It transforms the gray-level values of the pixels of an image to evenly occupy the entire range (0 to 255 in an 8-bit image) of the histogram, increasing the contrast of the image. The pixels out of range were set to zero[24]. The IMAQ PCI-1408 card was set to process the images of interferogram at the rate 30 images/s. One time-average interferogram of the vibrating plate over the frame acquisition period (1/30 s) was grabbed and stored as a reference speckle inteferogram. The successive time-averaged interferograms are subtracted from reference interferogram continuously and displayed on the computer screen. Experiments were conducted on a vibrating rectangular plate fixed at one end and free at the other end. Dimensions of the plate were 110 mm × 53 mm × 3 mm (Fig. 2). Cyclic load for study of the vibrations was applied at the free end. A large number of experiments were conducted for enhancement of SNR in the image of the fringe pattern using Symlet wavelet filtering. The experiments show that Symlet wavelet filtering significantly removes speckle noise from the interferogram. Before filtering by Symlet wavelet, preprocessing of speckle image was done. It was observed that if SNR in the recorded fringe pattern is moderate, preprocessing of the image by average filtering is effective. If the SNR in the recorded fringe pattern is low, preprocessing of the image by median filtering is effective.

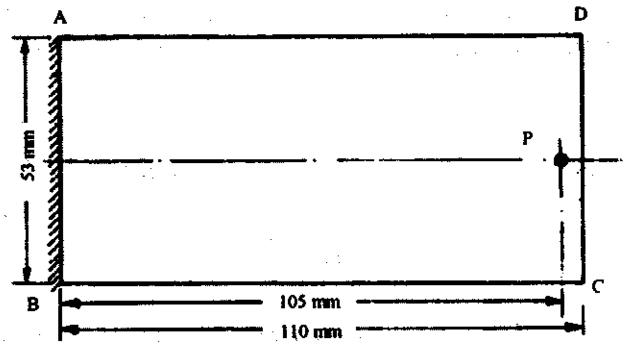

Figure 2. Sketch of a 110 mm × 53 mm × 3 mm rectangular plate fixed at one end and free at the other end.

A large number of vibration fringes were recorded for rectangular plate at different frequencies. Figure 3(a) shows a typical vibration fringe pattern of the rectangular plate when exited by a sinusoidal load of 4.045×10^{-3} N at 1.471 kHz. The load is applied at point P. The excitation is produced by the combination of function generator, amplifier, and model exciter. The fringe pattern covers 96 mm length of the rectangular plate from the fixed end.

Figure 3(a). A typical fringe pattern of vibrating rectangular plate when exited by a sinusoidal load of 4.045×10^{-3} N at 1.471 kHz.

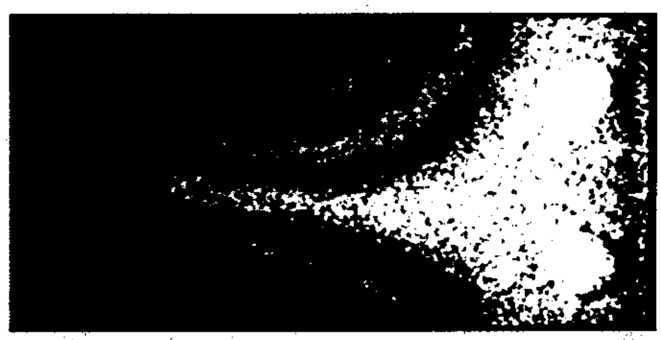

Figure 3(b). Filtered image of fringe pattern shown in Fig. 3(a) by average filtering followed by Symlet wavelet filtering.

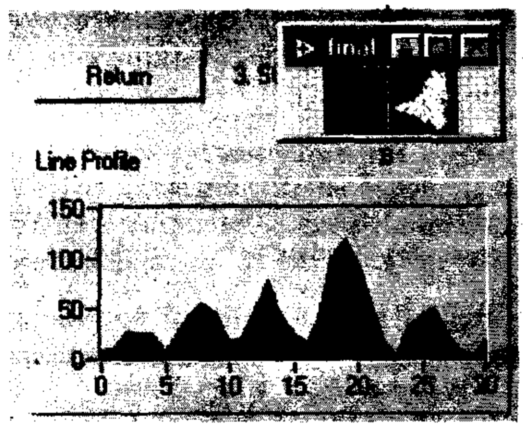

Figure 4. Line profile of fringe pattern shown in Fig. 3(b).

When average four filtering followed by Symlet wavelet is implemented on the fringe pattern shown in Fig. 3(a), filtering results are shown in Fig. 3(b). Vibration amplitude is calculated for the filtered fringe pattern shown in Fig. 3(b). Calculations for amplitude of vibration along the line AB on the fringe pattern [shown in Fig. 3(b)] are done using fringe width measured from the line profile (shown in Fig. 4) and Eqn (5).

Points on the maximum intensity fringe have zero amplitude. On both the sides of the maximum intensity fringe, points on the second and the third maximum intensity fringes have vibration amplitudes 0.20238 μm and 0.36325 μm, respectively. Data for amplitude along the length and the breadth of the cantilever is generated from the speckle interferogram shown in Fig. 3(b). Surface profile of deformed plate at a particular instant of time drawn for the interferogram [Fig. 3(b)] is shown in Fig. 5.

The frequency and the amplitude at different points on the surface of the plate are measured by piezoelectric accelerometer (model No. 4374 DELTA SHEAR® accelerometer manufactured by Brüel & Kjær, Denmark). The variation in results for amplitude obtained from the accelerometer and the experimental data from the fringe pattern is less than 0.06 μm which may be due to the charge sensitivity of the accelerometer. If the fringes are thin and the position of accelerometer is not truly represented by a point, small deviation in both the results may occur. Mounting of the accelerometer may also influence the results.

4. DISCUSSION & CONCLUSION

Experimental investigations reveal that the DSPI can be effectively used to monitor/measure vibrations of components. Accuracy of measurement is increased

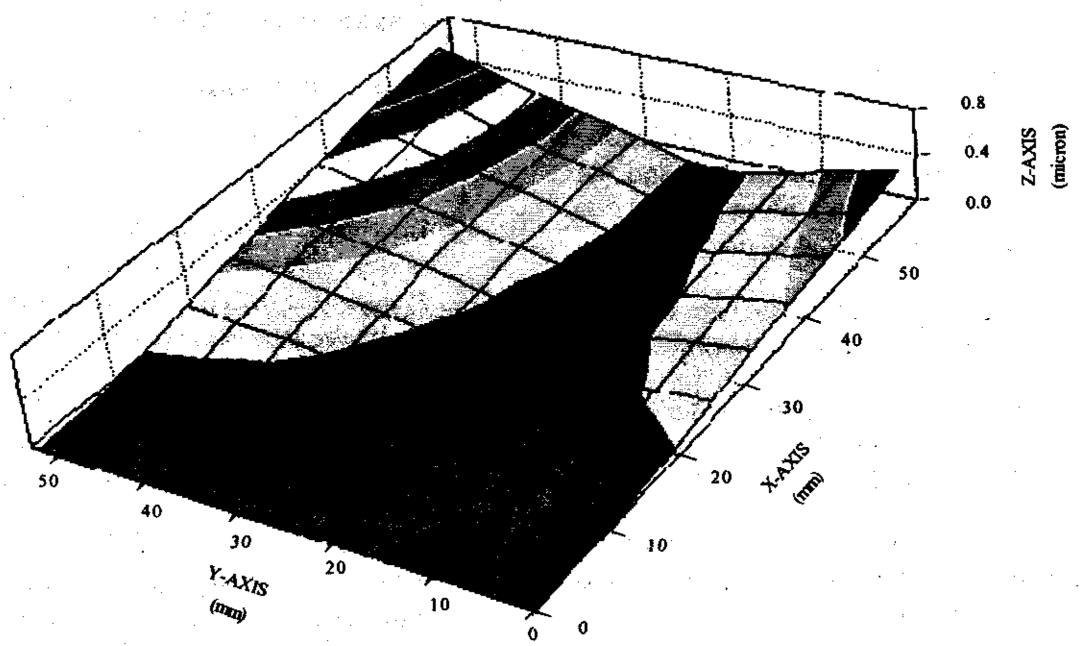

Figure 5. Surface profile for fringe pattern shown in Fig. 3(b)

by reducing speckle noise and improving the SNR in the DSPI fringes. From the experimental results it appears that in the condition when the noise in the speckle interferogram is moderate, the combination of average filtering and Symlet wavelet filtering is effective, and in the condition when the noise in the speckle interferogram is more, the combination of median filtering and Symlet wavelet filtering is more effective. The variation in values of measurement obtained from the filtered speckle interferogram and the value of measurement obtained from the accelerometer is less than 0.06 μm. The DSPI technique can be implemented for measurement of large deformations. This real-time full-field deformation measurement technique has large number of applications in industry for non-destructive evaluation of the components. In the present form, the experimental setup cannot give information about the direction of motion. However, the phase-shifting method can be implemented to know the direction of motion.

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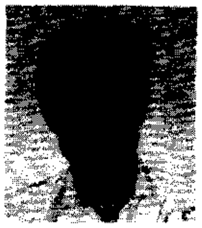

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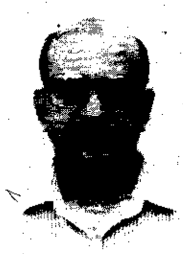

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