Wavelet filtering applied to time-average digital speckle pattern interferometry fringes

Rajesh Kumar, Shashi Kumar Singh, Chandra Shakher*

Laser Applications and Holography Laboratory, Instrument Design Development Centre, Indian Institute of Technology Delhi, New Delhi - 110 016, India

Received 27 March 2001; received in revised form 25 June 2001; accepted 24 July 2001

Abstract

In this paper we are presenting a filtering scheme using Symlet wavelet to remove the speckle noise from the time-averaged digital speckle pattern interferometry fringes. To demonstrate the potential of Symlet wavelet filtering, experiments are conducted to remove the speckle noise from the fringes recorded for the surface of computer hard disk. Experimental results demonstrate that this filtering removes the speckle noise to the large extent.

Keywords: Digital speckle pattern interferometry; Vibration; Contrast; Histogram equalization; Symlet wavelet

1. Introduction

There are several optical techniques available as a non-invasive tool for measurement/monitoring of vibration. Conventional holographic interferometry, due to higher sensitivity and other limitations is difficult to use in hostile industrial environment. Digital speckle pattern interferometry (DSPI) is a simplification of the conventional holographic/speckle technique and can be implemented with high processing speed [1–4]. In DSPI, a digital equivalent of developing, fixing and displaying the hologram can be accomplished at video rate. Due to this reason, DSPI is considered to be more suitable for on-line measurement in laboratory as well as in industry. DSPI system has been used to study static deformation, strain, stress, in-plane and out-of-plane vibration, thermal expansion, and temperature gradient, etc. in the mechanical components [4–16]. Due to presence of speckles, time-average DSPI fringes have inherent noise. Several methods have been demonstrated to improve the quality of DSPI fringes [5–9]. Kauffmann and Galizzi have used Daubechies (db) wavelet filtering to reduce speckle noise in computer generated speckle correlation fringes [17]. But the db wavelet is not much effective at the edges of the fringes [9,18,19]. Our investigations show that to remove speckle noise in DSPI fringes a filtering scheme using Symlet wavelet is more suitable. The Symlet wavelet, which is a linear phase filter, is more effective at the edges of the fringes in comparison to Daubechies wavelet [18,19]. Above mentioned filtering scheme to remove the speckle noise is implemented on the time-averaged DSPI fringes recorded for the surface of the casing of computer hard disk.

2. Mathematical analysis of time-average DSPI and description of wavelet filtering

In single exposure, when vibration frequency is much greater than the frame rate of CCD camera, intensity is averaged over the frame period τ and is given by [20]

\[ I(x, y) = A_0^2 + A_r^2 + 2A_0A_r \cos[(2\pi/\lambda)(\alpha(x, y, t) + \phi_0 - \phi_x)] \tau, \]

(1)

where \( A_0, A_r \) are the electric field amplitudes of the object and reference beams respectively; \( \phi \) is phase of reference beam and \( \phi_0 \) is a position dependent phase of the object beam which corresponds to the original state of the object; \( \alpha(x, y, t) \) is position dependent out-of-plane displacement of the object relative to some reference position at time \( \tau \); \( y \) is
geometric factor which depends on the angle of illumination and angle of observation.

If the vibration in the computer hard disk is harmonic due to excitation of its motor then for harmonic frequency \(\omega\), the time-average intensity is written as

\[
I(x, y) = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_0 - \phi_1)
\]

\[
J_0[(2\pi/\lambda)y a_0(x, y)],
\]

(2)

where, \(a_0(x, y)\) is phase dependent out-of-plane displacement of harmonically vibrating object related to some reference position and \(J_0\) is a zero order Bessel function.

Time average subtraction technique eliminates the background intensity \(A_1^2 + A_2^2\), which results in image quality improvement. The result is

\[
I(x, y) = 2A_1A_2\left[J_0[(2\pi/\lambda)y a_0(x, y)] \right] \cos[2(\phi_0 + \phi_1) + t]
\]

(3)

The term \(\cos[2(\phi_0 + \phi_1)]\) represents phase dependent high frequency speckle information [20,21]. The Bessel function \(J_0\) represents the modulation, spatially modulating the brightness of the speckle pattern. The fringe contrast at higher vibration amplitude is reduced significantly with time-average method. The classical way to remove noise and restore some of the lost contrast is to use digital N-look averaging/look transform.

Arsenault and April demonstrated that when image intensity is integrated with finite aperture and logarithmically transformed, it can be approximated to Gaussian additive noise [22]. Recently Donoho [23] proposed a wavelet thresholding procedure for recovery of functions from additive Gaussian noisy data. Kaufmann and Galizzi implemented a similar method to reduce speckle noise in TV holography fringes generated by computer. In their work they have used DAUB4 developed by Daubechies [17]. which is specified by only four wavelet filter coefficients. Daubechies introduced scaling function \(\phi(x) = \sqrt{2}\sum_{n}\phi(2x - n)\) for wavelet \(\phi_{n}\) \((\phi_{n}\) are the coefficients associated to a ‘standard’ multiresolution analysis and the corresponding orthonormal basis). However, more symmetric wavelet filters make easier to deal with the boundaries of the image [19]. Symmetric filters are linear phase filters. More precisely, a filter with filter coefficients \(a_{n}\) is called linear phase if the phase of the function \(a(\xi) = \sum_{n} a_{n}e^{-i2\pi n\xi}\) is a linear function of \(\xi\), i.e., if for some \(l \in \mathbb{Z}\), \(a(\xi) = e^{-i2\pi l}a(\xi)\). This means that \(a_{n}\) are symmetric around \(l\). \(a_{n} = a_{-n}\).

The phase introduced by Daubechies for Symlet wavelet is given below

\[
\Phi^1(\xi) = m_{0}(\xi/2)m_{0}(\xi/4)m_{0}(\xi/8)m_{0}(\xi/16)\ldots
\]

\[
= \prod_{j=1}^{\infty}[m_{0}(2^{-j-1}\xi)m_{0}(2^{-j-2}\xi)]
\]

(4)

where \(m_{0}(\xi) = \frac{1}{\sqrt{2}}\sum_{n}\phi_{n}e^{-i2\pi n\xi}\). The phase \(\Phi^1\) of the Symlet wavelet is closer to linear phase [19] than that of \(\phi_{n}\). \(\Phi^1(\xi) = \prod_{j=1}^{\infty}m_{0}(2^{-j}\xi)\).

To reduce speckle noise in the speckle correlation fringes the algorithm begins by evaluating the logarithm of the fringe pattern. Thus we have

\[
\hat{I}(m, n) = \hat{I}_0(m, n) + \hat{S}(m, n)
\]

(5)

where, \(\hat{I} = \ln|I|\), \(I\) being the fringe pattern to be filtered, and \(\hat{I}_0\) is the noise-free fringe pattern, which is contaminated by the speckle noise distributions \(S\).

The different steps of noise reduction method can be mathematically expressed as [17]

\[
\hat{I} = \text{WT}^{-1}\{T_{\delta}\text{WT}\{\hat{I}\}\}
\]

(6)

where, \(\hat{I}\) is the estimate for the noise-free fringe data; \(\text{WT}\) and \(\text{WT}^{-1}\) denote, respectively, the forward and inverse wavelet transform, and \(T_{\delta}\) is a threshold operator, which depends on the parameter \(\delta\).

The selection of the threshold scheme and the threshold \(\delta\) are the most important factors to define the performance of the method. In practice, two approaches are used. The first approach, which is optimal in theory, is soft thresholding defined by

\[
T_{\delta}(W) = \begin{cases} W - \delta & \text{for } W > \delta, \\ 0 & \text{for } -\delta \leq W \leq \delta, \\ W + \delta & \text{for } W < -\delta, \end{cases}
\]

(7)

where, \(W\) is a wavelet coefficient.

The hard threshold scheme is given by

\[
T_{\delta}(W) = \begin{cases} W \text{ if } |W| > \delta, \\ 0 \text{ otherwise.} \end{cases}
\]

(8)

3. Experimental

Fig. 1 show the schematic of the DSPI set-up used to record the vibration pattern of the surface of the casing of the computer hard disk. A beam of 30 mW He-Ne laser of wavelength 632.8 nm is split into two mutually coherent beams by a beam splitter BS1. One of the beams illuminates the vibrating surface of the hard disk (Make: Segate, Model ST3390A) fixed by screws at two opposite sides. The reference beam is spatially filtered and collimated before interference to ensure interference angle close to zero degree. The image wave is combined with the reference wave to form a speckle interferogram that is converted into a video signal by the photoelectric action of the video camera. The video analog output from HTC-550B/W CCIR CCD camera is fed to the PC-based image-processing system developed using National Instrument’s IMAX PCI-1408 card. LabVIEW 5.0 based program [24] in graphical programming language was developed to acquire, process and display the image. The program uses histogram report as an input and then implements accumulated linear histogram equalization after subtraction of time-averaged images. The histogram equalization function is a contrast restoration function. Precision
of the function depends on the number of class intervals used in the histogram. The IMAQ PCI-1408 card is set to process the images at the rate of 30 images/s. One time-averaged image of the object is grabbed and stored as a reference image. The successive time-averaged images are subtracted from reference image continuously and displayed on computer screen. A large number of mode shapes are recorded. Fig. 2(a)–(c) show some of the typical modal patterns of the vibrating surface of the computer hard disk till it stabilizes after the motor is excited.

Wavelets are new families of orthonormal basis functions as described earlier, which do not need to have of 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 [17,25]. As it is shown in Section 2 that Symlet wavelet is the linear phase filter which is more effective at the edges in the image of fringes, we have conducted detailed experiments to see the effect of Symlet wavelet filtering on the time-averaged DSPI fringes. Fig. 3(a)–(c) show the filtering results when Symlet wavelet is implemented on the raw images shown in Fig. 2(a)–(c) respectively. Fig. 4(a)–(c) are the results of filtering scheme when Symlet wavelet is implemented on median filtered image of

Fig. 1. Experimental set-up of DSPI for vibration measurement.

Fig. 2. (a)–(c). Different mode shapes of vibrating surface of computer hard disk.

Fig. 3. (a) Processed fringe patterns obtained by applying Symlet wavelet on the fringe pattern shown in Fig. 2(a). (b) Processed fringe patterns obtained by applying Simlet wavelet on the fringe pattern shown in Fig. 2(b). (c) Processed fringe patterns obtained by applying Simlet wavelet on the fringe pattern shown in Fig. 2(c).
points on the bottom fringe (brightest fringe) in the image of Fig. 4(c) have zero amplitude. Points on the middle and upper fringes in the figure have vibration amplitudes 0.20238 and 0.36235 μm, respectively. Value of the geometric factor for our experimental set-up is 1.938.

4. Discussion and conclusion

The recorded fringe patterns show flexural and some other complex mode shapes of vibration on the surface of the casing of the computer hard disk. From the experimental results it appears that the Symlet wavelet filtering removes speckle noise to the large extent for time-average fringes obtained by DSPI.

Acknowledgements

Financial assistance from Propulsion Panel of Aeronautical Research & Development Board (AR & DB), Government of India is gratefully acknowledged. Rajesh Kumar also wishes to acknowledge the financial assistance from All India Council for Technical Education (AICTE). New Delhi. Authors gratefully acknowledge the comments made by referee to improve the manuscript.

References