Compact holographic optical element-based electronic speckle pattern interferometer for rotation and vibration measurements

Viswanath Bavigadda
Technological University Dublin

Mohesh Moothanchery
Nanyang Technological University, Singapore

Manojit Pramanik
Nanyang Technological University, Singapore

See next page for additional authors

Recommended Citation

Viswanath Bavigadda, Mohesh Moothanchery, Manojit Pramanik, Emilia Mihaylova, Vincent Toal, "Compact holographic optical element-based electronic speckle pattern interferometer for rotation and vibration measurements," Proc. SPIE 10127, Practical Holography XXXI: Materials and Applications, 101270X (6 April 2017); DOI: 10.1117/12.2251266

Authors

Viswanath Bavigadda, Mohesh Moothanchery, Manojit Pramanik, Emilia Mihaylova, and Vincent Toal

Compact holographic optical element-based electronic speckle pattern interferometer for rotation and vibration measurements

Bavigadda, Viswanath; Moothanchery, Mohesh; Pramanik, Manojit; Mihaylova, Emilia; Toal, Vincent

2017

Bavigadda, V., Moothanchery, M., Pramanik, M., Mihaylova, E., & Toal, V. (2017). Compact holographic optical element-based electronic speckle pattern interferometer for rotation and vibration measurements. Proceedings of SPIE - Practical Holography XXXI: Materials and Applications, 10127, 101270X-.

https://hdl.handle.net/10356/80209

https://doi.org/10.1117/12.2251266

Compact holographic optical element-based electronic speckle pattern interferometer for rotation and vibration measurements

Viswanath Bavigadda[a,c], Mohesh Moothanchery[b], Manojit Pramanik[b], Emilia Mihaylova[a,d] and Vincent Toal[a,*]

[a]Centre for Industrial & Engineering Optics, Dublin Institute of Technology, Dublin, Ireland
[b]School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore
[c]European Gravitational Observatory, Cascina PI, Italy
[d]Department of Mathematics, Informatics and Physics, Agricultural University, Plovdiv, Bulgaria

ABSTRACT

An out-of-plane sensitive electronic speckle pattern interferometer (ESPI) using holographic optical elements (HOEs) for studying rotations and vibrations is presented. Phase stepping is implemented by modulating the wavelength of the laser diode in a path length imbalanced interferometer. The time average ESPI method is used for vibration measurements. Some factors influencing the measurements accuracy are reported. Some advantages and limitations of the system are discussed.

Keywords: Holographic optical elements, ESPI, Speckle, Phase stepping

1. INTRODUCTION

Electronic speckle pattern interferometry (ESPI) is a non-contact optical interferometric technique used to study full-field static deformations and vibration.[1-3] Conventional ESPI systems can include expensive bulk optics such as beam splitters, combiners, mirrors etc. The alignment of these components is a critical and time consuming task which needs great care. Use of conventional ESPI systems in an industrial environment is nearly impossible, because these ESPI systems are highly sensitive to environmental vibration. These drawbacks can be overcome by modifying the design of the ESPI system with the introduction of holographic optical elements (HOEs).

Traditionally ESPI systems combining phase stepping methods and an out-of-plane sensitive system configuration[4] were used to measure defects or deformations. In-plane sensitive ESPI system configurations were used to study rotations of objects.[5] In this paper we discuss the analysis of fringes due to rotation obtained using phase shifting that is due to drive current change in a laser diode source. The same HOE based ESPI system was also used for vibration measurements as well.

Lokberg and Hogmoen[6,7] introduced an alternative measurement technique to overcome illumination power reduction observed in stroboscopic ESPI[8] system. This technique was implemented by modulating the optical path difference sinusoidally at the same frequency as that of the object vibration, but with variable amplitude and phase, to map contours of constant amplitude and of constant phase in an unbalanced interferometer. This technique was further extended first by Atcha and Tatam,[9] and later by Olszak and Patorski[10] using fibre-optic based ESPI systems. We extend this measurement technique further by simplifying the ESPI system design using HOEs.

2. THEORY OF FRINGE ANALYSIS

The most common method used for obtaining correlation fringes is the subtraction of two speckle interferograms corresponding to displaced and undisplaced positions of the test object. When a test object is displaced statically, a

* E-mail: vincent.toal@dit.ie

Practical Holography XXXI: Materials and Applications, edited by Hans I. Bjelkhagen, V. Michael Bove, Proc. of SPIE Vol. 10127, 101270X · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2251266

set of phase shifted speckle images are recorded corresponding to the test object in displaced position. To obtain speckle correlation fringes, a reference speckle pattern corresponding to the rest position of the test object is subtracted from the set of phase shifted speckle patterns corresponding to the displaced position of the test object. When a test object vibrates the time average ESPI method is suitable to obtain correlation fringes. In time average ESPI the intensity of the correlation fringe brightness follows a Bessel function distribution. The visibility of the time average Bessel fringe pattern decreases as the amplitude of vibration increases. Therefore the time average Bessel fringes were converted to cosine fringes using stroboscopic illumination from the laser source.[10] As the laser beam energy delivered to object is reduced due to chopping of light in stroboscopic ESPI, an alternative measurement technique called reference beam phase modulation is adopted for current measurements. Theory for both the rotation and vibration fringe patterns obtained using our measurement techniques are outlined in the following subsections.

2.1 Rotation fringe analysis using phase of differences method

A phase of differences method is used for the rotational fringe analysis obtained using HOE based ESPI system. In this method a single image at rest position and four images after object rotation and were recorded to evaluate the static phase.

The intensity distribution of speckle image corresponding to rest position of the test object can be expressed as

$$I_i = I_1 + I_2 + 2\sqrt{I_1 I_2} cos\, \varphi_R \quad (1)$$

I_i is the initial speckle pattern intensity corresponding to the rest position of the test object, I_1 , I_2 are reference and object speckle pattern intensities, φ_R is the phase difference between object and reference beams.

When a point on the object undergoes a small out-of-plane displacement, *d* in the plane of the illuminating beams, the phase difference between them is altered by $\Delta\varphi$ and is

$$\Delta\varphi = \frac{4\pi}{\lambda}\, d \quad (2)$$

The intensity distribution of speckle images corresponding to rotated or displaced positions of the test object images is represented by

$$I_{f,n+1} = I_1 + I_2 + 2\, cos\left(\varphi_R + \Delta\varphi + \frac{2n\pi}{4}\right) \quad (3)$$

where n = 0,1,2,3, $\Delta\varphi$ is the phase difference due to the object displacement.

The resultant subtracted speckle fringe patterns after introducing a phase shift for displaced test object position are expressed as below

$$I'_{f,n+1} = \left| I_{f,n+1} - I_i \right| = 4sin\left(\varphi_R + \frac{\Delta\varphi}{2} + \frac{n\pi}{4}\right) sin\left(\frac{\Delta\varphi}{2} + \frac{n\pi}{4}\right) \quad (4)$$

which represents a fringe pattern having intensity maxima at $\Delta\varphi = (2p+1)\pi$ where p is an integer, and minima at $\Delta\varphi = 2p\pi$, the fringes being modulated by speckle.

A wrapped phase distribution can be obtained from a set of phase shifted speckle correlation fringe patterns as[11]

$$\Delta\varphi = tan^{-1}\left(\frac{I'_4 - I'_2}{I'_1 - I'_3}\right) \quad (5)$$

The wrapped phase map can be unwrapped using several methods and different unwrapping algorithms. Under normal illumination and observation condition, an unwrapped phase is directly related to the out-of-plane displacement as

$$d = \left(\frac{\lambda}{4\pi}\right)\Delta\varphi_u \quad (6)$$

where d = displacement of the test object; $\Delta\varphi_u$= unwrapped phase; λ = wavelength of laser 658 nm.

We use an out-of-plane sensitive HOE based ESPI system, hence an out-of-plane tilt angle δ of the test object can be expressed in terms of number of fringes, p observed in the field of view.[11]

$$\delta = \frac{p\lambda}{L} \quad (7)$$

where p = number of fringes in the field of view, L and λ = wavelength of the laser.

2.2 Vibration time average fringe analysis using phase modulation

The time average ESPI technique is a powerful tool for mapping in-plane and out-of-plane vibration modes of a test object. When a test object vibrates harmonically at a frequency ω, the correlation fringes are obtained using subtraction of two speckle patterns corresponding to displaced and undisplaced positions. Then the brightness at any point of the correlogram is averaged over a time much longer than the period of vibration 2π/ω and has an intensity distribution in the form of a Bessel function. In practice ESPI is used either to measure only in-plane or out-of-plane displacement. For the present theoretical discussion we assume an out-of-plane ESPI system in normal illumination and observation geometry. When a test object vibrates at an angular frequency ω, amplitude a_0 and phase φ_0 then the displacement, a is given by

$$a = a_0 \cos\,(\omega t + \varphi_0) \quad (8)$$

In standard time average ESPI the intensity of the interference pattern at a particular instant is given by[9, 12]

$$I_\tau = I_o + I_r + 2\sqrt{I_o I_r} \cos\,(\psi) J_0\left(\frac{4\pi}{\lambda} a_0\right) \quad (9)$$

where I_τ is the instantaneous value of I. I_o, I_r are the object and reference beam intensities respectively, $\psi(x,y)$ is the phase difference between the object and the reference beams before the object displacement begins.
Consider a second pattern recorded with a phase shift π, and given by

$$I'_\tau = I_o + I_r + 2\sqrt{I_o I_r} \cos\,(\psi + \pi) J_0\left(\frac{4\pi}{\lambda} a_0\right) \quad (10)$$

Following subtraction of Eq. (9) from Eq. (10) we take the absolute values so that the pattern can be displayed on a TV monitor with brightness B given by

$$B = 4\sqrt{I_o I_r}\left| J_0\left(\frac{4\pi}{\lambda} a_0\right) \cos\,(\psi)\right| \quad (11)$$

For heterodyning in the interferometer, the optical path difference, b, is modulated at the same frequency as that of the vibrating object, but with amplitude a_r and phase φ_r, and

$$b = a_r \cos\,(\omega t + \varphi_r) \quad (12)$$

Now Eq. (11) is written as

$$B = 4\sqrt{I_o I_r}\left| J_0\left(\frac{4\pi}{\lambda}\{a_o^2 + a_r^2 - 2a_o a_r \cos\,(\varphi_o - \varphi_r)\}^{1/2}\right) \cos\,(\psi)\right| \quad (13)$$

2.2.1 Reference beam phase modulation

The time average ESPI method provides vibration amplitudes of a test object only. To measure the phase information we need to phase modulate the optical path difference in the interferometer. The resulting fringe pattern is then determined by the relative motion between the object and the phase modulating device. We use laser drive current modulation technique to implement the phase modulation in an unbalanced HOE based ESPI.

The phase difference (ϕ) between the object and reference beams in an unbalanced interferometer with a path length difference $2l$ is

$$\phi = \frac{2\pi}{\lambda}(2l) \tag{14}$$

When the laser wavelength is modulated, the relative phase between the beams changes by

$$\Delta\phi = \frac{4\pi l}{\lambda^2}\left(\frac{d\lambda}{di}\right)\Delta i \tag{15}$$

where i = drive current of the laser diode.
From Eq. 15, the amplitude of the iso-amplitude contours is given by[12]

$$a_r = \frac{2l}{\lambda}\left(\frac{d\lambda}{di}\right)\Delta i \tag{16}$$

As we vary the amplitude of reference beam path modulation in the interferometer by varying the laser diode current, i, the regions where $a_r = a_o$ and $\varphi_r = \varphi_o$, will be displayed with maximum brightness.

3. EXPERIMENTS AND RESULTS

The proposed HOE based ESPI system consists of two HOEs. A reflection holographic optical element (RHOE), provides the reference beam in the interferometer, and a transmission holographic optical element (THOE) provides normal illumination of the test object, making the ESPI system sensitive only to out-of-plane displacement (see, Fig. 2). The set up for recording a reflection HOE is shown in Fig. 1. A polarizing beam splitter (PBS) was used with two half wave plates (HWP1 & 2) to split the laser beam intensity while maintaining vertical polarization states of the two resulting beams. The beam from the laser diode was spatially filtered (SF) and collimated (L1, L2), and used to illuminate a silver halide photographic plate (Geola PFG-03C).

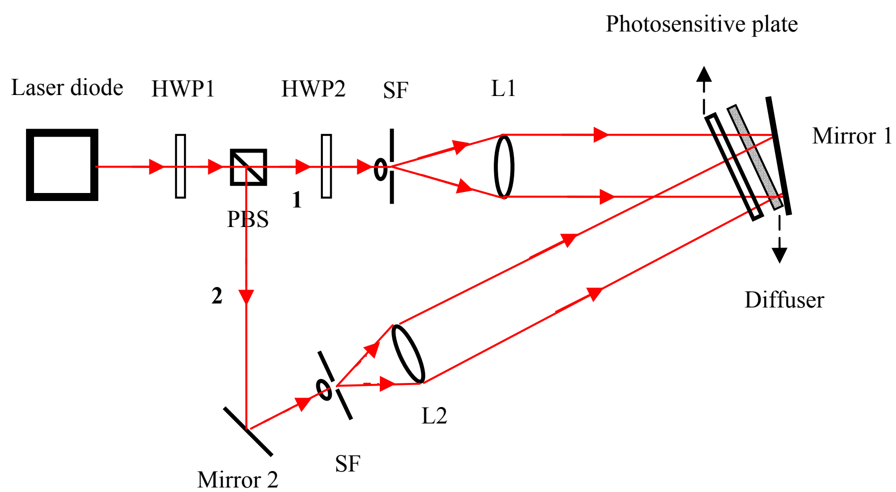


Fig. 1. Recording set-up for HOEs: reflection hologram of a diffuser and a transmission grating.

A ground glass plate was introduced between the mirror and the silver halide emulsion and a reflection hologram of the resulting speckle pattern was recorded whose reconstruction was intended to serve as a reference beam in the ESPI system. The light transmitted by the photographic plate was reflected by the mirror at 30^0 to the surface normal of the photographic plate. The sensitivity of the silver halide layer is 3 mJ/cm^2. The total beam power was about 0.5 mW/cm^2 so the layers were exposed for approximately 6 sec. The holograms were developed using SM-6 developer, followed by bleaching using PBU-Amidol.[13] To record a transmission holographic optical element (THOE), mirror 1 and the diffuser were removed and the intensities of beams 1 and 2 were equalized.

3.1 Results: Rotational fringe analysis

The dual HOE based ESPI system as shown in Fig. 2 was used for measuring both out-of-plane rotation and vibrations of different flat metal plates. The laser beam is spatially filtered (SF) and collimated (CL) to illuminate the RHOE, which generates a speckle reference beam for the ESPI. The same spatial filter and collimator were used as in the recording set up. The beam transmitted by the RHOE illuminates the THOE which diffracts the light to illuminate the test object. An unwanted secondary reflection grating is usually recorded along with the THOE. The two HOEs are held together in a single holder and both are therefore (to avoid specular reflection from THOE) illuminated slightly (~3^0) off-Bragg. The object and reference beams were allowed to interfere on the focal plane of the CMOS camera (AVT Guppy F-032B). This camera with 640×480 pixels was interfaced to a laptop (Dell-Inspiron) using an IEEE1394 firewire port.

In case of rotation measurements, the test object rotation was controlled manually. An aluminium plate of diameter 5 cm and 1 mm thickness, coated with retro-reflective paint (for improving light reflection from the object) was attached to a mirror mount (Newport MFM-100) whose motion was controlled using precision adjusters. The field of view was adjusted to 25 mm by an aperture. The optical path length difference in the interferometer was 13 cm. A virtual instrument developed in LabVIEW 8.2 was used for generating fringe patterns. In our experiments the frame rate of the camera was set at 25 Hz with an external digital pulse which was supplied by the DAC board. The software stores the image and subtracts it from the next subsequent image to display the correlation fringes. Thus the reference for subtraction is updated every 40 ms, so that fringes are not affected by the thermal and mechanical disturbances in the laboratory occurring at frequencies less than about 25 Hz.

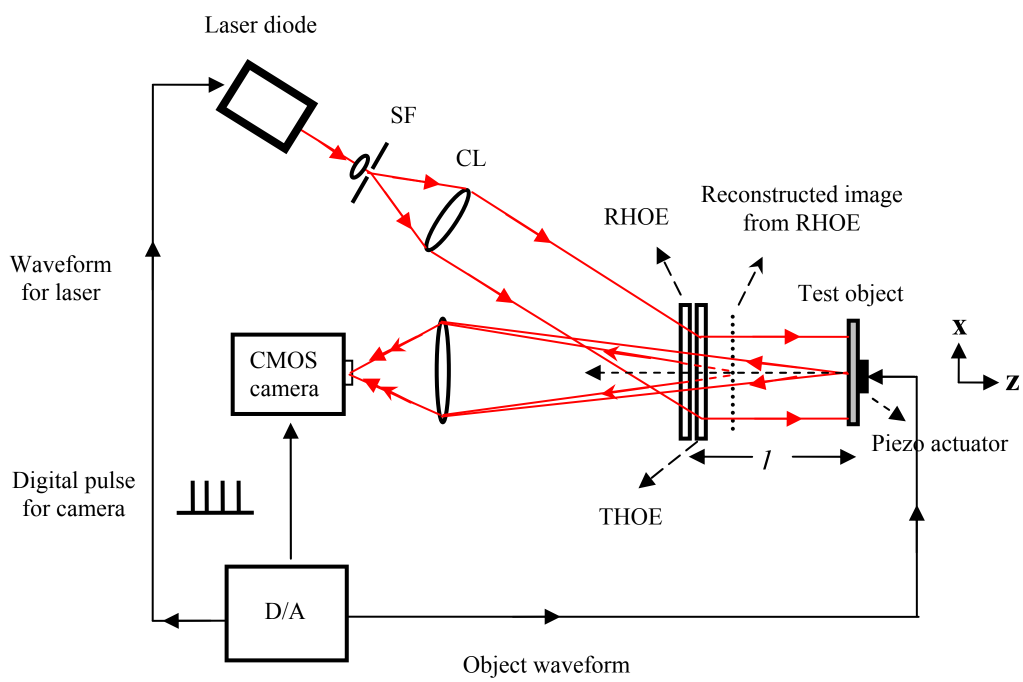


Fig. 2. Out-of-plane sensitive HOE based ESPI system.

The current change (0.6 mA) required for a phase shift of 2π was experimentally determined by measuring a full fringe shift (One full fringe is defined as the replacement one dark or bright fringe by the consecutive one). This current change value was divided into equal increments to obtain four drive current values corresponding to phase shifts of 0^0, 90^0, 180^0, and 270^0. A constant phase shift was then introduced between four consecutive frames by changing the diode laser drive current (Δi=0.15 mA, for 90^0). We have chosen a linear region in laser output power Vs drive current plot for introducing constant phase shifting.[14,15]

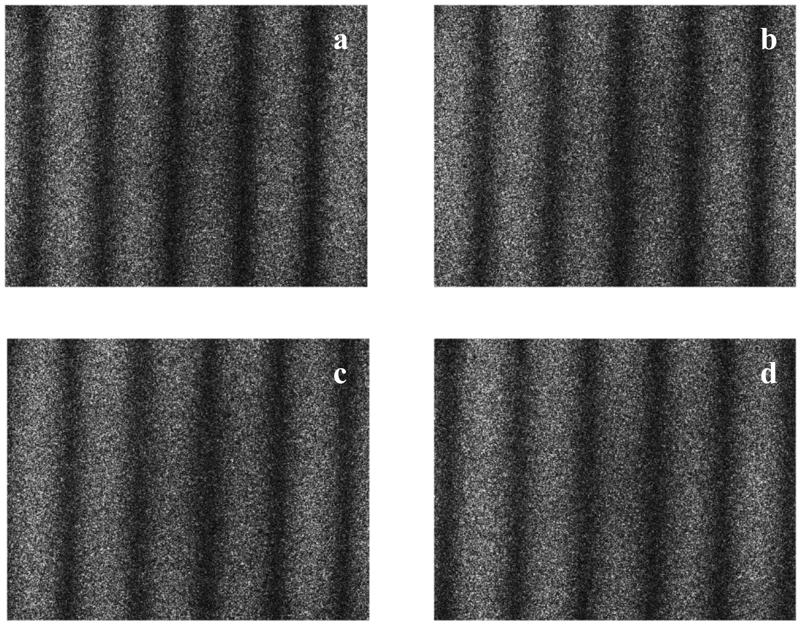
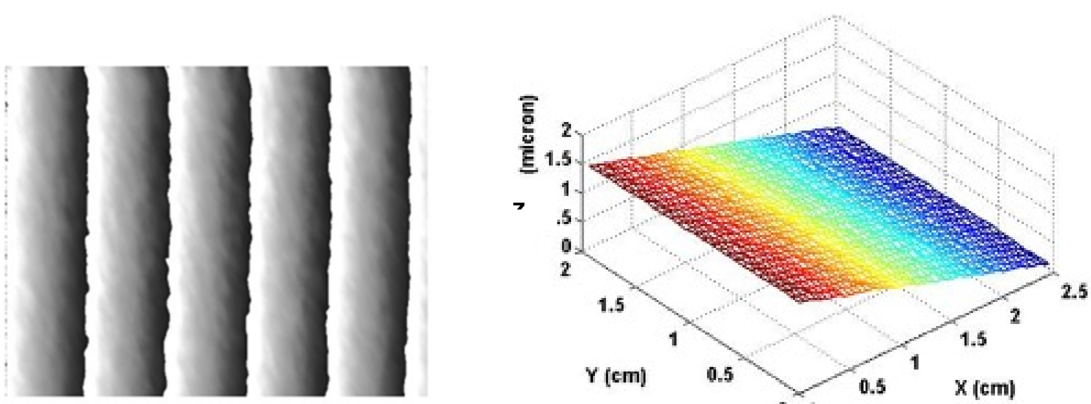


Fig. 3 Phase stepped speckle subtraction fringes (a) 0^0 (b) 90^0 (c) 180^0 (d) 270^0.

Fringe patterns were obtained in the following way. First, a reference speckle pattern was captured while the test object was at rest and without laser current modulation. Then the test object was rotated by 0.13 mrad and a speckle pattern corresponding to displaced object position without laser current modulation was obtained. Then the laser drive current was altered in steps and four phase shifted speckle patterns were obtained. The reference speckle pattern was subtracted from each of these four phase shifted speckle patterns to obtain the fringe patterns shown in Fig. 3.



(a) **(b)**

Fig. 4 Static fringe analysis on a flat specimen: (a) Wrapped phase map, (b) 3-D Displacement map of the flat surface.

The wrapped phase map calculated using Eq. (5) was median filtered with window size 3x3 and is shown in Fig. 4(a). The filtered and wrapped phase is then unwrapped using a multi-grid algorithm,[16] scaled using Eq. (6), and finally a 3-D displacement profile is shown in Fig. 4(b). The rotation or tilt was verified by using a laser pointer beam reflected from a small mirror attached to the rear of the metal plate; the movement of the reflected light was measured. The measured angle for a field of view 2.5 cm, λ = 658nm and M = 5 was approximately 0.14 mrad and this is in agreement with the angle calculated using Eq. (7).

3.2. Vibration fringe phase mapping results

The dual HOE based ESPI system (Fig. 2) was also used to study vibration modes of a square aluminium plate 4 cm×4 cm and 1 mm in thickness. A National Instruments digital to analogue converter (D/A) was used to provide two LabVIEW software controlled sinusoidal waveforms of same frequency but with different amplitude and phase, one to drive a piezoelectric actuator (PZT) attached to the test object and the other to modulate the diode laser drive current. A rectangular pulse (25 Hz) triggered image acquisition by the camera. A rectangular waveform, generated synchronously with the image acquisition pulse, caused the laser drive current to change, producing a phase change of π in the interferometer at the beginning of each frame. Subtraction of the successive π phase shifted speckle interferograms removed the background speckle noise,[12] and the resulting interferogram was displayed with high contrast as shown in Fig. 5.The time average vibration mode pattern was observed at 1406 Hz without path length difference modulation. The bright fringes were moved to the first order by modulating the laser wavelength with $\Delta\lambda = 1.11pm$. From Eq. 15 the amplitude of vibration in the brightest fringe regions in Fig. 5(b) and (c) is 0.4 μm. Fig. 5(c) shows the result when the phase of the path difference modulation was altered by 180^0.

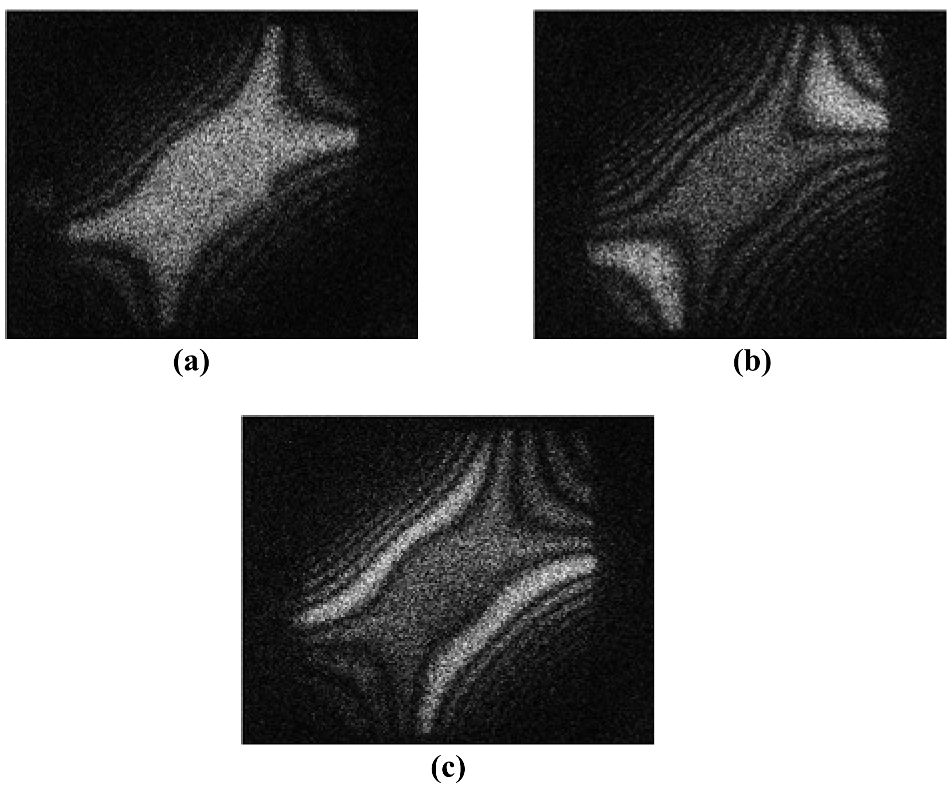


Fig. 5. Square plate vibrating at 1406 Hz: (a) ordinary time average fringes. Time average fringes by modulating the laser wavelength of (b) Δλ=1.11pm (c) Δλ=1.11pm with 180^0 phase shift.

4. DISCUSSION AND CONCLUSIONS

The dual HOE based ESPI system has some limitations. When the object is not flat, then the change in path length difference is different at different positions of the object. This problem can be overcome by first obtaining shape information of the object using two wavelength speckle interferometry.[17] This shape information is used for correcting the displacement data obtained using the ESPI system. While measuring rotations, phase errors may arise from the phase stepping algorithm that was used for calculating the phase map. The phase error is due to wavelength instabilities or inaccuracies in phase shifts. The phase error was calculated using the intensity line profile of the phase shifted fringe patterns (Fig. 3) for a particular pixel and found to be $\pi/10$.[18]

In our experiments a small drift in phase value was noticed across iso-amplitude contours (Fig. 5) when the test object vibrates in a pure mode. This might be due to thermal and mechanical drift present in the interferometer. By adjusting the phase of the path length difference modulation, this variation can be minimized. In our experiments around 2^0-15^0 phase variation in the interferometer was observed. We have demonstrated use of a simple and compact HOE based ESPI system for vibration amplitude and phase measurements. We have also demonstrated it for measuring rotation. The advantage of HOE based ESPI system is that it is easy to align. The phase maps were produced using the reference beam phase modulation method by varying the laser diode drive current, a fast and easily implemented method. The accuracy of the phase measurements depends on the vibration amplitude.

ACKNOWLEDGEMENTS

This work was supported by DIT's Fiosraigh Research Scholarship programme. The authors would like to thank the School of Physics Dublin Institute of Technology and the FOCAS Research Institute for technical support. The authors would also like to acknowledge the financial support from Tier 1 grant funded by the Ministry of Education in Singapore (RG41/14: M4011285). V. Bavigadda thanks Dr. Paul Kumar Upputuri of Nanyang Technological University, Singapore for helping with the phase unwrapping algorithm.

REFERENCES

[1] Upputuri P K, Kalyani Y, Mohan N. K, and Kothiyal M. P., "Time-average TV holography for vibration fringe analysis," Appl. Opt., 48, 3094-3101, (2009).
[2] Upputuri P K, Mohan N. K, and Kothiyal M. P, "Time average vibration fringe analysis using Hilbert transformation," Appl. Opt., 49, 5777-5786, (2010).
[3] Upputuri P K , Mohan N K, and Kothiyal M. P, "Measurement of static and vibrating microsystems using microscopic TV holography" Optik, 122, 49-54, (2011).
[4] Rastogi P K., Editor, [Digital speckle pattern interferometry and related techniques], pp.231, John Wiley and sons Ltd., First edition, (2001)
[5] Jallapuram R, Healy C., Mihaylova E. and Toal V., "In-plane sensitive electronic speckle pattern interferometer using a diffractive holographic optical element," Am. J. Phys. 79, (4), (2011)
[6] Lokberg O. J. and Hogmoen, K., "Use of modulated reference wave in electronic speckle pattern interferometry," J. Phys. E: Sci. Instr. Vol. 9, 847-851, (1976).
[7] Lokberg O. J. and Hogmoen, K., "Vibration phase mapping using electronic speckle pattern interferometry," Appl. Opt. Vol. 15, No. 11, 2701-2704, (1976).
[8] Anderson D.J., Valera, J. D. and Jones, J. D.C., "Electronic speckle pattern interferometry using diode laser stroboscopic illumination," Meas. Sci. Technol., 4, 982-987, (1993).
[9] Atcha H. and Tatam, R. P., "Heterodyning of fibre optic electronic speckle pattern interferometers using laser diode wavelength modulation," Meas. Sci. technol., 5, 704-709, (1994).
[10] Olszak A., Patorski, K., "Modified electronic speckle pattern interferometer with reduced number of elements for vibration analysis," Opt. Comms., 138, 265-269, (1997).
[11] Creath K, "Phase-shifting speckle interferometry," Appl. Opt.24, 3053–3058, (1985).
[12] Bavigadda V., Jallapuram, R., Mihaylova E., Toal V., "Electronic speckle-pattern interferometer using holographic optical elements for vibration measurements," Opt. Lett., 35(19), 3273-3275, (2010).

[13] http://www.geola.lt/lt/holography_materials/chemistry/
[14] Bavigadda V, Jallapuram R, Toal V, Mihaylova E. Vibration phase measurements using holographic optical elements based electronic speckle pattern interferometry. Proc SPIE, 73870E-1-8. (2010)
[15] Bavigadda V., Mihaylova E., Jallapuram R. and Toal V., "Vibration phase mapping using holographic optical element-based electronic speckle pattern interferometry," Opt. Lasers Engng., Vol. 50, No. 8, 1161-1167, (2012)
[16] Tatam R. P., Davies J. C., Buckberry C. H., Jones J. D. C., "Holographic surface contouring using wavelength modulation of laser diodes," Opt. Lasers Technol., Vol. 22, No.5, 317-321, (1990)
[17] Ghiglia D. C. and Pritt M. D, [Two-Dimensional Phase Unwrapping: Theory, Algorithms and Software], Wiley-Interscience, First edition, (1998)
[18] Hariharan P., Oreb B. F. and Eiju T., "Digital phase-shifting interferometry: a simple error-compensating phase calculation algorithm," Appl. Opt. Vol. 26, No. 13, (1987)