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Vibration Phase Measurements using Holographic Optical Elements

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Vibration phase measurements using holographic optical elements based electronic speckle pattern interferometry

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ABSTRACT

The application of an out-of-plane sensitive electronic speckle pattern interferometer (ESPI) using holographic optical element (HOE) to vibration amplitude and phase mapping is reported. The novelty of the proposed system is the use of a speckle reference wave stored in a reflection holographic optical element (HOE). The incorporation of a HOE minimizes the alignment difficulties. The HOE based ESPI system is compact containing only a diode laser, HOE and a digital CMOS camera. The measurement technique is a combination of time averaged ESPI and reference beam phase modulation in an unbalanced interferometer. The reference beam phase modulation is implemented by modulating the drive current of the diode laser. The presented HOE based ESPI system is easy to align and compact and thus suitable for industrial non-destructive testing and vibration analysis.

Keywords: Electronic speckle pattern interferometry (ESPI), Holographic optical element (HOE), Vibration, Amplitude, Phase, Reference beam modulation.

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 consist of expensive bulk optics such as beam splitters, combiners and mirrors etc. The alignment of these components is a critical and time consuming task which needs great care. Use of the 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).

Effectively a group of optical elements is replaced by one or two HOEs. The compact HOE based ESPI system consists of a laser, a HOE, and a CCD/CMOS camera, whose alignment is easy. These ESPI systems will bring optical non-destructive testing within the reach of industry users at affordable cost.

An application of HOE based ESPI system was first reported by Petrov and Lau [4] who described portable ESPI systems used to measure deformations. The systems incorporated HOEs recorded using different holographic recording materials and methods. Our research group also previously reported the use of HOEs in ESPI[5-7] and laser Doppler vibrometry[8]. In the present paper we report the use of a reflection holographic optical element in an ESPI system using reference beam path modulation in a time average ESPI system for the first time.

The most common method used for recording correlation fringes is the subtraction of two interferograms corresponding to displaced and undisplaced positions of the test object. When a test object vibrates at high frequencies (few kilohertz), the time average ESPI method is suitable to obtain correlation fringes. In a time average ESPI the intensity of the correlation fringes follows a Bessel function distribution. When an object is vibrating sinusoidally at high frequency, the motion would be complex, so it is necessary to obtain a phase map. Some attempts were made to convert the Bessel fringes to cosine fringes by use of stroboscopic illumination from the laser source for extraction of the phase map[9]. The stroboscopic illumination can be synchronised with object vibration by using mechanical choppers, Bragg cells or pulsed laser systems. Pulsed laser illumination may be accompanied by reduction in output power depending on the duration of the pulse. Lokberg and Hogmoen[10, 11] introduced a new technique to overcome this problem by modulating the optical

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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[12], and later by Olszak and Patorski[13] using fibre-optic based ESPI systems. We extend this measurement technique further by simplifying the ESPI system design using HOEs.

2. THE MEASUREMENT TECHNIQUE

2.1 Time average ESPI

The time average ESPI technique is a powerful tool for mapping in-plane and out-of-plane vibration modes and for non-destructive testing of dynamic deformations. The camera records a new interferogram every 40ms. These fringe patterns have 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

$$a = a_0 \cos\left(\omega t + \varphi_0\right) \tag{1}$$

In standard time average ESPI the intensity of the interference pattern at a particular instant is given by[14]

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

Consider a second pattern recorded with a phase shift π, and is given by

$$I'_\tau = I_o + I_r + 2\sqrt{I_o I_r}\cos\left(\psi + \pi\right) J_0\left(\frac{4\pi}{\lambda} a_0\right) \tag{3}$$

Following subtraction of Eq. (3) from Eq. (2) we take the absolute values so that the pattern can be displayed on a TV monitor with brightness *B* given by

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

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

$$b = a_r \cos\left(\omega t + \varphi_r\right) \tag{5}$$

Now Eq. (4) is written

$$\mathrm{B} = 4\sqrt{I_o I_r}\left| J_0\left(\frac{4\pi}{\lambda}\left\{a_0^2 + a_r^2 - 2a_0 a_r \cos\left(\varphi_0 - \varphi_r\right)\right\}^{1/2}\right)\cos\left(\psi\right)\right| \tag{6}$$

We have not implemented filtering of high spatial frequency variations in the speckle pattern represented by the $\cos\left(\psi\right)$ term. The noise caused by speckle pattern can be minimised by implementing a low-pass filter to replace $\cos\left(\psi\right)$ with its averaged value. The low-pass filter can be designed using a spatial filtering kernel, for example, a 3×3 or 5×5 kernel which calculates a new pixel value by using the original pixel value and its neighbours.

2.2 Reference beam modulation

The reflection HOE based ESPI system is shown in Fig. 4. The phase difference between the object and reference beams in an unbalanced interferometer with a path length difference $2l$ is

$$\phi = \frac{2\pi}{\lambda}(2l) \tag{7}$$

If the laser wavelength is modulated, Eq. (7) is differentiated and we have

$$\frac{d\phi}{d\lambda} = -\frac{4\pi l}{\lambda^2} \tag{8}$$

The relative phase between the beams changes as

$$\Delta\phi = \frac{4\pi l}{\lambda^2}\left(\frac{d\lambda}{di}\right)\Delta i \tag{9}$$

where *i* is the laser drive current. As we vary the amplitude of reference beam path modulation in the interferometer by varying the laser diode current, *i*, the regions where $a_r = a_0$ and $\varphi_r = \varphi_0$, will be displayed with maximum brightness. Hence the amplitude of vibration on iso-amplitude contours is[12]

$$a_r = \frac{2l}{\lambda}\left(\frac{d\lambda}{dV}\right)\Delta V \tag{10}$$

The required waveforms were generated using National Instrument's digital to analog converter (USB 6229) in the LabVIEW environment. Two sinusoidal waveforms were generated in synchronisation at the same frequency but with independently controllable amplitudes and phases. These waveforms were used respectively to vibrate the object and to modulate the path difference.

In synchronism with the frame pulse sent to the camera, a rectangular waveform was generated to allow the phase difference to be altered by π at the beginning of each frame so that consecutive frames could be subtracted from one another to obtain the result in Eq. (4). This waveform was added to the path difference modulation waveform and passed to the laser controller. Figure 1 shows an example of the combined waveform. The reference beam frequency is at a lower value than any object vibration frequency of interest, only for oscilloscope display purposes.

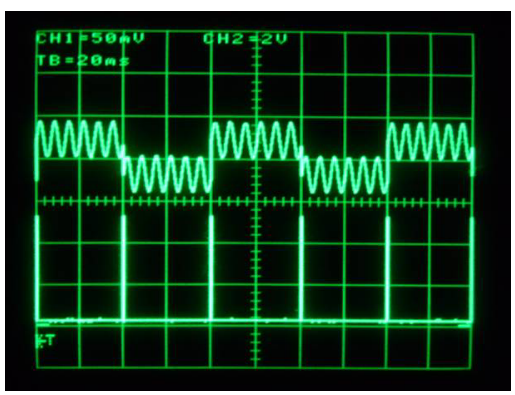

Fig. 1 Image capturing trigger pulse (lower trace) synchronised with rectangular π phase shifting waveform superimposed on the path difference modulation signal (upper trace)

3. EXPERIMENT

3.1 Laser diode emission spectrum calibration

It is necessary to study the mode map of the laser emission to choose drive current and temperature values that guarantee a stable region of operation free of mode jumps. Initially the distributed feedback diode laser (ONDAX) temperature was fixed at 33.8^{0}C using a thermo-electric cooler integrated in the laser controller (ITC502). An optical spectrum analyser (Advantest Q8384) was used to study the mode map of the laser. The wavelength change was measured in while changing the drive current from 29mA to 70mA and from 70mA to 29mA and the results are shown in Fig. 2. The red circles represent current increasing from 29 to70mA; there are two mode jumps within the range. The first occurs at 46.5mA and the second at 61.8mA. The drive current was then reduced from 70 to29mA (black square dots). The mode map shows hysteresis i.e. non identical paths for increasing and decreasing current. Mode jumps occur while current is decreasing, the first at 54.3mA and the second at 41.2mA. The stable region between 47mA and 54mA is suitable for the use in ESPI system. The DC level of the drive current was fixed at 51mA for modulation. The average slope, $\frac{d\lambda}{di}$,of the region is about 5.1pm/mA and the output optical power changes by 0.8mW/mA, which is about 2.5% of the maximum output power.

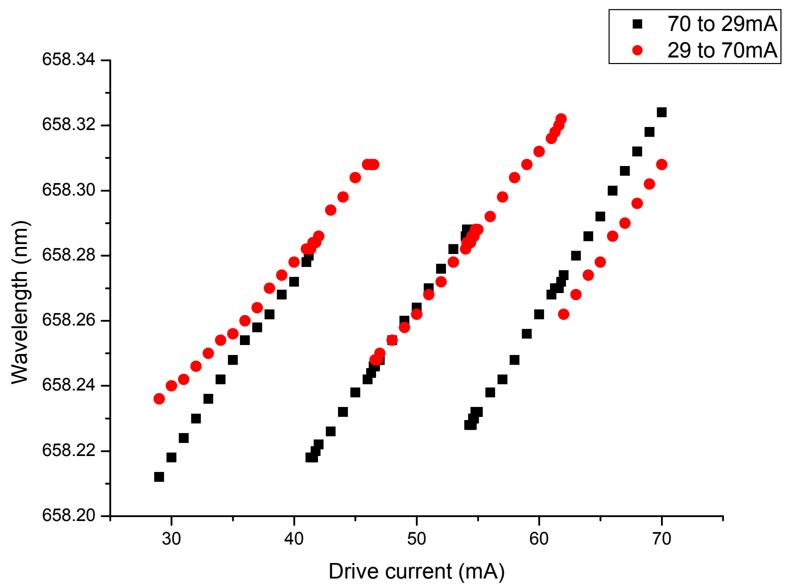

Fig. 2 Mode map of the laser diode showing wavelength variation with drive current

3.2 Recording a speckle pattern in a reflection HOE

The set up for recording the reflection HOE is shown in Fig. 3. The beam from the laser diode was spatially filtered and collimated, and used to illuminate a silver halide photographic plate (Geola PFG-03C). 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 3mJ/cm^2. The total beam power was about 0.5mW/cm^2 so the layers were exposed for approximately 6sec. The holograms were developed using SM-6 developer, followed by bleaching using PBU-Amidol[15].

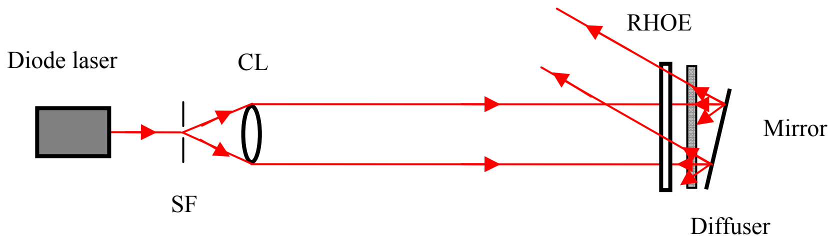

Fig. 3 Recording set up of the reflection HOE

3.3 Out-of-plane HOE based ESPI system

The out-of-plane sensitive HOE based ESPI system is shown in Fig. 4. The beam from the diode laser was spatially filtered and collimated and illuminated the reflection HOE. The illumination angle was 25^0 to the surface normal of the HOE. Upon illuminating the reflection HOE (RHOE) the stored speckle image was reconstructed. The undiffracted part of the illuminating beam was transmitted by the RHOE, illuminating the test object which scattered the beam generating a speckle pattern which served as the object beam in the interferometer. The reference and object beam interfered in the focal plane of the CMOS camera.

The camera (AVT Guppy F-036B) was set in externally triggered mode and supplied by D/A board with a digital pulse (25Hz) to initiate each image. Two sinusoidal waveforms were generated simultaneously using the same D/A board for heterodyning of the interferometer. A phase shift of π was introduced between consecutive images which are subtracted from one another to reduce background speckle noise, and to improve contrast of the fringe patterns. The system is also rendered insensitive to mechanical and thermal interferometric disturbance occurring on time scales slower than the frame rate of the camera.

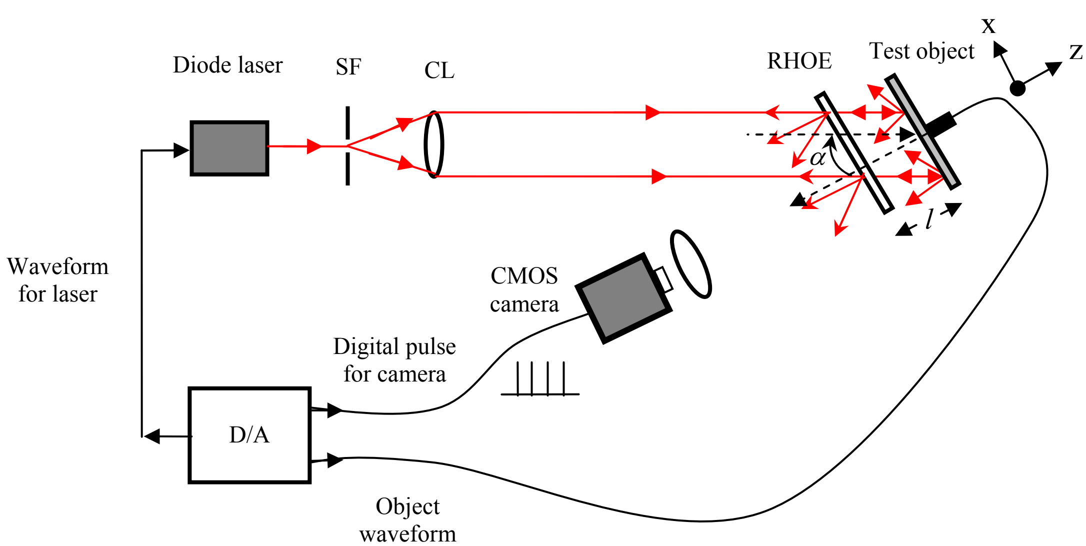

Fig. 4 Out-of-plane sensitive reflection HOE based ESPI system

(SF-Spatial filter, CL-Collimating lens, D/A-Digital to analog converter board, l -Distance between HOE and test object)

3.4 Sensitivity of the ESPI system

In the ESPI setup shown in Fig 4, the co-ordinate axes x, z were shown. The angles of illumination and observation of the object are $\alpha = 25^0$ and $\beta = 180^0$ respectively to the surface normal of the test object. The phase change due to the object displacement is given by[16]

$$\Phi = \frac{2\pi}{\lambda}\left[w(\cos\alpha - \cos\beta) + u(\sin\alpha + \sin\beta)\right] \tag{11}$$

where α, β are the illumination and observation angles measured with respect to the surface normal of the test object and w, u are out-of-plane and in-plane displacement components along z and x directions respectively.

$$\Phi = \frac{2\pi}{\lambda}\left[w(1.906) + u(0.422)\right] \tag{12}$$

This shows that reflection HOE based ESPI system is not only sensitive to out-of-plane displacement components but also sensitive to in-plane displacement components.

3.5 Speckle size

The pixel dimensions are 6µm (Horizontal), 6µm (Vertical). The laser wavelength is 658nm and the F number of the lens used was 5.6. The speckle size is given by[3]

$$\sigma = 2.44\lambda F \tag{13}$$

$$\sigma = 8.99\mu m$$

This suggests the speckle size is a little over a pixel size.

4. RESULTS AND DISCUSSION

A circular aluminium plate of diameter 5.4 cm, attached at its center to a piezoelectric actuator, was used as a test object. Initially the test object was excited at frequencies typically of a few kilohertz. The object frequency of vibration was varied while consecutive images were subtracted continuously from one another. At a particular vibration frequency a resonant mode pattern appears on the TV monitor containing nodes and antinodes. These are known as vibration modes, and the process of scanning vibration modes was repeated to find different possible vibration modes. To map vibration amplitude, the reference beam path length was modulated in the interferometer. The object and reference beam path lengths were modulated at the same frequency, but their phase difference was initially set at 0. The amplitude of the reference beam path length varied in such a way that the path length difference in the interferometer was zero and the maximum intensity in the fringe pattern indicated those parts of the object oscillating with the same amplitude as the reference beam path length modulation.

The image resulting from the subtraction had very low contrast and looked practically black to the eye; this is because the modulation of the speckles on a rough surface is usually only a few gray levels. Therefore an exponential image intensity transformation was performed on gray scale images using a look up table (LUT) to increase fringe contrast and brightness.

Software was developed using LabVIEW to interface the CMOS camera and to control its frame rate and also to obtain vibration fringe patterns. The peak to peak amplitude of the applied square waveform for π phase shift was 44mV, approximately in agreement with the value calculated using (9). Vibration resonant modes were found at 1018Hz and 6620Hz without reference modulation, by introducing a π phase shift between consecutive images and subtracting them from one another. The corresponding fringe patterns are shown in figure 5 (a) and 6(a) respectively. The path difference in the interferometer was 5.6cms. When the test object was excited at 1018Hz, reference beam path length modulation of needed to obtain the bright fringe shown in fig 5(b), which represents an iso-amplitude line where $\varphi_r = \varphi_0 = 0$, corresponded to a voltage modulation of 51mV. The relative phase between the beams was changed by 180^0 while still modulating at 51mV and the result presented in fig. 5(c) shows an iso-amplitude line where $\varphi_r = \pi$ and $\varphi_0 = 0$. The amplitude of vibration on the iso-amplitude line shown in fig. 6(b) and 6(c) was calculated using (10) to be 0.44μm.

The reference beam path length was modulated at 6620Hz mode with amplitude of 57mV to obtain bright iso-amplitude areas, which are shown in fig. 6(b) and 6(c) respectively. There is 180^0 relative phase shift introduced between the beams in fig. 6(c). The amplitude of vibration on the iso-amplitude lines in fig. 6(b) and (c) is 0.495μm. The intensity ratio of the reference and object beams in the interferometer is about 1:2. The beams can be balanced by using more efficient reflection HOEs.

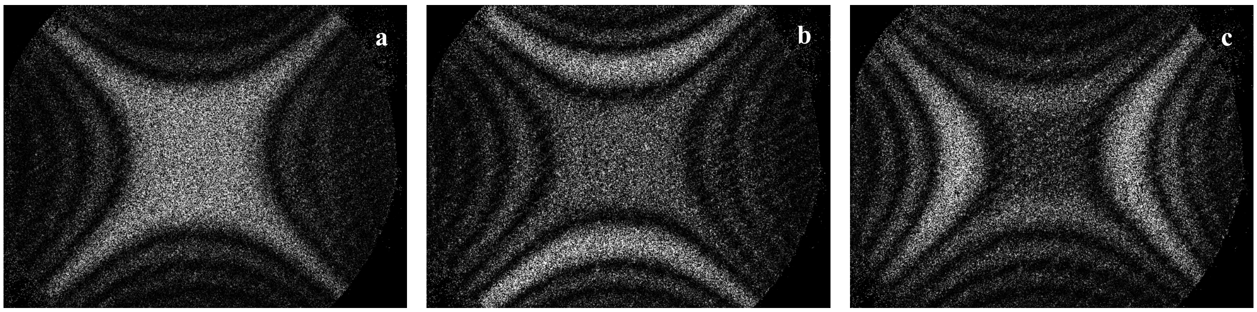

Fig. 5 (a) Vibration mode at 1018Hz without laser modulation (b) Reference beam modulated at 1018Hz with 51mV amplitude (c) 180^0 phase shift

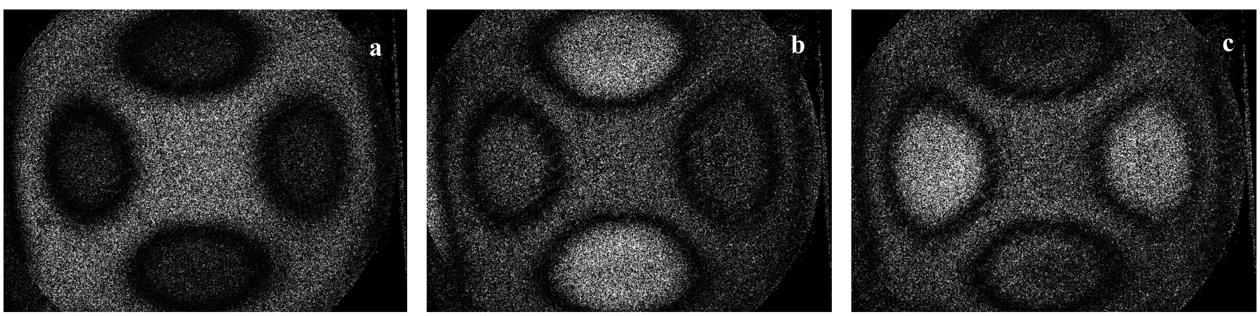

Fig. 6 (a) Vibration mode at 6620Hz with out laser modulation (b) Reference beam modulated at 6620Hz with 57mV amplitude (c) 180 phase shift

5. CONCLUSION

We have developed an out-of-plane sensitive reflection HOE based ESPI system for vibration amplitude and phase measurement using reference beam path length modulation. We have demonstrated the possibility of miniaturization of ESPI system for the industrial application using the simplest possible optical setup. The limitation imposed by the D/A board in generating low amplitude waveforms of the order of 50mV, requires further hardware improvement. A buffer amplifier will be introduced between the D/A board and the piezoelectric actuator to allow operation at higher frequency for more extensive modal vibration studies in the near future. The complete phase map will also be extracted by adjusting the amplitude of path modulation and its phase so that object points vibrating in phase with the path modulation will be mapped out on the entire surface of the object. The variation in power output during laser modulation has been neglected, but there might be some effect on fringe contrast. The power variation can be minimised by increasing path length difference the ESPI system. The presented interferometer is not sensitive to out-of-plane displacements only but can be made completely out-of-plane sensitive by adding one more HOE. The presented ESPI system can also be used for the design of a low cost Doppler vibrometers[8].

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