Out-of-plane Vibration Analysis with a Transmission Holographic Optical Element Based Electronic Speckle Pattern Interferometer

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Out-of-plane vibration analysis with a transmission holographic optical element based electronic speckle pattern interferometer

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ABSTRACT

A simple electronic speckle pattern interferometer (ESPI) using a transmission holographic optical element (THOE) is presented. The THOE is designed to create a speckled reference beam in the interferometer. It is a transmission hologram of a diffusely transmitting glass plate A specific requirement for the fabrication of the THOEs is for them to be recorded at one wavelength at which the recording material is photosensitive and reconstructed using a near infrared laser diode which can be current modulated for phase shifting purposes. A partially reflective glass plate provides illumination of the object along the normal to its surface, ensuring that the system is sensitive only to out-of-plane displacement of the object. The intensity of the object beam can be controlled by using reflective glass plates with different reflection coefficients. It is demonstrated that the HOE based system can be used for vibration measurements and modal analysis. A big advantage of the system is its simplicity.

Keywords: ESPI, interferometry, mode analysis, vibrations, holographic optical elements, HOE

1. INTRODUCTION

Electronic speckle pattern interferometry (ESPI) is a full field measurement technique for studying the deformation of an object surface. ESPI utilizes the formation of speckle when coherent light illuminates any rough surface. Random speckles are used as carriers of information from which phase information can be extracted. An ESPI system is basically a two beam interferometer in which at least one of the beams must be a speckled beam.   ESPI was first reported by Archbold et al[1] but the development was attributed to Butters and Leendertz [2]

Conventional optical elements are used for specific functions, for example sending light rays in a particular direction. These optical elements work by reflection or refraction. Holographic optical elements (HOE) are based on the principle of diffraction and are used as alternatives to conventional optical elements in many applications[3, 4]. One such application is in speckle interferometry[5]. The ESPI system presented in this paper incorporates one transmission HOE (THOE) and a partially reflecting mirror. The basic idea in a HOE based ESPI system is the use of a speckled reference wave, which is stored in a holographic optical element [6, 7].

The HOE based ESPI system presented here is sensitive only to out-of-plane displacement components. The geometry of recording and reconstruction of HOE is based on this requirement. Phase shifting in this ESPI system can be implemented by modulation of the laser drive current in a near infrared diode laser operating at 763nm.

Our HOE based ESPI system was used to study vibration behaviour of a circular aluminium plate attached to a piezo-electric vibrator and very good quality fringes were obtained.

2. THEORY

We need to estimate the angles to use in recording the HOE at wavelength λ so as to be able to reconstruct the recorded holographic image from the HOE at another wavelength λ'. In this work a 532 nm Verdi laser was used to record the holograms and a 763nm near infrared distributed feedback (DFB) diode laser was used for reconstruction. Phase shifting can be implemented by modulating the wavelength of the near infrared diode laser in an unbalanced interferometer[8, 9]. There are no commercial holographic recording materials available which are sensitive at 763nm to record a hologram. So in this work an alternative approach was to record HOEs in the visible region and reconstruct them in the near infrared region. The change in reconstruction wavelength changes the Bragg diffraction angle for reconstruction. We previously used the same theoretical approach for a reflection HOE based ESPI system[7]. The changes in the angles of illumination and diffraction can be calculated according to the approach shown in Fig. 1. However, the influence of material shrinkage and aberrations were not considered in the following derivation.

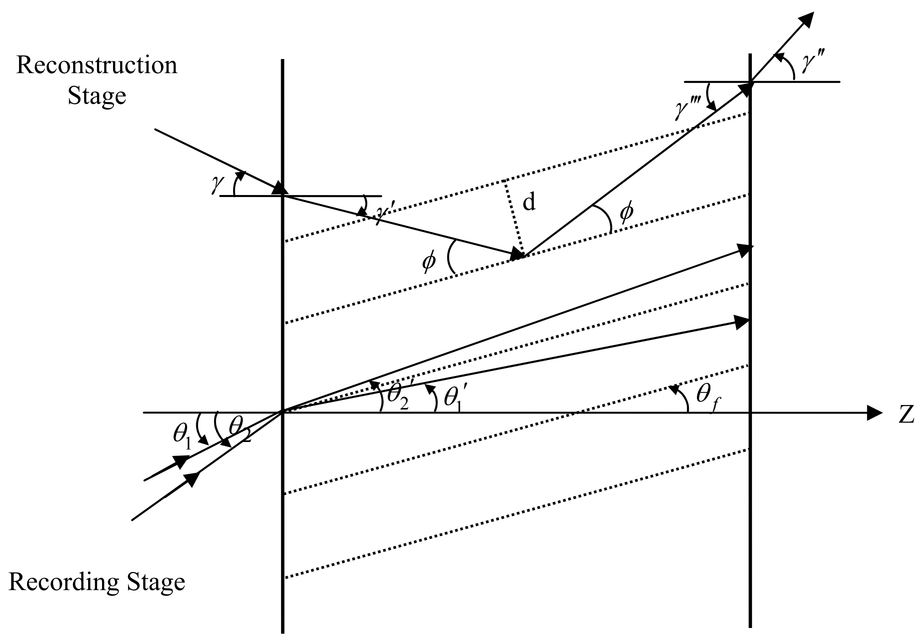


Fig. 1. Geometry of recording and reconstruction of a THOE

The recording beams produce an interference pattern inside the material with fringe spacing *d* given by

$$d = \frac{\lambda / \mu}{2\sin\left(\frac{\theta_2' - \theta_1'}{2}\right)} \tag{1}$$

where λ = wavelength of the recording laser beams, θ_1, θ_2 are the incident angles of recording beams ; θ_1', θ_2' are the angles of refraction of the recording beams inside the recording medium. All the angles were measured with respect to Z axis.

μ = refractive index of the recording medium, which is around 1.5 for acrylamide based photopolymer material [10].

For successful reconstruction at a different wavelength we apply Bragg's law

$$2d\sin\varphi = \lambda' \tag{2}$$

where λ' = wavelength of the reconstruction beam; φ = Bragg diffraction angle

We apply Snell's law to find γ the illumination beam angle outside the recording medium,

$$\sin\gamma = \mu \sin\left\{ -\sin^{-1}\left[\frac{\lambda'}{\lambda} \sin\left(\frac{\theta_2' - \theta_1'}{2} \right) \right] + \frac{\theta_1' + \theta_2'}{2} \right\} \tag{3}$$

Applying Snell's law gives the reconstruction angle for λ' outside of the recording material

$$\sin\gamma'' = \mu \sin\left\{ \sin^{-1}\left[\frac{\lambda'}{\lambda} \sin\left(\frac{\theta_2' - \theta_1'}{2} \right) \right] + \frac{\theta_1' + \theta_2'}{2} \right\} \tag{4}$$

Using equations (3) and (4) a MATLAB code was written to calculate angles of recording at one wavelength and reconstruction at a different wavelength.

3. EXPERIMENT

3.1 Production of holographic optical elements (HOEs)

The design of HOEs is a crucial step towards realization of a HOE based ESPI system. The laser beams used for recording and reconstruction are of different wavelengths, so the angles of illumination are chosen in such a way that upon reconstruction one can implement an out-of-plane sensitive ESPI system.

The recording set-up is shown in Fig. 2. The laser light emitted by the source is divided into two parts using a polarising beam splitter (PBS) and two 532nm half wave plates (HWP1, HWP2). The use of half wave plates provides control over polarisation state of the recording beams and their intensities. The incoming vertically polarised light was rotated to an appropriate angle by the HWP1, and then its vertical and horizontal components were separated by the PBS. The transmitted horizontal component was rotated into the vertical plane by the HWP2. Both beams were spatially filtered (SF) and collimated (CL). The recording angles were $\theta_1 = -30^0$ and $\theta_2 = 30^0$; the corresponding illumination and diffraction angles at 763nm were $\gamma = -45^0$ and $\gamma'' = 45^0$. These angles of recording and reconstruction were calculated using equations (3) and (4). In one of the beams a ground glass plate was introduced to record a speckle pattern in the transmission hologram.

3.2 Recording material used for THOEs

We used a green sensitised acrylamide based photopolymer to record our THOEs. This photopolymer material was developed at Centre for Industrial and Engineering Optics[11, 12]. It consists of a polyvinylalcohol binder in which a monomer, electron donor and a dye sensitizer are dissolved. When a dye molecule absorbs a photon in the presence of an electron donor, free radicals are produced that cause local polymerisation of the acrylamide. A local variation in the refractive index takes place due to the polymerisation. The recording material was exposed for 120sec at 4.3mW/cm^2. The maximum diffraction efficiency achieved was 22%. In the reconstruction stage the illumination angle at 763nm was approximately $\gamma = -45^0$ and the diffraction angle was $\gamma'' = 45^0$. The theoretically calculated angles and experimental angles are in good agreement.

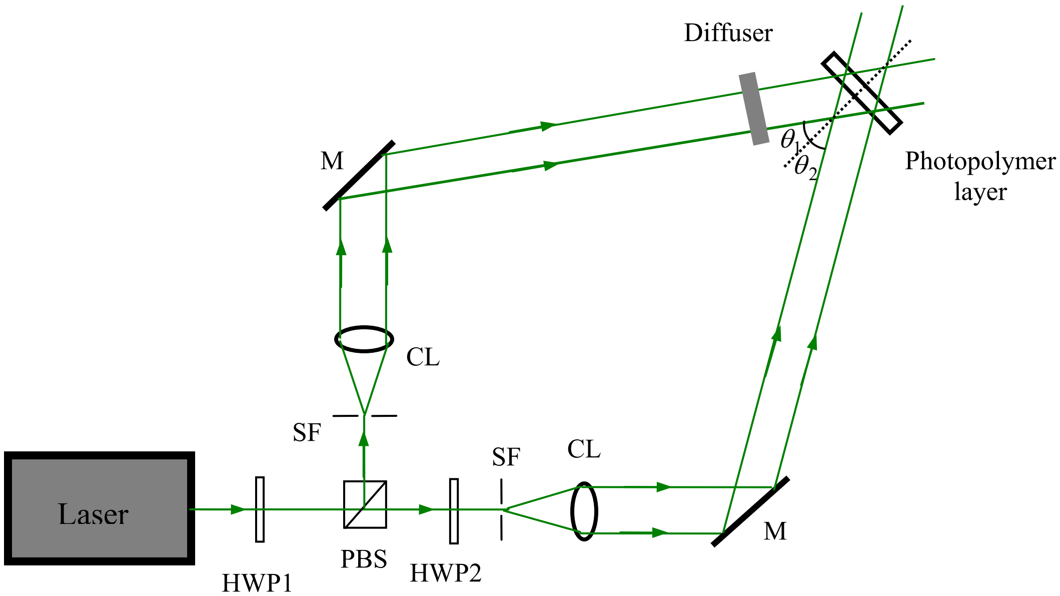


Fig. 2. Recording geometry of a THOE.
(HWP- Half wave plate, PBS- polarizing beam splitter, SF-spatial filter, CL-collimating lens, M-mirror).

3.3 THOE based Out-of-plane ESPI system

The optical set-up of an ESPI system using a combination of a THOE and a partial mirror is shown in Fig. 3. The light beam from a distributed feed back (DFB) near infrared diode laser has an elliptical cross section. The elliptical beam was converted into a circular one by introducing an anamorphic prism pair (APP). This beam was spatially filtered (SF) and collimated (CL). The light illuminating the partially reflecting mirror (PRM) is partially reflected while the rest is transmitted. The angle of reflection measured with respect to the normal to the mirror is 45^o. The light reflected from the mirror illuminates the test object which generates the object beam. The partially transmitted beam illuminates the THOE which generates a speckled reference beam by diffraction. In the reconstruction stage a near infrared DFB diode laser (λ = 763nm) was used to illuminate the THOE, hence a shift in the Bragg angle of diffraction occurs on reconstruction.

In this setup the angles of illumination and observation of the object are along the surface normal of the test object which determines the sensitivity vector of the ESPI system. The phase difference due to the object displacement is given by [13]

$$\Phi = \frac{2\pi}{\lambda}\left[w\left(\cos\alpha - \cos\beta\right) + u\left(\sin\alpha + \sin\beta\right)\right] \tag{5}$$

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

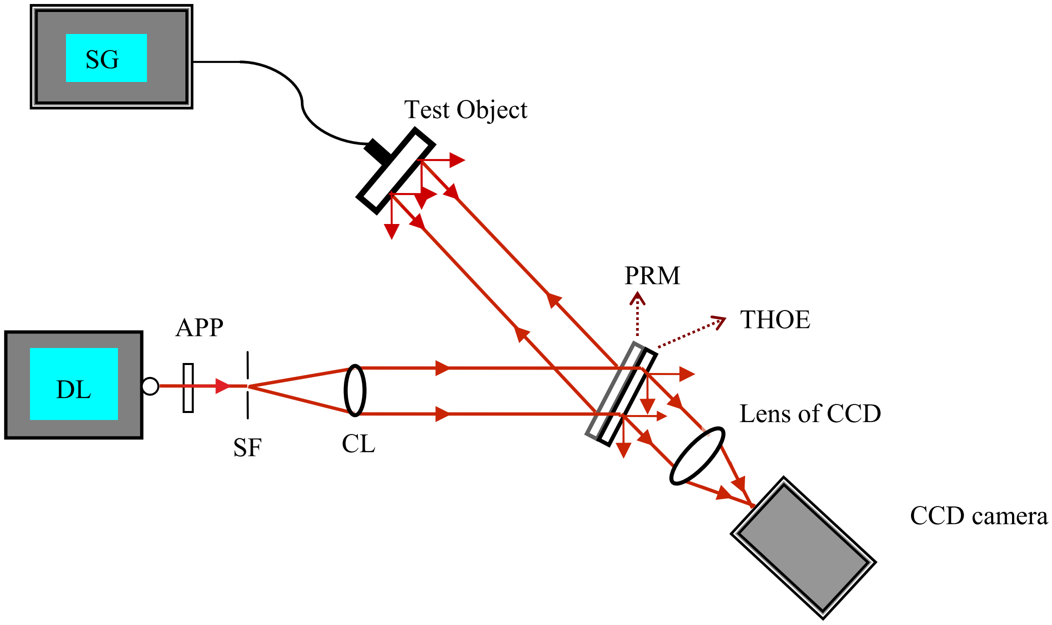


Fig. 3. Out-of-plane sensitive THOE based ESPI system

Substituting values of illumination and observation in equation (5) gives

$$\Phi = \frac{4\pi w}{\lambda} \tag{6}$$

This shows that our THOE based ESPI system is sensitive only to out-of-plane displacement components.

4. EXPERIMENTAL RESULTS

4.1 Histogram analysis

The ESPI experiments for detection of vibration modes were done using the system shown in Fig. 3. A THOE and a mirror of reflectivity R=0.3 were used in the ESPI system. The object was a circular aluminium plate 5.4 cm in diameter, attached to a piezo-electric actuator at its centre and driven by a sinusoidal signal generator.

The laser system used in our ESPI produces a beam with Gaussian intensity profile. Consequently even if the surface scatters light uniformly in all directions the image appears brightest in the centre. Histograms of the images of the object, reference and combined beams provide quantitative information about their intensity over all the pixels. The images of the object and reference beams and their histograms are shown in figures 4 and 5. These images were captured using a PULNIX 2013 analog CCIR camera with 768×576 pixels.

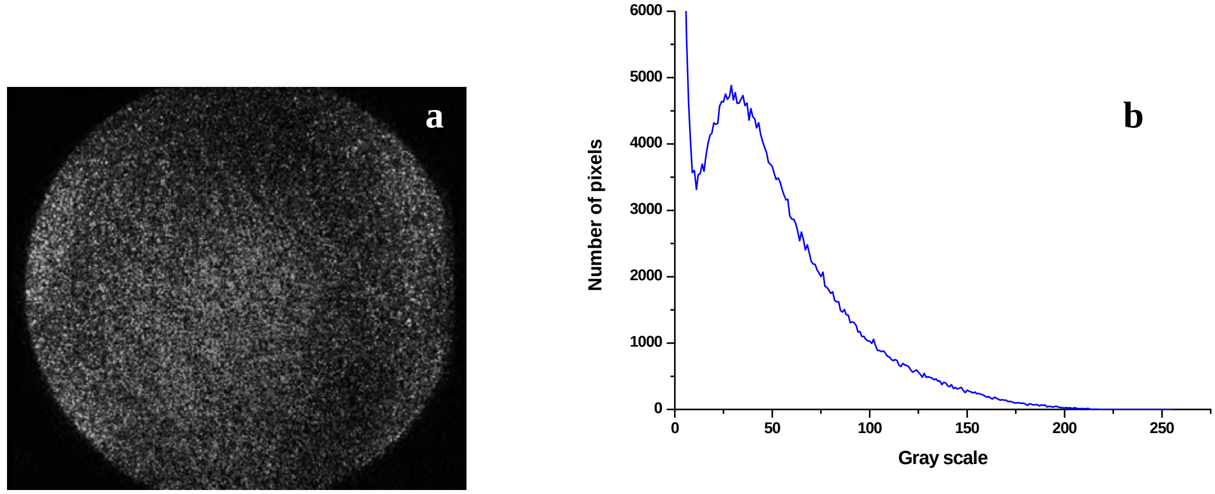


Fig. 4: (a) Image of the object beam. The field of view is $4.9mm \times 3.6mm$; (b) Image histogram of the object beam.

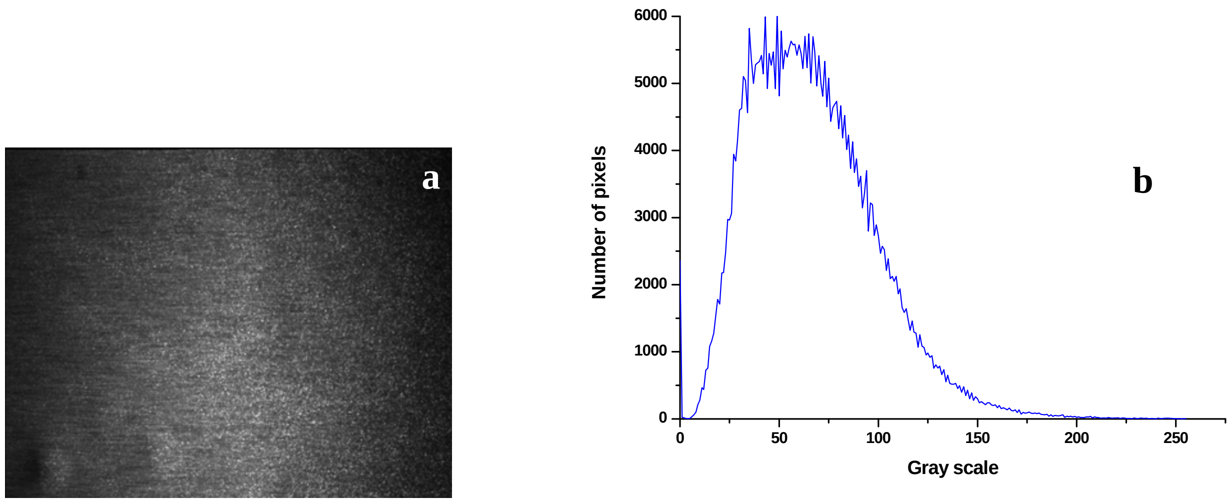


Fig. 5: (a) Image of the reference beam. The field of view is $4.9mm \times 3.6mm$; (b) Image histogram of the reference beam.

The histogram of the object beam has mean value 47 and median value 26. The histogram of the reference beam shows that part of the image is saturated but the mean and median distributions are only 66 and 63 respectively. The image of the combined beams is shown in Fig 6 (a). The corresponding histogram of fig. 6 (a) is shown in fig. 6(b) and its mean and median values are 89 and 98 respectively. The total intensity of the combined beams should be twice that of either of one beam over all the pixels in an ideal system. In this ESPI system the reference beam is brighter (mean 66) than the object beam (mean 47). We would like reference and object beam intensities to be the same and preferably gray level value nearer 128 to provide a good modulation speckle depth and contrast. The aperture of the camera lens can be increased to achieve the gray level value around 128 provided that the speckle size is not too small.

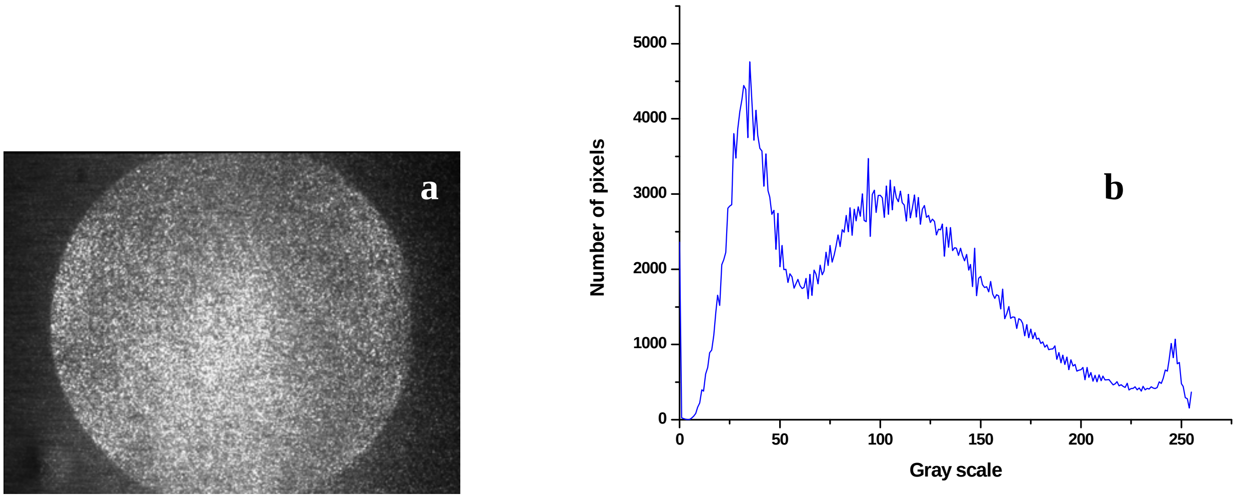
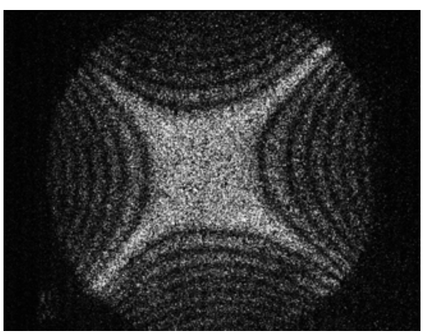


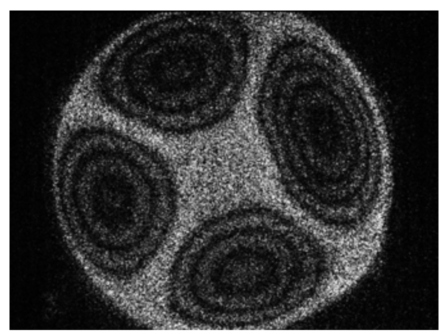
Fig. 6: (a) Image of the combined beams. The field of view $4.9mm \times 3.6mm$; (b) Image histogram of the combined beams.

4.2 Vibration modes of a circular aluminium plate attached at its centre to a piezo-electric vibrator

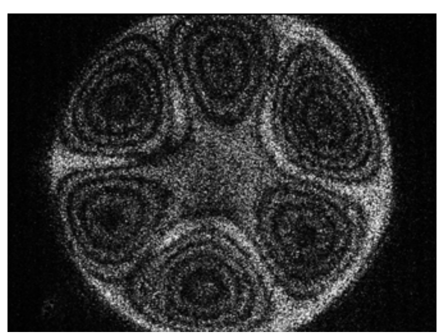
Figure 7 presents some of the resonant vibration modes. These were obtained by altering the drive voltage after capturing a time averaged frame, thus subtracting interferograms at different voltages from one another. All the fringe patterns were captured in time average mode. The field of view is $4.9mm \times 3.6mm$ for all the modes shown in Fig. 7.



(a) Mode @ 1kHz



(b) Mode @ 6.7 kHz



(c) Mode @ 9.1 kHz

Fig. 7. Resonant vibration modes of a circular aluminium plate 5.4 cm in diameter, attached to a piezo-electric actuator at its centre and driven by a sinusoidal signal generator.

The presented ESPI system uses only one HOE and a partially reflecting mirror in parallel. Hence the HOE based ESPI system is very compact and easy to align. It is possible to adjust the relative intensities of the object and the reference beams by tilting the HOE and partial reflecting mirror combination appropriately.

4.3 Speckle size

The pixel dimensions are 6.5µm (horizontal) and 6.25µm (vertical). The F number of the lens used was 11 and λ =763nm.

The speckle size was calculated using the following formula[13]

$$\sigma = 2.44\lambda F \tag{7}$$

$$\sigma = 20.47\,\mu m$$

So this suggests that the speckle size is almost 3 times bigger than a single pixel. In general speckle size should be of the order of a pixel or more so that we can observe the changes in the speckle pattern when a test object is displaced.

5. CONCLUSION

An ESPI system with a transmission HOE and a partially reflective mirror is presented. We have successfully recorded speckle pattern in a transmission HOE in visible laser light for reconstruction in near infrared laser light for use in a simple ESPI system. The theoretically calculated and experimentally obtained angles of recording and reconstruction are in agreement with each other. The system is simple and compact. It is demonstrated that a THOE based ESPI system can be used for whole field out-of-plane vibration measurements. We have successfully tested a circular aluminium plate attached to a piezoelectric vibrator. The shapes of the resonant modes can be found in real time by varying the frequency and amplitude of the excitation signal. The analysis of image histograms of reference and object beams provides useful information for further optimisation of fringe quality. In the near future the wavelength of the near infrared diode laser will be modulated to introduce phase shifting in this ESPI system to obtain phase and displacement information of the vibrating object. The presented novel ESPI system can also be used for the design of a low cost laser Doppler vibrometer.

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