A New Versatile Electronic Speckle Pattern Interferometer For Vibration Measurements

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A NEW VERSATILE ELECTRONIC SPECKLE PATTERN INTERFEROMETER FOR VIBRATION MEASUREMENTS

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A thesis submitted for the degree of Doctor of Philosophy PhD to the Dublin Institute of Technology

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In memory of my father
ABSTRACT

Electronic speckle pattern interferometry (ESPI) has been widely used for vibration amplitude and phase measurements. Conventional ESPI systems are bulk and expensive and need careful alignment of all the optical components which is a time consuming task. To overcome these problems alternative compact ESPI systems were developed using fibre-optical components or holographic optical elements (HOEs). The fibre-optic based ESPI systems suffer from random phase fluctuations induced by environmental temperature changes. Hence HOEs can be used as more powerful alternative optical elements to design ESPI systems.

The time average ESPI method is widely used for vibration studies. The time average method combined with phase stepping can be used for automatic vibration measurements. Using this technique higher vibration amplitudes cannot be measured because fringe patterns follow Bessel function intensity distribution. To overcome this problem an alternative technique can be used by modulating the phase of the reference beam in an unbalanced interferometer.

This thesis reports a novel ESPI system for vibration measurements by combining use of holographic optical elements (HOEs) and optical path length modulation (reference beam phase modulation). The optical path length modulation is implemented using laser diode wavelength (frequency) modulation.

Different HOE based ESPI systems are reported in this thesis using either a single HOE or dual HOE. This thesis examines performance of different HOE based ESPI systems that are sensitive to out-of-plane displacement components using laser diodes operating either in the near infrared or visible electromagnetic spectrum.

Vibration modes of a circular metal plate clamped at the edges of a loud speaker and a circular metal plate driven by a piezoelectric actuator (PZT) were studied using a single RHOE based ESPI system and a hybrid (transmission HOE with a partially reflecting mirror) HOE based ESPI system respectively using a near infrared laser diode (763nm). Optical path length modulation technique was implemented using a laser diode operating in visible electromagnetic spectrum (658nm). Vibration mode patterns of a circular metal plate driven by a PZT actuator were obtained using both single RHOE and dual HOE based ESPI systems. Using optical path length modulation technique in a dual HOE based ESPI system detailed phase and amplitude maps of a circular metal plate driven by a PZT actuator are obtained. The dual HOE based ESPI system was also used for measuring rotations of a circular metal plate mounted on a mirror mount.

In conclusion we have developed a compact HOE based ESPI system to conduct vibration measurements. A few potential future developments are also suggested at the end of the thesis.
Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy is entirely my own work and has not been taken from work by any other person. All the relevant works or quotations or paraphrase of another person has been duly acknowledged in the work:

This thesis was prepared according to the regulations for the postgraduate study by research of the Dublin Institute of Technology and has not been submitted either in part or in whole for an award at any other Institute or University.

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Signature ______________________ Date 28/01/2013
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CHAPTER 1
INTRODUCTION

Vibration analysis is used to detect precursors of machine failure, so that the damaged parts may be replaced or repaired well before an expensive failure occurs. The aims of vibration analysis can be the prevention of a fatigue induced failure or the detection of noise-generating parts. Many rotating mechanical components such as electric motors, turbine blades also vibrate to some degree. But as the components get older and reach the end of their lifetime, they began to vibrate more dramatically and in distinct ways. Continuous monitoring of these machines detects the signs of wear and damage and enables the prevention of expensive machine failure. Vibrations in these mechanical components are often undesirable leading to energy losses in the form of mechanical sound, and they may also degrade these machines. Vibration measurements of such mechanical components provide valuable information for modifying their mechanical design for greater efficiency and noise reduction.

Generally vibration measurements are carried out using accelerometers. Accelerometers are transducers which measure the acceleration of a vibrating body by converting mechanical movements into electrical signal. They are widely used because of their small size, high sensitivity and their ability to measure vibrations over a large frequency range. There are also some disadvantages in using accelerometers for vibration studies. One of these is that the accelerometer is kept in contact with a vibrating body. In general the mass of the accelerometer is neglected compared to mass of the vibrating body. But when the vibrating body is a thin plate or shell or some other lightweight structure, then the accelerometer mass may cause the
natural frequency to change [1]. Another disadvantage is the problem of electromagnetic interference in vibration testing using piezoelectric accelerometers on certain test objects such as electrical circuit breakers [2, 3]. In such cases optical interferometric techniques such as laser Doppler vibrometry are preferred due to their high sensitivity [4] and immunity to electromagnetic interference. In optical interferometric techniques, a coherent light is divided into two beams which are made to interfere after one of them illuminates the object under study so that when the phase of this beam is modulated, the interference pattern modulates in intensity. The Laser vibrometry techniques are used to conduct measurements at a single point on the surface of the vibrating object. To obtain complete object vibration information, the object has to be scanned. A complicated optical set up is required to scan the object. Vibrometers designed using bulk optics suffer from lack of a direct linear phase read out, signal deterioration due to random shifts in phase and polarization changes and fluctuations in source intensity [5]. Alternatively a full-field optical interferometric technique based on speckle pattern formation such as electronic speckle pattern interferometry (ESPI) can be used for reliable vibration measurements [6-9].

1.1. Introduction to speckle interferometry

A speckle pattern interferometer is a two beam interferometer with at least one of the interfering beams being a speckle pattern [10]. A speckle pattern is produced by scattering of light by an optically rough surface (that is the surface height variation should be at least of the order of the wavelength of the illuminating laser beam) when a coherent light beam illuminates it [11]. A typical speckle pattern generated by a metal plate when illuminated by a collimated laser beam at 658nm is shown in Fig.1.1. The speckle pattern was obtained using a monochrome CMOS camera (600×480 pixels). The speckle size was 17.6µm (see Section 2.1.2).
In speckle interferometry a coherent light from the source is split into two beams. One of the beams illuminates the test object which generates a speckled object beam and the other can be used directly as a smooth reference beam or it can be used to illuminate another fixed rough surface to generate a speckle reference beam. The object and reference beams are superimposed according to the principle of interferometry which produces a speckle interferogram. To measure the displacement of a test object, speckle interferograms corresponding to two object positions, one before and another after the displacement are recorded on a photographic plate. When the processed plate is illuminated, the resultant speckle pattern distribution contains speckle fringes, which are called correlation fringes. The contrast of these fringes depends on the phase difference between the speckle patterns corresponding to two different positions of the object [10]. Photographic processing of these plates is time consuming. Introduction of electronic detector such as a video camera/digital camera for recording and processing speckle patterns enables real time observation of fringes on a TV monitor. A speckle interferometer which uses a video (digital) camera for the detection of correlation fringes is called an electronic (digital) speckle pattern interferometer (ESPI/DSPI). In an ESPI system generally the correlation fringes are generated by subtraction of speckle interferograms corresponding to two different positions of the object.
A circular metal plate of area 2.5mm×2.5mm was illuminated with 658nm laser beam.

A subtracted speckle fringe pattern corresponds to a rotation of 0.3mrad is shown in Fig. 1.2

1.2. Historical development of speckle interferometry techniques

1.2.1. Speckle photography

In speckle interferometry correlation fringes were obtained by the superposition of a photographic negative consisting of a speckle interferogram corresponding to the object at rest and another speckle interferogram corresponding to displaced object position [10]. But the photographic process was tedious and an alternative approach to obtain correlation fringe pattern using speckle photography was reported by Burch and Tokarski [12] and Archbold et al. [13]. Speckle photography does not use a reference beam rather it uses displacement of speckles directly for measurements. Burch and Tokarski used photographic plates for recording speckle patterns and introduced displacement between photographic exposures. The exposures were varied using a shutter. The recorded speckle patterns were illuminated using a converging spherical laser beam. The fringes were obtained as an optical Fourier transform of the amplitude transmission function of the transparency. In principle the fringes provided by the optical Fourier transform of the multiply exposed photographic plate should
give a set of fringes similar to those produced by a set of pinholes with transmission coefficients proportional to the exposure times. In this way the speckle photography system was used for the first time to measure in-plane and out-of-plane displacements. Archbold et al. used speckle photographic systems to record a double-exposure of an object using single or two beam illumination for measuring in-plane displacements and strain. The in-plane displacement measurement range was limited by the speckle size when the measurements were carried out using double exposure correlation fringes. If the object is displaced by an amount larger than the speckle width then the displacement can be measured using fringes formed in the optical Fourier transform of the doubly exposed transparency.

Tiziani reported measurement of in-plane sensitive time average vibrations and lateral displacements using the optical Fourier transform of a photographic speckle image [14]. Time average vibration patterns were recorded on a photographic plate using a single exposure. The optical Fourier transform was applied using an appropriate diaphragm to select regions of approximately constant movement. In an alternative approach double exposures were used to record a time average vibration speckle pattern on another speckle pattern corresponding to the object at rest. In this case the minima of the resulting Bessel fringe pattern differ from the minima that were obtained for single exposure pure vibration fringes. In another method a double exposure was recorded at extreme positions of the vibration using stroboscopic illumination. This changes the cosine fringes from the original Bessel fringes to sinusoidal ones. Using this technique displacement up to 0.2mm was measured. Tiziani also reported measurements of small tilts by recording speckle patterns on photographic plates using double and multiple exposure techniques [15]. The recording part was different from previously reported techniques. A photographic
plate was used to record images of the speckle patterns at the focal plane of a lens using double exposure technique. An optical Fourier transform was used to obtain Young’s fringes corresponding to tilt in the object when the plate was illuminated with coherent light. When the test object was illuminated at two different illumination angles between the exposures, the resulting fringe pattern representing tilt was additionally modulated. The fringe spacing depends on the illumination angles.

1.2.1.1. Digital speckle pattern photography

Formation of a speckle pattern formation can be modelled as a statistical process. Therefore quantitative information can be retrieved using the correlation properties of the displaced clusters of speckles. Digital speckle photography (DSPh) is the digital version of speckle photography in which photographic recording was replaced with a digital recording and reconstructed by a computer. In DSPh a sequence of images were recorded and stored as digital frames before and after displacement of the object. These images were compared using cross-correlation. This eliminated the displacement directional ambiguity. DSPh has evolved as a real time measurement technique since 1980. Some of the developments in DSPh are discussed here.

M A Sutton et al reported a method for determination of in-plane displacements using digital image correlation technique [16]. To obtain displacement information of an object, images (512×512) corresponding to displaced and undisplaced positions were captured; then correlated digitally. Suppose A and B are arrays containing two dimensional intensity distributions from the undeformed and deformed object positions. Small subsets (10×10) from the array stored in B are related to small subsets of same size of array A by a homogenous linear mapping. The subset of array A was compared mathematically with all subsets of array B, so that the subsets which minimize the square of the difference provided local displacement maps. The
deflections of a cantilever beam of the order of 0.5mm were studied using this

Sjodahl developed an algorithm for the measurement of in-plane
displacement components and tested the robustness of the algorithm when the object
was subjected to displacement gradients [17]. He has compared the subsets of speckle
pattern images, obtained before and after the displacement, using cross correlation and
applied a maximum search routine near the correlation peak in order to obtain
subpixel accuracy. The cross correlation was performed in the frequency domain for
faster calculations. The correlation coefficient was calculated using the discrete
Fourier transform and point by point multiplication. The location of the maximum
value of correlation coefficient provides the mean translation between subsets of
displaced and undisplaced images. Using the algorithm 120 speckle patterns were
simulated and divided into 12 data sets to test its robustness. The indices of the
Fourier transform matrix control the reliability and accuracy of the algorithm. The
algorithm also depends on the speckle size, speckle decorrelation and subimage size
(16×16 or 32×32).

Sjodahl reviewed recent developments in DSPh [18]. In this paper he has discussed
3D deformation field measurement using DSPh. Many engineering problems such as
material fracture are irreversible, so it is necessary to obtain complete deformation
fields for all three components simultaneously. He also suggested that it was
necessary to separate in-plane components from out-of-plane components because
out-of-plane movement can cause the speckles to move in-plane in the image field
unless one uses a telecentric lens (a compound lens which has its entrance and exit
pupils at infinity). A method of separating out-of-plane components from in-plane
components was to use stereoscopic DSPh [18]. In this system two cameras were used
with their optical axes parallel. The lenses were translated sideways until the images
on the two detectors overlapped. If the object is flat then the two cameras will image the same area on the object without image distortion. Therefore image fields from two cameras can be combined without any correction, for further analysis.

Another development was to use an ESPI system combined with DSPh for the measurement of all the three displacement components [19]. The ESPI system was used for measurement of out-of-plane displacement components using phase shifting technique while in-plane components were measured using a DSPh system. All the displacement maps were combined to produce a 3D deformation field.

Groves et al reported a combined shearographic and DSPh system for full surface strain characterization [20]. In this system the shearography configuration was used to measure out-of-plane displacement gradients while DSPh image processing technique was used to measure the in-plane displacement gradients. The image processing algorithm used in DSPh was based on optical flow field rather than cross-correlation. A single mode optical fibre was used for illuminating the surface. Shear was introduced using a simple set up that was similar to Michelson interferometry by tilting one of the mirrors with respect to another. The optical flow field is defined as the displacement distribution of the apparent motion of the intensity pattern on the image plane of the observer. It was assumed that the change in pixel intensity was solely due to the motion of the speckle pattern and this change in intensity directly provides displacement information by introducing a constraint on the intensity

1.2.2. Speckle interferometry

Speckle interferometry was first reported by Archbold et al in 1969 [21]. The speckle interferometric system was designed to observe surface vibration nodal patterns visually, using a telescope having an iris diaphragm placed at its entrance pupil. When
a surface vibrates in a complex manner only the speckle patterns in the areas that do not move are readily picked up due to their high contrast compared to the rest of the points on the object. Further development of speckle interferometry was carried out by Leendertz [10], Butters and Leendertz [22], Jones and Leendertz [23]. Leendertz demonstrated a modified Michelson interferometer replacing mirrors with optically rough surfaces, for measuring out-of-plane displacements and an in-plane system for measuring in-plane displacements of a stretched bar having a hole drilled in it. Butters and Leendertz [22] developed a speckle interferometer using a doubly exposed photographic plate. The speckle patterns corresponding to before and after the displacement of the test object were recorded on the photographic plate. A Fourier transform of the double exposure photographic plate produces linear fringes in its Fourier plane. A grid was used in the Fourier plane to obtain good contrast speckle fringes by inverse Fourier transformation. Jones and Leendertz [23] developed a three beam speckle interferometer for strain measurement in a plain sheet of brass, by mounting a mirror perpendicular to the object at one of its edges.

Duffy developed two speckle interferometric systems, using double aperture imaging, for measuring the displacement components normal to the line of sight or in-plane displacement components [24]. The first system was used to record a fine grid pattern within the speckle pattern on a doubly exposed negative corresponding to two different test object positions. In the second system the recording of speckle patterns was similar to the first one, but spatial frequency content of a doubly exposed negative was limited to a narrow frequency band using a double aperture in the Fourier transform plane, to produce good contrast fringes in the output plane representing constant contours of displacement.
A speckle interferometric method for measuring small out-of-plane displacements with improved contrast fringes of an edge clamped centrally loaded circular diaphragm was reported [25]. The principle was to use an ESPI configuration that was developed by Leendertz [10] with a modified double aperture imaging system to image the diffuse object beams simultaneously. Use of a simple double aperture with Fourier filtering provides fringes with poor contrast but introduction of a ground glass in one of the apertures followed by Fourier filtering gives good contrast fringes.

### 1.2.3. Speckle pattern shearography

Hung and Hovanesian developed a speckle interferometer to measure three displacement components and strain of a cylindrical surface. Photographic plates were used to record speckle fringes using double exposures and superposition of photographic negatives and positives [26]. Although the method is full-field, calculation of displacement and strain was carried out point by point. An image shearing speckle pattern interferometer for measuring bending moments of a square metal plate was reported by Leendertz and Butters [27]. Shear was introduced in the speckle interferometer by a simple relative tilt between the mirrors in a set up that was similar to a Michelson interferometer. Hung and Taylor demonstrated a shearing interferometer using two glass wedges in front of a double aperture imaging system and measured out-of-plane displacement derivatives of a cantilever and circular metal plate using Fourier filtering [28]. An alternative shearing interferometer was also developed by Hung [29] using tilt of a mirror in Michelson interferometer configuration to measure displacement derivatives using double exposure photographs. A simple shearing interferometer was developed by Hariharan [30] using two identical gratings attached to the lens mount of the camera used to the
record speckle pattern of the object. Shear was introduced in the images by rotating the gratings in their own plane in opposite directions by a small amount.

1.2.4. Electronic speckle pattern interferometry

The ESPI system was initially demonstrated by Butters and Leendertz [31], Macovski et al [32] simultaneously. Butters and Leendertz developed an ESPI system using dual beam illumination geometry, in which both the beams illuminate the test object from opposite sides to its normal and at equal angles. The correlation fringe patterns were obtained using subtraction of two recorded speckle patterns corresponding to two different object positions with a vidicon TV camera having 180×350 pixels. The ESPI system was applied to measure vibrations of a disc and torsion of a square metal plate. Macovski et al [32] developed time-lapse interferometric systems using a vidicon TV camera and subtraction of speckle patterns. The systems were developed for measuring out-of-plane or normal stress of a plastic block and surface contours of metal sheets of different shapes.

Cookson et al used a pulsed ruby laser source in an ESPI system for minimizing mechanical and airborne disturbances, so that the system was tested in an industrial environment [33]. They have used double pulsed addition of speckle patterns with electronic filtering. Lokberg developed an alternative ESPI system to obtain laser pulses from a continuous laser light by chopping it in synchronization with the TV frame rate, to study vibrations of unstable objects [34]. Vibrations of very low frequency were studied in time average ESPI using a double pulse technique while single pulse techniques with short exposure times were used to to study biological objects such as the human ear drum in vivo.
Lokberg and Hogmoen used reference beam phase modulation, which was a well-known technique in holography [35], in an out-of-plane sensitive time average ESPI system, to obtain amplitude and phase of the test object [6]. The reference beam was modulated at the same frequency as that of the vibrating object using a mirror mounted on a piezoelectric transducer or a high frequency loudspeaker. The phase modulation technique was used to extend the measurement range (up to 8.4µm = 53rd order of \( J_0^2 \) of time average ESPI). This technique was used to map constant contours of phase across sinusoidally vibrating objects in a fast and simple way [7]. A dual channel signal generator was used for generating two sinusoidal waves, one for object and the other for a piezoelectric transducer driven mirror located in the reference beam to implement phase shifting.

An ESPI system using a speckle reference beam was demonstrated by Slettemoen [36]. The fringe contrast was poor due to the speckle reference beam. Later, contrast was improved by using a double aperture system to separate the spatial frequency content of the power spectra (Weiner spectra) of the recorded intensities of self and cross interference of the object and reference beams. The video signal is high-pass filtered to remove unwanted background speckle noise. In another paper by Slettemoen discussed an ESPI system using a low coherence laser source to demonstrate coherence length compensation by a speckle reference beam [37].

A significant development was the use of digital image processing techniques for obtaining good contrast fringe patterns in ESPI systems [38]. Speckle patterns corresponding to two object positions were stored in a digital frame store. The displacement of the object was detected using subtraction of the stored digital speckle patterns. The resulting fringe pattern was later subjected to nonlinear post-processing.
such as level slicing to improve the contrast of the digital speckle fringes. A speckle pattern shearing interferometer was also developed using a Fresnel bi-prism, to measure derivatives of static displacements and vibrations with digital image processing techniques [39]. Nakadate et al reported a computer aided speckle interferometry system [40]. This system was applied to measure out-of-plane sensitive displacements using an absolute subtraction arithmetic operator on displaced and undisplaced speckle patterns which were stored digitally. These fringe patterns were compared with the digitally produced correlation fringes generated by operating an exclusive-or arithmetic function on two binary speckle patterns. An alternative man-machine interactive method was also reported which uses a light pen and a key board to correct positions of minimum points of dark fringes. The displacements were calculated using a fringe counting method. These displacement fringes were polynomially fitted using the least squares method and differentiated to give strain information.

Lokberg reviewed speckle interferometry techniques for measuring vibrations, static or slow displacements, shape and strain [41]. The basic ESPI principle was compared with conventional holography and advantages were discussed.

1.2.4.1. Temporal phase shifting in ESPI

An important development reported by Creath was the introduction of phase shifting technique in speckle interferometry to obtain quantitative data of the object displacement [42]. This technique was similar to phase shifting interferometry (PSI) [43]. PSI is a technique which can determine the shape of an optically smooth surface or wavefront by calculating the phase map from a set of measured intensities. The same process of phase calculation was used on speckle interferograms in speckle interferometry. The phase shifting in the speckle interferometer was introduced by
piezoactuated mirror located in the object beam path. The Carre four frame algorithm was used for phase calculation using the arctan function [44]. This kind of phase map is called raw or wrapped phase map and contains $2\pi$ jumps. These ambiguities were removed by adding or subtracting $2\pi$ until adjacent pixels differ in phase by less than $\pi$. This process is called integration of $2\pi$ ambiguities. Finally an object displacement map was produced from the integrated phase data.

Nakadate et al also reported a digital speckle pattern interferometer combined with fringe scanning technique to determine displacement of the object [45]. In this technique the object was deformed in 9 steps. At each step 4 fringe patterns phase shifted by $0$, $\frac{\pi}{2}$, $\pi$ and $\frac{3\pi}{2}$ were obtained. These fringe patterns were subtracted from relevant reference speckle patterns and fringes corresponding to displacement were obtained. An absolute phase map was calculated by removing the discontinuities present at $-\pi$ and $\pi$. The phase map at the 9th deformation state was obtained by summing all the phase maps of adjacent deformation states. The purpose of fringe scanning technique was to obtain deformation information when the fringe pattern was not visible at larger deformations. The out-of-plane displacement of a circular metal plate (1.4$\mu$m) and in-plane displacements of a rectangular brass plate with a hole (14$\mu$m) were measured.

Slettemoen discussed the theoretical maximum fraction of acceptable measurements in phase shifting speckle interferometry [46]. Theory was derived considering a smooth reference beam in the speckle interferometer. The ratio of reference beam intensity to saturation intensity and dynamic range of the camera were considered as the important parameters for optimization of phase measurements. Phase accuracy in speckle interferometry measurements depends on electronic noise, speckle modulation
depth and dynamic range of the camera and was theoretically found to be about \( \frac{1}{50} \)th to \( \frac{1}{100} \)th of a fringe period [46]. There are other methods which can be used for measuring displacement fringes such as reference beam phase modulation in ESPI and optically phase-locked ESPI [6, 47].

1.2.4.2. Spatial Phase shifting in ESPI/DSPI

Temporal phase shifting was widely used in speckle interferometry for obtaining displacement information of a test object. But if the phase of the object wave changes within the time required for introducing temporal phase shift, then spatial phase shifting is an alternative [48]. Phase shifting takes place in space instead of time so it is called spatial phase shifting. Spatial phase shifting can be implemented using three different methods. In the first method several CCD cameras can be used for recording phase shifted images, but in this technique all the cameras should be aligned precisely to the accuracy of fraction of a pixel which is very difficult [49]. In the second method phase shifted fringes can be recorded in different parts of a single camera, but this technique has spatial resolution limitation [50, 51]. In these systems phase shifting can be obtained using a computer generated hologram. The final method is the generation of spatial carrier fringes (a grating like structure) whose fringe spacing should correspond to the distance that covers at least three pixels of the CCD camera [52]. This method is cost effective because it uses a single CCD camera. Phase at a particular pixel is calculated with the help of neighbouring pixels using either 3 or 4 frame phase shift algorithms. The calculated phase is assigned to the central pixel. In this way phase at every pixel is calculated and integrated to give a complete phase map [52]. The difference-of-phases method is used to determine the resultant phase map and hence the displacement map of the test object.
1.2.4.3. Combined ESPI and shearography

An interesting development introduced in the 1990’s was to combine ESPI systems with the other forms of interferometric technique. Krishna Mohan et al [53] integrated an out-of-plane ESPI system with an out-of-plane speckle shearing interferometer to measure simultaneously out-of-plane displacement components and their derivatives. The system used a configuration that was similar to the Michelson interferometer configuration for object beam delivery. One of the mirrors was replaced by an adjustable bimirror. The reference beam was delivered by a single mode optical fibre. Initially one of the mirrors is tilted so that half of the detector records an image that corresponds to out-of-plane displacement. Shear was introduced by tilting half of the adjustable bimirror so that the other half of the recorded image contains a sheared image. Sjodahl and Saldner took a different approach by combining phase stepped ESPI with electronic speckle photography technique to measure out-of-plane and in-plane displacement components simultaneously with the same set of images [19]. Four phase shifted speckle patterns corresponding to displaced and undisplaced positions of the object were obtained. The phase map corresponding to out-of-plane displacement was obtained using a four frame algorithm followed by phase unwrapping. The phase maps corresponding to two in-plane components were calculated using cross-correlation of sub-images (16×16 or 32×32) of different phase stepped speckle patterns. Some attempts were made to study the errors associated with phase stepping, decorrelation and fringe visibility and speckle size was optimised in order to improve the quality of the data obtained from ESPI [54, 55].

Joenathan and Torroba developed a simple off-axis reference beam electronic speckle shearing pattern interferometer in which sheared images were imaged onto a diffuser using a split lens [56]. The speckle patterns generated by the diffuser were imaged
onto a TV camera to study lateral and radial shear of an edge clamped, centrally loaded, circular diaphragm. The purpose is to increase system flexibility with respect to the F-number of the imaging system and the shearing mechanism. A similar configuration was used in a modified shearing interferometer with a holographic grating as a shearing element [57].

1.2.4.4. Development of in-plane ESPI

Leendertz also developed an in-plane sensitive speckle interferometer [10]. Developments in in-plane sensitive speckle interferometric systems and their application to determine elastic constants and strain measurements were discussed by Jones [21, 58]. In the 1980’s a little attention was paid to the improvement in the optical design of in-plane ESPI systems. Research was mainly focussed on automatic measurement of deformation using ESPI systems including digital image processing methods to obtain reliable results [38-40].

In-plane ESPI systems are classified, based on the illumination and observation directions, as

- Dual beam symmetric illumination and observation along the normal [31]
- Oblique illumination and observation [59]
- Normal illumination and dual direction observation [60]
- Dual beam symmetric illumination and observation [61]

The dual beam symmetric illumination and observation along the normal method was implemented by Butters and Leendertz, eliminating sensitivity to out-of-plane displacement components. The system is shown in Fig. 1.3.
Figure 1.3 Dual-beam symmetric illumination and observation along normal in-plane ESPI system

Usually the test object is observed along the surface normal in an ESPI system, providing high sensitivity to in-plane displacements.

Figure 1.4 Oblique illumination and observation in-plane system with increased sensitivity

An oblique illumination and observation in-plane ESPI system was reported with increased sensitivity to the in-plane displacements [59]. The system is shown in
Fig. 1.4. In this ESPI system, a right angle prism was placed in front of the test object to make angles of illumination and observation greater than $45^0$ to the surface normal of the test object. Thus the ESPI system was made more sensitive to in-plane displacements.

A modified in-plane ESPI system was developed with normal illumination and dual direction observation geometry by Sirohi et al [60] for implementing spatial phase stepping. The ESPI arrangement is shown in Fig. 1.5. This ESPI system is a modification of Duffy’s two aperture system [24], though it is not purely sensitive to in-plane displacements, but enables spatial phase stepping to be implemented.

![ESPI System Diagram](image)

**Figure 1.5 Normal illumination and dual direction observation in-plane ESPI system**

Another modified in-plane ESPI system was reported [61] with dual beam symmetric illumination-observation geometry. The ESPI arrangement is shown in Fig. 1.6. In the dual beam symmetric illumination and normal observation in-plane ESPI system [31] the scattered fields were observed along the optical axis. Here however, instead of observing scattered fields along the optical axis, the scattered fields were observed
along the illumination beam directions and imaged as two separate images on the focal plane of the CCD camera (meaning that the images are spatially separated). The in-plane sensitivity is the same as for the dual beam symmetric illumination and normal observation arrangement.

**Figure 1.6 Dual beam symmetric illumination-observation in-plane ESPI system**

Only the dual beam symmetric illumination and normal observation ESPI system is purely in-plane sensitive and the rest of the in-plane ESPI systems have some sensitivity to out-of-plane displacements (It is assumed that the object is flat).

**1.2.4.5. Vibration measurements using ESPI**

The time average ESPI method is widely used for vibration studies [8, 62]. Direct use of the time average method does not provide phase information of the vibrating object. When an object is vibrating sinusoidally at higher frequency (typically of the order of 10 kHz), then its motion would be complex. It is necessary to measure both the amplitude and phase distribution across the object to determine the complete object motion. The visibility of the time average Bessel fringe pattern decreases as the amplitude of vibration increases. So, the time average Bessel fringes were converted
to cosine fringes by using stroboscopic illumination from the laser source for phase map extraction [9, 63]. The stroboscopic ESPI method has the disadvantage that the optical energy delivered is reduced due to the chopping of the laser light. This may limit use of the stroboscopic ESPI method for the study vibrations of larger sized objects.

Lokberg and Hogmoen introduced a new technique to overcome this problem by modulating the path length difference in an unbalanced interferometer sinusoidally at the same frequency as that of the object vibration, but with variable amplitude and phase, to map contours of constant phase and of constant amplitude (iso-amplitude) [6, 7]. This technique was further extended first by Atcha and Tatam [64] and later by Olszak and Patorski [65] using fibre-optic based ESPI systems. Vibration studies using a holographic optical element (HOE) based ESPI system was reported by Lau using the stroboscopic ESPI method [63].

1.2.4.6. Recent developments in electronic/digital speckle pattern interferometry
The introduction of optical fibres has paved the way for the development of alternative ESPI systems [9, 64-68]. A stroboscopic ESPI system built with optical fibres was discussed [9], in which illumination from a diode laser source was synchronised with turning points (stationary points) of the object vibration. A speckle shearing interferometer using a highly birefringent optical fibre was reported [66]. The interferometer is phase stepped without mechanical movement of components, by modulation of the relative phase of the polarization states induced by straining the fibre. To study the phase map of a harmonically vibrating test object, a heterodyning method was introduced in an electronic speckle pattern interferometer [64, 65]. Also reported is the use of a frequency modulated fibre-optic based ESPI system for the study of in-plane and out-of-plane displacement components of a vibrating object [67, 
Holographic optical elements (HOEs) were introduced in ESPI system by Petrov and Lau to provide a holographically generated reference beam. This modification has made ESPI systems simple, easy to align and compact [69, 70].

Yang and Ettemeyer developed a greatly miniaturized (based on glass fibre concept) 3D ESPI system of size $65 \times 65 \times 76\text{mm}^3$ in volume for quantitative stress/strain measurement of objects with area $30 \times 40\text{mm}^2$ [71]. Determination of shape information is an essential prerequisite for stress/strain evaluation of complicated surfaces. The same 3D ESPI system can also be used for shape measurement of the test surface. The ESPI system is particularly useful for obtaining deformation information in the regions where high stress gradients are present such as near boundaries of the object.

A portable digital speckle pattern interferometer to measure residual stresses using the hole-drilling technique has been reported by Viotti et al [72]. The concepts discussed by Viotti are the stiffness of the design which has to keep the relative motion between the optical parts below an acceptable level and negligible relative motion between the interferometer and specimen. We can conclude from the above historical development that the increasing interest is on building compact and portable ESPI systems which can perform well in the industrial environment.

1.2.4.7. Holographic optical elements in ESPI

A holographic optical element (HOE) can be considered as a generalized grating structure. A HOE can be produced by recording an interference pattern between two or more optical beams on a photographic plate. The wavefronts of the optical beams can be plane or spherical or even more complex in shape. A HOE can reproduce the functions of multiple lenses or it can serve multiple functions eg. as a lens, beam
splitter and spectral filter simultaneously. HOEs are wavelength selective because their focal length, aberrations etc., vary with the wavelength. HOEs are based on the principle of diffraction and are used as alternatives to conventional optical elements in many applications [73, 74]. One such application is the use of HOEs in speckle interferometry. Shakher and Rao used holographic lenses for focussed and defocused speckle photography [75]. In their work, a double exposure technique was used to record changes in the speckle pattern due to the displacement; and then optical Fourier transformation was performed using a point-by-point filtering method and correlation fringes were obtained. In plane translations up to 100µm were measured.

Burkle and Joenathan introduced a new method of shearing in an electronic speckle pattern shearing interferometry (ESPSI) system using a holographic grating (500 lines/mm) [57]. A ground glass plate was used between the holographic grating and CCD camera, so that there is no need to resolve the fringes present in the holographic grating. This arrangement makes the shearing mechanism more flexible.

Petrov and Lau developed out-of-plane ESPI systems using HOEs recorded using photo-thermoplastic and silver halide materials [69, 70]. Reconstruction from the HOE provides a speckle reference beam in the ESPI system. The test object is seen through the HOE; the reference, and object beams are overlapped and brought onto the focal plane of the CCD camera to record resultant speckle interference pattern. Lau et al also reported a HOE based ESPI system for vibration studies using stroboscopic illumination [63].

Mihaylova et al reported ESPSI systems using a holographic grating recorded using photopolymer materials [76, 77]. The systems were similar to the one reported by Burkle and Joenathan [57] which incorporates a HOE and diffuser for introducing
shear in the system. The amount of shear in these ESPSI systems was varied either by changing the distance between diffuser and a HOE or by changing spatial frequency of the HOE during its recording. The systems were used to study speckle shearing correlation fringes of a PVC pipe bending and vibrating modes of aluminium diaphragm respectively.

Guntaka et al developed a combined system with a reflection holographic optical element recorded in photopolymer layer for use in holographic interferometry and ESPI [78]. A reflection HOE is used as a beam splitter in an out-of-plane sensitive ESPI. It is adjusted in such a way that there should be no holographic interferometric fringes present in the system. Guntaka et al also reported an out-of-plane sensitive HOE based ESPI using reflection HOE incorporating a laser diode operating in the near infrared region (785nm) [79, 80]. The purpose of using a laser diode was to use its current modulation capabilities for introducing phase stepping in the ESPI system.

A phase shift of $\frac{\pi}{2}$ introduced between five frames and phase map was calculated using a five frame phase shift algorithm.

An out-of-plane sensitive HOE based ESPI system for vibration studies using path difference modulation in an unbalanced ESPI system was reported by the author Bavigadda et al [81]. This system utilized drive current modulation capabilities of a laser diode to modulate the laser wavelength at the same frequency as that of vibrating object for analysis of Bessel fringes in a time average ESPI.

1.3. Motivation for the project

Electronic speckle pattern interferometers using conventional optical elements can be difficult to align and are bulky and expensive. Use of holographic optical elements in
the ESPI systems, can remove the alignment difficulties and makes the system compact and inexpensive. This thesis reports the development of a versatile, compact and low cost electronic speckle pattern interferometer for vibration measurements using holographic optical elements.

**Objectives**

The objectives of the work were the following

- Design and fabrication of reflection holographic optical elements (RHOE) for an out-of-plane sensitive ESPI system for vibration measurements using a near infrared (IR) distributed feedback (DFB) laser diode.
- Design and fabrication of transmission holographic optical element (THOE) for a hybrid HOE based out-of-plane sensitive ESPI system for vibration measurements using a near IR DFB laser diode.
- Development of an out-of-plane sensitive RHOE based ESPI system for vibration measurements using a visible wavelength stabilised laser diode.
- Development of a purely out-of-plane sensitive HOE based ESPI system using a combination of a RHOE and THOE for vibration phase and amplitude measurements.
- Development of reference beam phase modulation by using laser wavelength modulation in an unbalanced out-of-plane sensitive HOE based ESPI systems for vibration (and static displacement) phase and amplitude measurements.
1.4. Summary of thesis

**Chapter 2:** Focuses on theory of various speckle measurement techniques, and discusses practical speckle interferometric systems for precision measurement and their advantages and disadvantages. This chapter also includes various fringe analysis methods, which can be used in speckle interferometry for interpreting measured quantities. Finally phase measurement using laser wavelength modulation is discussed.

**Chapter 3:** Briefly discusses holography, types of holograms and holographic recording materials. Holographic optical elements, and the advantage and disadvantages for their use in speckle interferometry are also discussed.

**Chapter 4:** The fabrication of reflection HOEs for an RHOE based ESPI system and transmission HOEs for hybrid HOE based ESPI systems using a near infrared distributed feedback (DFB) laser diode (763nm) is discussed. The near infrared DFB laser was characterised using a spectrum analyser. Vibration resonant modes of two different test objects are reported. The limitations of these HOE based ESPI systems are also discussed. The reference and object beams in the THOE based ESPI system were studied using histograms in order to balance their intensities.

**Chapter 5:** The use of a visible wavelength (658nm) stabilised diode laser for out-of-plane sensitive HOE based ESPI systems is described. The laser was characterized using an optical spectrum analyser. Vibration phase and amplitude measurements of a circular metal plate using two different HOE based ESPI systems are discussed. Firstly a reflection holographic optical element was used in an out-of-plane sensitive HOE based ESPI system. The algorithm used for generating speckle correlation fringes with high contrast is described. Secondly, the development of a HOE based
ESPI sensitive only to out-of-plane displacement is discussed. In this system two HOEs, a reflection HOE and a transmission grating were used. A modified algorithm was developed for generating speckle correlation fringes with good contrast. The principle of the measurement technique used in both of the HOE based ESPI systems is also discussed. Speckle modulation measurements performed using HOE based ESPI system were also discussed. Finally, static measurement using phase stepping in a HOE based ESPI system is discussed. The chapter summarizes vibration information about the test objects, and concludes with a discussion of the limitations of the HOE based ESPI systems and recommendations for future improvements.

Chapter 6: Sums up the achievements and also discusses future scope of the work.

Appendix: All the MATLAB and LabVIEW codes are discussed in this section.
References


CHAPTER 2

SPECKLE TECHNIQUES

2.1. Speckle effect

When a laser beam illuminates any optically rough surface granular dark and bright spots of random shape and size are formed in space; this effect is called the speckle effect. This effect occurs only when the roughness of the surface is at least comparable to the wavelength of the illuminating light \([1]\). The light scattered from the surface has contributions from many independent scattering centres. Propagation of this scattered light to a distant point results in addition of these scattered components producing speckles. The speckle effect can be observed in two ways, firstly in free space geometry in which the intensity of the interference pattern varies randomly with position, called objective speckle and secondly when the speckle pattern is observed with an imaging system such as a camera and is called image speckle or subjective speckle.

![Figure 2.1 Speckle pattern formation by a coherent light](image)

Figure 2.1 Speckle pattern formation by a coherent light
Fig. 2.1 shows scattering of light in all directions by a rough surface when illuminated by a laser light. The image of the speckle pattern is shown in Fig. 1.1. The bright spots are formed when the interfering beams are in phase and the dark spots are the result of interference of out of phase beams. When a speckle pattern is observed through a very small aperture then the small speckles are eliminated and only large speckles appear. Speckles were considered as noise initially in many experiments but later researchers found that the object motion changes the speckle pattern. This basic property of speckle was used as an information carrier and speckle based measurement techniques were developed for displacement measurement. Speckle patterns have many interesting properties which have been extensively discussed by Goodman [2, 3]. The speckle pattern is extremely complex and has no direct relationship to the macroscopic properties of the object. Speckles can be described quantitatively by the methods of probability and statistics. The probability density function for the intensity in a speckle pattern can be written as

\[ P(I) = \frac{1}{\langle I \rangle} \exp \left( -\frac{I}{\langle I \rangle} \right) \]  

(2.1)

where \( \langle I \rangle \) is the intensity of the speckle pattern averaged over many points in the scattered field and \( P(I) \) is the probability that the intensity exceeds \( I \).

### 2.1.1. Contrast

A measure of the contrast in speckle pattern is the ratio of the standard deviation of the intensity to the average intensity [1]

\[ C = \frac{\kappa}{\langle I \rangle} \]  

(2.2)
\[ \kappa = \sqrt{\langle (I - \langle I \rangle)^2 \rangle} = \sqrt{\langle I^2 \rangle - \langle I \rangle^2} = \langle I \rangle \]  

(2.3)

where \( \langle I^2 \rangle = 2 \langle I \rangle^2 \) [1]. This shows that the fully developed speckle pattern has a contrast of unity [1].

### 2.1.2. Objective and subjective speckle

The schematic for the objective speckle pattern is shown in Fig.2.2. Assume an area of dimensions \( L \times L \) is illuminated by a monochromatic beam of wavelength \( \lambda \).

Figure 2.2 Objective speckle pattern

The scattered rays from the object interfere on a screen which is placed at a distance \( Z \) from the object. The speckle pattern is the result of the interference of large number of scattered rays. The average size, \( \sigma \), of the objective speckles can be expressed as [1]

\[ \sigma = \frac{\lambda Z}{L} \]  

(2.4)

From (2.4) it is clear that the average size of the speckles observed in the light scattered by the rough surface at a given distance from the surface increases as the area illuminated decreases.
The speckle pattern is considered to be made up of a set of gratings of varying spatial frequency. The maximum spatial frequency of the grating formed by the interference of the light scattered from the edges of the illuminated area, hence speckle size depends on size of the illuminated area and the distance from the object to viewing position.

If a speckle pattern is imaged onto the screen using a lens then it is called a subjective speckle pattern. The experimental set up for obtaining a subjective speckle pattern is shown in Fig. 2.3. Light scattered by each point on the object is imaged as a point on the screen. The resultant speckle pattern intensity on the screen is the sum of the all interference patterns produced by scattering from different points on the object surface lying within the resolution limit of the lens, which have been imaged by the lens.

![Subjective speckle pattern](image)

**Figure 2.3 Subjective speckle pattern**

The size of a point in the image is determined the property of the lens called the point spread function. The point spread function describes the irradiance distribution that results from a single point source in the object space. In other words it describes a lens’ ability to image a point. A point source produces diverging spherical waves. To
form an image point, a lens has to produce converging spherical waves. A lens can only image with converging waves that are partly spherical due to its finite aperture. The resulting image is an Airy disc pattern which interferes with other Airy disc patterns from other points within the resolution limit of the lens on the surface of the object to form a speckle pattern with speckle width $\sigma$ given by.

$$\sigma \approx 1.22(1+M)\lambda F$$

(2.5)

where $M =$ magnification of the imaging lens, $F$ is the $f$-number of the imaging system which is given by

$$F = \frac{f}{D}$$

(2.6)

where $f =$ focal length of the imaging lens, $D =$ diameter of the imaging lens. An important point to be noted is that the speckle size can be adjusted by varying the aperture size. This property is beneficial in speckle photography and interferometry.

2.2. Speckle photography

Let us assume that an object is illuminated with a laser beam either obliquely or normally. The object is imaged on to a photographic plate capable of resolving speckle pattern as shown in Fig. 2.4 (a). When the object was at rest its corresponding image was recorded. After the object was loaded, another image of the displaced speckle pattern was recorded on the same plate. We now have two speckle patterns, one of them translated locally by $d$. Now we need to find displacement $d$ at various locations on the plate to obtain the deformation map. To obtain the displacement the recorded and developed photographic negative (specklegram) is placed in a set-up as shown in Fig. 2.4 (b) [4]. The specklegram is illuminated by a parallel beam of laser
light. The specklegram diffracts the illuminated light over a large cone depending on the speckle size. This diffracted light is collected by a lens and observed at the back focal plane of the lens. Physically, the diffracted light is equivalent to the Fourier transform of the amplitude transmittance of the specklegram. The intensity distribution at the Fourier transform plane contains a strong central peak surrounded by light whose intensity decreases with distance from the central peak, and is called the halo. Physically the formation of a halo can be interpreted in the following way.

**Figure 2.4 Speckle photography: (a) Set up for in-plane displacement recording (b) Set-up to observe diffracted field from specklegram at the focal plane of the lens**

Consider a specklegram as a combination of large number of sinusoidal gratings of continuously varying pitch and random orientation. When the specklegram is
illuminated these gratings diffract the laser beam in different directions forming the halo at the focal plane of the Fourier transform lens. When the displacement varies from point to point, then each point on the specklegram is interrogated using a narrow laser beam to obtain the displacement.

2.2.1. Digital cross-correlation fringes (DSPh)

In speckle photography, a recorded double exposure needs to be processed using chemicals, which is a time consuming task and hinders real-time measurements. To speed up the process, the speckle patterns corresponding to displaced and rest positions are recorded using a video camera. These images are used for evaluation of displacement fields. The displacement fields are calculated using a cross-correlation algorithm [5-7]. The algorithm does not follow individual speckle movement; rather it follows the movement of a number of speckles acting as a sub-image. The size of the sub-image determines the spatial resolution of the displacement map. If the sub-image size becomes very small, then it is difficult to find corresponding sub-images in both displaced and undisplaced images and their correlation will decrease. The algorithm finds statistical similarity between the sub-image say $S_1$ of the reference image and the different sub-images of the displaced image. The sub-image scans over the sub-images of the displaced image. Wherever the sub-image of the reference image finds the maximum correlation with the sub-image of the displaced image, that part of the image is considered as sub-image $S_2$ of the displaced image. This process is repeated to find all other sub-images of the displaced image, until the entire displacement field is determined. The height of the cross-correlation provides how similar are sub-images and hence it determines the accuracy of the measurement.
2.3. Fringe patterns in speckle interferometry

Speckle correlation fringe patterns are obtained in speckle interferometry by using addition of fringe patterns corresponding to displaced and undisplaced fringes respectively.

2.3.1. Addition fringes

When a laser illuminated object is displaced the speckle pattern changes from its previous state to a new state. The speckle pattern changes can be detected by encoding the information using the phenomenon of interference of the object beam with a smooth or diffuse reference beam [8]. If two fields or object and reference beams, having complex amplitudes $a_1$ and $a_2$ and intensities $I_1$ and $I_2$ respectively are added coherently the resultant intensity distribution can be expressed as

$$I_{sp} = |a_1 + a_2|^2$$  \hspace{1cm} (2.7)

$$I_{sp} = |a_1|^2 + |a_2|^2 + a_1^*a_2 + a_1a_2^*$$  \hspace{1cm} (2.8)

$$I_{sp} = I_1 + I_2 + 2\sqrt{I_1I_2} \cos(\phi_{sp1} - \phi_{sp2})$$  \hspace{1cm} (2.9)

$$I_{sp} = I_1 + I_2 + 2\sqrt{I_1I_2} \cos(\phi_{sp})$$  \hspace{1cm} (2.10)

where the intensity of the resultant interference pattern is $I_{sp}$. $I_1$ and $I_2$ are the average intensities of the reference and object beams respectively $\phi_{sp1}$ and $\phi_{sp2}$ are their corresponding phases. $\phi_{sp}$ is the random phase of the interference pattern. If the object is displaced then the object beam contains additional phase information about the displacement hence the resultant interference pattern changes to
\( I'_{\text{sp}} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi_{\text{sp}} + \delta) \)  \hspace{1cm} (2.11)

where \( \delta \) is the phase difference due to the object displacement.

The addition of speckle patterns for different object positions gives

\[
I_{\text{add}} = 2I_1 + 2I_2 + 4\sqrt{I_1 I_2} \cos\left(\phi_{\text{sp}} + \delta \right) \cos\left(\frac{\delta}{2}\right) \hspace{1cm} (2.12)
\]

The two interference patterns corresponding to displaced and undisplaced positions are recorded on a single photographic plate called a double exposure specklegram. It may be seen that the first two terms are due to the background random speckle noise and the third term indicates intensity modulation. The third term in equation (2.12) would have maximum value wherever \( \cos\left(\frac{\delta}{2}\right) = 1 \) and would be zero wherever \( \cos\left(\frac{\delta}{2}\right) = 0 \). There is no correlation between the two fields when \( \delta = (2n+1)\pi \), where \( n \) is an integer. When \( \delta = 2n\pi \) then the two fields are correlated. In other words the bright fringes are correspond to correlated speckle fields and dark are correspond to uncorrelated speckle fields.

The fringe patterns in electronic speckle pattern interferometry (ESPI) can be produced by filtering the video signal corresponding to the primary speckle interferograms. In practice the method is applicable to time average case only, for the study of vibration (see Section 2.3.4). The bias component of intensity is removed from the primary speckle interferograms by high-pass filtering of the video signal [9]. The filtering is implemented on the video signal with analogue electronic circuits. The addition technique does not need any image storage or processing but the fringe contrast is poor.
2.3.2. Subtraction fringes

The subtraction of speckle patterns corresponding to displaced and undisplaced positions is predominantly used in electronic speckle pattern interferometry.

The intensity of speckle patterns corresponding to undisplaced and displaced positions is given in eq. 2.10 and 2.11 respectively. The resultant subtracted speckle pattern intensity is represented by

\[ I_{\text{sub}} = I_{sp} - I_{sp}' = 4\sqrt{I_1 I_2} \sin \left( \phi_{sp} + \frac{\delta}{2} \right) \sin \left( \frac{\delta}{2} \right) \]

(2.13)

The dark fringes are formed wherever the two speckle patterns are fully correlated, that is wherever \( \delta = 2m\pi \). The bright fringes would be formed wherever \( \delta(2m+1)\pi \).

The bright fringes are formed wherever the two speckle patterns corresponding to displaced and undisplaced positions of the object are uncorrelated.

2.3.3. Time average ESPI fringes

In the ESPI technique the camera records position dependant intensity at the image plane for the test object. In practice an optical arrangement is used for the measurement of either in-plane displacement components or out-of-plane components. We shall consider an object vibrating harmonically and study the vibration using the time average method. To obtain complete information about the vibration we need to obtain information about position dependant amplitude, frequency and phase of the vibration. Let us consider an out-of-plane sensitive ESPI system for the present discussion.

Let us consider an object driven by a sinusoidal harmonic force with amplitude \( a_0 \) frequency \( \omega \), so the out-of-plane displacement, \( a \), is described as
\[ a = a_0 \cos(\omega t + \varphi_0) \]  

(2.14)

where \( \varphi \) is the phase of the vibration. In an out-of-plane ESPI system the test object is illuminated and observed along its surface normal. The phase difference in the interferometer is given by

\[ \Phi(t) = \frac{4\pi}{\lambda} a_0 \cos(\omega t + \varphi_0) \]  

(2.15)

The intensity measured at the image plane of the camera due to the interference of the object and reference beams can be written as

\[ I_i = I_o + I_r + 2 \sqrt{I_o I_r} \cos[\psi(x,y) + \Phi(x,y,t)] \]  

(2.16)

where \( I_i \) 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.

In the standard time averaging technique it is assumed that the exposure time of the CCD camera is much larger than the period of the oscillation of the test object [9]. The time averaged intensity at the image plane recorded by the CCD camera at each pixel during finite exposure period, \( T \), is given by

\[ I_{av} = I_o + I_r + 2 \sqrt{I_o I_r} \left[ \frac{1}{T} \int_{t-T}^{t-T} \cos[\psi(x,y) + \frac{4\pi}{\lambda} a_0 \cos(\omega t + \varphi_0)] dt \right] \]  

(2.17)

\[ I_{av} = I_o + I_r + 2 \sqrt{I_o I_r} \left[ \frac{1}{T} \int_{t-T}^{t-T} \left( \cos(\psi) \cos\left(\frac{4\pi}{\lambda} a_0 \cos(\omega t + \varphi_0)\right) \right) dt \right] \]

\[ -2 \sqrt{I_o I_r} \left[ \frac{1}{T} \int_{t-T}^{t-T} \sin(\psi) \sin\left(\frac{4\pi}{\lambda} a_0 \cos(\omega t + \varphi_0)\right) dt \right] \]  

(2.18)
[Note: the Bessel function is defined as \( \frac{1}{2\pi} \int_0^{2\pi} e^{i\eta \cos \zeta} d\zeta = J_0(\eta) \)]

The fourth term in Equation 2.18 becomes zero (because sin function is an odd function)

Rewriting equation (2.18) gives

\[
I_{\omega r} = I_o + I_r + 2\sqrt{I_o I_r} \cos(\psi) J_0 \left( \frac{4\pi}{\lambda} a_0 \right)
\]  

(2.19)

So the time averaged intensity pattern consists of a speckle pattern modulated by a zero order Bessel function.

Consider recording of two different interference patterns when the object is in motion.

The first pattern is given by the equation (2.19). The second interference pattern can be obtained by introducing a shift of \( \pi \) to the first pattern and is given by [9]

\[
I_{\omega r}' = I_o + I_r + 2\sqrt{I_o I_r} \cos(\psi + \pi) J_0 \left( \frac{4\pi}{\lambda} a_0 \right)
\]  

(2.20)

Subtracting (2.19) from (2.20) gives the difference of the intensities as

\[
\Delta I = 4\sqrt{I_o I_r} \cos(\psi) J_0 \left( \frac{4\pi}{\lambda} a_0 \right)
\]  

(2.21)

The term \( \cos(\psi) \) varies much more rapidly than \( J_0 \left( \frac{4\pi}{\lambda} a_0 \right) \) so by introducing a low pass filter this term is replaced by its average value. Sometimes the difference of the intensities gives negative values. These values can be removed by calculating the absolute value of the difference of the intensities which is equivalent to the rectification of the electronic signal. The rectified signal is given by [9]
Fringe function \( B = (\Delta I)^2 = 8I_oI_rJ_0^2\left(\frac{4\pi}{\lambda}a_o\right) \) (2.22)

From Equation 2.22 the fringe function is defined as the square of the difference of the two interference patterns. The brightest fringe corresponds to the node of the motion, because the zero order Bessel function is maximum when its argument is zero. The fringe pattern contains no phase information according to Equation 2.22.

The phase information of the motion can be obtained by modulating the optical path difference in the interferometer at the same frequency as that of the vibrating object [10, 11]. It can be shown that by increasing the modulation amplitude of the path difference, we can increase the range of amplitude measurement with this technique.

In this technique even though the test object is in motion, modulation of the path difference effectively freezes object motion. This technique is called temporal heterodyning.

In heterodyne interferometry, the reference beam phase modulation is given by

\[ b = a_r \cos(\omega t + \phi_r) \] (2.23)

The argument of the Bessel function becomes the vector sum of the phasors representing motion of the object and reference beam modulation.

\[ B = 8I_oI_rJ_0^2\left(\frac{4\pi}{\lambda}\left(a_o^2 + a_r^2 - 2a_o a_r \cos(\phi_o - \phi_r)\right)^{1/2}\right) \] (2.24)

In general Equation 2.24 represents a complicated fringe pattern. However for the regions where \( a_o = a_r \) and \( \phi_o = \phi_r \), the Bessel function argument becomes zero, hence the maximum brightness corresponds to the regions of the object which are vibrating in phase with the reference beam. The zero argument of the Bessel function is easy to
move to any place on the object by changing the modulation amplitude of the path length difference. Now the brightest fringe no longer represents the areas with zero amplitude, rather it represents the areas vibrating with the same amplitude as that of the path difference modulation in the interferometer. In general the phase of the vibration can be mapped out by setting $a$, at a given value and noting the region of maximum brightness as $\varphi$ is varied. $a$ can be adjusted to maximize the brightness of the zero order fringe.

2.3.4. Phase shifting with subtraction in time average ESPI

The displacement of the test object is detected by generating ‘secondary correlation fringes’ from primary speckle interferograms by using addition [12] or subtraction [13] of two primary speckle interferograms which are captured at different points in time. To remove the negative values of intensity in the subtracted image, either it is full-wave rectified using absolute values or a square law demodulation is applied. The advantage of using the subtraction method for generating secondary fringes is that it provides high contrast fringes compared to the addition method. A disadvantage of the subtraction technique is that it is highly sensitive to mechanical and environmental instabilities that may occur between the acquisitions of two primary speckle interferograms to be subtracted. The method also requires some form of image storage.

Creath et al. reported image subtraction for observation of time average vibration fringes [14]. In this technique a stored reference frame containing self interference intensities of both object and reference beams was continuously subtracted from incoming images which were captured during vibration. Fringe contrast and signal-to-noise ratio are used for comparison, since these quantities are dependent on the
techniques used. The reference frame was created by vibrating a reference mirror at high amplitude while the object was at rest. Nakadate et al designed a digital speckle pattern interferometer (DSPI) for measuring surface strain and slope of the vibration amplitude using an image shearing camera with a Fresnel bi-prism and digital image subtraction [15]. The images resulting from subtraction were processed with non linear image processing techniques such as image level slicing.

To improve contrast of the vibration fringes in a time average ESPI, a phase shift of \( \frac{\pi}{2} \) was introduced between subsequent frames either in the reference beam or in the object beam. These subsequent frames were subtracted to give high visibility fringe patterns [16, 17]. A phase shift of \( \pi \) increases the visibility compared to \( \frac{\pi}{2} \) phase shift [18]. If the phase shift becomes zero then the subtraction of two fringe patterns with constant amplitude displacements will result in zero.

Vibration fringes obtained using phase stepping in a time averaged electronic speckle pattern interferometer was reported by Joenathan et al. [18]. The contrast of the fringes was relatively high (0.9) for a phase step between 30° and 180° and reached maximum at 180° for extremely low electronic noise and low fringe density. For larger vibration amplitude, high contrast (0.9) fringes were obtained using a \( \pi \) phase shift rather than with a \( \frac{\pi}{2} \) phase shift. The vibration phase stepped (less than \( \pi \)) fringes had the same contrast as those of \( \pi \) phase shifted fringes except that the speckles were smoothed. A phase shift of \( \frac{\pi}{2} \) was introduced between any two frames in a four phase step method. The contrast of the fringes obtained with extra phase steps (0, \( \frac{\pi}{6}, \frac{\pi}{3} \)) in
addition to $\frac{\pi}{2}$ along with incoherent superimposition was higher than the four-phase-step method with only $\frac{\pi}{2}$ phase shift between pairs. The reference update method or subtraction of $\pi$ phase shifted frames that are acquired in sequence was also reported by Moran et al. [19] and Atcha et al. [11]. Garcia et al. used a holographic optical element for spatial phase stepping in ESPI [20]. The HOE diffracts the object beam into four separate orders and introduces equal phase changes between these orders. The secondary correlation fringes were obtained using subtraction of a reference frame from phase stepped speckle patterns.

2.3.5. Phase shifting in addition ESPI fringes

To obtain speckle correlation fringes in ESPI, two speckle patterns corresponding to displaced and undisplaced positions were subtracted. The subtraction technique is widely used to remove background intensity in time average vibration or static deformation studies. It is difficult to carry out measurements in industrial environments using time average or subtraction ESPI methods, because of mechanical and thermal disturbance. Generally measurements carried out using the time average ESPI method, use a CCD camera with frame rate of 25Hz. This means the ESPI system can be stable for exposure periods of the order of 40ms, but speckle interferograms would be decorrelated if the mechanical disturbance exceeds more than a speckle and also if the motion is transient. So to overcome these problems addition of speckle patterns was carried out using an analogue video camera, reported by Cookson et al using pulsed lasers [21].

Moore et al reported addition of speckle patterns in ESPI, using a CCD camera to study deformations in harsh environmental conditions by using a double-pulsed laser
source [22]. They have implemented a phase stepping process to obtain phase information automatically. Generally a four frame phase shifting algorithm is used to obtain phase information by filtering the phase stepped speckle patterns and calculating the wrapped phase [23]. They tried to implement the same four frame algorithm using addition phase stepped fringes by filtering the speckle noise, but the phase information was lost. So they took an alternative approach of implementing a modified three frame phase step algorithm [22]. The algorithm is considered as a two stage process. First, a phase map is calculated which is the combination of random speckle and displacement phase and is given by

$$\phi + \Delta \psi = \tan^{-1}\left(\frac{\sqrt{3}(I_1 - I_2)}{2I_1 - I_2 - I_3}\right)$$  \hspace{1cm} (2.25)

Then random speckle must be subtracted from each pixel. The random speckle phase is calculated from

$$\phi(x, y) = \cos^{-1}\left(\frac{I_1 + I_2 + I_3 - 6I_B}{\sqrt{3(I_2 - I_3)^2 + (2I_1 - I_2 - I_3)^2}}\right)$$  \hspace{1cm} (2.26)

where $I_B = I_o + I_r$ and is estimated using local neighbourhood pixels (43×43 pixels).

From Eq. 2.26 it is clear that two solutions exist for $\phi$ at each pixel. The correct solution at each pixel is chosen by reference to a comparison phase map. The reference phase map is obtained using subtraction fringes and a three frame phase step algorithm [22].

The addition fringe patterns produced by the double pulsed lasers have poor visibility. This problem can be overcome by acquiring two sets of double pulsed addition fringes which are phased to the object’s vibration frequency of interest and these are
subtracted from each other [12]. But if any rigid body motion occurs between the two pulses the addition fringe pattern contains another pattern corresponding to the rigid body motion.

To improve the visibility of double pulsed addition fringes, an alternative approach using digital processing methods was used by Davilla et al [24]. The processing procedure is divided into three steps. In the first step the fringe patterns were enhanced by subtracting the addition fringes from a reference interferogram. In the second step, speckle noise was reduced by applying a spectral subtraction image-restoration method and improved visibility was obtained. The image restoration was carried out as outlined. Two double-pulsed addition fringe sets were obtained and subtracted from one another to obtain improved visibility fringes. A restored image is calculated by subtracting a Fourier transform of the reference image from a Fourier transform of the improved visibility fringe pattern. In this image restoration method subtraction takes place in the Fourier domain hence it is called spectral subtraction image restoration method. In the last step a wrapped phase map was obtained by means of a Fourier transform method with bandpass filtering.

The addition-fringe visibility can also be increased by digital filtering [25]. Some methods that use subtraction of double-pulsed addition fringes may improve fringe visibility, but limit the measurement range. The measurement range can be increased by enhancing the contrast of double-pulsed addition-fringe patterns using a spatial filter based on the local standard deviation of intensity.

The fringe pattern obtained using the addition method has poor visibility but has good environmental noise protection. On the other hand fringe patterns obtained using subtraction method have high visibility. But the acquisition of a pair of speckle
images is controlled by the frame period which is typically of the order of 40ms. The speckle patterns may be prone to environmental and thermal disturbances if these are of shorter period than 40ms. To retain the advantages of the addition as well as of the subtraction method, Pouet et al developed a technique called the additive and subtractive decorrelated ESPI method [26]. This method is the combination of addition and subtraction by introducing interframe speckle phase decorrelation. They used an optical modulator for stroboscopic illumination and a mirror for tilting and hence decorrelation.

2.4. Electronic speckle pattern interferometry (ESPI)

In speckle interferometry the fringe pattern corresponding to the displacement was originally recorded on a photographic film. Instead of using slow photographic processing, electronic recording resulted in a versatile measurement method called electronic speckle pattern interferometry (ESPI). A CCD camera can be used to detect the irradiance. In ESPI a high resolution is not required because the camera only has to resolve individual speckles. The speckles are made larger than a single pixel by adjusting the camera lens aperture (Eq. 2.3). The fringe quality is limited by the number of speckles within a given pixel. Optimum fringe quality can be obtained when the speckles are completely resolved and the reference beam intensity is approximately equal to the average speckle pattern intensity of the object beam.

The continuing interest in the ESPI method is for the following reasons

- Non-contact nature of the measurement with sub-micrometer accuracy
- The possibility to reach remote areas
- Data storage on frame grabbers or video tapes for analysis at a later stage
• Quantitative analysis using phase stepping methods or continuous phase modulation

• Variable sensitivity

The ESPI system can be used for measurement of in-plane and out-of-plane displacement and deformation, strain analysis, surface contouring and vibration analysis. A block diagram of the structure of a HOE based ESPI system is shown in Fig. 2.5. It contains an optical part that generates speckle interferograms, and an electronic part that generates correlation fringes for analysis.
2.4.1. In-plane sensitive ESPI system

In general we wish to measure displacement components in three dimensions. The three axes coordinate system is shown in Fig. 2.6. The coordinate axes Y, Z lie in the plane of the diagram but the X axis is directed outwards. The displacement
components along the Z direction are out-of-plane (OOP) components, and those along X and Y axes are in-plane components.

**Figure 2.6 Optical configuration of an in-plane ESPI system**

In engineering practice obtaining stress and strain information is essential. Fig.2.6 shows an in-plane sensitive ESPI system [27]. It measures in-plane displacement components along the Y axis. In this system two beams illuminate the object at the same angle on either side of the surface normal of the test object. There is no specific reference beam in this system but one of the two beams can act as a reference beam and the other as an object beam. The optical axis of the camera should be along the surface normal to make the system sensitive only to in-plane displacement components. The speckle patterns generated by the two illuminating beams are brought onto the focal plane of the CCD camera using a lens. These two beams interfere and produce a speckle interference pattern. Images of two different speckle interference patterns when the object is at rest and in displaced positions are captured, stored and subtracted one from the other to obtain speckle correlation fringes.
2.4.2. **Out-of-plane sensitive ESPI system**

An out-of-plane sensitive ESPI with a smooth reference beam [27] is shown in Fig. 2.7. For simplicity the laser and some standard optical elements have been omitted. The laser light from the source is divided into two beams using a beam splitter.

![Diagram of out-of-plane ESPI system](image)

**Figure 2.7 Optical configuration of an out-of-plane ESPI system**

One of the beams illuminates the test object and the other serves as a reference beam. The illumination angle $\theta$ must be small so that the system has little sensitivity to the in-plane displacement components and maximum sensitivity to the out-of-plane displacement components. The reference beam is brought in-line with the object beam using a beam combiner by adjusting its position in such a way that the reference beam should appear to come from the centre of the aperture system (to avoid classical interferometric fringes). This alignment is a time consuming task and needs care. The optical axis of the CCD camera must be coaxial with the surface normal of the test object in an out-of-plane sensitive ESPI. Numerous beam combiner methods have been proposed, for example using a cube beamsplitter. The object and reference beams are brought onto the focal plane of the CCD camera to record the speckle interference pattern when the object is at rest and in displaced positions.
2.4.3. Sensitivity vector

Any two beam speckle interferometer is able to measure displacement components. The magnitude of the component is determined by the sensitivity vector, which is a function of illumination and observation directions. The sensitivity vector is also used to establish a relationship between phase change and displacement.

2.4.3.1. Single beam illumination geometry

![Single beam illumination and observation geometry](image)

The geometry of a single beam illumination is shown in Fig. 2.8. Let us assume the test object is illuminated at angle $\theta_1$ to the surface normal and the scattered beam observed at angle $\theta_2$ to the surface normal. Upon deformation the point under observation moves by $\hat{L} = u\hat{i} + v\hat{j} + w\hat{k}$ from its initial position. The phase change due to the displacement is [28]

$$\Phi = \frac{2\pi}{\lambda}(\hat{c}_2 - \hat{c}_1) \cdot \hat{L} = \frac{2\pi}{\lambda} \left[w(\cos \theta_1 + \cos \theta_2) + v(\sin \theta_1 - \sin \theta_2)\right]$$  \hspace{1cm} (2.27)
where \( \hat{c} = \hat{c}_2 - \hat{c}_1 \) is sensitivity vector and \( \hat{c}_1, \hat{c}_2 \) are the propagation vectors along the illumination and observation directions and \( \lambda \) is the wavelength of the laser light.

\( \hat{i}, \hat{j}, \hat{k} \) are the unit vectors along the axes X, Y and Z. \( u, v \) are the in-plane displacement components and \( w \) is the out-of-plane displacement component.

### 2.4.3.2. Out-of-plane ESPI

When \( \theta_1 = \theta \) and \( \theta_2 = 0 \) then the phase change is

\[
\Phi = \frac{2\pi}{\lambda} \left[ w(1 + \cos \theta) + v \sin \theta \right]
\]

(2.28)

It is possible to choose the illumination beam direction close to the surface normal so that the system is sensitive only to out-of-plane displacement components. The phase change is rewritten as

\[
\Phi = \frac{2\pi}{\lambda} (1 + \cos \theta) \ w
\]

(2.29)

When the illumination and observation directions are along the surface normal then the phase change becomes

\[
\Phi = \frac{4\pi}{\lambda} \ w
\]

(2.30)

### 2.4.3.3. In-plane sensitive ESPI

In case of an in-plane sensitive ESPI system the test object is illuminated by two beams on either side of the surface normal. Fig 2.9 shows a general in-plane sensitive ESPI system. The object is illuminated by two beams at angles \( \theta_i, \theta'_i \) respectively. The angles of illumination and observation are measured with respect to the surface.
normal. The angle of observation is $\theta_2$. The scattered beams are observed in the same direction along the propagation vector $\hat{c}_2$. When the object is displaced then the phase changes in both the scattered beams and is related to path length difference as [28]

$$\Phi = (\vec{c}_1 - \vec{c}_2) \cdot \vec{L} = \frac{2\pi}{\lambda} \left[ v \sin \theta_1 \sin \theta_1' + w \cos \theta_1 - \cos \theta_1' \right]$$

(2.31)

Figure 2.9 Geometry of two beam illumination with their propagation vectors

where $\vec{c} = \vec{c}_1 - \vec{c}_2$ is sensitivity vector and $\hat{c}_1, \hat{c}_1'$ are propagation vectors along the two illuminating beams respectively and $\hat{c}_2$ is the propagation vector along the direction of observation.

In a particular case where $\theta_1 = \theta_1' = \theta$ then the phase difference becomes

$$\Phi = \frac{4\pi}{\lambda} (v \sin \theta)$$

(2.32)

This shows that the system is only sensitive to in-plane displacement components.

### 2.4.4. Speckle shearing interferometry

Fig. 2.10 shows an electronic speckle pattern shearing interferometer in a Michelson interferometer configuration. The interferometer consists of two mirrors and a beam.
splitter and detector. The test object is illuminated with a collimated beam at an angle \( \theta \) to the surface normal. The collimated beam is in Y-Z plane. The scattered light from the test object was imaged onto the focal plane of the detector using a lens. Initially a speckle pattern corresponding to test object at rest is captured. A small tilt is introduced in one of the mirrors to introduce a lateral shift \( \Delta y \) between the two speckle patterns. The amount of shear can be varied by changing the amount of tilt in the mirror.

![Diagram of electronic speckle pattern shearing interferometer in Michelson interferometer configuration](image)

**Figure 2.10** Electronic speckle pattern shearing interferometer in Michelson interferometer configuration

Any pixel on the detector records intensity due to the coherent addition of intensity coming from two points on the object. Introduction of shear between speckle patterns produces a fringe pattern sensitive to the rate of change of phase across the object.

A speckle pattern (which is the result of coherent addition of two sheared speckle patterns) corresponding to object at rest, is captured. When the test object is displaced
another speckle pattern is captured by the detector. These two speckle patterns are subtracted to provide speckle fringes sensitive to the rate of change of phase or displacement gradients across the object. When a test object is deformed, an arbitrary point on the object \((x, y)\) is displaced to \((x+u, \ y+v, \ w)\) and a neighbouring point \((x, \ y+\Delta y)\) is displaced to \((x+u+\Delta u, \ y+v+\Delta v, \ w+\Delta w)\). The phase change occurred between the two neighbouring points is

\[
\Delta \Omega(x, y) = \frac{2\pi}{\lambda} \left[ (\sin \theta) \frac{\partial v}{\partial y}(x, y) + (1 + \cos \theta) \frac{\partial w}{\partial y}(x, y) \right] \Delta y
\]  

(2.33)

where \(\theta\) is the angle that the illumination beam makes with the \(Z\) axis. \(\Delta y\) is the shear along the \(Y\) axis, \(u, v\) are the in-plane displacement components and \(w\) is out-of-plane displacement component. \(\frac{\partial v}{\partial y}\) and \(\frac{\partial w}{\partial y}\) are first order partial derivatives of the out-of-plane and in-plane displacements of the deformed object.

For an out-of-plane sensitive shearing interferometer, the strain contours can be represented as

\[
\frac{\partial w}{\partial y}(x, y) = \frac{\lambda}{2\Delta y}
\]  

(2.34)

Some variations in the design of shear elements for shearing interferometers are reported in here [30-32].

2.4.5. Shape measurement with ESPI

ESPI systems can also be used for studying the surface shape and the spatial derivatives of these shapes. The shape of an object can be measured by displacing or tilting the object [33] or using two-wavelength techniques [34, 35] or by tilting the illumination beams [36]. Joenathan et al. reported contouring using an in-plane
sensitive ESPI system [33]. The contour fringes were obtained by subtracting the images corresponding to before and after the tilt of the object. The contours fringes were tilted about one of the planes of the object. These contour fringes are dependent on the tilt and the orientation of the object. The orientation of the contour planes was changed by introducing a small rotation of the object along with the tilt. The contour interval is [33]

\[ d = \frac{\lambda}{2\varphi_i \sin \Theta} \]  

(2.35)

\( \varphi_i = \) angle of tilt; \( \Theta = \) off-set angle of the object

Tatam et al. applied wavelength modulation of laser diode in a fibre-optic ESPI system of contouring surface [34]. Contours of a disc brake hub of height between 0.5-5mm were obtained through switching between two wavelengths of a laser diode by altering its drive current. Peng et al. reported a simple multi-wavelength ESPI system for contouring a diffuse object having a non-flat surface, using a laser diode [35]. The change in the laser diode temperature produces change in the wavelength. The laser wavelength change can also be produced by altering the laser drive current. The change in the drive current induces concurrent change in output power as well, which degrades the fringe contrast. To maintain constant power the temperature of the laser diode was varied in their experiments. This technique was limited by the speckle decorrelation effects due to the change in the wavelength of the laser diode. In a two-wavelength interferometry the contour interval can be calculated using an equivalent wavelength and is [34]

\[ \Lambda_{12} = \frac{\lambda_1 \lambda_2}{2(\lambda_2 - \lambda_1)} \]  

(2.36)

66
Peng et al. also reported a modified dual-beam ESPI system for contouring applications by introducing tilt in the illumination beams while the object was stationary [36]. The shift in the illuminating beams was introduced by shifting the collimating lens laterally. This method has an advantage over single wavelength object tilting method [33] because the object is stable and hence is suitable for many practical engineering applications.

Contouring three dimensional objects was carried out with an ESPI system in combination with a fringe-projection technique [37]. The shape of these objects was measured by introducing small shifts in the position of the optical fibres which carry the object and reference beams. When the optical fibre that was delivering the object beam was shifted slightly, and the object beam was given a small translation then grid contour fringes superimposed upon the image were obtained upon subtraction of the speckle images. When the object was slightly tilted along with object beam shift a fringe pattern is produced representing the depth of the object.

Groves et al. reported shape and slope measurement using a source displacement shearographic system [38]. The correlation fringes formed by a shearographic system by source displacement contain carrier fringes along with the speckle fringes representing slope. In this system the sensitivity of the correlation fringes to slope depends on the angle between the illumination and camera optical axis, applied shear and the distance by which the source is displaced. When the source is displaced in the direction orthogonal to the illumination direction the carrier fringes are minimized. A source displacement in the source-object direction would produce carrier fringes. So minimizing the source displacement in the source-object direction would minimize the generation of the carrier fringes. A three phase step algorithm provides a phase
map. Another phase map was obtained using a flat plate and this phase map was used for correcting the phase map to obtain shape information of the object.

2.4.6. ESPI with vibrating object

Vibration of a test object can be harmonic, anharmonic or transient. The time average principle is widely used for the measurement of harmonic vibrations, while pulsed illumination is used for the measurement of anharmonic or transient object deformations. Pulsed illumination is of two types, one is dual-pulse illumination and the other is stroboscopic illumination. In case of pulsed illumination for harmonic vibration measurement two laser pulses are synchronised at the turning points (or at any two points) of the object vibration. Two specklegrams are captured at these points and are correlated to form fringe patterns representing object deformation between the points [39]. The disadvantage of dual-pulse ESPI is that it usually requires high power lasers.

Stroboscopic ESPI is generally used for the measurement of harmonic vibrations of large amplitudes which cannot be measured using time-average ESPI principle. In stroboscopic ESPI, a train of pulses whose frequency is the same as that of the object vibration frequency, the duration of the pulses being shorter than the object vibration period, illuminates the test object [40]. The resultant fringe pattern has cosine intensity distribution. The phase of these cosine fringes can be extracted using a phase stepping technique. The description of speckle interferograms of a vibrating object in ESPI is simplified by using the concept of fringe function, which was introduced by Stetson [41] for holographic interferometry and later extended to the ESPI technique.
2.5. **Practical ESPI systems**

In general all the ESPI systems built using conventional bulk optical components such as beam splitter/combiner, mirrors etc are categorized into two divisions based on the nature of the reference and object beams.

In the first case consider an interferometer which consists of a smooth reference beam and a speckled object beam. The statistics of the resultant speckle pattern depart from those of original object speckle pattern. In the second case consider an interferometer consisting of speckle reference and object beams. The resultant interference pattern is also a speckle pattern but statistically it is very similar to the original speckle patterns.

**2.5.1. Smooth and speckle reference beam in ESPI systems**

A smooth reference beam based ESPI system is shown in Fig. 2.11 [42]. Collimated laser light illuminates the test object using a beam splitter. The optical elements such as lens and beam combiner are arranged in such a way that the references beam should appear as if it is originating from the centre of the lens aperture system.

![Figure 2.11 Out-of-plane ESPI system with smooth reference beam](image)

*Figure 2.11 Out-of-plane ESPI system with smooth reference beam*

(BS- Beam splitter; BC- Beam combiner; MO- Microscopic objective)
This is required to avoid the spatial carrier fringes results from the misalignment of the optical elements.

A speckle reference beam based ESPI system is shown in Fig. 2.12 [42]. A beam splitter is used for illuminating test object as well as reference surface. The scattered light from the test object serves as object beam and the reference surface generates a speckled reference beam. The alignment of optical elements for beam collection is easy as the both the beams are speckled in nature. The lens aperture system is used for resolving the speckle pattern by the detector by adjusting the f-number.

The problem is that the modulation intensity distribution obtained from a speckled reference beam system differs from that obtained from a smooth reference beam system in that the number of points or pixels which modulate weakly, or not at all, is significantly greater. This leads to a reduction in fringe contrast and the need to replace low modulation pixel values by a suitable combination of near neighbour values.

![Diagram of Out-of-plane ESPI system with speckle reference beam](image)

**Figure 2.12 Out-of-plane ESPI system with speckle reference beam**
2.5.2. Fibre-optic based ESPI system

The experimental arrangement of fibre-optic based ESPI system is shown in Fig. 2.13 [11]. A diode laser (LD) operating at 785nm was coupled into a directional coupler (DC) through an optical isolator (OI), microscopic objective (MO) and micro-positioning (MP) system. The optical isolator was used to reduce feedback into the laser, which may cause unwanted effects on the laser output power. The intensity ratio of the reference and object beam can be varied with the directional coupler. The light scattered by the object was collected by a lens and combined with the reference beam on the focal plane of the CCD camera using a beam combiner. The fibre optic state of polarization (SOP) controller in the input fibre was used to ensure that the SOPs of the object and reference beams were matched. The controller consists of two fibre coils of a length sufficient to produce a $\pi$ retardation in the first coil and a $\pi/2$ retardation in the second coil.

The reference beam delivering fibre was wrapped around a hollow piezoceramic cylinder to produce a phase shift of $\pi$ by applying an external voltage. The piezoelectric modulator was used to modulate the path length and hence the phase of the reference beam. The signal processing unit was used to generate all the waveforms required to heterodyne the interferometer. Two sinusoidal waveforms were generated at the same frequency, but with different amplitudes and phase, one to drive the test object and the other to either modulate the laser drive current or to control the piezoelectric modulator. The correlation fringes were obtained by subtracting two successive images corresponding to two different object positions. The contrast of the fringe pattern was enhanced by introducing a phase shift of $\pi$ between successive images. The $\pi$ phase shift was introduced continuously between successive images by the fibre wrapped piezoelectric modulator.
Figure 2.13 Experimental arrangement for out-of-plane sensitive ESPI implemented using single mode optical fibre and a laser diode [11]

The fibres used in interferometry are normally single mode. The basic requirement of the single mode fibre is that the core diameter should be small enough to restrict transmission to single mode. The number of modes allowed in a given fibre is determined by the material of the fibre, the wavelength of the light passing through the fibre and the core diameter of the fibre.

Advantages of using single mode fibre-optic ESPI system

(a) Remote objects can be tested
(b) No alignment is required once the light is coupled to fibre. Some of the bulk optical elements in conventional systems can be replaced by compact fibre optical elements such as directional couplers.

Disadvantages of using fibre-optic based ESPI system

Two difficulties arising from the small core diameters of single mode fibres are
(a) The efficiency with which light can be coupled into the fibre core is limited.

(b) The power density of the guided beam is high, which leads to limiting power handling capacity.

(c) An important limitation in using optical fibres in ESPI system is the high phase sensitivity to temperature fluctuations.

In the interferometer fibres cause often a problem with feedback of light into the laser cavity. This becomes a serious problem when diode lasers are used. The main source of feedback is the reflection from the ends of the fibre, both at the input and output. This can be reduced by preparing ends of the fibre so that they are at an angle to the normal, so that the feedback light is steered away from the laser. However such measures are not sufficient to reduce feedback completely and a Faraday optical isolator must be used.

2.6. Fringe analysis

Electronic speckle pattern interferometry has a very important feature, producing correlation fringes in real time corresponding to the displacement of the object. The correlation fringes provide useful information about the displacement of the object, but have a few drawbacks such as the fact that it is impossible to determine the sign of the phase change from the fringe pattern alone. The motivation for analysing the fringe pattern is to convert it into a form of data that can be related to the physical quantities of interest. The initial developments in fringe analysis were the image processing techniques such as skeletonising and fringe tracking that were used to indentify fringe maxima and minima [43]. These are entirely intensity based methods but phase distribution extraction methods are widely used at present.
Phase extraction process generally consists of four main stages as shown in Fig 2.14 [44]. The intensity distribution is specified by \( I(x, y, t) \), where \( x \), \( y \) are spatial indices and \( t \) the time index. The phase shifted versions of the intensity captured at different instants of time are digitized and stored in the electronic hardware. In the first stage, the wrapped phase, \( \Phi_{\text{wrap}}(x, y, t) \) is extracted by measuring the fringe intensities when known phase shifts are introduced between the interfering beams. The phase shift can be a function of either of position in the image or of time. The two cases are known as spatial and temporal phase shifting respectively. Phase shifts of 60° or 90° or 120° (constant unknown phase shifts can be introduced) between consecutive speckle patterns. The next step is the calculation of the phase map. The phase lies in the range \((-\pi, \pi)\). If the true phase is greater than \( \pi \), then the measured value will be 2\( \pi \) lower. This type of discontinuity or jump in phase change value is known as wrapped phase. Phase unwrapping is a process carried out to remove the discontinuities in phase change by adding integral multiples of 2\( \pi \) to the phase change.
Figure 2.14 Analysis of speckle interferograms

Then following displacement of the object a second unwrapped phase map is calculated and the change in phase \( \Delta \Phi_{\text{wrap}}(x, y, t) \) due to displacement is obtained by subtracting the maps from one another. The unwrapping process can be carried out either along one or more of the spatial axes or along the time axis. The final step is the conversion of unwrapped phase map \( \Delta \Phi_{\text{unwrap}}(x, y, t) \) to the parameter of interest in the coordinate system of the object. If this is a displacement map \((u, v, w)\), then a simple conversion factor \( \frac{\lambda}{4\pi} \) is needed. If a strain map \((\varepsilon)\) is of interest then numerical differentiation is necessary.

2.6.1. Digital phase shifting in ESPI

In ESPI correlation fringes having dark and bright regions are produced either by image subtraction or addition. Fringe counting measurements cannot provide
complete information of the deformation of the object surface. Sometimes it is hard to find fringe centres as well. So, quantitative data in speckle interferometry can be obtained using a phase shifting or stepping method. The phase of the test object relative to the reference wave can be obtained using intensities of multiple phase shifted speckle patterns. The phase shifted fringe patterns are produced by stepping the relative phase between the interfering beams at constant time intervals in a controlled manner, by using a modulator either in the reference beam or in the object beam. These phase shifted speckle patterns are combined using either a 3 frame or 4 frame or 5 frame algorithm. The phase value at each point on the object is calculated using an arctan function for the ratio of intensity differences using one of the above mentioned algorithms. This phase map contains some phase jumps due to the random nature of the speckle; the calculated phase map is called as modulo 2π phase map. This method can provide a highly accurate phase map if the ambient conditions are stable or well controlled. Creath reported for the first time phase shifting in a digital speckle pattern interferometry [45]. In this method each data frame was obtained by integrating intensity over the time it takes to move the piezoelectric transducer through 2α=90° change in phase. A four frame Carre algorithm was used to calculate phase modulo 2π map. The bad data points with low modulation were removed by applying median windows of different sizes.

**Phase stepping algorithms:**

*Three frame phase stepping algorithm*

\[ I_{f,n+1} = I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos \left( \phi_r + \Delta \phi + \frac{2n\pi}{3} \right) \]  \hspace{1cm} (2.37)
where $n = 0, 1, 2, \ldots$ $\varphi_R$ is the phase difference between object and reference beams, $\Delta \varphi$ is the phase difference due to the object deformation or displacement.

Phase-stepped speckle patterns are obtained as [46]

$$I_{j,n+1}' = I_{j,n+1} - I_j,$$  \hspace{1cm} (2.38)

$$I_{j,n+1}' = 4\sqrt{I_1 I_2} \sin \left( \varphi_R + \frac{\Delta \varphi}{2} + \frac{n\pi}{3} \right) \sin \left( \frac{\Delta \varphi}{2} + \frac{n\pi}{3} \right)$$ \hspace{1cm} (2.39)

In Eq. 2.37 three variables are unknown, the background intensity $= I_1 + I_2$, modulation intensity $2\sqrt{I_1 I_2}$ and $\Delta \varphi$ phase difference due to the object motion. To determine these parameters we need at least three phase shifted speckle patterns.

From Eq. 2.38 the phase difference for three frame phase shifting method is calculated as [47]

$$\Delta \varphi = \tan^{-1} \left( \frac{\sqrt{3} (I_1' - I_3')} {2I_1' - I_2' - I_3'} \right)$$ \hspace{1cm} (2.40)

Where $I_1', I_2', I_3'$ are the intensities of the interferograms with phase steps of $0, \frac{2\pi}{3}, \frac{4\pi}{3}$ respectively.

Four frame phase stepping algorithm

Another popular algorithm to calculate phase difference is a four frame algorithm. After loading the test object four phase shifted images are obtained corresponding to phase shifts of $0, \frac{\pi}{2}, \frac{3\pi}{2}$ respectively. The phase difference is calculated as [48]
\[ \Delta \varphi = \tan^{-1} \left( \frac{I'_1 - I'_2}{I'_1 - I'_3} \right) \] (2.41)

where \( I'_1, I'_2, I'_3, I'_4 \) are the intensities of the interferograms with phase steps of \( 0, \frac{\pi}{2}, \frac{3\pi}{2} \) respectively. The disadvantage of this algorithm is that it is more susceptible to errors induced by the miscalibration of the phase shifting device.

**Five frame phase stepping algorithm**

The five frame algorithm was proposed by Schwider et al [49] as an improvement to the four frame algorithm. The concept of the algorithm is to eliminate the phase error by using a suitable combination of sets of phase shifted images (first four frames as set 1 and next four frames as set 2 chosen from five frames). The phase difference is calculated as [50]

\[ \Delta \varphi = \tan^{-1} \left( \frac{2( I'_1 - I'_4 )}{I'_1 - 2I'_3 + I'_5} \right) \] (2.42)

where \( I'_1, I'_2, I'_3, I'_4, I'_5 \) are the intensities of the interferograms with phase steps of \( -\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi \) respectively.

The sources of errors for phase difference map are, continuously changing background intensity, inaccurate phase steps between the phase shifted images and non-linear (relationship between the input and output of an image is not linear) nature of the camera [50, 51].
2.6.2. Phase modulation in time average ESPI

The time average ESPI method is widely used for vibration studies. Direct use of the time average method does not provide phase information. When an object is vibrating sinusoidally at higher frequency, then its motion may be complex. It is necessary to measure both the amplitude and phase distribution across the object to determine the complete object motion. For the first time Aleksoff has demonstrated phase modulation in a time averaged holographic interferometer [52]. These fringes were obtained when the reference beam is modulated at the same frequency as that of the vibrating object. The resulting holographic reconstruction shows the combined effects of vibration amplitudes and phases. In this way relative phases of vibrating object points can be determined.

Phase modulation can be produced using different methods which are categorized into two different groups. The first group is comprised of those methods which produce phase shift within the interferometer such as a moving mirror, moving grating, translating a glass plate, rotating a half wave plate or analyser, or acousto-optic or electro-optic modulators. A mirror driven by piezoelectric transducer was the most commonly used method for modulating the phase of a reference beam in ESPI [53]. One of the ways of producing phase modulation is by rotating a half wave plate (birefringent crystal). This introduces a frequency shift in circularly polarized light passing through the birefringent crystal [54]. A radial grating which can be rotated about its axis was used for producing frequency offset [55]. The physical origin of the frequency shift produced by a moving grating is the Doppler effect. A phase-shifting electronic speckle pattern shearing interferometer with a very simple shearing device is reported by Mihaylova et al [56]. Two partially reflective glass plates were used to
introduce the shear in the interferometer. One of the glass plates was driven by a piezoelectric transducer for introducing phase shifting.

It is known that the Bragg reflection of light by travelling ultrasonic waves in water produces a shift in the frequency of light which is identical to the ultrasonic driving frequency [57]. This effect was used for shifting light frequencies in optical heterodyning techniques. The frequency shifted light component can be separated from the unshifted light beam. This method was employed for optical phase modulation and the device used for phase modulation is an acousto-optic modulator. Some researchers have incorporated a Pockels cell for phase modulation in the interferometer [58]. A Pockels cell consists of an electro-optic crystal such as Lithium Niobate. The polarization state of the light beam propagating along a particular optical axis in the crystal can be changed by applying a variable voltage. The disadvantage of the methods mentioned [54-58] is that the components are internal to the interferometer, susceptible to spurious phase modulations and great care has to be taken for their alignment. When a PZT is used for phase modulation by vibrating reference mirror in the interferometer as reported by Lokberg and Hogmoen [53], the PZT may respond nonlinearly to applied voltage. So the PZT has to be calibrated at all frequencies of the vibrating object of interest of which is a disadvantage.

On the other hand the required change in phase can be produced by controlling the laser source. Induced current modulation in semiconductor laser diodes was presented by Dandridge and Goldberg [59]. Current modulation in laser diodes causes two effects. Firstly amplitude modulation due to the change in the operating point of the laser and secondly frequency shifts of emission due to the induced change in the optical path length of the laser cavity. Tatam et al exploited the wavelength modulation capability of a laser diode for surface profiling [34]. A phase-shifting
speckle interferometer was reported by Kato et al by using the frequency modulation of a laser diode for automatic deformation measurements [60]. Frequency modulation was achieved by modulating the temperature of the laser diode. Temperature of the laser diode was modulated for introducing phase shifting because the injection current change causes mode hopping and large alternating bias intensity in the interferograms and the assumption of constant intensity of speckle interferograms for phase extraction is violated. Atcha and Tatam successfully used the wavelength modulation capability of laser diodes via injection current modulation in a fibre-optic ESPI system and demonstrated extraction of constant amplitude and phase contours of a sinusoidally vibrating object [11]. These fiber-optic based ESPI systems were modified as speckle shearing interferometers and used for measuring phase maps and thus gradient of displacements of a vibrating object [61]. The laser diode wavelength was modulated for introducing phase stepping in a compact reflection holographic optical element based ESPI system [62]. The laser was operating in the near infrared region at 784nm. The laser wavelength was modulated by altering its injection current and a 5 frame algorithm was used for phase map calculation of static displacements.

2.7. Summary

The formation of speckle pattern and some statistical properties have been discussed. Speckle patterns are observed in free space as well as with imaging lenses. The difference between the two cases is discussed. The development of speckle interferometry starting from speckle photography followed by speckle interferometry and electronic speckle pattern interferometry has been discussed. Various speckle correlation fringe detection methods including time average fringe generation are discussed. The nature of the displacement (in-plane or out-of-plane components) measurements depends on illumination geometry in speckle interferometry. Hence the
sensitivity vectors are derived corresponding to in-plane and out-of-plane ESPI configurations respectively. Practical implementation of ESPI systems based on the nature of the reference beam such as speckle or smooth reference beam are discussed. Compact ESPI systems implemented using optical fibres and their advantages and disadvantages are discussed. Finally, phase extraction techniques such as digital phase shifting techniques in ESPI are discussed. In case of vibration measurements time average ESPI technique combined with phase modulation techniques to obtain phase maps are also discussed.

In the next chapter holographic optical elements (HOEs) and their fabrication and use in ESPI systems are discussed.
References


CHAPTER 3

HOLOGRAPHIC OPTICAL ELEMENTS (HOEs)

In the previous chapter speckle techniques were discussed. In this chapter the principle of holography and its application to holographic optical elements will be discussed.

3.1. Introduction

Photography is method of recording an image of a three dimensional object by using spatial variation of intensity of the light scattered from the object. A photograph does not contain relative phases of light waves originating from the different parts of the object. So a photograph contains only a two dimensional image of a three dimensional object. Significant information about an object is obtained only when the relative phases of light waves from different points on the objects are also recorded. This is possible using holography, which uses interference of an object beam with a reference beam. The object and reference beams must be derived from the same coherent light source. The recorded image is retrieved by illuminating the hologram with a reference beam. The reference beam is diffracted by the hologram during the retrieval stage. The retrieved image is a true replica of the original three dimensional object.

3.2. Hologram formation

A hologram is recorded on a photographic plate as an interference pattern due to the object and reference beams. The hologram is reconstructed to retrieve the object information by illuminating the developed photographic plate with the original reference beam. Fig. 3.1 shows a schematic of formation of a hologram.
The complex amplitude due to the object beam at any point \((x,y)\) on the photographic plate is given by [1]

\[
o(x, y) = |o(x, y)| \exp[-i\delta(x, y)]
\]

(3.1)

while that due to the reference beam can be expressed as

\[
r(x, y) = r \exp[i2\pi\zeta x]
\]

(3.2)

Where \(\zeta = \sin \theta/\lambda\)

So the resultant intensity at any point on the photographic plate, is given by

\[
I(x, y) = |r(x, y) + o(x, y)|^2
\]

(3.3)

\[
I(x, y) = r^2 + |o(x, y)|^2 + 2r|o(x, y)| \cos[2\pi\zeta x + \delta(x, y)]
\]

(3.4)
The amplitude and phase of the light scattered from the object are encoded as amplitude and phase modulation respectively of a set of interference fringes equivalent to a carrier fringe pattern of spatial frequency $\zeta$.

The amplitude transmittance of a processed photographic plate is assumed to have a linear relationship with intensity of the interference pattern $I(x, y)$, so the resultant amplitude transmittance of the hologram is [1]

\[
t(x, y) = t'_o + \beta T |o(x, y)|^2 + \beta T r \exp[-i2\pi\zeta(x, y)]o(x, y)\exp[-i\delta(x, y)] + \beta T r \exp[i2\pi\zeta(x, y)]o(x, y)\exp[i\delta(x, y)]
\]

(3.5)

where $t'_o = t_o + \beta T r^2$ is the constant background transmittance.

When the processed hologram is illuminated with the original reference beam as shown in Fig.3.2, the amplitude of the transmitted wave is

\[
u(x, y) = t'_o r \exp[i2\pi\zeta x] + \beta T r |o(x, y)|^2 \exp[i2\pi\zeta x] + \beta T r^2 o(x, y) + \beta T r^2 o^*(x, y)\exp[i4\pi\zeta x]
\]

(3.6)

Where * denotes complex conjugate.

The first term in (3.6) represents the transmitted beam. The second term represents a halo around the transmitted beam. Third term is identical to the object wave, but represents a virtual image of the object in its original position. The fourth term represents conjugate of the object wave which is a real image. By recording and illuminating with an off-axis reference beam the conjugate object wave and transmitted wave can be spatially separated from the virtual image wave as shown in Fig.3.2.
3.3. Types of Holograms

Holograms are divided into two categories, transmission and reflection type holograms based on their recording geometry. In both cases the principle of image formation is same. The object and reference beams approach from the same side of the photosensitive medium to record a transmission hologram whereas they approach from opposite sides to record a reflection hologram.

3.3.1. Transmission holograms

The recording geometry of a transmission hologram is shown in Fig. 3.3 [2]. The laser beam from the source is divided into two parts by a beam splitter (BS). One of the beams is reflected by a mirror (mirror 1) and spatially filtered (by SF1) to illuminate the test object. The scattered light from the object surface serves as an object beam. The other beam from the beamsplitter is reflected by a second mirror (mirror 2) and spatially filtered (SF2) to act as a reference beam. The object beam and reference beams interfere at the plane of the photographic plate to record a transmission hologram, which is a generalized grating structure. The hologram of the object is
reconstructed by illuminating with the reference beam after the development of photographic plate.

![Figure 3.3 Recording geometry for a transmission hologram](image)

### 3.3.2. Reflection holograms

The recording geometry of a reflection hologram is shown in Fig. 3.4 [2]. In reflection hologram recording, the object and reference beams travel in opposite directions and interfere at the plane of the photographic plate. A laser beam from the source is divided into two parts by a beamsplitter. One of the beams is reflected by the mirror and spatially filtered to illuminate the object and provide the object beam. The other beam is spatially filtered and serves as reference beam. After the development of the photographic plate the holographic image is reconstructed with the reference beam. When illuminated with a white light, the reflection hologram reconstructs the holographic image at the Bragg angle corresponding to the recording wavelength. The angle of reconstruction depends on the reconstructing beam wavelength.
3.4. Recording materials

A hologram is recorded by interfering an object beam and a reference beam that are derived from the same laser source. An ideal holographic material should have the following features. It should resolve the fine interference pattern produced by the object and reference beams, have high diffraction efficiency, low scatter and high sensitivity [2, 3]. There are many photosensitive materials available for holographic recording. Out of these materials, silver halide emulsions and dichromated gelatin are successful in recording high efficiency transmission and reflection holograms [4, 5]. In the following sub-sections two important recording materials, silver halide emulsions and photopolymers are discussed. Each of these materials has some advantages and drawbacks.

3.4.1. Silver halide photographic materials

In silver halide photographic emulsions, silver halide (AgH where H is typically bromine Br) is present in the form of micro-crystals or grains dispersed in gelatin. The
silver halide molecules dissociate into positive silver and negative bromine ions. When a photographic emulsion is illuminated with laser light, the light energy is absorbed by the negative bromine ion releasing an electron which combines with the silver ion to form a neutral silver atom.

\[ h\nu + Br^- \rightarrow Br + e^- \]  (3.7)

\[ e^- + Ag^+ \rightarrow Ag \]  (3.8)

A single silver atom is not stable, so if a second halide ion releases another electron that can be trapped by a second silver ion a more stable two atom silver speck is formed. Four silver atoms formed in this way form a stable silver speck or latent image. This latent image is converted into a visible photographic image by a chemical development process. The developer solution contains a reducing agent which targets grains containing stable silver specks and reduces all the silver halide ions in such grains to silver atoms. The unexposed parts of the photosensitive film can be removed by acid fixing which removes unexposed silver halide leaving pure gelatin and causes local emulsion shrinkage, which is to be avoided in such applications as holographic data storage and reflection display holography. This process results in an amplitude hologram with low diffraction efficiency.

Bleaching transforms the amplitude hologram into a phase hologram, which has much higher diffraction efficiency, by converting the opaque developed silver back into silver halide whose refractive index differs from that of the pure gelatin. In this way the original modulation of the optical density or opacity of the amplitude hologram is converted into modulation of the refractive index and thickness. This bleaching process is called rehalogenation.
An alternative bleaching method called reversal bleaching removes the developed silver grains as soluble silver salt leaving the undeveloped silver bromide. No fixing is needed.

In yet another method a rehalogenating bleach can be used without fixing. The developed silver is converted to a silver halide as before but silver ions also diffuse from unexposed regions into exposed regions a process which dominates at very high spatial frequencies. This method is effective at preventing shrinkage of the emulsion as no material is removed.

The purpose of bleaching is to transform the variation in the optical density in the hologram into variation in the thickness or refractive index or both. In an amplitude hologram the intensity of reconstructing light decreases as it passes through the hologram and its amplitude changes depending on how opaque are the different parts on the hologram, so the hologram is called an amplitude hologram. In a phase hologram technique the variation in the optical density is converted into variation of refractive index or thickness or both. In reconstruction due to the variation of the refractive index or thickness the optical path of the reconstructing beam is altered and thus phase is altered, as it passes through the completely transparent hologram. This type of bleaching produces a phase hologram. A phase hologram can be 100% efficient while an amplitude hologram achieves only 3.7% efficiency at maximum.

The major drawback of the silver halide materials is the requirement for wet processing of the emulsions. Silver halide emulsions are not very suitable for applications such as holographic interferometry and data storage. The advantages of silver halide emulsions for recording holograms are that they are readily available, low cost, environmentally stable and possess long shelf life.
3.4.2. Photopolymers

Photopolymers became popular in recent years [6-8]. The advantages of photopolymers are that because of their self developing capability no chemical processing is required, they are easy to prepare, durable and low cost. Photopolymer materials also have some disadvantages such as poor photosensitivity, low refractive index modulation and but produce scatter free holographic images due to their grainless structure. A photopolymer consists of the following components, a monomer, a photosensitive dye, initiator and a binder [6, 7].

A hologram is formed in the photopolymer due to the refractive index modulation that arises from several photochemical and photophysical processes which occur during photopolymerization. The photopolymerization process can be divided into in three steps, initiation, propagation and termination.

When a dye molecule $D$ is exposed to light of a particular wavelength, within its absorption band, it is excited to a singlet state $D_1^*$

$$D + h\nu \rightarrow D_1^*$$

The singlet state dye molecule is very unstable. It can return to ground state either by emitting a photon (fluorescence) or by transferring nonradiative energy to another molecule (electron donor –ED) this process is called fluorescence quenching.

$$D_1^* \rightarrow h\nu + ED \text{ (fluorescence)}$$

$$D_1^* + ED \rightarrow D + ED \text{ (fluorescence quenching)}$$

The singlet state dye molecule may undergo some intersystem crossing into the triplet excited state which is a more stable state with a longer lifetime.
The dye molecule in the triplet state may return to ground state by nonradiative decay (triplet quenching). However due to the longer life time of the triplet state, the dye molecule in triplet state can react with an electron donor and forms a free radical. Tryethanolamine (TEA) $\left(HOCH_2CH_2\right)_2N$ is used as an electron donor in the photopolymer.

$$D_3^+ + \left(HOCH_2CH_2\right)_2N \rightarrow D^- + \left(HOCH_2CH_2\right)_3N^+ \quad (3.13)$$

The TEA radical becomes an uncharged free radical by losing a proton.

$$\left(HOCH_2CH_2\right)_3N^+ \rightarrow \left(HOCH_2CH_2\right)_2NCH^+CH_2OH + H^+ \quad (3.14)$$

The polymerization is initiated by these TEA free radicals in the presence of a monomer. The initiating free radical breaks the carbon-carbon double bond of the monomer and shares the free electron with $\pi$ electrons of one of the carbon atoms. This process leaves a carbon bond with an unpaired electron. Acrylamide denoted by $ACR$ is used as a monomer in the photopolymer.

$$TEA^+ + ACR \rightarrow TEA - ACR^+ \quad (3.15)$$

This free radical monomer behaves in a similar fashion as explained above by breaking the carbon-carbon double bond and another monomer molecule unit. In this way the monomers are converted to polymer and the chain increases in size each time by one monomer molecule. The polymerization continues until the monomer is consumed or by termination reaction. The termination reaction of free radical polymerization takes place in two different ways namely disproportionation or
combination. The disproportionation occurs by the abstraction of a hydrogen atom of one of the polymer chains by another leading to double bond formation.

$$ACR_m^\cdot + ACR_n^\cdot \rightarrow ACR_m + ACR_n$$  \hspace{1cm} (3.16)

The polymerization can be terminated by the combination free electrons of the two free radical polymer chains by forming a covalent carbon-carbon bond. In this case the two radical polymer chains combine to form a single long polymer chain.

$$ACR_m^\cdot + ACR_n^\cdot \rightarrow ACR_{m+n}$$  \hspace{1cm} (3.17)

The monomer free radicals react with dye radical and cause dye bleaching in the form of a dyhydro dye. This is also an important process in recording mechanism of photopolymer. The polymerization mechanism converts carbon-carbon double bonds of monomer to single carbon-carbon polymer bond which decreases molecular refractivity. This process is accompanied by the concentration changes in monomer which also contributes to a difference in refractive index between the polymerized and unpolymerized regions.

3.5. **Holographic optical elements (HOEs) in ESPI systems**

Conventional optical elements are used for specific functions, for example sending light rays in a particular direction. These optical elements use their shape to redirect rays by reflection or refraction. Optical elements such as beam splitters/combiners, lenses, collimators, diffraction gratings and filters can be constructed holographically by interfering two laser beams and are called holographic optical elements (HOEs). These HOEs work on the principle of diffraction and are used as alternatives to conventional optical elements in many applications [9-11]. One such application is the use of HOEs in speckle interferometry. Archbold and Ennos [12] pointed out that the
use of lenses in speckle interferometry limits the number of observable correlation fringes. To overcome this problem HOEs can be used in speckle interferometry, giving diffraction limited performance [13].

The important features of HOEs are

- Wavelength selectivity
- Lightweight, because they are fabricated in layers of the order of tens of μm in thickness
- Fabrication of a HOE is relatively cheap and easy because no precision shaping of a surface is required
- Multiple optical elements can be recorded on a single photographic plate, hence spatial overlapping of optical elements are possible
- HOEs can generate unique optical functions that are not possible by conventional reflective or refractive optical elements, so they provide greater flexibility in system design.
- A HOE functions independently from the substrate geometry (i.e. shape independent). This feature strongly contrasts with conventional optical elements.

HOEs are sensitive to environmental changes but some of the holographic recording media such as silver halide emulsions are well developed and able to resist environmental effects for a long time. Fig. 3.5 (a) shows schematically lens characteristics of a HOE [14]. A single HOE can be made to work as a lens, beam splitter and spectral filter simultaneously (shown in Fig. 3.5 (b)). This demonstrates that a HOE can serve multiple functions.
Figure 3.5 Characteristics of holographic optical elements

3.5.1. Developments in speckle interferometry using HOEs

In principle a HOE can be used as a beam splitter/recombiner in a speckle reference beam ESPI system without the losses associated with conventional optics. Holographic optical elements have been used for in-plane and out-of-plane displacement sensitive ESPI systems and also to introduce shear in a speckle interferometer [15]. Joenathan and Sirohi reported a speckle shear interferometer using a holographic grating [16]. They have demonstrated the advantage of using first order diffracted beams along with the zero order beam to measure slope of the deformed object. Shear was introduced by two first order diffracted beams from the
grating placed before the photographic plate which was used to record a double exposure hologram. Similarly two second order diffracted beams from the grating were used to measure curvature of the displaced test object.

Burkle and Joenathan reported an electronic speckle shearing pattern interferometer using a holographic grating and diffuser [17]. When the grating is placed in front of the CCD camera, then the interferometric fringes of the grating must be resolved by the CCD camera. The pitch of the grating should be less than 100 lines/mm to resolve interferometric fringes by the camera. At this low spatial frequency higher diffraction orders are present that result in multiple beam interference. To overcome this difficulty and also to make speckle size in the final image independent of the spatial frequency of the grating a ground glass was used in the interferometer.

The application of a HOE based ESPI system to measure deformations was first reported by Petrov and Lau [18]. The systems incorporated HOEs recorded using photo-thermoplastics and silver halide emulsions. Vibration studies using a HOE based ESPI system were reported by Lau et al. using the stroboscopic ESPI method [19]. Garcia et al used a holographic optical element for spatial phase stepping in ESPI [20, 21]. The HOE diffracts the object beam into four separate orders and introduces equal phase changes between these orders. Thus there is no need to translate the HOE to introduce phase shifting. Transient deformations of a cantilever were studied using the HOE based ESPI system [20].

Whelan et al. reported a digital speckle pattern interferometry system incorporating a holographic grating and optical fibres [22]. This system demonstrates the use of two illumination wavefronts for measuring out-of-plane displacements of the test object. The holographic grating was used for multi-beam illumination which reduces the
number of directional couplers required. This system also minimizes the phase errors
due to the polarization or phase drift associated with dual-fibre schemes.

Kornis et al. reported an adaptive speckle pattern interferometry system to measure
shape contours, and to perform comparative deformation measurements [23]. A single
optical arrangement was used both for recording a HOE and to reconstruct from it in
the ESPI system with computer controlled beam stops and splitters. For comparative
deformation measurements, a hologram was recorded for the deformed and
undeformed states of the master object with different reference beams. Upon
reconstruction, the recorded hologram replaces the master object in comparative
deformation measurements. Next the test object is placed in the ESPI system. The test
object is illuminated with the laser beam which produces an object beam. When the
test object is at rest, the object beam interferes with undeformed master object beam
to produce a new speckle field which is stored in computer. Next, the object is
displaced and the speckle pattern produced by interference of the object wave with the
reconstructed deformed master object beam, is recorded. These two interference
patterns are subtracted from each other to generate fringes corresponding to the
difference of the displacements of the master object and test object. Shape
measurement was carried out using a two wavelength method.

HOE based ESPI systems were also reported by our colleagues for measuring
photopolymers [25] respectively. Wu et al. developed a high speed speckle
interferometer to measure the velocity of a centre clamped circular object [26]. Spatial
phase stepping was used to overcome the upper limit of measured velocity which
depends on interferogram sampling at the Nyquist limit. The velocity measurement
range was extended up to four times the Nyquist limit. A pair of crossed phase
gratings was used to provide phase stepping on different regions of the same detector, minimizing the cost of the system. Spatiotemporal speckle interferograms for a region were recorded at 20,000 frames/sec for an object vibrating harmonically at 518 kHz with maximum velocity 0.1 of the Nyquist limit.

3.5.2. HOE based ESPI systems

The ESPI system reported here only contains HOEs and a CCD/CMOS camera so it is cost effective and easy to align. The reflection HOE (RHOE) based out-of-plane sensitive ESPI system is shown in Fig. 3.6. The light from a diode laser is spatially filtered and collimated using a collimating lens. The collimated light illuminates a reflection HOE which generates a speckled reference beam and rest of the light is transmitted by the HOE and illuminates the test object.

![Figure 3.6 RHOE based out-of-plane sensitive ESPI system](image)

The scattered light from the object passes back through the HOE. Both the reference and object beams are brought onto the focal plane of the CCD/CMOS camera using a lens and they interfere. The displacement is detected by using pixel to pixel subtraction of the images corresponding to two different positions. This ESPI system is not only sensitive to out-of-plane sensitive displacement components but also to in-plane sensitive components. If the illumination and observation directions make only
a small angle with each other then the system is largely sensitive to out-of-plane displacement only. By adding one more HOE to the system (Chapter 5, Fig. 5.15) it can be made sensitive only to out-of-plane displacement components.

![Diagram of THOE based out-of-plane sensitive ESPI system]

**Figure 3.7 THOE based out-of-plane sensitive ESPI system**

An alternative system can be arranged as shown in Fig. 3.7. A divergent laser beam can be used to illuminate both the test object and the transmission holographic optical element (THOE). A diffuse speckle pattern is recorded in the THOE. A speckle reference beam is reconstructed from the transmission hologram (THOE) by illuminating it with a laser beam at the appropriate (Bragg) particular angle. The ESPI system is simplified because the beam combiner is replaced by a transmission hologram (THOE). This ESPI system does not require 3D and 1D translation stages that are required for the optical arrangement of a smooth reference beam based ESPI system. If a THOE has 100% diffraction efficiency, then the arrangement wastes no light. The light reflected from the object passes through the hologram completely, because it is off-Bragg. Thus a high efficiency hologram combines reference beam and object beam holographically and provides maximum contrast ESPI fringes.
3.5.2.1. Advantages of HOEs

- HOEs can produce a diffraction-limited image
- HOE acts as a beam splitter as well as combiner
- Use of a self-processing photopolymer for HOE recording removes the need for chemical processing
- No alignment difficulty at all – one can assemble the system in few minutes
- Use of a diode laser and a small CMOS camera makes system portable
- Economical and compact

3.6. Summary

The principle of hologram formation for off-axis illumination is discussed. The division of holograms into different types, viz. transmission and reflection holograms based on their recording geometry are discussed. To record a hologram a photosensitive medium is required. There are different photosensitive materials available commercially or they can be prepared in the laboratory. We have discussed the characteristics and working principles of photographic recording materials such as silver halide emulsions and photopolymers which were used in our experimental work. Finally the advantages of holographic optical elements (HOEs) and their applications in speckle metrology are discussed. The configurations of two different ESPI systems using a single reflection HOE and a transmission HOE are discussed.
References


CHAPTER 4

HOE BASED ESPI SYSTEMS WITH NEAR INFRARED DIODE LASER

4.1. Introduction

The characterization of the spectral emission of a near infrared diode laser is discussed in this chapter. The design and fabrication of HOEs are also discussed. The design of HOEs is a crucial step towards the realization of a HOE based ESPI system. The laser beams used for recording and reconstruction are of different wavelengths in this chapter so the angles of illumination and diffraction must be chosen in such a way that upon reconstruction one has an out-of-plane sensitive ESPI system. These angles were calculated using the theory discussed. HOE based ESPI systems were built using two different approaches. In the first approach, a single reflection HOE (RHOE) was used. In the second approach a combination of a partially reflecting mirror (PRM) and a transmission HOE (THOE) were used. Diffraction efficiencies of HOEs required for beam balancing in ESPI systems are discussed. The laser drive current calibration for phase modulation is also discussed.

4.2. Considerations in HOE based ESPI systems

The aim of the project is to build a compact out-of-plane sensitive ESPI system for vibration measurements. The ESPI system can be made compact by reducing the number of optical components in two ways. In one of the ways beam splitters/combiners are replaced by HOEs for dividing or combining the reference and object beams. In the other way the optical elements required for phase shifting such as
stretchable optical fibres, liquid crystals or glass wedges can be replaced by the laser diode source with its wavelength shifting capability. Such a laser diode can be used for introducing phase modulation in an unbalanced interferometer for obtaining phase and amplitude maps. These kinds of laser diodes are commercially available in the market but they normally operate in the near infrared (NIR) region of electromagnetic spectrum. If we use a laser diode operating in NIR region, there is a problem with recording HOEs. Holographic recording materials which are sensitive in the NIR region are almost non-existent. Therefore we have taken an alternative approach of recording HOEs in the visible region and reconstructing them with an NIR laser diode. In the following sections we discuss NIR laser diode characteristics and theory for HOE recording and reconstruction at different wavelengths.

4.2.1. Laser source

Lasers are monochromatic light sources, which in theory means they produce light at single wavelength, but in practice, there is a narrow wavelength range in which light is emitted. An optical spectrum analyser is used to perform the wavelength versus power measurements and is a very useful tool for characterising semiconductor lasers and light emitting diodes. If the laser cavity is much longer than the wavelength, which is usually the case, more than one wavelength will be emitted. In this present study the emission spectrum of a distributed feedback (DFB) laser operating in the near infrared (NIR) has been characterised using an optical spectrum analyser (ADVANTEST Q8384). DFB lasers contain a diffraction grating on one side of the cavity (as opposed to mirrors at each end of the cavity in conventional lasers) that reflects light back into the active region in the cavity. Feedback via the grating causes interference effects that allow oscillation only at the wavelength at which interference is constructive, reinforcing the generated light.
4.2.1.1. Temperature control of the diode laser

Temperature control of the laser diode is an important issue when laser wavelength modulation capability is used for interferometric measurements. The reason is that as the temperature changes the laser cavity expands or contracts and the laser jumps from one longitudinal mode of operation to another i.e. a change in wavelength. So random modulation of laser output wavelength which results from temperature fluctuation in the HOE based ESPI system is to be avoided.

Figure 4.1 Temperature controller unit for laser diode

The temperature controller is designed both to set the laser operating temperature and to detect the laser temperature fluctuations and correct them. The laser diode is mounted on a copper block above a Peltier element or thermoelectric cooler (TEC) as shown in Fig. 4.1. The TEC is made of a semiconductor material which imposes a temperature difference ($\Delta T$) between its facets as a function of the current fed to it. Depending on the polarity of the current in the TEC it can cool or heat the laser diode via a copper block (Cu block).
A thermistor is used to measure the temperature of the laser mount. A thermistor is a resistance element whose resistance depends on the temperature (the thermistor possesses a negative temperature coefficient). The thermistor used in our experimental system has a resistance of $10k\Omega$ at $25^\circ C$ and its resistance decreases as the temperature increases as shown in Appendix E. In this way, the temperature regulator controls the temperature of the diode by adjusting the current supplied to the Peltier to compensate for thermal fluctuations and to maintain a constant temperature. Typically small temperature changes of the order of $\pm 0.1^\circ C$ can be compensated by the TEC element to bring the laser diode rapidly back to the required operating temperature.

4.2.1.2. Wavelength modulation of the laser

In an unbalanced interferometer, phase shift can be introduced by modulating the laser wavelength, which can be done either by modulating the drive current of the laser [1] or by modulating the laser temperature [2].

When the drive current is varied there will be a corresponding change in temperature of the laser diode. Both the refractive index of the active region and cavity length will change. Compared to the refractive index change, the cavity dimensional changes are negligible. This means that the change in the drive current of the laser diode will change the refractive index of the active region, which will change the laser frequency because the optical path length in the cavity has changed. Since the laser diode works as a cavity and laser output occurs at only specific wavelengths or modes, the wavelength of the laser can be tuned by changing the drive current.

In the case of temperature modulation, it influences both the optical path length of the cavity and gain curve of the semiconductor material. The temperature dependence of these two factors is different. Both result in discontinuities in the graph of wavelength
as a function of temperature. Every time either temperature or current reaches a critical value, the laser wavelength jumps from one longitudinal mode to another. Typically the graph of wavelength variation with temperature looks like a stair case.

4.2.1.3. Experiments: Laser characteristics

A laser beam from the DFB laser diode operating in near IR (Eagleyard Photonics EYP-DFB-0763-00050-1500-SOT02-0000) with 50mW maximum output power and maximum drive current 120mA, was coupled into a single mode fibre which fed the light signal to the optical spectrum analyser. The optical spectrum analyser can measure wavelength with an accuracy of ±0.1nm. The laser wavelength of the diode was set at 763nm by fixing the temperature of the laser diode at 20°C (temperature was maintained constant with an accuracy of ±0.01°C) which corresponds to a resistance of 13.672kΩ (with error of ±0.5Ω) of the thermistor provided in the temperature controller.

![Output power variation with laser drive current](image)

Figure 4.2 DFB diode laser power variation with drive current

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The wavelength change with the drive current variation was studied as explained below. The drive current was varied in steps of 5mA. The current change was measured to an accuracy of ±0.01 mA using the built-in meter in the laser-diode controller (Model ITC502). At each step the laser was allowed a few minutes to settle down. Fig. 4.2 shows the output power of the IR laser diode plotted against the drive current. The measurements were carried out twice and the Fig. 4.2 represents average of the two measurements. The power was measured using a Newport power meter (Model 840-C) with in an accuracy of ±2%. This laser shows two modes when drive current ($I_{LD}$) varies between 75 mA and 85 mA. The threshold drive current is 30mA. The output power of the laser varies almost linearly in the regions from $I_{LD} = 55$ mA to $I_{LD} = 74$ mA and from $I_{LD} = 88$ to $I_{LD} = 119$ mA. To modulate the DFB laser diode drive current for phase shifting in the HOE based ESPI system it is essential to avoid the region where two modes appear i.e. from 74.1 to 87.9mA.

![Near IR diode laser spectrum at drive current 80mA](image)

**Figure 4.3** DFB diode laser emission spectrum showing two modes
Fig. 4.3 shows laser emission in two modes when the drive current reaches about 80mA.

Fig. 4.4 shows the laser in a single mode when the drive current reaches 90mA. From Fig. 4.4 the line-width of the laser emission spectrum can be calculated from

$$\Delta \nu = \frac{\Delta \lambda}{\lambda}$$  \hspace{1cm} (4.1)

$\Delta \lambda$ is smaller than 0.02nm and its value is unknown from spectrum analyzer measurements, hence $\Delta \nu$ can be smaller than 10.3GHz (order of 10MHz).

**Figure 4.4 DFB diode laser emission spectrum in a single mode at 90mA**

The specifications of the laser give the maximum value of spectral line-width as 10MHz. The reason for obtaining such a large measured line-width is that the optical spectrum analyser does not have enough resolution to measure the wavelength with
the required precision of the order of $10^{-4}\,nm$ to measure line widths in the MHz range.

Sometimes it is convenient to quote a power level in dB so it must be in relation to some fixed power level. One dBm is the signal power level in relation to 1mW.

$$\text{Power level (dBm)} = 10 \times \log_{10} \left( \frac{\text{signal power}}{1\,mW} \right)$$

(4.2)

From Fig. 4.4 the peak power is $P = 1.9\,\mu W$

The actual power measured using a power meter at 90mA laser drive current was 29mW. This shows that only a fraction of the laser light was coupled to the fibre.

Figure 4.5 DFB laser diode wavelength variation with the drive current

Fig. 4.5 shows the wavelength variation with the drive current. The wavelength changes were measured with an accuracy of ±0.02nm. The graph shows that the wavelength changes linearly with the drive current when the drive current varies...
between 60mA and 75mA and between 89mA and 119mA. These are the preferred regions for optical phase modulation in an unbalanced interferometer for phase shifting. From Fig. 4.5, it is seen that when the drive current changes by 5 mA, the wavelength changes by 0.011nm. So a drive current change of 1mA induces wavelength change of 0.0022nm or 2.2 pm and correspondingly the laser output power changes by 0.8mW.

\[ \Delta \nu = -\frac{c}{\lambda^2} \Delta \lambda \]  

(4.3)

\[ \frac{\Delta \nu}{\Delta i} = \frac{c}{\lambda^2} \frac{\Delta \lambda}{\Delta i} \]  

(4.4)

\[ \frac{\Delta \nu}{\Delta i} = 1.1 \text{GHz mA} \]  

(4.5)

\[ \frac{\Delta \lambda}{\Delta i} = 2.2 \text{ pm mA} \]  

(4.6)

From the specification sheets \( \frac{\Delta \lambda}{\Delta i} = 3 \text{ pm mA} \). So, it is clear that the experimentally obtained value of \( \frac{\Delta \lambda}{\Delta i} \) is in fair agreement with the manufacturer’s specified value.

The coherence length is of the order of several meters (~30m).

4.2.2. Recording and play back of HOEs

The motivation for deriving theoretical equations is to calculate the angles at which to record the HOE at wavelength \( \lambda \) and reconstruct the recorded holographic image from the HOE at another wavelength \( \lambda' \). In this part of the work the 763nm near infrared distributed feedback diode laser described above is used. Phase shifting is implemented by modulating the wavelength of the laser diode in an unbalanced
interferometer [3-5]. There are no commercial holographic recording materials available which are sensitive to near infrared wavelength (763nm). 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 during reconstruction. Champagne proposed a theoretical model [6]. He considered a coordinate system in which the origin coincides with the surface normal of the photosensitive material, and assumed that the light source is a point source. The point source position was designated in three dimensions. The same coordinate system applies during the reconstruction stage and aberrations due to wavelength shift are estimated theoretically and experimentally [6, 7].

Champagne has only derived theory for reconstruction of HOEs for point-source objects and images. I extend the approach for more interesting case of object and image planes (rather than points). The shift in the angles of illumination and diffraction can be calculated according to the following approach [8, 10]. However, the influence of materials shrinkage and aberrations are not considered in the following derivation.

4.2.2.1. Transmission holographic optical element

Figure 4.6 shows the sign convention adopted for the design of HOEs [8]. The +Z axis is the normal to the plane of the photosensitive recording medium and is the reference direction for measurement of angles.
The angles of incidence of the two recording beams are $\theta_1$ and $\theta_2$ for a transmission HOE. $\theta_1$ is measured in the anti clockwise direction starting from the $Z$ axis and varies from $0^\circ$ to $+90^\circ$ and $\theta_2$ from $0^\circ$ to $-90^\circ$ measured in the clockwise direction. Refractive index is denoted by $\mu$ and air has refractive index value 1. According to Snell’s law the refraction angles $\theta_1'$ and $\theta_2'$ inside the photosensitive material are given by:

$$\sin \theta_1' = \frac{\sin \theta_1}{\mu} \quad (4.7)$$

$$\sin \theta_2' = \frac{\sin \theta_2}{\mu} \quad (4.8)$$

These two beams interfere inside the photosensitive recording material to record an interference fringe pattern shown in Fig 4.7.

The fringe angle $\theta_f$ measured with respect to the $Z$ axis, is the angle that the recorded fringes make with the $Z$ axis.

$$\text{Fringe angle } \theta_f = \frac{\theta_2' + \theta_1'}{2} \quad (4.9)$$
Fringe spacing, \( d \), is the distance between two dark or bright fringes and is given by

\[
d = \frac{\lambda}{2 \mu \sin \left( \frac{\theta'_2 - \theta'_1}{2} \right)}
\]  

(4.10)

where \( \lambda \) is the wavelength of the recording light.

When the hologram is reconstructed at a different wavelength \( \lambda' \), then Bragg’s law can be written as

\[
2d \sin \varphi_r = \lambda'
\]  

(4.11)

Fig 4.7 shows the ray diagram for recording and reconstruction beam angles inside and outside the recording medium [8].

\[\text{Figure 4.7 Geometry of recording and reconstruction of a THOE}\]
Substituting (4.10) in (4.11) gives

\[
\sin \phi_r = \frac{\lambda'}{\lambda} \sin \left( \frac{\theta_2' - \theta_1'}{2} \right)
\]  

(4.12)

Probing angle \( \gamma' \) at wavelength \( \lambda' \) inside the recording material is given as

\[
\gamma' = \phi_r - \theta_f
\]  

(4.13)

To find \( \gamma \) the probe beam angle outside the recording medium, we have to apply Snell’s law

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

(4.14)

\( \mu \) = refractive index of the recording material, which is around 1.5 for silver halide photographic emulsions [9] and for photopolymers.

The reconstruction angle at \( \lambda' \) inside the recording material is

\[
\gamma'' = \phi_r + \theta_f
\]  

(4.15)

Applying Snell’s law gives the reconstruction angle at \( \lambda' \) outside of the recording material

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

(4.16)

Using equations (4.14) and (4.16) a MATLAB code was written to calculate angles of illumination and diffraction at 763nm for the holographic gratings recorded at 633nm.
With the help of this theoretical approach holograms can be recorded at any chosen wavelength, $\lambda$, and can be reconstructed at a different wavelength, $\lambda'$.

### 4.2.2.2. Reflection holographic optical element

In the case of a reflection hologram, interfering beams approach the photosensitive layer from opposite directions, so the fringe angle is always around 90° with respect to the +Z axis [10, 11].

A specularly reflected ray from a diffusively reflecting flat object tilted at angle $\alpha$ to the +Z axis will re-enter the photosensitive layer making angle $\theta_2$ with the +Z axis.

- $\theta'_1$ = the reference beam angle with respect to +Z axis inside the medium
- $\alpha$ = tilt of the object measured with respect to +Z axis.
- $\theta_2$, the angle made by the object beam with respect to +Z axis outside the recording medium and is obtained from the above geometry (Fig. 4.8) as

$$\theta_2 = 180^\circ + \theta_1 - 2\alpha$$ (4.17)

![Reflection hologram recording geometry (Denisyuk method)](image-url)
Fig 4.9 shows the ray diagram of a RHOE for recording and reconstruction beam angles inside and outside the recording medium [10, 11].

\( \theta_1', \theta_2' \) are the recording angles inside the recording material and are calculated using Snell’s law. \( \theta_i \) is half of the inter-beam angle.

Hence spacing \( d = \frac{\lambda}{2 \mu \cos \left( \frac{\theta_1' + \theta_2'}{2} \right)} \) \hspace{1cm} (4.18)

Fringe angle \( \theta_f = 90^\circ + \left( \frac{\theta_1' - \theta_2'}{2} \right) \) \hspace{1cm} (4.19)

When the hologram is reconstructed at a wavelength \( \lambda' \) different to that of the recording wavelength \( \lambda \), the condition for the successful reconstruction of the image can be obtained by applying Bragg’s law for \( \lambda' \)

\[ 2d \cos \varphi_k = \frac{\lambda'}{\mu} \] \hspace{1cm} (4.20)

From equations (4.18) and (4.20)

\[ \text{Bragg angle } \varphi_k = \cos^{-1} \left[ \frac{\lambda'}{\lambda} \cos \left( \frac{\theta_1' + \theta_2'}{2} \right) \right] \] \hspace{1cm} (4.21)

From Fig.4.9, \( \gamma' = \varphi_k + \left( \frac{\theta_1' - \theta_2'}{2} \right) \) \hspace{1cm} (4.22)

where \( \gamma' \) = the probing angle inside the recording material
Figure 4.9 Recording and reconstruction ray diagram inside the recording medium

The probing angle outside the recording material can be obtained by applying Snell’s law

\[
\gamma = \sin^{-1} \left[ \mu \sin \left( \cos^{-1} \left( \frac{\lambda'}{\lambda} \cos \left( \frac{\theta'_1 + \theta'_2}{2} \right) \right) + \frac{\theta'_1 - \theta'_2}{2} \right) \right]
\]

(4.23)

\[
\gamma'' = \phi_k - \left( \frac{\theta'_1 - \theta'_2}{2} \right)
\]

(4.24)

where \(\gamma''\) is the diffracted beam angle inside the recording medium.

By applying Snell’s law the diffraction angle of the reconstructed beam outside the recording material is obtained and is given by the following equation.

\[
\gamma'' = \sin^{-1} \left[ \mu \sin \left( \cos^{-1} \left( \frac{\lambda'}{\lambda} \cos \left( \frac{\theta'_1 + \theta'_2}{2} \right) \right) - \frac{\theta'_1 - \theta'_2}{2} \right) \right]
\]

(4.25)
Using equations (4.23) and (4.25), a MATLAB code was written to calculate illumination and diffraction angles for a hologram recorded at a wavelength \( \lambda \) and reconstructed at a different wavelength \( \lambda' \). Also the recording angles \( \theta_1 \) and \( \theta_2 \) are chosen in such way that the reconstructed beam from the hologram travels almost along the –Z direction i.e. \( \gamma'' \approx 0'' \). This condition is essential for an out-of-plane sensitive ESPI system as the reference beam enters the CCD camera exactly parallel to the camera axis.

In the following section experimental work is reported using reflection HOE for different ESPI systems. The angles of recording were chosen in such a way that the HOE based ESPI systems are sensitive mostly to out-of-plane displacement components.

4.3. Single HOE based ESPI system with near infrared diode laser

A very simple and cheap system involves just a single RHOE, with a small angle (~10°) between camera and illumination axes so that in-plane sensitivity is negligible. The purpose of the RHOE is to provide a speckle reference beam in the interferometer when illuminated with the infrared laser beam. All of the undiffracted light is used to illuminate the object. It is possible to adjust the relative intensities of the object and reference beams in this ESPI system by tilting the HOE appropriately.

4.3.1. Reflection HOE fabrication

The recording geometry of a reflection HOE by the Denisyuk method is shown in Fig. 4.10 [10]. The light from a He-Ne laser (\( \lambda = 633 \text{nm} \)) was expanded by a spatial filter consisting of a 40X microscopic objective and pin hole of 10µm diameter and collimated by a lens of 15cm focal length. The light was partially transmitted by a glass coated silver halide emulsion layer (PFG-03M supplied by Geola). The light
beam illuminating the surface of the silver halide emulsion served as reference wave. The beam transmitted through the silver halide emulsion layer illuminated the object, a flat diffusely reflecting plate.

**Figure 4.10 Recording geometry of a RHOE by Denisuyk’s method**

The light scattered by the object illuminated the silver halide layer from the rear side serving as an object wave. These two beams interfered at the recording plane to produce a reflection hologram. The recording angles were $\theta_1=66^\circ$, $\theta_2=50^\circ$ which corresponds to the object tilt $\alpha=98^\circ$ (See Section 4.2.2.2 for theory). All the angles are measured with $\pm 1^\circ$ accuracy. The recorded holograms were developed using the JD4 process [12]. JD4-A solution contains 4gms of metol or elon and 25gms of ascorbic acid powder in 1000ml of distilled water. JD4-B solution contains 70gms of sodium carbonate anhydrous and 15gms of sodium hydroxide in 1000ml of distilled water. The bleach solution is prepared by dissolving 35gms of copper sulphate pentahydrate, 100gms of potassium bromide and 5gms of sodium bisulfate monohydrate in 1000ml of distilled water. The hologram was developed for 20secs in a solution containing equal parts of (JD4-A) and (JD4-B), then rinsed with water followed by bleaching and finally agitated in distilled water containing 2 drops of Kodak Photoflo per litre. Then the hologram was allowed to dry naturally for about 4 hours.
4.3.2. Diffraction efficiency of RHOE

Assume the reflectivity of the object is \( R_0 \) and diffraction efficiency of RHOE is \( \eta_R \).

When a laser beam with intensity \( I \) illuminates the RHOE, part of the light is diffracted, which provides speckle reference beam which is represented as \( \eta_R I \). The light scattered by the test object is represented by \( (1-\eta_R)R_0 I \). The scattered light passes back through the RHOE and collected by the CCD camera and is denoted by \( (1-\eta_R)R_0 I \). For maximum modulation in interferometric signal the reference and object beam intensities must be equal, hence

\[
\eta_R I = (1-\eta_R)R_0 I
\]

\[
\eta_R = \frac{R_0}{1+R_0}
\]

To equalize the object and reference beam intensities, if for example the reflectivity of the test object is \( R_0 = 0.05 \), then the diffraction efficiency of the reflection HOE should be around 4.7\%. Because most objects are of low reflectivity, equalizing beam intensities is easy in a RHOE based ESPI system, because the diffraction efficiency of the RHOE needs to be less than the reflectivity of the object.

4.3.3. Experiment: ESPI system with a RHOE

The optical set-up for the ESPI system using a RHOE is shown in Fig.4.11 [10]. The light beam from a distributed feedback (DFB) near IR diode laser has an elliptical cross section. The elliptical beam was converted into a circular shape by an anamorphic prism pair (PS877-B Thorlabs). This beam was further spatially filtered and collimated (using the same spatial filter and collimating lens as in the recording set up). The reflection holographic optical element (RHOE) generates the speckled
reference beam upon illumination. Undiffracted light passing through the RHOE serves to illuminate the object. In the reconstruction stage an infrared (IR) diode laser of wavelength 763nm was used to illuminate the RHOE. The probing angle (Section 4.2.2.2) was $\gamma = 10^\circ$ and the diffracted beam angle $\gamma''$ relative to the $-Z$ axis was approximately $0^\circ$. The object and reference beams were brought onto the focal plane of the CCD camera to interfere. Since the object is illuminated at $10^\circ$ to the normal there is some sensitivity to in-plane motion.

![Figure 4.11 Out-of-plane sensitive ESPI system using a RHOE](image)

Figure 4.11 Out-of-plane sensitive ESPI system using a RHOE

(APP- Anamorphic prism pair, SF- spatial filter, CL-collimating lens, CCD-charge
coupled device camera, SG-signal generator)

The phase change due to the displacement of the object is given by equation (2.13) [10]

$$\delta = \frac{2\pi}{\lambda'} \left[ v(0.17) + w(1.98) \right]$$

(4.28)

where $\delta$ = phase difference before and after deformation, and $v, w$ are in and out of plane displacement components respectively. So our interferometer is sensitive
primarily to out-of-plane displacements of the test object. The relative intensities of
the beams could be adjusted by slight rotation of the HOE.

4.3.4. Results: Fringe patterns obtained with RHOE based ESPI system

A vibrating circular aluminium diaphragm 4cm in diameter attached to a loud speaker
was used as an object. The object was excited by applying a sinusoidal voltage using a
signal generator. A LabVIEW (Version 7.1) coded virtual instrument (VI) was used to
generate an ESPI fringe pattern using a National Instrument’s IMAQ-1409 frame
grabber card. No image processing filters were used in the fringe generation. Some of
the vibration modes are shown in Fig. 4.12 [10]. These were obtained by deliberately
altering the drive voltage after capturing a time averaged frame, and subtracting
interferograms at different voltages from one another. A ‘V’ shaped mark present in
the fringe pattern is a holographic image used for identification of holographic image
reconstruction.
Figure 4.12 (a), (b), (c) and (d) Fringe patterns obtained using RHOE based out-of-plane sensitive ESPI system

We found experimentally that thin plates resonate only in certain modes. This means due to the boundary conditions imposed upon the plate (e.g. clamped at the edges), it can vibrate only at certain allowable frequencies and show node patterns. Nodes are the points on the plate that vibrate with zero amplitude, while other surrounding points have non-zero amplitude. The subtraction of images corresponding to two object positions leads to dark fringes in Fig. 4.12, because these points are at rest. Resonant modes shown in Fig. 4.12 (a), (b) and (d) respectively vibrating at 4.2kHz, 5.1kHz and 10kHz are pure modes hence they are symmetric with respect to the centre. The resonant mode vibrating at 8.2 kHz shown in Fig. 4.12 (c) is a mixed mode hence the pattern is not symmetric.
4.3.5. Discussion and limitations

- For phase measurements the near IR laser diode wavelength can be modulated in an unbalanced interferometer. But use of a single RHOE limits the path length difference in the interferometer to 5-8 cm, because the object beam needs to be overlapped with the reference beam. The small path length differences need larger values of drive current modulation amplitudes for phase shifting. However the laser output power also modulates with the drive current modulation. The power variation would be higher for larger drive current modulation. This causes reduction in fringe contrast. Hence it is preferable to use a hybrid or dual HOE based ESPI system combined with phase modulation.

- This system is sensitive to in-plane displacement components also. So the HOE should always be illuminated at (Bragg angle) small angles ~10° (Eq. 4.28) to ensure negligible in-plane sensitivity.

4.4. Hybrid HOE based ESPI system with near infrared diode laser

The main reason for using a transmission holographic optical element in ESPI system is that it was difficult to produce a strong diffusely reflecting HOE (it still is). The combination of a partially reflecting mirror (PRM) and a diffusely transmitting HOE was used in the HOE based ESPI system to provide object and reference beams with better results.

4.4.1. Advantages

- The hybrid HOE based ESPI system is compact because the transmission HOE acts as a beam splitter and provides the reference beam in the interferometer.
• Self processing photopolymer layers were used for producing transmission HOEs, so no wet chemical processing is required.
• The hybrid HOE based ESPI system was made to be purely out-of-plane displacement sensitive.
• HOEs are inexpensive and can be mass produced.
• Partially reflecting mirrors (PRMs) with different reflection coefficients can be used to balance the beams in the interferometer.

4.4.2. Transmission HOE fabrication
The transmission HOE recording geometry is shown in Fig. 4.13 [8]. The vertically plane polarized light from the laser source of wavelength 532nm is passed through a half wave plate (HWP1) to rotate the plane of polarization. A polarising beam splitter was used to split the beam into two parts. The reflected light is vertically polarised but the transmitted light is horizontally plane polarised. Use of another half wave plate changes the state of polarisation of the transmitted light from horizontal to vertical. The angles of recording (Section 4.2.2.1) were $\theta_1 = +30^\circ$ and $\theta_2 = -30^\circ$. The corresponding theoretically calculated illumination and diffracted beam angles for the reconstruction at 763nm were $\gamma = +45^\circ$ and $\gamma' = -45^\circ$ respectively. In one of the recording beams a ground glass plate was introduced to record a speckle pattern. The intensities of the two beams were balanced by adjusting HWP1 to get good contrast holographic fringes or efficient holographic gratings.
The transmission holographic optical elements were recorded in erythrosine-B dye sensitised acrylamide based photopolymer. The photopolymer was developed in the Centre for Industrial and Engineering Optics [13, 14]. This photopolymer is a self developing dry layer. It consists of a polyvinylalcohol binder in which a monomer, electron donor and a dye sensitizer are dissolved. The mechanisms of recording are explained in Chapter 3 in detail.

The total power of the recording beams was varied from $3mW/cm^2$ to $6mW/cm^2$ for exposure times from 160 sec to 80 sec to obtain maximum diffraction efficiency for THOE with a diffused image. A beam spot of 5mm in diameter from a He-Ne laser (632.8nm) was used for measuring diffraction efficiency of diffuse transmission gratings. The diffraction efficiency is defined as the ratio of diffracted beam intensity to total illuminating beam intensity. The maximum diffraction efficiency measured
was 22%. In the reconstruction stage the illumination angle at 763nm was approximately +45° and the diffraction angle was -45°. The theoretical calculations and experiment are in agreement. (All the angles were measured with an accuracy of ±1° with a protractor by using a laser beam of 2mm in diameter).

4.4.2.1. Diffraction efficiency of THOE

Assume the reflection coefficient of a partially reflecting mirror is \( R_i \), the reflectivity of the object is \( R_o \) and the diffraction efficiency of THOE is \( \eta_T \). When a laser beam with intensity \( I \) illuminates the partially reflecting mirror, part of the light is reflected to illuminate the test object and is represented as \( R_i I \). The light scattered by the test object is represented by \( R_o R_i I \). The scattered light passes through the partially reflecting mirror and collected by the CCD camera and is denoted by \( (1-R_i)R_o R_i I \).

The light transmitted by the partially reflecting mirror is denoted by \( (1-R_i)I \). This light illuminates the THOE which diffracts a speckled reference beam represented by \( \eta_T (1-R_i)I \).

For maximum modulation of interferometric signal the reference and object beams should have equal intensities. So

\[
\eta_T (1-R_i)I = (1-R_i)R_o R_i I
\]

(4.29)

\[
\eta_T = R_o R_i
\]

(4.30)

If we know the values of the reflectivities of the partially reflecting mirror \( R_i \) and object \( R_o \), we can determine the diffraction efficiency \( \eta_T \) of THOE that is required to balance the beams in the interferometer.
For example, if we use PRM with reflection coefficient 0.3 and object reflectivity 0.05, then required diffraction efficiency of THOE is 1.5%. When the reflectivity of PRM is changed to 0.7 using the same test object, the required diffraction efficiency is 3.5%. The conclusion is that when the reflectivity of the object is low say 0.05, we need a THOE with very maximum diffraction efficiency of ~5%. As the object reflectivity increases the required diffraction efficiency also increases as they are directly proportional to each other.

The required maximum diffraction efficiency of THOE is about 3.5%. So we have a THOE with higher diffraction efficiency than required which is advantageous (By rotating the THOE slightly, the amount of light diffracted by the THOE can be reduced to balance the intensities of the interfering beams). The photopolymer grating diffraction efficiency falls rapidly with the rotation of grating typically within \( \pm 2^0 \) but for a THOE with diffused image the diffraction beam intensity falls considerably by rotating \( \sim \pm 5^0 \). So the reference beam intensity can be made equal to the object beam intensity by rotating the THOE in the ESPI system.

### 4.4.3. Experiment: Hybrid ESPI system with THOE

The optical set-up for the ESPI system using a combination of a THOE (with a diffuse image stored in it) and a partial mirror is shown in Fig. 4.14 [8]. The light beam from a distributed feedback (DFB) near IR diode laser has an elliptical cross section. The elliptical beam was converted into a circular in shape by an anamorphic prism pair (Thorlabs PS877-B).
Figure 4.14 Out-of-plane sensitive ESPI system using a diffuse THOE and partially reflecting mirror (PRM)

(LD-diode laser, APP-anamorphic prism pair, SF-spatial filter, CL- collimating lens, SG-signal generator, PRM-partially reflecting mirror)

This beam was spatially filtered and collimated (using the same spatial filter and collimating lens as reported in section 4.3.1). The partially reflecting mirror (with R=0.3 or 0.7) reflects part of the light illuminating it and transmits the rest. The angle of reflection from the mirror is 45°. The light reflected from the mirror illuminates the test object. The partially transmitted beam illuminates the THOE which generates a speckled reference beam by diffraction. In the reconstruction stage a near IR DFB diode laser (λ=763nm) is used to illuminate the THOE, hence a shift in the Bragg angle of diffraction occurs on reconstruction. The THOE is rotated to adjust the reference beam intensity so that the object and reference beams intensities are balanced in the interferometer.

A picture of the laboratory experimental set up of the THOE based ESPI is shown in Fig.4.15.
In this setup the angles of illumination and observation of the object are along the surface normal of the object. The phase difference $\delta$ due to the object displacement is given by Equation (2.13) [15]

Substituting corresponding angles (normal illumination and observation)

$$\delta = \frac{2\pi}{\lambda'} [2\omega] = \frac{4\pi\omega}{\lambda'}$$

(4.31)

where $\lambda' = 763nm$

4.4.4. Results: Vibration fringe patterns

A circular aluminium plate 5.4cm in diameter was attached to a piezo-electric actuator at its center and driven by a sinusoidal signal generator. A mirror of reflectivity $R=0.3$ along with the THOE was used in an out-of-plane sensitive ESPI system. The fringe patterns were captured in time average mode. Some of the vibration fringe patterns are shown in Fig. 4.16 (a), (b), (c) and (d) [8]. The subtraction process was similar to the one reported in section 4.3.2.
Figure 4.16 (a), (b), (c) and (d) are the vibration fringe patterns obtained using a THOE based out-of-plane ESPI system

We have changed the test object in the form of a metal plate, edge clamped to a loud speaker to a piezo electric actuator driven plate. The actuator was calibrated by setting up a Michelson interferometer and is more suitable for repeatable quantitative vibration measurements.

Resonant vibration modes were observed at 1 kHz, 5.8 kHz, 6.7 kHz and 9.1 kHz. The dark fringes appear in the fringe patterns wherever the vibration amplitude is zero, while the other regions of the object with bright fringes have non-zero vibration amplitudes. Vibration modes at 1kHz, 6.7kHz and 9.1khz are pure hence mode shape
is symmetric. The mode observed at 5.8 kHz seems like a mixed mode, hence it is asymmetric.

4.4.4.1. Study of fringe contrast using histograms

The object beam, reference beam, and the combined beams were captured for intensity measurement purposes and are shown in Fig. 4.17 (a), Fig. 4.18(a) and Fig. 4.19(a) respectively.

![Figure 4.17](image1.png)  ![Figure 4.18](image2.png)

**Figure 4.17** (a) object beam (b) histogram of the object beam

**Figure 4.18** (a) reference beam (b) histogram of the reference beam
The histograms of the reference beam with the object beam, reference beam, and the combined beam are shown in Fig. 4.17(b), Fig. 4.18(b), and Fig. 4.19(b) respectively. The vertical axis represents the number of pixels having a particular gray level. The horizontal axis represents gray level from 0 to 255. The distribution of gray values determines the contrast.

Figure 4.19 (a) combined beams (b) histogram of the combined beams

The histogram of the combined beam intensity is spread over a range of gray values. The histogram of the reference beam is widely spread but the mean and median gray values are low. These gray values can be increased to 128. The histogram of the object beam is very narrow and has lower mean gray level. A narrow peak in the histogram indicates that only few pixels were illuminated with low intensity. We want to have the object and reference beams equally bright with an average gray level in each of 128 to get good contrast fringe patterns.

An interline system CCD camera having $752 \times 582$ pixels (Pulnix PE2013) was used in this study. The pixel dimensions are 6.5μm (horizontal) and 6.25μm (vertical). The
spacing between pixels is 8.5µm. \( F \) number of the lens used was 11 and \( \lambda = 763\text{nm} \). The speckle size was calculated as

\[
\sigma = 2.44\lambda F
\]

\[
\sigma = 20.47\mu\text{m}
\]

So this suggests that the speckle size is almost 3 times bigger than a single pixel. When the spacing between pixels (8.5µm) is considered, the speckle size is two times bigger than a single pixel size. In general speckle size should be of the order of at least a pixel width so that we can observe the changes in the speckle pattern when a test object moves. Suppose there are 10 speckles illuminating a pixel. According to the statistical properties of speckle pattern half of them will become dark and the rest become bright when a test object is displaced by the order of one quarter of a wavelength. This causes no effective change in the intensity of the speckle pattern at that particular pixel leading to information loss. So it is good to set each speckle to be of the order of a pixel in width.

4.4.5. Discussion

The advantage of the hybrid HOE based ESPI system is that larger path length differences can be introduced in the interferometer compared to the RHOE based ESPI system. Larger path length differences need only small amplitudes of drive current for introducing phase shifting. When the laser drive current modulates the associated output power also modulates which may decrease fringe contrast. This can also be source of error in calculating phase maps because the calculations are entirely based on intensity values. So using small drive current modulation amplitudes minimizes output power variations and increases the fringe contrast.
If we remove the THOE from the hybrid HOE based ESPI system and use only a partially reflecting mirror and place it near to the test object (as in Fig. 3.7), makes the system sensitive to in-plane displacement components as well. The interferometer with only partial reflecting mirror will have a smooth reference beam. The arrangement using a smooth reference beam needs careful alignment using additional conventional optical components such as beam splitters. This makes the system more complex and expensive and alignment of the system becomes time consuming.

4.5. **Calibration of drive current and output power variation with external voltage**

To study the dynamic behaviour of a vibrating test object using ESPI, the phase difference in the interferometer must be modulated. A VI was written in LabVIEW to generate two independent sinusoidal signals from a digital to analogue (D/A) board allowing also a variable phase difference to be introduced between them. The signal from one channel can be used to vibrate the test object and the other output used to modulate the laser drive current by applying it to the modulation input of the laser diode controller. A change in wavelength of a fraction of a nanometre can be induced by a voltage of a few mV applied to the modulation input. So for calibration purposes a basic potential divider electric circuit was used to provide millivolt input for modulation of diode laser drive current. The circuit is shown in the Fig. 4.20. This circuit was used because a VI (virtual instrument) written in LabVIEW was not working properly to produce small changes in the D.C. level (mV range) of modulation input.
Figure 4.20 Voltage divider DC circuit for providing modulation input

This circuit is built to apply only a few mV to the modulation input of the current controller of the diode laser to determine the voltage required to obtain a phase change of $\pi$ in an unbalanced interferometer. The drive current was modulated in constant current mode. (Constant current mode means that the laser diode operates without a photodiode feedback loop, at constant current. The optical output power may vary because of temperature changes). The output voltage measured between points A and B, varies between 0 and 88.3mV. This voltage was fed to the modulation input of the laser diode controller and the modulation amplitude of the drive current and the corresponding laser power levels were noted from the indicators on the controller.

Fig. 4.21 shows variation of drive current as a function of the modulation input voltage. For 1 mA modulation of drive current change it is necessary to apply approximately 57mV change in external voltage. This is in agreement with specifications provided by the manufacturer (20mA/V±5%). The drive current was measured with accuracy of ±0.1mA (as provided in the specification sheet, see Appendix-E).
Drive current variation with external voltage

Figure 4.21 Drive current change with the modulation input voltage

Output power variation with external voltage

Figure 4.22 Laser power change with the modulation input voltage
Fig. 4.22 shows the laser output power variation with the modulation input voltage. For 50mV change in modulation voltage approximately 1.5mW optical power change is observed from Fig. 4.22 (1.5mW/mA). The power was measured with in accuracy of ±3%. But from our measurements in Fig.4.2 the power change is only 0.8mW/mA. The reason for the difference is not known.

4.5.1. Phase change relationship with the drive current

In an interferometer the phase difference is related to the path difference by

\[
\phi = \frac{2\pi}{\lambda} (d)
\]

where \( \phi \) is the phase difference corresponding to the path difference, \( d \),

![Phase change with drive current variation](image)

Figure 4.23 Phase change introduced by the change in drive current
For small changes in the wavelength

\[ \Delta \phi = -\frac{2\pi}{\lambda^2} \Delta \lambda (d) \]  \hspace{1cm} (4.34)

Rearranging eq. 4.34

\[ \Delta \phi = \frac{2\pi}{c} \Delta \nu (d) \]  \hspace{1cm} (4.35)

It is important to calculate the drive current modulation needed for a phase change of \( \pi \) or its multiples.

For example with a 5cm path length difference in the interferometer the frequency change needed for a phase change of \( \pi \) is given by

\[ \Delta \nu = \frac{c}{2d} \]  \hspace{1cm} (4.36)

\[ \Delta \nu = 3GHz \]  \hspace{1cm} (4.37)

From Eqs. 4.5 and 4.37. The required drive current change is

\[ \Delta i = 2.64mA \]  \hspace{1cm} (4.38)

In this way the drive current changes needed for all other multiples of \( \pi \) were also calculated assuming linear variation of phase with the drive current. This process was repeated for different path length differences in the interferometer and graphs drawn which are shown in Fig. 4.23. It is clear that for 50cm path difference only 2.7mA of drive current change is needed to obtain a phase change of 10\( \pi \) whereas for 5cm path difference 27mA drive current change is needed to obtain the same change in phase. In general for larger path length differences we need lower drive current modulation.
amplitudes for phase shifting. Low modulation amplitudes involve smaller changes in laser output power and so are used preferably when phase maps are to be obtained.

4.6. Summary

HOEs were used to build compact ESPI systems. A laser diode operating at 763nm can be used for introducing phase modulation in unbalanced HOE based ESPI systems. This feature also makes the ESPI system simple as no phase shifting optics are required. The laser diode characteristics such as wavelength and output power changes with the drive current have been studied. The wavelength change with drive current variation was $\Delta \lambda / \Delta i = 2.2 \text{ pm/mA}$ ($\Delta \nu / \Delta i = 1.1 \text{ GHz/mA}$) (Fig. 4.5) and the corresponding output power change with drive current was $0.8 \text{ mW/mA}$. As there are no holographic materials sensitive at 763nm, HOEs are recorded at visible wavelengths (RHOE at 632nm and THOE at 532nm) and reconstructed at 763nm. The shift in the Bragg diffraction angle with wavelength change was discussed. The diffraction efficiencies of HOEs required for beam balancing in the RHOE and hybrid HOE based ESPI systems were discussed. The analysis of histograms of reference and object beams provides useful information for further optimisation of fringe contrast. An external voltage was applied to the diode laser to study its modulation characteristics.

We have not implemented phase shifting with a near IR diode laser in HOE based ESPI systems for vibration analysis, because we found a visible wavelength stabilised diode laser which can be phase modulated and used for recording HOEs. This removes a big obstacle for designing a compact HOE based ESPI system. In the next chapter use of the diode laser operating in the visible region for phase modulation in the interferometer is discussed.
References


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CHAPTER 5

VIBRATION MEASUREMENTS USING HOE BASED ESPI
SYSTEMS WITH VISIBLE DIODE LASER SOURCE

5.1. Introduction

The main aim of this chapter is to describe the use of a wavelength stabilized diode laser operating in the visible region (658nm) in out-of-plane sensitive HOE based ESPI systems. There were two technical difficulties which arose in the HOE based ESPI system using a near infrared diode laser as a source (763nm). Firstly, there was no commercially available photosensitive material to record HOEs at 763nm. Secondly, reconstruction of HOEs in the near infrared wavelength requires a shift in the reconstruction angles and makes it quite difficult to align the system for purely out of plane sensitivity.

These problems were overcome by using an Ondax SureLock™ wavelength stabilized laser diode operating in the visible region of the electromagnetic spectrum. Single mode operation of this laser is achieved by incorporating a volume holographic grating in the laser package. The laser can be used both to record the HOEs for ESPI systems and as the laser source in the HOE based ESPI systems, with path length difference modulation enabled by varying the drive current.

The HOE based ESPI systems can be used for reliable measurements of vibration [1-3]. Vibration measurements using ESPI are carried out by three different methods. They are time-average ESPI, stroboscopic ESPI, and dual pulse ESPI methods [1, 4 and 5]. In this chapter we will only focus on the time-average ESPI method which
was used for vibration measurements performed with the HOE based ESPI systems. Phase stepping technique [6] to measure static displacements or out-of-plane rotations using a HOE based ESPI system is also discussed.

5.2. Laser diode with volume holographic grating

A laser diode (SureLock™) operating at 658nm was obtained from Ondax. The stability of the laser diode was studied by setting up a Michelson interferometer with a path length difference of 40±0.1cm. The fringe pattern captured using a CCD camera is shown in Fig. 5.1. The fringe pattern was observed for a 60mins to study the stability of the laser. A sudden decrease in visibility of the fringes over a short period of time was observed which indicated mode hopping. A more rigorous study of wavelength variation due to changing laser diode drive current was carried out.

As described in Chapter 4, Section 4.2.1.3, the visible laser diode spectrum was characterised using an optical spectrum analyser (ADVANTEST Q8384). The wavelength stabilised laser diode contains a volume holographic grating [7] on one side of the cavity that scatters light back into the active region in the cavity.

![Michelson interferometric fringes](image)

**Figure 5.1 Michelson interferometric fringes**

Feedback from the grating causes interference effects that allow oscillation only at the wavelength at which interference is constructive, reinforcing the generated light. Light from the visible laser diode was coupled into a single mode fibre (with core
diameter 9.5µm and cladding diameter 125µm) which feeds the light signal to the optical spectrum analyser via a fibre connector. The laser wavelength of the diode was set at 658nm (within ±0.1nm) by fixing the temperature of the laser diode at 33.8°C±0.01°C which corresponds to a resistance of 6.83kΩ (with in ±0.5Ω) of the thermistor provided in the temperature controller.

The wavelength was measured while changing the drive current from 35mA to 70mA and in the reverse direction from 70mA to 35mA and the results are shown in Fig. 5.2. The squares represent current increasing from 35 to 70mA; there are two mode jumps within the range. The first occurs at 47.5mA and the second at 62.8mA. The drive current was then reduced from 70 to 35mA (circular 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 59.3mA and the second at 46.6mA. The stable region between 49mA and 57mA is suitable for phase modulation for use in an ESPI system. The average slope, $\frac{d\lambda}{dt}$ of the region is about 5.5±0.2pm/mA (calculated from two more repeated measurements). The corresponding frequency change per mA was calculated using Eq. 4.4 and is 3.8±0.01GHz/mA.
Figure 5.2 Wavelength variation with drive current

Fig. 5.3 shows the laser emission spectrum at 40mA. The line-width of the laser emission spectrum can be calculated using Eq. 4.1, and is $\Delta \nu = 27.7\,GHz$

Figure 5.3 Diode laser emission spectrum at 40mA
The specifications of the laser system give the spectral line-width as 50MHz. The reason for obtaining such a large difference in line-width is that the optical spectrum analyser does not have enough resolution to measure the wavelength with a precision of the order of $10^{-4}$ nm to measure line widths in the MHz range.

The drive current was varied in steps of approximately 0.3mA around the laser threshold region and then in steps of 1mA. At each step the laser was allowed a few minutes to settle down. Fig. 5.4 shows the output power of the laser diode plotted against the drive current. The power variation with drive current of the laser is 0.8mW/mA (with in error of ±3%), which is about 2.8% of the maximum output power.

**Figure 5.4 Output power variation with drive current change**
5.3. Waveforms for ESPI

The required waveforms were generated using National Instrument’s digital to analog converter board (USB 6229) in the LabVIEW environment. Two synchronised sinusoidal waveforms were generated at the same frequency but with independently controllable amplitudes and phases (Fig. 5.5). These waveforms were used respectively to vibrate the object and to modulate the drive current in the laser and hence the path length difference in the interferometer.

In synchronism with the frame pulse sent to the camera, a rectangular waveform (upper trace in Fig. 5.6) 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. 5.1.

This waveform was added to the phase modulation waveform and passed to the laser controller. Fig. 5.7 shows an example of the combined waveform. The reference beam frequency is at a lower value than any object resonant vibration frequency of interest, only for oscilloscope display purposes.

Figure 5.5 Synchronised object (upper trace) and path modulation (lower trace) waveforms
Figure 5.6 Image of the camera trigger pulse (lower trace) with the phase shifting pulse (upper trace)

Figure 5.7 Image of camera trigger pulse (lower trace) synchronised with π phase shifting rectangular waveform superimposed on the path modulation signal (upper trace)

5.4. Image acquisition and processing

The image acquisition software was developed in LabVIEW 8.2. A front panel of the image acquisition software is shown in Fig. 5.8. The software can be divided into three stages which are camera initiation, image acquisition and processing. To initiate image acquisition some sub VI’s that can initiate camera were assigned with appropriate parameters such as camera frame rate (25Hz) image area in pixels (640×480) and image type (8 bit or 12 bit).
The camera frame rate can be controlled using an external digital trigger. In our experiments the frame rate of the camera was set at 25Hz with an external digital pulse which was supplied by the DAC board. The software can be used in two modes which are, display of live images and display of subtracted images. 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 40ms, so that fringes are not affected by the thermal and mechanical disturbances in the laboratory occurring at frequencies less than about 25 Hz.

The area of interest (AOI) can be chosen manually for faster image acquisition at up to 60frames/sec. Some image processing facilities such as image filters, look up tables (LUT) and image pixel transformations such as stretching pixel values, were implemented in the processing stage. The image processing filters can be chosen by...
changing kernel size. The image processing can be controlled by clicking on the start image processing button. A video of a sequence of live or subtracted images can be saved for demonstration or offline processing. For more details of waveform generating software see Appendix B.

5.5. Reference beam phase modulation

An out-of-plane ESPI system with normal illumination and observation geometry was used for vibration measurements. When a test object vibrates harmonically at an angular frequency $\omega$, amplitude $a_0$ and phase $\phi_0$, and the correlation fringes are obtained using subtraction of two speckle patterns corresponding to displaced and undisplaced positions. The brightness is averaged over a time much longer than the period of vibration $2\pi/\omega$ and is [8]

$$B = 4\sqrt{I_o I_r} \left| J_0 \left( \frac{4\pi}{\lambda} a_0 \right) \cos(\psi) \right|$$  \hspace{1cm} (5.1)

where $\lambda$=wavelength of laser beam, $\psi$=phase difference between object and reference beams. The background intensity term, $I_o + I_r$ due to the object and reference beams, was removed by subtracting successive ‘$\pi$’ phase shifted speckle patterns from one another. To obtain phase and amplitude information, the reference beam phase can be modulated with the same frequency as that of the test object vibration, but with different amplitude $a_r$ and phase $\phi_r$. Then the brightness is modified as follows [1],

$$B' = 4\sqrt{I_o I_r} \left| J_0 \left( \frac{4\pi}{\lambda} \left( a_0^2 + a_r^2 - 2a_0 a_r \cos(\phi_0 - \phi_r) \right)^{1/2} \right) \cos(\psi) \right|$$  \hspace{1cm} (5.2)
The brightness $B'$ modulates only by a few gray levels. This makes the correlation fringe detection difficult. So we simply square the brightness $B'$ and display the result

$$B'' = 16I_0I_r \left| J_0 \left( \frac{4\pi}{\lambda} \left( a_0^2 + a_i^2 - 2a_0a_i \cos(\varphi_0 - \varphi_i) \right)^{1/2} \right) \cos(\psi)' \right| ^2 \quad (5.3)$$

The noise caused by speckle can be minimised by implementing a low-pass filter to replace $\cos(\psi)$ with its averaged value \[8\]. As the path length difference is modulated, by modulating the laser drive current, $i$, those points on the object where $a_0 = a_i$ and $\varphi_0 = \varphi_i$ are imaged with the maximum brightness.

The phase difference between the object and reference beams in an unbalanced interferometer with a path length difference $2L$ is given by Eq. 4.33.

From Eq. 4.33 and 4.34, when the current changes by $\Delta i$ the phase difference between the beams changes by

$$\Delta \phi = \frac{4\pi L}{\lambda^2} \left( \frac{d\lambda}{di} \right) \Delta i \quad (5.4)$$

From Eq. 5.4 the amplitude of vibration on iso-amplitude contours or fringes is

$$a_r = \frac{2L}{\lambda} \left( \frac{d\lambda}{di} \right) \Delta i \quad (5.5)$$

The amplitude of vibration in (5.5) can be expressed in terms of frequency modulation amplitude

$$a_r = 2L \left( \frac{\Delta \nu}{\nu} \right) \quad (5.6)$$
Where $\Delta \nu = \text{amplitude of frequency modulation}$, $\nu = \text{frequency of the laser beam}$, $l = \text{optical path length}$.

5.6. Experiments

Simple ESPI systems are developed using holographic optical elements (HOEs). The simplest system was realized using a reflection holographic optical element (RHOE). A speckle pattern recorded in a RHOE upon reconstruction provides a reference beam in the interferometer and replaces the beam splitter in a conventional ESPI system. Precise alignment difficulties that are associated with conventional smooth reference beam ESPI systems can be significantly minimized using a HOE that generates a speckled reference beam in the ESPI system.

5.6.1. Single reflection HOE based ESPI system

This system contains a minimum number of optical components. The reference and object beam intensities can be adjusted by rotating the RHOE slightly with respect to the surface normal of the test object. By rotating the HOE, the incident angle of the laser beam is changed and so the HOE is now illuminated off-Bragg and its diffraction efficiency is reduced. HOE fabrication and its use in the ESPI system are explained in the following subsections.

5.6.1.1. RHOE fabrication

The set up for recording the reflection HOE is shown in Fig. 5.9. The beam from the laser diode was spatially filtered using a 40X microscope objective and a pin hole of 10µm diameter and collimated using a lens of focal length 15cm, and used to illuminate a silver halide emulsion (Geola PFG-03C) coated on glass substrate (6.3cm×6.3cm). A ground glass plate was introduced between the mirror and the silver halide emulsion (the purpose of using ground glass plate was to ensure that one
of the recording beams is speckled) 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 angle between the recording beams is $150^0 \pm 1^0$. The sensitivity of the silver halide layer is $2\text{mJ/cm}^2 - 3\text{mJ/cm}^2$ [9]. The total beam power was $0.5 \pm 0.01 \text{mW/cm}^2$ so the layers were exposed for approximately 6sec. The holograms were developed using SM-6 developer [10], followed by bleaching using PBU-Amidol. The diffraction efficiency of the RHOE was 20%. (The diffraction efficiency was measured using reduction in transmitted intensity at the Bragg angle)

![Diagram of setup for recording a reflection HOE](image)

**Figure 5.9 Set up for recording a reflection HOE**

5.6.1.2. **Out-of-plane sensitive RHOE based ESPI system**

The out-of-plane sensitive HOE based ESPI system is shown in Fig. 5.10. The beam from the diode laser was spatially filtered and collimated (with the same spatial filter and collimating lens as in recording set up) and used to illuminate the reflection HOE to reconstruct the stored speckle image. 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 beams interfered in the focal plane of the CMOS camera.
The camera (AVT Guppy F-036B) was set in externally triggered mode and supplied by a D/A board with a digital pulse (25Hz) to initiate each image capture. 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 were subtracted from one another to reduce background intensity and to improve contrast of the fringe patterns [11, 12]. In this way the system is also rendered insensitive to mechanical and thermal interferometric disturbance occurring on time scales slower than the frame rate of the camera.

![Diagram](image.png)

**Figure 5.10 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)

### 5.6.1.3. Results: Vibration modes of a circular plate driven by piezoelectric actuator

A circular aluminium plate of diameter 5.4 cm and thickness 1mm attached at its centre to a piezoelectric actuator was used as a test object. Initially, the plate 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 particular vibration frequencies resonant mode patterns appear on the computer monitor. Frequency scanning was used to find all the possible vibration modes.

![Vibration mode images](image)

**Figure 5.11 Vibration mode at 1018Hz** a) without laser modulation b) laser drive current modulation of 1mA (51mV) c) 1mA (51mV) with 180° phase shift

To map the vibration amplitude, the path length difference in the interferometer was modulated by altering the laser drive current at the same frequency as the object vibration, but the phase difference was initially set at 0°. At some points in the image changes in path length difference due to laser wavelength, exactly match changes in path length difference to the object vibration and maximum intensity is observed in the fringe pattern at those points.

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 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. The unmodulated path length difference in the interferometer was 5.6cm. The peak to peak amplitude of the applied square waveform for ‘π’ phase shift was 0.88mA (44mV), approximately in agreement with the value calculated using Eq.5.4. Vibration resonant modes were found at 1018Hz and 6620Hz. The corresponding fringe patterns are shown in Figures 5.11(a) and 5.12(a) respectively. When the test object was excited at 1018Hz, a current modulation of 1mA (51mV) was needed to obtain the bright fringe shown in Fig. 5.11(b), corresponding to those points on the object which are vibrating at the same amplitude as that of the path length difference due to laser current modulation. The relative phase between the object excitation and the laser drive current modulation was changed by 180° while still modulating the laser current at 1mA and the result shown in Fig. 5.11(c). The amplitude of vibration in the brightest fringe area shown in Fig. 5.11(b) and (c) was calculated using Eq. 5.6 to be 0.47µm.

All the images in Fig. 5.11 contain nearly straightline spurious fringes (parallel to the diagonal of the images). These are reconstructed from RHOE, and they are formed during the recording of the RHOE. These fringes may be formed due to photographic plate movement during the recording process.

At 6620Hz, the reference beam path length was modulated at an amplitude of 1.1mA (~50mV) and a bright iso-amplitude fringe was obtained as shown in Fig. 5.12(b). When 180° relative phase was introduced between the object excitation and the laser drive current modulation a bright iso-amplitude fringe was obtained as shown in Fig. 5.12(c). The amplitude of vibration on the iso-amplitude areas in Fig. 5.12(b) and (c) is 0.53µm. The intensity ratio of the reference and object beams in the interferometer
is about 1:5. The intensity ratio was obtained using mean values of reference and object beam histograms.

![Image](image1)

**Figure 5.12** Vibration mode at 6620Hz (a) without laser modulation (b) laser beam modulated at 1.1mA (57mV) amplitude (c) 1.1mA (57mV) with 180° phase shift

### 5.6.1.4. Intensity as a function of laser modulation voltage in single RHoe based ESPI

Using time-average ESPI, it is possible to determine the test object amplitude and/or phase distribution by modulating the optical path difference in an unbalanced interferometer. Usually phase is modulated by driving a mirror in the reference beam path using a piezoelectric crystal or wrapping an optical fibre around a piezoelectric cylinder which delivers the reference beam.
Laser diodes are increasingly used to build compact optical systems; it is possible to use these lasers in an ESPI system as has been shown. Additionally the laser wavelength can be directly modulated, by varying the laser drive current using an external varying voltage. This alters the path length difference in the interferometer. The interferogram intensity variation with laser wavelength modulation with the test object at rest is shown in Fig. 5.13. The intensity variation follows a zero order Bessel function of the first kind. The test object and laser modulation drive voltages were set at zero and an image was recorded and stored. The modulation voltage was changed in steps of 2 or 3mV and the images were recorded at each of the modulation voltages and stored on the computer. Average intensities were measured offline on areas of 50×50 pixels. The average gray level values were plotted against the modulation voltage as shown in Fig. 5.13.

![Diode laser modulation at 834Hz while test object at rest](image)

**Figure 5.13** The intensity variation in the interferometer with reference beam modulation
For a path difference of 5.6cm and a wavelength/current coefficient of 5.5\textit{pm/mA}, the first order maximum of the Bessel function was observed at around 53mV (~1mA) of modulation voltage. This is in agreement with the modulation voltages for the fringe patterns shown in Fig. 5.11 (b), (c) and Fig. 5.12 (b), (c) and validates the technique being used to measure vibration amplitudes. The Bessel variation of intensity also provides valuable information about the linear region (16mV-28mV), in which phase stepping can be implemented for the extraction of phase maps of a vibrating object.

5.6.1.5. Limitations of single RHOE based ESPI system

The distance between the RHOE and the test object is limited by the size of the holographic image as well the angle between recording beams. The RHOE was recorded on a 63\times63mm\textsuperscript{2} silver halide emulsion with a 5cm diameter collimated laser beam. To obtain interference between the object beam and the speckle reference beam from RHOE, the test object was adjusted in such a way that object and reference beams overlap on the focal plane of the CMOS camera. The distance between the RHOE and the test object was 24mm±1mm. This restricted the path length difference in the interferometer requires higher drive current modulation amplitude (of the order of 1mA) to measure the vibration amplitude of the test object. The contrast of the fringe pattern at these vibration amplitudes is 0.65 (Fig. 5.13) which is well above acceptable contrast levels even though laser power varies by about 4\%. The smaller optical path length differences also limit the vibration amplitude sensitivity (resolution).
Sensitivity to in-plane motion

In Fig 5.10 the angles of illumination and observation of the object are $\alpha = 25^\circ$ and $\beta = 180^\circ$ respectively, relative to the surface normal of the test object. The phase change due to the object displacement is given by [13]

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

(5.7)

where $w, u$ are out-of-plane and in-plane displacement components along $z$ and $x$ directions respectively.

$$\Phi = \frac{2\pi}{\lambda} \left[ w(1.9) + u(0.4) \right]$$

(5.8)

This shows that the RHOE based ESPI system is not only sensitive to out-of-plane displacement components but also sensitive to in-plane displacement components to the extent of one fifth of the out of plane sensitivity.

If a phase map is obtained using the RHOE based ESPI system, it is therefore sensitive to in-plane displacement components. We need to separate in-plane displacement components from the out-of-plane displacement components.

5.6.2. Out-of-plane sensitive dual HOE based ESPI system

The RHOE based ESPI system is not only sensitive to out-of-plane sensitive displacements but also sensitive to in-plane displacements. So to build a system which is purely sensitive to out-of-plane displacements, one more HOE i.e. a transmission grating is added to the ESPI system. This combination of HOEs makes the illumination and observation directions normal to the surface of the object. In the following sections HOEs, their fabrication and use in ESPI system are discussed.
5.6.2.1. Diffraction efficiency considerations

The diffraction efficiency of the RHOE, or fraction of incident light intensity converted to ESPI system reference beam intensity, is $\eta_R$. The undiffracted light amounting to a fraction $1 - \eta_R$ of the incident light intensity is further diffracted by a transmission HOE (THOE) which is a holographic diffraction grating of efficiency $\eta_T$, to illuminate the object along the normal to its surface.

The object is assumed to be a flat diffusely scattering surface with diffuse reflectivity $R_o$, which is also the fraction of incident light assumed to pass back through both HOEs to illuminate the detector.

For maximum modulation of light intensity at the detector, the reference and object beams illuminating the detector should have equal intensities, so

$$\eta_R I = (1 - \eta_R) I (1 - R_F) \eta_T R_o$$

(5.9)

where $I$ is the incident intensity (minus Fresnel loss) at the RHOE.

Absorption and scattering have been neglected but the effect of Fresnel loss in the intensity of the incident light at the THOE ($1 - R_F$) has been included.

The reflection coefficient $R_F$ for vertical polarisation is given by

$$R_F = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}$$

(5.10)

Where $\theta_i$ is the angle of incidence and $\theta_t$ is the angle of transmission.

From Eq. 5.10, $R_F$ is about 0.9 for an incident angle of $45^0$ and a refractive index of 1.5. It is further assumed that the loss in intensity of the light reflected by the object...
due to Fresnel reflections beam is about 4% at each surface, a total loss of about 15% for all four surfaces. We now have

$$
\eta_R = 0.76(1 - \eta_R)\eta_T R_o
$$

(5.11)

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<td>0.146</td>
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Table 5.1 values of $\eta_T$ for various values of $\eta_R$ and $R_o$
By assuming values of $R_o$ and $\eta_R$, values of $\eta_T$ can be found using Eq. 5.11. A list of values for these parameters is given in table 5.1.

Values of $\eta_T$ greater than 1.0 are obviously excluded. The optimal choice of diffraction efficiency for each of the HOEs depends on the reflectivity of the object which is likely to be low, except for polished metal surfaces or surfaces coated with retroreflecting paint. The acceptability of the latter is not known. The combined diffraction efficiency of the two HOEs should be as close to 1.0 as possible to avoid wasting light. Values of $\eta_T$ greater than 0.4 are highlighted.

At lower values of object reflectivity we need to use an RHOE of low efficiency. As object reflectivity increases, we can use a RHOE of higher efficiency while still retaining a high efficiency THOE. To ensure maximum versatility and to cope with a range of surface reflectivity from 0.05 to 0.35, we would need to supply a series of RHOEs ranging in $\eta_R$ from 3% to 10% along with THOEs ranging in $\eta_T$ from 50% to 90%. (shaded part of table 5.1)

Undiffracted light bypasses the object completely. So assuming an illuminated area on the HOEs of 5cm in diameter, and angle of incidence at the HOEs of 45° the HOE the object distance should also be 5cm. Some separation is required in any case so that the path difference in the interferometer can be modulated in amplitude and phase.

5.6.2.2. Effect of temperature and humidity on HOEs

Silver halide emulsions

Silver halide holograms (reflection or transmission) are not greatly affected by temperature changes in the environment.
The effect of relative humidity on silver halide holographic emulsions (Agfa 8E75HD) was reported by Wuest and Lakes [14]. These studies were applicable only to reflection holograms. The reconstruction wavelength varies with the relative humidity in two ways. Firstly, the wavelength needs to increase as the relative humidity at the reconstruction is increased. Secondly, the reconstruction wavelength also depends on the relative humidity at the hologram recording stage. Analysis indicates that the reconstruction wavelength of the hologram decreases as the relative humidity increases at the recording stage. The reconstruction wavelength changes with humidity in both cases but this change increases at the time of reconstruction but decreases at recording. There was a shift in the reconstruction beam angle at peak wavelength when the humidity values at recording and reconstruction were unequal. This is due to shrinkage of the emulsion which causes an inclination of Bragg planes.

**Photopolymer**

An acrylamide based photopolymer holographic material developed at the Centre for Industrial and Engineering Optics was used in our experiments. Naydenova et al reported a visual indication of environmental humidity using a colour changing hologram using the acrylamide based photopolymer [15]. In the experiments they have used reflection holograms to study the effect of humidity changes on the reconstruction wavelength with a white light source for reconstruction.

To calibrate the humidity response of the hologram, the change of the spectral peak position was determined for different relative humidity values. The increase in the relative humidity causes an exponential increase in the reconstructed wavelength [15, 16]. The sensitivity of reconstruction wavelength change to relative humidity is different at lower and higher relative humidity values. With lower relative humidity
changes the reconstruction wavelength shift was low, but it changes dramatically with higher humidity changes.

The effect of temperature changes on reconstruction wavelength was also reported by Naydenova et al [16]. They have studied how the reconstruction wavelength changes with temperature in reflection gratings. As the temperature of the humidity chamber was varied from 15\(^0\)C to 50\(^0\)C and keeping the relative humidity at a particular value and the reconstructed wavelength was measured. At lower relative humidity values the temperature change does not affect the reconstruction wavelength. But at higher relative humidity values the reconstruction wavelength increases linearly with the temperature.

They have also reported that the colour or wavelength change of the reflection hologram was reversible and repeatable. The stability of the hologram was observed over 12 hours duration at 50\(^0\)C and 15\% relative humidity. There was no shift in the reconstruction wavelength observed. So the holograms were stable over time at higher temperatures and lower humidity values.

It was reported by Naydenova et al [16] that when the relative humidity changes from 5\% to 80\%, the reconstruction wavelength changes typically by 130nm. But humidity changes during an ESPI experiment are not expected to be very great.

### 5.6.2.3. Fabrication of HOEs

The set up for recording HOEs is shown in Fig. 5.14. The light from the Ondax 658 nm diode laser (Section 5.2) was split into two parts using a polarising beam splitter (PBS) and a half wave plate (HWP1). A second half wave plate (HWP2) was used to rotate the polarisation state of beam (beam 1) so that beam 1 and 2 were in the same vertical polarisation state. The beam ratio can be adjusted using the half plate HWP1.
The RHOE was recorded using a spatially filtered (SF) (with 40X objective and pinhole of 10µm diameter) and collimated (lens L1, focal length 15cm) beam by Denisyuk’s method using beam 1 with the intensity of beam 2 set to zero. A diffuser was introduced between the mirror (Mirror 1) and the photosensitive plate to provide a speckled object beam.

**Figure 5.14 Recording set up of HOEs: reflection hologram of a diffuser and transmission grating**

To record a THOE, mirror 1 and the diffuser were removed and the beam 1 and 2 intensities were equalized. In this way, the recorded RHOE and THOE can be put together in a single holder. On reconstruction by beam 1, the RHOE provides a speckle reference beam for the ESPI system, and the THOE diffracts light transmitted by the RHOE to illuminate the test object in the direction of beam 2.

For RHOE recording PFG-03C silver halide emulsion on glass substrate (6.3cm×6.3cm) was used; the laser beam intensity was 500µW/cm² and exposure time was 6s and SM-6 [10] processing was used. The diffraction efficiency of the RHOE was 12%. The THOE was recorded in HP-P silver halide holographic emulsion on
The angle between the recording beams was 30°. The intensity was 600µW/cm² and exposure time was 5s; SM-6 [10] processing was used. The diffraction efficiency of the THOE was 20%. To balance the beam ratio between reference and object beams in the interferometer the RHOE was rotated slightly (~3°) off Bragg and restricted the diffraction efficiency within 3%. In this case the THOE diffraction efficiency should be between 67% and 95% as opposed to the reported value 20% according to the table 5.1 (for 5% reflectivity of the object). The silver halide emulsions used for THOE recording (HP-P) are usually used for recording colour holograms. This might have caused lower efficiency and also SM-6 processing needs to be optimized. Another point to consider here is that both the HOEs were slightly rotated off-Bragg to avoid a secondary reflection from the THOE into the camera, so the diffraction efficiencies of the both HOEs were decreased.

5.6.2.4. Dual HOE based ESPI system

The dual HOE based ESPI system is shown in Fig. 5.15. 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 secondary reflection from THOE) illuminated slightly (~3°) off-Bragg. The object and reference beams were allowed to interfere on the focal plane of the CMOS camera (AVT Guppy F-036B). 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 PZT attached to the test object and the other to modulate the diode laser drive current.

A rectangular pulse (25Hz) triggered image acquisition by the camera. A rectangular waveform generated synchronously with the image acquisition pulse, causes the laser drive current to change, producing a phase change of $\pi$ in the interferometer at the beginning of each frame. Subtraction of the successive $\pi$ phase shifted speckle interferograms removes the background speckle noise [11, 12] and the resulting interferogram is displayed with high contrast. The path length difference in the interferometer is 24cm.

The co-ordinate axes of the object $x, z$ are shown Fig 5.15. The angles of illumination and observation of the object are $\alpha = 0^\circ$ and $\beta = 180^\circ$ respectively to the surface normal of the test object. Using Eq.5.7, the phase change due to the object displacement is given by [13]

![Figure 5.15 Out-of-plane sensitive HOE based ESPI system](image-url)
The pixel dimensions are 6\(\mu\)m\(\times\)6\(\mu\)m \[18\]. The laser wavelength is 658nm and the F number of the lens used was 4. Using the Eq. 2.3 the speckle size is given by \[19\]

\[\sigma = 6.4\mu m\]

The speckle size was thus about the same size as a pixel.

5.6.2.5. Results: Vibration modes of a circular metal plate driven by a piezoelectric actuator

From Fig. 5.16 the brightest fringe was moved successively to the first, second, third, fourth and fifth order by modulating the laser wavelength by \(\Delta \lambda = 0.93 \text{pm}\), \(\Delta \lambda = 1.93 \text{pm}\), \(\Delta \lambda = 3.00 \text{pm}\), \(\Delta \lambda = 4.11 \text{pm}\), \(\Delta \lambda = 5.10 \text{pm}\) respectively. The modulation of wavelength is obtained using \(\Delta \lambda = \left\{ \frac{\Delta \lambda}{\Delta i} \right\} \Delta i\). It is clear from Fig. 4.21, a change of 50mV changes drive current by approximately 1mA. When the path length difference is constant (for a flat object), a change in modulation voltage (drive current) provides displacement of the object (Eq. 5.5). We know from Fig. 5.2, \(\frac{\Delta \lambda}{\Delta i} = 5.5 \text{pm/mA}\), for example a modulation voltage change of 8.5mV drive current changes by 0.17mA, hence wavelength change is 0.93pm. The calculated displacements corresponding to each of the fringe orders is 0.3\(\mu\)m, 0.7\(\mu\)m, 1.1\(\mu\)m, 1.5\(\mu\)m and 1.8\(\mu\)m respectively. The displacement values corresponding to each order are tabulated in Table 5.2. According to the Table 5.2, the maximum change in the laser drive current was 0.9mA and the corresponding change in laser output power 0.74mW. There was a phase drift along the bright fringe region in Fig. 5.16, when

\[
\Phi = \frac{4\pi w}{\lambda}
\]  
(5.12)
Figure 5.16 Circular plate vibrating at 834Hz. Time average fringes modulating the laser wavelength (a) $\Delta \lambda = 0.93\,\text{pm}$, (b) $\Delta \lambda = 1.93\,\text{pm}$ (c) $\Delta \lambda = 3.00\,\text{pm}$ (d) $\Delta \lambda = 4.11\,\text{pm}$ (e) $\Delta \lambda = 5.10\,\text{pm}$
Table 5.2 Displacement corresponding to brightest fringe at 834Hz

Laser modulation voltage was changed. This phase drift was compensated by adjusting the phase of the path length modulation (Fig.5.16 (b), (c), (d) and (e)).
Figure 5.17 Circular plate vibrating at 1017.3Hz (a) Ordinary time average fringe. Time average fringes by modulating the laser wavelength (b) $\Delta\lambda=0.96\text{pm}$ (c) $\Delta\lambda=0.96\text{pm}$ with $180^\circ$ phase shift (d) $\Delta\lambda=5.22\text{pm}$ (e) $\Delta\lambda=5.22\text{pm}$ with $180^\circ$ phase shift
The laser power variation is approximately 3.7% of the output power, so this might affect contrast of the fringes a little but still we can see good contrast fringes.

<table>
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<td>Modulation voltage (mV)</td>
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<td>47.5</td>
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<tr>
<td>Drive current change (mA)</td>
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<td>0.9</td>
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<tr>
<td>Displacement (µm)</td>
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<td>1.9</td>
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Table 5.3 Displacement corresponding to the fringe order at 1017.3Hz

In our experiments a small drift in phase value was noticed across iso-amplitude contours 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 minimised. In our experiments around $2^0$-$15^0$ phase variation in the interferometer was observed.

A vibration mode pattern observed at 1017.3Hz is shown in Fig. 5.17. The ordinary time average fringe pattern obtained by continuous $\pi$ shifted frame subtraction is shown in Fig. 5.17 (a). The bright fringe was moved to the first order as shown in Fig. 5.17(b) by modulating the laser wavelength with $\Delta \lambda = 0.96 \text{ pm}$. The phase of the reference beam was changed by $180^0$ with respect to the phase of the object beam which results in bright fringe movement as shown in Fig 5.17(c), while the laser wavelength modulation was still at $\Delta \lambda = 0.96 \text{ pm}$. The bright fringe was moved to fifth order by modulating the laser wavelength with $\Delta \lambda = 10.47 \text{ pm}$ as shown in Fig.5.17 (d). An additional phase difference of $180^0$ between the beams in the interferometer results in the fringe pattern shown in Fig. 5.17(e). The displacement data for Fig. 5.17 (b), (c) and (d), (e) is given in Table 5.3.
Mode 3

Figure 5.18 Circular plate vibrating at 5600.5Hz: (a) Ordinary time average fringe pattern. Time average fringes by modulating the laser wavelength (b) $\Delta \lambda=1\text{pm}$ (c) $\Delta \lambda=1\text{pm}$ with 180° phase shift (d) $\Delta \lambda=4.29\text{pm}$ (e) $\Delta \lambda=4.29\text{pm}$ with 180° phase shift.
A vibration mode pattern observed at 5600.5Hz is shown in Fig. 5.18. The ordinary time average fringe pattern obtained by continuous $\pi$ shifted frame subtraction is shown in Fig. 5.18 (a). The brightest fringe was moved to a new position as seen in Fig. 5.18 (b) by modulating the laser wavelength with $\Delta \lambda = 1 \text{pm}$. From Eq. 6.6 the amplitude of vibration in the brightest fringe regions in Fig. 5.18 (b) and (c) is 0.4µm. Fig. 5.18(c) shows the result when the phase of the path length difference modulation is altered by $180^0$.

The same process was repeated to measure higher order fringes. The brightest fringe was moved to fifth order as seen in Fig. 5.18 (d) by modulating the laser wavelength with $\Delta \lambda = 4.29 \text{pm}$. From Eq. 5.5 the amplitude of vibration in the brightest fringe regions in Fig. 5.18 (d) and (e) is 1.6µm. Fig. 5.18(e) shows the result when the phase of the reference beam modulation is altered by $180^0$. The displacements corresponding to the fringe orders are tabulated in Table 5.4.

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<td>Displacement (µm)</td>
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**Table 5.4 Displacement corresponding to the fringe order at 5600.5Hz**

The vibration fringe patterns observed at 6620Hz are shown in Fig. 5.19. The ordinary time average vibration fringe pattern is shown in Fig. 5.19(a). The brightest fringe was moved to first order as seen in Fig. 5.19(b) by modulating the laser wavelength with $\Delta \lambda = 1.24 \text{pm}$. 
Mode 4

Figure 5.19 Vibration mode of a circular plate observed at 6620Hz. (a) Ordinary time average fringe pattern (b) Time average fringes observed by modulating the laser wavelength with $\Delta \lambda = 1.24\text{pm}$ (c) $\Delta \lambda = 1.24\text{pm}$ with 180° phase shift (d) $\Delta \lambda = 3.43\text{pm}$ (e) $\Delta \lambda = 3.43\text{pm}$ with 180°
From Eq. 5.5 the amplitude of vibration in the brightest fringe regions in Fig. 5.19 (b) and (c) is 0.4µm. Fig. 5.19(c) shows the result when the phase of the path length difference modulation is altered by 180°.

The bright fringe is moved to third order by modulating the laser wavelength with \( \Delta \lambda = 3.43 \text{pm} \). From Eq. 6.6 the amplitude of vibration in the brightest fringe regions in Fig. 5.19 (d) and (e) is 1.2µm. Fig. 5.19(c) shows the result when the phase of the path length difference modulation is altered by 180°. The displacement corresponding to the fringe order is tabulated in Table 5.5.

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<td>Displacement (µm)</td>
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<td>1.2</td>
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Table 5.5 Displacement corresponding to the fringe order at 6620Hz

The amplitudes of vibration in some of the higher frequency modes are greater than in the lower frequency ones. This is because the higher frequency modes were driven at higher voltages than the lower frequency modes.

5.6.2.6. Amplitude and phase maps

By using the reference beam phase modulation technique in ESPI, we can separate the phase information from the amplitude information. Thus we can obtain complete information about the vibrating test object. In the following subsections we discuss the process of extracting phase and amplitude maps at different resonant vibration frequencies.
5.6.2.6.1. Phase contouring

Phase modulation and Eq. 5.3 can be used to map constant phase contours independently of amplitude variations. Initially the phase difference between object and reference beams was set at a value $\varphi_r$. Then the path difference modulation amplitude was varied between zero and a maximum value determined by the object vibration amplitude distribution. The variation in the path difference amplitude makes the fringe pattern change, but the centre of the brightest fringe is always placed where the object vibration phase value $\varphi_0$ equals the path difference phase value $\varphi_r$. So, we can conclude that the change in the path difference amplitude traces out the line of the constant phase where $\varphi_0 = \varphi_r$ across the object. To obtain the complete phase map of the object, the path difference phase was then varied in steps of $\Delta \varphi_r$, and the process repeated shifting the position of the brightest fringe by varying the path difference modulation amplitude. In this way a phase map can be obtained in few minutes, the time depending on the complexity of the phase map.

A circular aluminium plate of diameter 5.4cm and thickness 1mm, attached at its centre to the piezoelectric actuator was vibrated at different resonant frequencies. Fig. 5.20(a) shows an ordinary time-average ESPI recording of the plate vibrating at 916 Hz obtained by continuous $\pi$ shifted frame subtraction. After scanning a time-averaged vibration mode pattern, the laser drive current was modulated to map the test object vibration amplitude and phase.

According to Eq. 5.3, the Bessel function reaches a maximum value only when $a_0 = a$, and $\varphi_0 = \varphi_r$. Initially $\varphi_r$ was set at $\varphi_0 = \varphi_r = 0$. The amplitude of the laser modulation $a_r$ was varied until the maximum brightness was moved from zero order.
to the first order fringe. This means the amplitude of vibration at the first order fringe $a_0$ is the same as the reference beam modulation amplitude $a_r$.

To map a phase value, the path length difference modulation amplitude $a_r$ (where $a_0 = a_r$) was fixed and the phase of the path difference modulation $\varphi_r$ was varied to see the brightest fringe (where $\varphi_0 = \varphi_r$). Since this mode is a pure mode only two constant phase contour lines corresponding to $\varphi_0$ and $\varphi_0 + \pi$, respectively were observed as shown in Fig. 5.20(b) and (c). The amplitude of the first order fringe derived from Eq. 5.5 is 0.1µm.

Figure 5.20 Circular plate vibrating at 916Hz: (a) ordinary time average fringe. Time average fringes by modulating the laser wavelength (b) and (c) with 180° phase shift
A phase map was obtained by fixing the phase of the path difference modulation at a particular value \( \varphi_r = 0^\circ \) and the modulation amplitude was varied in steps of \( \Delta a_r \) corresponding to current changes of 0.08mA. The resulting fringe patterns corresponding to each amplitude value were captured. Then the path length difference phase was changed to a new value \( \varphi_r = 30^\circ \), and the path difference amplitude variation in steps of \( \Delta a_r = 0.08mA \) was repeated as above and fringe patterns were captured. The phase was changed in steps of \( 30^\circ \) from \( 0^\circ \) to \( 330^\circ \) and the corresponding fringe patterns were captured. These sets of fringe patterns provide phase contour lines upon processing and thus a phase map.

![Figure 5.21 Constant phase contour line drawing for reference phase when the object is vibrating at 916Hz](image)

Adobe Photoshop CS5 software was used for contour extraction. To obtain a phase map the following image processing steps were applied in sequence on every fringe pattern [20]. Initially a Gaussian blur with a radius of 10 pixels was applied to the image of the fringe pattern to reduce high frequency noise in the image. Then the
Pixel values were redistributed by applying the auto levels option to set the darkest pixel to 0 and brightest pixel to 255. These images were thresholded at a particular grey value so that we can see brightest pixels only, i.e. the image was converted into a binary image. This binary image was then subjected to trace contour filtering. The purpose of the filter was to find the highest brightness areas and thinly outline them for an effect similar to the lines in a contour map.

This process was repeated to obtain contours from all other images captured at different values of the path length difference modulation amplitude. By overlaying these contours on each other, a constant phase contour line could be drawn in the direction of increasing amplitude as shown in Fig. 5.21. The arrow indicates the direction of the contour drawing.

Phase contours for other reference phase values were also drawn in similar fashion. These individual phase contours were overlaid on each other to produce detailed phase map of the vibrating object for e.g. as shown in Fig. 5.22) at 916Hz.

An amplitude map was obtained by fixing the path length difference modulation amplitude at a particular value $\alpha$, and its phase was varied in steps of $\Delta \phi = 30^\circ$. The resulting fringe patterns corresponding to each of these phase values were captured. Then the path length difference modulation amplitude was set at a new value by altering the laser drive current; the phase variation was repeated in steps as above and fringe patterns were captured. These sets of fringe patterns captured at different path length difference modulation amplitudes provide iso-amplitude contour lines upon processing and thus an amplitude map.

The disadvantage with this offline image processing is that, it takes at least an hour to obtain a phase or amplitude map. Although the method is time consuming, we have
shown how to extract the phase maps using commercial software (Adobe Photoshop CS5) that is widely available.

Figure 5.22 Phase distribution across the object when vibrating at 916 Hz

Figure 5.23 Amplitude distribution across the object when vibrating at 916 Hz
Fig. 5.23 shows an amplitude map of the object when it is vibrating at 916Hz. The constant amplitude contours are shown as dotted lines. These lines correspond to laser drive current modulation amplitudes of 0.08mA, 0.16mA, 0.24mA, 0.32mA respectively. Using these current modulation values displacements were calculated from Eq. 5.5 and are 0.16µm, 0.32µm, 0.48µm, 0.64µm respectively. The higher order iso-amplitude lines can be detected also but their intensity decreases rapidly due to the nature of Bessel function. If the amplitude of vibration is decreased so that a smaller number of correlation fringes are displayed then a complete amplitude map can be obtained.

Extracting vibration phase and amplitude information using path length modulation technique is difficult. The constant phase contours for pure vibration modes have the nodal point as common center and the phase value changes continouously [2]. In our studies vibration modes are composite and they do not have single nodal point as commom center, hence some of the constant phase contours intersect with others. At these intersections phase values may not be determined. The phase contours across the heart shape bright fringe in Fig. 5.20 do not change rapidly rather they change continuously around the periphery of the object. The limitations of the above method are high level of uncertainty in phase values at lower vibration amplitudes and phase value determination becomes difficult at the intersection of phase contours for complex modes.
Figure 5.24 Circular plate vibrating at 1060Hz: (a) ordinary time average fringe. Time average fringes by modulating the laser wavelength (b) and (c) with 180° phase shift.

Figure 5.24(a) shows an ordinary time-average ESPI recording of the plate vibrating at a higher frequency 1060 Hz obtained by continuous π shifted frame subtraction. This is a composite mode and phase varies continuously over the object surface (Fig. 5.24(b)). Fig. 5.24(b) and (c) show constant phase contours corresponding to \( \phi_0 \) and \( \phi_0 + \pi \), respectively. The amplitude of vibration at the brightest fringes is 0.4µm.
Figure 5.25 Phase distribution across the object when vibrating at 1060 Hz

Fig. 5.25 shows a phase map of the object when it is vibrating at 1060Hz. The constant phase contours are shown as continuous lines. In this case, the phase variation appears diagonally symmetric.

Figure 5.26 Amplitude distribution across the object when vibrating at 1060 Hz

Fig. 5.26 shows an amplitude map of the object when it is vibrating at 1060Hz. The constant amplitude contours are shown as dotted lines. The amplitude distribution is non-symmetric and varies across the object.
Fig. 5.26 shows an amplitude map of the object when it is vibrating at 1060Hz. The constant amplitude contours are shown as dotted lines. These lines correspond to laser drive current modulation amplitudes of 0.08mA, 0.16mA, 0.24mA, 0.32mA respectively. Using these drive current modulation values displacements were calculated from Eq. 5.5 and are 0.16µm, 0.32µm, 0.48µm, 0.64µm respectively.

5.6.2.6.2. Accuracy of phase map

![Graph showing phase shift vs vibration amplitude](image)

**Figure 5.27** Phase shift required to reduce the intensity of the zero order fringe by 100% as a function of vibration amplitude (assuming equal amplitudes of path length difference modulation and object vibration)

The accuracy of phase measurement using this technique depends on the object vibration amplitude. From Fig. 5.27, it is clear that larger vibration amplitudes give better accuracy. Fig. 5.27 was obtained by adjusting phase of the path length difference to reduce the intensity by 100% at different path difference oscillation.
amplitudes. The curve shown in Fig. 5.27 is based on Eq. 5.3. At large object and path length difference oscillation amplitudes, only a small change in the cosine term in Eq. 5.3 is needed to make the argument of the Bessel function differ considerably from zero. At large vibration amplitudes the zero order fringe is a narrow line while at smaller amplitudes the fringe width increases; in this case we have to determine the centre of the fringe.

5.6.2.7. Vibration modes of square metal plate driven by piezoelectric actuator

The dual HOE based ESPI system was tested with one more test object, a square aluminium plate 4cm×4cm and 1mm in thickness attached to a piezoelectric actuator. The vibration measurement technique was the same as that used for the circular metal plate. The time average vibration modes were scanned and two were observed at 1406.1Hz and 4980Hz without path length difference modulation.

The time average fringes at 1406.1Hz are shown in Fig.5.28. The bright fringes were moved to first and second order by modulating the laser wavelength with $\Delta \lambda = 1.11 \mu m$ and $\Delta \lambda = 2.16 \mu m$ respectively. From Eq. 5.5 the amplitude of vibration in the brightest fringe regions in Fig. 5.28(b) and (c) is $0.4 \mu m$ and in Fig. 5.28(d) and (e) it is $0.8 \mu m$. Fig. 5.28(c) and (e) show the results when the phase of the path difference modulation was altered by $180^0$. The measured displacement values corresponding to the fringe order are tabulated in Table 5.6.
Figure 5.28 Square plate vibrating at 1406.1Hz: (a) Ordinary time average fringe pattern. Time average fringes obtained by modulating the laser wavelength with (b) $\Delta\lambda=1.11\text{pm}$ (c) $\Delta\lambda=1.11\text{pm}$ with $180^\circ$ phase shift (d) $\Delta\lambda=2.16\text{pm}$ (e) $\Delta\lambda=2.16\text{pm}$ with $180^\circ$ phase shift
<table>
<thead>
<tr>
<th>Fringe order number</th>
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<tr>
<td>Modulation voltage (mV)</td>
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<td>19.7</td>
</tr>
<tr>
<td>Drive current change (mA)</td>
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<td>0.4</td>
</tr>
<tr>
<td>Displacement (µm)</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Table 5.6 Displacement corresponding to the fringe order at 1406.1Hz**

The time average fringes at 4980Hz are shown in Fig. 5.29. The bright fringes were moved to first and fourth order by modulating the laser wavelength with $\Delta \lambda = 1.57 \text{ pm}$ and $\Delta \lambda = 4.78 \text{ pm}$ respectively. From Eq. 5.5 the amplitude of vibration in the brightest fringe regions in Fig. 5.29(b) and (c) is $0.6 \mu\text{m}$ and in Fig. 5.29(d) and (e) it is $1.7 \mu\text{m}$. The measured displacement values corresponding to the fringe order are tabulated in Table 5.7

<table>
<thead>
<tr>
<th>Fringe order number</th>
<th></th>
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</tr>
</thead>
<tbody>
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<td>43.5</td>
</tr>
<tr>
<td>Drive current change (mA)</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Displacement (µm)</td>
<td>0.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Table 5.7 Displacement corresponding to the fringe order at 4980Hz**
Figure 5.29 Square plate vibrating at 4980Hz: (a) Ordinary time average fringe pattern. Time average fringes observed by modulating the laser wavelength with (b) $\Delta \lambda=1.57\text{pm}$ (c) $\Delta \lambda=1.57\text{pm}$ with $180^\circ$ phase shift (d) $\Delta \lambda=4.78\text{pm}$ (e) $\Delta \lambda=4.78\text{pm}$ with $180^\circ$ phase shift
5.6.2.8. Interferogram intensity as a function of laser modulation voltage in dual HOE based ESPI

The intensity variation in the interferometer with path length difference modulation while the test object is at rest is shown in Fig. 5.30. The intensity variation follows a zero order Bessel function of the first kind. A code was developed in LabVIEW to acquire live images continuously. This code was initiated while the test object was at rest and the laser modulation were set at zero and an image was recorded and stored. The modulation voltage was changed in steps of 0.2 or 0.3 mV and the images were recorded at each of the modulation voltages and stored on the computer. The average intensity measurements were carried out offline. An area of 50×50 pixels was chosen, and the average intensity of each image measured in gray levels. The measured gray level values were plotted against the modulation voltage as shown in Fig. 5.30. For a path difference of 24 cm and a wavelength to current coefficient of 5.5 pm/mA, the first order maximum of the Bessel function was observed at around 12 mV modulation voltage. This is in agreement with the values associated fringe patterns shown in Fig. 5.28 (b), (c) and Fig. 5.29 (b), (c) (The path difference for Fig. 5.28, 5.29 and 5.30 was the same set at 24 cm). The variation of the intensity is not a smooth curve, as is evident from Fig. 5.30. This is because the D/A card can generate voltage levels about 50 mV without significant noise but these low voltage waveforms are too noisy. This problem may be minimised by using a lock-in amplifier to generate low voltages typically about 10 mV or less using other expensive DAC cards.
Figure 5.30 Intensity variation with the reference beam modulation in HOE based ESPI system designed with two HOEs

5.6.2.9. Rotation measurements using phase stepped dual HOE based ESPI system

The dual HOE based ESPI system as shown in Fig. 5.15 was also used for measuring rotation or tilt of a metal plate. In this experiment the test object rotation was controlled manually. A metal (aluminium) plate of diameter 5cm and 1mm in thickness, coated with retro-reflective paint (for improving light reflection from the object) was attached to a mirror mount (Newport) and its motion was controlled using precision adjusters. The field of view was adjusted to 25mm (by adjusting the collimated beam size with an aperture). The optical path length difference in the interferometer was 13cm. A virtual instrument developed in LabVIEW 8.2 was used for generating fringe patterns. A CMOS camera (Guppy F032B) with 640× 480 pixels was interfaced to a laptop (Dell-Inspiron) using an IEEE1394 firewire port.
The current change (0.6mA) required for a phase shift of $2\pi$ was experimentally determined by measuring a full fringe shift. This current change value was divided into four equal increments to obtain five drive current values corresponding to $0^0$, $90^0$, $180^0$, $270^0$, $360^0$. A constant phase shift $\pi/2$ was then introduced between five consecutive frames by changing the diode laser drive current ($\Delta i=0.15mA$, for $\pi/2$).

From Figure 5.2, it is clear that laser wavelength varies linearly with drive current in
specified ranges of drive current. We have chosen the current range between 48mA to 53mA for introducing constant $\pi/2$ phase shifting. The shift between the first and fifth frames differs slightly from $2\pi$, but this could be neglected as it is only necessary that the phase shifts be equal.

Fringe patterns were obtained in the following way. At 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 0.13mrad and speckle pattern corresponding to displaced object position without laser current modulation was obtained. Then the laser drive current was varied in steps and obtained four $\pi/2$ phase shifted speckle patterns. The reference speckle pattern was subtracted from each of the phase shifted speckle patterns and also from $0^0$ phase shifted pattern. These fringe patterns are shown in Fig. 5.31.

In MATLAB R2010a a command ‘atan2’ was used instead of simple arctan for phase calculations (Appendix-D). The command ‘atan2’ takes into account the signs of the trigonometric functions of the angles and assigns the angle into respective quadrant. The wrapped phase map shown in Fig. 5.32(a) was calculated directly from images of speckle patterns (without filtering phase stepped speckle fringes) shown in Fig. 5.31. This phase map is noisy because of the presence of high spatial frequency speckles. Some of the points in the speckle pattern are completely dark and some others are saturated, so a low pass (average) or median filter with kernels of size 5×5 or 7×7 or 9×9 can be applied. In this experiment an average image filter with 7×7 kernel was applied to obtain smoothly a varying wrapped phase map [21] shown in Fig. 5.32(b). A grey level of 255 in the wrapped phase map represents a phase shift of $2\pi$. 
The wrapped phase map was calculated using a frame algorithm as given [22]

\[ \Phi_w = \tan^{-1}\left( \frac{2(I_4 - I_5)}{I_1 - 2I_3 + I_5} \right) \]  

(5.13)
5.6.2.9.1. Phase unwrapping

The phase map shown in Fig. 5.32(a) is called a wrapped phase map because the phase values corresponding to each pixel within the image are wrapped between $-\pi$ and $+\pi$ due to the nature of arctangent function that has been used for phase calculations. The wrapped phase map contains $2\pi$ phase discontinuities. To obtain a smooth phase map of the object deformation, it is necessary to remove these $2\pi$ phase steps or discontinuities. The process of removing these $2\pi$ phase steps is called phase unwrapping or integrating the phase [23].

The most common method of unwrapping is by scanning pixels sequentially along a row or column. Wherever the phase jumps are detected, an offset of $2\pi$ is either added to or subtracted from the pixel’s phase value depending on the sign of the jump. Starting at the top of any column in the phase map the offset is set to zero. Scanning down the pixels in the column, the phase jumps are examined by calculating the phase difference between adjacent pixels. The algorithms which follow the above mentioned unwrapping procedure are not robust when dealing with noisy wrapped phase maps. To overcome the above difficulties a new and robust algorithm called 2D-SRNCP algorithm was developed at the General Engineering Research Institute (GERI) at Liverpool John Moores University, U.K [24]. We have used the 2D-SRNCP algorithm for phase unwrapping of our wrapped phase maps. This algorithm is freely available at [http://www.ljmu.ac.uk/GERI/90225.htm](http://www.ljmu.ac.uk/GERI/90225.htm). The 2D-SRNCP phase unwrapper is written in the C programming language. So the PC should have both MATLAB and Visual C++ or C++ installed to run the code. This C code is callable from Matlab using the ‘mex’ - ‘Matlab Executable’ dynamically linked subroutine functionality. The C code must be compiled in Matlab first, before it is called.
The 2D SRNCP algorithm belongs to the class of quality guided path algorithms. In general, these algorithms unwrap the highest quality pixels with highest reliability values first and lowest quality pixels with lowest reliability value last to prevent error propagation. In the 2D SRNCP algorithm the reliability of a pixel is defined based on the second differences (meaning difference of phase gradients) between a pixel and its neighbours. By using second differences of phase values of the adjacent pixels, detection of inconsistencies in the phase map can be improved. The unwrapping path is determined by the reliability of the pixels [24]. The reliability of a pixel is defined as the inverse of the second difference between the pixel and its neighbours. The 2D SRNCP algorithm follows non-continuous or discrete paths for unwrapping. The phase maps still contain some errors which cannot be detected, but the algorithms are very robust in practice compared to continuous path unwrapping algorithms.

To explain the unwrapping process some definitions are required such as considering neighbouring pixels to form an edge. An edge is an intersection of two pixels that are
connected either horizontally or vertically. The reliability of an edge is defined as the summation of the reliabilities of the two pixels that the edge connects. The unwrapping is first performed on those edges with higher reliability. An unwrapping path cannot be defined relative to the reliability of the pixels. Instead, it is defined by inspecting the value of the reliability of the edges.

![Diagram](image)

**Figure 5.34 3D displacement map of a metal plate**

An unwrapping process completes in 2-3 seconds (this may vary depending on PC hardware and complexity of the wrapped phase map) and the resulting phase map is displayed as an image as shown in Fig. 5.33. The phase value of each pixel lying in the range $[-\pi, +\pi]$ is represented by a grey level within the dynamic range of the CMOS camera to enable display of the phase map as a black and white image. The dark pixels correspond to a phase value of $-\pi$ and white pixels which are saturated correspond to phase value of $+\pi$. The unwrapped phase map of metal plate rotated by $\sim 0.15$ mrad is shown in Fig. 5.33. There is a smooth transition of intensity from bright to dark across the phase map.
From the phase map, a 3D displacement map is calculated as [25]

\[ \Omega = \left( \frac{\lambda}{4\pi} \right) \Phi_u \]  

(5.14)

Where \( \Omega \) = displacement of the metal plate; \( \Phi_u \) = unwrapped phase; \( \lambda \) = wavelength of laser 658nm.

From the Fig. 5.31 and 5.32, metal plate rotation can be calculated using field of view and number of fringes present in the fringe pattern as shown

\[ \theta = \frac{n\lambda}{FOV} \]  

(5.15)

Where \( n \) = number of fringes; \( FOV \) = field of view; \( \lambda \) = wavelength of the laser

For field of view 2.5cm and \( \lambda \) = 658nm and \( n=5 \), \( \theta=0.13 \text{mrad} \).

This tilt was verified by illuminating the rear of the metal plate mount to which a mirror was attached; the movement of the reflected light from a green laser pointer was measured. The measured angle was 0.15mrad and this is in agreement with the angle calculated using field of view.

The reason for choosing a five frame algorithm was that it minimizes calibration error and allows correct phase calculation when phase steps differ from \( \pi/2 \) only requiring phase steps to be equal. The errors in phase shift were thus minimized but still exist. From Fig. 5.31(a)-(e) and Fig. 5.35, it is clear that the phase shifts do differ. Fig. 5.35 shows intensity profiles for five phase shifted frames along a row pixel (210). The exact phase deviation was not calculated but estimated to be of the order of \( \pi/20 \). It is clear that from Fig. 5.35, the phase deviation between 0° and 360° was \( \sim \pi/10 \).
Figure 5.35 Intensity profile of the phase shifted fringe patterns for a particular pixel

The uncertainty in displacement measurement was not greater than ±0.01 μm. A3D profile of the object displacement is shown in figure 5.34. The out of plane displacement at the edge of the field of view was found to be 1.9 μm with uncertainty of ±0.01 μm.

5.6.2.9.2. Limitations of phase stepped dual HOE based ESPI system

Laser power changes: When a frequency modulated laser diode is used for introducing phase stepping or phase shifting by increasing its drive current, a problem arises with laser power. Changes in drive current result in change in the laser output power. In this case, our assumption of constant intensity in the phase extraction algorithm is violated. The intensity variations may cause some errors in the phase calculations and can be minimized either by normalizing the interferograms [26] or using an amplitude stabilizer for the laser diode [27]. The disadvantages are that implementing these methods can complicate laser diode based interferometers. To overcome these problems, Ishii and Onodera modified the phase-extraction algorithm
making it insensitive to power changes [28]. In this algorithm at least six frames are required to calculate the phase. The phase is calculated from a least-squares fit to an interferogram, which includes intensity variations due to the changes in laser power.

**Speckle decorrelation:** Speckle decorrelation results in random phase errors introduced between any two speckle patterns which correspond to two positions of the test object [29]. In deriving speckle correlation fringes either using subtraction or addition, we assume the intensities of speckle patterns corresponding to the two positions are same, but this not the case in practice. The decorrelation is divided into two categories, image plane decorrelation and pupil plane decorrelation. The image plane decorrelation is caused by in-plane displacement of the object which produces transverse displacement of speckles. The pupil plane decorrelation is caused by the out-of-plane rotations of the object which produces rotation of the speckle field in front of the camera lens.

But, from the tilt measurements, we can conclude that the rotations less than 1milliradian may affect phase measurements but do not decorrelate the speckle fringes up to 6µm (pixel size of CMOS camera 6µm).

**Low modulation:** Low modulation of the speckles is another fundamental limitation in all phase shifting techniques [23] in ESPI. The speckle pattern is sampled by finite sized detector elements; hence the intensity recorded by a detector element is the average value over its area. To resolve a speckle pattern the speckle size should be made of the order of area of a single detector by adjusting the f/No. of the lens system. With this speckle size two speckles influence one pixel. To overcome this problem, the detector element size should be made of the order of 1/10th to the size of original detector element. Present technology doesn’t allow us to reduce the size of the
detector elements and even if we could the S/N ratio would decrease. The only way is to increase speckle size but this means reducing the aperture and therefore the intensity of light reaching the detector.

5.6.2.9.3. Measurement errors

Vibration measurements: For a test object which is not flat, the vibration amplitude also varies with the reference surface (RHOE surface serves as reference). If the path length difference in the interferometer is on average 1m and the distance from the RHOE to the object varies by ±2cm there would be a maximum of 2% error in vibration amplitude. Assuming a flat surfaced test object, from Fig. 5.25 it is clear that the phase accuracy depends on the vibration amplitude. At larger amplitudes ~ 4μm, the phase value can be measured with an accuracy of ±5° and it can be improved to ±1° at vibration amplitude larger than 4μm.

Rotation measurements

Phase error due to phase step algorithm: Phase errors may arise from the phase stepping algorithm that was used for calculating the phase map. The five frame phase shifting algorithm used for calculating the phase difference between object and reference beams improves the phase accuracy [22] compared to four frame algorithm [30]. Hariharan reported that a 2° deviation in the phase step of 90° produces a maximum error of ±0.02° in the calculated phase map. Similarly a deviation of 5° in the phase step (95° instead of 90°) results a maximum error ±0.1° in the phase map.

Phase error due to intensity variation: For a path length difference of 13cm, a phase shift of 180° can be introduced by changing the laser drive current by 0.3mA. The output power of laser diode operating at 51mA is around 20mW. For 1mA of current change the power changes by 0.8mW. The power changes by 0.48mW during the
acquisition of five phase stepped sets of fringes. Thus the relative power change was 2.6%. From the expression (4) derived by Hariharan in ref. 31 [31], we calculated the maximum phase error due to power change is ±0.7°.

5.6.2.10. Performance and limitations of the dual HOE based ESPI system

Thermal performance

Thermal performance of HOEs is not something we considered. Thermal performance means any change associated with HOE characteristics such as diffraction efficiency, diffracting angle with the temperature.

Consider what would happen if the air temperature changed by 1 degree. This changes the refractive index of the air and so that would alter the optical path length and influence the results. The coefficient of refractive index with temperature changes by 0.87×10⁻⁸/°C. For example, say the path length difference is 20cm then 1°C temperature change would later the optical path length by 1.2×10⁻⁹m which is very small. As we are doing continuous subtraction (in vibration work) such effects (or changes) would be cancelled out as the temperature can’t change quickly. In case of static loading experiments if the load is applied slowly, the temperature fluctuations may influence results, even so the path length changes are so small, they can be neglected.

Limitations from optics:

Laser: The laser diode is stable under current modulation (tested for continuous sinusoidal modulation) but the beam quality is poor. If visible DFB devices become available at reasonable cost, we could fabricate better HOEs for better fringe quality. Another limitation with the laser is its lower coherence length ~ 6m (line width =
50MHz) compared to coherence length of the near infrared DFB laser diode ~ 30m (line width = 10MHz).

**Spatial filter:** The beam quality is rather poor with a dark central spot (which actually represents the single mode operation of the laser diode) so to obtain a clean and expanded laser beam we have used a spatial filter and almost 70% of the power was lost. This prevents testing larger objects as they need more power.

**Field of view:** It is best to use collimated laser light, illuminating the test surface along the normal to minimise sensitivity to in-plane movement. At present we use HOEs which are 63mm×63 mm, so this is the maximum object surface area we can examine. We can remove collimating optics and use divergent illumination with a sufficiently narrow cone angle so that in-plane sensitivity does not pose a problem. However, illumination of large objects requires a large path length difference, making it difficult to modulate the path length with adequate precision.

**Laser power variations:** One of the limitations of HOE based ESPI systems is the output power modulation that occurs during the drive current modulation of the laser diode. When the path length difference is set at 25cm and the drive current amplitude modulation is ~0.8mA we can measure displacements of ~2µm. We know that for every 1mA of drive current change the associated output power changes by 0.8mW. During the measurement of displacement of the order of 2µm, the output power of laser changes by 0.64mW. This is about 2.2% to the maximum output power (28mW) of the laser. The output power changes significantly (nearly by 10%) when we need to measure the displacements of order 8µm. The decrease in fringe visibility due to power variations can be reduced when long coherence length laser diodes are used in combination with long optical path length differences.
**Speckle reference beam:** The problem is that the modulation intensity distribution obtained from a speckled reference beam system differs from that obtained from a smooth reference beam system in that the number of points or pixels which modulate weakly, or not at all, is significantly greater. This leads to a reduction in fringe contrast and the need to replace low modulation pixel values by a suitable combination of near neighbour values.

**Limitations in HOEs:** The challenge is to make HOEs with high enough diffraction efficiency to give sufficient contrast in the image across the full aperture). The HOE used for object illumination should be as efficient as possible as most objects have low reflectivity. The reference beam is provided by a reflective holographic optical element. Its efficiency does not have to be very high.

**Limitation from electronics:**

**Limitations in generating waveforms for phase shifting:** A digital to analogue converter board (National Instruments USB 6229) can generate analogue waveforms of a few mV but these waveforms suffer from glitches of 100mV sustained over 2.6µsec. This electronic noise may have caused some errors in phase measurements but the glitch only stays on for 2.6µsec, so this might not be observed at the frame rate 25frames/sec of the CMOS camera. However, to improve the waveform quality we can consider a more expensive dual function generator using two PXI5402 cards manufactured by National Instruments.

**Limitations in driving the test object:** A digital to analogue converter (DAC) board USB 6229 of National Instruments was used for generating waveforms (digital and analogue) required for ESPI system. When a piezoactuator attached to the test object was driven by an analogue sinusoidal signal between 100Hz and 10kHz, the object’s
vibrational amplitude decreased and signal shape was distorted (a sine waveform appears as square waveform when observed using an oscilloscope). This was initially thought to be as a result of an impedance mismatch. But, from the specification sheets of piezo and DAC board, it was noted that the input impedance of piezo was few Ω’s and the output impedance of DAC board was 0.1Ω. This problem occurred due to limited drive current capabilities of the DAC board. Implementing a current amplifier between the DAC board and the piezoactuator would avoid this problem.

**Limitation from test object:**

**Non-flat object:** When the object is not flat, then the change in path length difference would be different at different positions of the object. This can be solved by first obtaining shape information of the object using two wavelength speckle interferometry [32]. This shape information is used for correcting the displacement data obtained using the ESPI system.

**Size of the object:** At present we use HOEs with dimensions 63mm×63mm so this is the maximum object surface area we can examine in a single view. If this proves unacceptable one can use divergent illumination with a sufficiently narrow cone angle so that in-plane sensitivity does not pose a problem. However illumination of large objects requires a large path length difference, making it difficult to modulate the path length with adequate precision. The Dantec Q-100 strain sensor is designed for use on an area of 35mm×25mm.

**Limitations in measuring range:**

**Measurement range:** The dual HOE based ESPI system can measure dynamic displacement (vibrations) between 0.3µm and 3.8µm and static displacements up to
2µm at present. The measurement range can be extended for measuring larger displacements [1]. One of the limitations of the dual HOE based ESPI systems is the restricted continuous tuning range of the laser diode frequency. The laser diode used in dual HOE based ESPI system (658nm) can be frequency modulated between 30-60GHz (Fig. 5.2). For a path length difference of 25cm and 60GHz frequency modulation, we could measure displacement up to 33µm assuming no decorrelation.

The limiting factor for measuring large vibration amplitudes is the nature of fringe patterns modulated by the Bessel function. As the object vibration amplitude increases the intensity of the fringes decrease dramatically. This makes it difficult to measure larger vibration amplitude using time average ESPI. Another limiting factor for measuring displacements is speckle decorrelation.

**Effect of speckle decorrelation:** Speckle decorrelation can occur due to vibration or environmental disturbances or if the object displacement is very large. Jones and Wykes reported that in-plane translations and out-of-plane rotations of order of 100µm and $10^3$ radians respectively may be tolerated before fringe visibility falls below an acceptable level [33]. In our dual HOE based ESPI system, the vibration fringes were observed for vibrational amplitudes up to 3.8µm, though the intensity of fringe pattern falls rapidly with increasing amplitude. Even though the dual HOE based ESPI system is sensitive to out-of-plane displacements, we can’t neglect the effect of possible in-plane motion or out of plane rotation which both result in speckle decorrelation. As the test object vibrates there might be some out-of-plane rotations that that may cause decorrelation.

**Frequency limit:** The dual HOE based ESPI system may not be able to cope in a high frequency noise environment (50kHz or more), such as in an aircraft maintenance
facility or in any industrial environment. But this limitation can be overcome by pulsing the laser diode in dual HOE based ESPI system.

5.6.2.11. Comparison to other ESPI systems

There are several companies that supply ESPI/ESPSI systems. Some parameters for comparing different ESPI/ESPSI systems available commercially in the market are given in the table 5.8. One of the leading companies that supply ESPI systems is Dantec Dynamics GmbH. They have produced a 3D ESPI system (Q-300) for measuring in-plane and out-of-plane displacements [34]. This system consists of two diode lasers (785nm), a high resolution CCD camera (1380×1035) and four laser illumination systems. This system was tested on an object with maximum size 200×300mm². They have also produced a handheld ESPI optical sensor (Microstar Q-100) with dimensions 54×54×59mm³ [35]. This miniaturized ESPI system design was possible by incorporating glass fibre optics. The Microstar system can measure 3D deformation and strain by mathematical differentiation of displacement maps rather than using shearography. The system can be attached to the test object so that rigid body motion effects of the test object on the measurement error are minimized.

Dantec have produced another ESPI system (Q-300TCT) to measure thermally induced stress maps of components such as printed circuits, flip chips, etc [36]. The measurements can be done fully automatically from room temperature up to 300°C on areas of 40×50mm². A digital image correlation system (Q-400) was also produced for vibration measurements by Dantec Dynamics [37].
Optonor, in Norway produces commercial tripod mounted ESPI/shearography systems for non-destructive testing. The shearography system (SNT4045) can also be used for vibration studies by exciting the object with electronic shakers [38]. The maximum object size that can be tested using this system is 2×2m². Deformations of the order of millimetre can be measured. The vibration maps are obtained by numerical integration of shearographic data. Optonor also produces an ESPI system (Vibromap1000) to measure amplitude and phase maps of vibrating objects of dimensions 2×2m² or more. It can measure vibration amplitude up to 10µm, in the frequency range of 30Hz-50kHz [39]. Optonor also produces an ESPI system (MicroMap 5010) for measurements of dynamic and static displacements of micromechanical structures (MEMS) in 3 dimensions and can be used for surface profiling measurements as well [40]. Microscopic objective lenses with different magnifications are used for imaging MEMS. This system can measure displacements >10µm on surfaces with dimensions between 245x330µm² micrometer and 9x12mm².

Another German company that produces shearography systems is ISI-SYS. The shearography system (SE3-NDT) can measure derivatives of static as well as dynamic

Table 5.8 Commercially available ESPI/Shearography/Digital image correlation systems
displacements [41]. This system also employs vibration excitation by using a piezo
shaker that mounts on to the test object. This system can be used to measure
deformation up to 0.3mm on surfaces with dimensions 8×10mm².

<table>
<thead>
<tr>
<th>ESPI system</th>
<th>Laser</th>
<th>Configurations</th>
<th>Measurements</th>
<th>Measurement range</th>
<th>Max. Object size</th>
<th>Dimensions</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>[40]</td>
<td>Diode</td>
<td>ESPI</td>
<td>Displacement</td>
<td>0.1-0.2mm</td>
<td>8×10mm²</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>[40]</td>
<td>Diode</td>
<td>ESPI</td>
<td>Strain</td>
<td>0.1-0.2mm</td>
<td>100×100mm²</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>[40]</td>
<td>Diode</td>
<td>ESPI</td>
<td>Stress</td>
<td>0.1-0.2mm</td>
<td>100×100mm²</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>[40]</td>
<td>Diode</td>
<td>ESPI</td>
<td>Strain</td>
<td>0.1-0.2mm</td>
<td>100×100mm²</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Table 5.9 Compact ESPI/Shearography systems reported in the literature

Several compact ESPI/Shearography systems have been reported in the literature. Some of the parameters of these compact ESPI systems are given in Table 5.9 for comparison. Huang et al [42] reported a shearography system using optical fibres and conventional optical elements. They have used diode laser wavelength modulation for introducing phase stepping in an unbalanced interferometer. This system was tested on a rectangular metal plate (100×100mm²) constrained along the edges. The same speckle shearography set up was used to detect defects in the test object [43].

Fomitchov and Krishnaswamy reported a portable combined ESPI/shearography system using an optical set up similar to Michelson’s interferometer [44]. To operate in shearography mode, they introduce a mirror in the reference beam path and slightly tilt another mirror. To operate in ESPI mode, the mirror blocking the reference beam is removed from the system.
Guntaka et al reported a compact reflection HOE based ESPI system using a near infrared diode laser operating at 784nm [45]. The phase stepping was introduced by frequency modulation of laser diode. The HOE was recorded at 633nm using He-Ne laser and the holographic speckle reference wave reconstructed at 784nm. They have measured displacements ~ 1.5µm of a circular duraluminium plate clamped at edges with pressure applied to displace the object.

Viotti et al reported a portable in-plane sensitive DSPI system for measuring residual stresses in metal plates using hole drilling [46]. All the three residual stresses are measured using only one symmetrical two beam illumination system. The residual stress components are calculated using the Carre four frame phase stepping algorithm [47]; the continuous unwrapped phase map is obtained by using an $L^0$-norm algorithm. The phase maps corresponding to before and after hole-drilling were obtained to compute residual stresses.
Bova et al. recently reported a portable speckle interferometer to measure highly localized gradients such as displacements around crack tips or strain relief occurring in residual stresses on small areas [48]. The system contains three single mode laser diodes operating at 660nm for illuminating in three different directions. The system is based on Michelson’s interferometer and the lasers can be moved within the set up, so that object can be illuminated at different distances. Rotations of a rigid body have been reported with displacements between 2 and 4µm.

For some comparison with commercially available ESPI/Shearography systems, field of view (size of the object) measured in vibration studies of a circular aluminium plate using the out-of-plane sensitive dual HOE based ESPI system are given in Table 5.10.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Drive current (mA)</th>
<th>Wavelength modulation (pm)</th>
<th>Frequency modulation (GHz)</th>
<th>Displacement (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>834</td>
<td>0.17 - 0.92</td>
<td>0.9 - 5.1</td>
<td>0.6 - 3.5</td>
<td>0.3 - 1.8</td>
</tr>
<tr>
<td>1017.3</td>
<td>0.17 - 0.95</td>
<td>0.9 - 5.2</td>
<td>0.6 - 3.6</td>
<td>0.3 - 1.9</td>
</tr>
<tr>
<td>5600.5</td>
<td>0.18 - 0.78</td>
<td>1.0 - 4.2</td>
<td>0.7 - 2.9</td>
<td>0.3 - 1.5</td>
</tr>
<tr>
<td>6620</td>
<td>0.22 - 0.62</td>
<td>1.2 - 3.4</td>
<td>0.8 - 2.3</td>
<td>0.4 - 1.2</td>
</tr>
</tbody>
</table>

**Table 5.10 some parameters measured during vibration of a circular aluminium plate driven by piezoactuator**

The dual HOE based ESPI can only measure vibrations up to 6.62 kHz. The reason is due to the limited drive current capabilities of the DAC board. All the parameters given in the Table 5.3 are measured when path length difference was set at 24cms (2l). The maximum drive current modulation amplitude is 0.95mA. The corresponding maximum wavelength and frequency modulations are 5.2pm and 3.6GHz respectively.

The specifications of the dual HOE based ESPI system are given in Table 5.11. These specifications were prepared in the same format in which the commercial systems are
specified. The dual HOE based ESPI system can measure out-of-plane displacements up to 4µm. The vibration measurement method is largely manual. The data for phase and amplitudes maps is acquired in few minutes but offline processing takes an hour for each phase map. The maximum size of the test object is limited to 54×54mm². The system dimensions are 100×100×400mm³.

<table>
<thead>
<tr>
<th>Measurement sensitivity</th>
<th>0.2 - 0.3µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring range</td>
<td>0.1 - 4µm</td>
</tr>
<tr>
<td>Measuring area</td>
<td>54×54mm²</td>
</tr>
<tr>
<td>Operating modes</td>
<td>Semi-automatic</td>
</tr>
<tr>
<td>Data interface</td>
<td>TIFF</td>
</tr>
<tr>
<td>Data analysis</td>
<td>Semi-automatic for vibration and static displacements</td>
</tr>
<tr>
<td>Dimensions of sensor head</td>
<td>100×100×400mm³</td>
</tr>
<tr>
<td>Weight</td>
<td>2kg (excluding breadboard and object)</td>
</tr>
<tr>
<td>Laser</td>
<td>Diode 35mW, 658nm</td>
</tr>
<tr>
<td>Processor</td>
<td>Pentium 4 (Laptop)</td>
</tr>
<tr>
<td>Operating system</td>
<td>Windows Vista</td>
</tr>
</tbody>
</table>

Table 5.11 Specifications of out-of-plane sensitive dual HOE based ESPI

5.6.3. Summary

A laser diode operating at 658nm (visible region) was used for fabricating the HOEs for HOE based ESPI systems. The laser acts as source as well as a phase modulator if used in an unbalanced interferometer. The laser wavelength variation with the drive current change was studied to find stable mod-hop free regions for phase modulation as well as HOE recording. A reflection HOE based ESPI system was constructed and used for studying vibration behaviour of a circular metal plate driven by piezoelectric actuator. To measure phase and amplitude information of a vibrating object the path length difference phase was modulated in amplitude and phase by modulating the drive current of the laser diode. The disadvantage of a single RHOE based ESPI system is that it has sensitivity to in-plane displacement components.
A transmission grating was added to make the RHOE based ESPI sensitive only to out-of-plane displacements i.e. dual HOE based ESPI system. Amplitude and phase maps of the vibration of a circular metal plate driven by a piezoelectric actuator were obtained using path length difference modulation in an unbalanced interferometer.

The dual HOE based ESPI system was also used for rotation measurements of metal plate using phase stepping in an unbalanced interferometer. The phase stepping was implemented by altering the laser current in steps. Measurement errors for vibration and rotations are also discussed. The limitations of both single RHOE and dual HOE based ESPI systems were discussed. The dual HOE based ESPI system was compared with commercially available compact ESPI systems and also with compact speckle interferometers reported in the literature. The specifications of the dual HOE based ESPI system is provided in Table 5.11. Even though there are limitations, the dual HOE based ESPI system serves as alternative compact low cost system for static and dynamic measurements. By implementing more facilities in dual HOE based ESPI system such as shearography, surface profiling and stroboscopic technique the versatility of the system can be improved. In the next chapter some future applications to be implemented with the dual HOE based ESPI system are discussed.
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This thesis has presented the development of different HOE based ESPI systems using a near infrared DFB laser and also using a visible wavelength laser diode. The main objective of the work was to develop an out-of-plane sensitive electronic speckle pattern interferometer (ESPI) using holographic optical elements (HOE), mainly for vibration measurements. This was achieved using combination of two HOEs, a reflection HOE and a transmission HOE. This dual HOE based ESPI system was used for quantitative measurement of phase and amplitude maps of a vibrating object. This system was also used for measuring static rotational displacements precisely. In this chapter we present a summary of the experimental work that was discussed in the previous chapters and some suggestions are provided for possible future development of the dual HOE based ESPI system.

6.1. Summary of the work presented

Initially, an out-of-plane sensitive reflection HOE based ESPI system using a near infrared distributed feedback (DFB) diode laser (763nm) was successfully developed. This system was used for vibration measurements of a circular metal plate attached to a loudspeaker. The reason for using a near infrared diode laser was that it can be operated in a single mode and also its wavelength can be varied by changing the drive current to introduce optical path modulation in an unbalanced interferometer. There were no holographic recording materials sensitive at 763nm available commercially. So, an alternative approach was adopted to record reflection HOEs at 633nm and reconstruct them at 763nm. Equations were derived (Section 4.2.2.2) using Snell’s
law of refraction and Bragg’s law of diffraction to determine the shift in the illumination and observation angles for a wavelength other than the wavelength of the HOE recording beams and a MATLAB code (Appendix-A) was developed to calculate angles of illumination and diffraction, so that the ESPI system was sensitive mostly to out-of-plane displacement.

Before using the near infrared DFB diode laser in HOE based ESPI systems, its wavelength variation with drive current was studied using an optical spectrum analyser. From this study, regions in which wavelength varies linearly with the drive current were identified so that phase modulation in an unbalanced interferometer could be implemented.

An out-of-plane sensitive transmission (hybrid) HOE based ESPI system was developed successfully using a near infrared DFB diode laser. Reconstruction from a RHOE is restricted by Bragg’s law of diffraction to a small range of angles, we wanted an out-of-plane sensitive ESPI system and this was difficult to obtain from an RHOE. It is also difficult to obtain even the low diffraction efficiencies in RHOEs to match low reflectivity test objects. The recording material needs to be of high spatial resolution in order to record the reflection HOE and the material tends to shrink, changing the reconstruction angle. For these reasons we tried using the PRM system with a THOE.

A partially reflecting mirror of reflectivity (R=0.3) was used to illuminate the object with a diffusely transmitting HOE to provide a speckle reference beam in an ESPI system. The diffusely transmitting HOE was recorded at 532nm and used at the near infrared wavelength of the laser diode in the ESPI system. Equations were also derived for the THOE (Section 4.2.2.1) for illumination and observation angles due to
the Bragg shift. A code was developed in MATLAB based on the equations to calculate illumination and observation angles. This system was sensitive purely to out-of-plane displacements. Self processing photopolymer material developed at the IEO centre was used as recording material for the THOE. Histograms of the object and reference beams (Section 4.4.5) were presented.

To avoid the difficulty of recording HOEs at one wavelength and playing back them at another wavelength, a diode laser whose wavelength is stabilized by a volume holographic grating rather than by distributed feedback and operating in the visible region at 658nm was used in a HOE based ESPI system. The diode laser was characterized using an optical spectrum analyser. The reflection HOE and transmission HOEs were recorded at 658nm in such a way that the ESPI system was only sensitive to out-of-plane displacements. Vibration measurements of a circular aluminium diaphragm (5.4cm in diameter and 1mm in thickness) driven by piezoelectric actuator were performed using the visible laser HOE based ESPI systems.

To map the vibration amplitude and phase, the reference beam (path length difference) in the interferometer was modulated at the same frequency as that of the vibrating test object. Vibration resonant modes were found at 1018Hz and 6620Hz without path length difference modulation, by introducing a phase shift of $\pi$ between consecutive images and subtracting them from one another [1]. The brightness of the fringes was very low so images were stretched (in terms of gray scale distribution) as discussed in Section 5.6.1.3. When the test object was excited at 1018Hz, the phase modulation needed to obtain the first order Bessel bright fringe which represents an iso-amplitude line where $\varphi_r = \varphi_0 = 0$, corresponded to a laser drive current modulation.
of 1mA. The displacement on the iso-amplitude line corresponding to 1mA was 0.5µm. A phase difference of 180° was introduced between the reference and object beam in the interferometer to obtain phase reversed first order bright fringes. The same process was repeated for a mode 6620Hz and the displacement of the first order Bessel bright fringe was 0.5µm. The limitations of the RHOE based ESPI system are also discussed.

Another HOE based ESPI system was developed using combination of a transmission HOE and a reflection HOE; it is referred as dual HOE based ESPI system. Vibration behaviour of a circular metal plate of 5.4cm in diameter and 1mm in thickness driven by piezoelectric actuator was studied using this ESPI system [2]. Vibration modes were observed at 834Hz, 916Hz, 1017.3Hz, 1060Hz, 5600.5Hz and 6620Hz. The first order Bessel bright fringe contours were mapped by modulating the path length difference in the interferometer. Vibrational amplitudes are tabulated in section 5.6.2.4. The diffraction efficiencies of HOEs required for balancing the beam intensities in the interferometer are considered with reference to various object reflectivities. The effect of temperature and humidity on the diffraction efficiencies of the HOEs is also discussed.

The phase maps of the circular metal plate driven by piezo are obtained by separating the amplitude information from the phase information by modulating the phase of the path length difference in the unbalanced interferometer, relative to the object vibration. Detailed phase maps are obtained of the circular plate when it was excited at 916Hz and 1060Hz respectively [3]. It becomes difficult to obtain higher order amplitude contours because the intensity of the brightest fringe drops quickly due to the Bessel function. But if the brightest fringe can be identified there is no problem. Speckle noise and reduced contrast can make it difficult to identify the brightest
fringe. Hence amplitude maps are not complete but this might be overcome using image enhancement methods.

The vibration behaviour of another test object, a square (4cm×4cm) thin metal plate was also studied using phase modulation in the interferometer. Vibration modes were observed at 1406.1Hz and 4980Hz. The first and second order Bessel bright fringe contours were mapped at 1406.1Hz and the corresponding displacements were 0.4µm and 0.8µm. The first and second order Bessel bright fringe contours were mapped at 4980Hz and their corresponding displacements were 0.6µm and 1.7µm.

The dual HOE based ESPI system incorporating a RH0E and a TH0E was also used to measure rotation of a metal plate attached to a mirror mount. Phase shifts of 90° were introduced between consecutive frames. Five phase shifted frames were obtained corresponding to the displaced object position. Then subtraction of a reference frame corresponding to the original position of the object provides correlation fringes. A five frame phase stepping (Schwider - Hariharn) algorithm was used for obtaining a wrapped phase map. This algorithm was implemented in MATLAB 2011a. Phase unwrapping was carried out using 2D-SRNCP algorithm developed at John Moores Liverpool University. The unwrapped phase map was transformed into 3D mesh displacement map in MATLAB R2011a. The displacement at the edge was found to be 1.9µm and the corresponding rotation was 0.15mrad.

The errors introduced in the phase stepping method as well as in vibration measurements were estimated. The limitations of the dual HOE based ESPI system are also discussed. These limitations were due to both optical components and the electronics used in the dual HOE based ESPI system. Another limitation is the dimensions of the laser beam width that determines the maximum size of test object.
that can be illuminated. The dual HOE based ESPI system was compared with other ESPI systems reported in the literature as well as with other commercially available ESPI systems. Specifications of the optical and electronic components used in the dual HOE based ESPI system components are provided in the Appendix-E.

Another important achievement is the generation of required waveforms, analogue and digital waveforms using a National Instruments USB6229 digital to analogue converter board (DAC) in LabVIEW environment. The dual HOE based ESPI system requires several waveforms. One is a digital pulse of 25Hz and duty cycle 0.01% to control frame rate of a CMOS camera. In addition to, two sinusoidal waveforms with same frequency but with variable amplitudes and phases are generated. Another waveform required is a rectangular waveform used for π phase shifting between consecutive camera frames. All the waveforms (digital and analogue) are initiated simultaneously by a master digital trigger. The laser drive current signal is modulated using a composite waveform which is the addition of a sinusoidal waveform to the π phase shifting rectangular waveform. This composite waveform is fed to the laser diode drive current controller. The software is explained in detail in Appendix – B.

In conclusion, a simple ESPI system using HOEs to obtain vibration amplitude and phase measurements was implemented. Use of HOEs significantly reduces the number of optical elements, leading to a compact ESPI system providing fringes of good contrast. These ESPI systems can facilitate optical non-destructive testing at low cost for industrial use.
6.2. Conclusions

To meet the objectives the following work was carried out.

- Different HOE based ESPI systems for measuring out-of-plane displacement components were developed using a near infrared (IR) distributed feedback (DFB) laser diode.
- A purely out-of-plane sensitive HOE based ESPI system using a combination of a RHOE and THOE (Dual HOE) was developed for vibration measurements.
- Path length difference modulation by modulating the drive current of a laser diode operating in visible wavelength was implemented in unbalanced out-of-plane sensitive HOE based ESPI systems for obtaining phase and amplitude maps of a vibrating flat metal plates.
- The dual HOE based ESPI system was also used for measuring small rotations (static displacements) of a metal plate using phase stepping method by laser drive current (wavelength) modulation.

6.3. Future work

Some ideas are discussed in this section for future development of the dual HOE based ESPI system.

6.3.1. Laser beam quality

The output beam profile of laser diode (658nm) has a Gaussian intensity distribution, so the intensity distribution is not uniform across the beam. This makes the diffraction efficiency of the HOEs spatially variable. This problem can be overcome simply by expanding the laser beam so that the central part of the Gaussian beam where the intensity remains relatively constant can be used to record HOEs with spatially
uniform diffraction efficiency. But this results in wasting a lot of available laser output power. An alternative method is to use a set of two aspheric lenses and is proposed by Hoffnagle and Jefferson, which converts laser output from Gaussian profile to flattop (constant intensity across the beam area) profile while retaining most of the beam power [4].

The optical configuration of the set of aspheric lens system is shown in Fig. 6.1. In the two aspheric lens system, one surface refracts the incident Gaussian beam to produce the desired flattop intensity distribution and the second recollimates the beam. The advantages of the lens system are that it is capable of converting the beam profile with high efficiency and it involves a simple coaxial optical arrangement, minimizing alignment issues. Another advantage is that the aspheric surfaces are convex, are rotationally symmetric and monotonic, hence their fabrication is easy.

![Figure 6.1 Beam reshaping system showing the path of a typical ray](image)

The aspheric lens set accepts essentially all (~99.7%) of the input beam; generates a flattop output beam for which diffraction effects can be controlled.
By using the above aspheric lens system, one can make HOEs which have spatially uniform diffraction efficiencies. At present the laser diode output beam contains a dark patch and so is not even Gaussian. Despite the best efforts in spatial filtering using 40X objective and 5µm pinhole, dark patch could not be removed.

This suggests that the laser diode output beam quality has to be improved, either by using an external cavity laser diode or a DFB visible laser for recording HOEs with spatially uniform diffraction efficiencies.

6.3.2. **Shape measurement using the dual HOE based ESPI system**

All the test objects reported in this thesis are flat plane surfaces. Most engineering components are non-flat surfaces; hence accurate information about the surface is obtained using surface profile or shape measurement techniques. The shape of an irregular surface can be measured using a two wavelength ESPI system. In the present studies we can use the dual HOE based ESPI system shown in Fig. 5.15. The diode laser used for experiments in Chapter 5 can also be tuned to two different wavelengths either by modulating its drive current or temperature [5, 6].

Surface contours using HOE based ESPI system can be obtained by illuminating the surface at two different wavelengths $\lambda_1$ and $\lambda_2$ either simultaneously or sequentially. When the surface is sequentially illuminated, the first speckle interferogram is recorded at $\lambda_1$ and stored. A second speckle interferogram is recorded by illuminating at a different wavelength $\lambda_2$. The surface contours are obtained by subtracting the first speckle pattern from the second speckle pattern. These subtracted fringes provide quantitative information as we know the depth resolution if $\lambda_1$ and $\lambda_2$ are known.
To obtain quantitative information about the shape of the surface, a phase shifting technique can be employed. As discussed in Chapter 5 section 5.6.2.9, a five frame phase shift algorithm can be applied here. Initially a reference speckle pattern can be stored when the surface is illuminated at wavelength $\lambda_1$. Then the wavelength is changed to $\lambda_2$ and five frames with appropriate phase shifts (90°) can be obtained by changing the drive current of the diode laser. To calculate wrapped and unwrapped phase maps the algorithms discussed in section 5.6.2.9 can be applied here as well.

From Fig. 5.2, it is possible to introduce 0.1nm difference in wavelength by tuning the drive current (while temperature of the laser kept constant) even though mode hops are present. From Eq. 2.34, contours of order of 4mm difference in depth can be measured when $\lambda_1$ is 658.3nm and $\lambda_2$ is 658.4nm. The diode laser wavelength can also be tuned by changing its temperature. The developments using temperature changes were explained in Chapter 2.

When the dual HOE based ESPI system used for measuring vibrations of a non-flat object, then the change in the wavelength would be different at different positions of the object. This problem can be solved by first obtaining shape information of the object using two wavelength speckle interferometry as discussed above. This shape information is used for correcting the displacement data obtained using ESPI system.

6.3.3. Pulsing diode laser in dual HOE based ESPI

To measure transient or anharmonic vibrations, time average ESPI technique cannot be applied. So transient motion can be measured by using exposure times that are short in comparison to the highest frequencies present in the motion [7]. These short exposures freeze the motion. In this way the phase of the object deformation is made constant during the exposure. Freezing the motion of the object is the basic principle
for determining the transient or anharmonic motion. These short exposures can be
provided either by using reduced exposure times of the camera or using a pulsed laser
illumination [7]. There are two different measurement techniques based on the
number of pulses that are fired during the exposure time of the camera and also on the
type of the motion such as harmonic, transient. The first is a dual pulse technique and
the second is a stroboscopic technique.

Fig. 6.2 shows the timing charts for pulsed and stroboscopic illuminations. Camera
acquisition is triggered by an external digital pulse (a) and (e). Assume that the object
is excited by a harmonic waveform as shown in Fig. 6.2(b) and (f). In case of pulsed
illumination the object deformation is acquired by firing two pulses corresponding to
two different positions of the object as shown in Fig. 6.2(c). A simple subtraction of
these images would produce a speckle correlation fringe pattern. The subtraction
method has a limitation that the minimum time between exposures is set by the
interval between the camera frames. This can be overcome by firing two pulses during
a single camera frame and the fringe pattern results from incoherent addition of two
laser pulses as shown in Fig. 6.2(d).

Stroboscopic illumination means illuminating the object for a brief interval at the
same point in each cycle of its vibration. A reference frame (usually captured with
object at rest) can be subtracted from the sum of all the stroboscopic exposures to
produce fringes. The principle of stroboscopic ESPI is very similar to that of double
pulse ESPI but differs in number of pulses fired in one cycle of object motion as
shown in Fig. 6.2(g). The double pulse technique needs high power laser as the
exposure time is very short. The stroboscopic technique needs lower laser power but
uses a greater number of pulses.
Diode lasers can also be used in pulsed mode by applying a digital pulse to the modulation input of the current controller. The diode laser (ONDAX SureLock™) is available only with low optical power and thus can be used only for stroboscopic illumination.

A limitation using stroboscopic illumination using diode lasers in ESPI is that the pulse used for illumination is accompanied by a chirp in the optical frequency. This chirp is the result of temperature change in the diode structure due to the modulation of the drive current. This frequency chirp prevents successful functioning of the ESPI system, but can be overcome by incorporating an equalization circuit in the diode

Figure 6.2 Timing charts for pulsed and stroboscopic ESPI measurements of harmonic vibration
laser drive current electronics [8]. The equalization circuit compensates for the two slowest thermal time-constants of the laser diode, typically of the order of about 10 ps and 100 ps [9] and also improves the bandwidth of the frequency modulation (FM) transfer function. By altering the values of two variable resistors in the circuit, the wavelength can be kept stable throughout the duration of the pulse.

Lau et al [10] have reported stroboscopic illumination in an HOE based ESPI system. We could improve the quality of the fringe pattern in this way and study practical engineering structures such as vibrations of turbine blades and aircraft surfaces.

6.3.4. **Electronic speckle pattern shearing interferometer (ESPSI) for vibration measurements**

The dual beam HOE based ESPI system can be modified and adjusted in such a way that an electronic speckle pattern shearing interferometer can be constructed using a transmission holographic grating and a (ground glass) diffuser as shown in the Fig. 6.3. The transmission holographic grating can be used as a shearing element in the interferometer. If only a transmission grating is used in the system, then the CMOS camera has to resolve the pitch of the holographic grating. This limits the applicability of the ESPSI system. To overcome the need for the grating frequency to be low, Joenathan and Burkle [11] introduced a ground glass diffuser in the ESPSI system. Mihaylova et al. from our research group have also reported a photopolymer diffraction grating based ESPSI system for measuring static displacement spatial derivatives [12]. Mihaylova et al. reported the same photopolymer diffraction grating based ESPSI system for vibration mode measurements of a edge clamped aluminium diaphragm but without phase mapping [13]. So, in future using the proposed ESPSI system phase and amplitude maps of vibrating objects can be extracted using phase modulation [3].
Figure 6.3 Optical set up of an ESPSI system using a transmission holographic grating

The intensities of the zero and first order of diffraction can be equalized by rotating the grating. This leads to off-Bragg angle reconstruction of holographic image and decreases the intensity of the first order. This offers possibility for fine adjustment of both image and sheared image intensities.

The mechanism of introducing shear in the interferometer is discussed below.

When two lights waves interfere, their relative phase $\Phi$ due to their geometrical path difference $L$, can be expressed as [12]

$$\Phi = \frac{2\pi}{\lambda} nL - \beta$$

(6.1)

where $\lambda$=wavelength of the laser $n$=refractive index of the medium through which the laser light is transmitted, $L$=relative geometrical path length and $\beta$= constant phase.

The change in relative phase can be expressed as
\[ \Delta = \delta \Phi = \frac{\partial \Phi}{\partial \lambda} \delta \lambda + \frac{\partial \Phi}{\partial n} \delta n + \frac{\partial \Phi}{\partial L} \delta L = \frac{-2\pi L n}{\lambda^2} \delta \lambda + \frac{2\pi L}{\lambda} \delta n + \frac{2\pi n}{\lambda} \delta L \]  
(6.2)

The environment is air with refractive index \( n = 1 \), when the object lies in \( x,z \) plane

\[ \Delta = \frac{2\pi}{\lambda} \left[ \frac{\partial u}{\partial x} \sin \theta + \frac{\partial w}{\partial x} (1 + \cos \theta) \right] \Delta x \]  
(6.3)

Where \( u,v \) are in-plane displacement components and \( w \) out-of-plane displacement component. \( \Delta x \) – shear introduced along the x-axis.

When the wavelength in the interferometer is modulated, then the phase \( \Delta \) should be differentiated with wavelength

\[ \frac{\partial \Delta}{\partial \lambda} = \frac{-2\pi}{\lambda^2} \left[ \frac{\partial u}{\partial x} \sin \theta + \frac{\partial w}{\partial x} (1 + \cos \theta) \right] \Delta x \]  
(6.4)

Assuming in and out of plane strains are fixed so the term in square brackets is constant and it is set equal to \( k \), then

\[ \frac{\partial \Delta}{\partial \lambda} = \frac{-2\pi}{\lambda^2} k \Delta x \delta \lambda \]  
(6.5)

So for given \( k \) we can introduce phase shift by altering the wavelength.

To extract phase and amplitude derivative maps of a vibrating test object phase shifting can be introduced in an unbalanced shearing interferometer by modulating the reference beam phase in a time average ESPSI. By modulating the drive current of laser diode, the phase difference in the interferometer can be shifted in steps of \( \pi/2, \pi, 3\pi/2, 2\pi \) and corresponding fringe patterns are used for the phase calculation using a five frame phase shifting algorithm.
6.4. Summary

A novel out-of-plane sensitive dual HOE based ESPI has been presented for extraction of phase and amplitude maps of vibrating objects by using diode laser wavelength modulation in an unbalanced interferometer [2, 3]. The vibrations of a circular metal plate driven by a piezo actuator were studied in the frequency range 800Hz to 6620Hz. The HOE based ESPI system was also used for measuring rotations of metal plate mounted on a mirror mount. Quantitative rotation measurements were obtained using temporal phase stepping. The complete information about the object is shown as an unwrapped phase map and as a displacement map. The instrument has been compared with other ESPI systems available in the market and systems reported in literature.

In future the dual HOE based ESPI system can be applied to shape measurement of non-flat test objects and for harmonic vibration measurements using stroboscopic illumination. A holographic grating based ESPSI system can be implemented by removing the RHOE from the dual HOE based ESPI system. The laser output beam intensity profile can be made spatially uniform using beam reshaping optics provided the original Gaussian laser output is clean and follows Gaussian intensity distribution. To increase the versatility of the dual HOE based ESPI system, it is important to measure the vibrations of a non-flat objects in future.
References


Appendix - A

Recording and Playback of HOEs

RHOE MATLAB code

% Refractive index of the holographic recording material
n=1.5;

% Ratio of the reconstructing to recording laser wavelengths
lr=763/633;

In_t1=50; Fn_t1=90;  % Enter theta 1 values here
In_t2=80; Fn_t2=100;  % Enter alpha values here

% Theta 1 value is defined for every iteration as
for(i=0:Fn_t1-In_t1)
    Tab_t1(i+1)=In_t1+i;
end

% Alpha value is defined for every iteration as
for(i=0:Fn_t2-In_t2)
    Tab_t2(i+1)=In_t2+i;
end

% Generates theta 1 values with in the interval specified by the length of the Tab_t1
for(t1=1:length(Tab_t1))
    % Generates alpha values with in the interval specified by the length of the Tab_t2
    for(t2=1:length(Tab_t2))
        % Theta 1 inside the holographic material
        temp1=sind(Tab_t1(t1))/n;

        % Theta 2 inside the holographic material
        temp2=sind(180-2*Tab_t2(t2)+Tab_t1(t1))/n;

        % asind means arc sin in degrees

        % Average value of theta 1 and theta 2 inside the holographic material
        temp3=[asind(temp1)+asind(temp2)]/2;
    end
end
% Half of the difference of the theta 1 and 2 inside the holographic material

\[ \text{temp4} = \frac{\text{asind(temp1)} - \text{asind(temp2)}}{2}; \]

\[ \text{dd} = \text{lr} \times \text{cosd(temp3)}; \]

if((dd<1))

% Bragg angle

\[ \text{temp5} = \text{acosd(dd)}; \]

% sin(gamma) which is angle of illumination at 763nm

\[ \text{temp6} = \text{n} \times \text{sind(temp4+temp5)}; \]

% sin(gamma double prime) which is angle of diffraction at 763nm

\[ \text{temp7} = \text{n} \times \text{sind(temp5-temp4)}; \]

else

\[ \text{temp6} = 0; \]

\[ \text{temp7} = 0; \]

end

% Generates table of values for gamma in degrees

\[ \text{gma(t1,t2)} = \text{asind(temp6)}; \]

% Generates table of values for gamma double prime in degrees

\[ \text{gma_dd(t1,t2)} = \text{asind(temp7)}; \]

end

\text{THOE MATLAB code}

% Refractive index of the holohraphic recording material

\[ \text{n} = 1.5; \]

% Ratio of the reconstructing to recording laser wavelengths

\[ \text{lr} = \frac{763}{633}; \]

\[ \text{In_t1} = -30; \quad \text{Fn_t1} = 30; \quad \% \text{Enter theta 1 values here} \]

\[ \text{In_t2} = -30; \quad \text{Fn_t2} = 30; \quad \% \text{Enter Theta 2 values here} \]
% Theta 1 value is defined for every iteration as
for(i=0:Fn_t1-In_t1)
    Tab_t1(i+1)=In_t1+i;
end

% Theta 2 value is defined for every iteration as
for(i=0:Fn_t2-In_t2)
    Tab_t2(i+1)=In_t2+i;
end

% Generates theta 1 values with in the interval specified by the length of the Tab_t1
for(t1=1:length(Tab_t1))
    % Generates alpha values with in the interval specified by the length of the Tab_t2
    for(t2=1:length(Tab_t2))
        % Theta 1 inside the holographic material
        temp1=sind(Tab_t1(t1))/n;
        % Theta 2 inside the holographic material
        temp2=sind(Tab_t2(t2))/n;
        % asind means arc sin in degrees
        % Average value of theta 1 and theta 2 inside the holographic material
        temp3=[asind(temp1)+asind(temp2)]/2;
        % Half of the difference of the theta 1 and 2 inside the holographic material
        temp4=[asind(temp2)-asind(temp1)]/2;
        dd=lr*sind(temp4);
        % Bragg angle
        temp5=asind(dd);
        % sin(gamma)which is the angle of illumination at 763nm
        temp6=n*sind(temp3-temp5);
        % sin(gamma double prime) which is the angle of diffraction at 763nm
        temp7=n*sind(temp3+temp5);
    end
end

% Generates table of values for gamma in degrees
\begin{verbatim}
gma(t1,t2)=asind(temp6);

% Generates table of values for gamma double prime in degrees

gma_dd(t1,t2)=asind(temp7);
\end{verbatim}

end
end
Appendix – B

Generation of digital counter pulse for camera external triggering virtual instrument (VI) written in LabVIEW

Fig. 1 Block diagram of the counter generation code

- Create a counter output channel to produce a pulse in terms of frequency

- Sets only the number of samples to generate or acquire a pulse without
specifying timing.

- Transitions the task to the running state to begin the measurement or generation
- Queries the status of the task and indicates if it completed the execution
- Clear the task. Before clearing this VI stops the task, if necessary, and releases any resources the task has reserved.

**Continuous generation of digital waveforms in synchronization with analogue waveforms – VI**

This VI demonstrates how to continuously output a waveform using an internal sample clock of the DAQ board. The automatic regeneration of data has been disabled, so that the new data has to be provided throughout the duration of the continuous analogue output (AO) operation. This allows the generation of any arbitrary frequency as this VI computes new data for each iteration of the loop, maintaining phase continuity of the signal.

**Front Panel**

The digital channel can be selected by choosing a digital line (corresponding to the physical channel on DAQ board) in the drop-down list tab. The frequency and duty cycle of the digital waveform can be set by specifying the parameters shown in upper right corner on the front panel.

An analog output sample clock was chosen as the sample clock for generating digital as well as analog waveforms in synchronization. Specifying higher sampling clock rates will produce smoother waveforms.

Instructions for running *front panel*
1. Select the Physical Channels to correspond to where the analogue and digital signals are output on the DAQ device.

2. Enter the Minimum and Maximum Voltage range.

3. Specify the desired Sample Clock Rate of the output Waveform.

4. Manually specify the analog output buffer size, in number of samples. A larger buffer would help non-regenerative operations avoid errors due to occasional high CPU load.

**Fig. 2 Front panel for generating analogue and digital waveforms in synchronization**
**Note:** The Analogue Output buffer has to be at least as big as the amount of data being written to the board per iteration. The recommended buffer size would be at least twice the amount of data being written to the board per iteration.

5. Enter the Waveform Information using function generator sub VI

![Block Diagram](image)

*Fig. 3 Part-1 of the block diagram for waveform generation*
Fig. 4 Part-2 Block diagram for analog and digital waveform generation in synchronization
**Block diagram:**

A1. Create an analogue output voltage channel or multiple channels

A2. Configure the task to prohibit the automatic regeneration of the data.

A3. Control for the sample clock rate.

A4. Call the DAQmx (Sample clock) VI to set the sample clock rate. Set the sample mode to Continuous.

A5. Call the analogue output buffer size sub VI, in number of samples.

A6. Read the actual sample clock rate (eventually coerced depending on the hardware used).

A7. Bundle sample clock rate and number of samples into a cluster.

**Note:**

- To synchronize Digital Output and Analog Output tasks, the easiest way is to simply use the Analog Output (AO) sample clock for the DO task. If doing this, make sure to start the digital task **before** the analog task to ensure both tasks start simultaneously.

- External trigger source supplied to the digital input (PFI0) from a counter output (pulse).

A8. Each of the control specifies Cluster of elements corresponding to three different analog waveforms.

A9. Unbundle the phase parameter from the cluster to introduce phase difference on-the-fly which is clearly visible for AO2.
A10. Unbundle by name all other parameters such as type of the waveform amplitude, and frequency.

A11. Call frequency generator sub VI.

A12. Add waveform 2 (AO1) and Waveform 3 (AO2) to get a composite waveform to introduce optical path modulation in the interferometer.

A13. All the analog waveforms were put into an array.

A14. Write the array of waveforms to output buffer.

A15. All the generated waveforms can be displayed using a waveform graph.

A16a. Call the start VI. This is only needed when the loop is executed for the first time.

A16b. Do nothing if the condition is false in the case structure.

A17. Loop continuously until the user presses the stop button. Every iteration computes and writes a new waveform to the buffer.

A18. Call the clear task VI to clear the task.

Digital task:

D1. Create a digital output voltage channel

D2. Configure the task to prohibit the automatic regeneration of the data.

D3. Call the DAQmx (Sample clock) VI to set the sample clock rate. Set the sample mode to Continuous.

D4. Call the digital output buffer size sub VI, and specify number of samples.
D5. Read the actual sample clock rate (eventually coerced depending on the hardware used).

D6. Bundle sample clock rate and number of samples into a cluster.

D7. Call start digital trigger VI.

Note: In this example, the Analog Input task will wait until it sees the digital trigger. If the triggering edge is defined as Rising, then the analog input task will begin as soon as a rising edge occurs on the specified digital line.


D9. Unbundle these controls by name for further flexibility.

D10. Call pulse width modulation sub VI which provide pulses with different duty cycles and frequencies.

D11. Write the digital waveform to output buffer using DAQmx write VI.

D12a. Call the DAQmx start VI. This is only needed when the loop is executed for the first time.

D12b. Do nothing if the condition is false in the case structure.

D13. Loop continuously until the user presses the stop button. Every iteration computes and writes a new waveform to the buffer.

Finally use the popup dialog box to display an error or warning if any.
Appendix – C

Imaging Software

Front Panel

Fig. 5 Front panel of the image acquisition and processing for real-time observation of speckle fringes in ESPI

Instructions for running front panel

1. To initiate image acquisition we need to start camera session by specifying camera name and camera control mode as shown in camera attributes on the front panel.

2. To configure acquisition we need to provide resources in terms of buffer numbers.
3. If we want to acquire a part of the image that can be done by specifying region of interest.

4. Post processing such as subtraction of acquired images and the filtering of images can be done by using subtraction sub VI, filtering VI, image stretching and look up table VIs.

5. Depending on buffer number specification we can hold a particular image in the buffer and call later for carrying out subtraction with another image.

6. Histogram of a live image or a subtracted image can be displayed continuously, if we configure for continuous images acquisition.

7. The live or subtracted image can be saved by pressing save tab.

8. This VI runs continuously until stop button is pressed or an error occurs.

Instructions for *Block Diagram*

1. Open camera session by calling IMAQdx open camera VI.

2. Open reference to the camera and set programmatically camera attributes (trigger mode and trigger activation enums and timeout) using IMAQdx property node.

3. Image buffer can be created using IMAQ create VI wherever necessary as shown in the block diagram (for previous image, current image, subtracted image).

4. All the trigger parameters are put into a cluster. These parameters can be unbundled for the laser use in image acquisition.

5. Camera configuration is carried out in a case structure so that whenever one of the trigger settings changes, unconfigure the acquisition, update the IMAQdx driver with the new settings and reconfigure the grab acquisition for continuous image acquisition.
6. If the case structure is false do nothing.

7. Use IMAQdx Get Image VI for extracting image from a specific buffer number.

8. The subsequent images were extracted using different IMAQdx Get Image VIs.

9. Use IMAQ absolute subtraction VI for image subtraction. Use IMAQ multiplication VI for image multiplication. The subtraction and low pass filtering and multiplication were carried out in a case structure to use only when they are needed.

10. Image processing was carried out using linear stretch VI and Look up table VI in a case structure. The result was displayed in an image indicator.

11. Call IMAQ write to VI to save an image.

12. Close IMAQ session using IMAQ close VI.

13. Loop continuously until the user presses the stop button. Every iteration computes and writes a new waveform to the buffer.

14. Finally use the popup dialog box to display an error or warning if any
Fig. 6 Part-1 of the block diagram of the image acquisition and processing for speckle fringe generation in HOE based ESPI
Fig. 7 Part-2 of the block diagram of the image acquisition and processing for speckle fringe generation in HOE based ESPI

XVII
Appendix – D

Five frame phase stepping algorithm for phase map calculation

% reads an 8-bit image shifted by 0º
i1_8B=imread('C:\Users\Desktop\0deg.bmp');
% converts 8-bit RGB to gray image;
A1=rgb2gray(i1_8B);
% reads with double precision value for A1
A=double(A1);
% creates a 2D image average filter with specified kernel size
filter = fspecial('average',[7 7]);
% computes a 2D convolution between A and filter kernel provides filtered image
fi1 = conv2(A, filter);
% reads an 8-bit image shifted by 90º
i2_8B=imread('C:\Users\Desktop\90deg.bmp');
% converts 8-bit RGB to gray image;
B1=rgb2gray(i2_8B);
% reads with double precision value for B1
B=double(B1);
% computes a 2D convolution between A and filter kernel provides filtered image
fi2 = conv2(B, filter);
% reads an 8-bit image shifted by 180º
i3_8B=imread('C:\Users\Desktop\180deg.bmp');
% converts 8-bit RGB to gray image;
C1=rgb2gray(i3_8B);
% reads with double precision value for C1
C=double(C1);
% computes a 2D convolution between A and filter kernel provides filtered image
fi3 = conv2(C, filter);
% reads an 8-bit image shifted by 270º
i4_8B=imread('C:\Users\User\Desktop\270deg.bmp');
% converts 8-bit RGB to gray image;
D1=rgb2gray(i4_8B);
% reads with double precision value for D1
D=double(D1);
% computes a 2D convolution between A and filter kernel provides filtered image
fi4 = conv2(D, filter);
% reads an 8-bit image shifted by 360º
i5_8B=imread('C:\Users\User\Desktop\360deg.bmp');
% converts 8-bit RGB to gray image;
E1=rgb2gray(i5_8B);
% reads with double precision value for E1
E=double(E1);
% computes a 2D convolution between A and filter kernel provides filtered image
fi5 = conv2(E, filter);
% calculates wrapped phase using Schwider-Hariharan 5 frame phase shifting algorithm
WrappedPhase=atan2(2*(i4-i2),i1-2*i3+i5);
% creates an RGB graphic window
figure(1);
% creates matrix of real numbers between 0 and 1
colormap(gray(256))
% scales image data to the full range of colormap and displays
imagesc(WrappedPhase);
% compiles files written in C++ but runs in MALTLAB
mex Miguel_2D_unwrapper.cpp;
% converts wrapped phase matrix values to single precision
WrappedPhase1 = single(WrappedPhase);
% runs the unwrapper code on single precision wrapped phase values
UnwrappedPhase = Miguel_2D_unwrapper(WrappedPhase1);

% creates an RGB graphic window
figure(2)

% creates matrix of real numbers between 0 and 1 for unwrapped phase values
colormap(gray(256))

% scales image data to the full range of colormap and displays
imagesc(UnwrappedPhase);

% converts unwrapped phase values to double precision matrix
UP = double(UnwrappedPhase);

% wavelength of the laser light is defined as
lambda = 658*1e-9;

% calculates displacement values from unwrapped phase map
displacement = UP*lambda/(4*pi);

% creates an RGB graphic window
figure(3)

% displays a 3D displacement map
mesh(displacement);
Appendix E

Specification sheets
## Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1101/P</th>
<th>1103/P</th>
<th>1107/P</th>
<th>1108/P</th>
<th>1122/P</th>
<th>1125/P</th>
<th>1135/P</th>
<th>1137/P</th>
<th>1144/P</th>
<th>1145/P</th>
<th>Unit</th>
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<tbody>
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<td><strong>Optical</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Min. output power (TEM(00))</td>
<td>1.5</td>
<td>2.0</td>
<td>0.8</td>
<td>0.5</td>
<td>2.0</td>
<td>5.0</td>
<td>10.0</td>
<td>7.0</td>
<td>15.0</td>
<td>22.5/21.0</td>
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<tr>
<td>Wavelength</td>
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<td>632.8</td>
<td>632.8</td>
<td>632.8</td>
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<td>632.8</td>
<td>632.8</td>
<td>632.8</td>
<td>632.8</td>
<td>632.8</td>
<td>nm</td>
</tr>
<tr>
<td>Mode purity (TEM(00))</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>&gt;95</td>
<td>%</td>
</tr>
<tr>
<td>Beam diameter (1/e² points, ±3%, TEM(00))</td>
<td>0.63</td>
<td>0.63</td>
<td>0.48</td>
<td>0.48</td>
<td>0.63</td>
<td>0.81</td>
<td>0.81</td>
<td>0.68</td>
<td>0.81</td>
<td>0.70</td>
<td>mm</td>
</tr>
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<td>Beam divergence (TEM(00), ±3%, mrad- full angle)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.7</td>
<td>1.8</td>
<td>1.3</td>
<td>1.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.15</td>
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<td>Polarization ratio (minimum, P versions)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>N/A</td>
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<td>730</td>
<td>1090</td>
<td>1090</td>
<td>730</td>
<td>435</td>
<td>435</td>
<td>257</td>
<td>257</td>
<td>-</td>
<td>MHz</td>
</tr>
<tr>
<td>Maximum noise (rms, 30 Hz to 10 MHz)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
<td>0.5</td>
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<td>±2.5</td>
<td>±2.5</td>
<td>±2.5</td>
<td>±2.5</td>
<td>±3.0</td>
<td>±2.5</td>
<td>±2.0</td>
<td>±2.0</td>
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<td>Max. mode sweeping contribution</td>
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<td>10</td>
<td>20</td>
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<td>2</td>
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<td>2</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Max. warm-up time (minutes to 95% power)</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>min.</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>&lt;0.10</td>
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<td>N/A</td>
<td>N/A</td>
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<td>&lt;0.02</td>
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<td>1700</td>
<td>1250</td>
<td>1250</td>
<td>1800</td>
<td>2300</td>
<td>3100</td>
<td>2300</td>
<td>3800</td>
<td>3800</td>
<td>V DC</td>
</tr>
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<td>4.9</td>
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<td>4.0</td>
<td>6.5</td>
<td>6.0</td>
<td>6.5</td>
<td>6.0</td>
<td>6.5</td>
<td>6.5</td>
<td>mA</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-overall length</td>
<td>9.50</td>
<td>9.50</td>
<td>7.00</td>
<td>7.00</td>
<td>10.71</td>
<td>15.79</td>
<td>19.13</td>
<td>15.79</td>
<td>25.00</td>
<td>25.00</td>
<td>inches</td>
</tr>
<tr>
<td>D-mounting diameter (±0.005 inches)</td>
<td>1.245</td>
<td>1.245</td>
<td>1.245</td>
<td>1.245</td>
<td>1.740</td>
<td>1.740</td>
<td>1.740</td>
<td>1.740</td>
<td>1.740</td>
<td>1.740</td>
<td>inches</td>
</tr>
<tr>
<td>B-distance: cable end to mounting surface</td>
<td>1.00</td>
<td>1.00</td>
<td>0.75</td>
<td>0.75</td>
<td>1.50</td>
<td>3.00</td>
<td>4.00</td>
<td>3.00</td>
<td>5.00</td>
<td>5.00</td>
<td>inches</td>
</tr>
<tr>
<td>A-distance: output end to mounting surface</td>
<td>0.75</td>
<td>0.75</td>
<td>0.50</td>
<td>0.50</td>
<td>1.50</td>
<td>3.00</td>
<td>4.00</td>
<td>3.00</td>
<td>5.00</td>
<td>5.00</td>
<td>inches</td>
</tr>
<tr>
<td>CDRH class (head &amp; 1200 Series power supply)</td>
<td>IIIa</td>
<td>IIIa</td>
<td>IIIa</td>
<td>II</td>
<td>IIIa</td>
<td>IIIb</td>
<td>IIIb</td>
<td>IIIb</td>
<td>IIIb</td>
<td>IIIb</td>
<td>-</td>
</tr>
</tbody>
</table>

**Notes:**
- **N/A** indicates data not applicable.
- **±** indicates variation range.
- **mrad** stands for milliradian.
- **V DC** stands for volts direct current.
- **mA** stands for milliamperes.
- **mm** stands for millimeters.
- **%** is a percentage.
### Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1101/P</th>
<th>1103/P</th>
<th>1107/P</th>
<th>1108/P</th>
<th>1122/P</th>
<th>1125/P</th>
<th>1135/P</th>
<th>1137/P</th>
<th>1144/P</th>
<th>1145/P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum starting voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 kV DC</td>
</tr>
<tr>
<td>Mode purity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Storage lifetime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Indefinite (hard-sealed)</td>
</tr>
<tr>
<td>Static alignment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Center to outer cylinder within ±0.01 inch. Parallel to outer cylinder within ±1 mR.</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>-40 to 70 °C (operating), -40 to 150 °C (non-operating)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude</td>
<td>0 to 10,000 feet (operating), 0 to 70,000 feet (non-operating)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity (no condensation)</td>
<td>0 to 100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock</td>
<td>25 g for 11 ms, 100 g for 1 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping weight</td>
<td>5 lb. (1100 Series heads); 10 lb. (1100 Series head and 1200 Series power supply)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Ordering Information

For more information on this or other products and their availability, please contact your local JDS Uniphase account manager or JDS Uniphase directly at 1-800-254-3684 in North America and +800-5378-JDSU worldwide or via e-mail at sales@jdsu.com.

**Sample: 1122P**
# Distributed Feedback Laser

GaAs Semiconductor Laser Diode with integrated grating structure

## Preliminary Specification

### EYP-DFB-0763-00050-1500-SOT02-0000

### General Product Information

<table>
<thead>
<tr>
<th>Product</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>763 nm DFB Laser with TO Housing</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Monitor Diode</td>
<td>O₂ Detection</td>
</tr>
<tr>
<td>Metrology</td>
<td></td>
</tr>
</tbody>
</table>

### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Temperature</td>
<td>Tₛ</td>
<td>°C</td>
<td>-40</td>
<td>85</td>
</tr>
<tr>
<td>Operational Temperature at Case</td>
<td>Tₑ</td>
<td>°C</td>
<td>-20</td>
<td>75</td>
</tr>
<tr>
<td>Forward Current</td>
<td>Iₑ</td>
<td>mA</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td>Vₑ</td>
<td>V</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Output Power</td>
<td>Pₑ</td>
<td>mW</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Stress in excess of the Absolute Maximum Ratings can cause permanent damage to the device. Operation at the Absolute Maximum Rating for extended periods of time can adversely affect the device reliability and may lead to reduced operational life.

### Recommended Operational Conditions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature at Case</td>
<td>Tₐch</td>
<td>°C</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Forward Current</td>
<td>Iₑ</td>
<td>mA</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Output Power</td>
<td>Pₑ</td>
<td>mW</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

Total output measured with integrated sphere.

### Characteristics at Tₑmb 25 °C at Begin Of Life

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Wavelength</td>
<td>λₑ</td>
<td>nm</td>
<td>762</td>
<td>763</td>
<td>764</td>
</tr>
<tr>
<td>Spectral Width (FWHM)</td>
<td>∆ν</td>
<td>MHz</td>
<td>2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient of Wavelength</td>
<td>dλₑ / dT</td>
<td>nm / K</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient of Current</td>
<td>dλₑ / dIₑ</td>
<td>nm / mA</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Power @ Iₑ = 120 mA</td>
<td>Pₑ</td>
<td>mW</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope Efficiency</td>
<td>S</td>
<td>W / A</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Measurement Conditions / Comments

See images on page 4.

Total output measured with integrated sphere.

---

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**DISTRIBUTED FEEDBACK LASER**  
GaAs Semiconductor Laser Diode  
with integrated grating structure

**PRELIMINARY SPECIFICATION**  

**EYP-DFB-0763-00050-1500-SOT02-0000**  

**DFB Laser**

---

**Characteristics at** $T_{\text{amb}}$ **25 °C at Begin Of Life**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Current</td>
<td>$I_{\text{th}}$</td>
<td>mA</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational Current @ $P_{\text{opt}} = 50$ mW</td>
<td>$I_{\text{op}}$</td>
<td>mA</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidemode Supression Ratio</td>
<td>SMSR</td>
<td>dB</td>
<td>30</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Cavity Length</td>
<td>$L$</td>
<td>μm</td>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divergence parallel</td>
<td>$\Theta_{</td>
<td></td>
<td>}$</td>
<td>°</td>
<td>6</td>
</tr>
<tr>
<td>Divergence perpendicular</td>
<td>$\Theta_{\perp}$</td>
<td>°</td>
<td>18</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial Mode (transversal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Mode (longitudinal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Measurement Conditions / Comments**

- $P_{\text{opt}} = 50$ mW
- E field perpendicular to Pin 2 - Pin 3 - plane fundamental mode

---

**Monitor Diode**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor Detector Responsivity</td>
<td>$I_{\text{mon}} / P_{\text{opt}}$</td>
<td>μA / mW</td>
<td>0.5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Reverse Voltage Monitor Diode</td>
<td>$U_{\text{MD}}$</td>
<td>V</td>
<td>3</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Monitor Linearity</td>
<td>$L_{\text{in MD}}$</td>
<td>%</td>
<td>-10</td>
<td></td>
<td>+10</td>
</tr>
</tbody>
</table>

**Measurement Conditions / Comments**

- $U_{\text{R}} = 5$ V, target values
- $P_{\text{opt}} = 10$ ... 50 mW, $U_{\text{R}} = 5$ V
DISTRIBUTED FEEDBACK LASER
GaAs Semiconductor Laser Diode
with integrated grating structure

PRELIMINARY SPECIFICATION

EYP-DFB-0763-00050-1500-SOT02-0000

**Package Dimensions**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>min</th>
<th>typ</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Plane</td>
<td>( \delta_p )</td>
<td>mm</td>
<td>3.65</td>
<td></td>
</tr>
<tr>
<td>Housing Diameter</td>
<td>( d )</td>
<td>mm</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Pin Length</td>
<td>( l )</td>
<td>mm</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

**Package Pinout**

| Ground       | 1   |
| Photo Diode (+) | 2   |
| Laser (+)     | 3   |

**Package Drawings**

---
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We focus on power.
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**Typical Measurement Results**

Output Power vs. Current

Spectra at Specified Optical Output Power

Unpacking, Installation and Laser Safety

Unpacking the laser diodes should only be done at electrostatic safe workstations (EPA). Though protection against electro static discharge (ESD) is implemented in the laser package, charges may occur at surfaces. Please store this product in its original package at a dry, clean place until final use. During device installation, ESD protection has to be maintained.

The DFB diode type is known to be sensitive against optical feedback, so an optical isolator may be required in some cases. Operating at moderate temperatures on proper heat sinks will contribute to a long lifetime of the diode.

The laser emission from this diode is close to the invisible infrared region of the electromagnetic spectrum. Avoid direct and/or indirect exposure to the free running beam. Collimating the free running beam with optics as common in optical instruments will increase thread to the human eye.

Each laser diode will come with an individual test protocol verifying the parameters given in this document.

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www.eagleyard.com

We focus on power.
Thermistor Data:

**Figure 3 - Thermistor Curve and Data**

<table>
<thead>
<tr>
<th>Resistance (Ohms)</th>
<th>Degrees C</th>
</tr>
</thead>
<tbody>
<tr>
<td>15895</td>
<td>15</td>
</tr>
<tr>
<td>15153</td>
<td>16</td>
</tr>
<tr>
<td>14451</td>
<td>17</td>
</tr>
<tr>
<td>13785</td>
<td>18</td>
</tr>
<tr>
<td>13155</td>
<td>19</td>
</tr>
<tr>
<td>12558</td>
<td>20</td>
</tr>
<tr>
<td>11991</td>
<td>21</td>
</tr>
<tr>
<td>11454</td>
<td>22</td>
</tr>
<tr>
<td>10944</td>
<td>23</td>
</tr>
<tr>
<td>10460</td>
<td>24</td>
</tr>
<tr>
<td>10000</td>
<td>25</td>
</tr>
<tr>
<td>9563</td>
<td>26</td>
</tr>
<tr>
<td>9149</td>
<td>27</td>
</tr>
<tr>
<td>8755</td>
<td>28</td>
</tr>
<tr>
<td>8380</td>
<td>29</td>
</tr>
<tr>
<td>8023</td>
<td>30</td>
</tr>
<tr>
<td>7684</td>
<td>31</td>
</tr>
<tr>
<td>7362</td>
<td>32</td>
</tr>
<tr>
<td>7055</td>
<td>33</td>
</tr>
<tr>
<td>6762</td>
<td>34</td>
</tr>
<tr>
<td>6484</td>
<td>35</td>
</tr>
</tbody>
</table>
1.5 Technical Data

(The technical data are valid at 23 ± 5 °C and 45 ±15% rel. humidity)

1.5.1 Technical data ITC502

**General Data**
- **Line voltage**: 100 V / 115 V / 230 V (-10%, +15 %) (fixed)
- **Line frequency**: 50 ... 60 Hz
- **Max. power consumption**: 90 VA
- **Supply mains overvoltage**: Category II (Cat II)
- **Operating temperature**: 0 ... +40 °C
- **Storage temperature**: -40 °C ... +70 °C
- **Relative Humidity**: Max. 80% up to 31 °C, decreasing to 50% at 40 °C
- **Pollution Degree (indoor use only)**: 2
- **Warm up time for rated accuracy**: ≤ 10 min
- **Operation altitude**: < 3000 m
- **Weight**: < 7 kg
- **Dimensions (W x H x D)**: including operating elements 220 x 120 x 376 mm³
  - without operating elements 220 x 110 x 351 mm³

**Current control**
- **Range of laser current I_{LD}**: 0 ... ± 200 mA
- **Compliance voltage**: > 6 V
- **Setting resolution (manual / remote control)**: 10 µA / 3 µA
- **Measurement resolution (manual / remote control)**: 10 µA / 1 µA
- **Accuracy**: ± 100 µA
- **Noise without ripple (10 Hz ... 10 MHz, rms), typ.**: < 1.5 µA
- **Ripple (50/60 Hz, rms), typ.**: < 1.5 µA
- **Transients, typ.**: < 0.2 mA
- **Drift, 24 hours, typ. (0...10Hz, without changing the ambient temperature)**: < 10 µA
- **Temperature coefficient**: ≤ 50 ppm/°C

**Power control**
- **Range of monitor current I_{PD}**: 5 µA ... 2 mA
- **Setting resolution (manual / remote control)**: 0.1 µA / 0.03 µA

---

1) non condensing
2) other ranges on request
### Measurement resolution (manual / remote control)
- 0.1 µA / 0.01 µA

### Accuracy
- ± 2 µA

### Photodiode bias voltage
- 0 ... 10 V

#### Laser voltage

**Measurement principle**
- 4-wire

**Measurement range**
- 0 ... 10 V

**Measurement resolution (manual / remote control)**
- 1 mV / 0.1 mV

**Accuracy**
- ± 20 mV

#### Analog control output

**Load resistance**
- ≥ 10 kΩ

**Output voltage for 0 ... I_{LD MAX}**
- 0 ... ± 10 V \(^1\)

**Transmission coefficient**
- 50 V/A ± 5%

#### LD Current limit

**Setting range I_{LIM}**
- 0 ... ≥ 200 mA

**Measurement resolution (manual / remote control)**
- 10 µA / 1 µA

**Accuracy**
- ± 0.5 mA

#### Analog modulation input

**Input impedance**
- 10 kΩ

**Small signal 3 dB bandwidth (CC mode)**
- DC ... 500 kHz

**Laser diode modulation coefficient (CC mode)**
- 20 mA/V ± 5%

**Laser diode modulation coefficient (CP mode)**
- 0.2 mA/V ± 5%

#### Current output TEC element

**Control range**
- - 2 A ... + 2 A

**Maximum output power**
- 16 W

**Compliance voltage**
- > 8 V

**Measurement resolution (manual / remote control)**
- 1 mA / 0.1 mA

**Measurement accuracy**
- ± 10 mA

**Noise and ripple (typ.)**
- < 1 mA

**Measurement resolution TEC voltage (manual / remote control)**
- 1 mV / 0.1 mV

**Measurement accuracy TEC voltage**
- ± 40 mV

---

\(^1\) sign depends on selected polarity
TEC Current limit

Setting range  
0 ... ≥ 2 A

Measurement resolution (manual / remote control)  
1 mA / 0.1 mA

Accuracy  
± 20 mA

Temperature sensors AD590, AD592, LM135, LM335

Control range (AD590, LM135)  
- 45 °C ... + 145 °C

Control range (AD592)  
- 25 °C ... + 105 °C

Control range (LM335)  
- 40 °C ... + 100 °C

Setting resolution (manual / remote control)  
0.01 °C / 0.003 °C

Measurement resolution (manual / remote control)  
0.01 °C / 0.001 °C

Accuracy  
± 0.1 °C

Temperature stability (24 hours)  
≤ 0.001 °C

Thermistor (2 kΩ / 20 kΩ range)

Measurement current  
100µA / 10 µA

Control range  
10 Ω ... 19.99 kΩ / 100 Ω ... 199.9 kΩ

Setting resolution (manual control)  
1 Ω / 10 Ω

Setting resolution (remote control)  
0.3 Ω / 3 Ω

Measurement resolution (manual control)  
1 Ω / 10 Ω

Measurement resolution (remote control)  
0.1 Ω / 1 Ω

Accuracy  
± 5 Ω / ± 50 Ω

Temperature stability (24 hours)  
≤ 0.5 Ω / ≤ 5 Ω

Temperature control input

Input resistance  
10 kΩ

Control voltage  
-10 ... +10 V

Transmission coefficient IC-sensors  
2 °C/V ±5%

Transmission coefficient thermistor (20 kΩ / 200 kΩ range)  
0.2 kΩ/V / 2 kΩ/V ±5%

---

1) Due to the nonlinear conversion from Ω to °C the stability in °C depends on the operating conditions and the characteristics of the thermistor. E.g. for a typical thermistor at a set point of 10kΩ (25°C), a 0.5Ω stability translates into about 1mK temperature stability. At a set point of 5kΩ (38°C), the stability is about 2mK.
1.5 Technical Data

**Temperature control Output**

- Load resistance: $> 10 \, \text{k}\Omega$
- Output voltage: $0 \ldots \pm 10 \, \text{V}$
- Transmission coefficient IC sensors: $50 \, \text{mV/°C} \pm 5\%$
- Transmission coeff. thermistor (20 kΩ / 200 kΩ range): $500 \, \text{mV/kΩ} / 50 \, \text{mV/kΩ} \pm 5\%$

**Temperature window protection**

- Setting range $T_{\text{WIN}}$: $0.5 \, \text{°C} \ldots 20 \, \text{°C}$
- Setting range $R_{\text{WIN}}$ (20 kΩ / 200 kΩ range): $50 \, \text{Ω} \ldots 2 \, \text{kΩ} / 500 \, \text{Ω} \ldots 20 \, \text{kΩ}$

**Computer Interface**

- Setting resolution: 16 Bit
- Measurement resolution: $12 \ldots 18 \, \text{Bit}$

1.5.2 Technical data ITC510

**General Data**

- Line voltage: $100 \, \text{V} / 115 \, \text{V} / 230 \, \text{V} \, (-10\%, \, +15 \%) \, (\text{fixed})$
- Line frequency: $50 \ldots 60 \, \text{Hz}$
- Max. power consumption: $150 \, \text{VA}$
- Supply mains overvoltage: Overvoltage category II (Cat II)
- Operating temperature: $-40 \, \text{°C} \ldots +70 \, \text{°C}$
- Storage temperature: $20 \, \text{°C} \ldots +40 \, \text{°C}$
- Relative Humidity: Max. 80% up to 31 °C, decreasing to 50% at 40 °C
- Operation altitude: $< 3000 \, \text{m}$
- Pollution Degree (indoor use only): 2
- Warm up time for rated accuracy: $\leq 10 \, \text{min}$
- Weight: $< 7 \, \text{kg}$
- Dimensions: $220 \times 120 \times 377 \, \text{mm}^3$

---

1) in High Resolution mode, at reduced measurement speed
2) non condensing
The PE2013 / PE2020 camera offers a high resolution operation with all the facilities associated with a ruggedised industrial camera in a miniature package. The choice of standards and numerous options make this a very user friendly camera.

The PE2020 has a 1/2" Interline Transfer Imager while the PE2013 has a 1/3" Imager. The camera has the facility to accept external syncs as well as outputting the internally generated syncs. The Gamma, AGC, MGC, frame and field modes are easily set for industrial applications by switches. Video output can be used by either the 12 pin connector or the BNC connector. The 75Ω impedance can be switched out to prevent loading of the video signal.

**Features**

- Super miniature size
- High resolution
  - 470 TVL (H) PE2013
  - 560 TVL (H) PE2020
- Shutter speed 1/50 sec to 1/10,000 sec
- Right-angled lens mount
  - L version available
- External sync
- Sync and Clock out
- Gamma, Manual gain switch
- Excellent Signal to Noise Ratio

**Spectral Response**

The PE2013 / PE2020 has an excellent low light sensitivity of 0.3 lux at f1.4. The good spectral response of the camera imager allows the camera to operate well into the high end infrared region. The signal to noise ratio of 56dB gives extremely good video images with no noise. This is useful for machine vision systems.

**Spectral Sensitivity Characteristics**

(Excluding light source characteristics, including lens characteristics)
Shutter Operation

The PE2013 / PE2020 has eight selectable shutter speeds ranging from 1/50 sec. up to 1/10,000 sec. The speeds are set using the mode switch located in the camera.

<table>
<thead>
<tr>
<th>CCIR</th>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
<th>Mode Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/50</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>1/120</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>1/250</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>1/500</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>1/1000</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td></td>
</tr>
<tr>
<td>1/2000</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td></td>
</tr>
<tr>
<td>1/4000</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td></td>
</tr>
<tr>
<td>1/10000</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td></td>
</tr>
</tbody>
</table>

Gain Control

The camera has a fixed internal gain but it can be used with a manual control if required.

Electronic Shutter Setting

Switch 4

<table>
<thead>
<tr>
<th>Elect Shutter ON</th>
<th>Elect Shutter OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Field / Frame Mode

The camera can be configured to give either the field output or frame output for higher resolution.

Switch 5

<table>
<thead>
<tr>
<th>Frame</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Gamma Selection

The PE2013 / PE2020 will operate in either Gamma 1.0 or 0.45 to suit all video applications.

Switch 6

<table>
<thead>
<tr>
<th>( \gamma = 1.0 ) ON</th>
<th>( \gamma = 0.45 ) OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Sync. Input / Output

The Sync. can be accepted into the camera or output by operating the changeover switch. Switch to Connector Side (Right Side) for external SYNC.
Physical Dimensions (mm/inch)

PE2013 / PE2020

PE2013L / PE2020L
Specifications

High Resolution CCD Miniature Camera

<table>
<thead>
<tr>
<th>Model</th>
<th>PE2013 / PE2013L</th>
<th>PE2020 / PE2020L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imaging Format</td>
<td>CCIR</td>
<td></td>
</tr>
<tr>
<td>Imager</td>
<td>1/3” interline system CCD</td>
<td>1/2” interline system CCD</td>
</tr>
<tr>
<td>Pixel</td>
<td>752 (H) x 582 (V)</td>
<td></td>
</tr>
<tr>
<td>Chip Size</td>
<td>6.00mm (H) x 4.96mm (V)</td>
<td>7.95mm (H) x 6.45mm (V)</td>
</tr>
<tr>
<td>Cell Size</td>
<td>6.50µm (H) x 6.25µm (V)</td>
<td>8.60µm (H) x 8.30µm (V)</td>
</tr>
<tr>
<td>Resolution</td>
<td>470 TVL (H)</td>
<td>560 TVL (H)</td>
</tr>
<tr>
<td>Scanning</td>
<td>625 lines, 2:1 Interface/Non-interface (External Changeover Switch)</td>
<td></td>
</tr>
<tr>
<td>Vertical Freq</td>
<td>50Hz</td>
<td></td>
</tr>
<tr>
<td>Horizontal Freq</td>
<td>15.625kHz ±1%</td>
<td></td>
</tr>
<tr>
<td>Sync</td>
<td>Internal/external (HD/VD) Auto Switch</td>
<td></td>
</tr>
<tr>
<td>S / N Ratio</td>
<td>36dB (Gain 0dB)</td>
<td></td>
</tr>
<tr>
<td>Min. Illum.</td>
<td>0.3 lux at f=1.4</td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>1.0 Vp-p composite video at 75Ω</td>
<td></td>
</tr>
<tr>
<td>AGC</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>Gain: Fixed / Manual (from 0 to 25dB) switchable on rear panel</td>
<td></td>
</tr>
<tr>
<td>Lens Mount</td>
<td>C Mount</td>
<td></td>
</tr>
<tr>
<td>Shutter</td>
<td>1/50 1/120 1/250 1/500 1/1,000 1/2,000 1/5,000 1/10,000 sec</td>
<td></td>
</tr>
<tr>
<td>Storage Mode</td>
<td>Flicker-less Shutter</td>
<td></td>
</tr>
<tr>
<td>Clock Output</td>
<td>Frame/Field (INT Changeover Switch)</td>
<td></td>
</tr>
<tr>
<td>Power Req</td>
<td>14.1875MHz</td>
<td></td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>DC10V~12V, 180mA</td>
<td></td>
</tr>
<tr>
<td>Size (W x H x L)</td>
<td>-10°C to 40°C</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>31mm x 29mm x 73mm (L: 31mm x 45mm x 87mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85g (L: 100g)</td>
<td></td>
</tr>
</tbody>
</table>

Due to ongoing product improvements, specifications may change without notice.

Pin Configuration

<table>
<thead>
<tr>
<th>Signal</th>
<th>S-VERSION</th>
<th>P-VERSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin</td>
<td>INT. SYNC.</td>
<td>EXT. SYNC</td>
</tr>
<tr>
<td>1</td>
<td>GND</td>
<td>GND</td>
</tr>
<tr>
<td>2</td>
<td>+12V</td>
<td>+12V</td>
</tr>
<tr>
<td>3</td>
<td>Video GND</td>
<td>Video GND</td>
</tr>
<tr>
<td>4</td>
<td>Video Output</td>
<td>Video Output</td>
</tr>
<tr>
<td>5</td>
<td>HD GND</td>
<td>HD GND</td>
</tr>
<tr>
<td>6</td>
<td>HD Output</td>
<td>HD Input</td>
</tr>
<tr>
<td>7</td>
<td>VD Output</td>
<td>VD Input</td>
</tr>
<tr>
<td>8</td>
<td>Clock GND</td>
<td>Clock GND</td>
</tr>
<tr>
<td>9</td>
<td>Clock Output</td>
<td>Clock Output</td>
</tr>
<tr>
<td>10</td>
<td>GND</td>
<td>GND</td>
</tr>
<tr>
<td>11</td>
<td>+12V</td>
<td>+12V</td>
</tr>
<tr>
<td>12</td>
<td>VD GND</td>
<td>VD GND</td>
</tr>
</tbody>
</table>
**HF25HA-1B**

- **Design achieving the high resolution**, supporting up to 1.5 mega pixel cameras
- **Designed for low distortion**, enabling faithful image input
- **Compact, lightweight and robust design**, supporting various systems
- **Focus & iris lock tab provided**, supporting environments such as vibration

<table>
<thead>
<tr>
<th>Focal Length (mm)</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris Range</td>
<td>F1.4 ~ F22</td>
</tr>
<tr>
<td>Operation</td>
<td>Focus</td>
</tr>
<tr>
<td>Iris</td>
<td>Iris</td>
</tr>
<tr>
<td>Angle Of View</td>
<td>2/3&quot;</td>
</tr>
<tr>
<td></td>
<td>1/2&quot;</td>
</tr>
<tr>
<td></td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>Focusing Range</td>
<td>∞ ~ 0.16</td>
</tr>
<tr>
<td>Object Dimensions</td>
<td>2/3&quot;</td>
</tr>
<tr>
<td></td>
<td>1/2&quot;</td>
</tr>
<tr>
<td></td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>Back Focal Distance</td>
<td>14.58</td>
</tr>
<tr>
<td>Exit Pupil Position</td>
<td>∞ ~ 32.4</td>
</tr>
<tr>
<td>Filter Thread</td>
<td>M25.5 × 0.5</td>
</tr>
<tr>
<td>Mount</td>
<td>C</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>45</td>
</tr>
</tbody>
</table>

**Remarks**
- With Metal Mount
- With Locking Knob for Iris and Focus

---

**HF35HA-1B**

- **Design achieving the high resolution**, supporting up to 1.5 mega pixel cameras
- **Designed for low distortion**, enabling faithful image input
- **Compact, lightweight and robust design**, supporting various systems
- **Focus & iris lock tab provided**, supporting environments such as vibration

<table>
<thead>
<tr>
<th>Focal Length (mm)</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris Range</td>
<td>F1.6 ~ F22</td>
</tr>
<tr>
<td>Operation</td>
<td>Focus</td>
</tr>
<tr>
<td>Iris</td>
<td>Iris</td>
</tr>
<tr>
<td>Angle Of View</td>
<td>2/3&quot;</td>
</tr>
<tr>
<td></td>
<td>1/2&quot;</td>
</tr>
<tr>
<td></td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>Focusing Range</td>
<td>∞ ~ 0.25</td>
</tr>
<tr>
<td>Object Dimensions</td>
<td>2/3&quot;</td>
</tr>
<tr>
<td></td>
<td>1/2&quot;</td>
</tr>
<tr>
<td></td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>Back Focal Distance</td>
<td>15.03</td>
</tr>
<tr>
<td>Exit Pupil Position</td>
<td>∞ ~ 28.6</td>
</tr>
<tr>
<td>Filter Thread</td>
<td>M25.5 × 0.5</td>
</tr>
<tr>
<td>Mount</td>
<td>C</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>45</td>
</tr>
</tbody>
</table>
Thorlabs’ Anamorphic Prism Pairs are used to transform elliptical laser diode beams into nearly circular beams by magnifying the elliptical beam in one dimension.

Mounted in Ø 1” housings that feature SM05 (0.535”-40) threads on one end, these prism pairs can be purchased with an antireflection coating for the 350 – 700 nm, 650 – 1050 nm, or 1050 – 1620 nm spectral range. These mounted prisms can be chosen with magnifications from 2.0 to 4.0.

An average throughput of 95% can be achieved if the prisms are oriented such that the incident light enters the prism pair at Brewster's angle, and each surface has the appropriate AR coating for the wavelength of the incident light. The maximum input beam width is 90% of the prism width, and the maximum beam height is given by the entrance opening height.

### Specifications
- **Material:** N-SF11 or N-KZFS8
- **Dimensional Tolerances:** ±0.15 mm
- **Angular Tolerances:** ±10 arcmin
- **Surface Quality:** 40-20 Scratch-Dig
- **Surface Flatness:** λ/10 @ 633 nm
- **Coating Options**
  - A: 350 – 700 nm (N-KZFS8)
  - B: 650 – 1050 nm (N-SF11)
  - C: 1050 – 1620 nm (N-SF11)

Please refer to our website for complete models and drawings.

**Pre-Aligned and Mounted**

Photograph of an actual 635 nm beam from a Hitachi laser diode beam before and after an anamorphic prism pair.

**Broadband Antireflection Coating**

- A Coating (350 - 700 nm)
  - AOI = 0°
  - AOI = 60°

**Broadband Antireflection Coatings**

- B Coating (650 - 1050 nm)
  - AOI = 0°
  - AOI = 60°

- C Coating (1050 - 1620 nm)
  - AOI = 0°
  - AOI = 60°
Thorlabs’ unmounted prism pairs are available uncoated or with an antireflection coating for the 350 – 700 nm, 650 – 1050 nm, or 1050 – 1620 nm range. The anamorphic expansion (one-dimensional expansion) can be adjusted by changing the angles and the offset between the prisms. The plots on the right show the angles at which the prisms must be set for various magnifications.

### Unmounted Anamorphic Prism Pairs

**Unmounted Anamorphic Prism Pairs Angles:**
- A Coating (405 nm), N-K2FS8
- B and C Coatings (670 nm), N-SF11

<table>
<thead>
<tr>
<th>ITEM #</th>
<th>S</th>
<th>£</th>
<th>€</th>
<th>RMB</th>
<th>ANAMORPHIC MAGNIFICATION</th>
<th>INPUT OFFSET L</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS870</td>
<td>118.97</td>
<td>85.65</td>
<td>103.50</td>
<td>Y</td>
<td>948.15</td>
<td>5.9 mm</td>
<td>N-KZFS8</td>
</tr>
<tr>
<td>PS871-A</td>
<td>150.36</td>
<td>108.26</td>
<td>130.81</td>
<td>Y</td>
<td>1,198.37</td>
<td>350 – 700 nm</td>
<td>N-KZFS8</td>
</tr>
<tr>
<td>PS871-B</td>
<td>150.36</td>
<td>108.26</td>
<td>130.81</td>
<td>Y</td>
<td>1,198.37</td>
<td>650 – 1050 nm</td>
<td>N-SF11</td>
</tr>
<tr>
<td>PS872-C</td>
<td>150.36</td>
<td>108.26</td>
<td>130.81</td>
<td>Y</td>
<td>1,198.37</td>
<td>1050 – 1620 nm</td>
<td>N-SF11</td>
</tr>
</tbody>
</table>

* Price is per pair
Compact Five-Axis Spatial Filters

- Compact, stable, 5-axis design
- New high-resolution, 100 TPI XYθₓθᵧ adjustment screws, 80 TPI Z-adjustment
- New zero-freeplay XY mechanism provides precise, smooth motion
- New independent, non-influencing locks on each axis lock the mechanism to maintain stable alignment
- Integral iris diaphragm aids in beam alignment

Our 910A Series Spatial Filter has a space-efficient design combining five-axis alignment with high stability for set-and-forget adjustment. Precise XY translation of the pinhole plus true gimbaling of the entire assembly are achieved with precision 100 TPI screws with new knobs including an integral hex hole, providing smooth, high-resolution motion. Our new zero-freeplay XY mechanism ensures accurate positioning and enhanced long-term stability. Translation along the optical Z-axis is accomplished without rotation of the pinhole by a knurled ring with a precision 80 TPI thread. Together, these adjustments provide all the flexibility needed to easily orient the spatial filter for optimum performance.

The lens holder has an integral iris diaphragm to aid in coarse alignment of the beam to the spatial filter and for blocking out stray light. Objective lenses and pinholes must be selected and purchased separately (see the Lens/Pinhole Selection Guide). These spatial filters are designed to accommodate all M-, MV-, and L-Series Objective Lenses (see page 817), and 910PH-Series Mounted Pinholes (see page 836).

Lens/Pinhole Selection Guide

<table>
<thead>
<tr>
<th>Objective Lens</th>
<th>Recommended Max. Input Beam Diameter (mm)</th>
<th>Calculated Pinhole Diameter* (µm)</th>
<th>Recommended Pinhole Diameter (µm)</th>
<th>Recommended Pinhole</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-5X or MV-5X</td>
<td>5.0</td>
<td>32.2</td>
<td>50</td>
<td>910PH-50</td>
<td>$722.99</td>
</tr>
<tr>
<td>M-10X or MV-10X</td>
<td>5.5</td>
<td>20.9</td>
<td>25</td>
<td>910PH-25</td>
<td></td>
</tr>
<tr>
<td>M-20X or MV-20X</td>
<td>5.0</td>
<td>11.4</td>
<td>15</td>
<td>910PH-15</td>
<td></td>
</tr>
<tr>
<td>M-40X or MV-40X</td>
<td>4.0</td>
<td>5.7</td>
<td>10</td>
<td>910PH-10</td>
<td></td>
</tr>
<tr>
<td>M-60X or MV-60X</td>
<td>3.5</td>
<td>3.7</td>
<td>5</td>
<td>910PH-5</td>
<td></td>
</tr>
</tbody>
</table>

*For 1 mm diameter beam at 632.8 nm, (see page 1419).

Specifications

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>XYZ θₓθᵧ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range, XY (in. [mm])</td>
<td>±0.083 (±1.8)</td>
</tr>
<tr>
<td>Range, Z (in. [mm])</td>
<td>±0.125 (±3.2)</td>
</tr>
<tr>
<td>Range, θₓθᵧ</td>
<td>±5 º</td>
</tr>
<tr>
<td>Sensitivity, XY (µm)</td>
<td>0.75</td>
</tr>
<tr>
<td>Sensitivity, Z (µm)</td>
<td>1</td>
</tr>
<tr>
<td>Sensitivity, θₓθᵧ (arc sec)</td>
<td>3</td>
</tr>
</tbody>
</table>

Ordering Information

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>910A</td>
<td>Compact Five-Axis Spatial Filter, XY (100 TPI), Z (80 TPI)</td>
</tr>
<tr>
<td>910P-MNT</td>
<td>Spare Pinhole Mount for 910A, Does Not Include PH Series Pinhole</td>
</tr>
</tbody>
</table>

Objective lenses can be found on page 817 and mounted pinholes on page 836.

Objective lens and mounted pinhole must be ordered separately (see pages 817 and 836).
Model 910A
Polarizer

2. YVO₄, Rochon Polarizer

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Wavelength Range (nm)</th>
<th>Extinction Ratio</th>
<th>Separation Angle(°)</th>
<th>C.A. (mm)</th>
<th>O.D. (mm)</th>
<th>L±0.1 (mm)</th>
<th>Unit Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRH7008</td>
<td>350-2200</td>
<td>&lt;5x10⁻⁶</td>
<td>6.0 @1550nm</td>
<td>8.0</td>
<td>25.4</td>
<td>17.0</td>
<td>$75</td>
</tr>
<tr>
<td>PRH7010</td>
<td>350-2200</td>
<td>&lt;5x10⁻⁶</td>
<td>6.0 @1550nm</td>
<td>10.0</td>
<td>25.4</td>
<td>19.0</td>
<td>$90</td>
</tr>
<tr>
<td>PRH7012</td>
<td>350-2200</td>
<td>&lt;5x10⁻⁶</td>
<td>6.0 @1550nm</td>
<td>12.7</td>
<td>25.4</td>
<td>21.0</td>
<td>$120</td>
</tr>
<tr>
<td>PRH7015</td>
<td>350-2200</td>
<td>&lt;5x10⁻⁶</td>
<td>6.0 @1550nm</td>
<td>15.0</td>
<td>30.0</td>
<td>23.0</td>
<td>$150</td>
</tr>
</tbody>
</table>

Polarization Beamsplitter Cube

- Widely used in most application
- Good Extinction Ratio

Standard Product Specifications

<table>
<thead>
<tr>
<th>Material</th>
<th>BK7 or SF glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension Tolerance</td>
<td>±0.2mm</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>&gt;100:1</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>60/40 scratch and dig</td>
</tr>
<tr>
<td>Beam Deviation</td>
<td>&lt; 3 arc minutes</td>
</tr>
<tr>
<td>Flatness</td>
<td>λ /4@632.8nm per 25mm</td>
</tr>
<tr>
<td>Transmittance</td>
<td>Tp&gt;95% and Ts&lt;1%</td>
</tr>
<tr>
<td>Reflectance</td>
<td>Rs&gt;99% and Rp&lt;5%</td>
</tr>
<tr>
<td>Coating</td>
<td>Polarization beamsplitter coating on hypotenuse face</td>
</tr>
<tr>
<td></td>
<td>AR-coating on all input and output faces</td>
</tr>
</tbody>
</table>

Standard Products Series

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Extinction Ratio</th>
<th>Size(mm)</th>
<th>Unit Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBS1005</td>
<td></td>
<td>5.0 x 5.0 x 5.0</td>
<td>$75</td>
</tr>
<tr>
<td>PBS1010</td>
<td></td>
<td>10.0 x 10.0 x 10.0</td>
<td>$80</td>
</tr>
<tr>
<td>PBS1012</td>
<td></td>
<td>12.7 x 12.7 x 12.7</td>
<td>$82</td>
</tr>
<tr>
<td>PBS1015</td>
<td></td>
<td>15.0 x 15.0 x 15.0</td>
<td>$90</td>
</tr>
<tr>
<td>PBS1020</td>
<td></td>
<td>20.0 x 20.0 x 20.0</td>
<td>$95</td>
</tr>
<tr>
<td>PBS1025</td>
<td></td>
<td>25.4 x 25.4 x 25.4</td>
<td>$120</td>
</tr>
</tbody>
</table>

Note: Above price is for narrow band only. Other sizes are available upon request.

Standard Coating

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow Band</td>
<td>532, 632.8, 780, 850, 1064, 1550 nm</td>
</tr>
<tr>
<td>Broad Band</td>
<td>450-650, 650-900, 900-1200 nm</td>
</tr>
</tbody>
</table>
Model 840-C
Hand-Held Optical Power Meter

- Power and precision typical of a benchtop meter
- Includes both DC and AC peak-to-peak measurement modes
- Power sensitivity from 100 pW to 2 W (-70 to +33 dBm)
- Wavelength and range settings
- Linear, dB, dBm and linear ratio readouts
- Background subtraction and digital averaging

The Model 840-C hand-held optical power meter is fully compatible with all of Newport’s 818 Series Low-Power Si, Ge and InGaAs detectors. Detectors connect to the power meter through an in-line calibration module that is dedicated to each detector (see System Specifications Table below for all compatible detectors). These detachable modules provide the Model 840-C with calibration and operating information specific to the assigned detector. Various detector accessories allow for free-space, as well as for fiber coupled power measurements. DC and AC peak-to-peak power measurements can be displayed in units of W and dBm on the instrument’s 4 digit, backlit LCD.

Instrument Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display Type</td>
<td>4-digit LCD w/ backlight</td>
</tr>
<tr>
<td>Sampling Rate (Hz)</td>
<td>2.5</td>
</tr>
<tr>
<td>Gain Ranges</td>
<td>6 decades, DC; 4 decades, AC Pk-Pk</td>
</tr>
<tr>
<td>Full Scale Readings, Low-Power Detector</td>
<td>100 nA–5 mA</td>
</tr>
<tr>
<td>DC Accuracy, 100 nA range, full scale</td>
<td>±(0.5% + 50 pA)</td>
</tr>
<tr>
<td>DC Accuracy, 1 µA to 5 mA range, full scale</td>
<td>±(0.25% + offset) See Manual</td>
</tr>
<tr>
<td>Peak-to-Peak Accuracy, 50 Hz to 1 kHz</td>
<td>Squarewave ±5%, Sinewave ±1%</td>
</tr>
<tr>
<td>Peak-to-Peak Accuracy, 1 kHz to 2 kHz</td>
<td>Squarewave ±1%, Sinewave ±2%</td>
</tr>
<tr>
<td>Peak-to-Peak Accuracy, 2 kHz to 5 kHz</td>
<td>Squarewave ±2%, Sinewave ±5%</td>
</tr>
<tr>
<td>Analog Output Accuracy, 100 nA range</td>
<td>±(2.5% + 15 mV)</td>
</tr>
<tr>
<td>Analog Output Accuracy, 1 µA to 5 mA range</td>
<td>±(2% + 10 mV)</td>
</tr>
<tr>
<td>Analog Output,BNC, 0-1 V into 1 MΩ</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>0.1 x AccuracyºC/ºC</td>
</tr>
<tr>
<td>Battery Life</td>
<td>18 hours (backlight on)</td>
</tr>
<tr>
<td>Battery</td>
<td>Ni-Cd rechargeable</td>
</tr>
<tr>
<td>Wall Power</td>
<td>AC adapter/Charger</td>
</tr>
<tr>
<td>Dimensions (H x W x D) [in. (mm)]</td>
<td>7.2 (183) x 3.0 (76) x 1.5 (38)</td>
</tr>
<tr>
<td>Weight [lb (kg)]</td>
<td>1.1 (0.5)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>0ºC to 50ºC, &lt;80% RH</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>-25ºC to 60ºC, &lt;90% RH</td>
</tr>
</tbody>
</table>

Additional Benefits

- Wavelength selection in 1 nm steps
- Audible tone for non-look tuning
- Rechargeable batteries for full portability
- Travel case included with power meter
- Most recent operating parameters are saved when unit is turned off
System Specifications

The 840-C is compatible with Newport’s Ge, Si and InGaAs detectors, allowing both free-space and fiber pigtailed measurements in the 200–1800 nm range. When using 818 Series detectors with the 840-C, a calibration module needs to be attached to the detector (818-xx/CM), assuring the correct reading at any pre-selected wavelength. Newport’s new 918D and 918L Series detectors can also be used with the 840-C, in combination with the 818P-DIN adapter.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (cm)</td>
<td>1.13</td>
<td>1.13</td>
<td>0.3</td>
<td>1 x 1</td>
<td>1 x 1</td>
<td>0.3</td>
<td>0.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>200–1100</td>
<td>400–1100</td>
<td>400–1100</td>
<td>400–1100</td>
<td>200–1100</td>
<td>780–1800</td>
<td>800–1650</td>
<td>400–1650</td>
<td>400–1650</td>
</tr>
<tr>
<td>Power Range (dBm)</td>
<td>5 pW to 200 mW</td>
<td>1 pW to 2 W</td>
<td>1 pW to 2 mW</td>
<td>100 pW to 2 W</td>
<td>100 pW to 2 W</td>
<td>100 pW to 140 mW</td>
<td>1 pW to 140 mW</td>
<td>100 pW to 200 mW</td>
<td></td>
</tr>
<tr>
<td>Display Resolution</td>
<td>0.01 dB or dBm</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>±2</td>
<td>±2</td>
<td>±2</td>
<td>±2</td>
<td>±3</td>
<td>±2</td>
<td>±2</td>
<td>±2.5</td>
<td></td>
</tr>
<tr>
<td>Applicable Wavelength Range (nm)</td>
<td>200–1100</td>
<td>400–1100</td>
<td>400–1100</td>
<td>400–1100</td>
<td>200–1100</td>
<td>780–1700</td>
<td>800–1650</td>
<td>400–1650</td>
<td></td>
</tr>
<tr>
<td>Linearity (%)</td>
<td>±0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEP @ 5 Hz and 1 A/W</td>
<td>50 fW/√Hz</td>
<td>50 fW/√Hz</td>
<td>50 fW/√Hz</td>
<td>3 pW/√Hz</td>
<td>3 pW/√Hz</td>
<td>4 pW/√Hz</td>
<td>30 fW/√Hz</td>
<td>3 pW/√Hz</td>
<td></td>
</tr>
</tbody>
</table>

1) At calibration temperature maintained to ± 0.2°C, -20 dBm level having 99% encircled energy on detector with no optical attenuator
2) -70 to +3 dBm for 818-F-IR
3) 0.01 A/W for the 818-IS-1
4) Append /220 for 220V version

Ordering Information

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>840-C</td>
<td>Hand-held Power Meter</td>
</tr>
<tr>
<td>840-C-CAL</td>
<td>840-C with test data and certificate</td>
</tr>
<tr>
<td>840-C/220</td>
<td>Hand-held Power Meter, 220V Version</td>
</tr>
<tr>
<td>840-C/220-CAL</td>
<td>840-C with test data and certificate</td>
</tr>
</tbody>
</table>

For more details on Newport’s low-power detectors and fiber optic accessories compatible with the 840-C, please see page 1090 thru page 1095.

Call Newport’s Application Sales Engineers to help you select the optical detector that best meets your application requirements.
Description:

Ondax’s 658nm Wavelength Stabilized Laser is a single mode, miniature laser in a standard TO package. The stabilization is achieved using the Ondax Volume Holographic Grating (VHG) PowerLocker®.

The laser has a very low temperature dependence and precise center wavelength over the locked region.

The narrow linewidth and long coherence length from a standard TO packaged laser enables many applications.

Features:

- Wavelength stability (~0.015nm/°C)
- Single frequency
- Coherence length (>2m)
- Hermetically sealed
- Custom wavelengths available

Applications:

HeNe replacement, flow cytometry, blood flow, metrology, bio Instrumentation, graphic arts, Raman spectroscopy, analytical instrumentation, sensing, and data storage.

Specifications:

**Single Frequency**

**Wavelength Stability:** ~0.015nm/°C

**Specifications:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power</td>
<td>Po</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>mW</td>
</tr>
<tr>
<td>Laser Reverse Voltage</td>
<td>Vr</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Photodiode Reverse Voltage</td>
<td>Vp</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>Topp</td>
<td></td>
<td>0</td>
<td></td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>Ts</td>
<td></td>
<td>-10</td>
<td></td>
<td>60</td>
<td>°C</td>
</tr>
</tbody>
</table>

1 At a case temperature of 25°C.

## Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Current</td>
<td>Ih</td>
<td>CW</td>
<td>30</td>
<td>50</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Operating Current</td>
<td>Iop</td>
<td>P_o = 35 mW</td>
<td>65</td>
<td>85</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>Vop</td>
<td>P_o = 35 mW</td>
<td>2.4</td>
<td>2.8</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Monitoring Output Current</td>
<td>Im</td>
<td>P_o = 35 mW</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>mA</td>
</tr>
<tr>
<td>Lasing Wavelengths</td>
<td>Lp</td>
<td>P_o = 35 mW</td>
<td>655</td>
<td>656</td>
<td>657</td>
<td>nm</td>
</tr>
<tr>
<td>Lp</td>
<td>P_o = 35 mW</td>
<td>T=Tc</td>
<td>657</td>
<td>658</td>
<td>659</td>
<td>nm</td>
</tr>
<tr>
<td>Lp</td>
<td>P_o = 35 mW</td>
<td>T=Tc</td>
<td>659</td>
<td>660</td>
<td>661</td>
<td>nm</td>
</tr>
<tr>
<td>Linewidth</td>
<td>Dl</td>
<td>P_o = 35 mW</td>
<td>50</td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Central Stabilized Temperature</td>
<td>Tc</td>
<td>P_o = 35 mW</td>
<td>15</td>
<td>30</td>
<td>40</td>
<td>°C</td>
</tr>
<tr>
<td>Stabilized Temperature Range</td>
<td>Tr</td>
<td>P_o = 35 mW</td>
<td>10</td>
<td>15</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>Beam Divergence, Perpendicular</td>
<td>Qv</td>
<td>P_o = 35 mW</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>deg.</td>
</tr>
<tr>
<td>Beam Divergence, Parallel</td>
<td>Qh</td>
<td>P_o = 35 mW</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>deg.</td>
</tr>
<tr>
<td>Off Axis Angle, Perpendicular</td>
<td>dQv</td>
<td></td>
<td>-3</td>
<td>3</td>
<td></td>
<td>deg.</td>
</tr>
<tr>
<td>Off Axis Angle, Parallel</td>
<td>dQh</td>
<td></td>
<td>-3</td>
<td>3</td>
<td></td>
<td>deg.</td>
</tr>
<tr>
<td>Emitter Size</td>
<td></td>
<td></td>
<td>1</td>
<td>X</td>
<td>3</td>
<td>um</td>
</tr>
<tr>
<td>Differential Efficiency</td>
<td>DE</td>
<td></td>
<td>1.1</td>
<td></td>
<td></td>
<td>mW/mA</td>
</tr>
</tbody>
</table>

Specifications are subject to change without notice. Each purchased laser is provided with test data. Please refer to this data before using the laser.

115-81002-XXX Rev. 5

850 E. Duarte Rd. Monrovia, CA 91016 Tel: (626) 357-9600 Fax: (626) 357-9321 sales@ondax.com
Output Power vs Forward Current (Typical)

Stabilized Temperature Range

Model Numbers:
- TO-656-PLR35
- TO-658-PLR35
- TO-660-PLR35

Specifications are subject to change without notice. Each purchased laser is provided with test data. Please refer to this data before using the laser.

115-81002-XXX Rev. 5

850 E. Duarte Rd. Monrovia, CA 91016 Tel: (626) 357-9600 Fax: (626) 357-9321 sales@ondax.com
Final Test Report

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Current(^1)</td>
<td>(I_{th})</td>
<td>CW</td>
<td>27 mA</td>
</tr>
<tr>
<td>Operating Current(^1)</td>
<td>(I_{op})</td>
<td>(P_0 = 35) mW</td>
<td>60 mA</td>
</tr>
<tr>
<td>Wavelength</td>
<td>(L_p)</td>
<td>(T_c)</td>
<td>658.294 nm</td>
</tr>
<tr>
<td>Central Stabilized Temperature(^2)</td>
<td>(T_c)</td>
<td>(I_{op})</td>
<td>30.4 °C</td>
</tr>
<tr>
<td>Stabilized Temperature Range</td>
<td>(T_r)</td>
<td>(I_{op})</td>
<td>19.2 °C</td>
</tr>
</tbody>
</table>

\(^1\)Measured at a Case Temperature of 30 degC. Supplier recommends operating diodes in constant current mode.
\(^2\)Central Temperature in stabilized temperature range.

Output Power vs. Forward Current (30 degC)

![Graph showing Output Power vs. Forward Current (30 degC)](image)

Wavelength vs. Temperature

![Graph showing Wavelength vs. Temperature](image)

Current (mA), Temperature (degC), Wavelength (nm)

![Graph showing Current (mA), Temperature (degC), Wavelength (nm)](image)

Tested By: 
Checked By: 
Approved By: 

6XSSOLHU recommends operating diodes in constant current mode.
AVT Guppy F-036B / F-036C

Small - easy - ingenious: Analog goes Guppy.

The AVT Guppy camera family is distinguished by an IEEE 1394 interface and an extremely compact design. It consists of thirteen different camera variants (each available in b/w and color) and, with a wide variety of sensors and bandwidths, offers the right solution for nearly any conceivable application. The Guppy is available optionally in a casing or board version (upon request) and therefore fits in the smallest spaces. A selection of high-quality, sensitive sensors (CCD, CMOS) help the Guppy provide outstanding image quality and true color. Four additional interlaced versions (EIA, CCIR) make it even more attractive to switch from analog to digital image processing. Due to its modularity and remarkable price/performance ratio, for many applications the Guppy is the ideal way to make the move to digital image processing.

Highlights
● IEEE 1394a
● WideVGA (752 x 480)
● Up to 64 fps (full resolution)
● Progressive scan CMOS, monochrome and color
● True parital scan (higher frame rates by smaller AOI)
● Flexible AOI, flexible speed (full Format_7 support)
● Asynchronous image trigger

Image preprocessing features:
- Auto gain, auto white balance
- Natural color response
- Programmable LUT
- HDR mode
- Binning
- And lots more ...

Smart frame grabber features:
- Single-shot, multi-shot, free-run
- 1 prog. input / 3 prog. outputs
- On-board RS-232 port
- And lots more ...

● Industry proven and robust housing
● C-Mount, CS-Mount (convertible via adapter)
● Optional OEM board level version, customized housings
AVT Guppy F-036B / F-036C

Camera Specifications

<table>
<thead>
<tr>
<th></th>
<th>Guppy F-036B (b/w)</th>
<th>Guppy F-036C (color)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image device</td>
<td>Type 1/3 (diag. 5.35 mm) progressive scan, CMOS MT9V022</td>
<td></td>
</tr>
<tr>
<td>Picture size</td>
<td>752 (H) x 480 (V) (all modes and color formats)</td>
<td></td>
</tr>
<tr>
<td>Cell size</td>
<td>6 µm x 6 µm</td>
<td></td>
</tr>
<tr>
<td>Resolution depth</td>
<td>8 bit (10 bit ADC)</td>
<td></td>
</tr>
<tr>
<td>Lens mount</td>
<td>C-Mount, CS-Mount (convertible via adapter)</td>
<td></td>
</tr>
<tr>
<td>Digital interface</td>
<td>IEEE 1394a (IIDC V1.3), single port</td>
<td></td>
</tr>
<tr>
<td>Transfer rate</td>
<td>100 Mbit/s, 200 Mbit/s, 400 Mbit/s</td>
<td></td>
</tr>
<tr>
<td>Frame rates</td>
<td>Up to 64 fps (full frames)</td>
<td></td>
</tr>
<tr>
<td>Gain control</td>
<td>Manual 0 - 12 dB, auto gain</td>
<td></td>
</tr>
<tr>
<td>Shutter speed</td>
<td>180 µs ... 979 ms</td>
<td></td>
</tr>
<tr>
<td>External trigger shutter</td>
<td>Programmable, programmable trigger delay</td>
<td></td>
</tr>
<tr>
<td>Smart features</td>
<td>Only b/w: binning (average); b/w and color: AGC (auto gain control), mirror; LUT, 1 config. input, 3 config. output, RS-232 port (serial port, IIDC v. 1.31); only color: AWB (auto white balance)</td>
<td></td>
</tr>
<tr>
<td>Power requirements</td>
<td>DC 8 V – 36 V via IEEE 1394 cable or 8-pin HIROSE</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>Less than 2 watt (@ 12V DC)</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>48.2 mm x 30 mm x 30 mm (L x W x H), w/o tripod and lens</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>50 g (without lens)</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>+5... + 50° Celsius without condensation</td>
<td></td>
</tr>
<tr>
<td>Storage temperature</td>
<td>-10... + 60° Celsius without condensation</td>
<td></td>
</tr>
<tr>
<td>Regulations</td>
<td>EN 55022, EN 61000, EN 55024, FCC Class B, CE, DIN ISO 9022-3, RoHS (2002/95/EC)</td>
<td></td>
</tr>
<tr>
<td>Options</td>
<td>Board level version, power out (HIROSE), AVT FirePackage / Active FirePackage / Fire4Linux</td>
<td></td>
</tr>
</tbody>
</table>
Publications

Journal papers


Conference proceeding papers

- V. Bavigadda, V. Toal, R. Jallapuram, E. Mihaylova, “Out-of-plane vibration analysis with a transmission holographic optical element based


Oral presentations

- Out-of-plane vibration analysis with a transmission holographic optical element based electronic speckle pattern interferometer, Optical measurement systems for industrial inspection VI, Munich, Germany, (2009)

Poster presentations

- V. Bavigadda, R. Jallapuram, E. Mihaylova, V. Toal, “Design of holographic optical elements for electronic speckle pattern interferometry,” Summer school on Opto-Informatics, 20\textsuperscript{th} -22\textsuperscript{nd} August 2008, National University of Ireland, Maynooth, Ireland.