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Multi-component shearography using optical fibre imaging-bundles

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ABSTRACT

Shearography is a full-field non-contact optical technique usually used for the investigation of defects in non-destructive testing. In shearography interferometric speckle patterns recorded before and after object deformation are correlated, often by subtraction, to yield correlation fringes sensitive to displacement gradient, a parameter closely related to surface strain. Shearography is sensitive to the component of displacement gradient that is determined by the direction of the illumination and viewing directions, the optical wavelength and by the magnitude and direction of the applied shear. To perform a multi-component measurement requires illumination, or viewing, from a minimum of three directions, followed by a coordinate transformation to obtain the in-plane and out-of-plane displacement gradient components. This would normally require the use of either multiple optical sources or multiple interferometer heads and multiple cameras. In this paper the authors use a single laser source, a single interferometer head and camera, with four views of the object ported from the camera lenses to the interferometer using a four-leg optical fibre imaging bundle. This approach allows four components of displacement gradient to be recorded simultaneously. Experimental results from the multi-component shearography instrument are presented.

Keywords: shearography, optical fibre imaging-bundle, multi-component measurement, surface strain measurement

1. INTRODUCTION

Shearography[1, 2], also known as speckle shearing interferometry, is a full-field optical technique usually used for non-destructive testing. Shearography is sensitive to the change in the displacement gradient induced when an object is deformed. To perform a measurement, the object is illuminated by an expanded laser beam forming a speckle pattern. This speckle pattern is optically processed using a shearing interferometer and the resulting speckle interferogram is recorded by a CCD camera. A Michelson interferometer is commonly used as the shearing device[1]; the speckle interferogram is formed by optically mixing the speckle pattern with an identical, but displaced, or sheared, speckle pattern in the interferometer. Speckle interferograms recorded before and after object deformation are correlated, often by subtraction, to yield correlation fringes that are sensitive to displacement gradient. To extract the phase information, and hence the displacement gradient information, from these correlation fringes, phase stepping techniques are commonly used[3].

The full characterisation of the surface strain of an object undergoing deformation requires the determination of six components of displacement gradient. In shearography, three components are determined by measuring displacement gradient from three measurement channels that have different illumination, or viewing geometries, followed by a coordinate transformation[4]. This processed is repeated with a different, usually orthogonal, shear direction, to yield the other three displacement gradient components[5].

In this paper the authors use a four-leg optical fibre imaging-bundle to view the object from four different directions. The four channel shearography technique provides duplicate measurements of the in-plane and out-of-plane displacement gradient components[6]. A good agreement between the duplicate measurements provides a high degree of confidence in the measurement accuracy. The duplicate measurements also provide redundancy when one of the channels is not able to perform a measurement, for example when the shape of the object causes shadowing on one of the channels. The four views from the individual legs of the optical fibre imaging-bundle are spatially-multiplexed,

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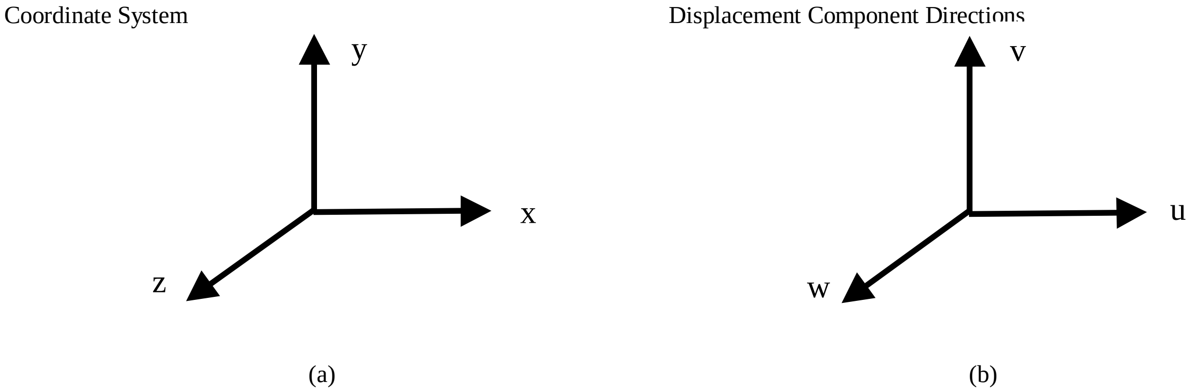
optically processed using a shearing Michelson interferometer and the resulting individual interferograms are recorded by quadrants of a CCD camera chip.

2. THEORY

2.1 Coordinate system

In this paper an orthogonal coordinate system is used with: the x-direction orientated horizontally at the object surface, the y-direction orientated vertically at the object surface, and the z-direction orientated normal to the object surface and towards the shearography instrument. These x, y and z components have associated u, v and w displacements, respectively orientated in the same directions as the coordinate system components. This coordinate system is shown in Figure 1.



(a) (b)

Figure 1 (a) shows the x, y and z directional components of the coordinate system. (b) shows the u, v and w displacement components, which are associated with the x, y and z directional components respectively.

2.2 Shearography

Shearography is sensitive to the component of displacement gradient determined by the direction of the sensitivity vector and by the direction of the applied shear. The sensitivity vector is the bisector of the illumination direction vector and the viewing direction vector. The measurement sensitivity is determined by the magnitude of the applied shear and by the optical wavelength. For colinear illumination and viewing, normal to the surface of the object, shearography is sensitive to the out-of-plane displacement gradient component, $\delta w/\delta x$:

$$\frac{\delta w}{\delta x} = \frac{\Delta\phi\lambda}{4\pi dx} \tag{1}$$

where $\Delta\phi$ is the phase change between the reference and deformed correlation interferograms, λ is the optical wavelength and dx is the applied shear. The other component of out-of-plane displacement gradient, $\delta w/\delta y$, may be obtained by applying a shear in the dy direction.

The in-plane displacement gradient is determined by combining measurements from a minimum of two measurement channels. In the simplest case one in-plane displacement gradient component may be determined using two-channel shearography instrumentation, with two illumination directions and a single viewing direction. The object is first illuminated at an angle θ and viewed normal to the surface to obtain a displacement gradient component that is composed of a contribution from the out-of-plane displacement gradient and the in-plane displacement gradient of interest. The object is then illuminated at an angle of $-\theta$ and this yields a second displacement gradient component. This second in-plane component has an out-of-plane component of the same sign and an in-plane component of opposite sign. Therefore subtraction of one of the measured displacement gradient components from the other yields the in-plane displacement gradient. The second orthogonal in-plane displacement gradient component may be obtained by rotating the illumination positions by 90° about the normal to the object surface.

2.3 Full surface strain measurement using shearography

To fully characterise the surface strain requires the measurement of six components of displacement gradient; two out-of-plane components and four in-plane components of displacement gradient. The strain tensor is given in equation 2 and the surface strain components that may be determined using shearography are highlighted in bold text.

$$S=\begin{pmatrix} \boldsymbol{\frac{\delta u}{\delta x}} & \boldsymbol{\frac{1}{2}\left(\frac{\delta u}{\delta y}+\frac{\delta v}{\delta x}\right)} & \frac{1}{2}\left(\frac{\delta u}{\delta z}+\boldsymbol{\frac{\delta w}{\delta x}}\right) \\ \boldsymbol{\frac{1}{2}\left(\frac{\delta v}{\delta x}+\frac{\delta u}{\delta y}\right)} & \boldsymbol{\frac{\delta v}{\delta y}} & \frac{1}{2}\left(\frac{\delta v}{\delta z}+\boldsymbol{\frac{\delta w}{\delta y}}\right) \\ \frac{1}{2}\left(\boldsymbol{\frac{\delta w}{\delta x}}+\frac{\delta u}{\delta z}\right) & \frac{1}{2}\left(\boldsymbol{\frac{\delta w}{\delta y}}+\frac{\delta v}{\delta z}\right) & \frac{\delta w}{\delta z} \end{pmatrix} \tag{2}$$

The measurement of the 3D components of surface strain was demonstrated by Kästle *et al*[7], Waldner and Brem[8] and by James and Tatam[4], in 1999. The illumination geometry described in these three papers had the optical sources located at three of the four corners of a square. James and Tatam determined this geometry as the optimum practical illumination geometry[4]. For this ideal symmetrical geometry, and for a position on the object surface located at the centre of the field of view the in-plane and out-of-plane displacement gradient components may be determined by addition and subtraction of the appropriate measured displacement gradient components:

$$\frac{\delta u}{\delta x}=\frac{1}{2dx}\left(\frac{\Delta\phi_1}{k_x}-\frac{\Delta\phi_2}{k_x}\right) \tag{3}$$

$$\frac{\delta v}{\delta x}=\frac{1}{2dx}\left(\frac{\Delta\phi_2}{k_x}-\frac{\Delta\phi_3}{k_x}\right) \tag{4}$$

$$\frac{\delta w}{\delta x}=\frac{1}{2dx}\left(\frac{\Delta\phi_1}{k_x}+\frac{\Delta\phi_3}{k_x}\right) \tag{5}$$

where the sensitivity vectors of channels 1, 2 and 3 are $(-k_x, k_y, k_z)$, (k_x, k_y, k_z) $(k_x, -k_y, k_z)$ respectively, $\Delta\phi_1$, $\Delta\phi_2$ and $\Delta\phi_3$ are phase changes measured from channels 1, 2 and 3 respectively and dx is the magnitude of the applied shear in the x-direction. Similar expressions may be generated for an applied shear in the dy direction.

For positions on the object surface other than at the centre of the field of view, and, more generally, taking into account small variations in the positions of the viewing and illumination directions relative to the ideal case a full coordinate transformation must be performed. The coordinate transformation is given in equation 6. Care must be taken to minimise errors in the coordinate transformation process by the use of a well conditioned coordinate transformation matrix[4]. In the general case the coordinate transformation is represented by:

$$\begin{pmatrix} \delta u/\delta x \\ \delta v/\delta x \\ \delta w/\delta x \end{pmatrix} = \begin{pmatrix} k_{x1} & k_{x2} & k_{x3} \\ k_{y1} & k_{y2} & k_{y3} \\ k_{z1} & k_{z2} & k_{z3} \end{pmatrix}^{-1} \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \end{pmatrix} \frac{1}{dx} \tag{6}$$

where the sensitivity vectors of channel n is given by (k_{xn}, k_{yn}, k_{zn}). In the ideal situation, described by Kästle *et al*[7], where k_{x3}, k_{y1} and k_{z2} are zero, $k_{x1}=-k_{x2}$, $k_{y2}=-k_{y2}$ and $k_{z1}=k_{z2}$, the coordinate transformation simplifies to the addition and subtraction of measured channels described previously by equations 3 to 5.

The measurement of four components of displacement gradient using shearography allows a duplicate determination of all of the in-plane and out-of-plane displacement gradient components. Where a good agreement is achieved between the duplicate measurements this provides a high degree of confidence in the measurement accuracy. In circumstances when no data is obtained from one of the four channels, for example when the shape of the object causes shadowing on one of the channels, the surface strain may still be fully characterised using data from the other three channels[6]. The ideal configuration for four measurement channels is with the viewing, or illumination, positions orientated symmetrically at four corners of a square.

3. EXPERIMENTAL

A single illumination direction and multiple viewing direction configuration is chosen so that a simple optical arrangement, using spatial-multiplexing, with a single laser source, a single shearing interferometer and single camera may be employed. The use of multiple sources and multiple interferometer heads and cameras in a wavelength-division-multiplexed instrument is expensive, and the use of multiple sources and time-division-multiplexing is not suitable for the deployment of the imaging head and interferometer head in conjunction with a pulsed laser, for investigation of transient and non-stationary phenomena.

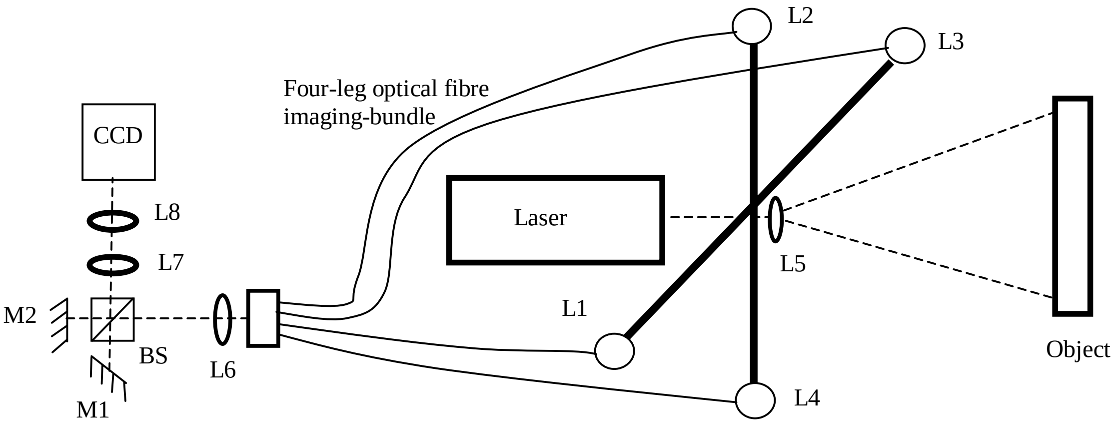
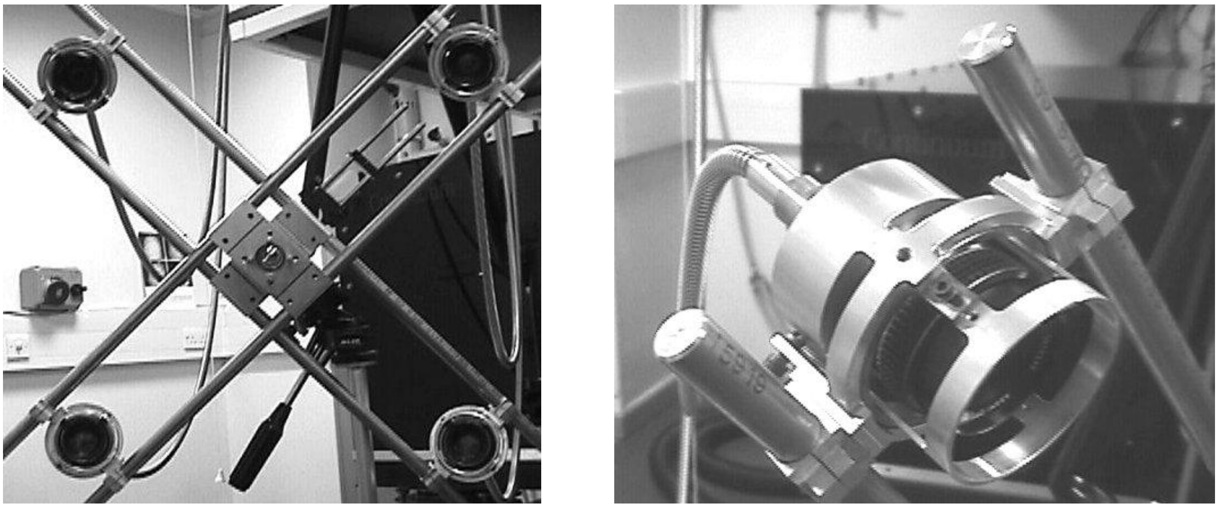


Figure 2 Experimental layout of the four-channel shearography instrument. L1, L2, L3 and L4, camera lenses; L5, beam expansion lens; L6, objective lens; BS, beamsplitter; M1, shearing mirror; M2, reference mirror; L7 and L8, imaging lenses; CCD, camera.

The experimental layout is shown in Figure 2. The object under investigation is illuminated by an expanded laser beam from a continuous-wave frequency-doubled Nd:YAG laser (Coherent DPSS 532, 532 nm, 300 mW optical power). The object is viewed from four directions, arranged symmetrically in a square around the illumination direction, by four camera lenses (Helios-44-2). The viewing head is custom made to restrict the number of degrees of freedom of movement of the camera lenses, whilst still allowing flexibility in the relative position of the object to the viewing head. Individual lenses are fitted in lens holders which allow rotation of the camera lens in two orthogonal directions, whilst keeping the principal plane of the lens system at a fixed position. The four lens holders are fitted to a rod system, which allows freedom of movement of the lenses to different distances from the centre of the head, and therefore permits different angles of viewing. The illumination head is shown in Figure 3(a) and a close-up of an individual lens holder is shown in Figure 3(b).



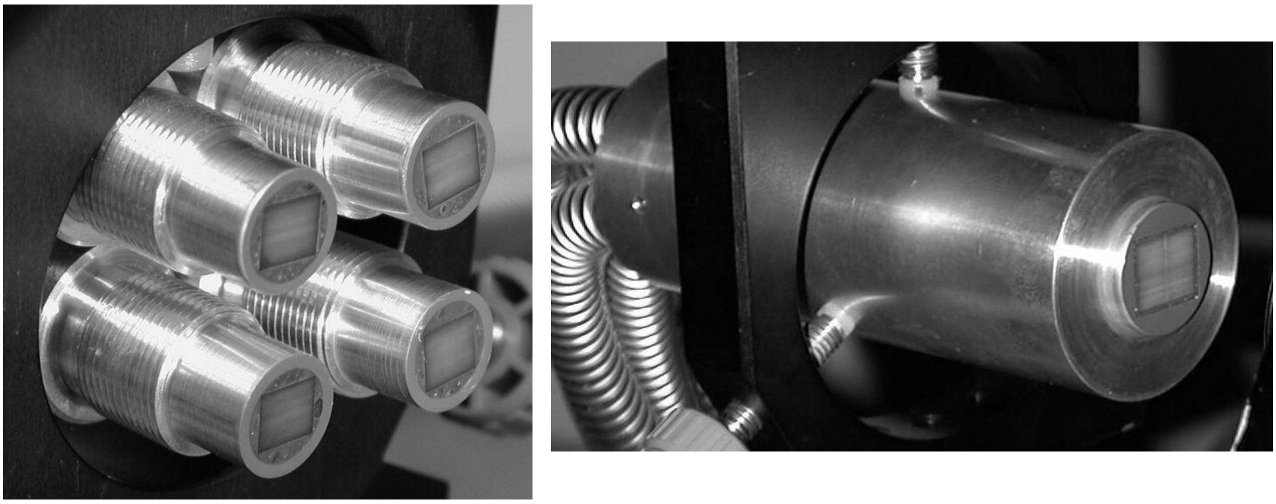
(a) (b)

Figure 3 shows (a) a photograph of the 4-channel illumination head and (b) a close-up photograph of a single lens holder in the illumination head.

Images from the four camera lenses are transferred via a four-leg optical fibre imaging-bundle to the interferometer head. Each leg of the optical fibre imaging bundle is composed of an array of 600 by 500 optical fibres arranged in a regular grid. The individual optical fibres in the array are 10 μm in diameter. The imaging-bundle is 4 m long and protected by an armoured sheath. At the distal end of the optical fibre imaging-bundle the four legs of the bundle are combined such that they form quadrants of a 1200 by 1000 optical fibre array, this is shown in Figure 4(b). In this way to four views of the object are spatially-multiplexed to a single image plane at the distal end of the imaging-bundle. The camera lens and interferometer ends of the optical fibre imaging-bundle are shown in Figures 4(a) and 4(b) respectively.

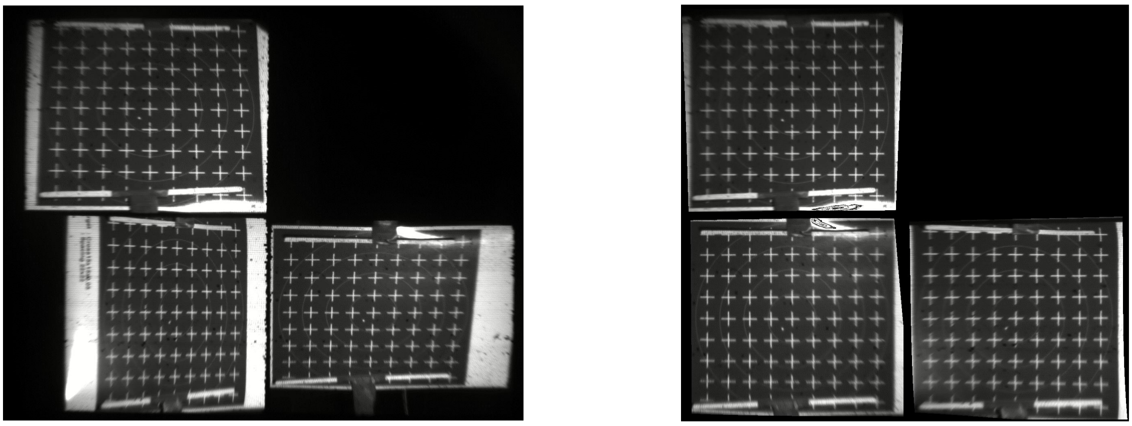
The interferometer is constructed using Microbench^{TM} opto-mechanical mounts (Linos Photonics Ltd). The image at the distal end of the imaging-bundle is expanded, passes through a shearing Michelson interferometer, composed of beamsplitter, reference mirror and shearing mirror, and is focused onto the CCD chip by two further lenses. The camera (LaVision Imager3, 1280 by 1024 pixels, 12 bit) captures speckle interferograms of the object surface before and after object deformation, using software written using the DaVis macro language (LaVision).

When multiple viewing directions are used, the individual images are subject to perspective distortion and when inter-channel data analysis is performed, there is a requirement from a correct image registration. To correct for these factors a test target containing a two-dimensional array of crosses is placed at the object position, and images are recorded from the four measurement channels. Image processing software then performs a *dewarping* procedure to correct for the perspective distortion. To meet the image registration requirements, one of the dewarped images is chosen as a reference and the other three channels are mapped onto that image using the image processing software. The image correction procedure determined using the test target is applied subsequently to data sets from the shearography technique. This is shown in Figure 5.



(a) (b)

Figure 4 (a) shows a close-up of the four legs of the optical fibre imaging-bundle at the camera lens end. Each leg has an array of 600 by 500 optical fibres. (b) shows a close-up of the optical fibre imaging-bundle at the interferometer end. The combined array size is 1200 by 1000 optical fibres.



(a) (b)

Figure 5 (a) Illustration of the perspective distortion when viewing the test target from three viewing directions. (b) shows the corrected image after performing the dewarping procedure.

4. RESULTS AND DISCUSSION

The instrumentation described in Section 3 was used to perform displacement gradient measurements from four channels on a flat plate test object. The test object was painted white and was clamped around the perimeter. A micrometer screw gauge, located behind the test object, was used to generate an out-of-plane deformation of a few microns towards the shearography instrument. The time period between recording the reference and deformed speckle interferograms was a few seconds. The magnitude of the applied shear was 5 mm. The object was located 1.1 m from the object and the viewing angles for the four viewing directions were all 17 °.

Figure 6 shows the composite image of the correlation fringes from the four viewing directions. In each quadrant of the image the expected form of the displacement gradient correlation fringes from a clamped plate subjected to an out-of-plane deformation can be clearly seen.

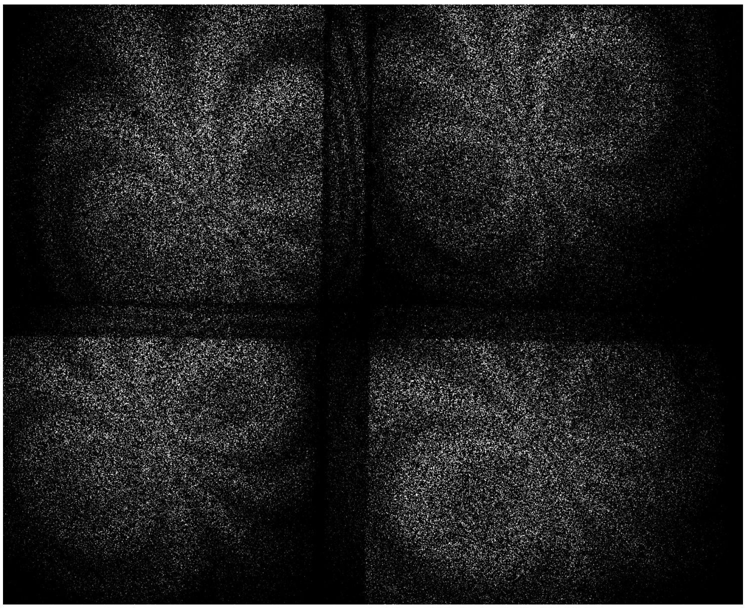


Figure 6 The experimentally determined correlation fringes from the four measurement channels are shown in each quadrant of the composite image.

To extract the optical phase, and hence the displacement gradient, from these correlation fringes requires a phase analysis technique that determines the direction of the displacement gradient. In a conventional shearography instrument phase-stepping would be used. When imaging though an optical fibre imaging-bundle the temporal stability of the correlation fringes is reduced as the fibre optic bundle is sensitive to environmental changes, such as temperature fluctuations and vibrations[9]. Currently investigations into the maximum time available to perform the phase-stepping process satisfactorily for this particular instrument are underway.

The contrast of the correlation fringes is reduced due to a sensitivity of the optical fibre imaging-bundle to changes in environmental conditions over time, which causes decorrelation of the speckle pattern over time. The reduction in fringe contrast due to environmental variations would be minimised by reducing the time between the collection of reference and deformed speckle interferograms, by for example using a double-pulsed laser source.

5. CONCLUSIONS

The use of optical fibre imaging-bundles to perform multi-channel shearography instrument has been demonstrated. The instrument uses illumination from a single direction, viewing from four directions, with image transfer using the imaging-bundle to the interferometer head, where the four views are spatially-multiplexed, optically processed, and recorded by a single camera frame.

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