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# Multi-wavelengths shearography for optical whole-field strain measurements

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## *Abstract*

We developed a shearographic sensor that allows measuring strain distributions on object surfaces. To acquire all necessary information three IR lasers with different wavelengths are used to illuminate the object simultaneously from different directions. The sensor head houses three synchronised B/W-cameras, each of which grabs the speckle fields of a single laser only. A standard phase stepping procedure is applied. Different shearing devices allowing to switch the shear direction and hence to acquire two derivative directions in sequence are discussed. We describe the sensor head and outline the evaluation procedure. Results of strain measurements during tensile testing are compared with strain gage measurements and illustrate the applicability in testing environments.

## *1. Introduction*

The measurement of strain is a key element in material characterisation and structural testing. Besides the ubiquitous resistive strain gauge (RSG), optical measurement techniques become more and more familiar. Electronic speckle pattern shearing interferometry or shearography has become popular as a tool for non-destructive testing[1,2]. It is mainly used to display on-line the formation of correlation fringes while loading an object. The fringe density and orientation give a qualitative understanding of flaws and inhomogeneities. The strength of the technique is that the whole-field displacement derivatives can be visualised. In addition, shearography is less sensitive to object vibrations compared to other speckle techniques and can therefore be applied in an industrial environment. Despite these advantages, it has scarcely been used for quantitative investigations as e.g. for strain measurements. This is mainly due to the difficulties in extracting properly calibrated strain values from the recorded phase fringe patterns.

Complete knowledge of a planar strain state requires the measurement of three strain directions (e.g. with a RSG rosette) or the measurement of the strain tensor, i.e. measuring the derivatives in x- and y-direction of the x- and y-displacement components. To measure these derivatives along one shear direction with shearography, independent phase maps are necessary. These are mostly realised by illuminating the object from different directions. In contrast to the shearographic systems described in the literature[2-5], our shearographic sensor is able to record the phase images of three lasers operating at different wavelengths simultaneously. In addition, a device that allows to switch between two orthogonal shear directions and a standard phase stepping equipment are incorporated. These tools enable to determine all six displacement derivatives accessible to shearography automatically without rearrangement of the lasers or the test specimen.

The sensor was developed within the Brite EuRAM project Multi-Wavelength Shearography (MuWaS). In the following, the principles for 2D shearographic strain measurements are outlined and the experimental arrangement is discussed. Finally, results of in-plane strain measurements during tensile testing of an aluminium bar are presented and compared with strain gage measurements.

## *2. Theory*

In the following, a brief derivation of the formula needed for the determination of all displacement derivatives from the recorded fringe patterns is given. For a more detailed description see [4]. Most important for the evaluation of the strain distributions from the recorded fringe patterns are the sensitivity vectors $\boldsymbol{k}_i$ , $i$=1,2,3, which are determined by the optical configuration shown in Fig. 1.

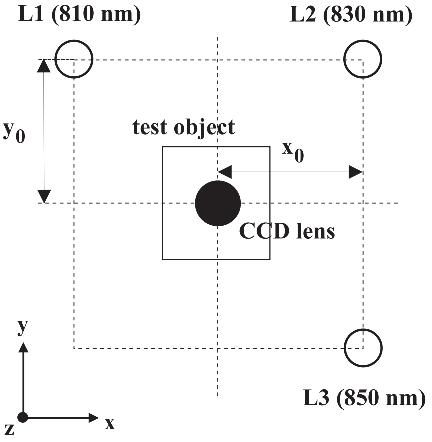

**Fig. 1:** Arrangement of lasers L1, L2, and L3 and CCD lens of the shearographic camera, projected onto the x-y-plane. Wavelengths are given in brackets.

The origin of the co-ordinate system is located on the front surface of the test object on the optical axis of the camera entrance lens. The lasers were placed at the corners of a rectangle with the mid-point co-ordinates (0, 0, $z_0$) and side lengths of $2x_0$ and $2y_0$, respectively.

Due to the symmetry of the configuration the in- and out-of–plane displacement derivatives in the two shear directions can be obtained by adding or subtracting two of the six phase fringe patterns $\Delta\varphi_{xi}$ and $\Delta\varphi_{yi}$, recorded for the three lasers $i$ = 1,2,3 in the two shearing directions $x$ and $y$:

$$\begin{array}{ll} \Delta\phi_{xx} = \Delta\varphi_{x2} - \Delta\varphi_{x1} = 2\,k_x \dfrac{\partial u}{\partial x}\Delta x & \Delta\phi_{xy} = \Delta\varphi_{y2} - \Delta\varphi_{y1} = 2\,k_x \dfrac{\partial u}{\partial y}\Delta y \\ \Delta\phi_{yx} = \Delta\varphi_{x2} - \Delta\varphi_{x3} = 2\,k_y \dfrac{\partial v}{\partial x}\Delta x & \Delta\phi_{yy} = \Delta\varphi_{y2} - \Delta\varphi_{y3} = 2\,k_y \dfrac{\partial v}{\partial y}\Delta y \;, \\ \Delta\phi_{zx} = \Delta\varphi_{x1} + \Delta\varphi_{x3} = 2\,k_z \dfrac{\partial w}{\partial x}\Delta x & \Delta\phi_{zy} = \Delta\varphi_{y1} + \Delta\varphi_{y3} = 2\,k_z \dfrac{\partial w}{\partial y}\Delta y \end{array} \tag{1}$$

where $\mathbf{d} = (u,v,w)$ is the displacement vector, and $\Delta x$, $\Delta y$ are the shear widths. $\boldsymbol{k}_2$ is given by

$$\left(k_x, k_y, k_z\right) = \frac{2\pi}{\lambda l}\left(x_0, y_0, l + z_0\right) \qquad \text{with} \qquad l = \left(x_0^2 + y_0^2 + z_0^2\right)^{1/2} . \tag{2}$$

This procedure is strictly correct for the origin at the front surface of the test object and for equal wavelengths of all three lasers only. In all other cases the phase fringe patterns $\Delta\phi_{xx}$, $\Delta\phi_{xy}$,... do contain small contributions of the derivatives of other components of the vector **d**, impeding a direct shearographic strain evaluation. Although the complete sensitivity matrix in every point on the object was calculated in our evaluations, those expressions will not be given here for brevity. Using the equations above as a first approximation, the wavelength effect of the three lasers is estimated as follows. Wavelengths of 810, 830 and 850 nm were used in our experiments. This yields deviations of ±1.3% in the recorded phase values, which can usually be neglected. In the case of large out-of-plane deformations, however, such small asymmetries lead to additional terms in Eq. (1), which can even dominate the in-plane phase contributions. For the experiment presented below the uncertainty due to asymmetries in the test set-up applied was estimated by numerical simulation to be smaller than ±5%.

## *3. The Shearographic Sensor*

### 3.1 Multi-wavelength camera

The multi-wavelength shearographic sensor is shown in Fig. 2. Diode lasers from Spectra Diode Labs (SDL) emitting at wavelengths of 810, 830 nm (vertically polarised) and 850 nm (horizontally polarised) are used. They operate in single longitudinal mode with an output power between 90 and 200 mW. Object illumination is performed without using any collimating optics. The box houses the shearographic camera. A f/1.9 CCD lens with a focal length of 35 mm (Schneider/Germany) serves as entrance lens of the sensor head and is situated within the "black hole" seen in Fig.2.

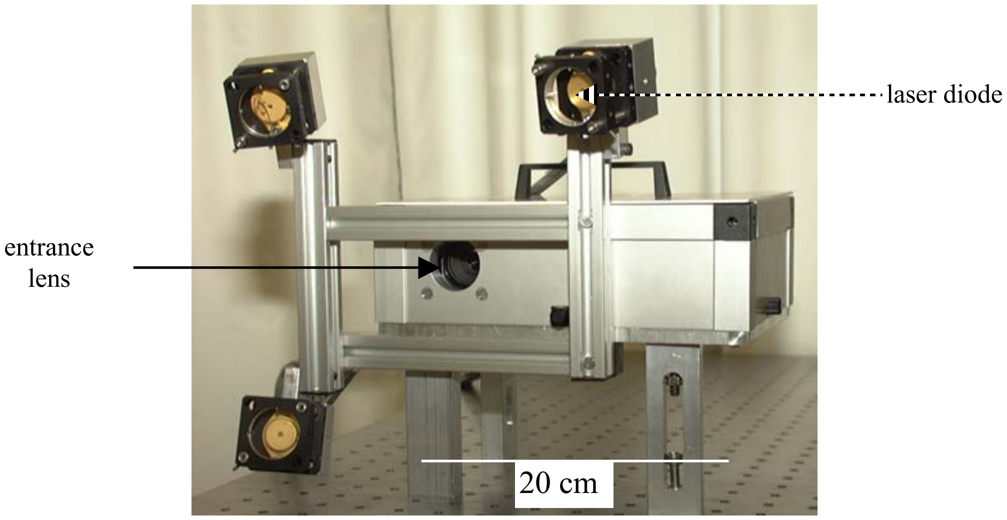

**Fig. 2:** Miniaturised shearographic sensor head. Note the three diode lasers for illumination.

The camera set-up is given schematically in Fig.3. Right after the entrance lens, a Michelson interferometer serves as the basic shearing element. The two realisations of automatic switch of the shear direction using polarisation separation or galvanometer scanners are described in section 3.2.

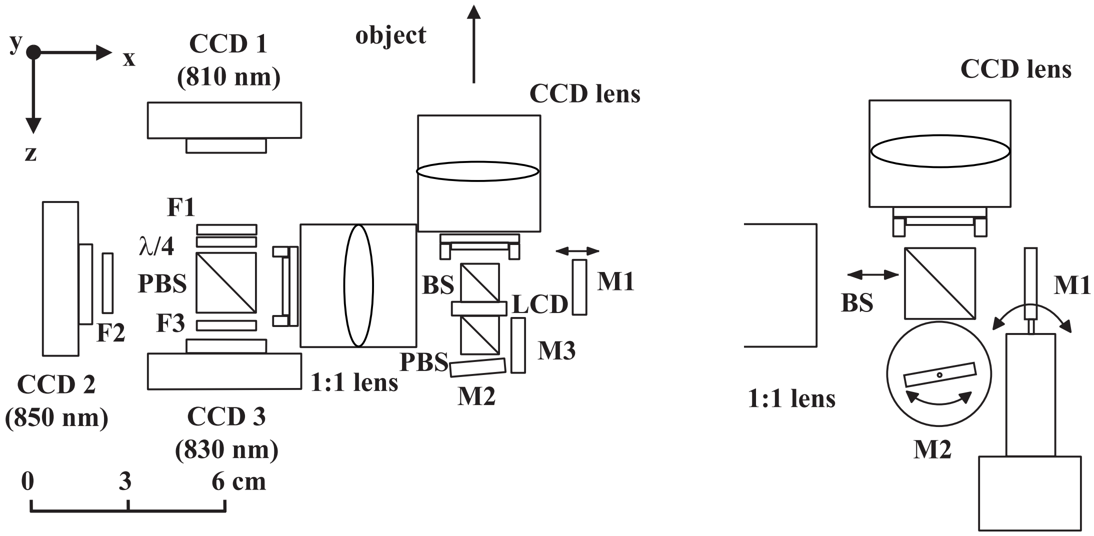

**Fig. 3:** Shearographic camera with beam splitter BS, bandpasss filters Fi and quarter waveplate λ/4. Two devices for automatic switch of shear directions are given: using a liquid crystal device LCD and a polarising beam splitter PBS (left), and using mirrors M1 and M2 mounted on galvanometer scanners (right). Details are given in the text.

Since the back focal length of C-mount lenses is too short to introduce the shear device and the colour separation optics, a photographic f/1.8 lens (Nikon/Japan) with a focal length of 35 mm with antireflection coating at $\lambda$ = 830 nm was added. It transfers the image of the entrance lens at unit conjugate ratio through the colour separation optics to the CCD cameras. The horizontally polarised light passes the polarising beam splitter cube (PBS), and the band pass filter F2 centred at 850 nm transmits this light onto CCD 2. The vertically polarised light is directed towards CCD 1. A band pass filter F1 with centre wavelength of 810 nm transmits the light of the corresponding diode and reflects all other wavelengths towards CCD 3. In order to increase the intensity on CCD 3 a $\lambda/4$-wave plate was added between the PBS and filter F1. This combination yields high speckle intensities on all three CCD cameras. In the case of polarisation preserving object surfaces, the intensities are up to 4 times higher on CCD 3, as compared to the use of a non-polarising beam splitter. For partially depolarised light, the filters ensure that each camera records a speckle image corresponding to one laser source only, preventing ghost images of the other laser wavelengths. The diode lasers were temperature tuned to the centre wavelengths of the band pass filters with a FWHM of $\Delta\lambda = 10 \pm 2$ nm. The similarity of the laser wavelengths allowed us to use filters that do not block UV and longer IR wavelengths, and consequently have a high transmission of approximately 80-90% at their centre wavelengths.

The speckle patterns are recorded with 3 synchronised b/w OEM board CCD cameras connected to the RGB input channels of a colour frame grabber. For image acquisition we used the machine vision system MVS 150/40 from Imaging Technology. On-board image processing was performed with a “C“-programmable pipeline processor. Capturing of 3 x 4 images and subsequent phase evaluation for all 3 illumination directions is performed in less than 500 ms. The “C“-program code for the image acquisition and processing board was included as a dynamic link library in a LabVIEW environment (National Instruments), which was used for controlling the shearographic system and the tensile testing machine.

### 3.2 Automatic switching of the shear direction

For switching of the shear directions a method developed by ILM [6] was used, where a liquid crystal device (LCD), a polarising beam splitter and an additional mirror were added to the Michelson interferometer (Fig.3). The mirrors M2 and M3 induce a shear along the x- and y-direction, respectively. Hence, the two polarisation's separated by the PBS are sheared in different directions. The LCD acts as a switchable $\lambda/2$ wave plate. In its neutral state the LCD does not affect the polarisation. When switched on, the LCD rotates the polarisation by 90°. Note that due to the PBS in the colour separation optics the images recorded by CCD2 have always the opposite image shear compared to the images from the other two CCDs. Phase stepping is done by shifting mirror M1.

Alternatively, the two mirrors of the Michelson interferometer were mounted on two galvanometer scanners (General Scanning), one with rotation axis parallel to the z- and the other with rotation axis parallel to the y-axis. This allowed to switch between the two directions of image shear and in addition to vary the shear widths. Typical switching times of the galvanometer scanners are 5-10 ms. The reproducibility of the deflection angles is about 20 µrad. After the galvanometer scanners have reached their thermal equilibrium, their drifts in deflection angle are low enough to hold good fringe visibility over typical periods of about 5-10 min. In order to implement the phase stepping procedure, the beam splitter BS of the Michelson interferometer was mounted on a piezo actuator.

## *4. Experimental results*

To illustrate the strain measurement procedure, we consider an aluminium bar of length 20 cm, of width 2.5 cm and of thickness 1 mm mounted on a 20 kN tensile testing machine (Zwick) [7]. The shearographic camera is installed in front of the testing machine on an optical table. The aluminium bar is loaded with forces from 0 N up to 1800 N in steps of 50 N. At each loading step the force is held constant for 4 s, during which time the phase fringe patterns of the three lasers were measured and transformed to the in- and out-of-plane phase fringe patterns. The testing procedure including the control of the testing machine as well as the shearographic data evaluation was automated. A typical tensile test including 46 measuring points, strain evaluation for the two in-plane components and the read-out of the strain gage values took approximately 4 minutes.

A typical example of the in- and out-of-plane phase images, which were measured for one loading step of 50 N and for a 1 cm image shear in y-direction, are presented in Fig. 4. Nearly homogeneous phase distributions for the terms $\partial u/\partial y$ and $\partial v/\partial y$ were obtained except for the dark areas that are caused by the wires of a x-y-strain gage which was applied in the middle of the test specimen for comparison. While the homogeneous phase distribution for $\partial u/\partial y$ corresponds to a small rotation of the bar around the z-axis, the phase distribution for $\partial v/\partial y$ corresponds to an increase in strain of approximately 20 µm/m per loading step of 50 N. The incremental strain at each loading step was derived by simply averaging the grey values within the rectangles 1 and 2 shown in Fig. 4. since for each loading step the phase remains within the zero order fringe. No differences were observed between the values of area 1 and that of area 2 that was located just above the strain gage. In contrast, a more complex phase distribution was measured for the out-of-plane displacement derivative $\partial w/\partial y$, and the correct fringe order has to be monitored.

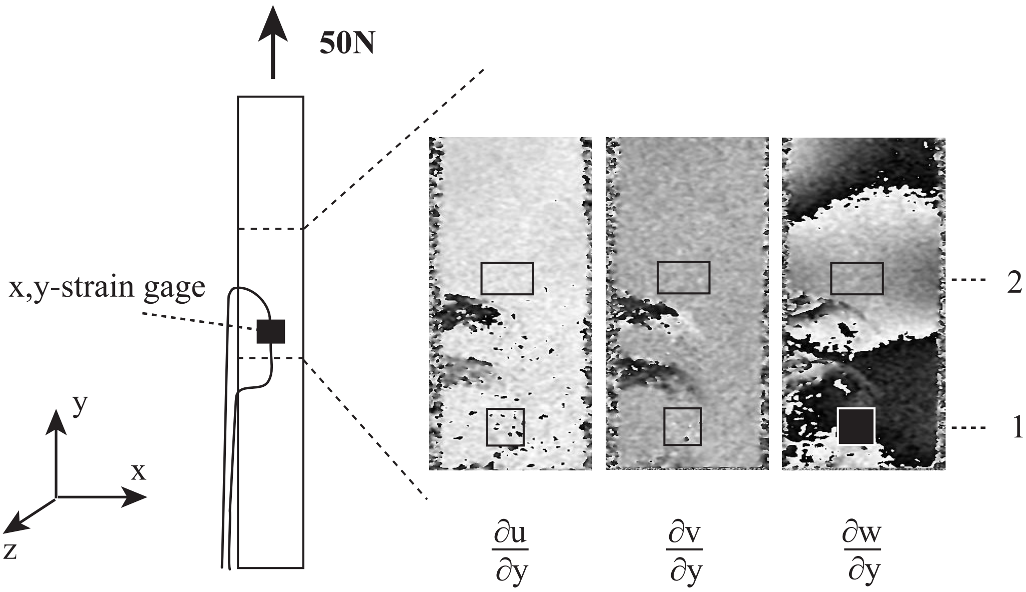

**Fig. 4:** In-and out-of-plane phase distributions of an aluminium bar determined with a 1 cm image shear in y-direction for a load step of 50 N.

The corresponding strain values are calculated according to Eq. (1) and (2) and added to the previous value. The resulting strain versus load is presented in Fig. 5.

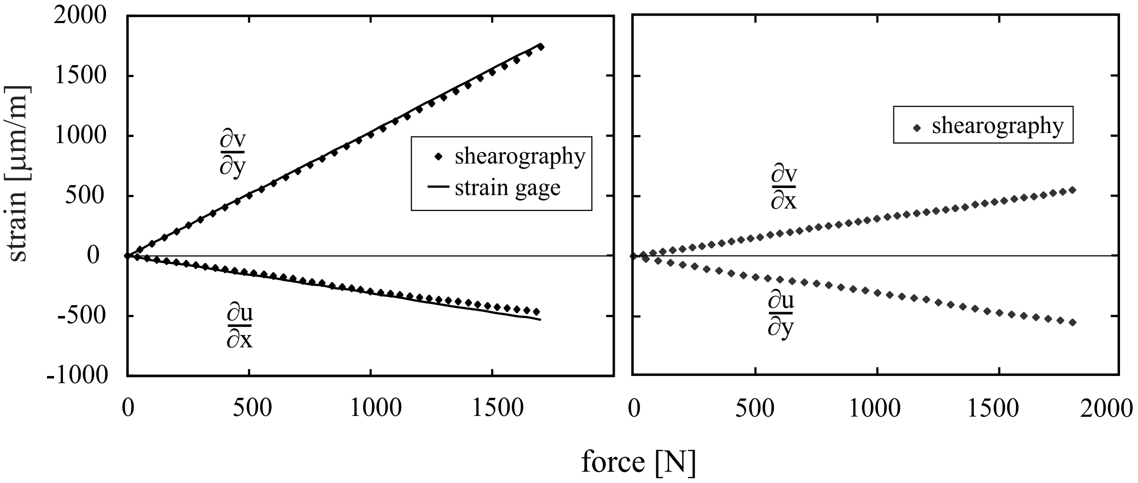

**Fig.5** Strain values of the 4 in-plane displacement derivatives. For comparison the strain values of a x-y-strain gage are included.

With a similar procedure for the x-shear the transverse strain $\partial u/\partial x$ is determined. The comparison of the shearographic strain data for $\partial v/\partial y$ and $\partial u/\partial x$ relative to that of the strain gage measurements showed good agreement. The deviations were below ±2% and ±10% for the longitudinal and transverse strain at maximum load, respectively.

We further see from Fig. 5 that the displacement derivative $\partial u/\partial y$ is just the negative of $\partial v/\partial x$. This result gives evidence that the x and y directions of the shearographic measurements coincide with the principal axes of the bar during tensile testing. It further reveals that the aluminium bar underwent a small anticlockwise rotation of 0.55 mrad around the z-axis during loading from 0 N up to 1800 N.

## *5. Conclusion*

A compact and lightweight multi-wavelength shearographic camera for the determination of 2D strain distributions has been presented. This apparatus is based on object illumination with 3 diode lasers emitting at wavelengths between 810 and 850 nm. Separation of the corresponding speckle images was achieved via their polarisation states and wavelengths. In contrast to the 2D-shearographic systems described so far in the literature, it has the advantage that the phase images of all three lasers can be recorded simultaneously for one shearing direction. In addition, two methods based on galvanometer scanners and a LCD have been discussed that enable to switch automatically between the two directions of image shear. A special illumination geometry and the corresponding algorithm for the evaluation of phase fringe patterns allowed the determination of all six displacement derivatives accessible to shearography. Possible errors of this procedure with respect to small asymmetries in the optical configuration have been addressed. Results of in-plane strain measurements with the multi-wavelength shearographic camera during tensile testing have been presented. Good agreement was achieved between the shearographic data and that of a strain gage applied for comparison. The results of this study demonstrates that multi-wavelength shearography is an effective tool for quantitative measurements of 2D strain distributions.

## *6. Acknowledgements*

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