XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

SHEARING MEASUREMENTS WITH TWO SHEAR DIRECTIONS

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Abstract: Shearography is a full field interferometric technique for the measurement of small deformation gradients. The main applications are non-destructive testing in material inspection and quality control. This contribution intends to present a new image shearing speckle pattern interferometer set-up for simultaneous measurement of two independent deformation gradients equivalent to two shear directions. Herein, we use the polarization effect to separate the two directions. The selection of the polarized images, which correspond to the shear direction, has been performed either by a polarization beamsplitter (PBS) or a rotatable polarizator. The utility of this new concept has been demonstrated by several measurements on a tensile testing machine.

Keywords: speckle interferometry, non destructive testing, polarization

1 INTRODUCTION

The significance of optical methods for non-destructive testing increases due to their fundamental non-contact methodology and high accuracy [1]. Shearography, a technique for full field interferometrical measurement of deformation gradients, is based on the phenomena of speckles. The object is illuminated by a laser source and imaged via a shearing element on a CCD camera. Thus, two laterally sheared images appear on the camera, or vice versa each pixel sees two neighboured object points. Comparing two different states of the object, whereat sample's deformation is induced in-between, yields the deformation differences or relative movements of these two neighboured points. Consequently, the sensitivity is defined by the distance between these points and rigid body movements or disturbances, that are caused by air turbulence, are eliminated by way of optics. This feature favours the operation of shearographic devices in industrial environment and for automated inspection [2].

The deformation gradient correspond to the strain value and can be measured with the shearographic method directly. Due to the methodology, an analysis of full field deformation gradients can be visualised in real-time [3,4]. Knowing the material properties the strain and stress fields can be calculated. But still using standard shearing systems only one deformation gradient direction can be registered and not all sets of information about the complete 3D- deformation can be captured simultaneously.

Now, this paper aims to present a fairly new concept for a complete monitoring of strain and stress fields by means of shearographic inspection. Using polarized laser and suitable optics, two independent deformation gradients can be registered. Section 2 summarises the basic theory of shearographic inspection. Section 3 presents the new setup. The main results will be presented in section 4. Finally, we would like to point out, that this new approach might be well suitable in material testing and quality control.

2 THEORY

Supposing a relative displacement vector **d** (u, v, w) and a shear distance Δx the first order approximation to the phase difference $\Delta\varphi$ (x, y) measured between different states of the object can be written in the form [5]

$$\Delta\varphi = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial x} \right) k \Delta x , \qquad (1)$$

where **k** is the sensitivity vector given by the difference vector of the wave vector $\mathbf{k}_O$ in observation direction and $\mathbf{k}_S$ the wave vector of the illumination. By choosing the illuminating plane wave $\mathbf{k}_S$ to be in the *x-z* plane, with the angle of incidence α_S relative to the surface normal, and the observing direction to be in *z* direction, $\Delta\varphi$ is calculated to

$$\Delta\varphi = \left[\pm\sin\alpha_S \frac{\partial u}{\partial x} + \left(1+\cos\alpha_S\right)\frac{\partial w}{\partial x}\right]\Delta x \quad . \tag{2}$$

The in-plane component *du*/*dx* can be neglected because α_S can be very small. Thus, the out-of-plane displacement derivative *dw*/*dx* will be favoured. By the use of two measurements, with suitable symmetrical angles of incidence $\pm\alpha_S$, the out-of-plane and in-plane components can be separated by simple addition and subtraction of the phase data. But nevertheless, to derive the information of the whole slant (*dw*/*dx*, *dw*/*dy*), elongation (*du*/*dx*, *dv*/*dy*) and distortion (*du*/*dy*, *dv*/*dx*), an additional orthogonal deformation gradient must be achieved.

3 NEW SHEARING SETUP

In order to record the deformations in two orthogonal directions a new shearographic setup using two different shear directions has been designed. Having in mind a flexible and easy to use system a zoom objective acts as the entrance lens. A Michelson interferometer is applied as shear element. As with the conventional setups one mirror is mounted on a piezo element for applying the common method to introduce the phase shift procedure. The other mirror is fixed on a holder to introduce a tilt. In the new setup an additional polarization beam splitter cube (PBS) and mirror are placed in the shear arm. A circular polarized laser beam illuminates the inspected specimen, whereat λ/4 plate is adjusted in front of the laser diode. Figure 1 shows schematically the new designed shearography instrument.

The horizontal polarization part of the light comes through the entrance lens of the detection device,

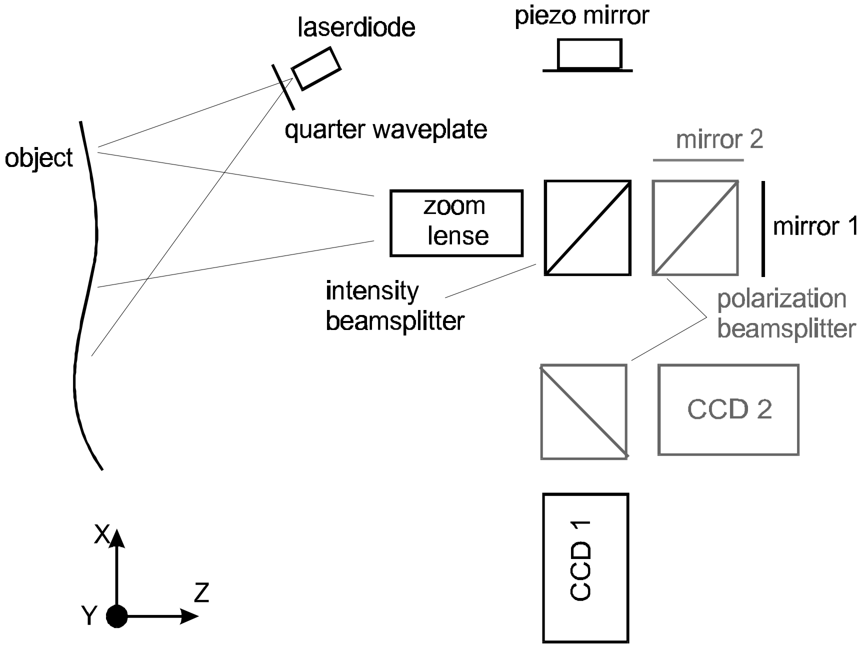


Figure 1. New setup for the measurement of two independent shear directions

passes through the PBS, is reflected at the conventional shear mirror 1, and finally, overlaps conventionally on to the camera CCD 1. The vertical polarized light is reflected at the PBS onto the additional mirror 2. It is also reflected at the second PBS and superimposed on CCD 2. Thus, this setup superimposes the circular polarized reference image and the two orthogonal polarized sheared images on the two CCD chips. Therefore, using a second PBS and camera behind the Michelson interferometer, the two sheared images can be separated on two cameras and overlaid with the reference part synchronously. In summary, two independent shear directions can be registered in one shearographic instrument.

The timing of the two cameras is synchronized and a color frame grabber is used for the digitizing of the two video signals. This setup allows to double the information during the time for a single measurement using a standard system. One should mention, that the two cameras need to be aligned precisely to obtain sufficiently good overlapping and accuracy of the two independent deformation gradients. The adjustment can be divided into a mechanical part and can be combined with a software alignment of the two images in the computer.

For applications, where the measuring time is not the limiting conditions the principle of the two shear directions can be also verified using a single camera. Substituting the second PBS and camera by a rotatable polarization filter the local alignment can be performed more easily. The reference image is independent of the filter position. A rotation of the filter selects the transmitted shear direction. Avoiding speckle decorrelation, the reproducibility of the filter position has to be very high. This demand results in a precision mechanical mounting.

To avoid mechanical elements, which also may introduce vibrations, we decided to make use of an optical rotatable polarization filter without any mechanical elements. Depending on an applied electrical field liquid crystal (LC) elements rotates the direction of polarization of the transmitted light. These LC devices are used mostly in the display technique. Combined with a fixed polarization filter this element acts like a precise rotating polarization filter. Since for this application two fixed positions are needed, especially designed elements with short switching times below 1 ms have been installed. Using this arrangement measurements with two independent shear directions can be performed with an automatically alignment of the two deformation gradients. Due to the fast switch between the shear directions, the time needed for the whole measurement, using a four phase step algorithm, is only 160 ms longer.

The whole system is controlled by a PC. A self written WIN95 program steers the capturing of the images, the phase evaluation up to the wrapped phase information. A phase filter and phase unwrapping algorithm are also implemented.

4 EXPERIMENTAL RESULTS

The first experiments have been performed with an arrangement of two synchronized cameras. A round plate, loaded by a central deformation, was used as test object. The illumination was nearly parallel to the observation direction. The system was sensitive mainly on out-of-plane deformations. Due to the dental form of the deformation the expected butterfly pattern appears. Depending on the polarization, respectively on the shear direction, the pattern are rotated by 90°. Figure 2 shows two phase maps, which are generated on a test object. Obviously the two shearing directions can captured simultaneously and separated without any crosslinks due to polarization.

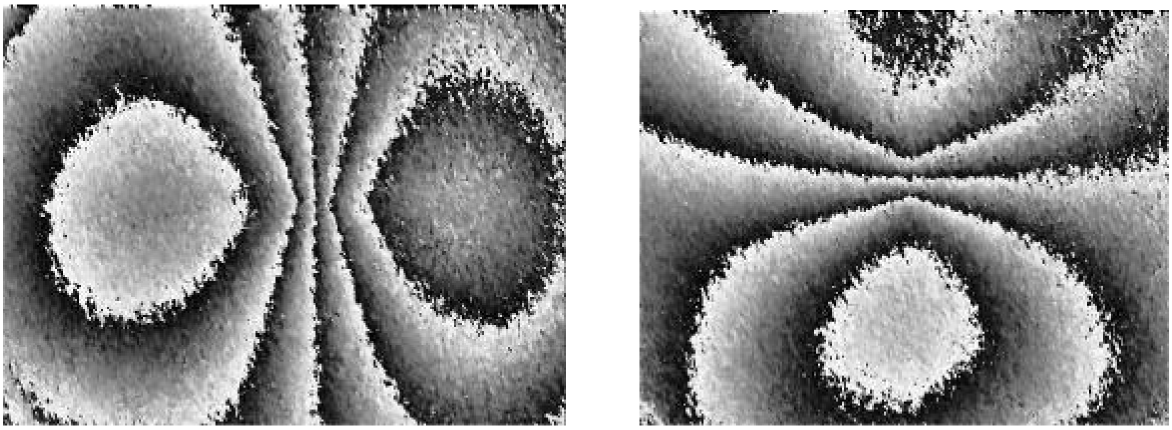


Figure 2. Phase maps with horizontal (left) and vertical (right) shear directions, simultaneously captured using two PBS's, two synchronized cameras and a color framegrabber

For further investigations the second camera was removed. The second PBS was used as a polarization filter and an additional LC was placed behind the Michelson interferometer. The first experiments where made to control whether the LC element has any influence on the quality of the measured phase images. In figure 3 the phase maps captured with this arrangement are shown. In this particular measurement the two shear directions are parallel. However the distance of the sheared images and so the sensitivity are different as shown by the fringe density.

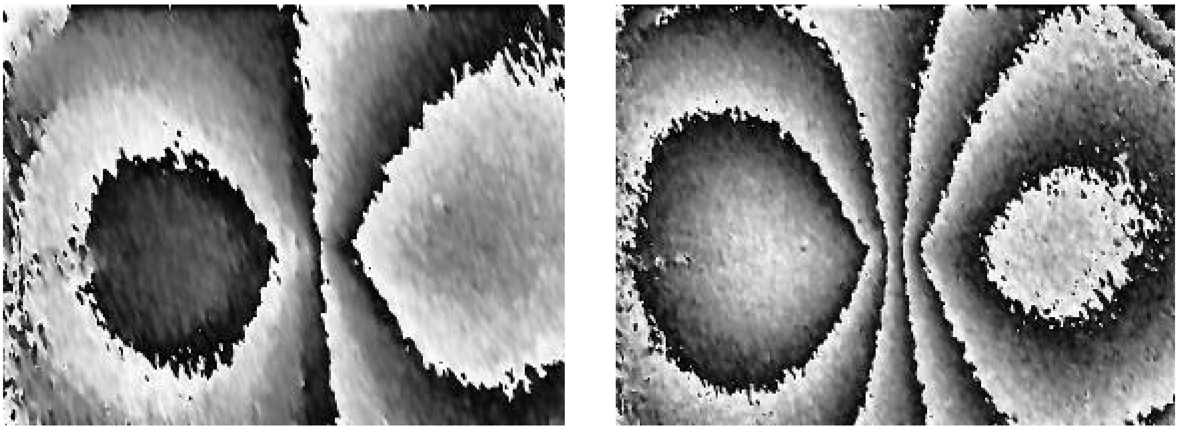
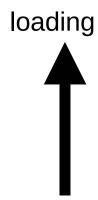


Figure 3. Phase maps measured with one camera, a LC element as a rotatable polarisation filter and different shear distances. The left picture represents the smaller shear distance and sensitivity, the right image shows the same deformation with a higher sensitivity.

No negative influence of the LC element on the quality of the measured deformation gradients could be found. Due to the smaller shear distances the phase map on the left side represents a less sensitivity measurement. The right side illustrates the same deformation but with higher sensitivity. The measuring range of this technique is limited by the resolution of the generated fringes. Therefore, this setup improves the application of this technique.

Finally, the new designed shearographic instrument was adopted to a tensile testing machine. Particularly, it is worthwhile to be mentioned, that in material inspection the objects are loaded over the elastic into plastic deformation. Due to the non reproducible loading each needed information must captured synchronously as fast as possible. Therefore, in order to prove the industrial applicability of the new shearing system various experiments on a tensile test machine had been performed. Figure 4 shows at the left side the intensity image of the probe, viewed with a vertical shear, the determined strain field in loading direction (middle) and vertical direction (right), where for a better visualisation the results are scaled 10x. Since the vertical displacement derivative is symmetric to the notch, no tilt at the loading can be seen. The vertical deformation derivative points out a small torsion at the loading of the tensile testing machine.



vertical sheared image parallel strain field *dw/dy* orthogonal strain field *dw/dx* (scaled 10x)

Figure 4. Strain fields of a notched bar in a tensile testing machine.

5 CONCLUSIONS

A new compact shearing concept for the simultaneous measurement of two independent shear directions has been presented. Using a conventional Michelson interferometer as a shear element and an additional polarization beamsplitter cube in the shear arm the light is separated in two orthogonal polarized beams onto different mirrors. The separation of the shear directions can be performed with the use of an additional camera and PBS or by the use of a rotatable polarization filter. For time critical applications two synchronized cameras might be preferred. In addition, we also present a setup with one camera and a LC cell as a quick rotating polarizator for the selection of the shear direction. Both concepts have been installed and their applicability was successfully demonstrated. With the use of two orthogonal shear directions or two different distances these method improve decisively the application of shearographical measurements in the field of quality control.

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ACKNOWLEDGEMENTS

This study was funded within the Brite/EuRam Project MuWaS by the European Community (Project N°: BE-96 3116). The fruitful collaboration with the company Dr. Ettemeyer & Co is gratefully acknowledged.

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