APPLICATIONS OF FULL FIELD OPTICAL METHOD FOR MEASURING STRAIN CONCENTRATION

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Abstract: Strain concentration indicates a weak position and possibly leads to a defect. To quantitatively identify localized strain concentration is becoming very important in the area of quality assurance. In the last decade, many industries adopted Computer-Aided-Engineering (CAE) tools to reduce the number of prototype builds and to speed up the development cycle. These analytical tools are relatively inexpensive to use and faster to implement than the costly physical testing methods as used in traditional design processes. There are, however, many variables that CAE tools cannot adequately address, such as, boundary conditions, material anisotropy, etc. Therefore, efficient experimental techniques are still necessary for component design validation. This paper shows an optical full field method to determine strain concentration: digital speckle pattern interferometry (DSPI). The capabilities as well as the limitations for industrial applications are investigated. An application of this method is demonstrated on a stamping die to validate a FEM results.
Key Words: Strain/stress, optical full field measurement, digital speckle pattern interferometry, FEM

Introduction: The transportation industry demands high quality components that are designed in a very short period of time, satisfy the highest strength requirements, and meet stringent safety standards. Especially in the automotive and aircraft industries, the development effort focuses on tailor-made design solutions conforming to the customer's expectations. To reduce cost and increase speed-to-market, rapid design optimization has become a key enabler.

In the last decade, many industries adopted Computer-Aided-Engineering (CAE) tools to reduce the number of prototype builds and to accelerate the development cycle. These analytical methods are relatively inexpensive to use and faster to implement than the costly experimental methods as used in traditional design processes. There are, however, many variables that Computer-Aided-Engineering (CAE) tools cannot adequately address, such as, boundary conditions, material anisotropy etc. Therefore, efficient physical experimental techniques are still necessary for component design validation.

A traditional experimental technique for determining component strain/stress characteristics is the application of strain gauges. Although inexpensive and effective for some applications, strain gauges provide only localized information and cannot capture true peak strain or high-resolution information when applied in regions having large strain gradient. Strain gauges also require careful and skillful application and are time consuming, limiting its usage for design optimization in an intensive, time-critical development effort.

This paper presents the recent advancement of DSPI for quantitative strain/stress analysis. By greatly miniaturizing the 3D-digital speckle pattern interferometry based on the fiberglass concept, the measuring system can be attached to an object to be tested. This makes it possible to accurately perform quantitative strain/stress measurement on complex components and under harsh environmental conditions.

Measurement Principles of 3D-DSPI: Holographic interferometry is a well-established method for measuring small displacements and deformations[1]. DSPI can be considered as an electronic version of holographic interferometry that uses a CCD camera instead of a photographic film to acquire and store the fringe images, while a computer is used to process the images[2]. Fig. 1 shows a schematic of the ESPI set-up for the measurement of the out-of-plane component of the displacement. The laser beam is split into two illuminating beams, one as the object beam and the other as a reference beam. The rays reflect from the object surface and the reference surface then recombined after passing through the beam combiner. This results in an interference pattern called 'speckle pattern' and is recorded by the CCD camera. Before the object is deformed, the phase difference between the object and the reference beams is ϕ. After the object is deformed, the phase difference becomes $(\phi + \Delta)$ and a phase change Δ results from the deformation.

Quantitative measurement of phase data can be obtained by use of the phase-shifting technique[3]. A piezo translator (PZT) as shown in Fig. 1 is used for this purpose. Because the phase distributions ϕ and $(\phi + \Delta)$ can be quantitatively measured, now the phase change Δ which relates to an object deformation can thus be easily determined by subtracting ϕ from $(\phi + \Delta)$. An example is presented in Fig. 1 in which a clamped circular plate is loaded centrally. If the angle between the illumination direction of the laser and the observation direction of the CCD-camera is equal to zero or close to zero, the phase change Δ is given by [4]:

$$\Delta = \frac{4\pi}{\lambda}\ w \tag{1}$$

where λ is the wavelength of applied laser, w represents the deformation perpendicular to object surface, also called the out-of-plane deformation.

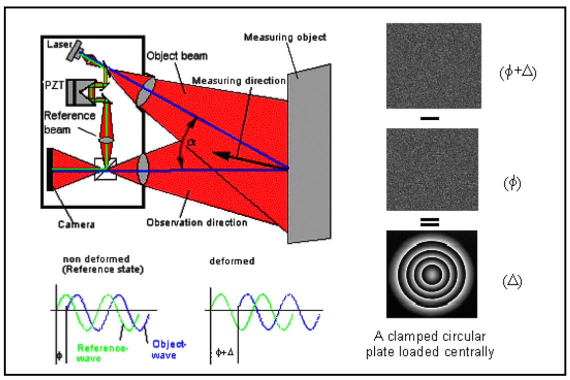


Fig. 1 Out-of-Plane Measurement

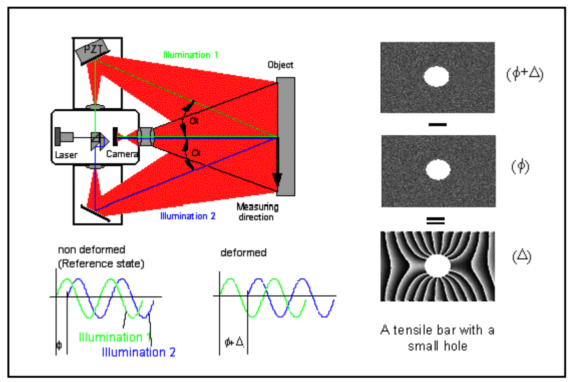


Fig. 2 In-Plane Measurement

To measure the in-plane component u or v, a dual-beam illumination is commonly used.[5] Fig. 2 shows the schematic of DSPI for in-plane measurement. The basic relation between the phase change Δ and the in-plane component u (if the illuminating plane lies in xoz-plane) or v (if the illuminating plane in yoz-plane) is as follows [6]:

$$\Delta = \frac{4\pi\ \sin\alpha}{\lambda}\ u\,(or\ v) \tag{2}$$

where α is the angle between the illumination and observation directions as indicated in Fig 2.

The combination of the set-ups for out-of-plane and in-plane measurement comprises a unique and very flexible measuring system for 3D-displacement measurement. Fig. 3 shows the commercially available 3D-ESPI system from Dantec-Ettemeyer GmbH, Germany, which has been applied in tensile, fatigue, thermal expansion, deformation, strain/stress, residual strain/stress, vibration, and nondestructive testing and research. The laser beams from the two arms in the horizontal and vertical directions are used to measure in-plane displacements u and v, respectively. The out-of-plane displacement measurement is made by using a laser beam from one of the four arms coupled with a reference beam inside the center sensor that is directly coupled to CCD array and with the closing of the other three beams. Fig. 4 shows a 3D-deformation field of a clamp under compression. The vectors (arrows) represent the in-plane displacement. The background colors represent the out-of-plane components of w.

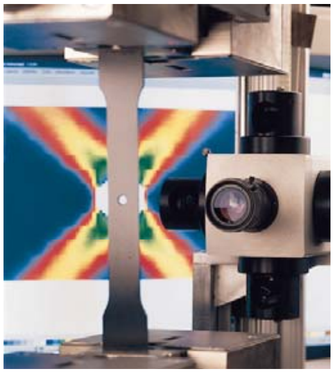


Fig. 3 3D-ESPI System Attached to a Universal Tensile Test Machine

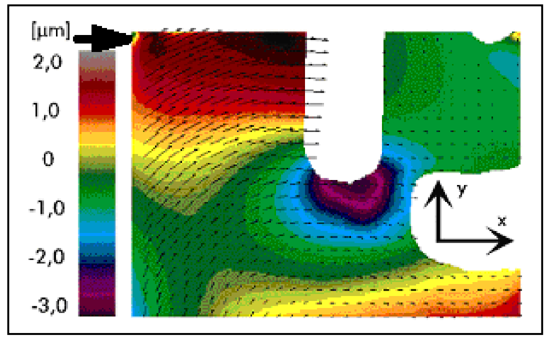


Fig. 4 3D Deformation Field of Compressed Clamp

Miniaturization of 3D-DSPI System: Although 3D-DSPI have provided 3D-deformation data which is required for determination of strain/stress, the application of 3D-DSPI for strain measurement under harsh industrial environmental conditions is still limited. This is in part attributed to the sensitivity of the technique to rigid-body movement. An solution to eliminate the relatively large rigid-body movement is to attach 3D-DSPI system onto the object under test so the movement can be greatly suppressed. Obviously, the key to realizing this concept is to radically miniaturize 3D-DSPI system. Fig. 5 shows a novel portable miniaturized 3D-ESPI system that is based on the fiberglass concept called the MicroStar, developed by Ettemeyer AG, Germany. This new sensor weighs one half pound and has ∅65×76 in volume. Several techniques may be used to attach the sensor to the test object, e.g. by tension in rubber bands, by temporarily gluing two of the three legs to the object under test. For ferromagnetic parts, an easily removable magnetic adapter ring may be attached to the sensor head. A CCD camera with a resolution of 768×582 pixels is mounted at the center of the sensor head which amounts to a maximum measurable area (view field) of 30×40 mm. By using this newly developed sensor, the quantitative strain analysis for complex industrial components under harsh environmental conditions becomes possible.

Fig. 5 The MicroStar Sensor

Determination of Stains: As described above, 3D-DSPI enables rapid and accurate determination of the three components of deformation u, v and w on the surface of an object. Because it is of a full field measurement, the distributions of u, v and w, i.e. the functions u(x,y), v(x,y) and w(x,y) over the entire surface can be obtained. Obviously, the in-plane strains at each point of the measured area can be determined by differentiating the in-plane components u(x,y) and v(x,y),

$$\varepsilon_x = \frac{\partial u}{\partial x}, \quad \varepsilon_y = \frac{\partial v}{\partial y}, \quad \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \qquad (3)$$

For a thin plate of thickness t, the bending strains are related to the second derivatives of the plate deflection w(x,y). They can be obtained by taking two consecutive differentiations of the out-of-plane component w,

$$\varepsilon_{xb} = -\frac{t}{2}\frac{\partial^2 w}{\partial x^2}, \quad \varepsilon_{yb} = -\frac{t}{2}\frac{\partial^2 w}{\partial y^2}, \quad \gamma_{xyb} = -t\,\frac{\partial^2 w}{\partial x \partial y} \qquad (4)$$

The magnitude and the direction of principal strain 1 and 2 can thus be determined with all the measured in-plane strain components, by means of the Mohr's Circle [7].

Potentials: being an optical method, 3D-DSPI enjoys the advantages of being full-field and non-contacting. Compared with the traditional strain measuring techniques, it offers several advantages which can be summarized as follows:

(1) 3D-DSPI measuring system provides a full-field strain/stress distribution with non-contact method. It has a high spatial resolution and is well suited to capture true peak strain in high strain gradient areas. Fig. 6 shows a comparison of strain measurement by 3D-DSPI and by strain gauges on a tensile test of fiber reinforced plastic specimen. While the specimen was loaded in tension, the left area of the ellipse was measured by four strain gauges and the right area by 3D-DSPI technique. Although the measured results of both techniques compared favorably at three positions, the strain value at the fourth strain gauge (close to the edge of the ellipse) does not compare well with that of 3D-DSPI in the similar location of opposite end. The difference arises from the high strain gradient in this region where the strain gauge technique is not well suited for measurement. However, the high local resolution of 3D-DSPI reveals the accurate strain values.

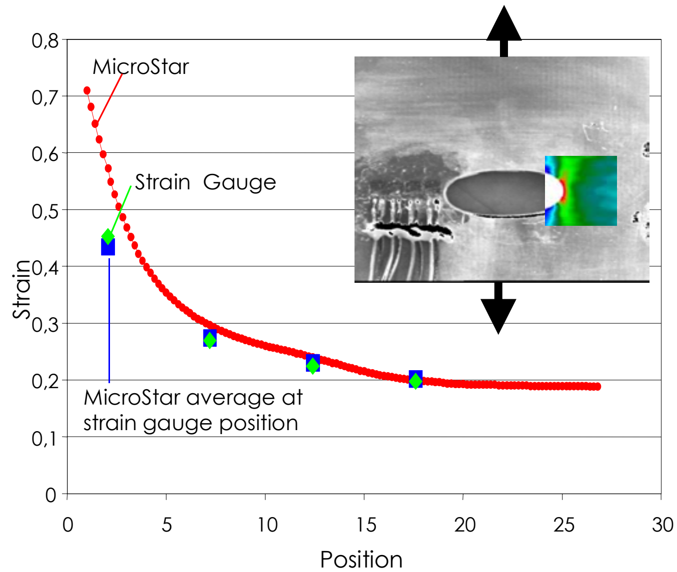


Fig. 6 3D-ESPI vs. Strain Gauges for a Tensile Test

(2) 3D-DSPI has a high measuring sensitivity and delivers accurate strain/stress data.

(3) 3D-DSPI measuring technique does not require any calibration prior to testing or any preparation like etching, polishing etc.

(4) The 3D-DSPI system can be applied to any materials such as steel, aluminum, or composite materials, etc. as long as the test region is optically accessible.

(5) The newly developed 3D-DSPI sensor based on the optical fiber concept is well suitable for both laboratory and harsh environmental conditions.

(6) DSPI can be used for one step measurement or a series measurement, thus it applicable to both small or large loading.

As a new strain measurement tool, 3D-DSPI is getting more and more acceptance by industries. It provides a continuous full-field data measurement, and can be used to calibrate, validate and improve static CAE/FEA models.

Limitations: 3D-DSPI is an experimental surface measuring technique. Like other surface measuring techniques such as holography, shearography, moiré method, strain gauges, and thermography, etc., the measured results obtained by 3D-DSPI are functions only of x and y, i.e. u(x,y), v(x,y) and w(x,y). Thus, one can determine only six components of the first two columns in the matrix ***H*** of the deformation gradient.

$$\boldsymbol{H} = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{pmatrix} \qquad (5)$$

The measurement of the gradients ∂u/∂z, ∂v/∂z and ∂w/∂z in the third column of matrix ***H*** is impossible. In two-dimensional state of stress, ∂w/∂z can be indirectly determined by measured in-plane strain ∂u/∂x and ∂v/∂y[8]:

$$\varepsilon_z = -\frac{\nu}{1-\nu}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \qquad (6)$$

where ν is Poisson ratio of the material under test.

Another limitation of the 3D-DSPI technique is that they are appropriate mainly for static or slowly variable load applications. To measure strains under dynamic loadings, the pulsed ESPI technique should be applied, see reference[9].

Applications: Strains at one lift lug of a stamping die-set were measured by 3D-DSPI sensor. The stamping die-set was left on the ground and the strains at the lift lug position were investigated while the die set was lifted. Fig. 7a shows the die-set and test set-up (right) and the measuring location (left). The images displayed in the following part of the paper are the measured results at that position.

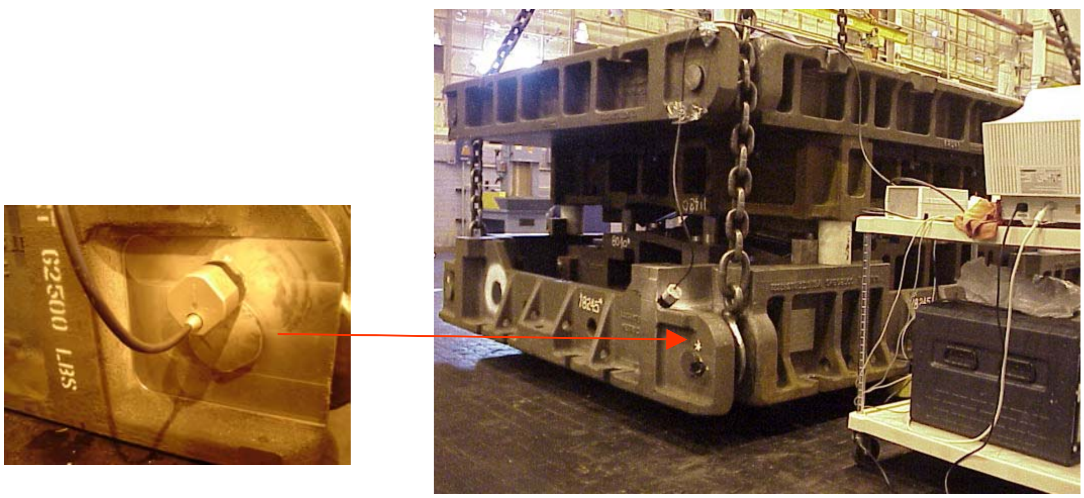
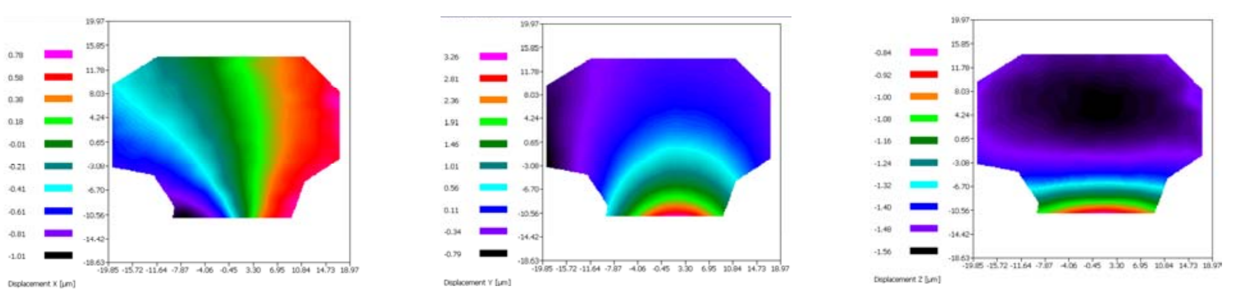
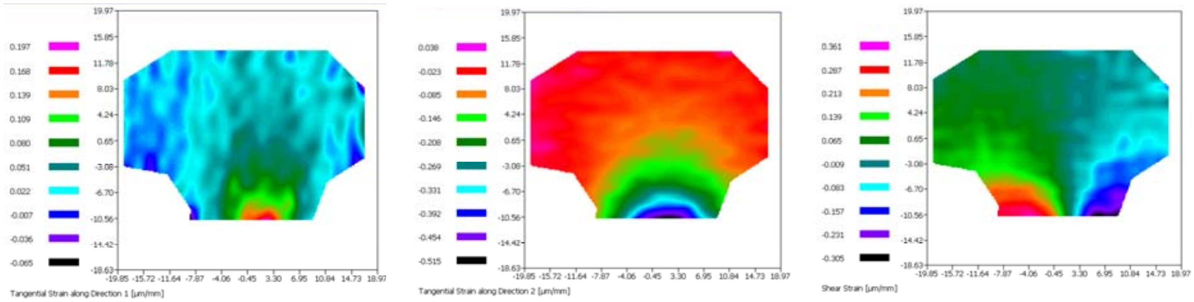


Fig. 7a Actual Test Set-Up (right) and the Measured Position (left)



Deformation in x-direction: U   Deformation in y-direction: v,   Deformation in z-direction: w

Fig. 7b Measured Results of 3D-Deformation Components



Strain in x-direction: ε_{xx} Strain in y-direction: ε_{yy}, Strain in z-direction: ε_{zz}

Fig. 7c Measuring data for strains

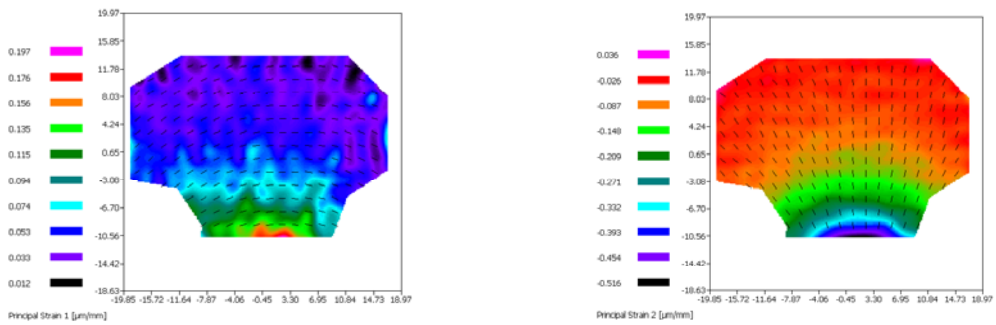


Fig. 7d Measured data for magnitude and direction of principal strain 1 and 2

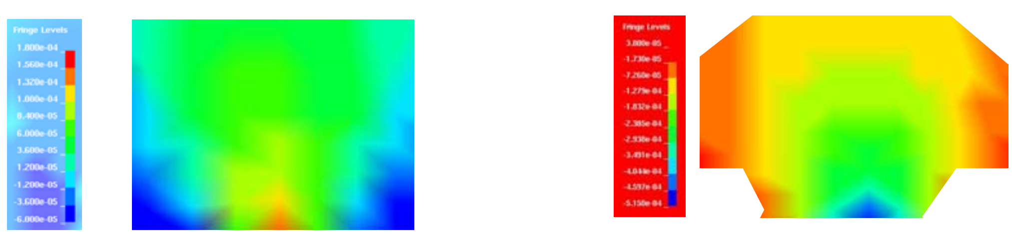


Fig. 8 FEA Simulation results of strains in x-direction ε_{xx} (left) and in y-direction ε_{yy}

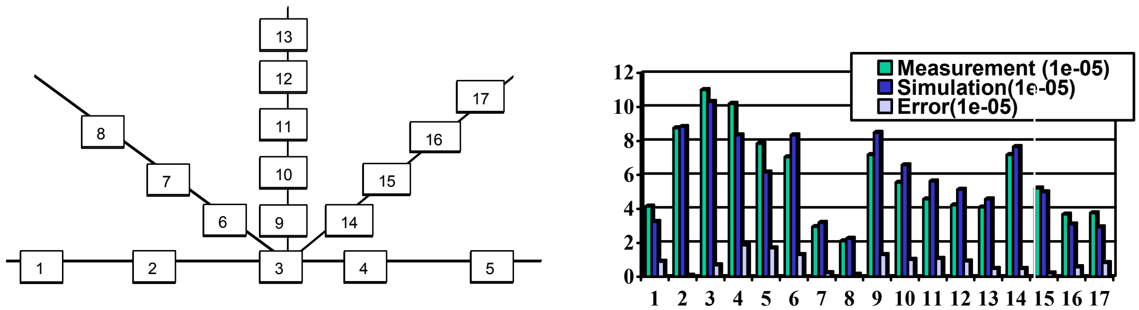


Fig. 9 A comparison of ε_{xx} between the measured and the simulated data (right) at 17 different points as indicated in the image above (left)

Fig. 7b shows the measured results for 3D-Deformation Components: u, v and w while the die set is lifted. The strains ε_{xx}, ε_{yy}, and γ_{xy} can be easily determined by a numerical differentiation shown in Fig. 7c. Fig 7d demonstrates the principal strain 1 and 2 which is obtained from the strain data according to the Mohr's Circle theory.

Fig. 8 shows the simulation data of strains in x and y direction obtained by FEM analysis. A comparison of stain ε_{xx} (strain in x-direction) between the measured and simulated data is illustrated in Fig. 9. The measured and simulated strain matches up very well.

Conclusions: The application of a 3D-DSPI system for strain analysis has been presented. This new optical technique allows fast, full-field strain/stress analysis on components. The utilization of the optical technique in measuring all strain and stress components in magnitude and direction can significantly reduce the time required for experimental stress analysis. The system can be used in great advantage to inspect component areas of concern with high strain concentrations to determine exact positions (and subsequent locations) for strain gauges application during the ensuing dynamic tests.

Furthermore, new features in the software allow for capturing the experimentally collected strain maps to validate and optimize analytically calculated strain results obtained by CAE tools.

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