Combine Simulation and Experiment in Automotive Testing with ESPI Measurement

Introduction

Today’s industry demands high quality component designs within a very short period of time to meet the toughest mechanical features and ultimate safety standards. Especially in automotive and aircraft industry, the development focuses on tailor-made design and solutions according to customer specifications. To reconcile economy issues, design optimization has become a key issue.

In the last decade, many industries introduced the Computer-Aided-Engineering (CAE) tools in order to decrease the number of prototype builds and to speed up the time of the development cycle. Although such analytical tools are relatively inexpensive to use and faster to implement as compared to the costly traditional testing design process; however, there are many variables that CAE tools cannot adequately consider, such as manufacturing processes, assembly, material anisotropy, and residual stresses. Therefore, still smart testing is required to validate the CAE results.

Traditionally, conventional experimental techniques use strain gauges for strain/stress measurements. However, strain gauges, though inexpensive in price and rugged for dynamic load applications, suffer from many shortcomings. Mainly strain gauges are point measurements that cannot capture true and high-resolution information when applied in high strain gradient areas. In addition to this, strain gauges require time consuming and careful application. Due to these pitfalls, strain gauges are not suitable for CAE validation.

Currently, many companies are looking for new other advanced strain/stress experimental techniques to improve the cost efficiency, and to overcome the limitations of the classical methods. These tough requirements and demands of the Market have led the Industry invent a new optical measuring tool, which could overcome these problems. Electronic Speckle-Pattern Interferometry (ESPI), as a full field and non-contact measuring technique, offers a cost effective, fast, and highly accurate measuring technique. Based on a lightweight, and a small size sensor design, coupled with new glass-fiber concepts, the implementation of ESPI in material testing has already achieved an interesting level of acceptance in research and industry.
Currently, ESPI commercial systems are used to detect small deformations with high resolutions (below 50nm); thus, detecting design critical areas during the early stages of testing. Although a good method, standard ESPI set-ups suffer from many restrictions. Some of these difficulties result from relatively large rigid body movement of components under test, harsh environmental conditions, vibration, and complex geometries of the analysed component. These restrictions have created the need for a more robust design in deformation measurement. The new proposed system is a laser-optical sensor for quantitative strain/stress measurement that could be widely used in the Industry. The concept of radical miniaturization of 3D-ESPI technique along with the combined contour and deformation measurements provide all necessary data for quantitative 3D strain analysis will be introduced in the following section.

ESPI Measuring Principle
Electronic Laser Speckle Interferometry allows, by means of defined guided light path, a full field and three-dimensional measurement of deformations $\Delta \delta$ on complex surfaces. The working principle is quite simple: the surface to be measured is illuminated by laser light from four (4) different directions and the reflected light is recorded by a high resolution CCD-camera. All illuminated surfaces show the so-called 'speckle-effect' (appearing as a fingerprint of the illuminated area) by which the microstructure of the tested substrate can be analyzed. The resulting speckle pattern is stored as a digital reference image. The specific speckle pattern changes with the test surface deformation; therefore, correlation fringes representing the displacement $\Delta \delta$ of the object will be visible. Appropriate image comparison or correlation techniques allow the detection of the three-dimensional movement (deformation tensor) of any point in the measuring area with high accuracy. Depending on the beam geometry or direction of laser illumination, the computed fringes correspond to out-of plane or in-plane displacements. The 3D strain tensor (1) at each point of the measured area can be calculated from the complete 3D deformation field according to the standard mechanical equations (plane stress model):

$$
\varepsilon_s = \frac{\partial u}{\partial x}, \varepsilon_y = \frac{\partial v}{\partial y}, \gamma_{yx} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

$$
\varepsilon_{ab} = \frac{1}{2} \frac{\partial^2 w}{\partial a \partial b}, \varepsilon_{y*b} = \frac{1}{2} \frac{\partial^2 w}{\partial y* \partial b}, \gamma_{y*b} = -\frac{1}{2} \frac{\partial^2 w}{\partial x \partial y} \quad (1)
$$

Classical strain measuring tools
A characterization of the tested component only by uniaxial stress/strain is not sufficient since critical design regions exercise multiaxial states of stress/strain. These multiaxial states of stress/strain are required in order to check the different failure criteria, e.g. maximum shear strain (Tresca) energy criterion, Von Mises, Maximum Principal Strain, Plane Stress, Plane Strain, etc. Currently, the standard of any Industry is to use strain gauges as they are seen to be the most reliable and accurate strain measuring sensors. There is a wide selection of strain gauges that are made from different materials, in different shapes and designs. Each strain gauge design has a unique application to fulfill that the user must know. Often the user has just only a vague impression of the object to be examined, and selecting a specific type of strain gauges means the user must predict the behaviour of the component beforehand. It has been found that a variety of different types of strain gauges are required to accomplish a proper data acquisition task. Another inherent complexity to using strain gauges is the surface preparation of the test object. This task is both labor intensive and time consuming. The strain gauge is glued directly to the surface of the component. Due to applied load, this electrical sensor records the integrated elongation of the component beneath it by changing its resistance. To ensure accurate results, a very careful sensor application is important: The surface has to be carefully smoothed and cleaned, the electrical cables have to be soldered, and the strain gauge has to be properly calibrated prior to data collection. A third major disadvantage inherent to the traditional strain gauges is that these sensors are point-measuring devices. The strain sensor solely measures the deformation component in its direction and at its location. Typically, critical design areas exercise high strain gradient fields that cannot be captured by point-measuring sensors, such as strain gauge. In order to capture such high strain gradient changes, a large number of very small size strain gauges is required; thus, impractical. Fig. 1 shows different types of strain gauges glued on a typically test object. Finally, it has to be mentioned that despite the above stated disadvantages the strain gauges suffer from, still they are very rugged and suitable for dynamic load applications.

Fig.1: Typical test object with strain gauges
Rapid strain analysis by miniaturization of ESPI

The application of speckle measuring tools such as ESPI and Moiré in the industry has always been a tough technical challenge. With the development of a new miniaturized, integrated 3D-ESPI sensor, the non-contact measurement of full field deformation of components became possible. Fig. 2 shows the new compact ESPI-device that was developed for component testing. Two (2) of the three (3) sensor ring legs are glued to the test object for inspection. Under incremental static load applications, the system measures the 3-D deformation tensor of a 1” x 1.4” test area. The 768x582 CCD camera, mounted at the centre of the sensor head, has enough pixel spatial resolution to capture the smallest deformation gradient changes at the test area.

Using the captured 3-D deformation tensor and knowing the optical path of the laser beam, the 3-D strain tensor, both in magnitude and direction, is calculated. Results are displayed as continuous, full-field colour maps.

The main advantages of using the ESPI system over the traditional strain measuring tools are:

- ESPI measuring system does not require any calibration prior to testing.
- ESPI system is portable. Using ISTRA software, acquired data could be post-processed on the testing site.
- Time saving in application, data acquisition, and post processing. With the new ESPI system, the inspection time of complex components can be reduced significantly.
- No substrate surface preparation (etching, polishing, etc.) is required to use ESPI.
- ESPI sensor can be applied to any substrate material (steel, aluminium, composite material, etc) as long as the tested region is optically accessible.
- Complex geometry. ESPI sensor can be applied to notches and edges as long as they are not too narrow and allow enough clearance for the sensor head.
- ESPI measuring system provides continuous full-field data measurement as compared to the traditional point measuring strain sensors; therefore, ESPI is suitable to be used in calibrating static CAE models as compared to strain gauges.

To ensure accurate and repeatable results, it is required that there is no relative movement between the ESPI sensor head and the tested surface. This requirement is achieved by designing an easily removable, magnetic adapter ring on the front end of the sensor head. Several ways are used to fix the sensor ring to the test object. This ring is clamped with rubber bands, fixed with magnetic bases, or glued to the surface directly (two out of the three legs are glued).

In order to further save test data acquisition time, and to inspect multiple regions of interest, multiple sensor rings could be applied simultaneously onto the tested part (Fig. 3).

Once the sensor head is fixed to the test object, a region of interest is defined by creating a border (disregard of erroneous regions). Contour (shape) measurements of the region of interest are then calculated. Static load is then applied incrementally to the test object. At each loading step, corresponding 3-D deformations are recorded automatically. Enhanced data post processing tools, included in the system control software, allow the further analysis and display of the strain-load curve of any region of interest (Fig. 4)
Finally, in order to present the acquired data of all different regions simultaneously, 3-D measuring results are mapped onto a 3-D Computer Aided Drawing (CAD) model of the tested component. Using known location point coordinates, both in the Field of Measurement as well as CAD model coordinate systems, the image re-sectioning process is accomplished. This 3-D data mapping capability provides a unique, direct comparison between the experimentally collected strain fields and the analytically calculated strain data by CAE methods (Fig. 5).

Applications

The ESPI system was used to measure the strain gradients of a clamp with a stress concentration notch. To be compared to the traditional strain gauge sensors, a uniaxial strain gauge was laid near the stress concentration notch of the clamp. Uniaxial strain data from both independent measuring tools are then acquired and compared to each other. The clamp is loaded with a compressive load (Fig. 6). The flow of arrows represents the x-y components of deformation (in-plane) while the colour map represents the z-component (out-of-plane). The white area on the right is the silicon coverage of the strain gauge. To eliminate erroneous results, the silicon / strain gauge wire area was excluded from the strain evaluation study. ESPI full field uniaxial $\varepsilon_{xx}$ data are mapped in Fig. 7. Simultaneously, the uniaxial strain data at the stress concentration notch was measured by the uniaxial strain gauge. A comparison of the strain gauge data with the ESPI results shows that the local strain gradients, even in the length of the relatively short strain gauge (about 0.1"), can be detected by ESPI while the strain gauge failed to show the strain gradient variation. This accuracy in the ESPI data is due to the use of a high pixel spatial resolution CCD camera (768x582 pixels) – mounted at the centre of the ESPI sensor head.

A second strain/stress analysis application, using the ESPI system, is demonstrated on a truck engine. Fig. 8 shows the ESPI sensor clamped to the sidewall of the engine block via magnetic bases. Another sensor head ring, shown in the upper right corner of the image, is glued to the test object for multiple area data acquisition purposes. The static load is applied through oil pressure above the cylinders onto the crankshaft. This hydraulic static load affects the mechanical strength and property of the engine wall.

The measuring deformation field is displayed in Fig 9. The multiaxial states of stress distribution, introduced by the mounting screw of the crankcase lower half and the motor unit, at different static loading steps, is to be analyzed. In the same figure the measured 3-D deformation shows the result of multiaxial combined loads of internal pressure (oil pressure), torsion, and 3 tension forces. For accurate stress/strain analysis, the computed 3-D deformation of the region of interest must be corrected by the contour (shape) calculations at that location.
In Fig. 10 maps of full-field principle stresses, shear stress and Von-Mises stresses are displayed. Clearly the principle stress 1 and the Von-Mises stress show the influence of the screw thread and the effect on the motor unit. Maximum stress occurs directly at the connection of the crankcase to the motor unit. No stress concentration occurs at the edges and corners of the region of interest. In addition to this, the knowledge of the out-of-plane component of the deformation (z-component) allows the calculation of geometry curvature (bulging), which gives an indication of the hoop stresses this component will encounter during its normal service life.

The ESPI system acquires the test data and stores them in digital format. Therefore, it is possible that, instead of measuring multiaxial combined loads simultaneously, to measure the data of single loads being applied individually. Using the superposition technique, the stored results would be added together with different corresponding weights. By summing up single load results, the complexity of the test set-up is greatly minimized to a few basic and simple loading conditions.
Summary

The new miniaturized ESPI system allows a full field, accurate, and fast stress/strain analysis on complex geometry components that are made of different materials. The easy to use, and the proper application of the ESPI sensor along with the calculation of the 3-D strain tensor, both in magnitude and direction, can reduce the experimental stress analysis time substantially. The ESPI sensor was successfully in detecting critical design areas early on in the design stages. Therefore, time consuming and expensive durability tests could be avoided. The ESPI system is a unique tool that, when used properly, determines the exact location of strain gauge sensors to instrument a new design component. In addition to this, this new testing tool enables the testing community reduce the number of strain gauges to a minimum for service durability data collection (less number of data acquisition channels).

The new ESPI sensor Q-100 is directly attached to the specimen; thus, ensuring accurate measurement of 3-D tensor deformation. It is pre-calibrated and no surface preparation of the test object is required. Finally, the new capability, added to the ESPI system, of mapping 2-D CCD camera data onto 3-D CAD models allows the user to view the results of multiple regions of interests simultaneously. In addition to this, this new feature enables comparing the experimentally collected strain maps to the analytically calculated strain results by CAE tools.

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