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Validation and Iteration of Computer Models using Full-field Optical Methods

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ABSTRACT

3D image correlation provides the ability to measure 3D coordinates, 3D displacements and the true surface strains of material and structures, without contact or without many difficulties associated with these measurements. This unique capability allows the equipment to be used for rapid full-field measurements in the material test lab to the fatigue test lab, providing the results of 10,000 contiguous strain gauges. This is particularly appropriate for complex and composite and light structures. Recent work is leading to an ASTM specification for these methods.

In addition, 3D image correlation can be used for measurements in extreme environments. In thermal conditions, it is used for fine measurements to well over 1000˚C. In windy conditions, it is being for wind tunnel tests. In vibration conditions, it is used in engine test cells. For remote applications, it can measure free space modal conditions.

Ideal for iteration and validation computer models and simulations, 3D image correlation is a general purpose strain measurement tool able to measure full-field deformation and strain in a broad variety of environments on most materials.

INTRODUCTION

Computer models have mostly been developed using basic material properties and with minimal experimental data input for attempts at verification and iteration. As materials and structures and their associated models have advanced and gotten more complex, experimental results have had difficulty providing enough information to be effectively useful. These computer models are being used with minimal verification, and hence providing questionable results, no matter how accurate the modeler considers his code. New full-field optical methods are providing, simply obtained, holistic material and structural responses that are directly comparable to their FEA models. These advanced measurement tools are being applied throughout the automotive industry and from dynamic tire analysis to precision quality control.

This paper will discuss three optical inspection methods that provide a broad range of inspection capabilities to the automotive industry from precise materials studies to the quality control of final components. These efficient measurements make sure that model boundary conditions are accurate for real parts and that manufactured parts are matching designed parameters.

The scientific full-field optical method of laser holography (or ESPI, digital holography) has been used for years to make full-field measurements to assist with model verification, but has been very difficult to implement effectively. With the advancement of imaging systems and computer processing, a new generation of optical inspection methods has arrived, and these are easily implemented by engineers and technicians. These methods provide full-field data from a mesh of 10,000 measurement points across the surface of the structure, which is directly comparable with the finite element mesh of the FEM, removing much of the guessing and assumptions of where to make verification measurements. These optical systems can measure of areas of interest or of entire structures, to micron level accuracy, under static or dynamically loaded conditions, providing the real holistic structural response for effective model verification and iteration.

TYPICAL OPTICAL MEASUREMENTS

The following are typical uses of optical measurement systems that have traditionally been performed with much more labor intensive measurement system, with substantially less holistic data.

MATERIAL PROPERTIES ANALYSIS

Beyond simple material properties, new materials have more complex responses; understanding these responses with full-field, multi-axial (true 3D) measurements provides data that was never possible before. These full-field measurements provide material properties of non-homogeneous and non-isotropic materials, even for seemingly homogenous materials like aluminum sheet. This data is critical as materials are pushed to there limits in advanced forming methods, even getting biaxial material properties on materials for design and for incoming inspection to confirm material quality and real forming limit curves.

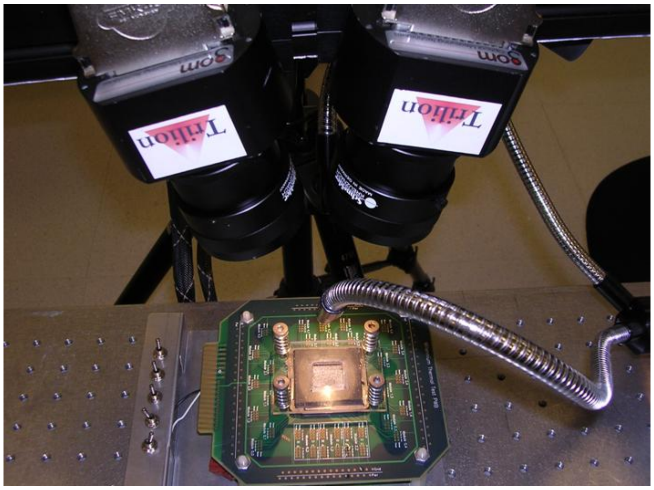
Figure 1 - Typical non-contact optical test set-up with specimen using dual digital photogrammetry cameras and a simply applied stochastic pattern.

FRACTURE MECHANICS

Understanding the micro-fatigue and fracture response of materials and structures is critical for life time prediction, system quality and warrantee analysis. Full-field methods make this study feasible and cost effective, proving real material data for the FEMs.

FATIGUE STUDIES

Time dependant structural loading studies, have typically required the precise and labor intensive mounting of strain gauges. With full-field optical methods, all areas of interest are being measured simultaneously, so engineering “guessing” of high-strain locations for strain gauges, are no longer as critical. In addition, sample preparation can be minutes rather than days.

RESIDUAL STRESS MEASUREMENT

Rapid analysis of residual stress analysis with non-contact measurement, using the hole drilling technique for stress relaxation, is an efficient tool for a broad range of residual stress analysis from engine blocks to exhaust manifolds.

THERMAL AND VIBRATION STUDIES

Non-contact optical methods provide simple ways of making complex measurements. Thermal displacement measurements of exhaust systems up to 1000 degrees is common place. 3D vibration response of simple to complex systems, even entire engines running, is simple and rapidly performed.

FORMING ANALYSIS

Complete analysis of first article from a forming sequence, and long-term lot monitoring and documentation, optical analysis confirms that designs are being implemented correctly. Answering are the dies made as designed, is the material as modeled, are the forming steps and rates functioning as predicted, all in one fast holistic analysis, simultaneously measuring shape, wall thinning, stresses, as well as numerous other parameters.

NONDESTRUCTIVE TESTING

For 6 sigma quality, lot or 100% inspection is sometimes necessary. Non-contact optical methods can provide ultra-rapid testing.

ASSEMBLY STUDIES

What happens to entire systems when they are assembled? Optical measurements can provide rapid, non-contact measurements of 3D coordinates, 3D deformations and surface strains, replacing accelerometers, displacement sensors, strain gauges, etc. with fast and easily implemented holistic measurements.

OPTICAL INSPECTION METHODS

The three optical methods described below are specifically for measuring 3D coordinates, 3D displacements and complex surface strains. Other related systems measure shape for reverse engineering and are based on similar principles.

PHOTOGRAMMETRY

Photogrammetry uses one or two video cameras (static or dynamic) to precisely measure the 3D coordinates of targets (simply applied metallic stickers) placed on all areas of interest on a structure or system. The keys to this technology are the precision calculation of the target positions, and the calibration targets in the field of view that provide certified calibration of the measurements.

3D IMAGE CORRELATION

3D Image Correlation Photogrammetry uses two video cameras to precisely measure 3D deformations and strains in materials. Sample preparation can take seconds, allowing the system to make 10,000 measurements of 3D deformation and strain simultaneously across the surface of the static or dynamically loaded materials or structures.

Applying a speckle pattern, provides these 10,000s of unique targets that are then tracked to 1/100th of a camera pixel. This measures the 3D coordinates of the sample surface to a fraction of a mil (thousandth of an inch), and allows for accurate measurement of 3D displacements and surface strains, as if you had thousands of adjacent rosette strain gauges across the surface of the test object.

FORMING ANALYSIS

Forming analysis photogrammetry, the third method, uses a pattern etched onto the raw material which is measured with a video camera after each forming operation. The measurement of the precise 3D location of each dot in the pattern, provides the 3D shape of the part, its wall thicknesses, stresses and plotting every point onto a forming limit diagram to analyze the forming response to the material properties.

3D IMAGE CORRELATION

A typical tensile test setup is shown in Figure 1. The measurement system is just placed infront of the sample, typically just on a tripod. The simply applied stochastic pattern consists of two layers. The first layer is white, such as dye penetrant developer, is used to eliminate glare or increase reflectivity. This is followed by black spray paint sputtered with about 50% coverage. From this very simple set-up, sub-micron coordinates of the entire surface of the object can be made as the part is loaded. From these precise 3D coordinates of the surface, the 3D displacements and all surface strains can be analyzed. These are displayed as a 3D model of the actual results, spatially analyzed with section lines and area statistics and temporally analyzed with multiple section lines and point value time plots, or plotted against analog inputs such as load, machine displacement or temperature. Any these values and numerous others can be exported for further analysis such as in MatLab or for model and simulation verification and iteration.

FRACTURE MECHANICS

Crack Propagation studies benefit from the full-field data, rapid image acquisition and wide dynamic range of 3D Image Correlation photogrammetry [4]. Figure 3 shows the strain evolution for this nonhomogeneous large grain titanium material, before and during crack propagation. This shows the strain developing along multiple grain boundaries and eventually propagating along another path. Even specific values such as crack opening displacement (COD) and crack tip opening displacement (CTOD) can be calculated because 3D coordinates are know for every point across the surface of the material.

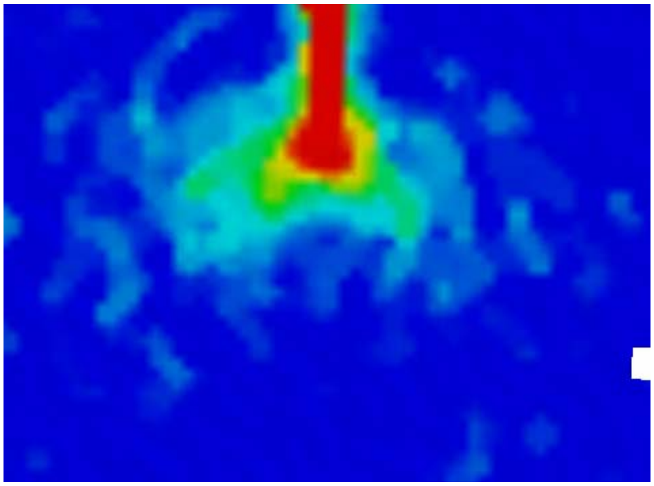

Figure 2 - Strain from crack propagation loading multiple paths along grain boundaries.

RESIDUAL STRESS MEASUREMENT

Residual stress measurement, using the blind hole drilling method, is fast and easy, even on-site or for nonhomogeneous materials. Work has been performed on engine blocks and other surface treated materials. The method is simple to implement and can even be used for stepped strain release to determine the depth of surface pre-stress.

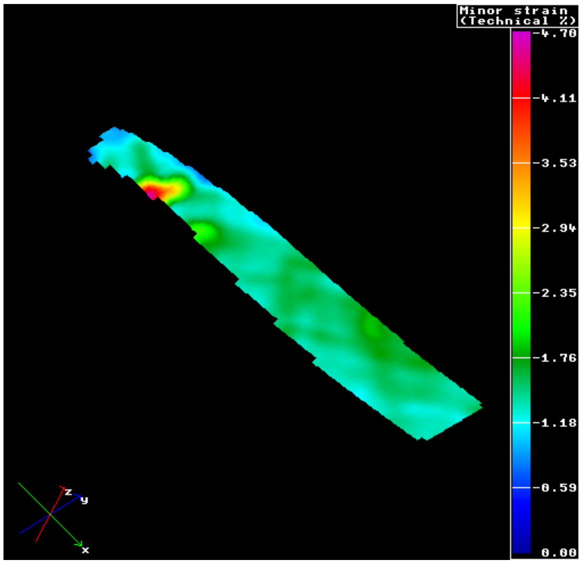

Figure 3 - Fatigue test of a composite beam showed three critical strain concentration areas that needed to be redesigned, saving additional prototypes

FATIGUE TEST

The fatigue testing requires minimal step and provide full structural response. The Fatigue test in Figure 4 shows the results of a fatigue test of a composite beam. The lower strain concentration (right, green) was a known weak spot (the least strain in this test), but the upper two on the left side (red & lt. green) were not known. This sample later broke at the red location. The third weak area (lt. green) would not have been detected by traditional means until another design cycle had removed the other two, costing additional time and money.

FORMING STUDIES

For sheet metal forming and hydro forming applications, 3D Image Correlation can be used to generate forming limit diagrams which are then used in computer models to predict material behavior during forming processes

[5]. Then it can the be used on sample parts to measure how the real material is responding and whether material thinning and strain values are within acceptable tolerances. Forming analysis of first article and lot inspection confirms that the parts are being manufactured as designed and will perform as their models predict.

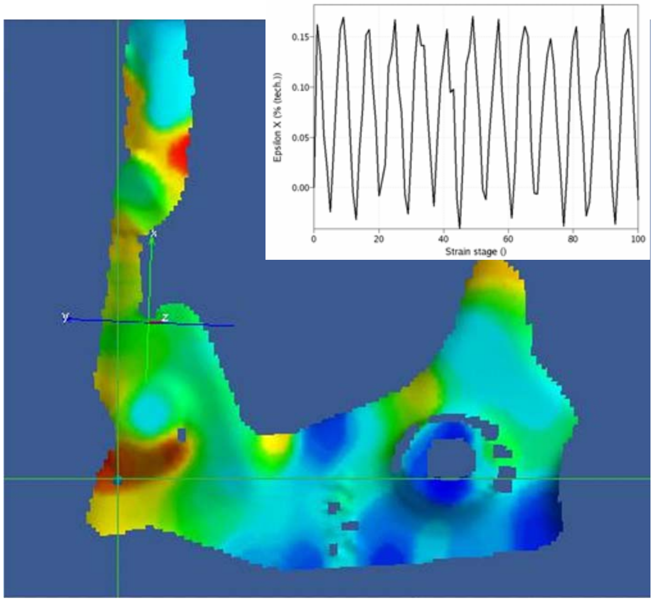

Figure 4 - Strains on a steering linkage are shown overlaid on shape of the part. A point plot shows the strain over fatigue test time.

DYNAMIC ASSEMBLY STUDIES

For real world testing, our latest photogrammetry instruments can measure the 3D response of complex systems, such as car engines, suspension systems and automotive components. Small target stickers are placed on each measurement point of interest. The two cameras, see Figure 5, image the target measuring its three-dimensional position. The cameras seen are high-speed cameras allowing hundreds of samples per second. The result is the real-time 3D displacement response of every target in the field-of-view. The waveforms shown are the frequency response of three targets on various components in an automobile engine along the same axis. The data set is so rich that the vibration response in any vector can be measured and displayed or the maximum displacements.

Figure 7 - Photogrammetry system measuring the response of multiple automobile engine components during startup.

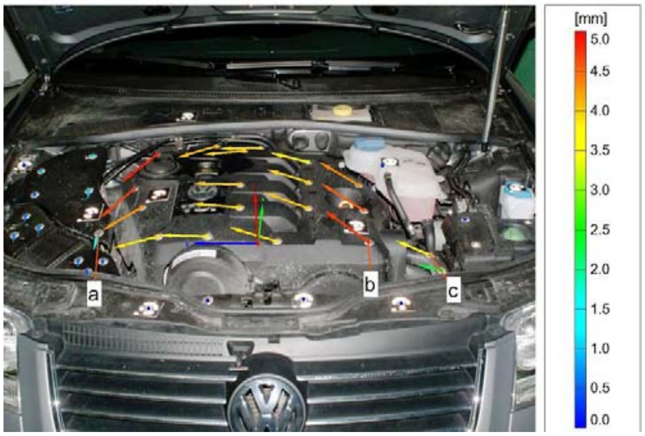

Figure 5 - 3D vectors showing dynamic 3D displacement of various components in complex engine going through start-up at 500 frames per second.

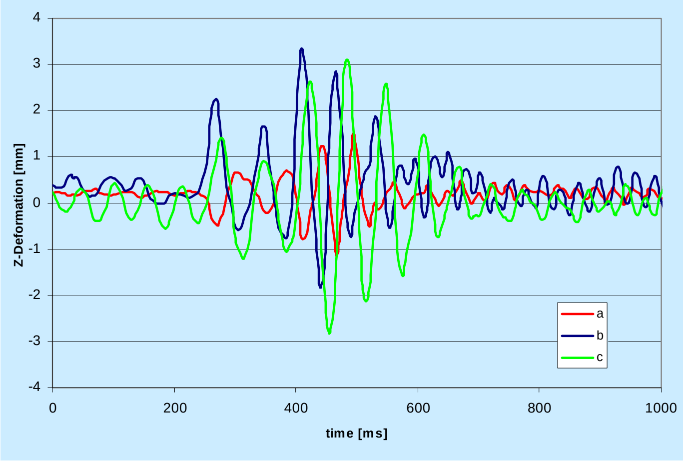

Figure 6 - Each target point provides a 3D displacement response up to a few hundred hertz, like having 3D accelerometers and 3D LVDTs at each target point.

CONCLUSION

Optical inspection methods are rapidly being adopted as the desired data collection method. With advances in algorithm and software development, they have become easy to use and extremely powerful. Many companies are saving money by reducing the amount of labor intensive strain gauges used, and with vastly increasing the amount of data gathered for better verification and iteration of computer models.

The reduction of strain gauges means less engineering involvement in attempting to predict the locations of strain concentrations, substantially less man-hours applying and calibrating gauges, and less prototype tests, as new, unexpected problems arise. Full-field methods are testing the entire structure simultaneously, so no test plan predictions are specifically necessary, because optical methods test known areas of concern as well as unexpected areas. We have seen many times where multiple strain concentrations were seen with our equipment, when only one was expected. As seen in Figure 4, the strain concentration on the lower right in this composite beam was a known failure point from nine previous prototypes. It is obvious that this prototype would fail this fatigue test at the new high-strain area in the upper left, which it did. What would have still been unknown, was that the strain concentration in the middle left, would have been the downfall of the next prototype with the other areas fixed. With this full-field data, all the areas of concern could be addressed at once, saving an entire prototype cycle! For some products, this could mean millions of dollars and months of development time. With full field methods, prototype development becomes much more efficient, getting products to market faster and with better quality.

The real drive toward the development of optical methods has been for the efficient verification and iteration of computer models. This is critical for understanding the behavior of our advanced materials and structures though the manufacturing process and their performance in the field. Full-field optical methods are now able to keep up with real manufacturing processes and real world testing. This data helps us understand the dynamics of materials as their complexity increases and as designs are refined. Models and simulations are improved with the establishment of correct boundary conditions. Models are then iterated to properly model the material and structure responses. Finally models are verified to predict material responses under real conditions.

Optical inspection methods are becoming the methods of choice for the future; Photogrammetry systems are here now to meet those needs.

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CONTACT

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