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Optical Measurements in the Automotive Test Lab

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ABSTRACT

Dynamic Photogrammetry and 3D Image Correlation are fully optical measurement methods that provide unique abilities to measure 3D coordinates, 3D displacements and even true surface strains of materials, without contact or without many difficulties associated with these measurements. These measurements can be static or completely dynamic, even in manufacturing or on the road. Advanced applications include determining rate dependent material characteristics of steels for forming or crash modeling, to prototype validation in fatigue or operational tests.

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, and is ideal for operational engine measurements, such as exhaust manifolds. Optical methods are ideal for wind tunnel testing because of they are non-contact. In vibration conditions, it is used in engine test cells. In production, parts can be tested without contact for true 6 sigma quality. 3D optical measurement methods provide unique measurement abilities and provide substantial cost savings with their rapid, holistic measurements.

INTRODUCTION

Full-field optical measuring techniques are increasingly being used in industry as development and design tools and for production inspection. Techniques such as moiré and holographic interferometry, for example, have been thoroughly described from the theoretical perspective [1] as well as the application engineering viewpoint [2], [3]. A variety of commercially available optical inspection systems combine exponentially increasing computer power, high-resolution digital cameras and compact mechanical design to provide turnkey operation for industrial applications.

At the risk of preaching to the converted, it is worthwhile to summarize the advantages of full-field measurements. What justifies the capital investment and other costs of change? As shown in Figure 1, there are many good reasons to seriously consider. A single-point gauge cannot show strain gradients, and could miss hot spots. This is particularly the case with non-homogeneous and anisotropic materials. Final results of optical measurements are compatible with finite element analysis software, and facilitate verification and iteration of models. Reduction of the number of required prototypes, quicker time to market, and improved product quality at lower cost provide a compelling return on investment justification. Perhaps most importantly, measurements that would otherwise be impossible become feasible, opening new avenues of investigation.

Benefits of Full-Field Measurements

- Visualize Strain Gradients and Hot Spots
- Verify and Iterate Finite Element Models
- Test Non-Homogeneous and Anisotropic Materials
- Reduce the Number of Required Prototypes ($$$)
- Quicker Time to Market
- Improved Product Quality at Lower Cost
- Make "Impossible" Measurements

Figure 1 - The benefits of full-field systems include visualizing strain gradients, verification and iteration of finite element models, and making previously impossible measurements.

This paper describes the use of the 3D image correlation technique in operational situations that take full advantage of its robust measuring principles. The power of image correlation provides superior dynamic range and ease of use for many test situations. Combined with pulsed illumination or high-speed video, it provides unparalleled capability.

3D IMAGE CORRELATION PHOTOGRAMMETRY

PRINCIPLES OF OPERATION

The object under test is viewed by a pair of high resolution, digital CCD cameras for the 3D deformation measurements. 3D image correlation technology is a combination of two-camera image correlation and

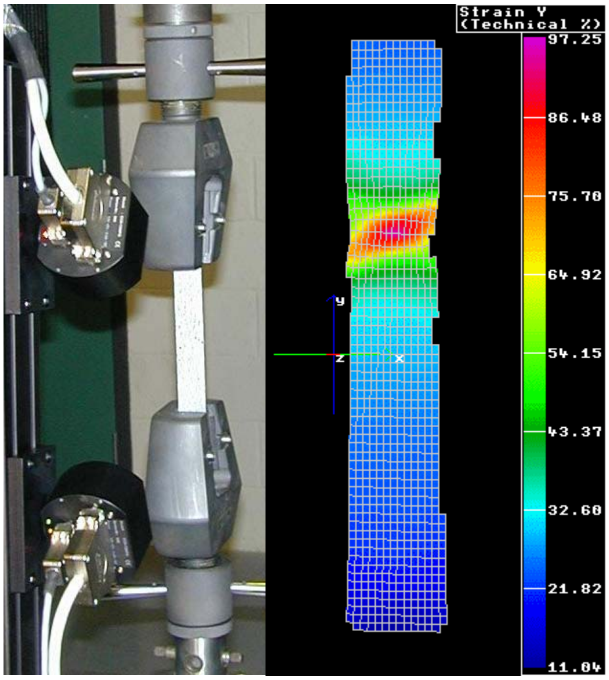


Figure 3 - 3D image correlation camera bar on a tripod, ready for measuring at a load frame. Since rigid body motion is not an issue, the same setup can be used with servo-hydraulic fatigue test machines.

photogrammetry. A random or regular pattern with good contrast is applied to the surface of the test object, which deforms along with the object. The deformation of this structure under different load conditions is recorded by the CCD cameras and evaluated. The initial image processing defines unique correlation areas known as macro-image facets, typically 5-20 pixels square, across the entire imaging area. The center of each facet is a measurement point that can be thought of as an extensometer and strain rosette. These facets are tracked in each successive image with sub-pixel accuracy. Then, using photogrammetric principles [4], the 3D coordinates of the entire surface of the specimen are precisely calculated. The results are the 3D shape of the component, the 3D displacements, and the plane strain tensor. An example of a commercial image correlation system configured for 3D measurement during a tension test is shown in Figure 2. The camera bar is mounted to a tripod that can simply be placed in front of the test sample at the correct working distance. Because rigid body motion has no effect on the measurements, this type of setup is perfectly adequate for use with servo-hydraulic machines as well as electric screw models.

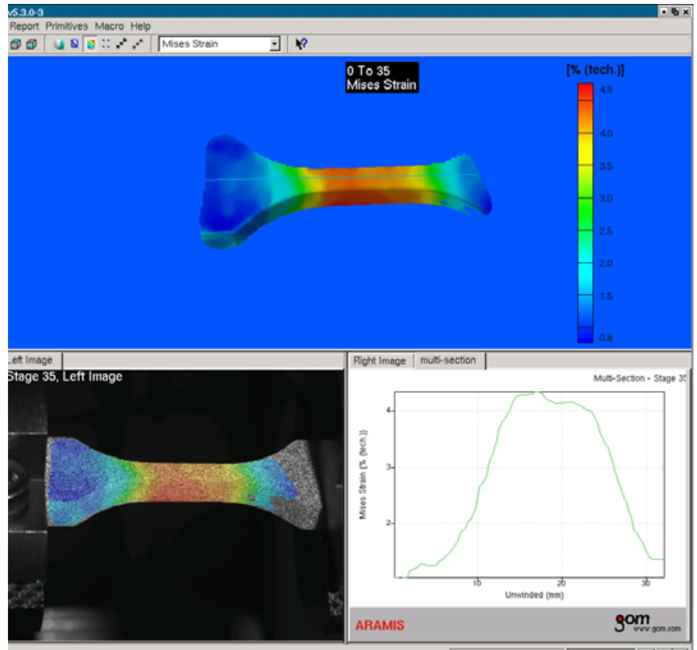


Figure 2 - 3D tensile coupon showing necking in gauge area, but also measured slippage in the grips.

HIGH TEMPERATURE MEASURMENT

Since 3D Image Correlation is a fully optical method operation in hazardous environments is a unique ability. Accurate high-temperature measurements, such as of engine components and exhaust systems, are readily achieved through oven windows or in the open air. As long as the cameras are not directly effected by the hazardous environment, they maintain their calibration and are accurate; light of course is unaffected by the environment. Deformation and strain measurement up to 1400ºC has been achieved. This equipment is being

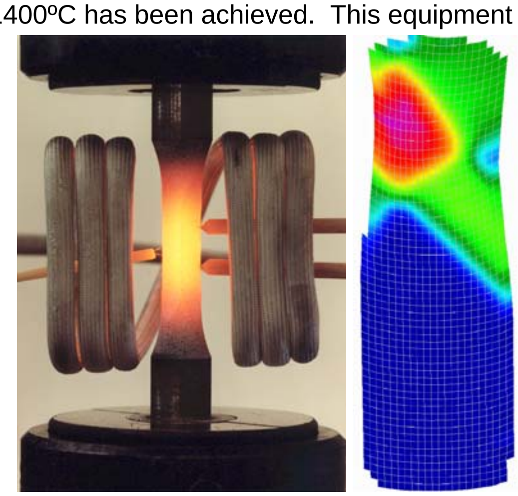


Figure 3 - 3D measurement of thermal and tensile loads at 1000^{o}C.

used daily for high-precision measurements of thermal expansion of low CTE ceramics to 1000ºC.

Induction heating of an advanced bi-metallic component was achieved using high-pass infrared filters called heat filters and other techniques. The result below shows the shape of the part and the strains from the tensile load at temperature. The use of the method is also regularly used through oven windows. Under these conditions, the oven window becomes part of the optical system and needs to be part of the system during calibration. Materials measurements of deformation and strain in the blast of a jet engine thrust can only be described as a hazardous environment "impossible" measurement, but is easily achieved. The key requirement to operation in a hazardous environments in that the surface coating on the material must be able to survive the hazardous environment. Fortunately, the specifications of a measurement coating is quite broad and really only needs to have some amount of contrast and good detail.

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

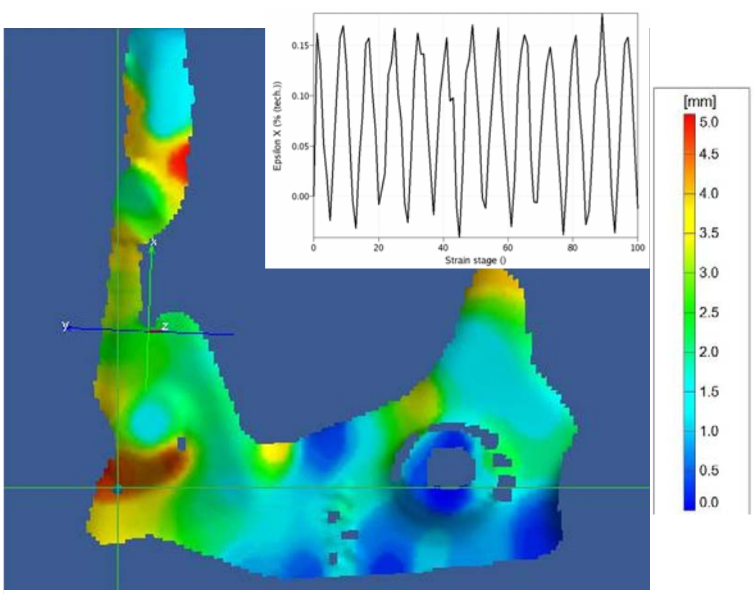
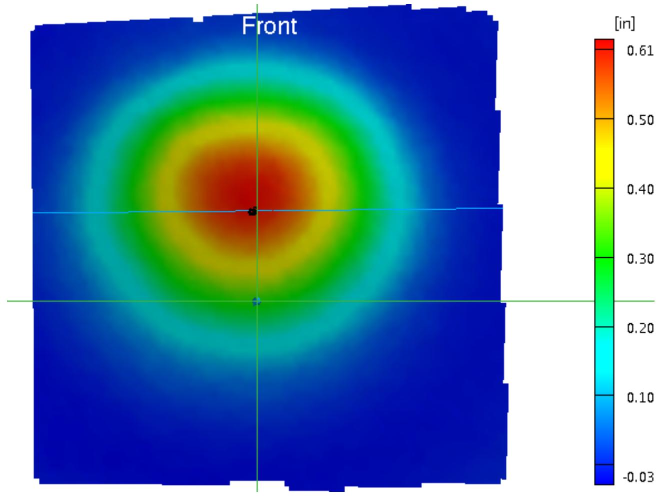


Figure 5 - Strains on a steering linkage are shown overlaid on shape of the part. A point plot shows the strain over fatigue test time.

DYNAMIC 3D MEASUREMENTS

The robustness of 3D image correlation photogrammetry becomes clearest when dynamic deformations are considered. Using a variety of high-speed cameras, the method can capture high-speed events, such as ballistic



and crash events. Furthermore, by adding a precision triggering module and stroboscopic illumination to standard "static" cameras, the system be applied to impact studies, non-stationary responses, and rotating objects such as tires, turbomachinery and jet engine components. The following examples demonstrate these capabilities.

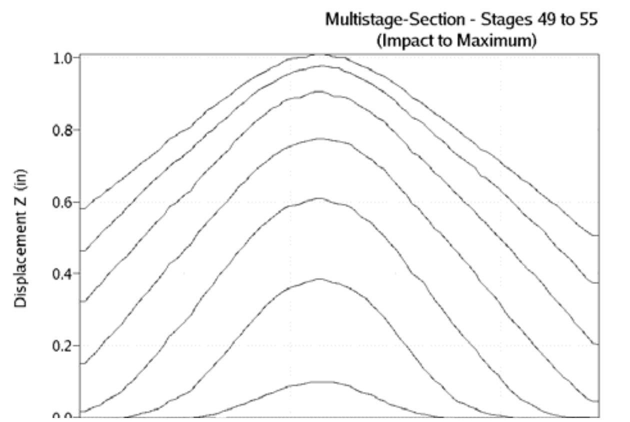


Figure 4 - Quantitative measurement of the out-of-plane displacement developing along a section line during the impact.

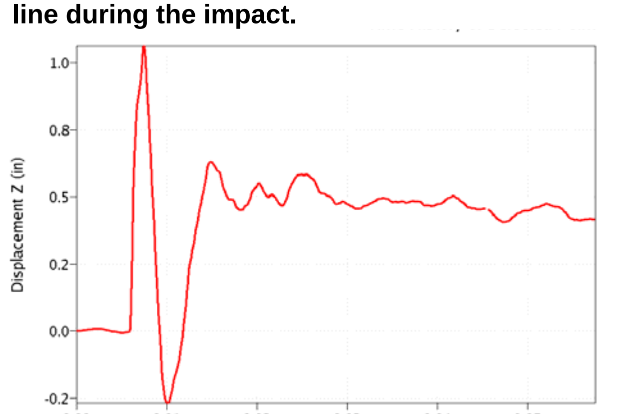


Figure 6 - Precise measurement of displacement at point of maximum displacement, as defined after the initial review of the full-field data. Plastic deformation is seen as the final difference.

Crash and Impact Tests

This typical ballistic result, shows the 3D shape of the impact at 10,000 frames per second. Results up to 100,000 frames per second are possible, while collecting approximately a seconds worth of data. The section line below shows the development of the displacement across the sample, while the Point Plot is a time history of one point through all of the collected images. To give you a sense of the immense amount of data collected, there are about 5,000 curves like this one available for each shot! Any and all data can be simply exported for use in MatLab or other external analysis program for model and simulation verification and validation.

High-Speed Tire Dynamometer Testing

For dynamic events such as a rotating tire, the shortest shutter times may not be adequate to prevent smearing of the applied pattern during the exposure. Then pulsed illumination is required. For this project, a pulsed arc discharge light was used. The light was configured for a 500 nanosecond discharge time. The arc lamp is suitable for speeds at least up to 150 miles per hour on automotive tires and has the advantage of being non-coherent, meaning that there are no laser safety requirements. Figure 8 shows the image correlation setup together with the tripod-mounted arc light and expansion optics.

A slip ring encoder on the road wheel generated an index pulse once per rotation, which was fed to a pulse/delay generator. By precisely varying a time delay, the rotational position of the tire could be controlled and synchronized to the pulsed illumination.

Figure 8: 3D image correlation can be combined with strobe illumination for dynamic deformation and strain analysis. Here the system is set up to study a tire at speeds up to 290 kilometers per hour. For related work such as flywheel testing, rotational speeds of 20-30,000 rpm can be achieved using short-duration (~5-20 nanosecond) laser pulses.

Figure 9 shows principal strains on the entire tire, showing a standing wave with highest amplitude near the load area. The result shown below was calculated from a reference condition of 3 miles per hour. It shows the evolution of a standing wave pattern near the load area as speed increased. Note that the software can calculate strains between any two different measurement conditions, and that additional images (measurement conditions) can be added to a measurement series. It would be no problem to import a reference image of the unloaded tire and then recalculate strains relative to this new reference point, if so desired. Alternatively, the relative

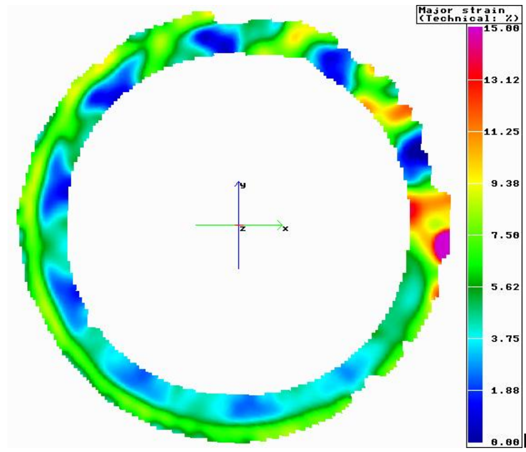
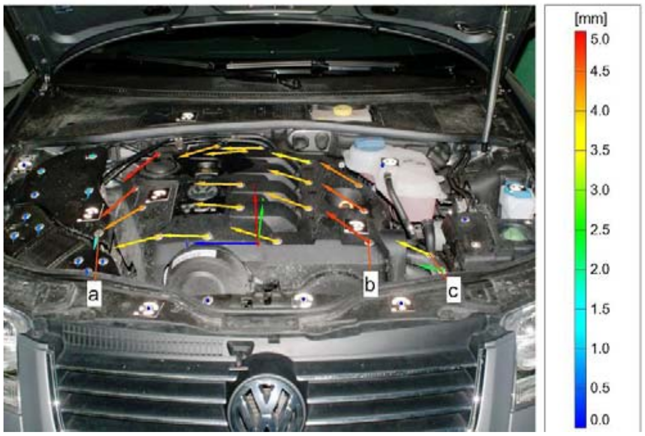


Figure 9: Principal strains on the tire at high speed, indicating a standing wave that has maximum amplitude at the load area.

strain between any two intermediate steps in a long measurement sequence can be calculated in addition to the automatically calculated strains relative to the first step.

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 10 - 3D vectors showing dynamic 3D displacement of various components in complex engine going through start-up at 500 frames per second.

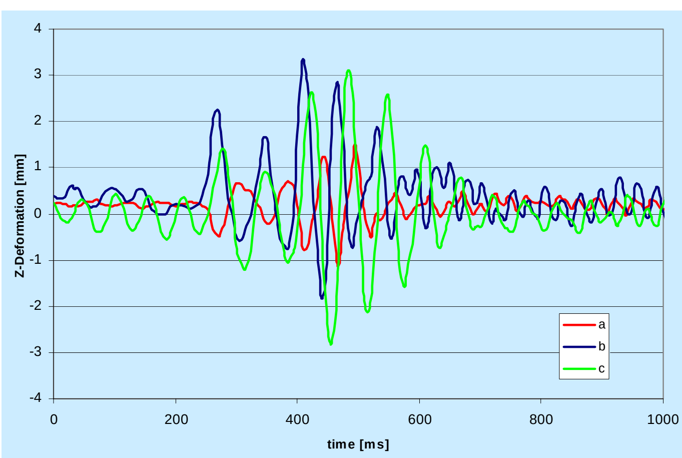


Figure 11 - Each target point provides a 3D displacement response up to a few hundred hertz, like having 3D accelerometers and 3D LVDTs at each target point.

CONCLUSION

3D image correlation photogrammetry is a powerful tool for dynamic displacement and strain analysis, providing full-field results with extensive quantitative analysis capability. Operational effects can be captured as easily as shooting a video, and precision synchronization can be achieved to capture peak strains during cyclic fatigue tests.

The use of synchronized flash illumination extends the applicability of 3D image correlation to high speed rotating components, providing unparalleled capability. Microsecond Illumination with Xenon flash and spark gap sources allow testing on dynamometers at hundreds or thousands of rpm, while Nanosecond Illumination with pulsed laser illumination facilitates strain measurements during spin pit testing on very high speed rotating components. An 18” diameter flywheel at 35,000 rpm was well within the dynamic capability of the system. There are no intrinsic obstacles to extending these measurements to 3D objects, such as bladed disk assemblies, using a pair of cameras.

2D or 3D image correlation photogrammetry can also be combined with high-speed cameras, adding quantitative shape, displacement and strain measurements to existing analysis for impact studies and other high-speed events. Beyond the camera types shown, double-shot and image-intensified cameras with 10 nanosecond inter-frame and exposure times can be used.

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