

OPTICAL METROLOGY THE KEY TO LEAN MANUFACTURING

John Tyson, Tim Schmidt, John Psilopoulos
Trillion Quality Systems
500 Davis Drive
Plymouth Meeting, PA 19462

ABSTRACT

Optical metrology has long been a high performance research tool for scientists in the laboratory. Modern forms of photogrammetry are now supporting engineering and manufacturing measurements. These optical metrology tools provide rapid, full-field measurements that are easy to use, broadly applicable and directly comparable to today's computer models and simulations. 3D Photogrammetry is the basis of Digital Image Correlation, White Light Scanning and Photogrammetry metrology. This technology is rapidly modernizing the automotive industry. Composite manufacturers like Boeing, PWA and General Atomics use the technology day in and day out, but smaller companies without the complex design and testing infrastructure can benefit even more. 3D Digital Image Correlation is finite element measurement, and allows you to intuitively understand the material response of complex structures under test, Dr. Paul Gradl, NASA Marshall, explained recently at a MSFC Optical Metrology Workshop. "An image is worth 1000 strain gauges." The ability to understand the full structural response rather than a bunch of strain gauge data, provide the CAE engineer with powerful tools to understand his structures and designs. Photogrammetry provides 6-DOF (degrees of freedom) measurement of structures with the same hardware, from door slams to vibration studies and modal analysis. This equipment can rapidly study thermal expansion to vibration and shock, with cameras running up to 10M fps, from materials studies to manufacturing quality control. This paper will discuss these advanced capabilities for the composites industry and beyond.

1. INTRODUCTION

Lean manufacturing is critical to the advanced development of the automotive industry and its competitiveness. Optical metrology is a powerful and easily implemented tool supporting engineering and manufacturing measurements. These optical metrology tools provide rapid, full-field measurements that are broadly applicable and directly comparable to today's computer models and simulations. The implementation into the automotive industry is a good example of full implementation to achieve lean engineering and lean manufacturing.

1.1 Materials properties advances

Materials and structural design continue to advance. Computer models have achieved great predictive power of materials and structures, but with more precise material parameters, these models will improve greatly and products will gain higher quality. Understanding the complex response of materials and structures in real varying manufacturing conditions is critical for the refinement of design and manufacturing implementation; to model what is really being built. 3D Digital Image Correlation (DIC) provides full-field 3D deformation and strain measurement, allowing for a more complete understanding of complex material responses. You may be

thinking of complex composite structures, but even simple homogeneous materials benefit from these measurements. The VP of R&D from a major tire company told me, “We have 65 computer modelers and no good experimental data validating those models. This [full-field dynamic strain measurement] technology is company critical.”

1.2 Stamping Forming Analysis

During stamping operations, forming verification with optical metrology, directly comparing against the engineering FEA computer model of stampings, hot and hydro formings, gives manufacturing direct control of its operations with better data. ARGUS is a photogrammetry system that provides this automated circle grid type analysis. This full-field analysis directly compares the entire formed part to the FEA model, measuring principle strains, material thickness, material flow and forming limits, just by any operator taking some pictures. This automated forming analysis saves hugely on manufacturing iterations caused by missed high strain areas, and unanticipated thinning. A key to automated forming analysis is that it performs identically, globally, and directly exports results into the quality control system, for global quality control, making it the perfect manufacturing communication tool.

1.3 Vehicle Dynamics & Assembly

Vehicle dynamics, from modal analysis and NVH, to large area deformation studies, are simple with a dynamic photogrammetry system like PONTOS. 3D photogrammetry provides the 3D coordinates of precision dot stickers on completed assemblies, replacing mechanical gauges such as LVDTs, clip gauges and accelerometers, with nothing to fixture, wire-up and troubleshoot. Instead of a few measurement points, believed to give the desired results and days to instrument, photogrammetry targets can be placed where ever data is desired and more, with no additional effort. Components can be analyzed in hours with full 3D data, simplifying the true understanding of component assembly response, providing all desired data for precise engineering comparison with design.

Optical metrology offers new ways to greatly improve the quality and efficiency of design and manufacturing optimization for leaner, smarter operations.

2. EXPERIMENTATION

2.1 Advanced Material Testing and Model Validation

The standard material testing with test machine is tensile and compression testing, extending to shear, torsional and biaxial testing. These are all ideally suited for the 3d image correlation method. A standard application of the ARAMIS technology is for materials testing, using standard load frames (tensile, compression & fatigue). Variations include bulge testing for automated forming limit curve measurement, to deep drawing materials studies, providing measurement abilities not possible with traditional methods. The method becomes critical in anisotropic materials such as composites to biomaterials, where the single point or average measurements mean very little.

For ARAMIS, each step result is the 3D coordinates of 10,000+ points (targets,

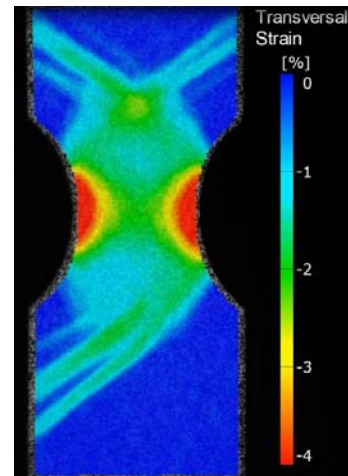


Figure 1 - Full-field strain result of simple steel sample, showing the complexity of the data, even for a simple measurement. The clip or strain gauge is missing so much.

nodes) across the surface of the specimen. Each measurement point is like one end of a clip gauge, a strain rosette node, or an LVDT. ARAMIS then tracks these points throughout the test, so their complex 3D deformations and strains are measured, calculating the true strain tensor for every point. Truly Finite Element Measurements.

The full-field ARAMIS data shows the real local deformation and strain variation, as well as the locations of maxima and minima. This is critical information for true material properties inputs into models, model iteration with boundary conditions adjustments, and for the FEA validation. A model iterated to match the real sample, becomes a much more accurate analysis, allowing advanced simulations to model the real material responses. This is a critical step towards the next advances in design and manufacturing, and improved product quality.

2.2 Stamping - Automated Forming Analysis

Automated forming analysis measurements, using the ARGUS measuring system, circular dots are etched to the raw sheet metal with a regular spacing of typically 1 mm to 5 mm prior to the forming process, just like circles for circle grid analysis. For this purpose, mainly patterns are used that are created by electro-chemical etching, laser etching or printing. These dots follow the deformation of the part during the forming process and survive even powerful stamping operations.

Then, the formed component is recorded with a digital CCD camera (with a resolution of typically 12 megapixels) from various views. Photogrammetric algorithms use these images to determine the 3D coordinates of the dots on the sheet metal. Thus, the entire surface of the shaped sheet metal is described according to the density of the etched structure. The center of these dots is used for determining the precise 3D coordinates of every point on the surface, and a spline fit analysis is used to calculate the true deformations and biaxial strains of the material, as well as the material thickness reduction.

The forming limit diagram compares the major and minor strain with the material characteristics. Thus, the forming process can directly be evaluated with respect to the material limits. Reports are automatically generated and uploaded to Company's quality control system providing feedback to engineering about each step of the forming process from design, die checkout and stamping operations.

For the Verification of the stamping process, the mobile ARGUS system particularly stands out for its simple and robust measuring process. This method is used by most car companies in the world.

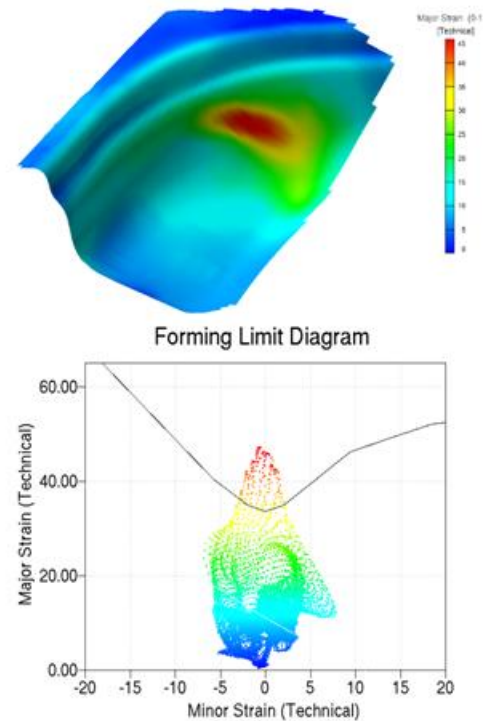


Figure 2 - Forming analysis showing material formed beyond its forming limit, material failure.

2.3 Powertrain - High Temperature, High Vibration Measurements

As a fully optical method, 3D Image Correlation (DIC) is a fully non-contact method. This allows ARAMIS have unique abilities in extreme or hazardous environments. Accurate high-temperature measurements are readily achieved in test lab, or even through an oven window. As long as the cameras are not directly affected by the hazardous environment, they maintain their calibration and are accurate; light is basically unaffected by the environment. Deformation and strain measurements up to 1400°C are typical. This equipment is being used daily for high precision measurements of thermal expansion of low CTE ceramics to 1000°C, a very demanding application.

The DIC method is regularly used for engine and powertrain studies, example in Figure 3. 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 requirements of a measurement coating (typically high temp paint) is quite broad and targets really only needs to have some amount of contrast and good detail. Structural coordinates are then imported with CAD interface, so all measurements are in vehicle coordinates.

Engine and Powertrain thermal 3D deformation and vibration studies easily measure hundreds of points, and all points are measured synchronously. This synchronous measurement is very powerful, allowing you to measure the reality of how all components are moving relative to each other, holistically, as a complete system. No other technology allows you to see the complete response of your system. The measurement is made of all desired points, and the engine block (or any component) is used for reference for all measurements, so even though the engine is at full load and vibrating on its mounts, all measurements are true to the engine itself.

Vibration studies utilize high-speed cameras to capture the 3D vibrations like hundreds of 3D accelerometers (typical system in Figure 4). We run the frame rate of the cameras at 10-15 times the desired measurement frequency, so if 200hz is being measured, the measurement is performed at 2000-3000 fps (frames per second), just like a bullet going through a balloon. These measurements are also uniquely able to provide 6 DOF (Degrees of Freedom) analysis of every component that we can get a few targets on. 6 DOF is deformation in X, Y, Z and Roll, Pitch & Yaw.

The power of optical metrology for lean engineering and manufacturing is that now you can get as many measurement points as you need, at a fraction of the cost (just paint dots) and on every component you need, all synchronously and fast.

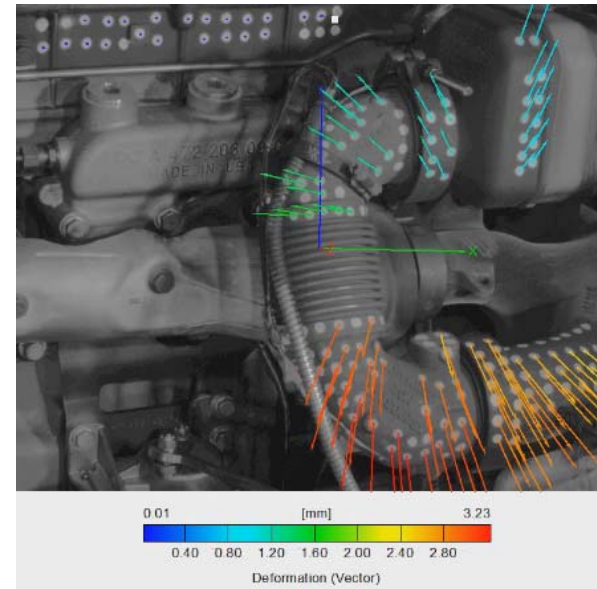


Figure 3 - Powertrain studies allow interrogation of data in car coordinates even long after the test.



Figure 4 - ARAMIS system with sensor on tripod and mobile measurement station for structural measurements.

In the time that you place on accelerometer or LVDT, the optical measurement is already completed with hundreds of measurements, and you are solving real problems rapidly.

2.4 Vehicle Dynamics - Dynamic 3D Photogrammetry

For real world testing, the photogrammetry system ARAMIS 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 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 3D deformation response of three targets on various components in the automobile door assembly. The data set is so rich that the vibration frequency response in any vector can be measured and displayed, or the maximum displacements.

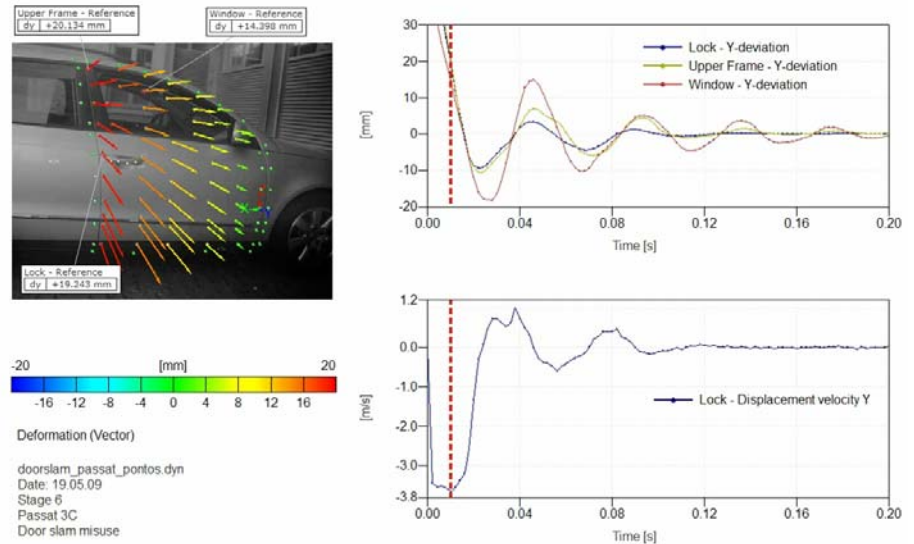


Figure 5 - Vehicle dynamics of a door slam, wind tunnel or assembly operation.

In addition to the 3D displacement of the many measurement points, the 6-degrees-of-freedom motion of components can be measured. The rotation of the door on the hinges is a major motion, but what other motions are present? The mirror is moving relative to the door in X, Y & Z. Is it also rotating? Relative deformation or motion of any component can be measured relative to any other component.

Thanks to the non-contact video data acquisition, the influence on the measurement object is very low, so that even a large number of measuring points is does not affect the response of the test object. Imagine getting meaningful acceleration values of a fuel line, when your accelerometer has more mass then that section of the fuel line.

Preparing for high-speed measurements, the camera recording frequency is an important measurement parameter. For vehicle development, larger components generally have lower resonant frequencies that can easily be captured with standard cameras (typical recording frequency 500 to 1000 Hz). Higher frequency measurements are performed with high-speed cameras, which can measure up to 10M frames per second. The rule of thumb for vibration studies is defining your highest desired vibration frequency (Hz) in order to determine your camera FPS (frames per second). For FFT frequency studies, the camera speed (FPS) needs to be 3-5x of your desired frequency (Hz), and for full waveform and modal analysis your camera speed (FPS) needs to be 10-15x your desired maximum frequency (Hz). So, if looking at NVH of up to 100Hz, 300-500 FPS is needed, or full waveforms, the camera speed of 1-2K FPS is needed. These speeds are standard for most modern high-speed cameras.

The accessibility and visibility of measuring points during the measuring process can be a limiting factor. While the measuring system is able to record even complex geometries within its field of view, sometimes mirrors or cutouts provide critical access. Some dynamic procedures require several recording systems in order to measure components from several sides simultaneously. On the other hand, the optical measuring technology does not limit the recordable displacements as long as the measuring points remain visible. Other quasi-static or repeating events, can allow sensor movement. A variety of methods are available for stitching data sets together to provide a complete result in one project. The deformation of a full windshield shown in Figure 6 shows the complexity of response and the large dynamic range of the measurement.

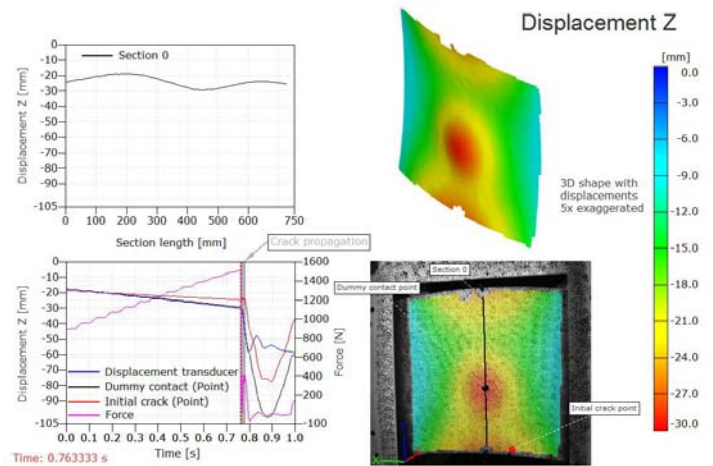


Figure 6 - Windshield deformation.

3. RESULTS

Dr. Paul Gradl, NASA Marshall Space Flight Center, said, the ARAMIS data is full-field image data and is intuitively understood. Image data is the perfect format for humans to understand. We see this visual data and there are no arguments about the data; it is intuitively obvious what is occurring to your structures.

3.1 Engineering Data – Greatly Improved Measurements lead to Better Designs

It was shown that the optical measuring technology simplifies test setups and allows for capturing numerous measuring points fast, efficiently and accurately. Therefore, this measuring technology often is a better alternative to the traditional displacement, strain and acceleration sensor technology, not only technically, but economically as well. Compared to traditional methods set-up and measurement are reduced by 100-1000x. A door slam test can be performed in 30 minutes, compared to 3-4 days of LVDT setup, with 50-1000x more data collected, providing a much better measurement, allowing better understanding of test data.

I (John Tyson) have witnessed engineering setup for automotive testing that used a string pot to measure a bracket displacement on a complex assembly. The data being collected was meaningless because the engineer was using the table as reference. There was so much in between to add to the displacements he was measuring. The ARAMIS showed the bracket was deforming within tolerance relative to the component body. It is so powerful when anything can be used as reference for any displacement measurement, and the data can be interrogated for the desired results.

3.2 Assembly Quality – Real-time Measurements lead to Better Quality

Manufacturing and Assembly quality measurement become simple collected and reported. Optical measurement systems are just imaging the structures, like human visual inspection, ARAMIS is just highly quantitative, and everything measured can be recorded and reported.

The measurement of the swing of every door on a manufacturing line to confirm correct hanging and motion, is easily quality control measurement. Validating robot and machine motion in 3D space and 6-degrees of motion are simple, instantaneous measurements. Tracking press and shear motions and die displacements, have changed how Ford designs their dies. Chrysler uses this equipment to measure stamping machine alignment, displacements and deformations; holistically “seeing” the results.

4. CONCLUSIONS

Holistic optical metrology can provide a complete knowledge based solution for the everyday issues that confront industry. Implementing optical metrology to the critical areas of validation and quality will dramatically improve the communication between departments and make entire processes more efficient. The complete understanding of the material, benefits the entire processes, from start to finish, achieving Lean Engineering. Data is being gathered more efficiently and completely with less time and resources wasted. In manufacturing, better assessments are possible resulting in complete solutions found of typical problems, and greatly improving quality at a lower cost, achieving Lean Manufacturing.

Optical measuring systems for digitizing, forming analysis and material property determination are a part of advanced process chains in the development of products and production processes for sheet metals and tools. Already today, time, costs and quality are optimized, thus increasing the competitiveness of these companies. These measuring technologies are used increasingly for automated inspection tasks due to their further integration in processes and the availability of powerful data processing systems. The data is linked and automatically uploaded to the quality control system for precision lean operations globally.

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