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FACTORY OF THE FUTURE, DESIGN, ANALYSIS AND VERIFICATION

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ABSTRACT

The Factory of the Future greatly uses optical measurement systems throughout the design and manufacturing of next generation material, structures and products. Optical metrology, Digital Image Correlation (DIC) and Photogrammetry, are critical measurement methods because of ability to measure the material or structure holistically, simply and rapidly. Advanced manufacturers, like Boeing, PWA, Ford 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, Dr. Paul Gradl, NASA Marshall, explained. 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 wing flexure (NASA Dryden) 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 Factory of the Future and beyond.

1. INTRODUCTION

Optical metrology is playing in important role in the Factory of the Future from engineering to manufacturing operations. As the technology has evolved, from its research origins to its current real-time capacities, it provides providing leaner and smarter ways to achieve better quality and optimized measurements. This paper reviews the integrated use of optical metrology throughout the design and manufacturing workflow. At each step of the manufacturing process, optical metrology is expanding our knowledge of materials and structures for improved quality, subsequently reducing costs, by reducing the time and effort to maintain and document quality. The advancement of computers and digital imaging now allows precision optical metrology to take manufacturing to higher levels of quality using simpler automated methods that synchronize perfectly with computer-aided engineering and design (CAE/CAD).

In its simplest form, 3D optical metrology uses two cameras for stereo imaging photogrammetry to locate points in 3D space by triangulation. Similar to your eyes, ARAMIS can locate and track points in 3D space. You know that that part is about 1” long; a 3D photogrammetry system can locate the points in 3D space with the precision of a coordinate measurement machine (CMM), to the micron level accuracy, by “not-so” simply using camera images. The powerful

Figure 1 – Typical 3D-DIC system showing integrated stereo cameras with pulsed lighting for vibration studies, and a rack-mounted computer with data logger.

software is able to interpolate the 3D image down to 1/1000th of a pixel of the camera, for incredible accuracy and resolution. And be able provide this same accuracy across the full-field of your components and products.

Optical metrology in engineering test, using 3D Digital Image Correlation (DIC) and stereo photogrammetry, reduces the need for mechanical gauges, while greatly increasing the quality/quantity of the data collected - all in a fraction of the time of standard wired sensors, like strain gages, LVDTs, clip gauges, and accelerometers. Using 3D-DIC is a highly versatile measurement method, providing 3D shape, 3D deformation and strain measurement over the complete surface of the material(s). Why put 20 - 200 strain gauges on a structure, when one DIC system measures the true strain tensor at 10,000 strain gauge locations in a fraction of the setup time and cost? One primary ARAMIS user calculated that using 3D DIC was 10x cost savings verses mechanical gages, 50x labor savings, and 100x improvement in the amount of collected strain data.

Optical metrology is transforming the way we measure things. 3D-DIC is the ideal tool for precision materials properties measurements, core to higher precision FEA models. Then for structurally testing, complex composites with DIC can be company-critical, because it provides the reality of structural response, with precision full-field measurements of all the components working together, to comprehensively understand what really is happening to your complex, nonhomogeneous structures.

On the NGC James Webb Space Telescope, the structural testing was monitored with 3D-DIC on all four sides of the satellite, saving having to mount and calibrate many 100s of LVDTs and saving 1-week/month of schedule, which was more than $2M of savings during a 3 month program.

For manufacturing quality, instantly measuring shapes for part validation, locating parts in real-time for precision assembly, monitoring assembly deformation and strain, confirming assembly tolerances - the applications are endless in manufacturing quality and lean manufacturing. Transparent manufacturing is the next step in lean, precision manufacturing. Understanding everything about streamlining your processes and methods lead to higher product quality.

1.1 Precision Material Properties

The most important parameter to understand in design are your core material properties. This establishes the basis for your computer models and all of your process data. 3D-DIC is the ideal tool for measuring material properties, primarily because it is fully noncontact and full-field, and provides rapid, holistic understanding of the materials under test. Any desired measurement can be made, matching clip gauge, strain gauge or extensometer. Just as simply as making one measurement, 10,000 measurements can be made in all three axes, providing ever greater accuracy. ARAMIS also provides automated tools to automatically determining all of your material parameters. Many test frames come with a DIC capability, but with one camera, 2D-DIC assumes a flat plane, and measurement errors come from unanticipated out-of-plane deformations, or from the true 3D nature of all parts, even mostly flat ones. 3D-DIC corrects for all of these errors and provides precision measurement data.

Understanding the complex response of materials and structures in varying manufacturing conditions is critical in refining designs and their manufacturing implementation; in other words, you want to model what is really being built. 3D-DIC provides full-field 3D deformation and strain measurement, creating a more complete understanding of complex material responses from true strain, to strain-rate and thermal dependencies. In addition to complex composite structures, even simple homogeneous materials benefit from these measurements.

1.2 Fracture Mechanics

3D image correlation is a full-field method, so no matter its complexity or wherever the fracture propagates, 3D-DIC tracks it. By interrogating the results of each test, 3D-DIC enables the test to be replayed, allowing you to place clip gauges and strain gauges, as desired, once you know the test outcome, to fully comprehend the results. If you need to reanalyze the test a year later, change the resolution, or change the measurement method, put another strain gauge on over there, 3D-DIC provides this capability, because you have the original images, fully documenting the test.

1.3 Structural Testing Holistically

For large structural testing, Trilion has replaced thousands of LVDTs (linear displacement sensors) with only four camera pairs for the James Webb Space Telescope, providing its manufacturer, Northrop-Grumman, real-time load versus displacement on all four sides of their satellite under structural test, saving the huge cost of mounting and calibrating those sensors, and more importantly saving them months on their test schedule.

The R&D VP for a major tire company stated, “We have 65 computer modelers and no good experimental data validating those models. This [full-field dynamic deformation and strain measurement] technology is company critical.”

For system model optimization and validation, as well as design verification and fatigue analysis, the real full-field 6-DOF deformations and strains of all of the interrelating materials can be directly compared to the computer finite element analysis (FEA) models.

1.4 Vibration and Shock Testing

Vehicle dynamics - from modal analysis to large area deformation studies – can be tested with ease with a dynamic photogrammetry system. 3D photogrammetry provides the 3D coordinates with precision dot stickers on completed assemblies, replacing mechanical gauges such as LVDTs, clip gauges, and accelerometers, with nothing to assemble, wire-up, calibrate and troubleshoot. Instead of a few measurement accelerometers, ‘believed’ to provide the desired results, taking days to install and calibrate the instrumentation, photogrammetry targets can be placed wherever data is desired, and moreover, with little effort. All of the calibration for the hundreds of sensors is done at one time for the stereo camera system. Components can be analyzed in hours, rather than days or weeks, with full 3D data/6-DOF, simplifying component assembly response, providing all the desired data for precise engineering comparison with design. The savings on test time can be huge, like 50:1. In addition, all vibration data is synchronous, providing advantages over laser scanning vibrometers and other scanning systems. Pushing the limits, shock testing with cameras running at up to 5M fps, provides data never achieved before.

1.5 Assembly Quality Control

Optical metrology offers new ways to greatly improve the quality and efficiency of manufacturing optimization for leaner and more intelligent operations. Understanding assembly line startup issues and precision measurements of full-field deformation and strain of assembly procedures and processes. Manufacturing and assembly quality measurements become simple when collected and reported. Measurements of real-time quality and operational accuracy lead to lean manufacturing and high product throughput. Optical measurement systems simply image the structures, like a human visual inspection, whereas 3D-DIC is highly quantitative – you can record and report everything you measure. GM is saving $100M per year with optical monitoring of their production stamping quality.

2. EXPERIMENTATION

2.1 Advanced Material Testing and Model Validation

3D-DIC fully automates precision measurement of complex composite material properties. Even von Mises measurements, critical for computer model inputs for composite designs, are easily measured. Using DIC, determining fatigue strength is a standard measurement in the automotive engine industry. As materials and structural design continue to advance and increase in complexity, FEA models achieve greater predictive power of materials and structures. Further advances will be based on more precise material parameters. With DIC, products achieve higher quality and performance.

Standard material testing of tensile and compression testing, extending to shear, torsional, and biaxial testing, are all ideally suited for a 3D image correlation method. DIC is the ideal tool for measuring material properties, particularly because it is fully noncontact and full-field. This allows rapid, holistic understanding of the materials under test. Any typical measurement

can be made, matching clip gauge, strain gauge or an extensometer. Just as simply as making one of these measurements, you can make 10,000 measurements in all three axes, even with |6-DOF. ARAMIS also provides automated tools to automatically determine material parameters, such as Engineering Stress, True Stress, Young’s Modulus, Yield Strength, Tensile Strength, Poisson Ratio, True von Mises, and more. Image correlation is also ideal for simple or

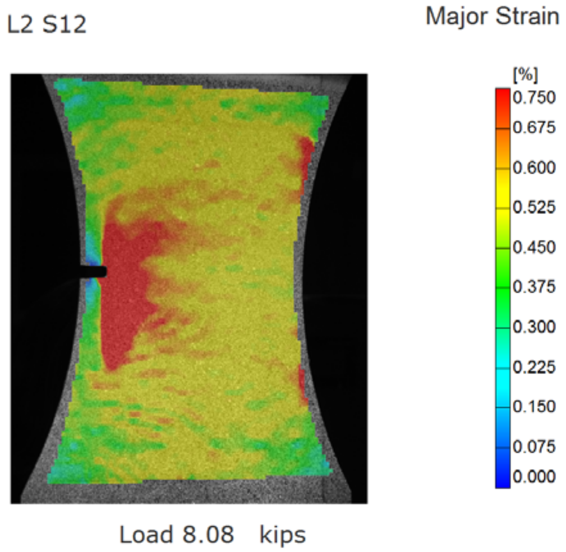

Figure 2 - Tensile Test with internal delamination. What would a clip or strain gauge say to understand this test?

advanced materials measurements of all typical tests such as tensile/compression, biaxial, shear, 3-point/4-point bend, buckling, torsion, fatigue, bulge, and forming tests. Standards are available from ASTM, ASNT, IDDRG, ISO, JEDEC, with more coming each year.

Full-field measurement methods become critical in anisotropic materials such as composites where the single point or average measurements are virtually meaningless. Shear strain is also quite difficult to measure locally, or more importantly, over larger areas. For 3D-DIC, it is quite easy to measure true shear strains across entire structures, from tissues to bridges.

For 3D-DIC, each stereo image measurement provides the 3D coordinates of 10,000+ points (targets, nodes) across the surface of a specimen. Each measurement point compares to one end of a clip gauge, a strain rosette node, or an LVDT. 3D-DIC software 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. For example, NASA's Glenn Research Center had problems measuring epoxy specimens with traditional methods. They developed an ARAMIS DIC method that tracked the actual material surface, precisely measuring the properties, ignoring grip slippage that was impacting the test, and provided complex properties like Poisson Ratio across the entire structure. Applying the same method to all of their material testing of metals and composites has greatly increased the accuracy of their materials data.

The 3D-DIC software ARAMIS has a materials test module which provides precision automated material property measurements from the full-field measurements. For standard tensile tests, ARAMIS provides engineering and true stress, stress-strain curves, and most of critical materials parameters such as Young's Modulus, Yield Strength, Tensile Strength, Poisson Ratio and is ideal for Shear, Bending, Torsion, Fatigue, Biaxial, Bulge testing. Specifically for composites, you can configure ARAMIS for measuring the true von Mises of composite specimens. ARAMIS is the ideal tool for determining material property measurements and developing accurate material models. For example, a recent test with a leading plastics company exposed a remarkable strain wave running across their sample - something that they had never seen to date.

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 property 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 toward subsequent advances in design and manufacturing, and improved product quality.

2.2 Fracture Mechanics

Fracture mechanic measurements can be complex. 3D image correlation is powerful because it measures the full-field, while the fracture is allowed to propagate freely. Since the data is collected from the unstressed reference condition, the data can be replayed at any time, placing gauges where desired to get a better understanding of the event. ARAMIS allows the placement of virtual clip gauges and strain gauges after you have determined where the cracks are developing and in the proper orientation.

A mechanical clip gauge provides only crack opening displacement (COD), but Digital Image Correlation can provide dX, dY, & dZ measurements, which are Mode 1, Mode 2, and Mode 3 fracture criteria. Dr. Kaspar Willam with the University of Houston, an expert in fracture mechanics, stated "We only know the fracture mode in ideal laboratory conditions where you control it. In the real world, it is a complex combination of modes, and you cannot know it." He was impressed to discover that his ARAMIS system continually measures all three modes.

Numerous researchers have programmed ARAMIS for fracture mechanics and calculating fracture parameters from the data. The new generation of ARAMIS allows even greater analysis capabilities for local analysis and advanced calculations.

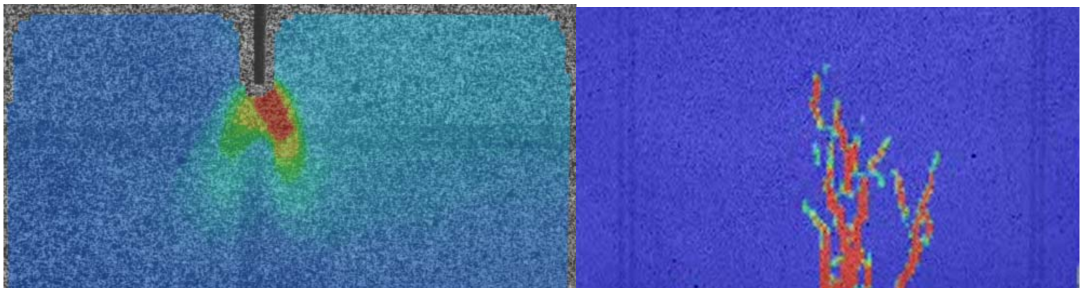

Figure 3 - Fracture of composite rocket motor housing at the Airborne Laser Directorate, Kirkland AFB (left); fracture in a fiber reinforced concrete (right).

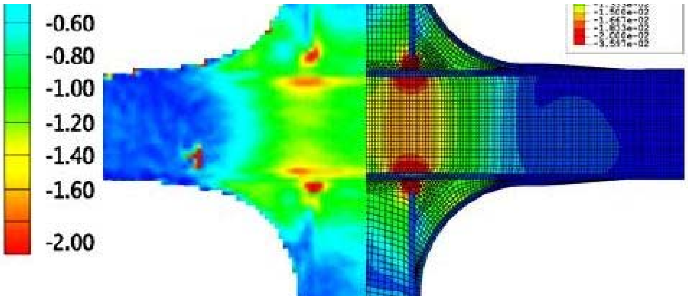

Figure 4 - Biaxial loading of composite joint, (left) reality ARAMIS measurement, verses FEA model (right)

2.3 Structural Testing Holistally

Structural testing becomes even more refined in understanding your structures holistically with a full-field method. Individual components can be modeled effectively, but when they start being combined into larger structures, the modeling assumptions exceed desired accuracies. Steve Openshaw of General Atomics, stated, “If you are developing with composites and are not using ARAMIS, you do not know what your structures are really doing.”

Buckling requires a real-time, full-field method for which optical measurements are ideally suited. When Ron Slaminko of Boeing Structural Testing was asked “You got the ARAMIS system for composite buckling studies, what are you using the system for now?,” he responded “Everything.” He continued describing that he had just run a test on a smaller wing structure to validate the computer model. Engineering had spent two weeks, putting 200 strain gauges across the structure. Ron and his technician patterned the structure in the morning and they tested in the afternoon. He instantly observed that the model was wrong and that the strain gauges were all in the wrong places. They used ARAMIS data to validate the model. This is a good example where ARAMIS is a better choice than strain gauges, and can save companies millions of dollars. Those 200 strain gauges at net price of $1000 each, was more than the cost of the

ARAMIS system, which is still in use today. ARAMIS is now equivalent to a strain gauge at many companies.

At a recent large test of composite wing spars, about one million dollars was spent on the strain gauging, while ARAMIS (as an existing system with no system cost) provided three orders of magnitude more data, and correlated perfectly with the strain gauges. Program management determined that the Air Force accepts ARAMIS strain data and will use Digital Image Correlation next time.

The ultimate structural field test was performed on the Space Shuttle Discovery, grounded for cracks in the External Fuel Tank (ET). Two custom ARAMIS sensors were mounted to the launch platform, measuring the ET while the tank was fully filled with cryogenic fuels, liquid hydrogen (LH2) and liquid oxygen (LO2). Engineers, from Trilion Engineering Services, were in the Launch Control Center, 2½ miles away, controlling the optical measurements through a fiberoptic network interface. ARAMIS data helped validate the FEA models and validate the repairs. Launch was then rescheduled the following month. Trilion was invited to Space Shuttle Discovery's final launch as VIPs, and given awards for our work, as the ET Photogrammetry team.

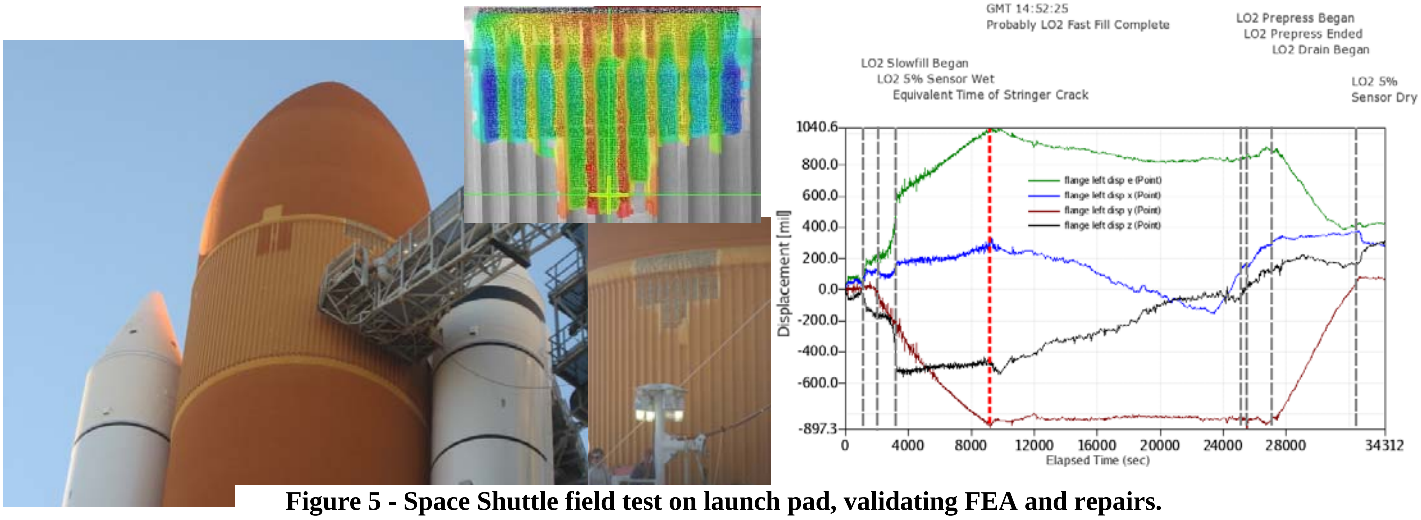

Figure 5 - Space Shuttle field test on launch pad, validating FEA and repairs.

3D image correlation displays its power when quick, critical tests are performed. Bladeout tests are the most expensive tests that the FAA requires of its engine suppliers. Trilion Engineering Services supports these tests by the primary jet engine manufacturers, as technical experts with high-speed ARAMIS.

Yet, the real beneficiaries of this technology are smaller companies, where ARAMIS compares to an engineer in a box, helping make better products, and documenting their quality. A favorite example is Dynamic Controls, a 5-person company at the time, who demonstrated to the US Army, using ARAMIS data, that their product outperformed their competitor, a major aerospace firm. The Army was so impressed by the data and subsequently awarded the order to Dynamic Controls.

2.4 High Temperature Measurements

As a fully optical method, 3D-DIC is a fully noncontact method. This enables ARAMIS to have unique abilities in extreme or hazardous environments. Accurate high temperature measurements are readily achieved, even through an oven window. As long as the cameras are not directly affected by the hazardous environment, they maintain their calibration and remain accurate. Light is basically unaffected by the environment. 3D deformation and strain measurements, up to 1400ºC, are typical. This equipment is being used daily for high-precision measurements of low coefficient of thermal expansion (CTE) ceramics to 1000ºC - a very demanding application.

Engine studies regularly use the 3D-DIC method. The key requirement to operating in a hazardous environment is that the surface coating on the material must be capable of surviving the extreme conditions. Fortunately, the requirements of a measurement coating (typically high temperature paint) is quite broad, and targets really only need to have some amount of contrast and good detail.

The CAD coordinates are then imported with the ARAMIS interface, so all measurements are in vehicle coordinates. Engine thermal 3D deformation and vibration studies easily measure hundreds of points, and all points are measured synchronously. This synchronous measurement is extremely powerful, enabling you to measure the reality of how all components are moving relative to each other, holistically, as a complete system. No other technology is capable of enabling you to see the complete response of your system. A key to a precision measurement in a hostile environment like an engine test cell, is measure all desired points relative to a good reference. The engine block, or any component, can be used for reference for all measurements, so even with an engine at full load and vibrating on its mounts, all measurements are true to the engine itself, in the engine's CAD coordinates.

Figure 6 - ARAMIS Thermography from a boom overlooking the B2 Aft Deck c/o AFRL

2.5 ARAMIS Thermography

An example of advanced measurement applications include the precision ARAMIS DIC and thermal measurements of the B-2 aft deck within the jet engine thrust to full power, performed from a 50-foot boom. ARAMIS Thermography combines the two methods to include temperature measurements. The system uses these thermal measurements to correct thermal expansion from the strains, to provide true mechanical strains, under complex thermal conditions. Material measurements of 3D deformation and strain in the blast of a jet engine thrust can only be described as near-impossible measurements in a hazardous environment, but are easily achieved with ARAMIS Thermography. The Air Force reported (ASIP 2008) that Trilion helped [them] solve a critical structures problem that they had been working on for 20 years.

2.6 Vibration and Shock Testing

Vibration studies use high-speed cameras to capture the 3D vibrations like hundreds of 3D accelerometers. For real world testing, the ARAMIS photogrammetry system can measure the 3D response of complex systems, such as engines, wings, fuselages, components, and even entire wind turbines in vibration. A wind turbine with 40m blades requires about a 100m field-of-view (FOV). Resolution is as about 2mm in-plane for this measurement.

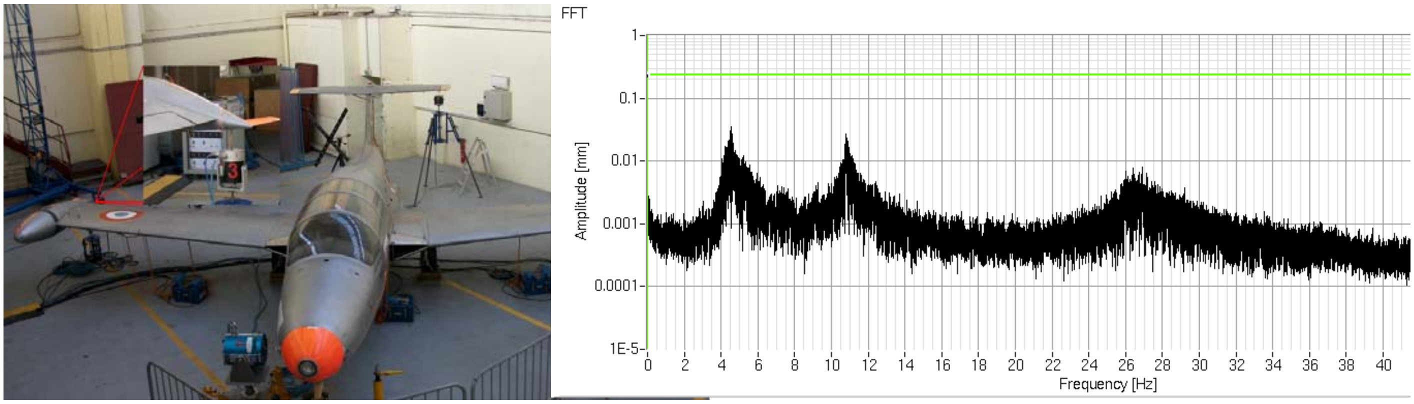

Figure 7 - Ground vibration study comparison with 50 accelerometers, ARAMIS took 2-hours to setup, verses 2-weeks. Data matched perfectly.

Target stickers are placed on each measurement point of interest. Two cameras image the target, measuring its three-dimensional position. These high-speed cameras provide hundreds of samples per second. The result is the real-time 3D displacement response of every target in the FOV. 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 you can measure of display the vibration frequency response in any vector, or the maximum displacements.

For high-frequency tests, the cameras run at a frame rate of 10-15 times the desired measurement frequency. Therefore, if 200hz is being measured, the measurement is performed at 2000-3000 frames per second (fps), just like a bullet going through a balloon. These measurements are also uniquely capable of providing 6-DOF analysis of every component by capturing a few targets. 6-DOF is deformation in X, Y, Z and Roll, Pitch, and Yaw.

In addition to the 3D displacement of the many measurement points, you can measure the 6-DOF motion of components. A door’s rotation on its hinges is a major motion, but many other motions may also be present. A mirror moves relative to the door in X, Y, and Z. Perhaps it also rotating. Again, you can measure relative deformation or motion of any component 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 does not affect the response of the test object. Imagine getting meaningful acceleration values of a fuel line, when your accelerometer has more mass than that section of the fuel line.

Preparing for high-speed measurements, the camera recording frequency is an important measurement parameter. Perhaps you want full waveforms or perform modal analysis, or are just interested in the FFT frequencies. For vehicle development, larger components generally have lower resonant frequencies that you can easily capture with standard cameras (typical recording frequency of 500 to 1000 Hz). High-speed cameras perform higher frequency measurements, which can measure up to 10M frames per second (FPS). The rule of thumb for vibration studies is defining your highest desired vibration frequency (Hz) in order to determine your camera’s FPS. For FFT frequency studies, the camera speed (FPS) needs to be 3 - 5 times that of your desired frequency (Hz). So, if you are looking at ground vibration studies of up to 100Hz, you need 300 - 500 FPS. For full waveform data and modal analysis, your camera speed (FPS) needs to be 10 - 15 times your desired maximum frequency (Hz). Consequently, if you are looking at vibration studies of up to 100Hz, you need 300 - 500 FPS. With full waveforms, you need camera speeds of 1 - 2K FPS. These speeds are standard for most modern high-speed cameras. Typically, above 10K FPS, the number of pixels used is reduced to get the desired speed, even to 100K - 300K FPS.

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 FOV, 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. Trilion is working on a 3-year fatigue test, where the ARAMIS system is brought to the lab once a day for the required measurement.

2.7 Assembly Quality Control

The power of optical metrology for lean engineering and manufacturing is that you can now get as many measurement points as required, at a fraction of the cost and on every component desired, all with speed and synchronicity. 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 issues rapidly. A major aerospace manufacturer calculated that using optical metrology was a 10x cost savings, a 50x labor savings and a 100x data improvement. Many manufacturers are finding that implementing optical measurement saves them substantially on test schedules and the engineers are getting better data, faster.

3. RESULTS

Dr. Paul Gradl of the NASA Marshall Space Flight Center, said “The ARAMIS data, as full-field image data, is intuitively understood. Image data is an ideal format for humans to understand. We analyze the ARAMIS results, and there are no arguments about the data, like we had with strain gauges; it is intuitively obvious what is occurring to our structures.”

3.1 Engineering Data – Greatly Improved Measurements lead to Better Designs

Having witnessed engineering setup for automotive testing that used a string pot to measure a bracket displacement on a complex assembly, it became apparent that the data being collected was meaningless because the engineer was using the table as reference. Much compliance existed in-between to add to the displacements being measured. Optical metrology saved the day, showing the bracket was deforming within tolerance relative to the component body. It is a powerful system when selecting anything as reference for any displacement measurement. You can interrogate the data and be truly accurate about what you are measuring. DIC reduces the assumptions you make about a test or a measurement.

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

Boeing states that ARAMIS DIC over strain gauges, provides them a 10:1 cost savings, a 50:1 manpower savings, and 100:1 data improvement. Boeing used ARAMIS DIC to get FAA flight certification of the B787, and now allows ARAMIS DIC to be used instead of strain gauges as an alternative method.

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

Using optical metrology, Manufacturing and Assembly quality measurement data are simply collected and reported. Optical measurement systems only image the structures, similar to traditional human visual inspection, optical measurement technology is highly quantitative, and everything measured can be recorded and reported, providing Enhanced Visual Inspection.

Composites do not assemble like metallic structures. Accumulated assembly strains develop toward their ultimate strength, weakening the structure, occasionally below design loads, yet do not appear to human inspection. Fatigue loads are substantially smaller and are easily exceeded without excellent quality control. Digital Image Correlation can monitor assembly strains, even operational strains over years of operation, similar to having millions of strain gauges permanently mounted and monitoring your structures. Trilion has monitored creep strains on hot-section turbine blades after a year of operation, measuring creep strain in the blades. Imagine being able look at a component after years of operation and measure it accumulated deformations and strains.

In manufacturing, optical metrology can be used to get the actual shape of a composite before assembly to confirm its proper fit, or quickly calculating the required shim. Documenting assembly deformation or strain to confirm assembly quality is now possible, where none is done now. With optical metrology, you can precisely locate a component or subassembly without tooling, and then document the as-built condition. While monitoring these structures throughout their lives using this same simple method makes it so easy.

4. CONCLUSIONS

Holistic optical metrology provides a complete knowledge-based solution for the everyday issues that confront industry, greatly reducing costs, improving development schedules and improving overall quality. Implementing optical metrology to the quality areas reporting back to engineering digitally dramatically improves communication between departments and make entire processes more efficient. Completely understanding your materials' behavior improves entire processes from start to finish – a primary objective of Lean Engineering.

Gathering data more efficiently and completely, with less wasted time and resources, allows for more educated assessments and resulting in more complete solutions to the typical issues that occur in the manufacturing arena – a primary objective of Lean Manufacturing.

Optical measuring systems for digitizing, forming analysis, and determining material properties are a part of advanced process chains in developing products and production processes for sheet metals and tools. Trilion has saved GM $100M per year monitoring their stamping quality.

Today, optical metrology optimizes time, costs, and quality, thereby increasing a company's competitiveness with Lean Engineering and Lean Manufacturing. These measuring technologies are increasingly being used for automated inspection tasks as they are integrated in the processes and availability of powerful data processing systems. The data is linked and automatically uploaded to the quality control system for lean precision operations globally.

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