FINITE ELEMENT MEASUREMENTS FOR REALITY IN COMPOSITES

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ABSTRACT

Optical metrology is fast becoming the measurement method of choice because of the great advantages over its mechanical progenitors. 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 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 composites industry and beyond.

1. INTRODUCTION

"If you are developing with composites and are not using ARAMIS, you do not know what your structures are really doing." Steve Openshaw, General Atomics, basically sums up this paper. Optical metrology is playing a greater role in engineering and manufacturing operations as the technology has grown from its research origins to its now real-time capacities, providing leaner and smarter ways to achieve better quality and optimized measurements. This paper will review the integrated use of optical metrology throughout the composite design and manufacturing workflow. At each step of the manufacturing process, optical metrology is greatly expanding knowledge of materials and structures for improved quality, and reducing costs, by reducing the time and efforts to maintain, and document, quality. The advancement of computers and digital imaging, now allows precision optical metrology to take manufacturing to new levels of quality using simpler automated methods, that synchronize perfectly with computer aided engineering and design.

3D optical metrology in its simplest form uses single camera photogrammetry to locate points in 3D space by triangulation, just like our eyes using stereo imaging can locate and track points in 3D space; imagine a baseball player hitting that 90mph ball out of the park. A 3D photogrammetry system can locate points in 3D space to the micron level, like a portable CMM (coordinate measurement machine), but by just using camera images.

Optical metrology in engineering design and materials properties determination using 3D Image Correlation (DIC), stereo photogrammetry, reduces the needs for mechanical gauges and greatly increases the quality and quantity of the data collected, all in a fraction of the time. Do you really need 200 strain gauges on that part? 3D Image Correlation, using the ARAMIS system, is a highly versatile measurement method that provides 3D deformation and strain measurement over the complete surface of the material(s). Why put 20-200 strain gauges on a structure, when one ARAMIS system measures the true strain tensor at 10,000 strain gauge locations in a tiny fraction of the setup time? ARAMIS can use cameras that can operate at up to 10 million frames per second, so full-field vibration and shock testing is also simple.

Figure 1 - ARAMIS system with integrated lighting for vibration studies.

Optical metrology is transforming the way we measure things. ARAMIS is the ideal tool for precision materials properties measurements. Structural test of composites with DIC is company critical. For manufacturing quality, instantly measuring shapes for part validation, real-time locating parts for precision assembly, monitoring assembly deformation and strain, confirming assembly tolerances, the applications are endless for advances in manufacturing quality and lean manufacturing.

1.1 Precision Material Properties

3D Digital Image Correlation (DIC) is the ideal tool for materials properties measurements, particularly because it is fully noncontact and full-field, allowing rapid, holistic understanding of the materials under test. Any desired measurement can be made, matching clip gauge, strain gauge or an extensometer. Just as simply as making one measurement, 10,000 measurements can be made in all three axes, even with 6-DOF (degrees of freedom). ARAMIS also provides automated tools to automatically determine material parameters.

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.

1.2 Fracture Mechanics

3D image correlation is a full-field method, so where ever the fracture propagates to, or its complexity, ARAMIS will track it. Interrogation of each test, allows the test to be replayed with clip gauges and strain gauges placed where desired to fully understand the results. Want to reanalyze the test a year later, change the resolution, change the measurement method, go ahead.

1.3 Holistic Structural Testing

For systems, the real full-field deformation and strains of all of the interrelating materials can be directly compared to the computer FEA models for model optimization and validation, as well as design verification and fatigue analysis. 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."

1.4 Vibration and Shock Testing

Vehicle dynamics, from modal analysis, to large area deformation studies, are simple with a dynamic photogrammetry system. 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, rather than days or weeks, with full 3D data, simplifying the true understanding of component assembly response, providing all desired data for precise engineering comparison with design.

1.5 Assembly Quality Control

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

2. EXPERIMENTATION

2.1 Advanced Material Testing and Model Validation

Precision measurement of complex composite material properties, including von Mises measurements, are critical for computer model inputs for composite designs, and for fatigue strength determination. As materials and structural design continue to advance and increase in complexity, FEA models achieve great predictive power of materials and structures. Further advances will be based on more precise material parameters. Products will then 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 the 3d image correlation method. Jack Coate (Air Force Research Lab) said, "How could we measure it any other way?" discussing a composite joint under tensile test. 3D image correlation is the ideal tool for materials properties measurements, 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, 10,000 measurements can be made in all three axes, even with 6-DOF (degrees of freedom). 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, etc. Image correlation is also ideal for simple or 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.

Measurement methods become critical in anisotropic materials such as composites, where the single point or average measurements mean very little. Shear strain is also quite difficult to measure locally, or more importantly over larger areas; for DIC it is quite easy to measure true shear strains across entire structures, from tissues to bridges.

For ARAMIS, each step is the 3D coordinates of 10,000+ points (targets, 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. ARAMIS then tracks these points throughout the test, so their complex 3D deformations and strains are measured. NASA Glenn Research Center had problems measuring epoxy specimens with traditional methods. They developed an ARAMIS method that tracked the actual material, precisely measuring the properties, ignoring slippage, unaffecting the test, and providing complex properties like Poisson Ratio across the entire structure. Application of the same method to all of their material testing has greatly increased to accuracy of their materials data.

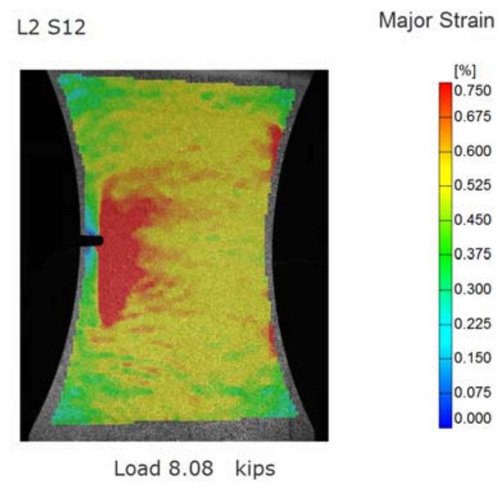

Figure 2 - Tensile Test with internal delamination. What would a clip or strain gauge say to understand this test?

The ARAMIS materials test module provides precision automated materials properties measurements utilizing full-field measurements, from standard tensile test provide 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, ARAMIS can be configured for measuring the true von Mises of composite specimens. ARAMIS is the ideal tool for the determination of materials properties measurements and the development of accurate material models. I was testing with a leading plastics company and commented on the amazing strain wave running across their sample, when I realized that they had never known that this happened.

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.

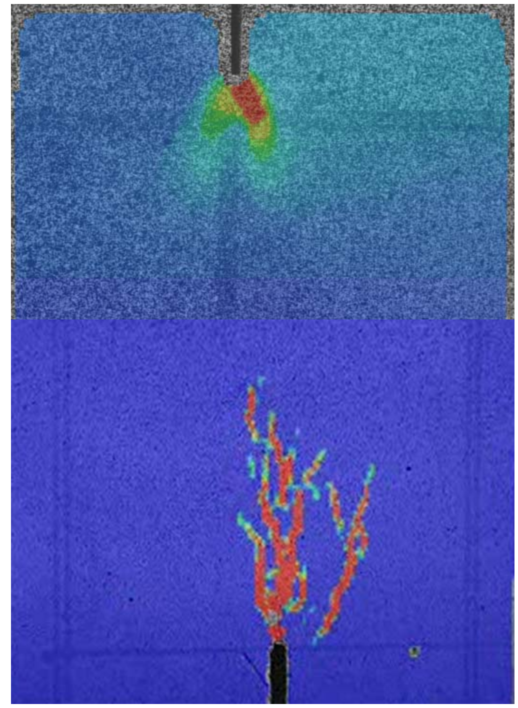

Figure 3 - Fracture of composite rocket motor housing at the Airborne Laser Directorate, Kirkland AFB (top).

2.2 Fracture Mechanics

Fracture mechanics measurements can be complex. Image correlation is powerful because it is measuring the full-field and the fracture is free to propagate freely. Since the data is collected from the unstressed reference condition, the data maybe replayed at anytime, placing gauges as desired to get a better understanding of the event. Clip gauges and strain gauges can be placed after you know where the cracks are going and in the proper orientation.

A clip gauge provide COD (crack opening displacement), but ARAMIS can provide dX, dY & dZ measurement, which are Mode 1, Mode 2 & Mode 3 fracture criteria. Dr. Kaspar Willam, U. Houston, an expert in fracture mechanics, stated “You only know the fracture mode in ideal laboratory condition where you control it. In the real world it is a complex combination of modes.” He was amazed to find that his ARAMIS system measures all three modes all of the time.

Numerous researchers have programmed ARAMIS for fracture mechanics and calculating fracture parameters from the data. The new generation will allow even great analysis capabilities.

2.3 Holistic Structural Testing

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

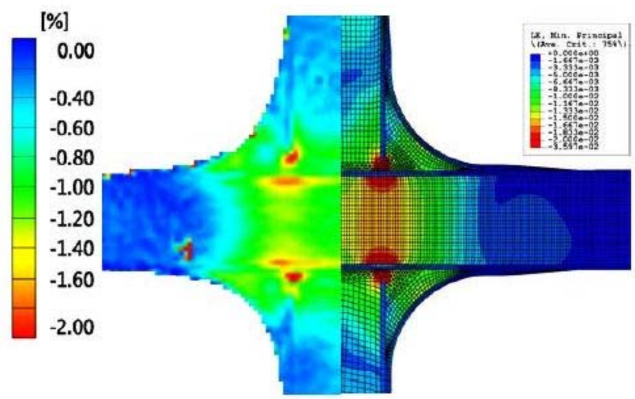

Figure 4 - Biaxial loading of composite joint, (left) reality ARAMIS measurement, verses FEA model (right)

Buckling requires a real-time, full-field method for which ARAMIS is ideal. I asked Ron Slaminko, Boeing Structural Test, “You got the ARAMIS system for composite buckling studies, what are you using the system for now?” “Everything.” was his response. He continued to explain 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 saw that the model was wrong, 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 millions of dollars.

At a recent large test of composite wing spars, about one million dollars was spent on the strain gauging, while ARAMIS (existing system, no system cost) provided 1,000x more data, and correlated perfectly with the strain gauges. Program manager found that the Air Force accepts ARAMIS strain data and will use ARAMIS next time.

The ultimate structural field test was 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 tanks were fully filled with cryogenic fuels LH2 & LO2. We were in the Launch Control Center 2½ miles away, controlling through fiberoptic network interface.

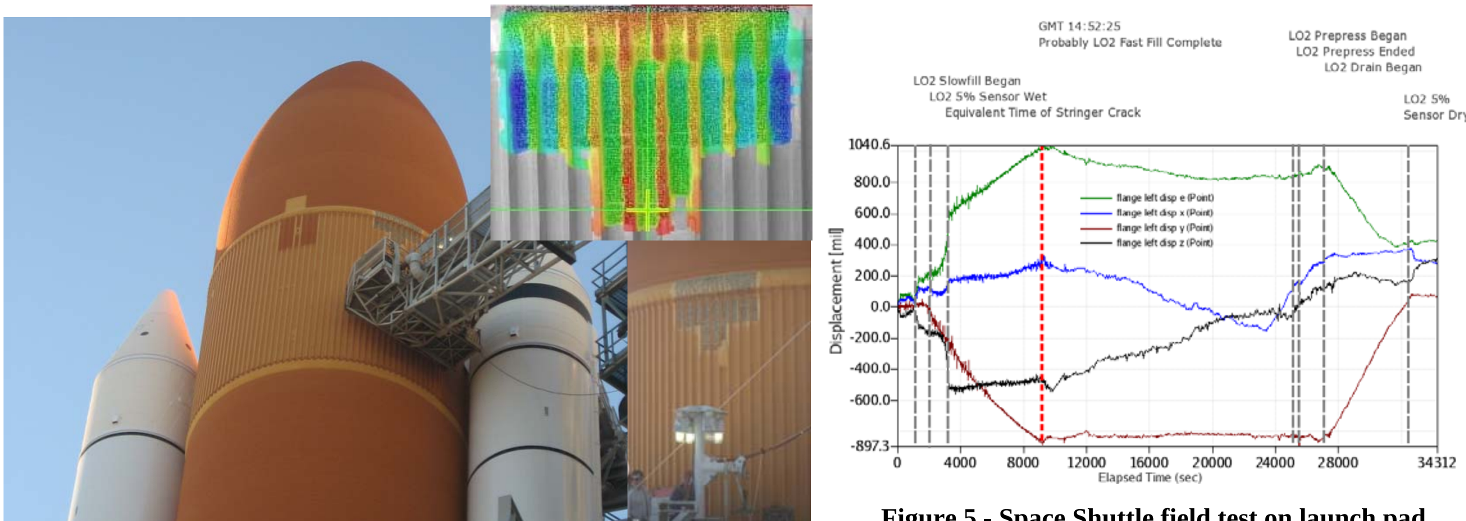

Figure 5 - Space Shuttle field test on launch pad, validating FEA and repairs.

ARAMIS data helped validate the FEA models and validate the repairs. Launch was then rescheduled for a month later. Trilion was invited to Space Shuttle Discovery's final launch as VIPs, and we were given awards for our work, as the External Tank Photogrammetry Team.

3D image correlation shows its power when fast, critical tests are performed. Bladeout tests are the most expensive tests that the FAA requires of its engine suppliers. Trilion supports many of these tests as experts. But, the real beneficiaries of this technology are smaller companies, where ARAMIS is like an engineer in a box and helps them make better products, and document their quality. My favorite example, is Dynamic Controls, a 5-person company at the time, which presented to the US Army, ARAMIS data that showed that their product outperformed their competitor, a major aerospace firm. The Army was amazed by the data and gave the order to Dynamic Controls.

2.4 High Temperature 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. 3D deformation and strain measurements, up to 1400ºC, are typical. This equipment is being used daily for high precision measurements of thermal expansion of low CTE ceramics to 1000ºC, a very demanding application.

The DIC method is regularly used for engine studies. 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 need 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 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.

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

Advanced measurement applications include the precision ARAMIS and thermal measurements of the B-2 aft deck within the jet engine thrust, to full power, all performed from a 50ft boom. ARAMIS Thermography combines the two methods to include temperature measurements, which the system uses to correct thermal expansion from the strains, to provide true mechanical strains, under complex thermal conditions. Materials measurements of 3D deformation and strain in the blast of a jet engine thrust can only be described as 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 had they had been working on for 20 years.

2.5 Vibration and Shock Testing

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

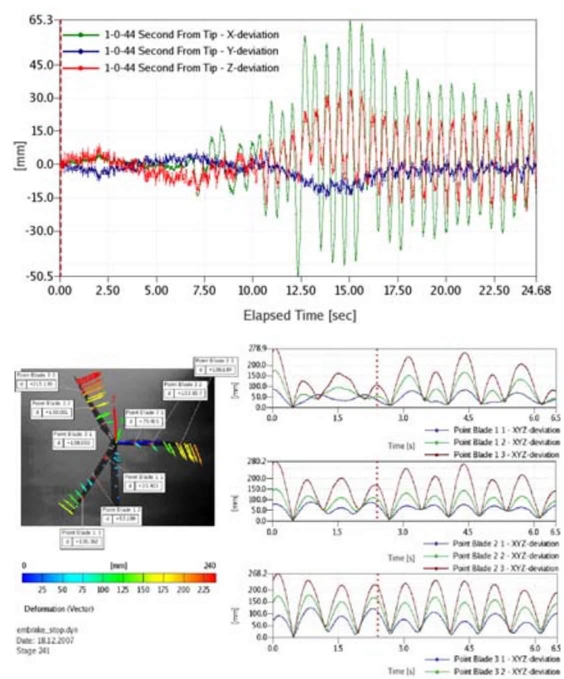

Figure 7 - 100m Field-of-View of Wind Turbine in operation.

Target stickers are placed on each measurement point of interest. 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.

For high-frequency tests, the cameras run at a frame rate of 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.

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 that then that section of the fuel line.

Preparing for high-speed measurements, the camera recording frequency is an important measurement parameter. Do you want full waveforms or doing modal analysis, or are you just interested in the FFT frequencies? 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 (FPS). 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). 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 10-15x your desired maximum frequency (Hz). So, if you are looking at vibration studies of up to 100Hz, you need 300-500 FPS, or full waveforms you need camera speed 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.

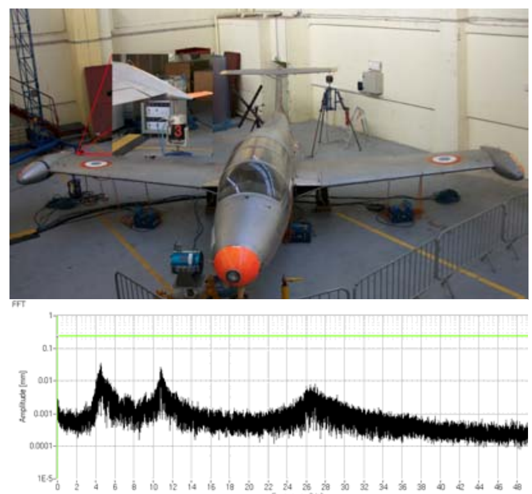

Figure 8 - Ground vibration study comparison with 50 accelerometers, ARAMIS took 2-hours to setup, verses 2-weeks. Data matched perfectly.

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

2.6 Assembly Quality Control

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 and on every component you need, all synchronously and fast. 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.

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 perfect format for humans to understand. We analyze the ARAMIS results, 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 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 you can pick anything as reference for any displacement measurement, you can interrogate the data.

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.

Composites do not assemble like metallic. Accumulated assembly strains build up towards the ultimate strength, weakening the structure, sometimes below design loads. Fatigue loads are substantial smaller and are easily exceeded without excellent quality control. ARAMIS can monitor assembly strains, even operational strains. We have monitored creep strains on turbine blades over years of operation.

Imagine getting the actual shape of a composite before assembly to confirm its fit, or quickly calculate the required shim. Documenting assembly deformation or strain, to confirm assembly quality, where none is done now. Image the computer telling the technician precisely where the composite should be placed without tooling, and then documenting the as built condition. Image monitoring those structures throughout their lives with the same simple method.

4. CONCLUSIONS

Holistic optical metrology can provide a complete knowledge based solution for the everyday issues that confront industry. Implementing optical metrology to the areas specified 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; Lean Engineering. Data is being gathered more efficiently and completely with less time and resources wasted. More educated assessments are possible resulting in complete solutions found to the typical problems that occur in the manufacturing arena; 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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