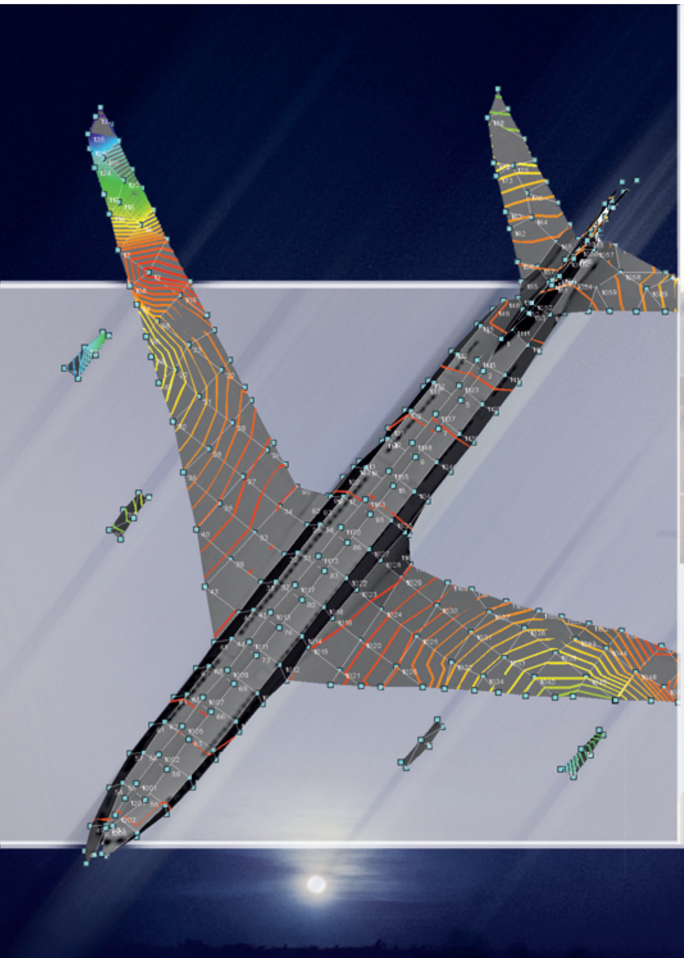
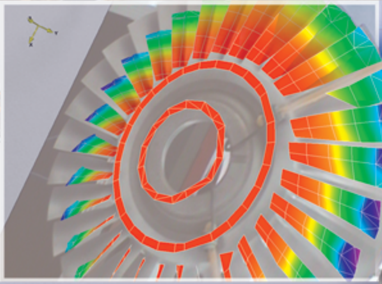
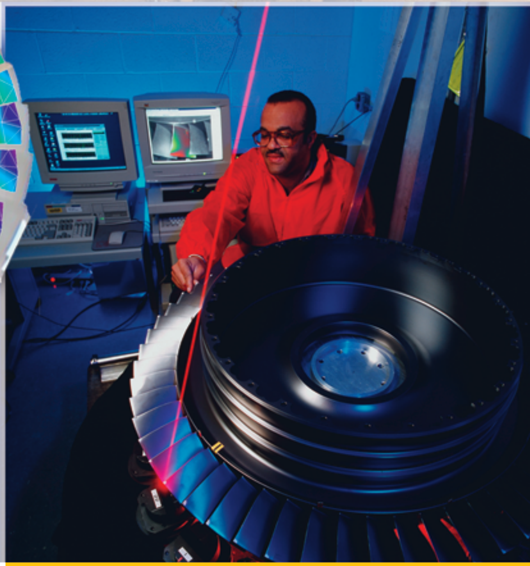
Polytec

Aerospace Vibration Testing







Laser-based Vibration Measurement Technology Helps to Increase Performance, Improve Time-to-market and Lower Costs in Aerospace Development

- Ground Vibration Testing
- Noise, Vibration and Harshness
- Experimental Modal Analysis
- Material and Fatigue Testing
- Engine Testing

Vibration Measurements in Aerospace Development

Structural testing is an integrated part of aerospace product design, development and manufacture. It is an essential step to ensure performance, quality, safety and reliability in the final product.

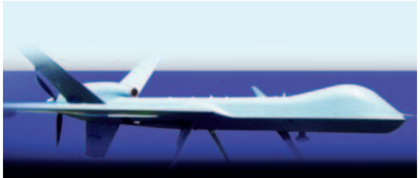
Today's market pressure for new, affordable high performance aerospace products is increasing the number of product variants and the complexity of tested structures. Product development and design refinement teams are requesting more efficient modal testing to increase throughput, while maintaining accuracy adequate to correlate with FE analysis models (i.e. load analysis, acoustic radiation, etc.).

In addition, these new structures require a substantial number of spatial data points. The combination of more structures and and more measurement points is rapidly increasing the costs of doing a traditional modal test with it's labor intensive approach of instrumenting structures with accelerometers and multi-channel data acquisition systems.

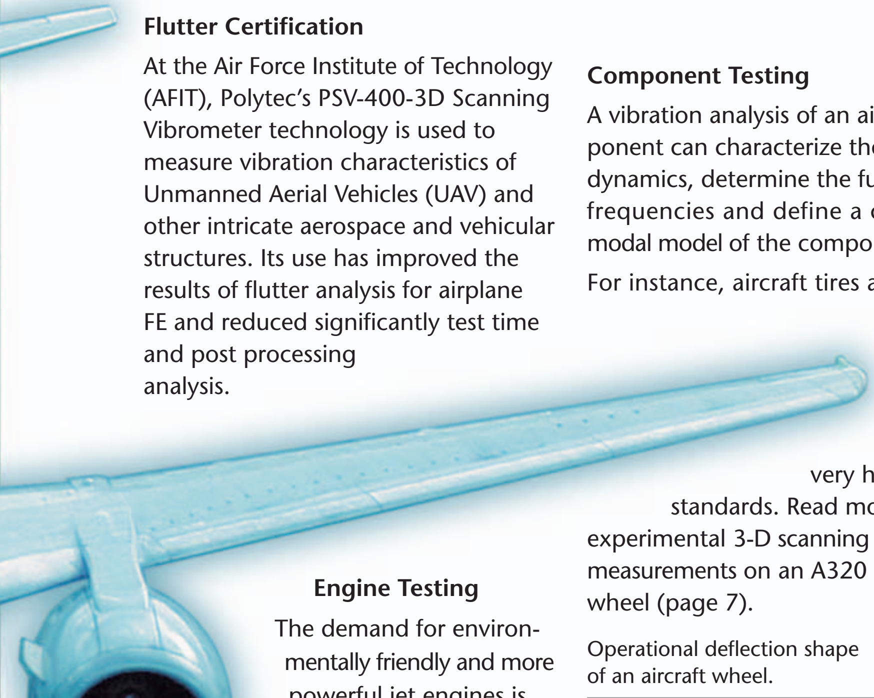
Noise, Vibration and Harshness

The fight for commercial aircraft orders has lead aerospace manufacturers to seek competitive advantages in two significant areas: fuel economy and increased passenger comfort. Consequently, today's aerospace engineers are more concerned with noise measurements than their predecessors were. By improving interior sound quality, aircraft engineers increase passenger comfort and desire to fly in a next generation commercial jet. In addition, by reducing exterior noise, the designer can improve the aircraft's acceptance in urban settings where air traffic is growing rapidly.

Polytec Vibrometers are a requirement for leading aerospace companies eager to make NVH measurements on their newest aircraft.



Predator UAV photo courtesy of General Atomics.



Flutter Certification

At the Air Force Institute of Technology (AFIT), Polytec's PSV-400-3D Scanning Vibrometer technology is used to measure vibration characteristics of Unmanned Aerial Vehicles (UAV) and other intricate aerospace and vehicular structures. Its use has improved the results of flutter analysis for airplane FE and reduced significantly test time and post processing analysis.

Engine Testing

The demand for environmentally friendly and more powerful jet engines is pushing engine design to new limits.

The correct interpretation of lifetime-relevant vibration phenomena is one of the most challenging and important tasks which can be successfully solved by laser vibrometry. Read the article on page 12.

Measurement of turbine blade vibrations. Photo courtesy:
Greg Roberts, Pratt & Whitney.

Ground Vibration Testing

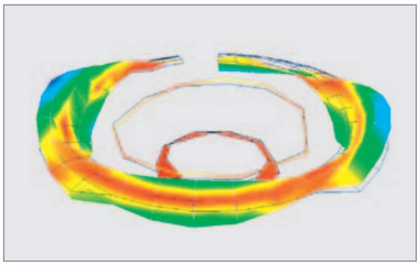
Ground Vibration Testing (GVT) is a costly requirement for new aircraft and aerospace structures. Data taken can be used for modal analysis and finite element (FE) model correlation, for loads analysis to prevent structural failure and flutter certification.

Component Testing

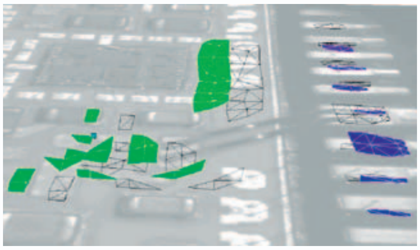
A vibration analysis of an aircraft component can characterize the structural dynamics, determine the fundamental frequencies and define a complete modal model of the component.

For instance, aircraft tires are critical components that must meet very high quality standards. Read more about experimental 3-D scanning vibrometer measurements on an A320 aircraft wheel (page 7).

Operational deflection shape of an aircraft wheel.



Find a comprehensive article about ground-based, dynamic testing of solar sails at NASA on page 4.



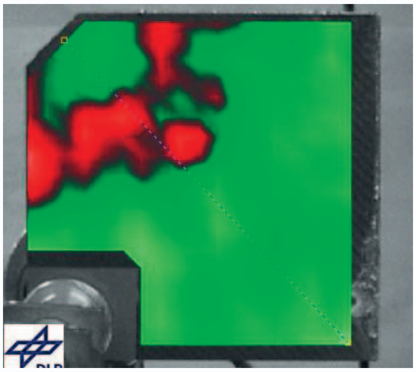
MEMS and PCB Testing

Laser vibrometry is the first choice for vibration testing printed circuit boards and micro-electro-mechanical sensors and actuators (www.mems-analysis.com).

Material Testing

Material delamination and cracking are common defects that can significantly degrade the performance of aerospace products. To find localized defects, both nonlinear laser vibrometry (www.polytec.com/usa/aerospace) and lamb wave detection (article on page 9) are successfully used as a means of non-destructive testing (NDT).

Material delamination detected by nonlinear laser vibrometry. Photo courtesy: IKP-ZFP, University of Stuttgart.



Flying the Best

Scanning laser vibrometry features rapid, full-field, non-contact (no mass loading) vibration measurement with high spatial and frequency resolution. By using Polytec's Scanning Vibrometers, aerospace development engineers and scientists can reduce both the time and complexity of vibration testing. Polytec vibrometers are the gold standard for non contact vibration measurement for aerospace development, quality control and aircraft health monitoring. Find more detailed information on page 15 or visit **www.polytec.com/usa/aerospace**.

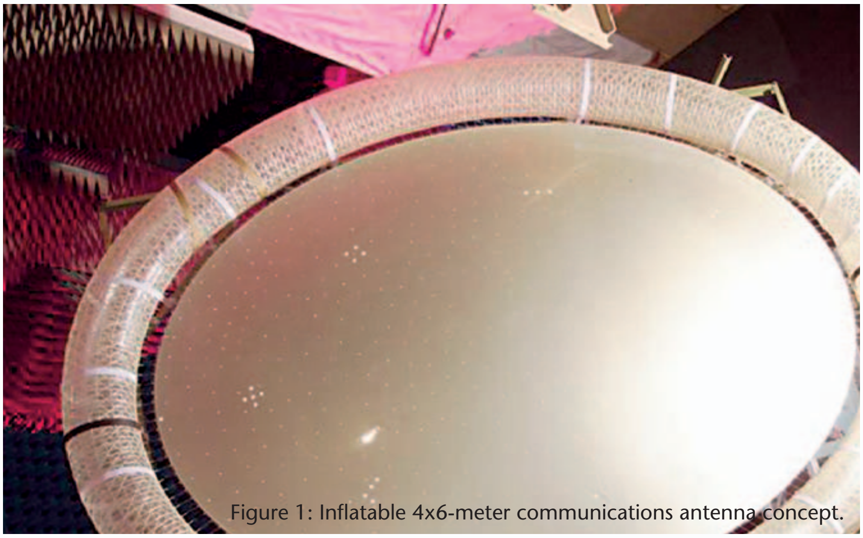


Figure 1: Inflatable 4x6-meter communications antenna concept.

Introduction

NASA has been developing Gossamer space structures for many years to reduce launch costs and to exploit the unique capabilities of particular concepts. For instance, dish antennas (Figure 1) are currently being pursued because they can be inflated in space to sizes as large as 30 meters and then rigidized to enable high data rate communications. Another example of a Gossamer structure is a solar sail that provides a cost effective source of propellantless propulsion. Solar sails span very large areas to capture momentum energy from photons and to use it to propel a spacecraft. The thrust of a solar sail, though small, is continuous and acts for the life of the mission without the need for propellant. Recent advances in materials and ultra-lightweight Gossamer structures have enabled a host of useful space exploration missions utilizing solar sail propulsion.

The team of ATK Space Systems, SRS Technologies, and NASA Langley Research Center, under the direction of the NASA In-Space Propulsion Office (ISP), has developed and evaluated a scalable solar sail configuration (Figure 2) to address NASA's future space propulsion needs. Testing of solar sails on the ground presented engineers with three major challenges:

- Measurements on large area surfaces thinner than paper
- Air mass loading under ambient conditions was significant thus requiring in-vacuum tests
- High modal density required partitioning of the surface into manageable areas.

This article will focus on the unique challenges with vacuum chamber, dynamic testing of a 20-meter solar sail concept at the NASA Glenn Plum Brook Facility (Figure 3).

In-Vacuum Setup

A Polytec Scanning Laser Vibrometer system (PSV-400) was the main instrument used to measure the vibration modes. The laser scan head was placed inside a pressurized canister to protect it from the vacuum environment (Figure 4). The canister had a window port from which the laser exited, and a forced air cooling system prevented overheating. A Scanning Mirror System (SMS) was developed and implemented, that allowed full-field measurements of the sail from distances in excess of 60 meters within the vacuum chamber.

The SMS (Figure 5) was mounted near the top of the vacuum chamber facility and centered over the test article, while the vibrometer head was mounted above the door frame of one of the large chamber doors. The SMS contained a stationary mirror that reflected the Polytec laser beam to a system of two orthogonal active mirrors.

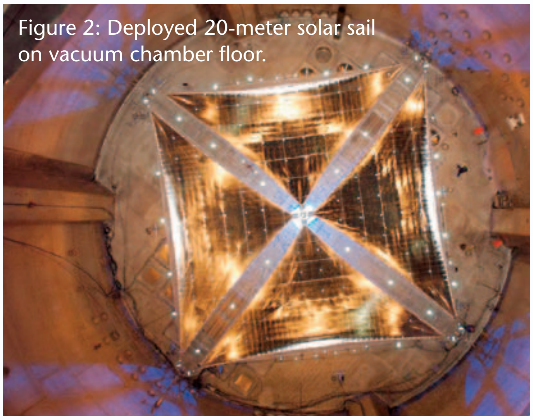


Figure 2: Deployed 20-meter solar sail on vacuum chamber floor.

Sail Away...

Laser Vibrometry Helps to Validate Gossamer Space Structures

NASA is pursuing the development of large ultra-lightweight structures commonly referred to as Gossamer space structures. These structures have large areas and small aerial densities, which complicates ground testing significantly as the ground operations interfaces and gravity loading can become cumbersome. Laser vibrometry has proven to be a critical sensing technology for validating the dynamical characteristics of these Gossamer structures, due to its precision, range, and non-contacting (zero-mass loading) nature.

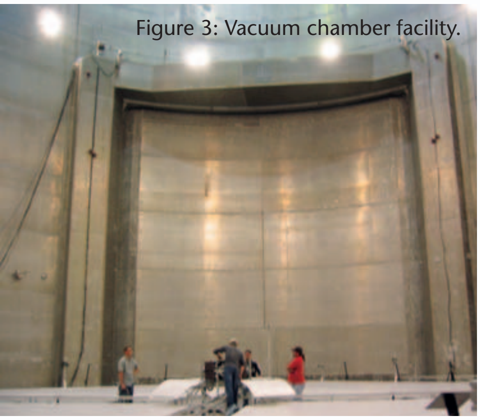


Figure 3: Vacuum chamber facility.

Figure 4: PSV-400 Scanning Vibrometer in pressurized canister.

These mirrors were used to scan the surface of the sail to find retro-reflective targets previously attached to the sail surface. These targets were essential to getting a good return signal and overcoming the specular nature of the reflective sail surface.

Fully Automated Test Procedure

A specially developed target tracking algorithm enabled automatic centering of the laser beam on each retro-reflective target. The initial laser system alignment, target tracking process, and entire data acquisition procedure was automated using the Microsoft Visual Basic (VB) programming language. Polytec's VB Engine and PolyFileAccess allowed the program to control all the functional capability of the Polytec system. The alignment of the vibrometer laser to the SMS steering mirrors was accomplished by software that used the vibrometer scan mirrors to trace out a square grid across a retroreflective target ring on the SMS. The strength of the laser return signal was measured during the scan. The software finds the angular location of the center of the target by calculating the centroid of this array of signal strength values and the corresponding mirror angles.

Once the laser was aligned to the SMS, a second program aligned the laser to the targets on the solar sail using the SMS steering mirrors. When all the targets were aligned and identified, then a third program incrementally read the target locations from a file and ran the entire data acquisition and storage process. For each target, the program would re-scan and center the laser prior to acquisition to ensure the highest quality dataset. This fully automated test procedure was considered critical, since many tests could take over 5 hours to run. Prior to the test, the vibrometer and SMS were certified for an 85-meter standoff distance (although larger distances are possible), well beyond the required distance of 60 meters for this test configuration.

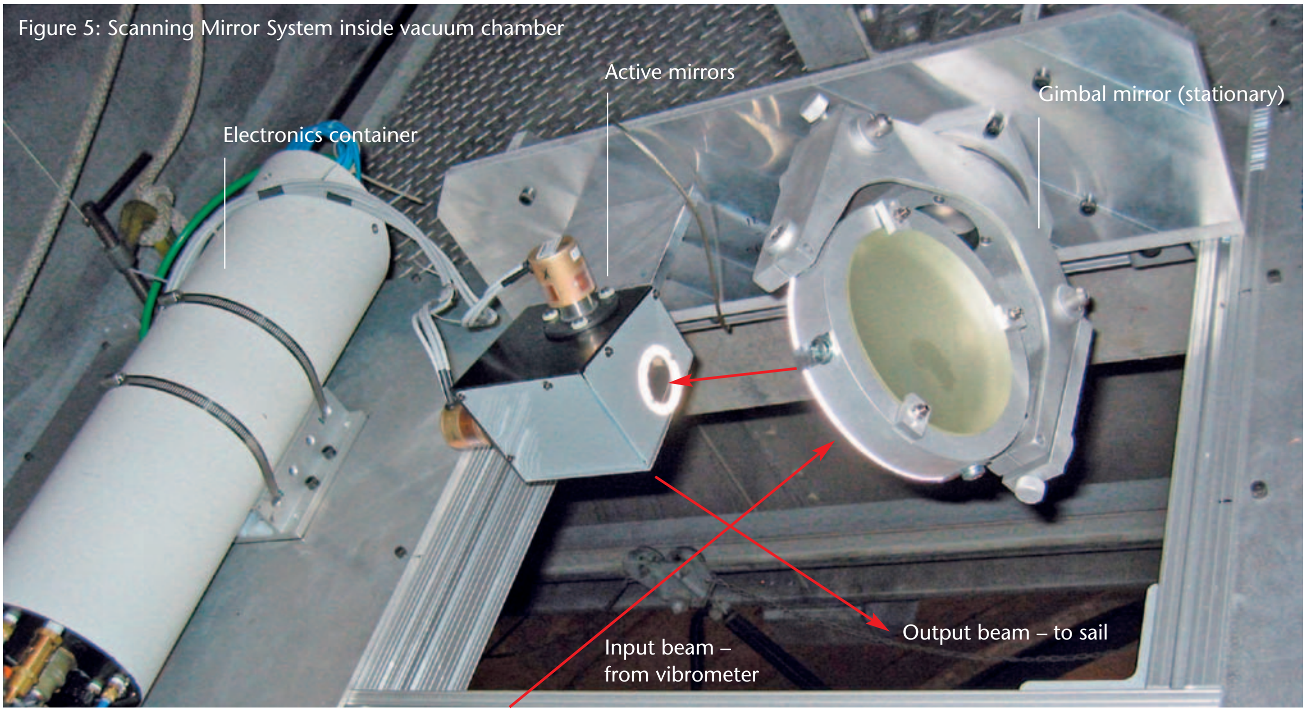
Excitation of Sail Motion

The baseline excitation method for the solar sail dynamics test used an electro-magnet mounted at each sail membrane quadrant corner near the-mast tip (2 magnets per sail quadrant), for a total of 8 magnets. A side view of the mounting fixture is shown in Figure 6. The magnet is mounted on a vertical translation stage with a linear actuator for precise, remote in-vacuum positioning of the magnet.

The magnet needs to be positioned within 5 mm of the sail to work properly, so small cameras were positioned next to each magnet and carefully aligned to ensure that the proper gap size was achieved. To reduce sail motion during vacuum pump down, the mast tips were secured with an electro-magnet that prevented vertical and lateral motion. Once at vacuum the voltage to the electro-magnet was removed, allowing a spring to pull the magnet away from the test article. The mast tips were then free to move with a soft suspension system gravity off-loader.

Most of the dynamics testing effort was focused on getting the best quality data possible on a single quadrant in-vacuum. The quadrant that had the most pristine sail membrane surface with few flaws was selected. The quadrant test used only the magnets on the quadrant of interest for stimulating the dynamics. The quadrant test was followed by a full sail system test, in which one corner magnet on each quadrant is driven simultaneously. This technique allowed for adequate excitation of the entire sail system and for the identification of major system level vibration modes. To reduce test time, the full sail system test only

Figure 5: Scanning Mirror System inside vacuum chamber



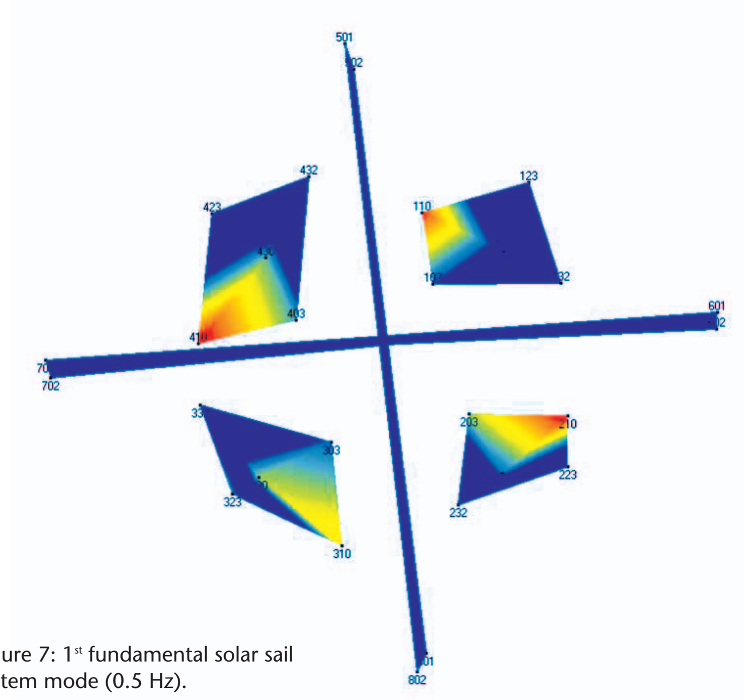


Figure 7: 1st fundamental solar sail system mode (0.5 Hz).

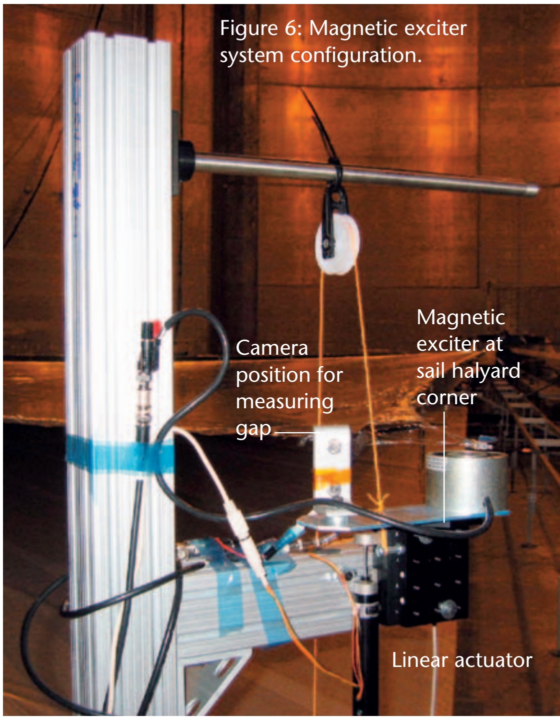


Figure 6: Magnetic exciter system configuration.

measured 5 sail membrane locations per uadrant and two mast tip measurements per mast. Since the test article configuration did not change from the quadrant tests to full sail system tests, the high spatial resolution quadrant test results with 44 measurements per quadrant could be compared with the lower spatial resolution system test results with only 5 measurements per quadrant.

Solar Sail Dynamics

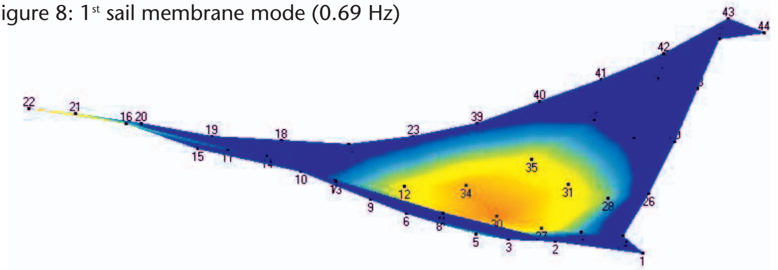
The 1st fundamental system mode of the solar sail identified was a "Pin Wheel Mode" with all quadrants rocking in-phase (Figure 7) at a frequency of 0.5 Hz. In this mode all the mast tips are twisting in-phase and the quadrants follow the motion by rocking and pivoting about the quadrant centerline. The 1st sail membrane mode, that has low mast participation, is a breathing mode (Figure 8) at 0.69 Hz. In this mode, the sail quadrant undergoes 1st bending through its centerline. Other higher order sail dominant modes were also found in which the long edge of the quadrant is in 1st bending, but the centerline undergoes either 2nd or 3rd order bending. These test results are important for updating structural analytical models that can be used to predict the on-orbit performance of the solar sail, free of gravity, to aid in further design iterations.

Conclusions

Laser vibrometry was successfully used to identify the fundamental solar sail system modes for structural model correlation. Also, higher order sail membrane modes were identified through a combination of many tests on each quadrant. The methodology described in this article is being further utilized for other Gossamer test programs, such as the antenna technology development program to validate large space based communication antennas.

We would like to thank NASA for granting permission to publish this article.

Figure 8: 1st sail membrane mode (0.69 Hz)



AUTHOR · CONTACT

James L. Gaspar
Research Engineer

Structural Dynamics Branch
NASA Langley Research Center

Hampton, Virginia, 23681

James.L.Gaspar@NASA.GOV

Where the Rubber Hits the Runway

Experimental 3-D Scanning Vibrometer Measurements on a Complete A320 Aircraft Wheel

Aircraft tires are critical components that must meet very high quality standards. Low frequency tire vibrations can affect aircraft handling while moving on the airport tarmac and may induce undesired fatigue-inducing vibrations (shimmy) in the landing gear. Vibration analysis can characterize the tire dynamics, determine the fundamental frequencies and define a complete modal model of the tire. From this model, engineers can objectively evaluate their concerns about the impact of vibrations on adjacent aircraft components. These concerns have very real consequences since excessive vibrations can lead to premature component fatigue and failure.

Experimental Setup

A complete A320 aircraft wheel was prepared with reflective spray and mounted on a shaker that was driven by a white noise excitation signal. The vibration response was measured in the radial, tangential and axial directions by a 3-D Scanning Vibrometer located 2.5 m from the wheel.

A high measurement point density was used with over 100 points on the tire and hub (Figure 1). Because of the non-periodic nature of white-noise excitation, a Hanning window with 66% overlap was used. Operational deflection shapes (ODS), frequency response functions (FRF) and coherence were measured from 30 to 400 Hz. Operational deflection shapes (ODS) were then constructed from the data. For more complete analysis and model verification, this experimental data can be passed to modal analysis software.

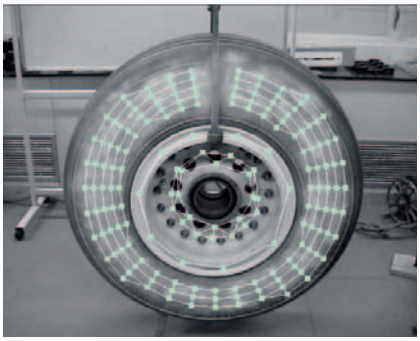
Results

Main resonances occurred at 37, 69 and 353 Hz. The ODS at 37 Hz shows a pure tire bending (Figure 2 a). At 353 Hz, a hub bending oscillation is combined with a higher tire bending shape (Figure 2 b). The FRFs (Figure 3) were clean and the deflection shapes were spatially well resolved. The coherence was reduced at frequencies between resonances, but in the regions around the peaks it was sufficient for operational modal analysis verification.

Summary

The 3-D Scanning Vibrometry improves the quality of experimental modal analysis of aircraft wheels by combining a simple setup procedure with a high measurement point density. Good deflection shapes are quickly and easily obtained without perturbing the structure. While only one example, this measurement represents a growing trend within the aerospace industry to perform 3-D tests on aircraft components.

Figure 1: Experimental setup and scan grid on the A320 wheel (courtesy Groupe SOPEMEA, Vélizy, France).



CONTACT

M. Jean-Marc Guilbault
Groupe SOPEMEA
Vélizy, France
guilbault@sopemea.fr

The complete measurement setup (including shaker and shaker controller) was provided by SOPEMEA. The aircraft wheel was supplied by Messier-Bugatti.

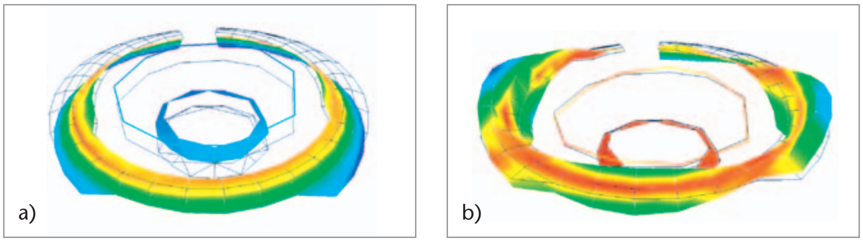


Figure 2: Operational deflection shapes at 37 Hz (a) and 353 Hz (b).

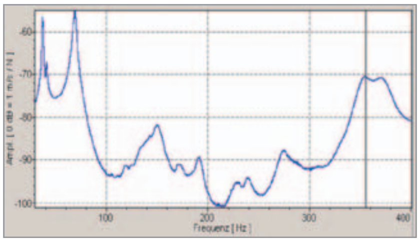


Figure 3: Average frequency response function

Healthy Airplanes

Health Monitoring of Aerospace Structures: Laser Vibrometry for Damage Detection Using Lamb Waves

Lamb wave inspection uses guided ultrasonic waves to detect damage in structures. Its commercial exploitation has been limited by drawbacks in current detection techniques. Using a new detection technology known as 3-D Scanning Laser Vibrometry, structural damage is clearly identified by locally increased in-plane and out-of-plane vibrations. The method is simple, fast and reliable, eliminating complex Lamb wave propagation studies, baseline measurements and signal post-processing.

Introduction

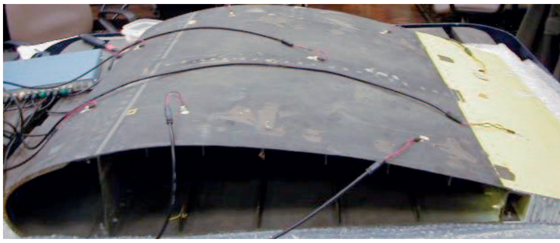
Aircraft designers, manufacturers and operators face many test and measurement challenges in the near future.

New, large capacity civil airframes that make greater use of composite materials are being developed and will be more widely used. At the same time, new military structures exhibit improved performance by relying on greater structural complexity.

End-users of these new aerospace structures demand reduced life-cycle costs and high operational availability. These goals can be achieved with the application of new materials and wider use of damage-tolerant design concepts that result in lighter structures and better performance.

While these new aircraft are being developed, the existing fleet is ageing and must be maintained.

A number of life extension programs have been considered and performed in recent years; civil structures are being converted from passenger aircraft to freighters and military aircraft are redesigned to add new weapon capabilities. These developments are a major challenge to existing aircraft structure inspection and maintenance methods.



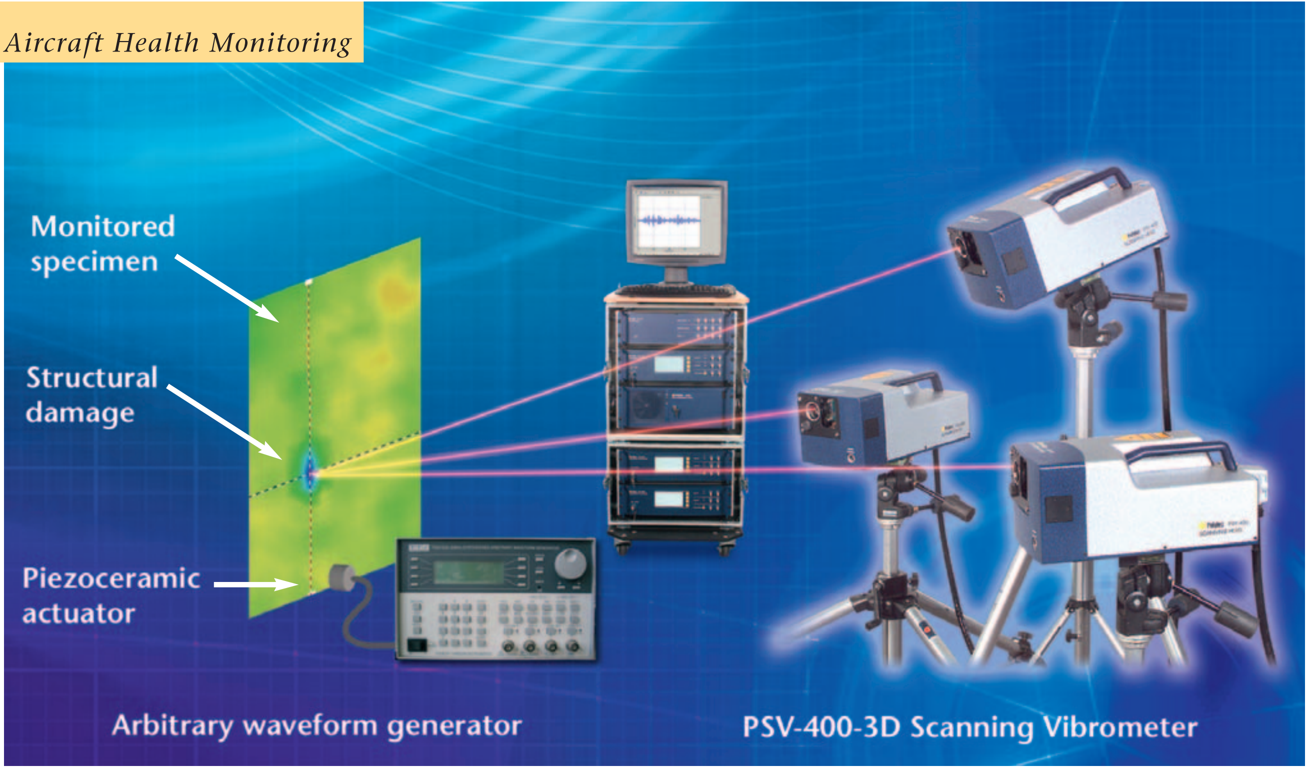


Figure 1: Experimental arrangements for Lamb-wave damage detection using 3-D laser vibrometry as a receiver.

Ageing aircraft structures require a significant maintenance effort. The application of new materials and damage-tolerant concepts in next-generation aircraft also requires enhanced and reliable structural health monitoring, with regular periodic inspections, to assure a safe and an extended operational life.

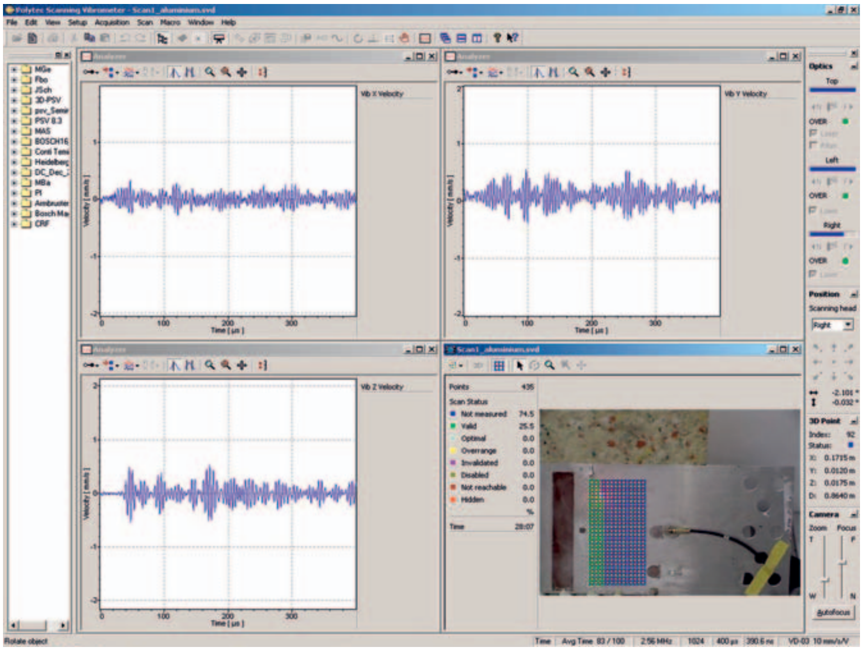
Damage Detection with Lamb Waves

A number of new technologies have been developed with the potential for automatic damage detection in aerospace structures. One promising technology is Lamb wave inspection, the most widely used damage detection technique based on guided ultrasonic waves, i.e. ultrasonic wave packets propagating in bounded media. While several Lamb-wave applications have been tried over the last 20 years, to date, the practical commercial exploitation of ultrasonic guided waves has been very limited.

There are three major drawbacks associated with current Lamb-wave damage detection techniques:

1. A significant number of actuator/sensor transducers are required for monitoring large structures. This is labor intensive, slow and costly. From the logistic point of view, it is not practical to cover an aircraft with many thousands of bonded or embedded transducers.
2. Lamb-wave monitoring strategies, often associated with complex data interpretation, require highly qualified NDT technicians for point-by-point field measurements. Consequently, broad deployment is restricted by higher costs and lack of properly trained technicians.
3. Current signal processing and interpretation techniques used for damage detection utilize signal parameters that reference baseline data representing the "no damage" condition. These parameters can be affected by effects other than structural damage such as changes in temperature or bad coupling between the transducer and the structure.

Figure 2: In-plane and out-of-plane Lamb-wave responses plotted using Polytec's PSV Software.



Points 435

Scan Status

- Not measured 74.5
- Valid 25.5
- Optimal 0.0
- Overrange 0.0
- Invalidated 0.0
- Disabled 0.0
- Not reachable 0.0
- Hidden 0.0

%

Time 28:07

-2.101 °
-0.032 °

3D Point
Index: 92
Status:
X: 0.1715 m
Y: 0.0120 m
Z: 0.0175 m
D: 0.8640 m

Time | Avg Time 83 / 100 | 2.56 MHz | 1024 | 400 µs | 390.6 ns | VD-03 10 mm/s/V

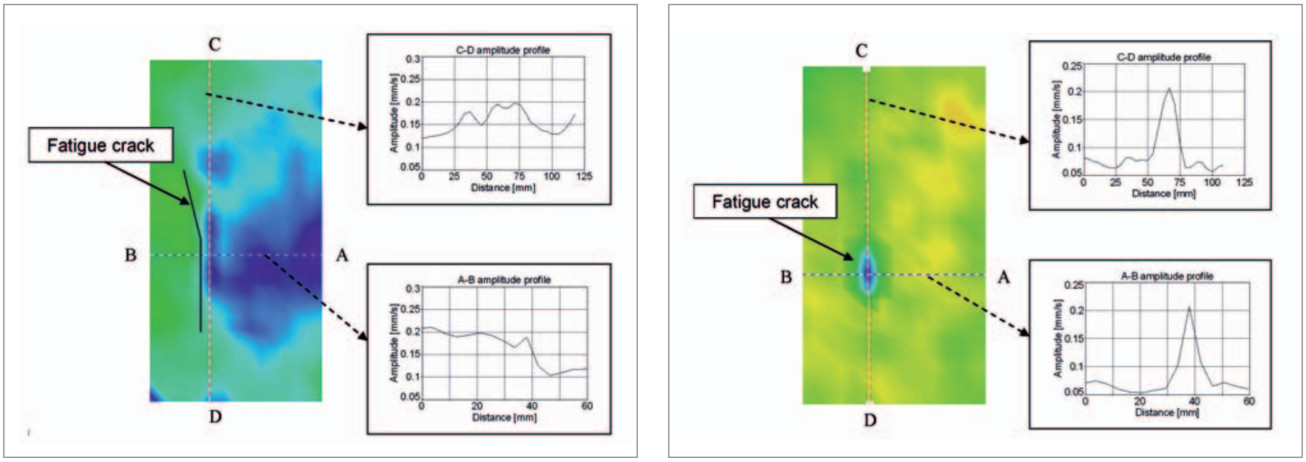


Figure 3: Fatigue crack detection in metallic structures using Lamb waves. RMS amplitude contour maps show amplitude profiles across fatigue cracks for: 75 kHz in-plane vibration (left) and 325 kHz out-of-plane vibration (right).

3-D Scanning Laser Vibrometry

Laser vibrometers can overcome many difficulties associated with Lamb-wave damage detection techniques.

In Figure 1, the application of a non-contact, multi-point scanning laser vibrometer to structural damage detection is illustrated. Lamb-waves from a piezoceramic transducer are sensed using the Polytec PSV-400-3D Scanning Vibrometer (Figure 2). The 3-D scanning vibrometer covers the complete optically accessible surface with a high density of sample points. At each sample point, the vibration vector is measured including both in-plane and out-of-plane components. These measurements are assembled into an intuitive 3-D animated deflection shape.

Examples of damage detected in aerospace specimens using Lamb-wave monitoring are shown in Figures 3 and 4. These results show that structural damage can be identified clearly by locally increased in-plane vibration amplitude (e.g. fatigue crack in Figure 3, left, and delamination in Figure 4) and by attenuation of out-of-plane vibration amplitude (e.g. fatigue crack in Figure 3, right).

Conclusion

Scanning Laser Vibrometry can reveal structural damage and its severity such as crack length and delamination area. Simple contour maps and profiles of Lamb-wave amplitude across the structure are sufficient to see the damaged areas and do not involve studies of complex Lamb-wave propagation in the structures, baseline reference measurements in undamaged structures, or signal post-processing to extract damage-related features. The method is straight forward, fast, reliable and immune to environmental effects.

AUTHOR · CONTACT

Prof. Wieslaw J. Staszewski

**Department of
Mechanical Engineering
Sheffield University**

Sheffield S1 3JD, UK

**w.j.staszewski@sheffield.ac.uk
www.dynamics.group.shef.ac.uk**

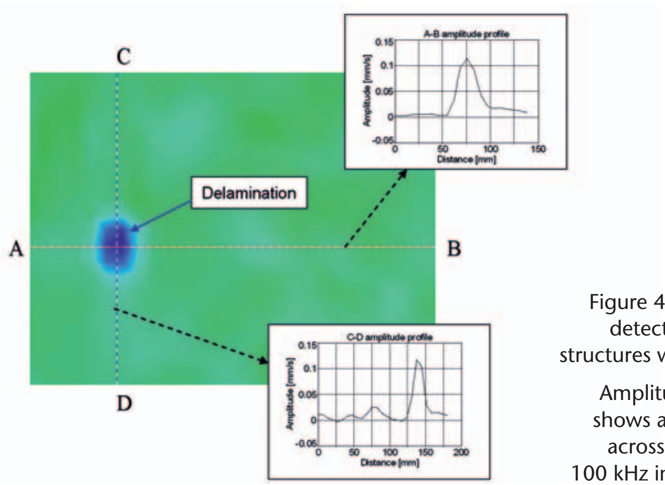


Figure 4: Impact damage detection in composite structures with Lamb waves.

Amplitude contour map shows amplitude profiles across delamination for 100 kHz in-plane vibration.

More information can be found in:
W.J. Staszewski, C. Boller and G.R. Tomlinson, Health Monitoring of Aerospace Structures, John Wiley & Sons, Chichester, 2003. The full text of this article (including references) is available on the Internet and can be downloaded on www.polytec.com/usa/aerospace.

Secure Power for Jet Engines

Using Scanning Vibrometry to Visualize Localization Effects of a Jet Engine Compressor Blisk

Blade integrated disk (blisk) technology is an innovation increasingly used in the design of jet engines. To be commercially effective, blisks must be designed and manufactured to specifications that insure long lifetimes. The dynamic properties of blisks can be used as an important quality check on the manufacturing and the design process. With this type of inspection, the correct interpretation of lifetime relevant vibration phenomena is one of the most challenging and important tasks. The non-contact measurements taken by the PSV-400 Scanning Vibrometer are essential for precise vibration mode visualization and discrimination between acceptable and unacceptable localized vibration amplitudes.

Introduction

The demand for environmentally friendly and more powerful jet engines is pushing the integral design of blade integrated disk to new limits.

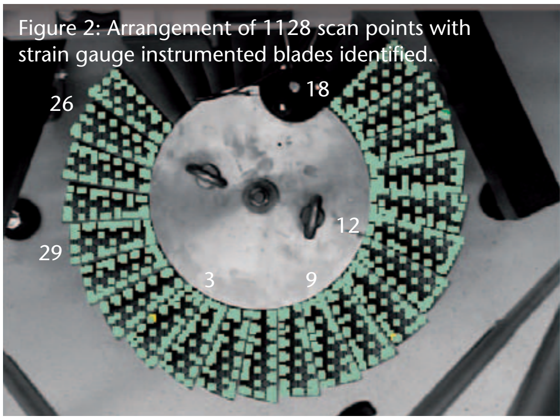


Figure 2: Arrangement of 1128 scan points with strain gauge instrumented blades identified.

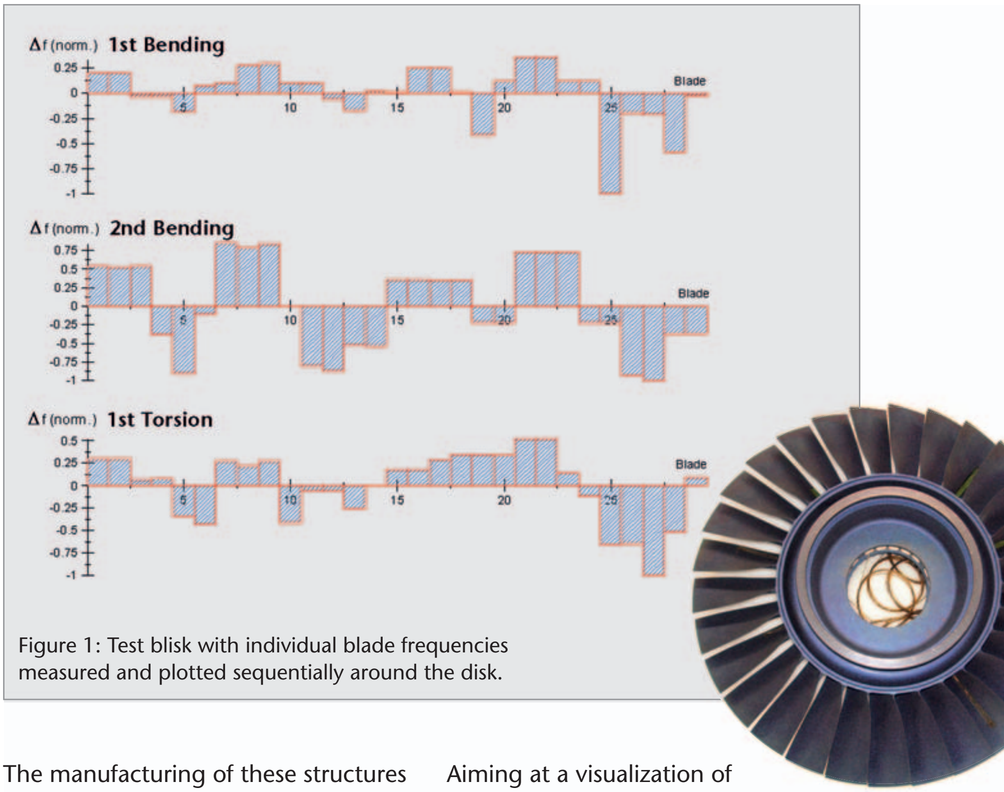


Figure 1: Test blisk with individual blade frequencies measured and plotted sequentially around the disk.

The manufacturing of these structures is either realized as one piece or based on friction welding so that weight-intensive blade foot constructions are not necessary. Consequentially, a stress optimized design is achieved allowing for higher rotation speeds. However, there are a number of important questions with regard to the structural dynamics of the blisk. The primary concern relates to the creation of individually different vibration behaviors for each blade (Figure 1) due to influences from manufacture imperfections (mistuning). These departures are not negligible in new jet engine designs. They can lead to localized vibration modes which produce high stresses in blades due to aerodynamic excitation.

Effect of Localization

If a localized vibration mode is excited during operation, maximum displacements can be more than twice as high compared to the perfect design (tuned). The strain level of blades affected by localization is particularly high negatively impacting the expected lifetime of the blisk. This tendency is intensified by an extremely low pure material damping value as a result of the integral construction.

Aiming at a visualization of vibration modes, and thus localization phenomena, laser scanning vibrometry can be regarded as powerful tool.

Experimental Setup

The blisk under test (Figure 2) contains 29 blades, of which the blades # 3, 9, 12, 18, 26 and 29 are instrumented with different types of strain gauges. Due to the additional mass, damping and stiffness resulting from each strain gauge an additional and non-negligible mistuning is generated. Before testing, a strain gauge calibration has been performed to define allowable limits.

The excitation is realized by applying an electro-dynamic shaker connected to the clamping device (Figure 3), using a periodic chirp signal in the range of the fundamental blade frequencies.

In order to determine the frequency response functions (FRF), a reference force cell is mounted on the shaker. Due to shadowing effects, the PSV- 400 scan initially includes just 22 blades. To complete the vibration mode information in circumferential direction, an additional ring-shaped scan close to the blade tips is carried out.

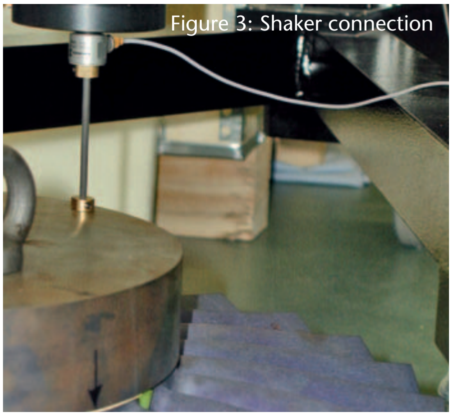
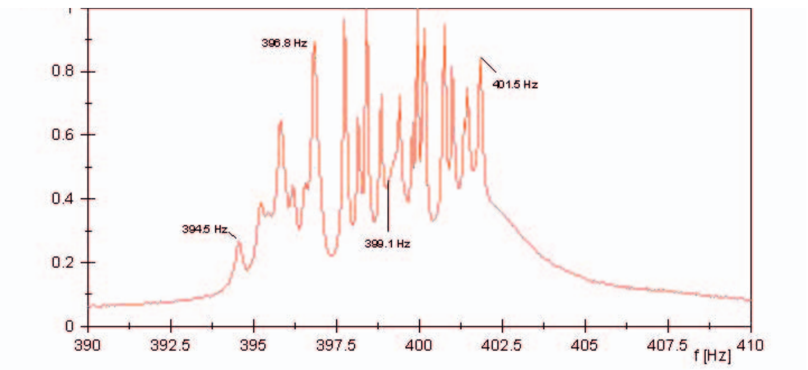


Figure 3: Shaker connection

Figure 4: Averaged Frequency Response Function.



Results

By plotting the average value of the frequency response functions (FRFs) for all scan points (Figure 4), it can be seen that a number of peaks appear inside the investigated frequency range. Some of the peaks result from blade mistuning, whereas others are assigned to modes dominated by a strongly coupled movement between disk and blade.

In Figures 5 and 6, a representative selection of modes is visualized. The cases a) – c) are characterized by strong couplings of disk and blade vibration, which is documented by the appearance of nodal diameter lines. Case a) corresponds to a mode with two nodal diameters known as "cyclic symmetry mode 2" (CSM 2), which appears distorted to a certain degree due to mistuning. For this reason, the pure sine shape of the unwound mode (traveling around the circumference of the disk at each blade), as expected for a tuned system, gets lost (Figure 5a).

The mode shapes b) and c) correspond to CSM 5 and CSM 1 whereas a corresponding assignment in d) is not possible. From the visualization a strongly localized mode shape appears in the vicinity of blade #3 presumably caused by mistuning. Such a mode is characterized by a largely isolated vibration of a single blade or of a group of adjacent blades. Blade #3 is instrumented with a strain gauge causing additional mass and stiffness and with that additional mistuning. Preliminary experiments show that the frequency assigned to this mode corresponds to the so called blade-alone frequency of the instrumented blade #3.

Conclusions

Based on data taken with the PSV-400 Scanning Vibrometer, localization effects at mistuned compressor blades could be verified. The knowledge of such phenomena is of essential significance with regard to the evaluation of lifetime.

Acknowledgement

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A German version of this article is available on the Internet and can be downloaded on www.polytec.de/aerospace.

AUTHOR · CONTACT

Dr. -Ing. Bernd Beirow

Brandenburg Technical University Cottbus

Chair of Structural Mechanics and Vehicle Vibrational Technology

D-03046 Cottbus, Germany

beirow@tu-cottbus.de

www.tu-cottbus.de/strukturmechanik/eng/indexeng.html

Figure 5: Selected vibration modes.

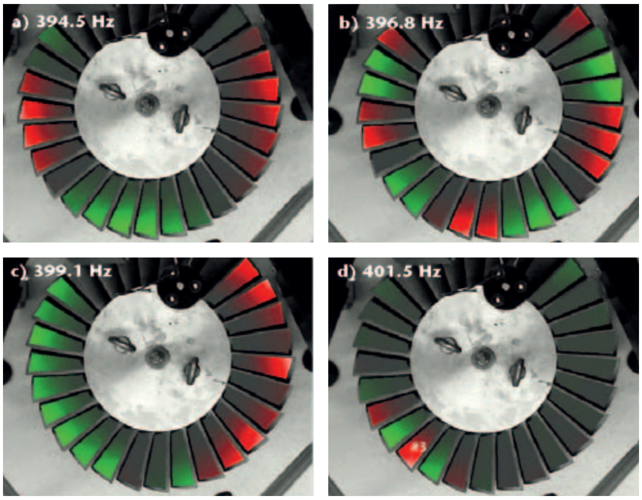
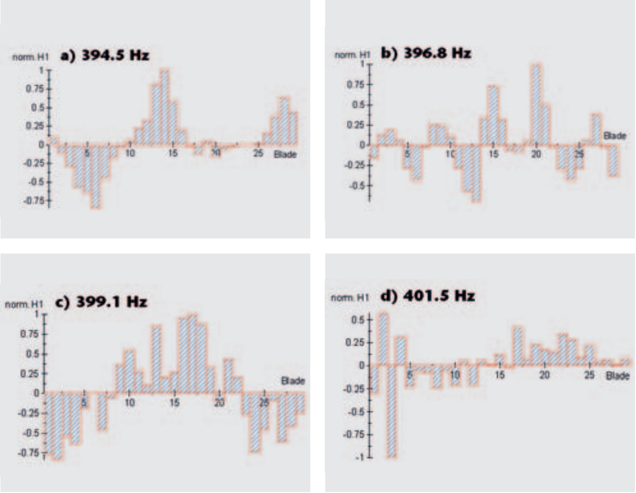
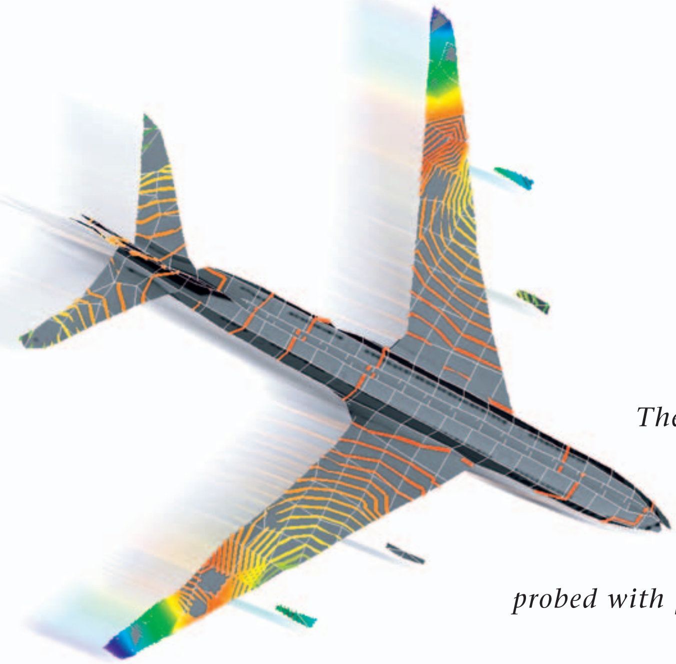


Figure 6: Selected modes corresponding to Fig. 4.

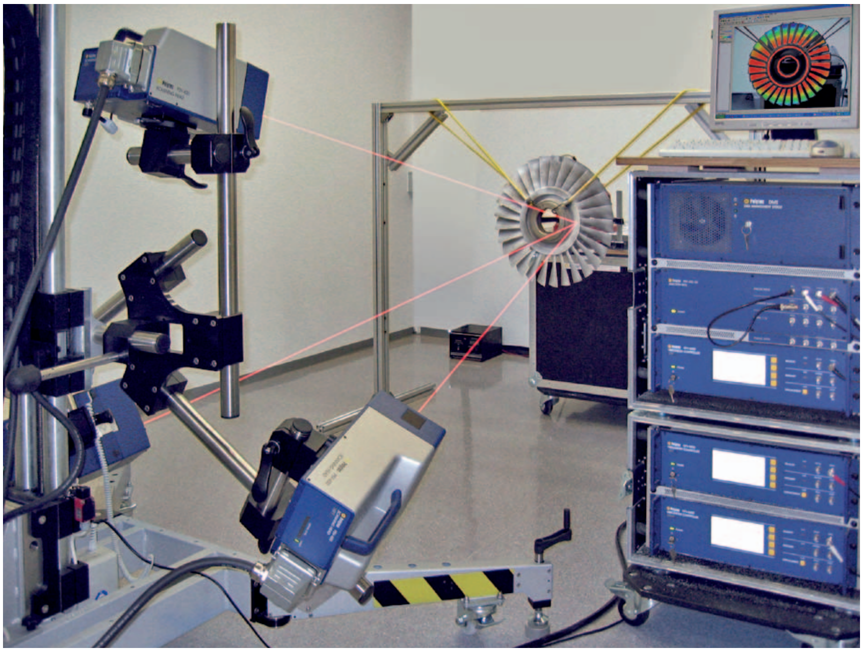




Polytec

Polytec Scanning Vibrometers

The PSV-400 and PSV-400-3D Scanning Vibrometers provide cutting edge measurement technology for the analysis and visualization of structural vibrations up to 20 MHz. Entire surfaces can be rapidly scanned and automatically probed with flexible and interactively created measurement grids, with no mass loading or added stiffness and no time.



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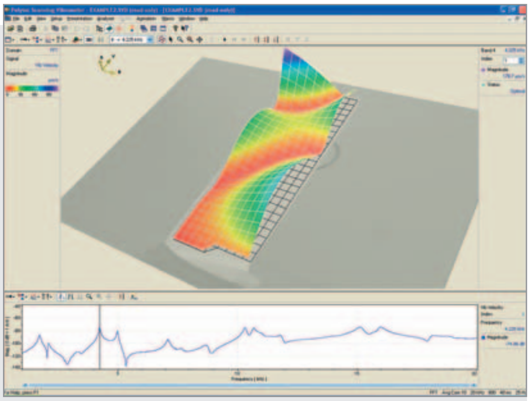
Polytec Scanning Vibrometers:

Benefits for Aerospace Testing



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- Simplifies frequency response measurements, calculation of deflection shapes and modal analysis
- Efficient large-scale vibration data acquisition and management
- Large stand-off distance for vibrometer and Geometry Scan Unit, up to 50 m for measuring typical surfaces of large objects
- High spatial and frequency resolution (0.001 Hz) e.g. for modal analysis on turbine blades
- Test data can be measured directly at FE nodes
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- Measurement of rigid body modes (including in-plane motions)
- Smooth transfer of measured data to modal analysis software and processing of multiple references for MIMO measurements
- Partial measurements on large structures can be grouped together (stitched) to form a global data set of 3-D geometry and 3-D vibration data

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Founded in 1967, Polytec GmbH is an ISO-9000 certified manufacturer supplying customers with the gold-standard in laser Doppler measurement solutions. All of our vibrometer systems are developped, engineered and manufactured to the highest standards and specifications. Engineering such a sophisticated product requires a truly multi-disciplined company. Polytec's long-standing reputation and undisputed performance advantages are well known. We are very proud of the Polytec Scanning Vibrometer. Its design and construction demonstrate our expertise in opto-mechanics, electronics, computer hardware & software, as well as applications knowledge in the field of mechanical engineering.

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Polytec GmbH (Germany)
Polytec-Platz 1-7
76337 Waldbronn
Tel. +49 7243 604-0
Fax +49 7243 69944
info@polytec.de

Polytec France S.A.S.
Bâtiment Orion – 1er étage
39, rue Louveau
92320 Châtillon
Tel. +33 1 496569-00
Fax +33 1 57214068
info@polytec.fr

Polytec Ltd.
(Great Britain)
Lambda House
Batford Mill
Harpenden, Herts AL5 5BZ
Tel. +44 1582 711670
Fax +44 1582 712084
info@polytec-ltd.co.uk

Polytec Japan
Arena Tower, 13th floor,
3-1-9, Shinyokohama,
Kohoku-ku
Yokohama-shi, Kanagawa
222-0033
Tel. +81 45 478-6980
Fax +81 45 478-6981
info@polytec.co.jp

Polytec, Inc. (USA)
North American Headquarters
16400 Bake Parkway
Suite 150 & 200
Irvine, CA 92618
Tel. +1 949 943-3033
Fax +1 949 679-0463
info@polytec.com

Polytec, Inc.
Central Office
1046 Baker Road
Dexter, MI 48130
Tel. +1 734 253-9428
Fax +1 734 424-9304

Polytec, Inc.
East Coast Office
25 South Street, Suite A
Hopkinton, MA 01748
Tel. +1 508 417-1040
Fax +1 508 544-1225

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