Polytec

InFocus

Optical Measurement Solutions

Laser-precise Measurement of Structural Dynamics and Durability
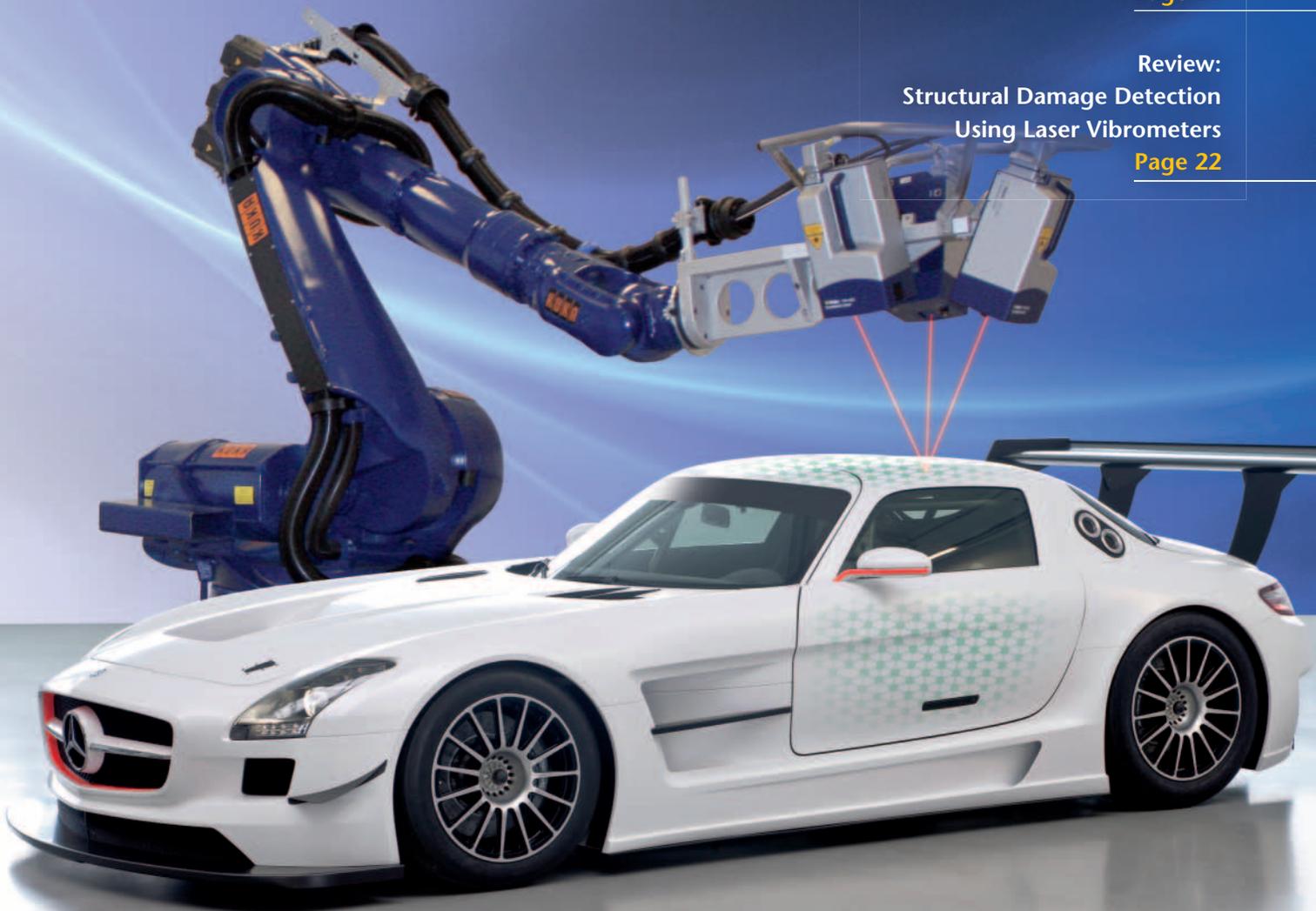
Eric Winkler

Dr. Hans-Lothar Pasch

Dear Readers,

"Design Right, First Time" – We are all familiar with that maxim. Increasing computer power enables significantly more development steps to be integrated into the early phase of the product creation process, when the design is still flexible and can be optimized relatively quickly and cheaply.

Despite major advances in reducing development lead times, simulating complex product attributes stretches even the fastest computers to the limits of their capabilities. Consequently, actual, real-world acoustic and vibration measurements on prototypes are still essential. In this context, Polytec has in recent years been focused on automating the optical modal test process using the RoboVib® structural test station and integrating its measurement operations into the CAE process.

Experience from numerous contract measurement services, together with feedback from our users, demonstrate that 3-D laser vibrometry used in conjunction with a robot can deliver a quantum leap in terms of efficiency and quality in the model validation process. The quality of measurement data accuracy and high measuring point density permits correlation of the test and FE models, at modest and higher acoustic resonance frequencies.

We hope that you enjoy reading this latest issue of InFocus and that it will provide you with lots of new ideas to help you in your work.

Eric Winkler
Vice President
Optical Measurement Systems

Dr. Hans-Lothar Pasch
Managing Director
Polytec GmbH

# Laser Vibrometer Enhances Operational Safety of Rail Bridge

The 110 year-old Müngsten bridge near Solingen, the highest railroad bridge in Germany, was the subject of intensive measurements undertaken by German railways operator Deutsche Bahn with Polytec in September 2010.

A number of laser vibrometers were deployed, from a safe distance of approximately 90 meters away, to measure the vibration and deflection caused by repeated traversing of a diesel locomotive over the bridge. 190 measuring points were used to check the bridge's static stability. The goal of the campaign was to compare the new lon-range RSV Remote Sensing Vibrometer with the proven OFV-505/-5000 standard vibrometer (photos). In the next issue of InFocus you can read more about the key measurements and the successful deployment of the newly developed RSV Vibrometer.

Photo: Christian Beier
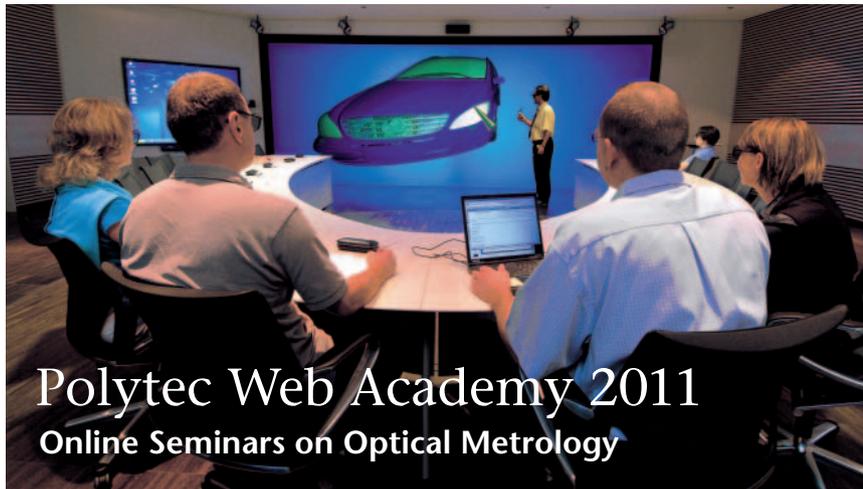
Polytec Web Academy 2011
Online Seminars on Optical Metrology

The Polytec Web Academy is an invaluable e-learning medium providing knowledge about applications and solutions in optical metrology conveniently, without obligation and free of charge. The topics include proven and effective measurement procedures for variables such as vibration, movement and surface topography. They cover a multitude of application areas such as automotive, aerospace, ultrasound technology and MEMS as well as biology, medicine and many more.

Polytec is offering these online seminars to convey technical know-how, application knowledge and product news directly and interactively via the use of multimedia. In addition, via the chatroom, there is the opportunity to discuss application issues directly with Polytec's experts.

The event schedule is available online on the web – these informative technology and application seminars can be booked and visited right now. There you'll also find the current list of topics and dates for future events. Register for your preferred seminars at the Polytec Web Academy at: **http://polytec.webex.com**.

Polytec Tutorial
Experimental Modal Analysis

Modal analysis is used to describe a structure in terms of its natural dynamic properties, which are its frequencies, damping and mode shapes. Without using a rigorous mathematical treatment, this article will introduce some concepts about how structures vibrate and some of the mathematical tools used to solve structural dynamic problems. Learn more about the basics of experimental modal analysis and download the tutorial from **www.polytec.com/ema.**

Mode 1   Mode 3
Mode 2   Mode 4
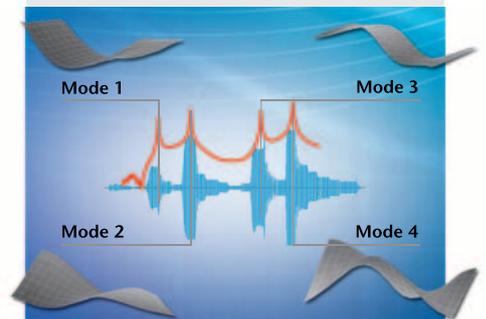
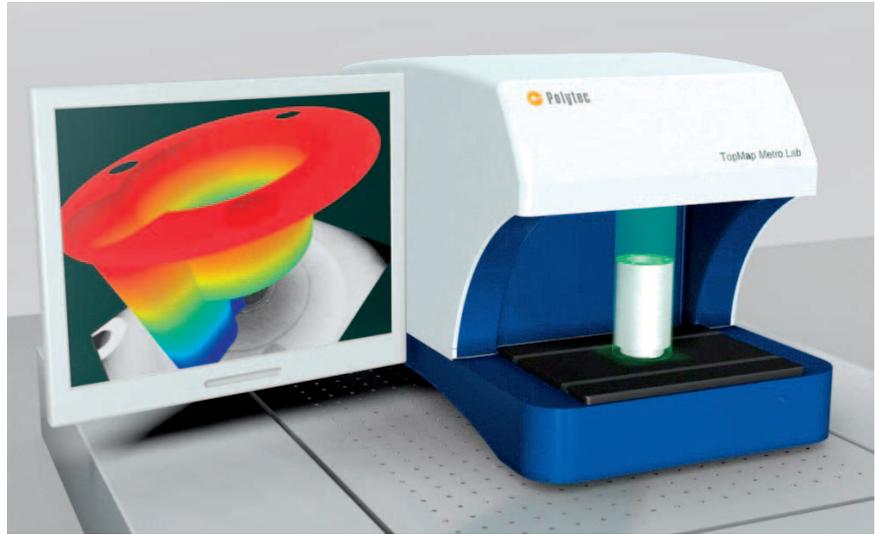# Polytec Surface Metrology
## New Technology Video

Surface measurements are critical to the successful manufacturing of tight toleranced, precision parts, for instance in the automotive, medical and other industries.

Non-contact scanning white-light interferometry is vastly superior to traditional contact measurement methods and has become the preferred tool for industrial quality control of precision part geometry and surface finish. This brand-new comprehensive video shows how the TopMap White-Light Interferometer works, how it is operated and which applications can be accomplished. Please download the video from **www.topmap.info**.

New Point Sensors

Polytec broadens its product portfolio for surface measurement by introducing TMS TopSens and TMS TopLine point sensors. Chromatic confocal imaging and confocal spectral interferometry technology enables the rapid characterization of surfaces for the determination of micro/nanotopography, optical surface roughness and the thickness measurement of transparent samples. The measuring heads contain no moving parts and are therefore robust and maintenance-free. These new sensors will enable Polytec to serve the needs of the electronics and microelectronics, semiconductor, automotive, micromechanical and optical industry sectors. Please find more information on page 27 and at **www.topmap.info**.
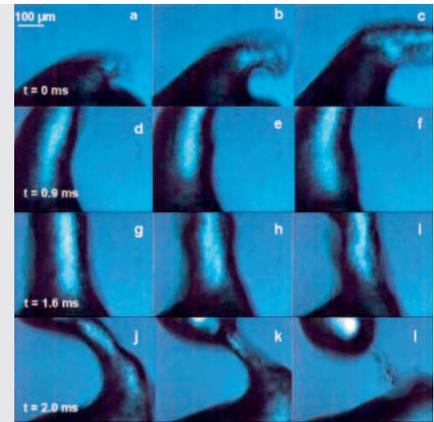
Faraday Was Wrong

Michael Faraday was not quite right when he assumed the appearance of "Faraday waves" were at a frequency of half the excitation frequency.

Capillary waves on fluids were first described by Faraday in 1831. The difficulty of accurately measuring their characteristics has limited research work to frequencies up to, at most, a few thousand Hertz. However, there are many practical applications requiring far higher frequencies, from the production of nanoparticles to pulmonary drug delivery via atomization. A Polytec MSA-400 Micro System Analyzer at 20 MHz excitation frequency was used by an Australian research team to determine the frequency spectrum of capillary waves on the surface of a fluid drop. They found that the capillary waves generated at a frequency f were not appearing at $f/2$ according to the theory associated with Faraday waves. This helps to explain why aerosol mists formed by high-frequency ultrasonic excitation of fluids can have droplet diameters far different from that predicted by the Faraday wave theory.

Source: Qi, A., Yeo, L.R., and Friend, J.R., Interfacial destabilization and atomization driven by surface acoustic waves, Phys. Fluids 20, 074103 (2008); http://dx.doi.org/10.1063/1.2953537

Simulation Model Updating

Measurement Services for Automated Vibration Measurement Through to Complete Modal Testing

Polytec supplies high-grade measurement data from experimental modal tests for simulation departments in the industrial R&D sector. A modal analysis on the FE model leads to seamless and highly efficient model updating.

As well as offering a wide range of contract measurement, equipment hire and other services carried out on-site or at one of Polytec's applications labs in North America, the UK, Germany, France, or Japan, we can also assist you throughout the whole project phase with expert advice and support.

Vibration Measurements

Vibrometers measure virtually any vibration, at velocities up to 30 m/s, at frequencies up to 1.2 GHz and at displacement resolutions in the picometer range. Compared to conventional sensors, laser vibrometers are faster, record many times more measuring points, and are reactionless and hence much more accurate. This provides our customers with comprehensive measurement data, including frequency response functions, operational deflection shapes, time diagrams and frequency spectra.

Automated Measurement with RoboVib®

Our RoboVib® Structural Test Station permits automated measurement, recording of all the 3-D vibrations of the surface of a body from multiple directions and points on the structure. A valuable benefit of this system is its high productivity, based on an ability to perform automatic measurements overnight. For more details see page 8, or visit **www.robovib.us**.

Complete Modal Test

An experimental modal test by Polytec encompasses planning, setup, measurement of the transfer functions and depiction of the deflection shapes, with the further option of modal analysis based on the measured data. Polytec vibrometer systems and software enable non-contact, precision measurement at a large number of measuring points, delivering very good MAC values when comparing experimentation and simulation. The measurement grid can be imported from the simulation, enabling direct comparison of the values at identical measuring points or nodes, thus ensuring easy model updating.

If you are a development or test engineer, benefit from the latest Polytec measuring technology and from the know-how of our experienced staff. They can help you to utilize the full potential of the measuring systems deployed and to obtain top-class measurement data.

More info: **www.polytec.com/service**
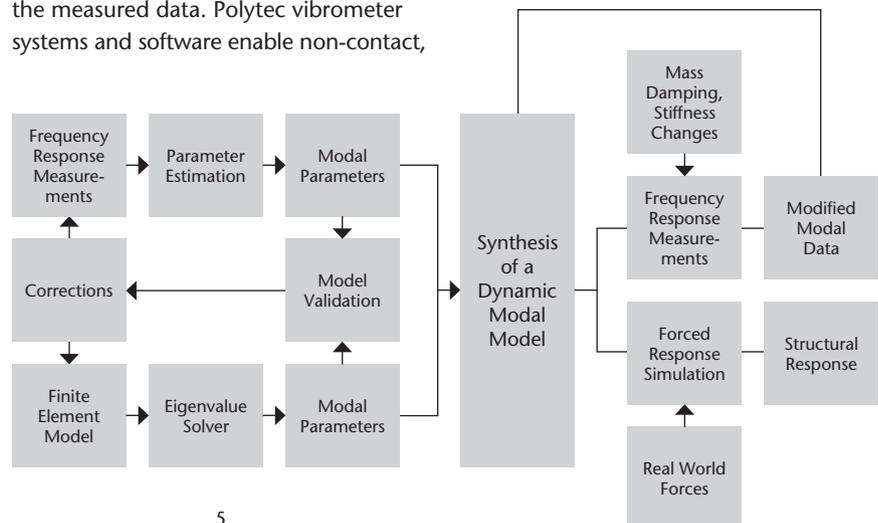
Closing the Data Gap
## Improved FE Model Validation by Automated Modal Testing with RoboVib®
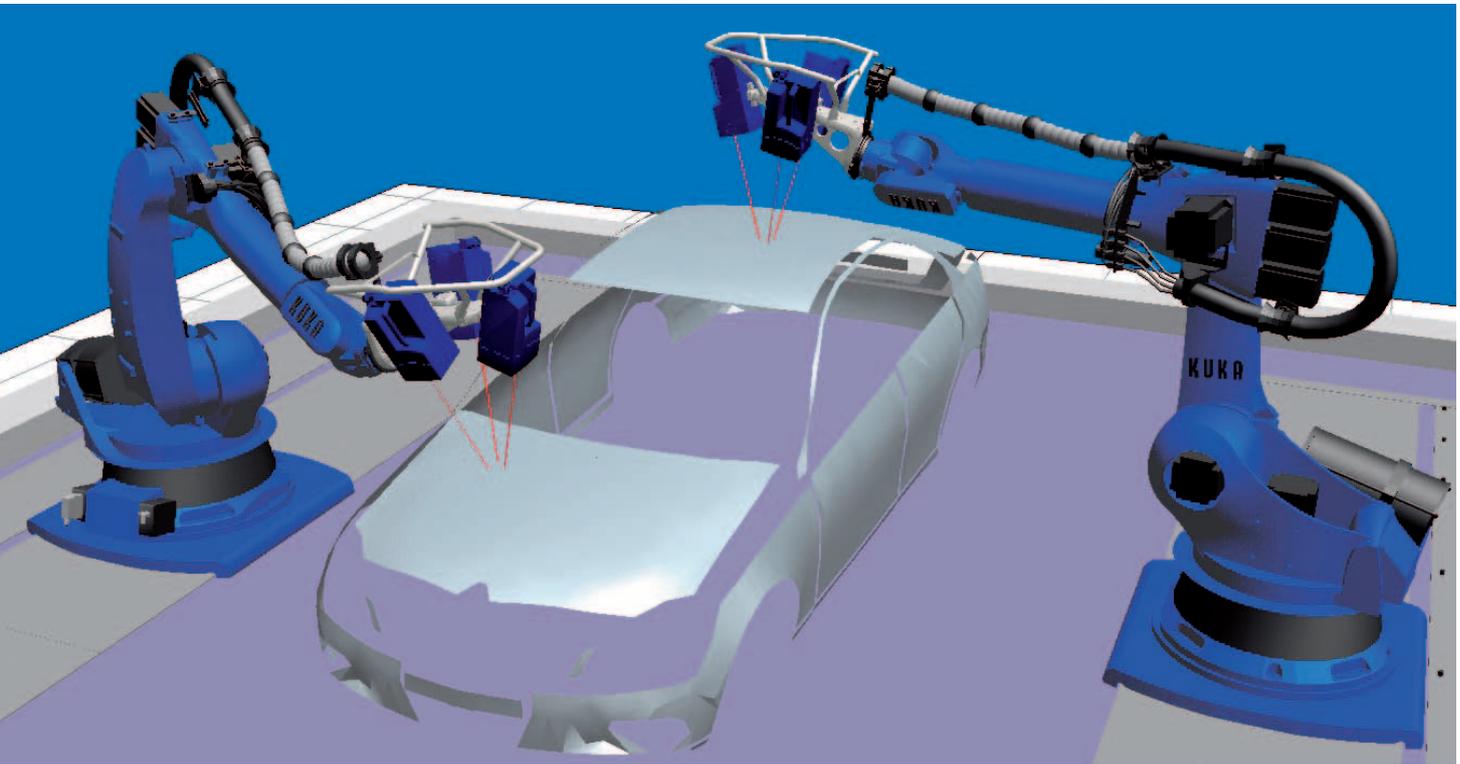
A new approach was presented during the ANSYS Conference & 28th CADFEM User's Meeting held in 2010 in Aachen, Germany, which facilitates the integration of experimental modal analysis test into the CAE data chain. This approach combines the properties of the PSV-400-3D Scanning Vibrometer with robotics and makes it possible to use CAE data for defining the test. The core benefit for the model updating process is the ability to work with imported FE geometries and coordinate systems, and to acquire data automatically at all of the nodal points.

Optical vs. Conventional Testing Approach

A case study compared the automated optical approach to conventional modal testing with accelerometers (Fig. 1). A cast alloy motorcycle gearbox cover was probed with both methods. The focus was not so much on comparing the efficiency of the methods but on the benefits for the FE (finite elements) model update. The FE model was a tetrahedral mesh type with 69019 elements and 19994 nodes.

Fig. 1: Comparison of two approaches to the FE model updating process. Center: FE model generation; left: accelerometer modal test; right: RoboVib® modal test.
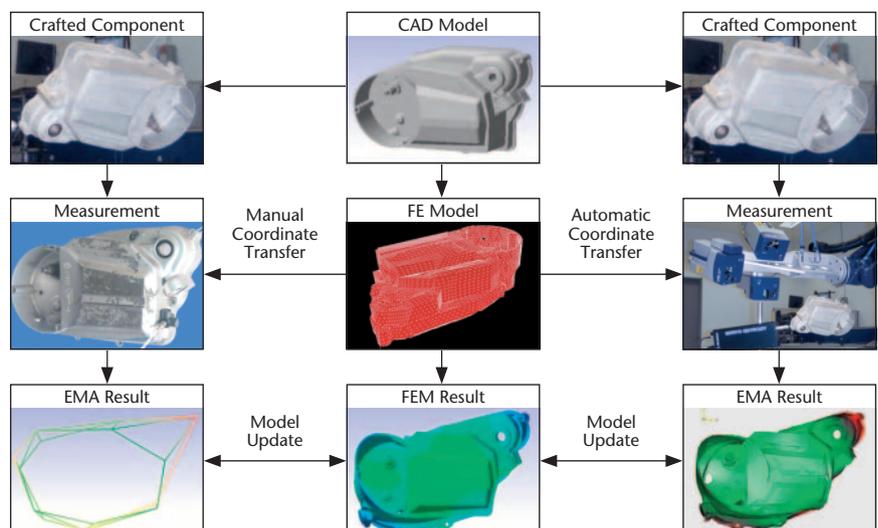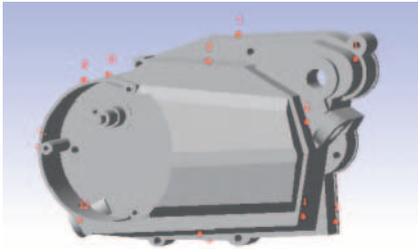
Fig. 2: CAD model with measurement locations. Wire frame model resulting from measurement points.
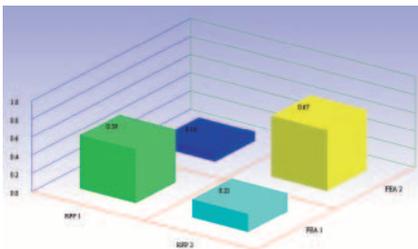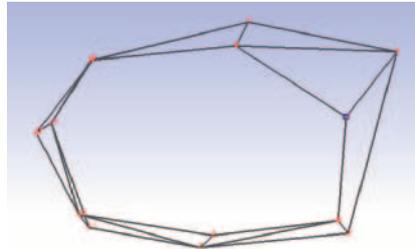

Fig. 5: MAC comparing FE simulation and tri-axial accelerometer measurements.

Fig. 6: MAC comparing FE simulation and RoboVib® measurements.

■ Accelerometer Test

When testing with accelerometers, an impulse hammer was used to excite the gearbox cover. Measurements were acquired at 14 measurement points as shown in Fig. 2. The locations were defined manually from the FE modal analysis results.

■ Test with RoboVib®

Optical methods are able to use measurement grids that are derived from existing FE models of an object under test. Being free from the constraints of physically mounted and cabled sensors, two major shortfalls of conventional testing methods are overcome: the limited spatial density of measurement nodes; and mass loading. By overcoming these constraints, the Modal Assurance Criterion (MAC) values
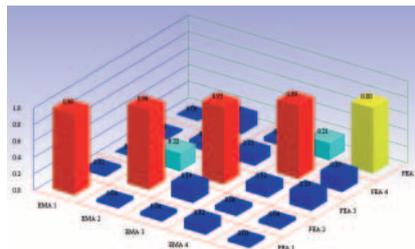
between measurement and simulation are considerably improved, which allows for a much better FE validation quality. The imported grid was coarsened by a factor of roughly 10, which still gives 100x more data points than the accelerometer test.

In order to optically scan the complete cover, the robot was taught positions so that all sides of the cover could be measured. After preparing the measurement during the daytime, the measurement was left to run overnight (Fig. 3). Data from 1630 nodes were acquired automatically and results from all robot positions were automatically stitched together into a single seamless file for analysis. Post-processing was performed in the VMAP Modal Analysis package. The results of the first two modes for

the different measurement techniques are displayed in Fig. 4, as well as the first two modes from FEA as a reference.

MAC Analysis

One major application of RoboVib® is to be able to compare and update finite element models (FEM). In this case study the VMAP modal analysis program from TechPassion was used to extract the modal parameters. It offers a native import of Polytec's binary file format. The mode shapes and Eigen frequencies can be compared to the values calculated from the simulation and the modal damping added to the FEM. The FEM can now be tuned to the real structure and an improved model can be derived using VMAP FE model updating tools.

■ Accelerometer Test

The modal analysis from the conventional accelerometer test was limited to the first 2 modes at 592 Hz and 933 Hz. The MAC values between the same modes from measurement and simulation are 0.67 and 0.59 (Fig. 5). These values lead to the conclusion that some parameters of the test, e. g. accelerometer masses and the location and orientation of the sensors, have a lowering influence on the quality of the measurement.

■ RoboVib® Test

Using a 100x higher point resolution allows higher modes of the gear box cover to be extracted. The MAC values between the same modes from measurement and simulation are close to 1, showing a much better match compared to the accelerometer test. Fig. 6 shows the MAC matrix for the first five modes, the diagonal values are close to 1 and the off-diagonal values are close to zero. This allows precise matching of the measured modes with the simulated modes.

1st Mode
592.1 Hz
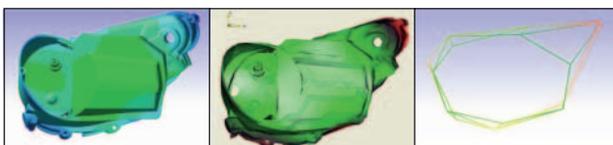
2nd Mode
932.5 Hz

Fig. 4: Comparison of mode shapes from FE analysis (left) with RoboVib® (center) and conventional measurements (right).

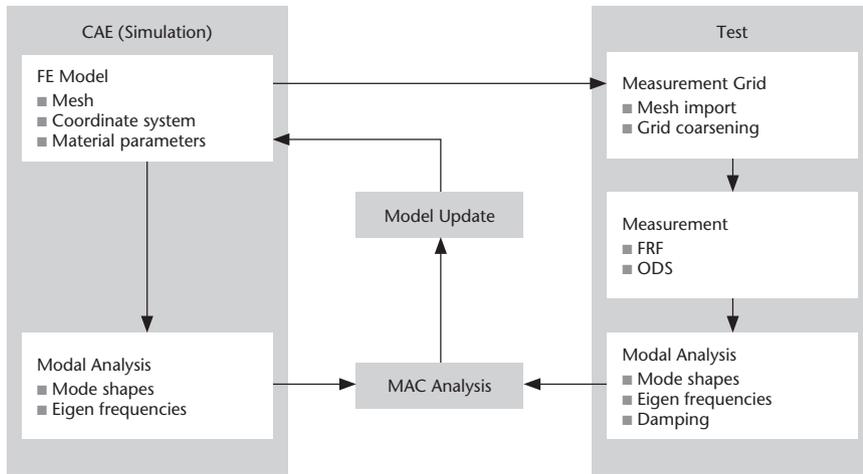**Fig. 3: Measurement of the gearbox cover with RoboVib®.**

CAE (Simulation)		Test
FE Model ■ Mesh ■ Coordinate system ■ Material parameters		**Measurement Grid** ■ Mesh import ■ Grid coarsening
	Model Update	**Measurement** ■ FRF ■ ODS
Modal Analysis ■ Mode shapes ■ Eigen frequencies	MAC Analysis	**Modal Analysis** ■ Mode shapes ■ Eigen frequencies ■ Damping

Fig. 7: CAE-Test Workflow.

Improving the Incompleteness Ratio

An FE mesh is generated to ideally represent the later prototype. The FE model should be able to predict the dynamic and durability parameters of these components for a defined operating condition. The results of the modal analysis, Eigen modes and Eigen frequencies are then validated by the resulting mode shapes and damping values from the experimental modal test (Fig. 7). FE models typically contain at least several thousand nodes. In practice a measurement for validating the FE model contains only a subset of

the FE nodes. In other words: the measurement is incomplete. This incompleteness is described by the term "incompleteness ratio":

$$i_r = \frac{n}{N} \quad \text{(eq. 1)}$$

where n is the number of measured nodes and N the number of nodes in the FE model. Other authors have shown that the quality of an FE model update strongly depends on the incompleteness ratio. E.g. Grafe states: "The real challenge of updating large FE models is not so much

the size of the models, as these can be solved by ever more powerful computers, but rather small incompleteness ratios" (Model Updating of Large Structural Dynamics Models Using Measured Response Functions, Doctoral thesis, University of London, 1998). In other words: the number of measurement nodes must be sufficiently high to ensure a correct update of the FE model.

The significant reduction of the incompleteness by means of the automatic approach with RoboVib® thus opens the path to an optimized model updating.

Authors · Contact

Dipl.-Ing. Jörg Sauer[a],
Dhanushkodi Mariappan[b],
Dipl.-Ing. (FH) Matthias Schüssler[a],
Dipl.-Ing. (FH) Arend von der Lieth[c],
Michael Stone[c]

oms@polytec.de

[a] Polytec GmbH; [b] TechPassion Technologies Pvt. Limited, Chennai, India;
[c] Polytec Inc., Dexter, MI, USA

This article is based on the same-titled paper presented at the ANSYS Conference & 28th CADFEM Users' Meeting, Nov. 3-5, 2010, Aachen, Germany. The full paper is available at:
www.polytec.com/fe-test-correlation

RoboVib® Structural Test Station
Automated, Full-Field 3-D Vibration Measurement

RoboVib® is an auto-configurable 3-D vibration measurement station for whole body vibration mapping of complex-shaped objects. By avoiding labor-intensive contact transducers, accuracy, throughput, and productivity are all increased. For example, the measurement time needed to characterize the optically accessible regions of an entire car body is decreased from several days to a few hours. In addition, the RoboVib® system can be run unattended, allowing measurements to be scheduled day or night. Due to the increased productivity, test fields and prototypes are used more efficiently and the results are available faster.

www.robovib.us

Optimization of Sound Emission Properties

Validation of FE Models with the 3-D Scanning Vibrometer

Eliminating unwanted noise is a top priority in automotive design. Many components, such as transmission casings, compromise the driving experience by the sound they emit. FE modeling is a vital and powerful tool used during systematic vibration and sound emission analysis. The IPEK – Institute of Product Engineering in Karlsruhe uses such techniques as part of its design process optimization.

Introduction

Complex FE modeling over wide frequency ranges is used to determine the eigenfrequencies and eigenvectors during model validation. Such models are an important means of realistically mapping the effect of design changes onto the final product.

In the traditional experimentation setup, acceleration sensors are used for vibration measurement and modal hammers or shakers are used to provide excitation. For complex structures, such a setup is complex, costly and susceptible to error. Measurement and excitation points must be defined with care, to ensure that all eigenfrequencies are excited and to produce adequate resolution of the corresponding eigenvectors. 3-D laser vibrometry is an interesting alternative, enabling a much larger number of measuring points to be attained with less effort and expense and without introducing additional mass influences into the system.

Mounting and Sample Excitation

Integral measurements with a laser vibrometer require that all measuring points are optically accessible. The most convenient solution would be a 3-D laser vibrometer mounted on a robot. Additionally, mirrors can be used to divert the laser beam, or the vibrometer or measurement object can be repositioned to measure otherwise hidden points. Pre-programming a robot to move the laser measuring heads around the measurement object enables complex structures to be measured. Optionally, the measurement object – including the excitation source used – can be pivot-mounted, though it is important then to ensure adequate stability of the arrangement. The resultant data sets are then combined with the Stitching feature of the scanning vibrometer software to reproduce a full body vibration map.
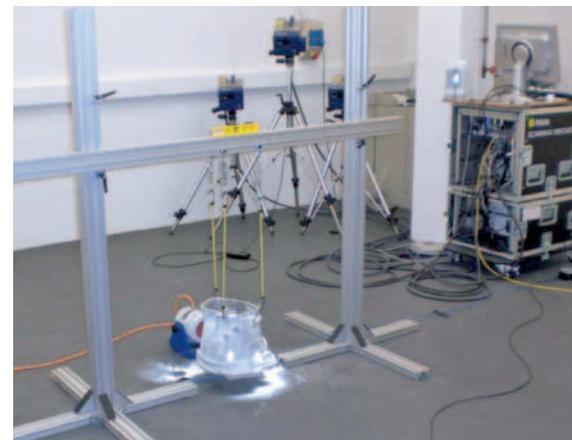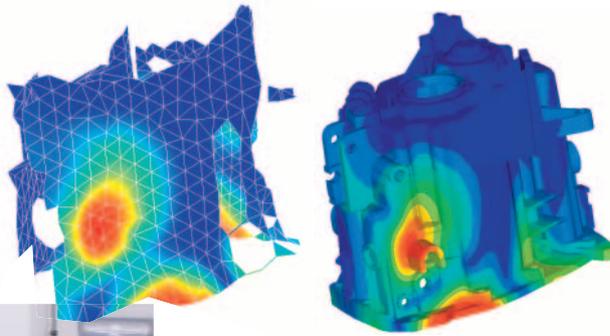

Fig. 1: Suspended mounting.

**Fig. 5: Eigenmode at 2800 Hz
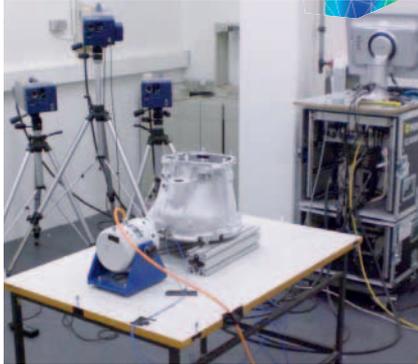(left: measured; right: modelled).**

Fig. 2: Upright mounting.

A measurement object, such as the transmission casing in this example, can be suspended from straps (Fig. 1) or in an upright mounting arrangement (Fig. 2), with the shaker and the structure isolated from the environment by rubber feet.

The quality of the mounting variants can be assessed by comparing the so-called Driving Point Function (DPF), the quotient of the spectrum of the system response at the point of excitation and that of the introduced force. Here a clearly defined sequence of resonances and anti-resonances, a falling or rising trend and an adequately large gap between the rigid body and structure modes should be identifiable (Fig. 3).

These criteria are met for both mounting variants. The rigid body modes occur in both variants at around 30 Hz, but in the upright mounting variant, some resonances are less distinct and between 600 Hz and 1000 Hz additional peaks are present. The upright mounting method's advantage of a quicker setup is offset by the disadvantage of overestimating the modal damping values and additional resonances.

As well as the mounting method, the stinger used to join the structure and shaker also has a major influence on the experiment result (Fig. 4).

The blue curve relates to a stinger variant with two clamp sets and the green curve relates to a variant with a simple stud screw clamp fixture. The results are similar in principle, though the simpler variants exhibit additional resonances in the low frequency range and much less distinct resonances in the high frequency range. Consequently, the short, thin, rigid-fixed stinger is better suited to the structure under investigation and to measurements in the frequency range above 1200 Hz.

Vibration Measurement and Evaluation

After specifying the experiment setup, the PSV-400-3D Scanning Vibrometer is applied to the transmission casing to determine the system responses at 600 measuring points and frequencies up to 4000 Hz. The associated transfer functions can be imported into LMS Test.LAB using the UFF format and evaluated there. In the evaluated range up to 3500 Hz, 16 eigenfrequencies were identified which can be classified as reliable, based on Auto-MAC and modal synthesis. The additional peaks in the upright mounting variant can be identified as non-structure modes by Auto-MAC analysis.

Correlation with the FE Model

Modal analysis is conducted by the Block-Lanczos method available in MD Nastran. To correlate the two models (Fig. 5), the experimental data is imported into MATLAB using the UFF format while the numerical data is imported by use of the MATLAB/Nastran interface IMAT FEA. The two datasets are then automatically positioned and correlated. For the first 16 eigenfrequencies, this results in a mean MAC correlation (Fig. 6) of 91% and a mean frequency variation of 1.28%. The MAC correlation is better in the low modes, while the frequency correlation is better in the higher modes.

Summary

The example shows that 3-D laser vibrometry can efficiently determine the modal parameters of a complex structure within a short space of time, particularly when the measurement object – including the excitation source – is rotated for measurements from different directions. By selecting suitable stingers, the vibration excitation can be reliably applied even in high

frequency ranges. It is possible to validate the FE model with the setup described here all across the evaluation range. The variations are within the limit values which can be attained with CAD data-based FE models.
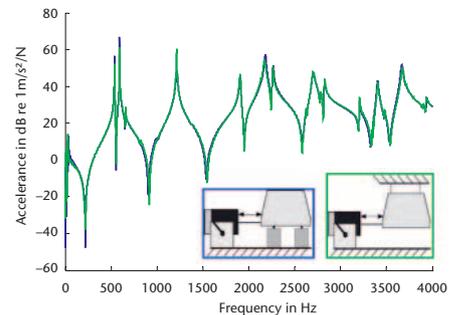

Fig. 3: DPF (Driving Point Function) of alternative mounting variants.
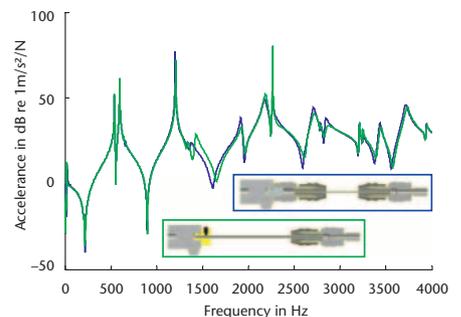

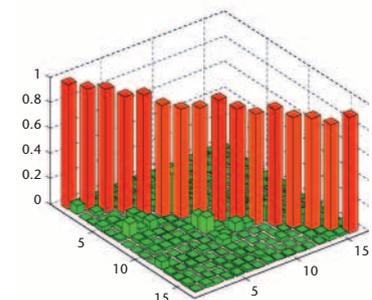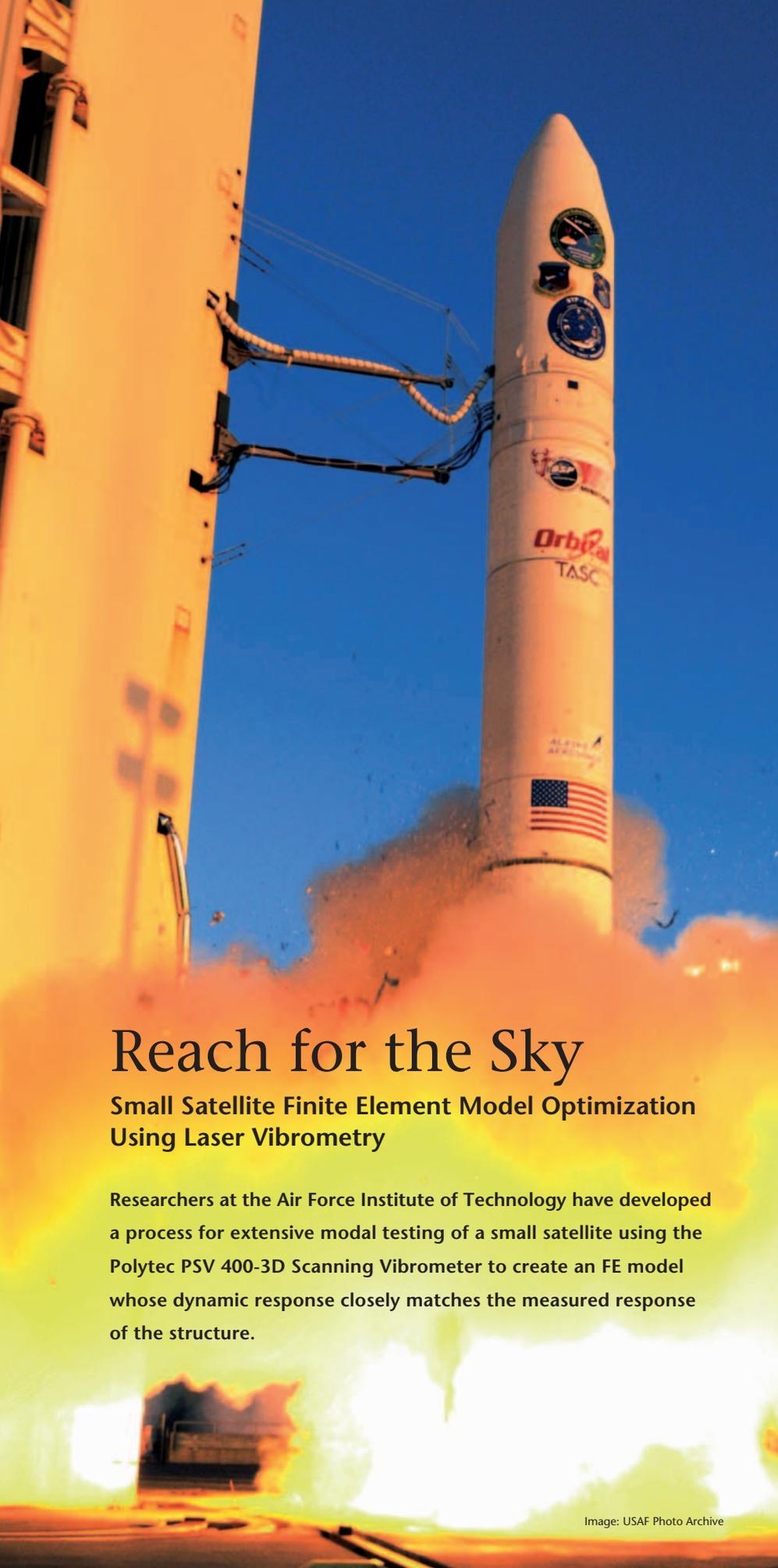**Fig. 4: Influence of coupling variant during excitation.**

Fig. 6: MAC analysis of the investigated modes

Authors · Contact
Prof. Dr.-Ing. Albert Albers
albert.albers@kit.edu
Dipl.-Ing. Thomas Maier
th.maier@kit.edu

IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, **www.ipek.kit.edu**

Reach for the Sky

Small Satellite Finite Element Model Optimization Using Laser Vibrometry

Researchers at the Air Force Institute of Technology have developed a process for extensive modal testing of a small satellite using the Polytec PSV 400-3D Scanning Vibrometer to create an FE model whose dynamic response closely matches the measured response of the structure.

Polytec

Introduction

One of the senior capstone design courses offered at the United States Air Force Academy is the Department of Astronautics FalconSAT program. It is a student-run, faculty led program to design, build, test, and eventually launch a small satellite.

FalconSAT-5 is the latest in the series of FalconSAT satellites from the US Air Force Academy (USAFA). The second of FalconSAT-5 structural engineering models (FS-5 SEM II, Fig. 1) was constructed in spring 2008 to validate design modifications resulting from a change in customer/payload requirements. In the meantime, the satellite has been launched on November 19, 2010 onboard a Minotaur IV launch system (large image).

Accurate predictions of the dynamic responses of space launch payloads (Fig. 2) are required by launch vehicle integrators, but not achieved easily. The finite element (FE) method has proven to be the best approach in creating accurate dynamic models of complex structures. Previous research efforts used measured vibration data from only a few locations on the surface of the satellite to validate the first three predicted modes of the FE model. However, given the capability to collect dense vibration data over thousands of grid points presents an opportunity to develop a more accurate FE model.
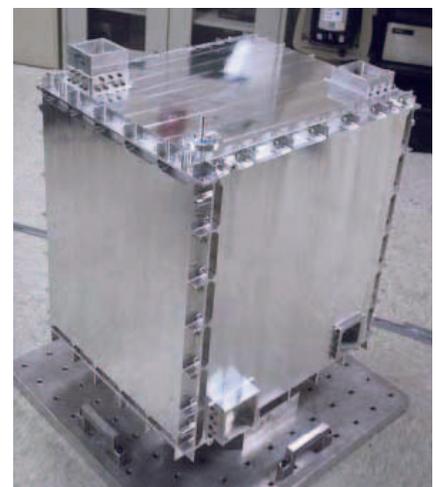

Fig. 1: FS-5 SEM II satellite.

Fig. 2: USAFA cadet and faculty member integrating the payload onto FS-5.

Image: USAF Photo Archive

Fig. 4: FS-5 SEM II with Polytec PSV-400-3D.

Researchers at the Air Force Institute of Technology have developed a process for extensive modal testing using the Polytec PSV 400-3D Scanning Vibrometer to create an FE model whose dynamic response closely matches the measured response of FS-5.

Model Tuning

The first step in the tuning process is generating the untuned FE model (Fig. 3). Since the primary structure of the FS-5 SEM II is comprised of relatively thin panels, bilinear plate elements are predominantly used in the FE modeling approach. The second step in the tun-

Fig. 3: Model of the FS-5 SEM II.

ing process is hand-tuning or adjusting the mass of each component of the FE model to match the measured mass. Measuring the mass of each structural component and carefully modeling the components results in very accurate FE mass matrices. The third step in the tuning process is measuring and extracting modal data from each panel and tuning the corresponding panel FE models by adjusting the Young's modulus of the panel materials. The vibrometer scans a grid of points spaced approximately one inch apart over the surface of each panel, collecting the operating deflection shapes through 1000 Hz as they are excited with an automated impact hammer. With each panel accurately modeled, a full satellite FE model is assimilated, leaving only connections between the panels, modeled by three columns of 6 degree-of-freedom (DOF) springs along each edge, as the design variable to tune. The fourth step in the tuning process is measuring modal data from the integrated satellite and tuning

the corresponding FE model by adjusting 6 DOF spring constants and Young's moduli of the adapter ring material, which represents the launch vehicle mating and ejection rings.

Experimental Setup

For panel testing, a harness which imparts the smallest amount of strain in the panel is desirable to simulate free vibration. To accomplish this, a horizontal test harness was built which uses a mesh of bungee cords to suspend the panels above the floor. The frame is adjustable in height to allow the excitation source to fit underneath. Excitation is provided via an electromagnetic shaker programmed to impart periodic impulses with an arbitrary waveform generator and amplifier.

A force cell located between the stinger and the impact plate allows the Polytec vibrometer software to accurately estimate frequency response functions (FRFs). This approach also provides a much better coherence than other methods. With the panels supported and excited, data is
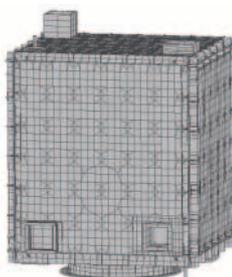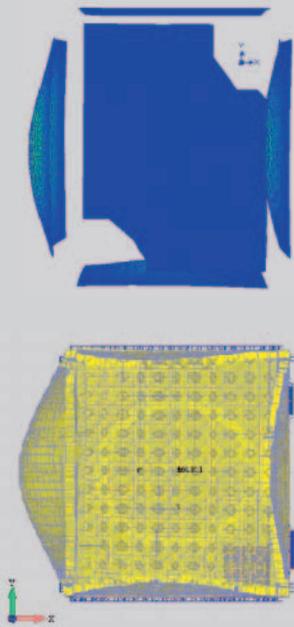
Fig. 5: Measured mode 5 (top) vs tuned FEM – asymmetrical X panel breathing.

collected on the dynamic response over the frequency range 0 to 1 kHz. Given the size of the SEM II panels, noise levels as low as those generated by people talking, can impart erroneous inputs or overrange the lasers, so care was taken to only collect data at night when noise levels were lower. Overall, eight modes were recorded for the side panels, six modes for the top panel, and five modes for the base panel.

Setup for testing the full SEM II (Fig. 4) begins with bolting the satellite stand plate to the floor to provide rigid boundary conditions. The same automated electromagnetic ping hammer that is used in panel testing is positioned at a 45 degree angle to the satellite horizontal in order to excite the greatest number of modes possible while maintaining excellent coherence. Aliasing and leakage are issues which can be remedied with sampling rate and window functions. Unlike the panel data, three translational velocities are measured at each measurement point resulting in three FRFs for

each measurement point. A best practice is to keep all scan points within 10 to 12 degrees of the field of vision for each head. In order to meet this restriction with the side panels, only one panel is tested at a time with the heads positioned directly facing the panel.

With data collected, complex-valued modal data is extracted from the raw data using curve-fitting software then converted to real-values for use in tuning. With a set of spatially dense real-valued data, optimization may begin. Optimization software algorithms vary the design variables (stiffness for panels and spring constants for the full satellite) while attempting to minimize a cost function based on differences between measured and analytical eigenvalues and eigenvectors. In order to keep the model parameters from departing too far from the nominal values, constraints are specified in the optimization input which keep the design variables within desired bounds. The end result is a tuned FE model which closely matches the modal measured data in the frequency range of interest.

Results

The laser vibrometer collection process for the panels yields modal data (Fig. 5) for the first eight modes of the side panels, six modes of the top panel, and five modes for the base panel in the frequency range from 0 to 1 kHz. Over 400 locations were scanned on each panel in order to collect this data. Over 6500 FRFs were collected on the full satellite from approximately 2200 measurement points on the five visible surfaces. Every panel's FE model was successfully tuned to match the measured data up to at least 600 Hz.

Cost function reduction is shown in Fig. 6. Overall, the tuned panel eigenvalues matching the squared measured natural frequencies to within 2% and the general decreases in the cost functions indicate successful panel tuning. The tuning process reduces the cost function for full satellite model tuning as well, though generally the value of the cost function increases with increasing numbers of modes tuned. The process allowed tuning up to the first five modes. Overall,
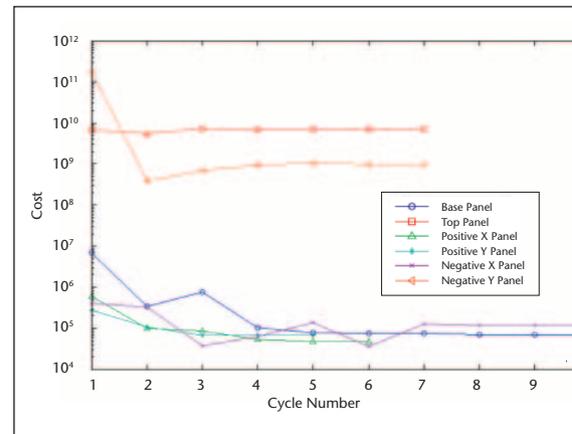

Fig. 6: Panel cost function reductions.

the tuned FE model eigenvectors for modes 4 and 5 yield modal assurance criterion (MAC) values which are improved by 31% and 33% over the untuned FE model respectively and natural frequency accuracy improved by an average of 7% when tuning the first five modes.

Conclusions

A Polytec 3-D Scanning Vibrometer was successfully used to develop and improve a FE model for FalconSAT-5. Several approaches used during creation of the tuning process were critical to its success. First, creating nodes on the untuned FE model directly from the structure geometry files allows the panel models to predict modal data that closely matches the measured values before adjusting design variables. Next, collecting vibration data using the Polytec laser vibrometer only at night is a large reason the measured FRF data has very low noise content. During the tuning stages of the process, the quality of the results and the ability of the software to converge are most sensitive to the desired allowable eigenvalue deviation.

Authors · Contact
Jay Anderson, Cole Doupe,
Prof. Jon Black, and Prof. Eric Swenson
eric.swenson@afit.edu

AFIT Air Force Institute of Technology,
Wright-Patterson AFB, Ohio
www.afit.edu

Machine Tools

Vibration Analysis to Assess the Dynamic Properties of an Inertia Friction Test Bench

Inertia friction welding is a compression welding technique used to join rotationally symmetrical components. In this process, two workpieces are set in rotational motion relative to each other with the aid of a flywheel and pressed onto each other with a defined compressive force (Fig. 1).

The frictional heat produced by this causes the materials to plasticize in the joining zone, resulting in compression of the components and subsequently, a join. The desire for high manufacturing accuracy and quality of weldments demands the use of production machines with good dynamic rigidity properties, particularly in view of the considerable process forces occurring during application.

Investigation Method and Results

To assess the dynamic machine response, an experimental modal analysis is conducted. The structural dynamic is measured with the aid of a 3-D Scanning Vibrometer, with the mechanical excitation of the machine structure provided by an electro-dynamic shaker. This makes it possible to investigate the vibration behavior of the inertia friction test bench very efficiently and with a high degree of detailing. Fig. 2 shows the measurement setup. The analysis of the vibration behavior and identification of eigenfrequencies is managed using the associated data management system. In order to record the complete machine, the vibrometer was repeatedly repositioned and the resultant measurement file was compiled
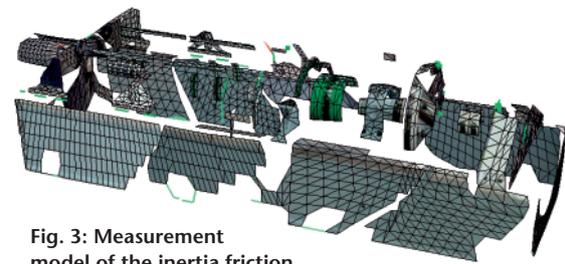
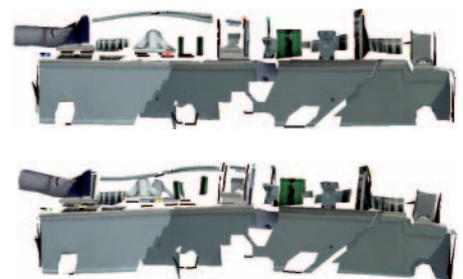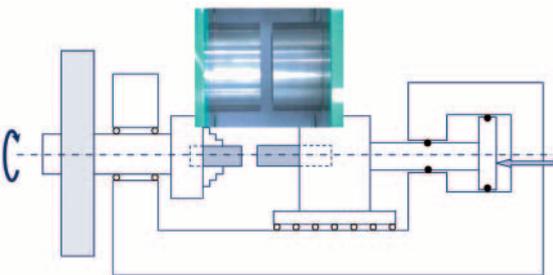**Fig. 1: Principle of inertia friction welding. Left: rotating flywheel; centre (gray): components being joined; right: compression drive**

Fig. 3: Measurement model of the inertia friction test bench.

Fig. 4: Normal mode of the machine at phase angle φ = 0° (top) and φ = 180° (bottom).
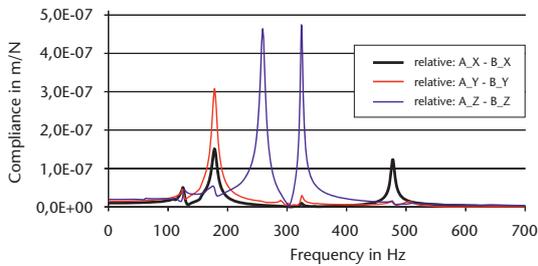
Fig. 5: Frequency response of the relative compliances of the two workpieces being joined (measuring points A and B) in X, Y and Z direction.

from 11 individual measurements with a total of 2,263 measuring points. Figure 3 shows the measurement model and Fig. 4 illustrates a normal mode of the inertia friction machine.

Of particular interest is the relative compliance between the two workpieces, as this is key in determining the attainable manufacturing accuracy. By synthesizing the recorded frequency response functions the relevant frequency response of the relative compliances can be calculated (Fig. 5).

Conclusions and Outlook

The structural dynamic investigation revealed that the first distinct eigenfrequencies are well above the process-critical frequency of 100 Hz and the

PSV-400-3D Scanning Vibrometer

Three-dimensional scanning laser vibrometry is a high-precision tool for test and simulation engineers. It enables quick and accurate determination of operational vibration forms and eigenforms of complex objects across a broad frequency range. The PSV-400-3D Scanning Vibrometer records vibrations by non-contact, zero mass-loading methods, providing an intuitive 3-D animation of the measurement results, as well as compatibility with modal analysis and FEM software.

www.polytec.com/psv3d

dynamic compliances are very low compared to typical machine tools. Based on the results obtained, conclusions can be drawn as to the expected machine behavior and the manufacturing accuracies, and adjustments can be established in order to optimize later machine designs.

Authors · Contact
Dipl.-Wirtsch.-Ing. (FH) Dipl.-Ing. (FH) Marc Lotz, Dipl.-Ing. Oliver Rösch, **oliver.roesch@iwb.tum.de**

Institute of Machine Tools and Industrial Sciences (iwb), Technical University of Munich, Garching, Germany
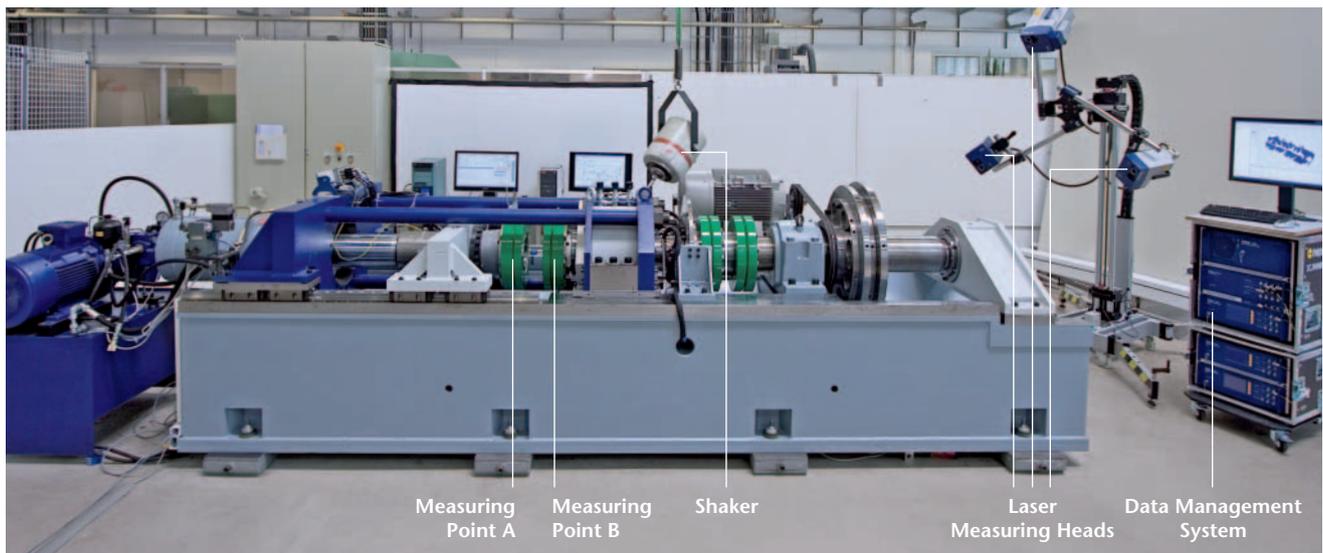**www.iwb.tum.de**

Fig. 2: Experiment setup to measure the dynamic properties of the friction welding machine (right: 3-D Scanning Vibrometer).

A Turn for the Better

Dynamic Gauging of Rotating Tools

Vibration and its modes are a key issue in terms of reducing sound emissions and in improving the safety of dynamic processes. The FGW Research Association for Tools and Materials based in Remscheid, Germany, is a private, non-commercial institution for applied research combined with affiliated commercial businesses which, for the last 60 years, has been researching many subjects, including the dynamic processes of circular saws.
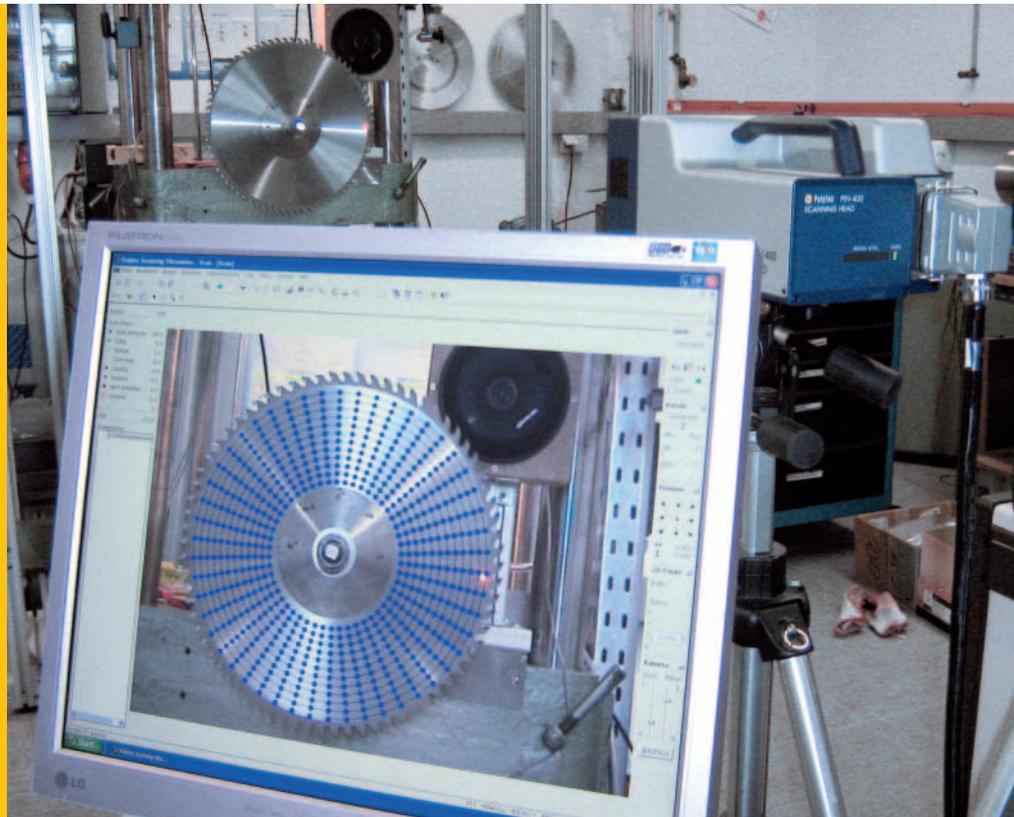

Fig. 1: Vibration measurement on a cutting wheel

Introduction

Disk-shaped tools – whether circular saw blades, abrasive cutting wheels or machine knives, are used in a wide variety of fields, including industrial production, craft trades and by private users. The circular saw blade, for example, is still one of the most effective tools. It is equally adept at cutting deep-frozen fish or steel bars heated to several hundred degrees. Different parting processes do, however, require specific tools. There is no "universal saw blade" for all applications. Yet all disk-shaped parting tools have one thing in common: their unfavorable diameter-to-thickness ratio, which results in a potentially flexible resonator that entails a high degree of sensitivity to vibration and kerf characteristics, which in turn reduces the efficacy and productivity of the tools. The demand for thinner saws for narrower cuts has been the subject of a broad field of research and development for decades, and it is one in which the FGW enjoys high international repute.

Measurement of Dynamic Properties

In order to improve the dynamic response of the tools, engineers try to increase attenuation properties and to introduce residual stress in a targeted manner. The aim is to prevent resonance effects by separating the natural frequencies of the tool from the excitation frequencies of the drive. However, at higher speeds, harmonic resonances may occur, leading to a demand for methods suitable for the dynamic determination of eigenfrequencies and modes over a wide frequency range.

In the cooperation project presented here between the FGW's Institute of Tool Research and Materials, and the University of Hanover's Institutes of Measurement and Automatic Control, and of Production Engineering and Machine Tools, dynamic investigations were made of abrasive cutting processes for working of natural stones using tools of different designs (Fig. 1). The setup included a so-called derotator which uses an optical dove prism to effectively 'freeze' rotating components to a standstill and make them accessible for optical measurement
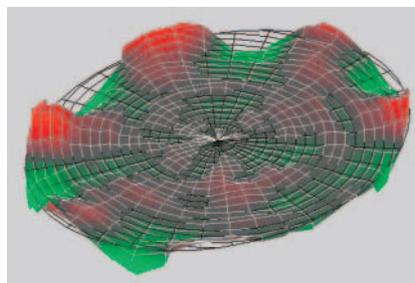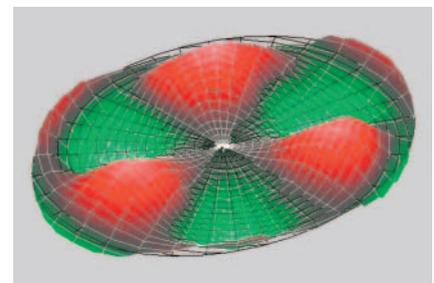

Fig. 2: Laboratory-fixed vibration mode.

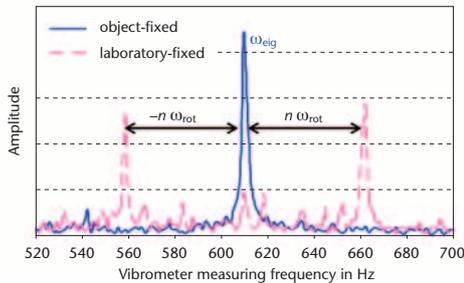
Fig. 3: Object-fixed vibration mode.

Fig. 4: Frequency split-up in laboratory-fixed measurements.

Fig. 5: Measured Campbell diagram of an abrasive cutting wheel.

$$\cos\left(n \cdot \omega_{rot}\, t\right) \cdot \cos\left(\omega_{eigen}\, t\right) = \frac{1}{2} \cdot \cos\left(\left(\omega_{eigen} + n \cdot \omega_{rot}\right) \cdot t\right) + \frac{1}{2} \cdot \cos\left(\left(\omega_{eigen} - n \cdot \omega_{rot}\right) \cdot t\right)$$

Eq. (1): Symmetrical split of the measurement signal.

by a laser vibrometer. Thus, vibrations can be measured "object-fixed", i.e. relative to the rotating structure, while the blade is turning. In theory, the natural frequencies split into forward and reverse waves which are depicted by a so-called Campbell diagram.

This frequency split could also be recorded experimentally (Fig. 4) when investigating the abrasive cutting wheel. The "object-fixed" vibration mode is measured with the combination of a scanning laser vibrometer and a derotator. Vibrations at a laboratory-fixed measurement point are determined with the aid of an electro-magnetic inductive measuring system. As the node lines of the structure-related vibration mode circulate at rotation speed with the blade, the signal at the laboratory-fixed point is modulated continuously. Mathematically, this modulation of the node pass-through can be expressed as a multiple of cosine terms and, applying the addition theorem, the symmetrical split is visualized in equation (1).

Fig. 2 shows the laboratory-fixed vibration mode of the cutting wheel (with frequency split) and Fig. 3 shows the object-fixed vibration mode without frequency split. In Fig. 5 the split-up of the natural fre-
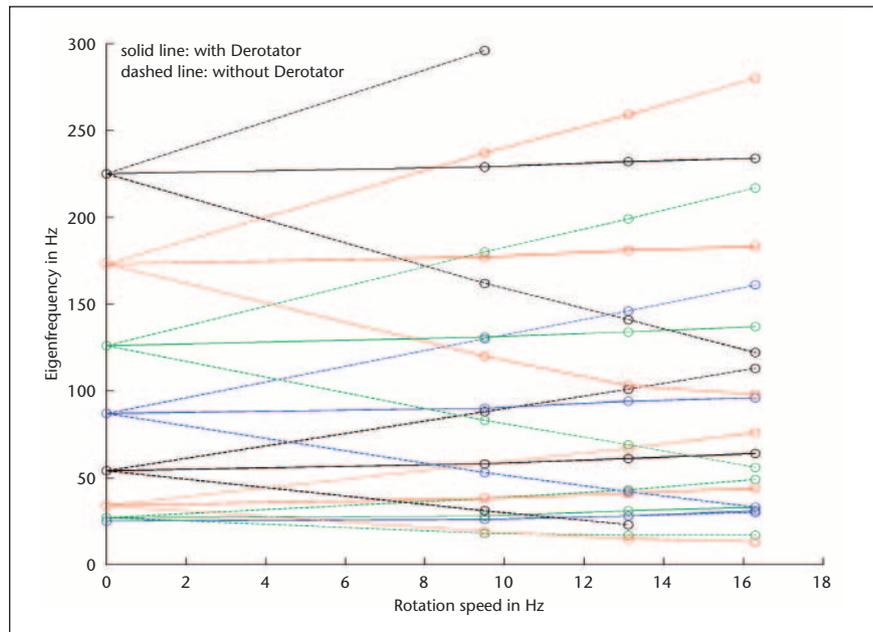
quencies at increasing rotation speeds is displayed in a Campbell diagram.

Summary and Outlook

The goal of the research project was to assess – and thereby reduce – the influence of vibration on the cut line in the process of abrasive cutting of natural stone. Applying the method described here, rotation speed-dependent eigenfrequency shifts could be determined and assigned to the corresponding eigenmodes. It thus provides a metrological tool for the dynamic assessment of selected plant and process parameters in terms of their effects on the overall process.

Author · Contact
Dr. Christian Pelshenke
pelshenke@fgw.de

FGW Research Association for Tools and Materials, Remscheid, Germany
www.fgw.de
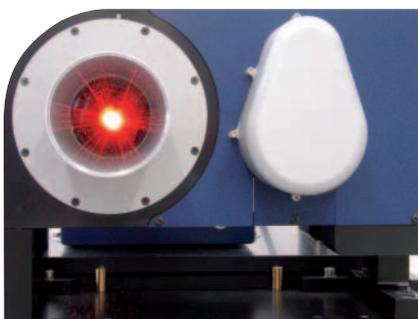
Polytec's Optical Derotator

The Optical Derotator enhances laser vibrometers in a simple way to perform non-contact vibration measurements on rotating parts like turbines, fans, or tires by tracking the rotating coordinate system. Order analysis and measurements of the operating deflection shapes including stiffening effects at rotational speeds of up to 24,000 RPM can be realized in this way.

www.polytec.com/derotator

Gain Control of Strain

Optical Measurement of the Dynamic Strain Field of a Fan Blade Using a 3-D Scanning Vibrometer

The 3-D Scanning Vibrometer certainly has the potential to accurately measure small (full-field) normal and shear strains at both low and high frequencies, where other optical techniques would definitely fail. Compared to strain gages, strains can be measured up to one order of magnitude smaller.

Introduction

A primary goal in many studies of structural dynamics is to identify the locations on a structure at which failures are most likely to occur. Fatigue damage is caused by fluctuating strain. It is therefore very desirable to identify the locations of maximum strain. To ensure dynamic and fatigue strength, it's also necessary to measure the distribution of dynamic strain on these structures. Furthermore, it is essential to obtain an accurate and full-field strain distribution when using experimental data to verify and update a finite element (FE) model.

One of most basic methods to measure strain is using strain gages. There are a lot of drawbacks to this method. The strain gage is fixed to one location, and in small, lightweight structures the strain gages and their connecting cables create an additional mass-loading effect and added damping. Determining the exact position of the strain gage on the test surface can be another difficulty, since the strain maxima in real components can deviate from the model-predicted locations due to, for example, manufacturing variations and tolerances. With-

out the guidance of an FE model it is very difficult to ensure that you have identified the precise location of maximum strain because it is not practical to use a large number of strain gages.

Many optical methods were developed in the search for a better strain measurement technique. Scanning Laser Doppler Vibrometry (SLDV), a non-contact optical method with high spatial and vibration resolution that has been in use since the 1990s, was recently enhanced for 3-D measurements, resolving the vibration into the out-of-plane and in-plane components.

Theoretical Background

Using one SLDV, only the transverse displacement w of a vibrating plate can be measured correctly. According to small deformation theory, the strain components in a plate due to bending are given by

$$\epsilon_{xx}(x, y, t) = -z\, \frac{\partial^2 w(x, y, t)}{\partial x^2}$$

$$\epsilon_{xy}(x, y, t) = -z\, \frac{\partial^2 w(x, y, t)}{\partial x \partial y}$$

$$\epsilon_{yy}(x, y, t) = -z\, \frac{\partial^2 w(x, y, t)}{\partial y^2}$$

with z the transverse distance relative to the center of the plate, $w(x, y, t)$ the transverse displacement, x and y the coordinates of a point along the surface of the plate and t the time.

On the other hand, strain at the surface of a structure is equal to the spatial derivative of the in-plane surface displacement. Surface strains are often of major concern because they are typically greater than internal strains and thus are more likely to lead to failures. The in-plane displacements can only be measured using the 3-D Scanning Vibrometer.

Experimental Setup and Measurement

An aluminum fan blade was selected as a test component, which came from the fan assembly shown in Fig. 1. The part was particularly interesting because of its 3-D curvatures, small size, low weight, high resonant frequencies and expected small strains. A second fan blade was equipped with strain gages, and both blades were mounted on a shaker and placed in front of the PSV-400-3D Scanning Vibrometer (Fig. 2).

The measurement grid was created using Polytec's PSV software. Alternatively it could also be imported from an FE model. The coordinates of three points

from the FE model were used in the PSV software to compare the results from the measurement and the FE model (same global coordinate system). The next step was to perform a precise measurement of the coordinates of all grid points using the Geometry Scan Unit and Video Triangulation feature of the PSV software.

During the measurement with the Scanning Vibrometer, a frequency sweep was executed in order to obtain a frequency spectrum of the fan blade without strain gages, as shown in Fig. 3. The resonant frequencies were identified by selecting the peaks in the frequency spectrum, visualizing the corresponding mode shapes and comparing them with the FE model.

The strain measurements were then executed at these resonant frequencies using a sine excitation at different vibration levels. The signals were generated using Polytec's on-board waveform generator and externally amplified. Using the attenuator button it was very easy to obtain vibration levels of 0 dB (10 V), -20 dB and -40 dB.

The effect of these strain gages can clearly be seen in Fig. 4, which shows the frequency sweep measurement of the fan blade with strain gages attached. It is clear that some resonant frequencies
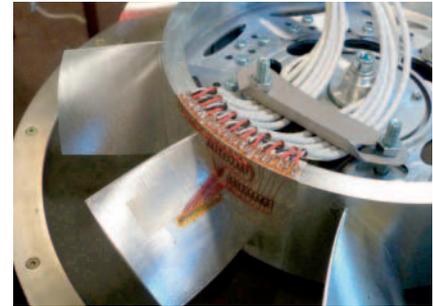

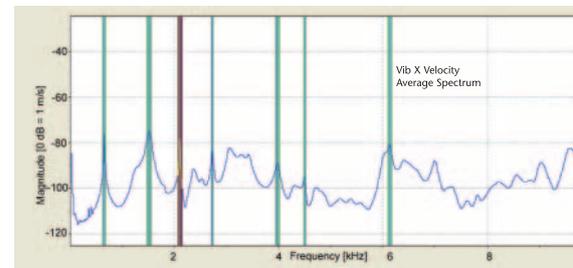**Fig. 1: Fan blade with strain gages in complete fan.**

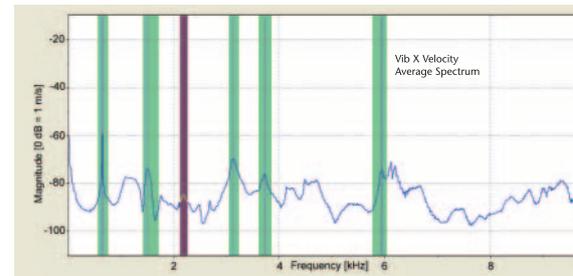**Fig. 3: Frequency spectrum of the fan blade without strain gages.**

Fig. 4: Frequency spectrum of the fan blade with 10 strain gages.

are shifted and that the amplitude of the associated peaks is reduced due to the added damping. In particular, the peak round 2 kHz has almost completely disappeared. This shows how important a non-contact (optical) method can be for small size structures. Using only strain gages it would be almost impossible to find all of the resonant frequencies and the correct (maximum) strains.

Model Validation

In this section the experimental results of both the 3-D Scanning Vibrometer and strain gages are compared with an FE model.
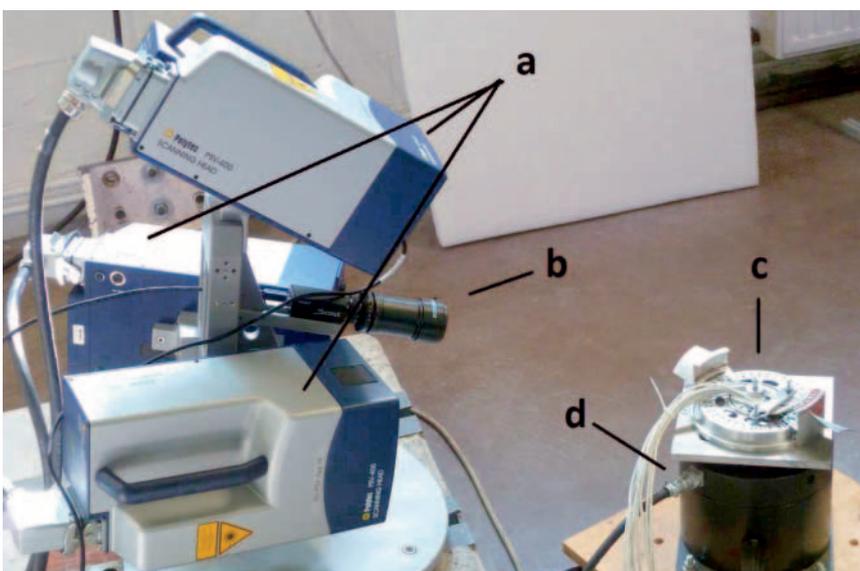

Fig. 2: Measurement setup: (a) PSV-400 scanning heads; (b) video camera; (c) fan blades mounted on (d) shaker.

After the measurements, the FE model was updated to obtain similar resonant frequencies. The resonant frequencies obtained by the FE model and 3D-SLDV are shown in Table 1. It's clear that attaching strain gages has a large influence on the (higher) resonant frequencies. Since the mode shapes of the FEM match the mode shapes measured with the Vibrometer, the differences between the resonant frequencies were not relevant, so no more effort was put into further updating (the boundary conditions of) the FE model.

Comparison of Strain Results

This section shows the strain distributions obtained from the 3-D Scanning Vibrometer measurements compared to the FEM results. In addition, the full paper features a comparison between the 3-D Scanning Vibrometer, FE model and strain gages using slices at the location of the strain gages (not shown here). As Fig. 5 shows, there is an excellent agreement in the normal strain between the FE model and the vibrometer. Only the measurement of the normal strain perpendicular to the curved surface (X-direc-

tion) shows more deviation. Additional investigations show that it is even possible to obtain satisfying results for the shear strain. The agreement for the shear strain in the XY-plane is slightly worse than for the other planes, but still satisfactory.

Conclusions

This investigation demonstrates that it is possible to obtain reliable dynamic surface strains from 3-D displacement data obtained with a 3-D Scanning Vibrometer. Shear strains as well as the normal strains can be measured accurately, as shown, by comparing the vibrometer measurement results with both a finite element model and strain gage measurements. It was proven that the dynamic behavior of the structure is changed by attaching strain gages to a fan blade. Some resonant frequencies were shifted and the peaks were greatly reduced at certain resonant frequencies. Non-contact measurements clearly do not exhibit these disadvantages. Moreover it was shown that the sensitivity of the vibrometer is much higher than strain gages. Strains can be measured up to one order of magnitude smaller compared to strain gages. The 3-D Scanning Vibrometer certainly has the potential to accurately measure small (full-field) normal and shear strains at both low and high frequencies, where other optical techniques would definitely fail.

	FE Model	3-D Scanning Vibrometer			
		Blade without gages		Blade with gages	
#	f [Hz]	f [Hz]	Rel. diff. [%]	f [Hz]	Rel. diff. [%]
1	650	650	0	650	0
2	2,015	2100	4	2188	9
3	3,082	2725	−12	2725	−12
4	4,183	3975	−5	3725	−11
5	5,865	6138	5	5950	1

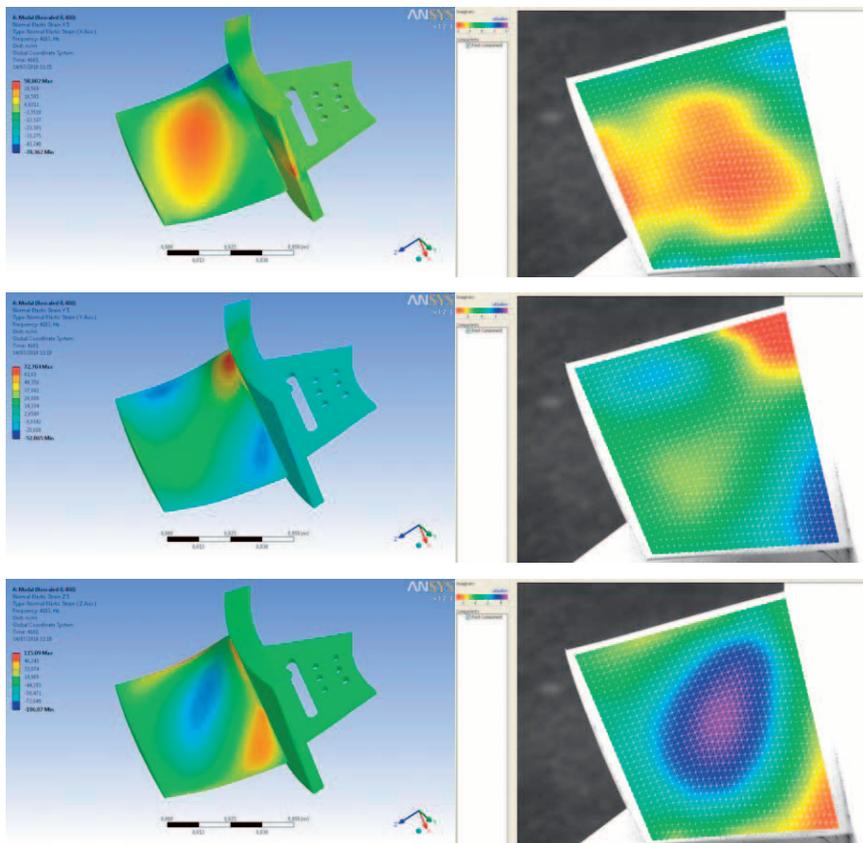**Table 1: Comparison of the resonant frequencies.**

Fig. 5: Normal strain at 3975 Hz. Left: FE model; right: vibrometer results; top: X-axis; middle: Y-axis; bottom: Z-axis.

Authors · Contact
Ing. Cedric Vuye [1,2,]
cedric.vuye@artesis.be,
Prof. Dr. Steve Vanlanduit [2]
steve.vanlanduit@vub.ac.be,
Dr. Ir. Flavio Presezniak [2],
Prof. Dr. Ir. Gunter Steenackers [2] and
Prof. Dr. Ir. Patrick Guillaume [2]

[1] Artesis Hogeschool Antwerpen,
[2] Acoustics and Vibration Research Group,
Dept. of Mechanical Engineering,
Vrije Universiteit Brussels, Belgium

For Plate-like Structures:

Strain Field Computation Using 1-D Scanning Laser Doppler Vibrometry

Millennium Dynamics Corporation is an active provider of engineering services and solutions to the Aerospace Industry. The team recently developed strain computation software for a plate-like structure based on out-of-plane velocity measurements using Polytec's single beam Scanning Laser Doppler Vibrometer. The plate structure may be dynamically excited using a piezoceramic actuator. The propagating wave velocity field is measured over a region of interest. Kirchhoff plate theory is used to compute the strain field at every instance of response measurement. The software was designed to accept measured response data files from Polytec's PSV-400 Scanning Vibrometer system in a universal file format (Fig. 1). The accuracy of the computed strain was validated against theoretical data. The

software was developed for The Boeing Company in support of lead-free circuit board design. The computed strains (Fig. 2) were found to be within 5% of the measured values at a number of locations during a real test.

Author · Contact

Vin Sharma, PhD,
vin.sharma@millenniumdynamics.com

Millennium Dynamics, Marietta, GA
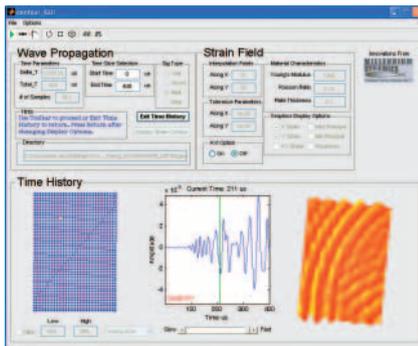**www.millenniumdynamics.com**

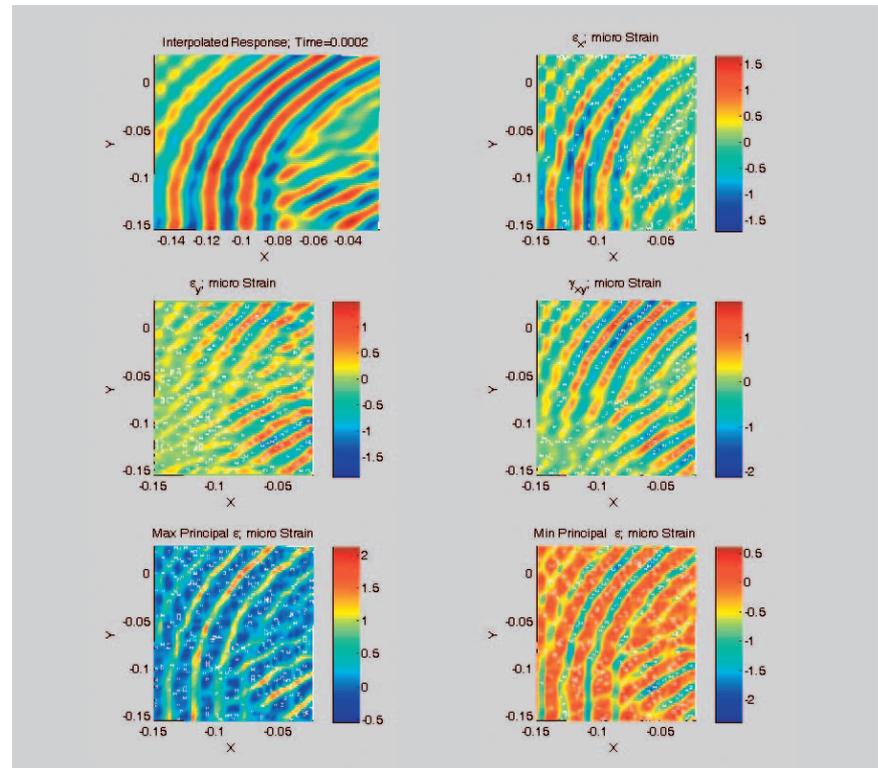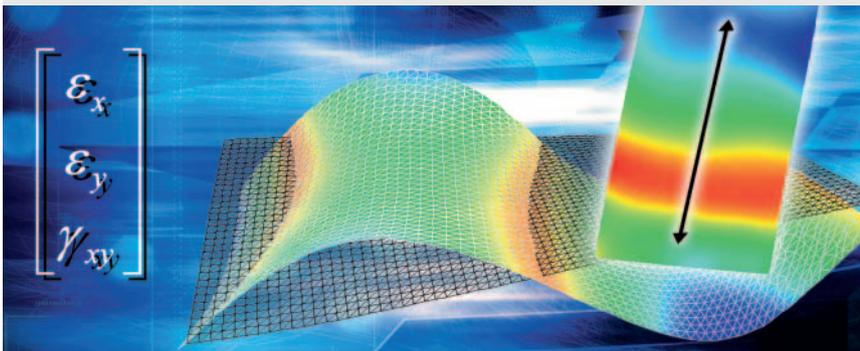Fig. 1: Screenshot of Millenium Dynamics' strain computation software.

Fig. 2: Strains computed from Scanning Vibrometer measurements.

Dynamic 3-D Stress and Strain Measurements

Polytec's StrainProcessor is a measurement extension developed for easy finite element model (FEM) updating and for comparisons to calculated stress and strain distributions. It comprises a set of hardware and software components enabling a PSV-400-3D Scanning Vibrometer – a well established tool for full field non-contact vibration mapping – to measure and analyze the dynamic strain and stress distribution on surfaces with high resolution and low noise.

www.polytec.com/strain

What's the Damage?

Structural Damage Detection Using Laser Vibrometers

Laser vibrometers offer reliable, fast and non-contact measurements attractive for damage detection in aerospace structures. This article demonstrates a few possible approaches including methods based on modal analysis, Lamb waves and nonlinear vibro-acoustic modulations. Laser-based velocity measurements are also used for strain estimation.

> *Various vibration-based characteristics can be used to detect structural damage. Recent years have demonstrated that laser vibrometers can be applied effectively for Lamb wave sensing and damage detection.*

Introduction

Aircraft designers, manufacturers and operators will face many 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 associated with greater structural complexity. All of these developments are a major challenge to aircraft structure inspection and maintenance methods. Existing, aging aircraft structures already require a significant maintenance effort. The application of new materials and wider use of damage-tolerant concepts in new aircraft will also require reliable damage monitoring for quality control, with regular periodic inspections to main-

tain safety. Over recent years, a number of new technologies have evolved with the potential for damage detection in aerospace structures. Methods based on non-contact optical/laser measuring techniques are particularly attractive for aerospace applications.

Low-Frequency Vibration Measurements

■ Modal Analysis

Experimental modal analysis was performed on various rectangular uncracked and cracked aluminum plates. The plates were freely suspended and excited using a piezoelectric stack actuator with a chirp signal starting at 1 Hz and crossing 2000 Hz in 2 s. The entire surface of each plate was then scanned using the 3-D Scanning

Vibrometer. Modal analysis was performed to obtain the Frequency Response Function (FRF) and vibration modes, as illustrated for one sample in Fig. 1.

Various vibration-based characteristics can be used to detect structural damage. The test performed focused on the natural frequency shift between damaged and undamaged samples which was 8% but only for the first vibration mode (not shown here). In general, this approach is easy and fast to perform but works only well for large and severe damage.

■ Crack Divergence Analysis

The 1st, 3rd and 6th vibration modes of the cracked aluminum plate were excited harmonically at different amplitude levels. These three excitations led to three different crack modes, i.e. opening, tearing, and sliding crack modes, respectively. The 3-D Scanning Vibrometer was used to measure relative velocity in the vicinity of the crack at two points, i.e. above and below the crack line. This data was used to analyze indirect crack divergence (Fig. 2).

Strain Estimation

It is well known that 3-D laser vibrometers can be used for static and dynamic strain analysis when deflection measurements are performed and additional calculations (e.g. Polytec StrainProcessor Software) used. Application examples in this area include strain analysis for damage detection. Another approach for estimating strain levels uses the relation of dynamic bending strain ξ with measured velocity v:

$$\xi \, (x, y, f) = \frac{K_{shape}}{c_L} \, v(x, y, f)$$

The method is particularly useful when small strain levels involved are difficult to measure with either electrical resistance or piezoelectric strain gages. This approach was used to estimate strain levels for the piezo-excitation used in the previous section. The analysis (Fig. 3) shows that the 1st vibration mode excitation produces the largest strain level for the excitation used.

High-Frequency Ultrasound Measurements

■ Nonlinear Vibro-Acoustic Modulation Technique

Non-contact measurements are useful when non-linear acoustics is applied for structural damage detection. The method relies on various nonlinear phenomena associated with ultrasonic wave propagation and wave interaction with contact-type damage. A vibro-acoustic modulation technique was used to demonstrate this approach. The cracked aluminum plate was modally excited with an electromagnetic shaker, then an ultrasonic 60 kHz sine wave was introduced to the plate using a piezoceramic transducer. Acoustical responses were measured using the 1-D Scanning Vibrometer. A series of modulation sidebands – corresponding to the frequency of the 1st vibration mode excitation – around the fundamental 60 kHz ultrasonic component, can be clearly observed in the response power spectrum (Fig. 4). The amplitude of the acoustical response (A0) and the first two modulations sidebands (A1 and A2) can be used to calculate the modulation index R = (A1 + A2)/A0 which can then be used to detect a fatigue crack in the plate.

■ Lamb Wave Based Inspection

Lamb waves are widely used for structural damage detection in plate-like structures (see LM INFO Special 2/2006 at **www.polytec.com/InFocus**). This damage detection approach often requires a significant number of transducers for monitoring of large structures, but recent years have demonstrated that laser vibrometers can be used effectively for Lamb wave sensing and damage detection. A simple example illustrating this approach is demonstrated in this section. A rectangular composite plate was monitored for hidden impact damage.
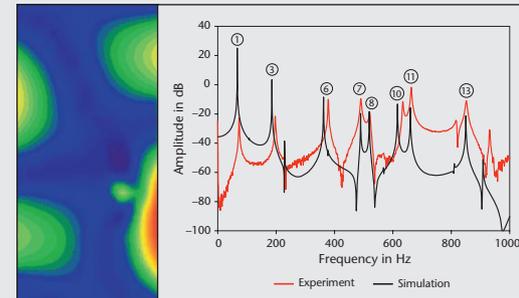

Fig. 1: Right: FRF amplitude; left: example of one vibration mode (mode 6) extracted.
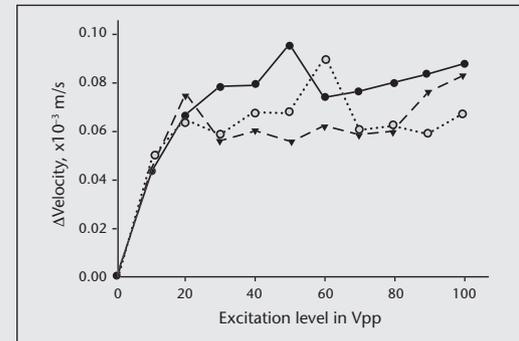

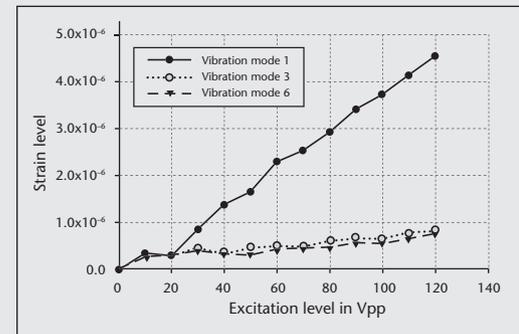**Fig. 2: Crack edge divergence analysis in x (in-plane) direction.**

Fig. 3: Strain level estimation based on velocity measurements.
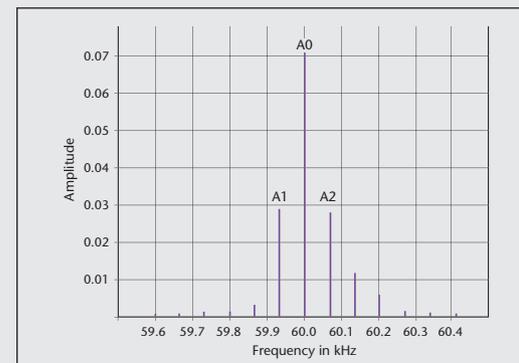

Fig. 4: Power spectrum displaying vibro-acoustic modulations in a cracked aluminum plate.

A transducer was surface bonded to the plate and used to introduce a 100 kHz ultrasonic signal to propagate Lamb waves that were captured using a 3-D Scanning Vibrometer. The plate was scanned to clearly reveal delamination in Fig. 5.
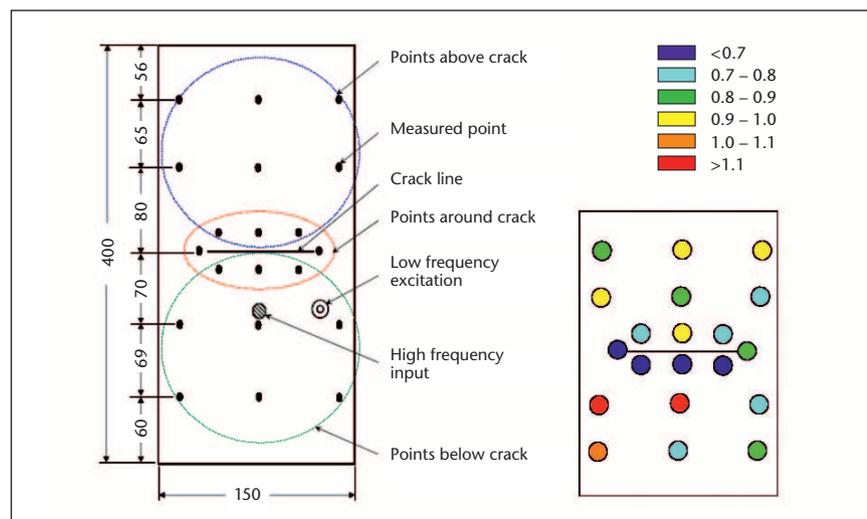
Optimal Sensor Location

Laser vibrometry offers relatively fast and non-contact low- and high-frequency measurements for a dense grid of structural locations. This is particularly useful when trying to identify optimal sensor location in applications related to modal analysis, nonlinear acoustics or guided ultrasonic waves. The problem is to find the best measurement position to obtain the largest value of the modulation index indicating damage. In the example described here, non-linear vibro-acoustic modulation test was used. Fig. 6 gives positions of low-frequency vibration and high-frequency ultrasonic excitation together with locations where responses were measured using the 3-D Scanning Vibrometer. Modulation indices were then calculated for all analyzed response locations (Fig. 6, right). Interestingly, the largest values of modulation intensity were obtained when the response measurements were taken in the lower part of the plate, where the excitation transducers were located. The study illustrates how to optimize sensor location to achieve the best damage detection results.
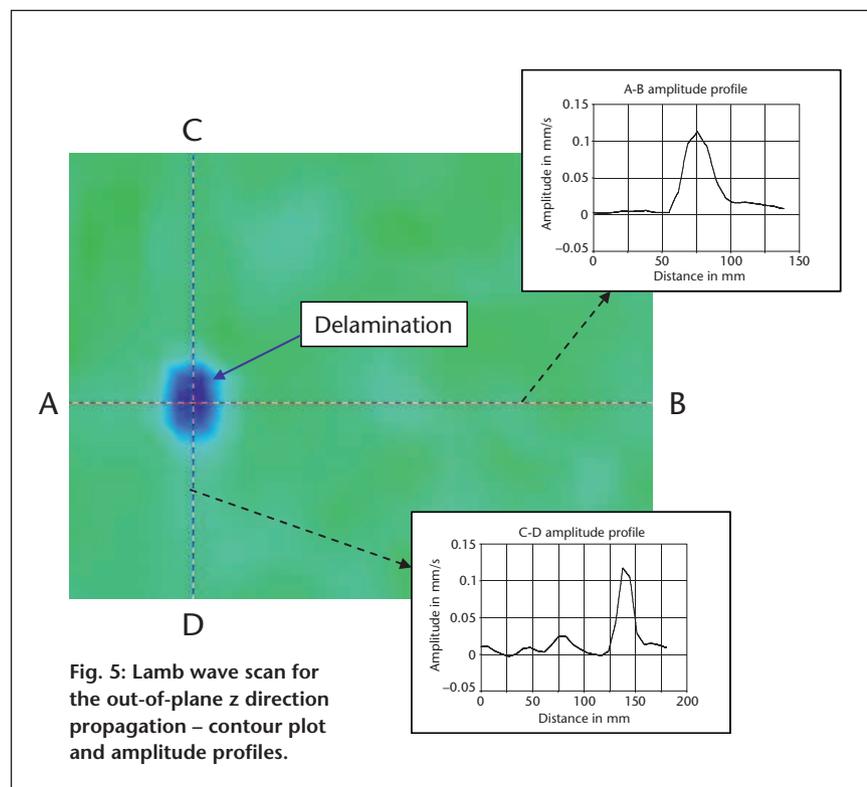
Conclusions

The article has demonstrated a number of possible applications of laser vibrometry for non-destructive testing and structural health monitoring. Low-frequency (vibration) and high-frequency ultrasound measurements with laser vibrometers were performed for in-plane and out-of-plane oscillations. The work presented illustrates applications related to modal analysis, crack divergence analysis, strain estimation, damage detection and optimal sensor investigations.

Fig. 5: Lamb wave scan for the out-of-plane z direction propagation – contour plot and amplitude profiles.

Fig. 6: Optimal sensor location analysis for fatigue crack detection based on nonlinear vibro-acoustic modulations. Left: transducer locations; right: modulation intensity distribution.

Authors · Contact

Dr. Ruztamreen B. Jenal,
Prof. Wieslaw J. Staszewski,
w.j.staszewski@sheffield.ac.uk,
Dept. of Mech. Engineering,
Sheffield University, UK

Dr. Andrzej Klepka, Prof. Tadeusz Uhl,
Dept. of Robotics and Mechatronics,
AGH University of Science and
Technology, Krakow, Poland

![Polytec logo]

in particular for measurements of critical joints. A proven and tested SHM method is based on the identification of defects by means of guided waves, as described in the following.

Functional Principle of Structural Health Monitoring with Guided Waves

Unlike the propagation of water waves or volume waves like airborne sound, guided waves (also referred to as Lamb waves or plate waves) have a number of special characteristics. They can occur in different vibration states (modes, see Fig. 1), have a low propagation loss, are focusable, and can propagate virtually undisturbed through tight bends and edges.

Structural Health Monitoring utilizes these properties by permanently embedding a number of ultrasonic transducers in a suitable geometric arrangement in the structure under test (Fig. 2).

The scientists at the Fraunhofer Institute of Non-Destructive Testing (IZFP) in Dresden are already integrating electronic circuit boards together with the actuators and sensors. Such intelligent structures require that the thickness of the elements is less than the acoustic wavelength, which is the case in common structures used in aviation and wind energy plants. The propagation and behavior of the waves generated by the transducers depend on the presence and size of possible defects, and are in turn detected by the same transducer array. Subsequently, they are localized by a special reconstruction algorithm. Figure 3 shows a defect and its location in a structure, derived from such data, determined by only four transducers.
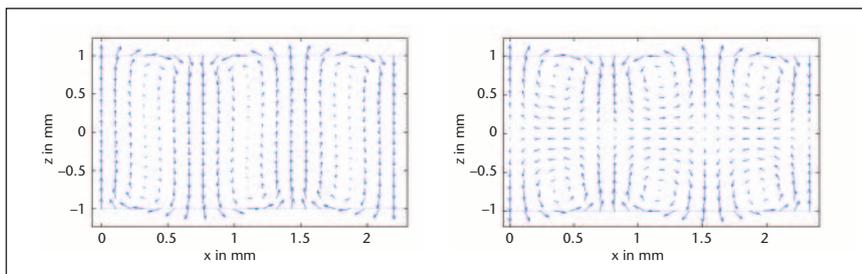
Safe Operation
Characterization of the Excitation and Propagation of Guided Waves for Structural Health Monitoring

Structural Health Monitoring

Structural Health Monitoring (SHM) uses a number of methods to evaluate the state of structures, plants and components in order to safeguard their operation over their period of operation. The aim is to detect problems such as fatigue cracks, deformation or other damage at an early stage so as to be able to initiate countermeasures. The inspection intervals are selected so that damage is revealed before a total failure occurs. In the airline indus-

try, for example, identifying whether damage has occurred or not can cut the necessary service times by as much as 40%. More detailed investigation can determine the location and scale of the damage, and identify whether the damage has an influence on the properties and reliability of the structure and whether a replacement or repair is necessary.

SHM examples include the testing of bridges and pipelines, wind turbines and aerodynamic lift components, and

Fig. 1: Visualization of the particle displacements of the two zero-order modes of a guided wave in a 2 mm steel plate at f = 2 MHz. Left: asymmetric mode; right: symmetric mode.

Fig. 2: Embedded ultrasonic transducers for Structural Health Monitoring on a wing segment.
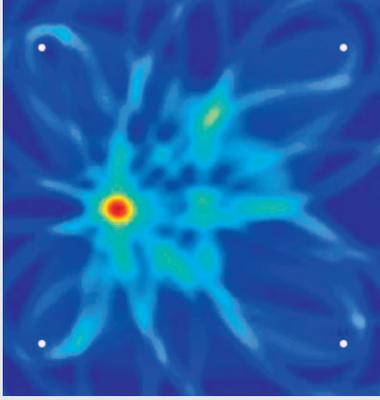
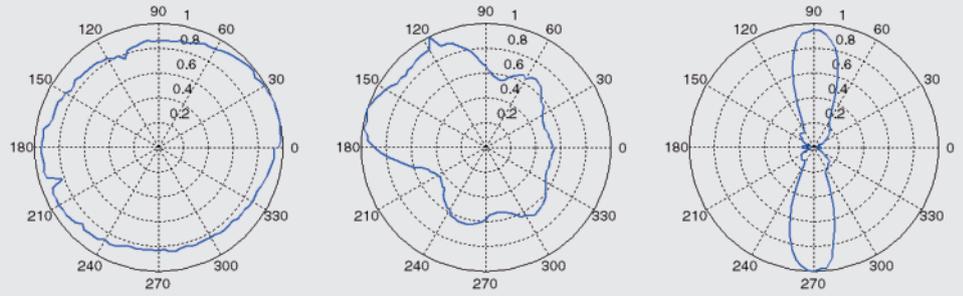Fig. 3: Localization of a defect (red) in a structure with four transducers (white dots in the corners).

Fig. 4: Directional chart of the source strength of a successful sensor integration (left), an incorrect sensor integration (center) and an integration with preferential direction (right).
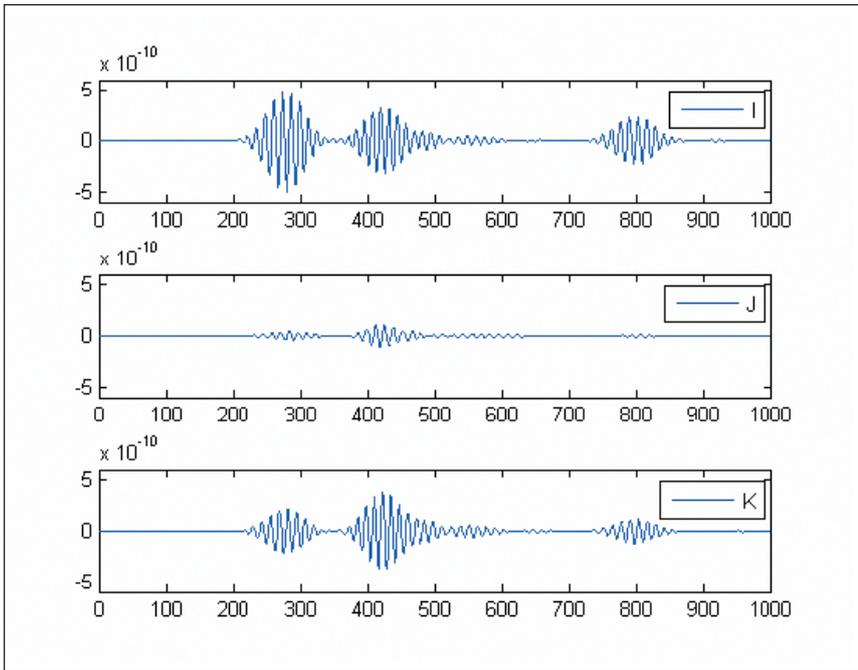

Fig. 5: Decomposition of the spatial directions of displacement over time measured in samples of a single measuring point (I in-plane parallel to wave propagation, J in-plane orthogonal to wave propagation, K out-of-plane direction.

Experimental Work

In developing suitable transducers for SHM, it is necessary to be able to characterize their excitation and reception properties and to precisely track the propagation of the waves with regard to attenuation loss or possible conversion effects. These investigations can be simply carried out, with high levels of accuracy, by using scanning laser vibrometry. This is a key technology in the development of the method.

A typical approach involves first incorporating the selected transducers into the structure under surveillance. The scanning vibrometer is used to measure and record the resultant wave fields over space and time. Afterwards, typical characteristic parameters such as coupling factor,

absorption coefficient or covering range are derived from the measurement data.

Of particular interest for a monitoring system is the directional dependency of the transducers. Ideally, the individual transducers in a monitoring system should have the same transmission properties in all angular directions. If they differ, false readouts or gaps in monitoring will result. To avoid this, the sound field of a transducer is plotted as a function of the propagation direction. Hence, the surface displacement measured by laser vibrometry are translated into a directional chart of the source strength, and then stripped out radially via the respective angular increments. In some special cases, it is advantageous to use transducers with one preferential

direction, as shown in Fig. 4 (right). If only the magnitude of the excitation or reception sensitivity is of interest, a one-dimensional characterization is sufficient. For more complex monitoring concepts it is advantageous to plot the complete wave field using 3-D scanning vibrometry. Using this method, the three spatial directions of vibration of the measuring point can be distinguished (Fig. 5). This enables the classification of various fault patterns, as they leave behind characteristic responses in the separated components of wave motion.

Summary

The methodology described is suitable both for the development of Structural Health Monitoring systems with regard to the selection, identification of the properties and the arrangement of the transducers, and for quality assurance of the method during operation, for example to detect defective transducers or faults in transducer integration. It therefore supports current trends in incorporating transducers and the associated electronics into wings and fuselage sections, as well as into rotor blades of wind energy plants. This meets the rising demand for a remote monitoring and diagnosis of stressed components.

Authors · Contact

Transducer characterization, Vibrometry
Dipl.-Ing. T. Windisch
thomas.windisch@izfp-d.fraunhofer.de
Dr. B. Köhler

Wave propagation, process development
M. Sc. L. Schubert,
Dipl.-Ing. B. Frankenstein

Fraunhofer Institute of Non-Destructive Testing IZFP, Dresden, Germany
www.izfp-d.fraunhofer.de

POLYTEC

Product News

MSA-050-3DSV
Micro System Analyzer

**3-D Vibration Measurements
Now Available for Microsystems**

The new MSA-050-3DSV Micro System Analyzer is designed for 3-D vibration analysis with high lateral resolution especially for microsytems, precision mechanics parts and for studies on the dynamics of HGAs and secondary actuators in the data storage industry. The frequency bandwidth of 2 MHz provides more than enough measurement capability e.g. for the decreasing size of hard disk components. The new device is based on three of Polytec's proven OFV-534 sensor heads, equipped with microscope objectives and a video camera. An integrated XY-traverse stage with full software support for high precision sample movement enables scanned measurements for obtaining 3-D deflection shapes. Data acquisition and processing are provided by powerful PSV Software.

www.polytec.com/microsystems

TMS TopSens and TMS TopLine

The new Point Sensors (see also page 4) can be configured for a wide range of applications, including:

Roughness Measurement

Our sensors are fully compliant with the new ISO 25178 regulation and are able to measure roughness values down to a few nanometers. They enable the acquisition of roughness profiles much faster than a classical tactile probe, and without any risk of marking the surface.

Thickness Measurement

The innovative Confocal Chromatic Imaging principle allows measurement of the thickness of transparent materials, with extremely high accuracy.

Profilometry & Microtopography

Interfaced with 3-D scanning devices, these optical sensors give access to full 2-D and 3-D measurements of complex objects or assemblies, with sub-micron accuracy.

Autofocus

Thanks to their extended measuring range, these sensors are the perfect solution for an accurate autofocus in vision systems.

Level control

Thanks to their non-contact technology, our sensors allow detection and measurement of fluids' level.

Online Inspection

These new optical sensors allow systematic control on production lines thanks to their very high measuring rates and advanced interfacing capabilities with the production line or the custom inspection machinery.

More info: www.topmap.info

Roughness Measurement

Thickness Measurement

Profilometry & Microtopography

Autofocus

Online Inspection
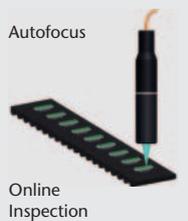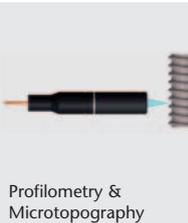
LSV 5.3 Software with New Features
Process Length and Speed Measurement Even Easier

The LSV 5.3 new software release is a comprehensive revision of the measurement and analysis software for LSV Laser Surface Velocimeters. In addition to being easy-to-use, it now has full Windows 7 support and many new features. The newly designed user interface provides improved zooming options and enables a graphical visualization of the signal quality. The brand-new trigger toolbar allows a manual start/stop length measurement. More toolbar buttons are dedicated to the setup dialog and acquisition settings. Various current values can be conveniently displayed and monitored in a resizable monitor popup dialog.

**More Info: www.velocimeter.us;
www.velocimeter.co.uk**

Trade Shows and Conferences

|			
Apr	26 – 29, 2011	A-TESTex/Analitika 9th specialized exhibition	Moscow, Russia
Apr	27 – 29, 2011	EuroPACT 2011	Glasgow, UK
May	02 – 05, 2011	AISTech 2011	Indianapolis, IN, USA
May	03 – 05, 2011	CONTROL	Stuttgart, Germany
May	03 – 05, 2011	Interwire	Atlanta, GA, USA
May	13 – 20, 2011	NIR 2011	Cape Town, South Africa
May	17 – 19, 2011	Noise and Vibration	Grand Rapids, MI, USA
May	23 – 25, 2011	40th Annual Symposium of the Ultrasonic Industry Association	Glasgow, UK
May	23 – 26, 2011	LASER – World of PHOTONICS 2011	Munich, Germany
June	07 – 09, 2011	Sensor & Test	Nuremberg, Germany
June	06 – Jul 02, 2011	METEC	Düsseldorf, Germany
Jul	10 – 14, 2011	18. ICSV International Congress on Sound and Vibration	Rio de Janeiro, Brazil
Jul	11 – 13, 2011	9th International Conference on Damage Assessment of Structures	Oxford, UK
Jul	13 – 15, 2011	Micromachine/MEMS 2011	Tokyo, Japan
Aug	19 – 22, 2011	IEEE	San Francisco, CA, USA
Aug	28 – Sep 02, 2011	CFM 2011	Besançon, France
Sept	14 – 16, 2011	Automotive Testing Expo China	Shanghai, China
Sept	18 – 23, 2011	International Conference on Smart Structures and Systems (ICOSSS´11)	Seoul, Korea
Sept	19 – 20, 2011	Polytec Ltd. User Group Meeting 2011	Gaydon, UK
Oct	03 – 06, 2011	International Congress of Metrology	Paris, France
Oct	04 – 06, 2011	MESURExpoVISION	Paris, France
Oct	25 – 27, 2011	Automotive Testing Expo North America	Novi, MI, USA
Nov	08 – 10, 2011	ICE Europe 2011	Munich, Germany
Nov	15 – 18, 2011	TOLEXPO	Paris, France

Reference our web site **www.polytec.com** for the most up-to-date information and links on trade fairs, events and seminars! Register for one or many seminars at the Polytec Web Academy at **http://polytec.webex.com**

Polytec Ltd. User Group Meeting
September 19th & 20th 2011 – Heritage Centre, Gaydon, UK

The 2011 Laser Vibrometer Users' and Technical Meeting is a two day event focused around education of the latest Polytec Technologies. The aim is to give current users and those developing an interest in laser vibrometers the opportunity to meet with and to hear about the work and experiences of others, compare notes, exchange knowledge, and to improve their own understanding and operation of laser Doppler vibrometers.

- **Day 1: Polytec Technology Day with Free Instrument and Software Training**
- **Day 2: Polytec Users, Application and Knowledge Transfer Day**

We look forward to hearing from you. Please find more information at **www.polytec-ltd.co.uk**.
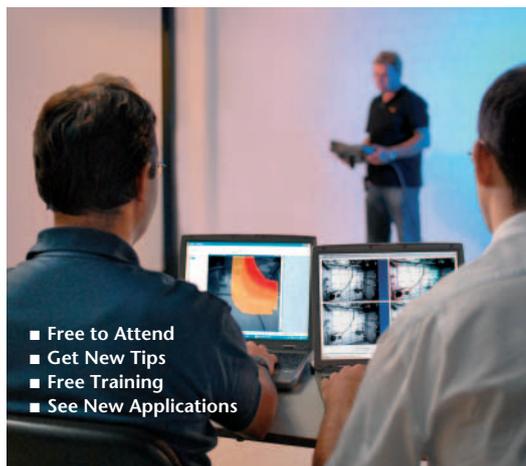
- Free to Attend
- Get New Tips
- Free Training
- See New Applications

Advancing Measurements by Light