

# InFocus

Optical Measurement Solutions



## Brakes

Analysis of operational deflection shapes at Continental Automotive Systems leads to silent brake designs [Page 4](#)

## Experimental Modal Analysis

Basic tutorial on this important CAD process, essential for rapid automotive development [Pull-out](#)

## Interior Noise

Improving damping material performance while reducing material usage [Page 10](#)

# Automotive Vibration Testing: Finding Solutions for Development and Production



Dr. Helmut Selbach



Eric Winkler

# Editorial

*Dear Reader,*

*Did you notice that our popular magazine has both a new face and a new name: InFocus - Optical Measurement Solutions? The new name was chosen to represent the whole range of our high-grade optical measurement systems designed to meet a growing number of non-contact, customer-driven measurement applications. To further emphasize this shift towards a broader application of optical sensing, we have renamed our "Laser Measurement Systems" business unit to "Optical Measurement Systems".*

*Our considerable experience in developing and manufacturing laser-based vibration and velocity measurement technology has been expanded to include optical sensor technologies that enable our customers to measure surface topography using white light interferometry. In addition, we are designing and building spectrometers for production testing of materials and goods. These spectrometers are currently distributed in Europe only; but, will soon be available worldwide as the market applications grow.*

*As you can see, there is a lot going on at Polytec. Continue reading to find many interesting contributions from our customers, including a special feature about automotive development and production. Pay special attention to the pull-out tutorial about experimental modal analysis and to the many innovative products from Optical Measurement Systems.*

*Keep up-to-date and have fun reading!*

Dr. Helmut Selbach  
Managing Director  
Polytec GmbH

Eric Winkler  
Vice President  
Optical Measurement Systems

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## Polytec Vibrometer Users Awarded 2006 DGAQS Prize

In recognition of their successful work on automatic test benches for production control, two Polytec customers, Mr. Pfichner (then PARI GmbH) and Mr. Fuchs (Dr. Fritz Faulhaber GmbH & Co. KG) received the 2006 DGAQS Prize. This prize is awarded biennially by the German Society for Acoustic Quality Control (DGAQS).

Both of the projects are based on the use of Polytec Vibrometers and were presented in the 2006/1 issue of our magazine (see [www.polytec.com/LM-INFO](http://www.polytec.com/LM-INFO)). The test facilities were systematically designed and developed starting with the selection of appropriate sensors and conditions. After a reliable correlation between measurement results, the parameters and criteria of production faults could be established and the test bench automation completed.

Faulhaber uses vibrometers for testing of micro drive systems, and PARI for testing of aerosol generators for liquid drugs.

DGAQS director Prof. Dr. Kotterba congratulating Mr. Fuchs (Faulhaber) and Mr. Pfichner (formerly PARI)



## Improved Quality – Lower Costs: New Laser Velocimeters at Aluminum Mill

ALUNORF in Neuss, Germany, the world's largest aluminum rolling and remelt plant, uses Polytec's non-contact, laser-Doppler instrumentation to simultaneously measure length and speed of aluminum plates in the manufacturing process. Several LSV-6000 Laser Surface Velocimeters are integrated into the production line and provide length and speed data for process control.

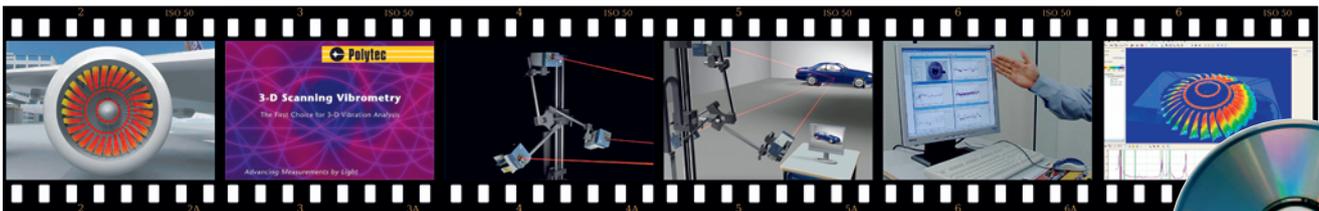


By using Polytec's innovative measurement technique, ALUNORF has implemented a fully automatic positioning system to position plates at the shears for high precision cut to length.

The speed measurement is used to synchronize roller conveyor speed with plate speed. This prevents abrasion and damage of the aluminum surface, as well as, reduce the maintenance frequency of cleaning the roller tables. The length measurement is used to position the plates at the crop shears, resulting in a reliable and repeatable cut length tolerance.

Laser Surface Velocimeters can measure surface speed and length of all types of materials and have been used in a variety of industries, providing reliable and accurate measurements from standstill to speeds of more than  $\pm 23,000 \text{ ft min}^{-1}$  in either direction.

 [www.polytec.com/lsv](http://www.polytec.com/lsv)



### New Instructional Video

## Learn About 3-D Vibration Measurement On Your Desktop

Polytec's PSV-400-3D Scanning Vibrometer has become an invaluable tool especially for automotive and aerospace development. Despite its high level of sophistication and performance, it is

based on a simple physical principle: the Doppler effect. In our brand new demo video, we show how the PSV-400-3D Scanning Vibrometer works and how it is operated.

View the video trailer on our web page and order your individual DVD at

 [www.polytec.com/psv3d](http://www.polytec.com/psv3d)



# Polytec News



## Polytec on the Scene:

### The Secrets of Stradivarius and Guarneri Violin Masterpieces

Polytec joined forces with Professor George Bissinger of East Carolina University and two highly respected violin makers to study the 3-dimensional vibration response of three old Italian master violins using the Polytec PSV-400-3D scanning system. This was a once-in-a-lifetime opportunity to test a Guarneri del Gesù and two Stradivarius masterpieces. Scans of various portions of each violin were stitched to provide a true 3-dimensional visualization. 3-D data also permits volume changes to be computed related to air forced through the f-holes, previously

shown to be a new radiation mechanism providing a major contribution to the sound near 500 Hz. Another indirect radiation mechanism – A1 cavity-mode-forced body motion – was seen quite strongly in one Stradivarius and one Guarneri del Gesù. The hope is to combine the Polytec vibrational data with acoustical and density/shape data also measured during the visit in order to develop a vibro-acoustic solid model. This would perhaps enable us to finally reveal some of the secrets of these masterpieces and apply this knowledge to modern violin making.

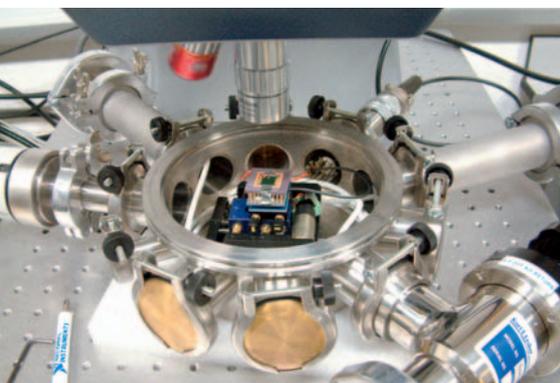
More info on the ECU homepage:  
[www.ecu.edu/news/poe/1006/violins.cfm](http://www.ecu.edu/news/poe/1006/violins.cfm)

View audio slide show on  
[www.newsobserver.com/1181/story/489521.html](http://www.newsobserver.com/1181/story/489521.html)



## British Center of MEMS Excellence:

### UK National Standards Laboratory Purchases Polytec MSA-400



NPL is the United Kingdom's national standards laboratory, an internationally respected and independent center of excellence for R&D, and knowledge transfer in measurement and materials science. To support the metrology and dynamic characterization of MEMS and other microstructures, NPL has added a Polytec MSA-400 Micro System Analyzer to its collection of working

in the micro and nano domain. The Polytec system was chosen for its small spot size and hence excellent lateral spatial resolution, for its ability to measure through a vacuum window and for its differential measurement capability that eliminates any relative motion between the tested device and its supporting structure. NPL's new Polytec MSA-400 covers frequencies to 1 MHz and measures dynamic motion in both the out-of-plane (Z axis) and in-plane (X-Y axes) directions. It is capable of measuring the frequency response of resonant devices (such as cantilevers, membranes, accelerometers, etc), as well as the time domain response of switches, actuators and other structures, displaying that response as still or animated deflection shapes for out-of-plane vibration, or Bode plots with motion amplitude for lateral measurements.

Data is easily taken, giving fast indication of the overall frequency response of a structure, with deflection shapes quantifying the motion at the resonant and other frequencies. Such information is essential to verify if design, manufacture and operation are correct for the device. The MSA-400 will also ensure that existing characterization work on PZT and other active materials will also be enhanced and extended.

The purchase of such a system shows NPL's commitment to supporting the emerging field of Microsystems and Nanotechnology and it is hoped that further work will ensure the development of calibration and certification techniques for the measurement of these challenging devices.

Read NPL's new MSA-400/vacuum chamber application note on

 [www.polytec.com/mems](http://www.polytec.com/mems)



# Automotive Vibration Testing

Laser vibrometry is firmly established as the automotive industry's gold-standard for non-contact vibration measurement. Its advantages include zero-mass loading, long standoff distance, high precision and sensitivity, fast set-up, ease of operation, high-throughput, and low operating costs. With so many advantages over contact transducers, laser vibrometry is quickly revolutionizing design development and experimental modal analysis in the automotive industry. It can be extended to the most difficult measurement tasks, such as red-hot, complex or microscopic structures. Polytec's comprehensive line of products and services provide an optimal solution for almost every automotive vibration measurement application.

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

## Sound & Vibration Characterization

The dynamic and acoustic properties of an automobile are one of the most important qualities affecting customer perception and vehicle sales. Polytec vibration measurement equipment is used by automotive manufacturers worldwide to improve and optimize their vehicles.

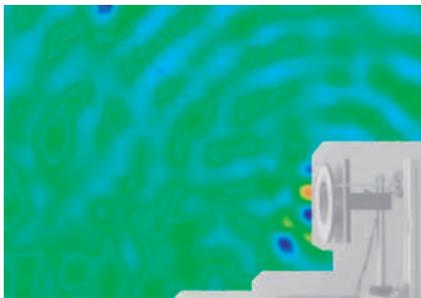
A luxury car manufacturer provides a perfect example. During pre-production prototype testing of a new engine configuration, there was evidence of alternator whine. Using a Scanning Vibrometer, the noise hotspots were identified. This data was combined with a FE model permitting an intelligent redesign that reduced the noise

and increased the component durability. Problem solved!

Read more about another project dealing with structure-borne sound intensity of car bodies derived from laser scanning measurements on page 6.



## How to See Brake Sounds



Under certain operating conditions, the complex dynamics between the brake caliper, brake pads and brake disk can cause undesired audible squealing. Measurements with Polytec's 3-D scanning vibrometer acquire complete vibration vector data showing the spatial dynamics of the brake disk. Using this technology, researchers at Robert Bosch GmbH have managed to track down the

causes of undesired noises when braking. The vibrometer can also measure the sound field set out from a squealing brake. For more information and to view a live animation of the brake sound field, visit

[www.polytec.com/automotive](http://www.polytec.com/automotive)

To learn how Continental Automotive Systems designs silent brakes by using operational deflection shape analysis, read the article on page 4.

## Experimental Modal Analysis

Modal data describe the dynamic properties of a structure and can assist in the design of almost any structure, helping to identify areas where design changes are most needed. Predicting the vibration characteristics of automotive components and systems is a standard CAE process in today's automotive development environment. DaimlerChrysler studied the suitability of Polytec's 3-D Scanning Vibrometer for data acquisition in car body modal testing and discovered that vibrometry can make the same measurements as accelerometers but quicker and more accurately, cutting modal testing costs substantially. DaimlerChrysler's technique and measurement results are summarized in the Application Note VIB-C-01 which can be downloaded from the Polytec website. To learn more about the theory behind this method, read our tutorial "Basics of Experimental Modal Analysis".

[www.polytec.com/automotive](http://www.polytec.com/automotive)

Modal Analysis can also be applied in engine development (see page 16).

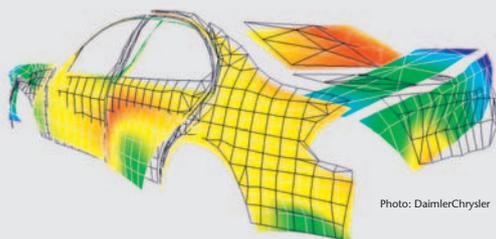
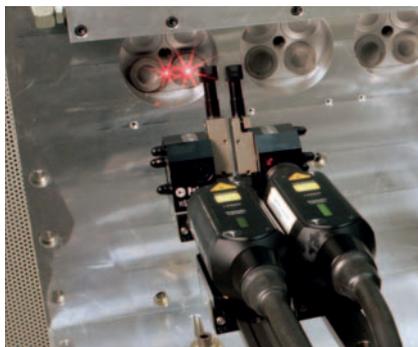


Photo: DaimlerChrysler

## Valve Train Testing



Combustion and the associated engine valve train movement are highly dynamic processes where extremely high speeds and accelerations can occur. Measuring valve motion presents some special

challenges including separating the valve motion from the superimposed whole body displacement of the cylinder head and measuring large displacements with high resolution. A differential, high speed vibrometer is an excellent measurement solution and can provide accurate valve motion graphs essential for optimizing the combustion process, fuel consumption, engine performance and service life. The measurement range of up to 30 m/s allows measurements even on high performance Formula 1 engine systems.

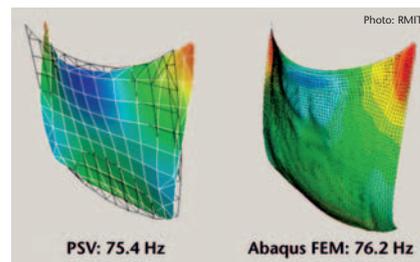
For more detailed information, please read the article on page 12 and view Polytec's Application Note VIB-C-03 at

[www.polytec.com/automotive](http://www.polytec.com/automotive)

## FE-Test Correlation for Damping Material Optimization

Material layout optimization can be performed effectively using finite element analysis. The optimization results need to be validated by measuring the vibration performance of real prototypes.

RMIT University, Melbourne, has applied the PSV-400 Scanning Vibrometer to the research of automotive panels such as the car door and bonnet. The natural frequencies and mode shapes being measured by the vibrometer are compared with the results of an FEA frequency extraction procedure. A good correlation between the simulation and experimental results gives confidence in the FEA model to perform an



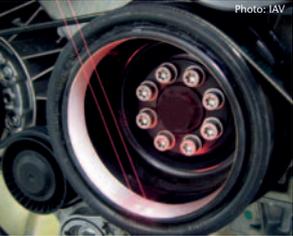
optimization study using genetic algorithms that will redistribute the liner material.

Read more on page 10 about a study performed at Dow Chemical Company to demonstrate the ability to improve liquid applied damping material performance while reducing the material usage.

## Tracking of Rotational Vibrations

Rotational movements of automotive components are always the subject of intensive optimization efforts by product development groups. The non-uniform rotation

induced by the firing of individual engine cylinders leads to torsional vibrations in the drive chain that cause undesired vibration and noise.



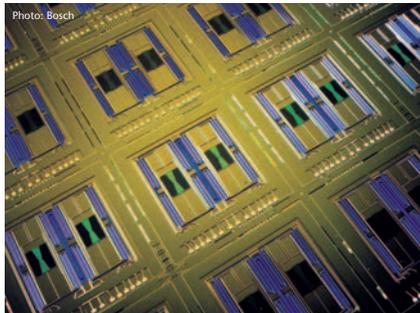
Rotational Vibrometers use remote laser probes to avoid contact and allow a quick and easy examination of the torsional vibrations while the components of interest are in operation.

Read more on page 14 to learn about how Rotational Vibrometers help determine the transmission behavior of a dual mass flywheel, and download our application note VIB-C-04 on

 [www.polytec.com/rotvib](http://www.polytec.com/rotvib)

## Development of Micro-Electromechanical Systems (MEMS)

As MEMS components in modern cars are increasingly taking on safety-relevant tasks, high sensor precision combined with lifelong reliability is of critical importance. Typical automotive applications of MEMS include engine control with pressure sensors, airbag actuation



by accelerometers, vehicle dynamic control, position sensors, light and moisture sensing, and distance sensors to avoid collisions. For example, engineers at Bosch are developing radar antennas including RF MEMS switches whose vibration behavior was designed with the aid of Polytec vibrometers. For more details please download the full article about "Automotive Sensors" at

 [www.polytec.com/mems](http://www.polytec.com/mems)

Please read also the article on page 9 to learn about MEMS pressure sensors from Melexis, a world-class automotive electronics producer, and how Polytec's MSA-400 Micro System Analyzer is used to reduce production cost.

## Vibration Tests on Electronic Circuits

Electronical interconnects are a common source for automotive failure, very often caused by broken wire bonds. Consequently, vibration testing of wire bonds is essential to finding and avoiding these problems. Non-contact laser vibrometers are ideally suited for this purpose, while contact transducers (accelerometers) are impossible to use due to size and mass loading. By making a 3-D Scanning Vibrometer measurement on a printed circuit board, an engineer can determine both in-plane and out-of-plane vibrations of bond pads. In the example above, FRFs and deflection shapes of opposite bond pads reveal frequencies that could be detrimental to the bonds.

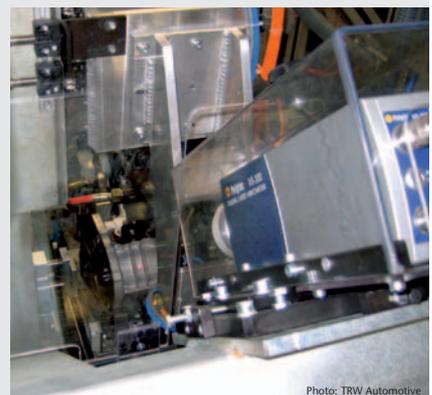


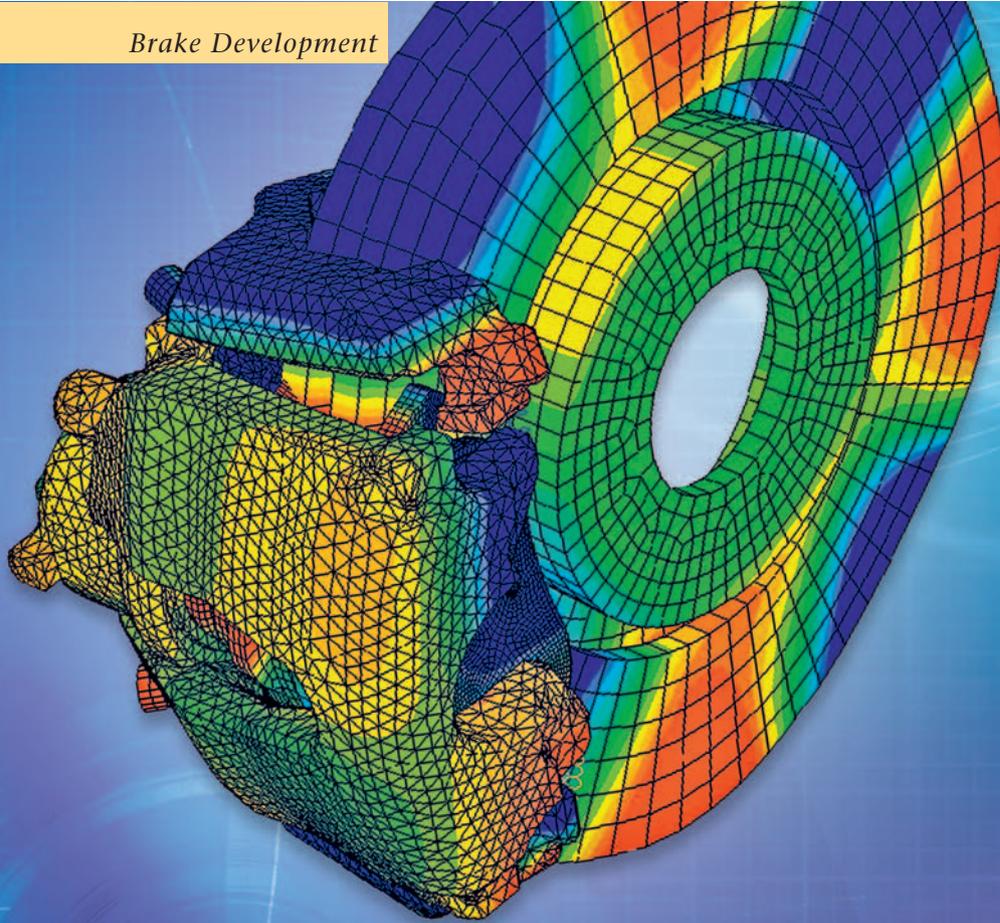
## Industrial Vibration Sensors for Production Testing

Acoustic quality control is a non-destructive process to assure the quality and reliability of products and manufacturing processes. In the car industry, non-contact vibrometers can be used to test engines, gear boxes, steering gears, cam rings, turbochargers and fuel pumps to name a few examples. At TRW Automotive in Gelsenkirchen, several fully automatic test stations use IVS-300 Industrial Vibration Sensors to provide

a 100 % inspection of motor pump assemblies before integration into the steering gear systems. Proper inspection assures that drivers will experience performance and reliability without distracting or annoying noise. Read more and download our magazine issue 2006/1 specially featuring an article entitled "100 % Quality Control in Industrial Production".

 [www.polytec.com/industrial](http://www.polytec.com/industrial)





Computer-aided simulation of brake noise has made impressive advances in the past few years. Likewise, 3D scanning vibrometry has substantially extended the possibilities of experimental vibration analysis. Scanning Vibrometry enables the measurement of both in-plane and out-of-plane operational deflection shapes of the relevant components in the same test setup. At Continental Automotive Systems the measurement of brake systems with scanning vibrometry including PSV-400-3D systems is fully integrated in the design optimization process to specifically avoid brake noises.

# Quiet Please!

*Eliminate Brake Squeal with Numerical and Experimental Vibration Analysis*

## Finite Element Simulations

Brake noise is an important concern in developing brake systems. Brake squealing is still the most frequently cited NVH concern. It is caused by self-excitation and includes usually just one frequency. The noise appears when certain temperatures and pressures are attained in the brake system. A first optimization to prevent self-excitation consists of a complex eigenvalue analysis with subsequent structural modifications to avoid unstable modes. The analysis is based on the vibration equation

$$f(t) = M\ddot{q} + D\dot{q} + Kq = 0$$

where  $f(t)$  is the force,  $M$  is the mass matrix,  $D$  is the damping matrix,  $K$  is the stiffness matrix and  $q$  is the displacement vector. Continental Automotive engineers simulate the complete brake system with all adjacent components featuring several hundred thousand

degrees of freedom. On the one hand, the complex Eigenvalue analysis can be started during the design process without any prototypes necessary. On the other hand, the method is too sensitive and shows more squeal frequencies than actually exist. Therefore, it is necessary to compare the results to simulation and dynamometer testing and verify whether the calculated ODS actually occur in practice. In Figure 1, the calculated operational deflection shape of a squealing brake system is shown.

## Experimental Data

In Figure 2, the test setup for measuring the operational deflections shapes with a 3D Scanning Vibrometer on the brake test stand is shown. The scan measurements are triggered when the brake brake squeal is detected by a microphone.

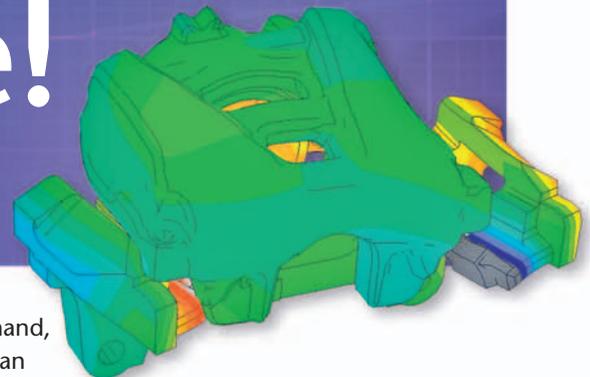
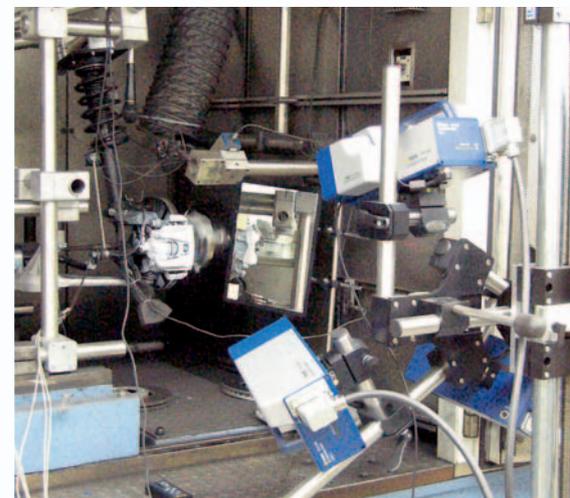


Figure 1: Calculated ODS (operational deflection shape) of a squealing brake system.

Figure 2: The setup of the 3-D Scanning Vibrometer to measure the operational deflection shapes of the brake caliper and rotor.



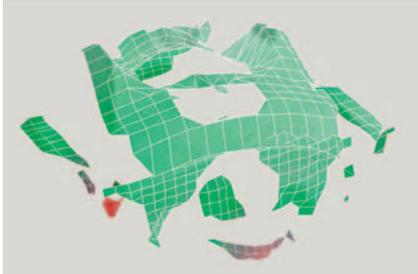


Figure 3: Operational deflection shape of a brake caliper measured by the vibrometer.

This guarantees that acquired data is correlated to specific sound behaviors.

The vibration behavior of the brake system is measured simultaneously from three different directions.

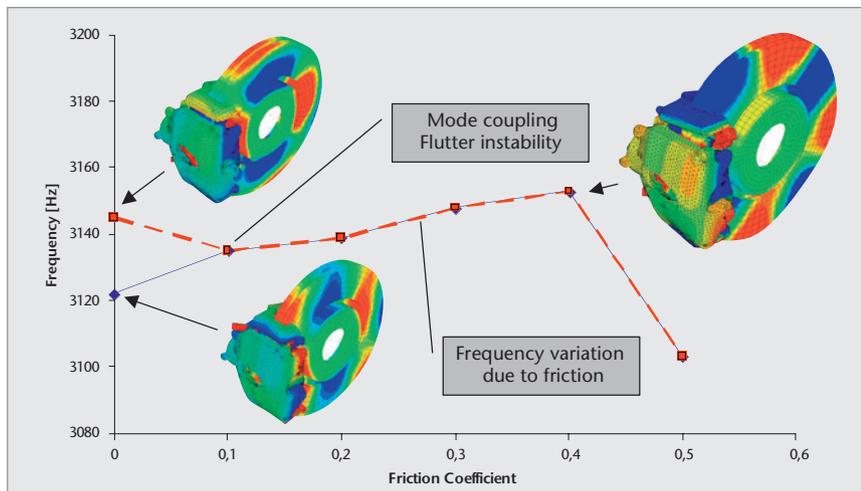
Instead of moving the sensor heads and stitching together the measurements from the different positions, surfaces not directly accessible from the sensor position are measured via mirrors. When measuring via mirrors, a coordinate transform of the measurements is necessary to make sure that all measurements both with and without a mirror are displayed in the same coordinate system. This is enabled automatically by predefining the mirror positions during the setup of the Scanning Vibrometer. In Figure 3, the operational deflection shape of a brake caliper measured with the Scanning Vibrometer is shown.

Extending the measurement to three dimensions, the 3D Scanning Vibrometer has become an essential tool to collect experimental data for the optimized design of brake systems. It enables the measurement of both in-plane and out-of-plane operational deflection shapes of the relevant components in the same test setup. In contrast to conventional measurements with tri-axial accelerometers, it enables fast and efficient non-contact and thus reactionless measurements at all optically accessible surfaces, while simultaneously increasing the number of measured points. An integrated distance sensor known as the Geometry Scan Module enables acquisition of the 3D spatial coordinates on a pre-defined measurement grid. If available, geometry data can also be imported from a FEM program.

### Suppression of Unstable Modes

As soon as the operational deflection shapes and mode shapes are known, the causes of self-excitation can be elucidated on the basis of mode coupling. In Figure 4, the interaction of two modes of the brake system (caliper and brake disk) are shown to depend on the friction coefficient. The dashed red line shows the frequency of one mode, the solid blue line the frequency of a close second mode.

Figure 4: Flutter instability due to mode coupling as a function of the friction coefficient.



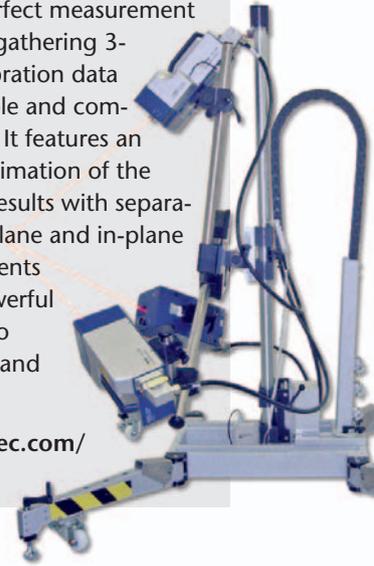
Polytec Product Information



## PSV-400-3D Scanning Vibrometer

The PSV-400-3D Scanning Vibrometer is the perfect measurement instrument for gathering 3-dimensional vibration data from both simple and complex structures. It features an intuitive 3-D animation of the measurement results with separation of out-of-plane and in-plane vector components as well as a powerful data interface to Modal Analysis and FEM Software.

[www.polytec.com/psv3d](http://www.polytec.com/psv3d)



By increasing the friction coefficient, the frequency of both modes are changed. At first, the frequency of the first mode is decreasing while the frequency of the second mode is increasing until the frequencies of both modes are the same at a friction coefficient of 0.1.

In this case both modes are coupled and result in a flutter instability as a result of interaction between caliper and brake disk. When increasing the friction further, the two modes remain coupled. In order to eliminate the brake noise, the structure is modified by shifting the resonance frequencies so that the mode coupling disappears.

### Summary

The analysis of mode shapes based on experimental data acquired with a 3D Scanning Vibrometer enables selective brake design modifications to avoid brake noises.

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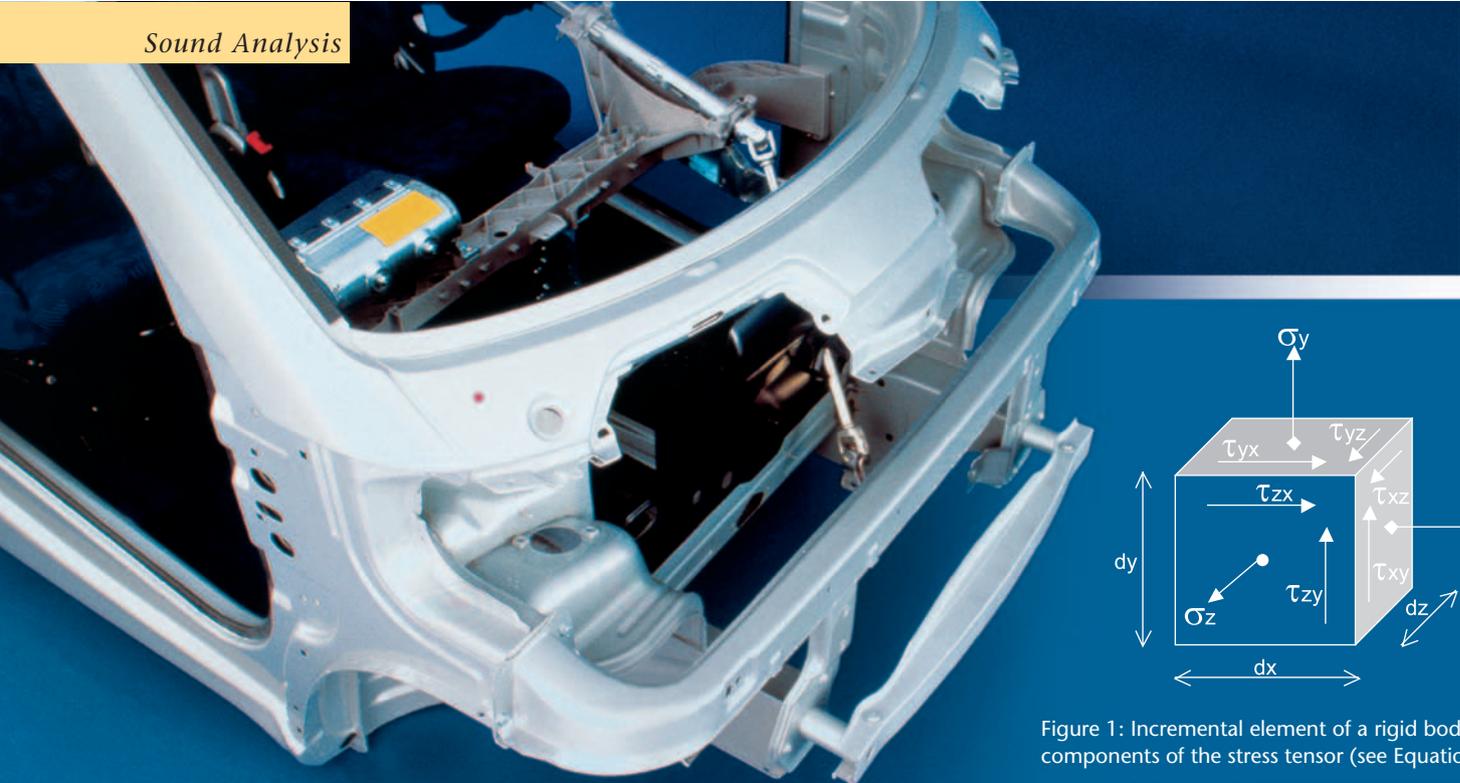


Figure 1: Incremental element of a rigid body with components of the stress tensor (see Equation 1).

# From Source to Sink

## Using Scanning Laser Vibrometer Measurements to Derive Structure-Borne Sound Intensity from Car Bodies

Automotive engineers want to relate the interior vehicle noise level to the forces applied to the body at the engine and chassis mounts. Although the acoustics of solids are much more complicated than in fluids, where measurements of intensity have been established for a long time, it is an ideal measurement application for scanning laser vibrometry when limited to thin plates. To further explain this point, a sound intensity analysis of structure-borne effects is discussed for a car roof panel.

### Base Equation for Intensity

Sound intensity represents, in vector form, the acoustic energy flow in a medium. Using continuum mechanics, a mechanical model for the intensity can be derived from the strain and stress. In a rigid body, these are tensors with normally six independent values, three in the normal direction and three in the tangential or shear direction (Fig. 1).

In basic mechanics, power is the product of force times velocity. Similarly, in continuum mechanics, multiplication of the respective tensors results in the intensity vector in three directions. Each component  $J_i$  of the intensity vector is the sum of three terms representing the different stresses (normal and shear) averaged over time (Eq. 1).

$$\begin{aligned} \text{Eq. (1)} \quad J_x &= -\left[ \overline{\sigma_x v_x} + \overline{\tau_{xy} v_y} + \overline{\tau_{xz} v_z} \right] \\ J_y &= -\left[ \overline{\tau_{xy} v_x} + \overline{\sigma_y v_y} + \overline{\tau_{yz} v_z} \right] \\ J_z &= -\left[ \overline{\tau_{xz} v_x} + \overline{\tau_{yz} v_y} + \overline{\sigma_z v_z} \right] \end{aligned}$$

$$\text{Eq. (4)} \quad \text{div} J_a = \frac{\partial J_{a,x}}{\partial x} + \frac{\partial J_{a,z}}{\partial z} = \nabla J_a$$

$$\text{Eq. (2)} \quad P_x(t) = B \cdot \left[ \overline{\left( \frac{\partial^2 \eta}{\partial x^2} + \mu \frac{\partial^2 \eta}{\partial z^2} \right) \cdot \frac{\partial \dot{\eta}}{\partial x}} + (1 - \mu) \overline{\frac{\partial^2 \eta}{\partial x \partial z} \cdot \frac{\partial \dot{\eta}}{\partial z}} - \frac{\partial}{\partial x} \left( \frac{\partial^2 \eta}{\partial x^2} \cdot \frac{\partial^2 \eta}{\partial z^2} \right) \cdot \dot{\eta} \right]$$

$$B = E \frac{h^2}{12}; \quad \eta \mapsto \text{out of plane movement} \quad E, \mu \mapsto \text{Youngs modulus, poisson ratio}$$

$$\text{Eq. (3)} \quad P_x(\Omega) = B \cdot \frac{1}{2} \text{Re} \left\{ \frac{\partial^2 \eta}{\partial x^2} \cdot \frac{\partial \dot{\eta}^*}{\partial x} + \mu \frac{\partial^2 \eta}{\partial z^2} \cdot \frac{\partial \dot{\eta}^*}{\partial z} + (1 - \mu) \frac{\partial^2 \eta}{\partial x \partial z} \cdot \frac{\partial \dot{\eta}^*}{\partial z} - \frac{\partial^3 \eta}{\partial x^3} \cdot \dot{\eta}^* - \frac{\partial}{\partial x} \left( \frac{\partial^2 \eta}{\partial z^2} \right) \cdot \dot{\eta}^* \right\}$$

### Mechanics of Structure-Borne Sound Intensity in Plates

In general, it is not possible to accurately measure stress and strain in a rigid body to satisfy Equation (1). The general intensity formula is applied to calculated values (CAE). Any experimental application is limited to plates, where it is possible to extrapolate from surface deflections (measured by scanning vibrometers) to interior responses.

After integration over the plate thickness and with restriction to the out-of-plane component, the power in the x-direction is given by Equation (2).

The next issue to consider is the time averaging of the product of two dynamic variables  $y(t) = x_1(t) \cdot x_2(t)$ . In the time domain, both variables oscillate with the same frequency. Applying this, the intensity averaged over time can be calculated (Equation 3) from the measured spectra in the frequency domain.

The real part denotes the active intensity. The imaginary part is known as reactive intensity and describes the energy that is oscillating over the surface of the structure but does not travel on average. The measurement systems used in modal analysis are not able to measure

read the Scanning Vibrometer data set, providing the mobility functions and the coordinates of the measurement grid. After passing some integrity checks, an averaged frequency response function (FRF) is plotted from the data. A single frequency is selected for the analysis and its FRF can be plotted as a 3-D shape over the measurement grid.

After checking the measurement data, an analysis can be performed at the frequency of interest. Active and reactive intensity can be evaluated. The result is plotted as a vector plot or a divergence plot. In particular, the divergence of the intensity vector field (see Equation 4) is an effective tool to find energy sinks and sources.

X) is visible in Fig. 3. The dissipation takes place in a more distributed way as compared to the analytical example shown in Fig. 2 with a point damper.

The real world sample is a roof taken from a passenger car by cutting at the top of the A, B and C pillars (Fig. 4), then fixed with a bungee support, and a damping pad was attached to the upper right quarter of the roof.

In Fig. 5, the energy input of the shaker located at the lower left corner can be identified clearly. The additional damping pad does not show a significant effect. This is due to a reinforcing roof bow in the middle between the two B-pillars which acts as a barrier to the sound waves, so that only a part of the energy reaches the upper part of the roof.

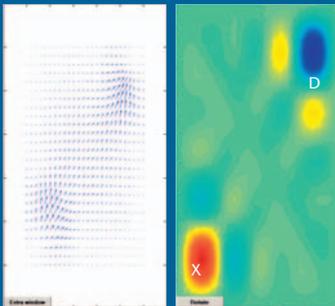


Fig. 2: Intensity (energy flow) of a simulated plate at 420 Hz with an exciter (Source X) and a damper (Sink D).

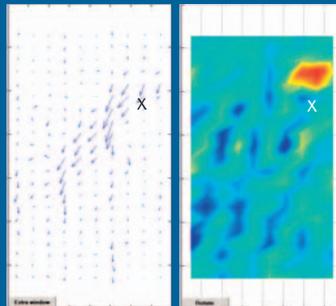


Fig. 3: Intensity of a locally damped steel plate at 420 Hz with an exciter located at X.

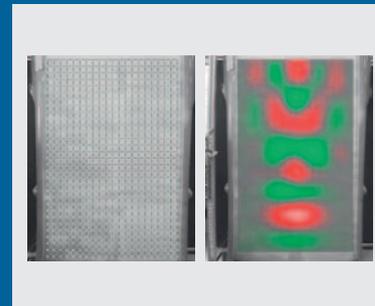


Fig. 4: Scanning Vibrometer measurement setup (left) and operational deflection shape (right) for the car roof.

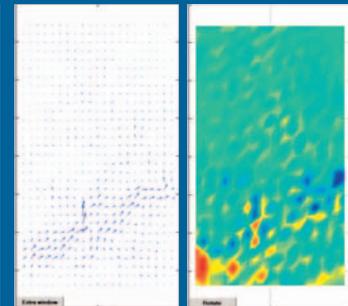


Fig. 5: Structure-borne intensity at 498 Hz of an isolated roof with single damping pad.

derivatives with respect to space, however Equation (3) has derivatives up to the third order and mixed derivatives that are necessary to get the terms needed for the intensity. In practice, this is the critical part of the method. The measurements can be done within a grid of measurement points during the scan and the interpolation is done separately in both surface directions x and z. Finally, a numeric algorithm is used to estimate the high order derivatives, using either cubic splines or harmonic functions.

### MATLAB Implementation

A MATLAB program with a convenient user interface has been developed to

### Experimental Results

When exciting a structure, a physical energy flow occurs if an energy sink like a damper is provided. This was first implemented using a simulated data set for a plate with dimensions 700 mm x 1100 mm x 1 mm and a single point damper. The simulated sample shows the expected behavior in the active intensity vector field and its divergence (Fig. 2).

Next, a steel plate supported by bungee cords was measured on a 21 x 10 point grid using the PSV Scanning Vibrometer. A rectangular bitumen foil had been added to the lower left corner as a damper so the energy flow would become defined. The exciter (Source

### Conclusion

When optimizing damping layers on automotive panels to improve the noise transfer function, a very effective sound intensity analysis can be made by using scanning laser vibrometry. The advantage of intensity over sound pressure measurements is that intensity represents the energy flow and reveals more significant information that can be used for NVH problem solving.

*This work was done at the Ford Acoustic Centre Cologne with the support of Martin Flick.*

*Bienert.Joerg@Siemens.com*



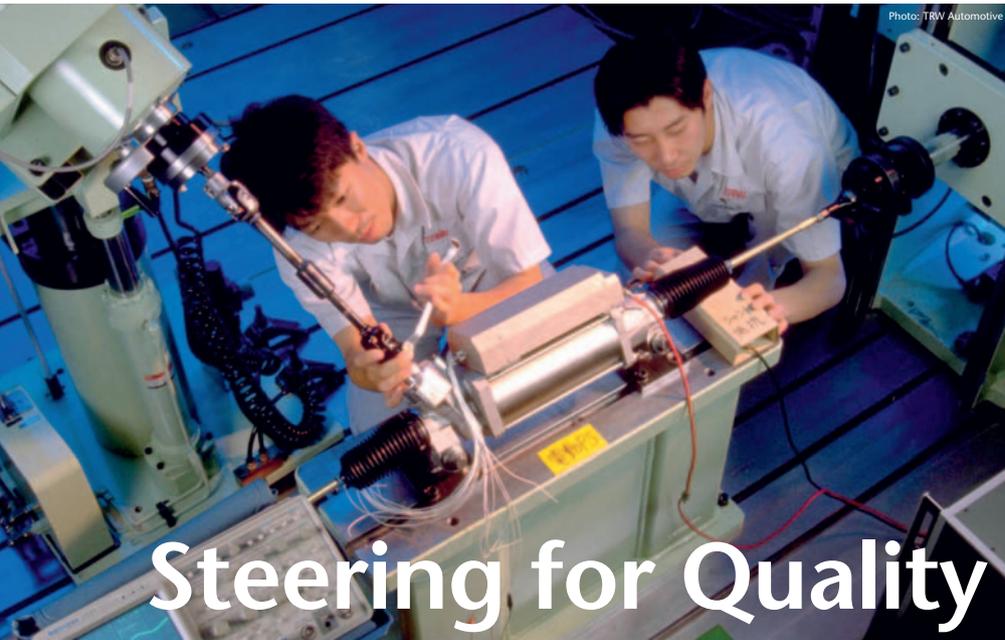


Photo: TRW Automotive

# Steering for Quality

## Determination of Vibration Modes in the Development of Steering Systems

TRW Automotive, with over 60,000 employees worldwide, is one of the largest global automotive suppliers for safety systems such as wheel suspension components, braking systems, steering systems, airbags and restraint systems. Acoustical and vibration tuning has always held a special spot within the mainstream activities of TRW's product development. To accomplish this task, the steering division uses two different types of non-contact Laser-Doppler Vibrometers to analyze vibrations on automotive components and systems.

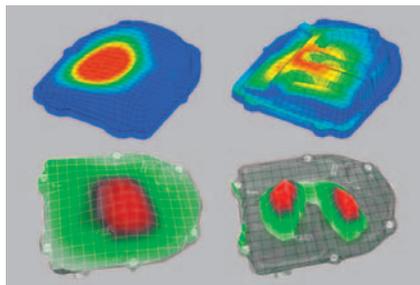


Figure 1: Vibration modes of a cover plate, determined by the FE model (above) and by scanning vibrometry (below).

In the production of steering systems, single-point vibrometers are used to capture the surface velocities at specified reference points on the steering systems in order to predict the noise performance in the vehicle before delivery (see page 3).

In the development centers in Düsseldorf and in Birmingham, PSV-400 and PSV-200 Scanning Vibrometers are used in addition to single-point vibrometers. Stationary deflection shapes of vibrating structures can be easily determined with this equipment even when the surface is uneven. In the Figure 1, there are two deflection shapes shown (1200 Hz and 3150 Hz) for a cover plate from an electro-hydraulic steering system. The frequencies needed to be shifted with the help of FE-based structural modifications to improve the cover performance. Specific challenges of this task were the material used, its complex material properties and some tooling-relevant aspects like lead time and costs.

Polytec Product Information



## PSV-400 Scanning Vibrometer

The PSV-400 is a quick and easy-to-use system for the analysis of full-field structural vibrations, helping to resolve noise and vibration issues in commercial, manufacturing and R&D markets.

[www.polytec.com/psv400](http://www.polytec.com/psv400)



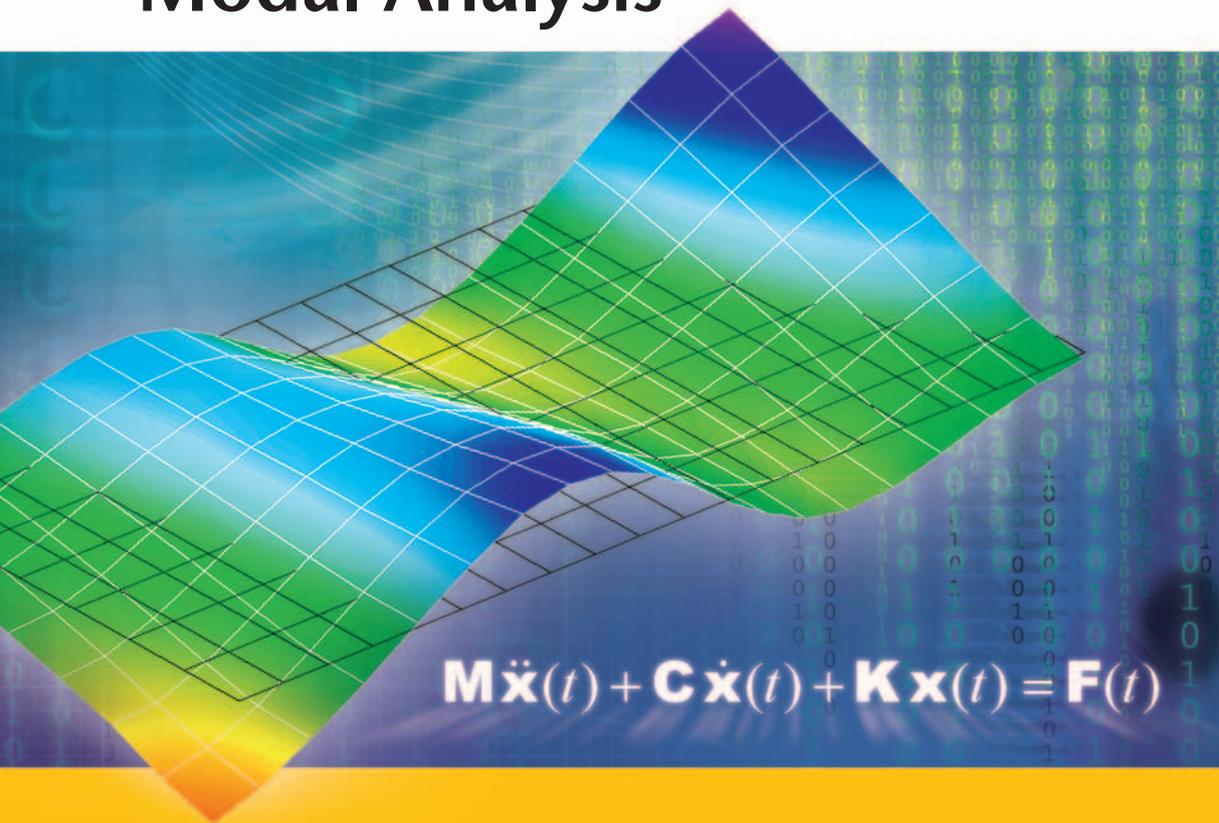
By integrating the scanning vibrometer into the cover design process, the FE model was correlated with real world data and prepared for structural optimization. The final validation of the optimized design fully met the expectations of the engineers.

A hybrid approach for vibration-related optimization of steering system components, employing numerical methods like CAE and simulation early in the development phase, can only be efficiently done if tools are available which enable a real-time verification of the model. The scanning laser vibrometer is an important tool in this respect, especially when data is acquired for stationary events and constant operating conditions. A screening approach with accelerometers can complement the vibrometer in some special cases, especially when scanning certain transient vibrations during start-up.

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# Basics of Experimental Modal Analysis



*Modal analysis is a method to describe a structure in terms of its natural characteristics which are the frequency, damping and mode shapes – its dynamic properties. 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.*

## What Good are Modal Data?

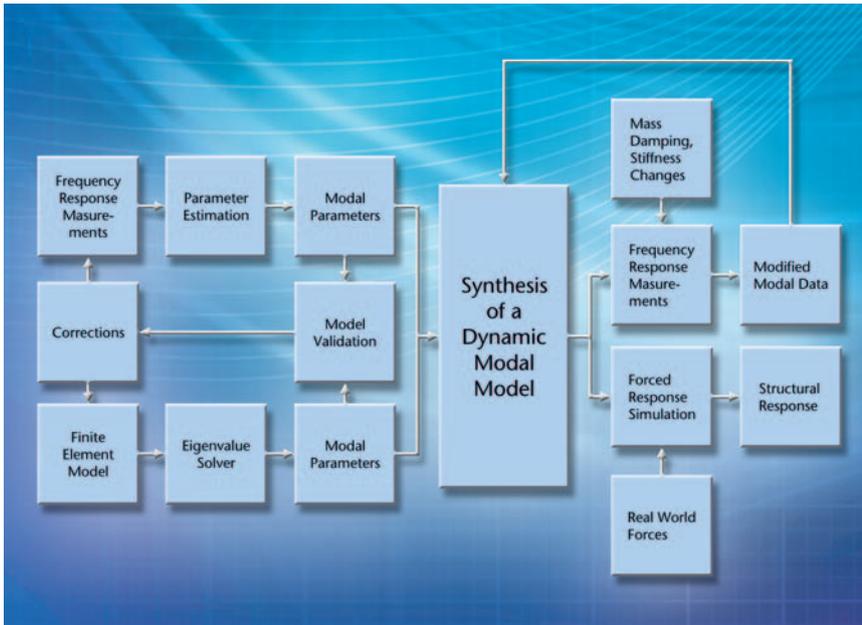
Modal data are extremely useful information that can assist in the design of almost any structure. The understanding and visualization of mode shapes is invaluable in the design process. It helps identify weakness in the design and areas where improvement is needed.

The development of a modal model, from either frequency response measurements or from a finite element model, is useful for simulation and design studies. One of these studies is structural dynamics modification.

This is a mathematical process which uses modal data (frequency, damping and mode shapes) to determine the effects of changes in the system characteristics due to physical structural changes.

These calculations can be performed without actually having to physically modify the actual structure until a suitable set of design changes is achieved.

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**Figure 1: Dynamic modal model development and modal testing in the design process.**

In addition to structural dynamic modification studies, other simulations can be performed such as force response simulation to predict system response due to applied forces. Another very important aspect of modal testing is the correlation and correction of an analytical model such as a finite element model. These are a few of the more important aspects related to the use of a modal model. A schematic is shown in Figure 1.

### A Simple Model

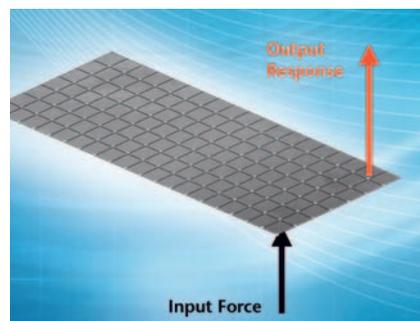
Modal analysis is often explained in terms of the modes of vibration of a simple, freely supported flat plate (Figure 2). A force that varies in a sinusoidal fashion is applied to one corner of the plate. While the rate of oscillation of the frequency is changed, the peak force will always be the same value. The response of the plate due to the excitation is measured with a laser vibrometer or with accelerometers. In the following, the response signal at one corner of the plate is analyzed.

When measuring the response on a point of the plate, the amplitude changes as the rate of oscillation of

the input force is changed (Figure 3). There will be increases as well as decreases in amplitude at different points when sweeping up in time.

Even with a constant input force to the system, the response amplitude varies depending on the frequency of oscillation of the input force. The response is larger when a force is applied with a rate of oscillation that gets close to a natural frequency (or resonant frequency) of the system and reaches a maximum when the frequency of oscillation is exactly matched to the resonant frequency. Transforming the time data to the frequency domain using the Fast

**Figure 2. Simple plate excitation/response model.**



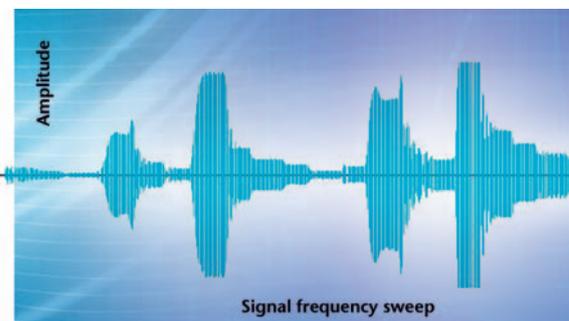
Fourier Transform generates something called the frequency response function (Figure 4). There are peaks in this function which occur at the resonant frequencies of the system.

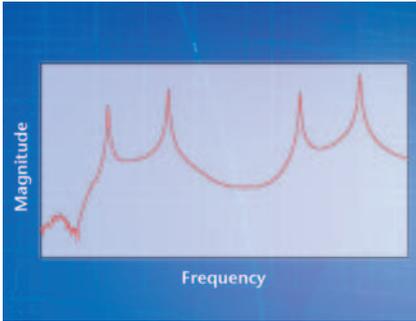
When overlaying the time trace with the frequency trace, the frequency of oscillation at the time at which the time trace reaches its maximum value corresponds to the frequency where peaks in the frequency response function reach a maximum (Figure 5), provided that the frequency change is linear over time.

Regarding the deformation patterns at the natural frequencies, they take on a variety of different shapes depending on which frequency is used for the excitation force. The shapes can be measured by using either a non-contact scanning laser vibrometer or by placing a set of distributed accelerometers on the plate and measure the amplitude of the response of the plate with different excitation frequencies. At each one of the natural frequencies a deformation pattern shows up that exists in the structure (Figure 6).

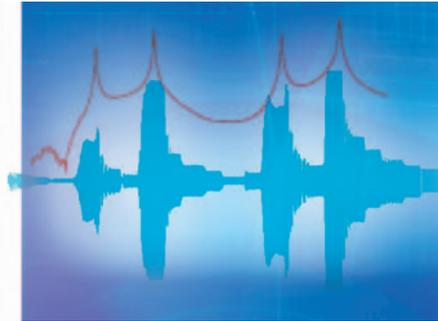
The figure shows the deformation patterns that will result when the excitation coincides with one of the natural frequencies of the system. At the first natural frequency, there is a first bending deformation pattern in the plate (mode 1). At the second natural frequency, there is a first twisting deformation pattern (mode 2). At the third and fourth natural frequencies, the second bending and second twisting

**Figure 3. Simple plate response upon a excitation frequency sweep.**

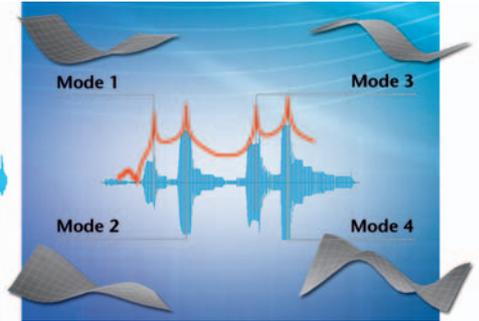




**Figure 4. Simple plate frequency response function.**



**Figure 5. Overlay of time and frequency response functions.**



**Figure 6. Simple plate sine dwell responses. The deformation patterns have been generated using PSV Software.**

deformation patterns are seen (mode 3 and 4, respectively). Such natural frequencies and mode shapes occur in all structures to some extent.

Basically, structure characteristics such as mass and stiffness determine where these natural frequencies and mode shapes will exist. Design engineers need to identify these frequencies and know how they might affect the response of the structure when a force excites the structure.

### Time Domain, Frequency Domain and Modal Space

In Figure 7, a simple cantilever beam is shown that is excited at the tip of the beam. The response at the tip of the beam will contain the response of all the modes of the system. This time response at the tip of the beam can be converted to the frequency domain by performing a Fourier Transform of the time signal. As described before, the frequency domain representation of this converted time signal is often referred to as the frequency response function, or FRF for short.

The cantilever beam will have many natural frequencies of vibration: there is a first, second and third bending mode as shown in Figure 7, and there are also other higher modes not shown.

Now the physical beam could also be approximated using an analytical lumped mass model or finite element model (shown in black in the upper

right part of the figure). This model will generally be evaluated using some set of equations where there is an interrelationship, or coupling, between the different masses, or degrees of freedom (DOF), used to model the structure.

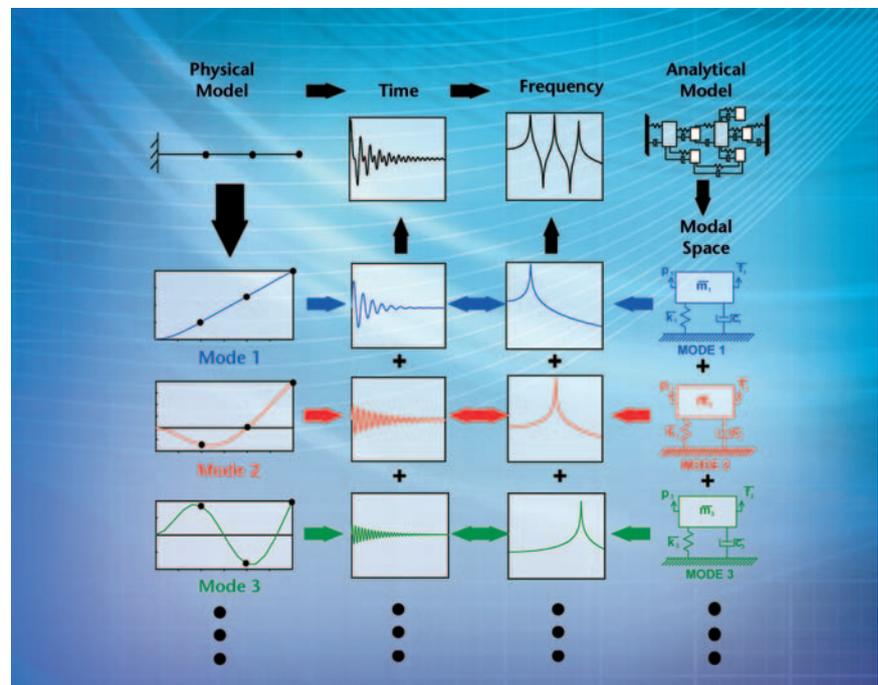
This means that if one pulls on one of the DOFs in the model, the other DOFs are also affected and also move. This coupling means that the equations are more complicated in order to determine how the system behaves.

As typically a large number of equations must be solved, matrices are often used for organizing them. The matrix representation of all of the equations of motion describing how the system behaves will look like

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t)$$

where  $\mathbf{M}$ ,  $\mathbf{C}$ ,  $\mathbf{K}$  are the mass, damping and stiffness matrices respectively;  $\ddot{\mathbf{x}}$ ,  $\dot{\mathbf{x}}$  and  $\mathbf{x}$  the corresponding acceleration, velocity and displacement and  $\mathbf{F}$  is the force applied to the system.

**Figure 7: Composing time and frequency response from simple modal models.**



Usually the mass is a diagonal matrix and the damping and stiffness matrices are symmetric with off-diagonal terms indicating the degree of coupling between the different equations or DOFs describing the system. The size of the matrices is dependent on the number of equations used to describe our system. Mathematically, something called an eigensolution is performed and the modal transformation equation is used to convert these coupled equations into a set of uncoupled single DOF systems described by diagonal matrices of modal mass, modal damping and modal stiffness in a new coordinate system called modal space described as

$$\begin{bmatrix} \backslash \\ \mathbf{M} \\ \backslash \end{bmatrix} \ddot{\mathbf{p}} + \begin{bmatrix} \backslash \\ \mathbf{C} \\ \backslash \end{bmatrix} \dot{\mathbf{p}} + \begin{bmatrix} \backslash \\ \mathbf{K} \\ \backslash \end{bmatrix} \mathbf{p} = \mathbf{U}^T \mathbf{F}(t)$$

where  $\mathbf{p}$  is the vector of the modal coordinates. So the transformation from physical space to modal space using the modal transformation equation is a process whereby a complicated set of coupled physical equations is converted into a set of simple uncoupled single DOF systems. As is shown in Figure 7, the analytical model can be broken down into a set of single DOF systems where the single DOF describing mode 1 is shown in blue, mode 2 is shown in red and mode 3 is shown in green. Modal space allows the system to be described easily using simple, single DOF systems.

### Multiple Reference Analysis (MIMO)

MIMO means Multiple Input/Multiple Output and is a measuring technique where multiple inputs (excitations, references) are used to excite the measurement object at the same time and multiple outputs (responses) of the vibration are measured to obtain a matrix of FRF's that describe how the vibrating system reacts to an excitation.

Multiple reference tests are an important tool when the structure under test exhibits a high modal density, closely coupled modes or repeated roots. The dynamic MIMO model is a linear frequency domain model where spectra (Fourier transforms) of multiple inputs are multiplied by elements of an FRF matrix to yield spectra of multiple outputs. The FRF matrix model can be written as:

$$\mathbf{v}_n(f) = \mathbf{H}_{nm}(f) \mathbf{r}_m(f)$$

Here  $m$  is the number of inputs (references),  $n$  the number of outputs (responses),  $f$  the frequency,  $\mathbf{v}_n(f)$  the vector of outputs,  $\mathbf{r}_m(f)$  the vector of inputs and  $\mathbf{H}_{nm}(f)$  the matrix of the FRF's describing the system. If  $\mathbf{H}_{nm}(f)$  is known, e.g. as a result from scanning vibrometer measurements where  $n$  is the number of scan points and  $m$  the number of the reference channels, the response of the system to a set of inputs can be predicted.

### Modal Data and Operating Data

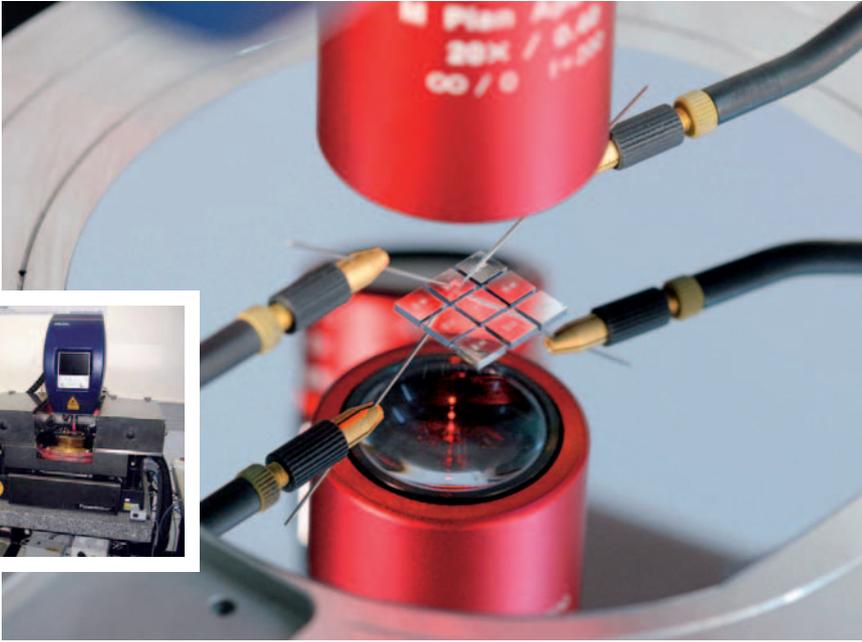
Modal data requires that the force is measured in order to determine the frequency response function and resulting modal parameters. Only modal data will give the true principal characteristics of the system. In addition, structural dynamic modifications and forced response can only be studied using modal data (operating data cannot be used for these types of studies). Also, correlation with a finite element model is best performed using modal data. However, modal data alone does not identify whether a structure is adequate for an intended service or application since modal data are independent of the forces on the system. Operating data on the other hand is an actual depiction of how the structure behaves in service.

This is extremely useful information. However, many times the operating shapes are confusing and do not necessarily provide clear guidance as to how to solve or correct an operating problem (and modification and response tools cannot be utilized on operating data). The best situation exists when both operating data and modal data are used in conjunction to solve structural dynamic problems.

Laser scanning vibrometry is ideally suited for modal tests because it provides an unambiguous phase reference, highly precise measurement data without mass loading problems and a high spatial resolution for detailed FEM correlations. Both complete and partial data sets can be exported to commercially available software packages for experimental modal analysis (LMS, ME'scope, and others).

### Acknowledgement

We wish to thank Dr. Peter Avitabile, Director of the Modal Analysis & Controls Laboratory at University of Massachusetts Lowell. The main part of this tutorial is taken from his article entitled "Experimental Modal Analysis – A Simple Non-Mathematical Overview" published in Sound & Vibration magazine, January 2001 ([http://macl.caeds.eng.uml.edu/umlspace/s&v\\_Jan2001\\_Modal\\_Analysis.PDF](http://macl.caeds.eng.uml.edu/umlspace/s&v_Jan2001_Modal_Analysis.PDF))  
E-mail: Peter\_Avitabile@uml.edu



# Pass or Fail?

*Quality Control of Automotive MEMS Pressure Sensors Using Polytec's Micro System Analyzer*

Melexis has designed and developed electronics for automotive systems for over a decade. Besides pure electronic products like microcontrollers and communication bus ICs, MEMS (Micro-Electromechanical Systems) play an important role in the Melexis product portfolio. MEMS pressure sensors are an important Melexis product used to measure oil and manifold air pressure in automotive systems.

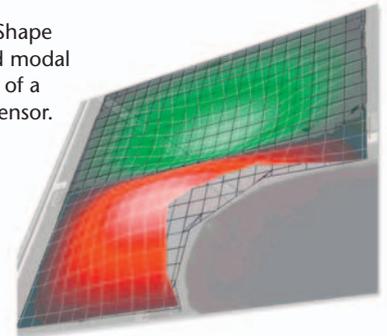
Micromachining technology is used by Melexis to manufacture these pressure sensors. The MEMS device senses the pressure through a temporary and reversible deformation to a specifically designed mechanical structure.

A typical structure consists of a thin membrane only a few tenths of a millimeter wide and etched into the solid silicon substrate containing the electronic circuit. This approach produces sensors that are low cost and acceptable

for high-volume automotive applications. In development, Melexis used the MSA-400 Micro System Analyzer to characterize specific mechanical sensor parameters. The vibrations of the electrostatically excited membranes (Figure 1) are measured by the vibrometer integrated in the MSA-400. The measured eigenfrequencies are the input for an algorithm that identifies the parameters of the membrane like thickness, edge length and intrinsic stress. The MSA-400 can also be used to find defective dies prior to packaging, thus eliminating subsequent unnecessary assembly steps, increasing throughput and lowering manufacturing costs.

[www.polytec.com/microsystems](http://www.polytec.com/microsystems)

Figure 1: Shape of the 2nd modal frequency of a pressure sensor.



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## Measuring Surface Topography in Automotive Production Applications Using Scanning White Light Interferometry

White Light Interferometry is a fast and precise method used to measure surface topography, providing an efficient tool for monitoring the quality of automotive component surfaces. In contrast to most competing methods, Polytec's TopMap family of Interferometers feature telecentric optics and precisely image difficult surfaces such as along high, steep edges or in deep, drilled holes.

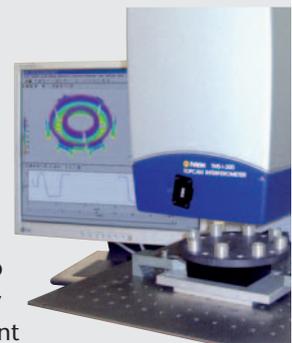
The image shows an automotive component with several parallel circular planes. Using the TopMap

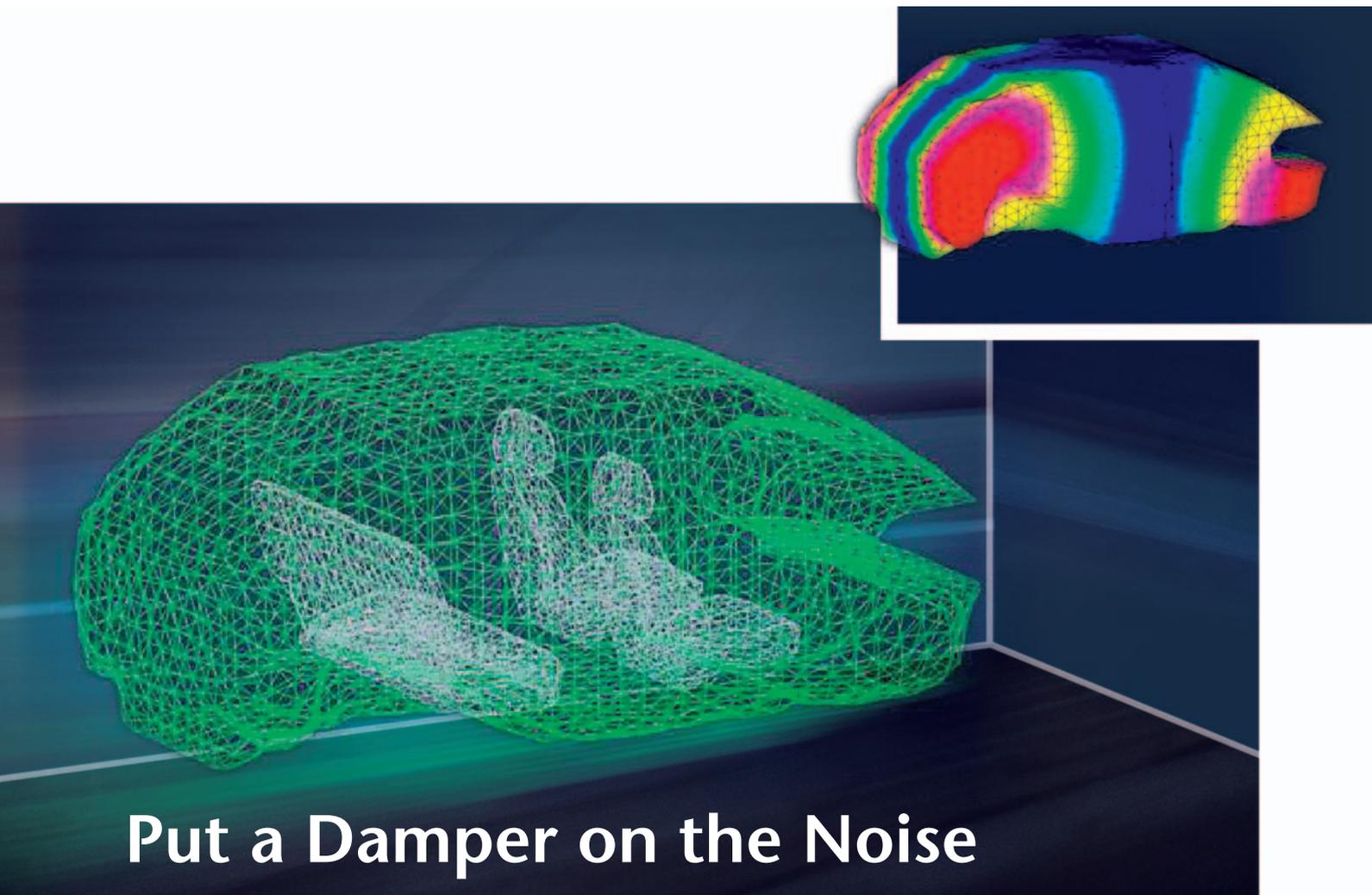
Interferometer, the distance, angles and waviness of the planes can be determined easily. The data feature a very high repeating accuracy and can be visualized as a cross-section or as a profile cut along a circle line. These automotive components are produced in high volumes with a production time of only a few seconds. The measurements enable automatic collection of quantitative data for statistical process control, especially for pass/fail decisions, but also for adjustment of CNC machines.

Polytec has designed dedicated models of the TopMap Topography Measurement

System to meet specific requirements from fast in-line throughput for production floor applications to high-resolution topography for metrology lab measurements.

[www.topmap.info](http://www.topmap.info)





# Put a Damper on the Noise

## *Using Laser Vibrometry to Optimize Damping Material Layout to Reduce Vehicle Body Interior Noise & Structural Vibration*

A comprehensive hybrid technique was developed to optimize the application of damping materials on vehicle bodies. The technique used finite element analysis (FEA) and experimental measurements to complement each other. In this example, it was used to suppress floorpan vibration and the associated radiated noise. By optimizing the application of damping material, a 3 – 5 dB reduction in the floorpan vibration level was achieved while saving 10% in material volume and mass. The optimized layout was validated on a body-in-white using a scanning laser vibrometer.

### Introduction

A process was developed to optimize the application of liquid damping material on an automotive platform. The approach consisted of four steps (Figure 1). First, the high vibration

areas of the vehicle floorpan were determined, indicating the areas in which damping materials are needed. Second, the vehicle transfer functions were measured to quantify the amount of noise resulting from floorpan vibration. Third, the material layout was optimized using FEA. Finally, an optimized product was measured to validate the predicted vibration performance.

Saeed Siavoshani, Ph.D., Jay Tudor and Dev Barpanda, The Dow Chemical Company, [SJSiavoshani@dow.com](mailto:SJSiavoshani@dow.com)



### Panel Vibration Measurements

A Polytec Scanning Vibrometer was used to measure the vibration response of the floorpan. To cover the entire vehicle floorpan surface, the laser beam was bounced off a static mirror placed at 45 degrees under the vehicle (Figure 1). Some of the measurement points used during the laser scan are shown in Figure 2. Small magnetic retro-reflectors were placed on the floorpan to ensure good signal quality at each measurement point.

Two shaker locations were used to stimulate vibration modes in the floorpan. The laser scan was completed by exciting one shaker at a time. Each shaker applied a swept sinusoidal force on the vehicle body from 20 to 300 Hz.

At each sampling point, the scanning laser vibrometer measured a frequency response function (FRF) between the vibration and the excitation force. Laser vibrometer mappings of the FRFs (not shown) revealed the highest

vibration areas are in the rear half of the vehicle. Concentrating the damping material in these areas was optimal and minimized structure-borne noise. Conversely, the laser vibrometer also identified low vibration areas where less damping material was needed to suppress the structure-borne noise; thereby, saving material, weight and cost.

### Floorpan Vibration to Interior Noise Levels

Compared to the body-in-white for the vibrometer measurements, a fully assembled vehicle was used to determine the amount of noise originating from the vibrating floorpan that reached a driver's ears. First, the interior acoustic modes were measured and calculated by FE modeling (title image) and compared to direct interior sound level measurements. Similar to structural vibration modes, these acoustic modes



Figure 1: Laser scan test setup.

highlight the most important acoustic frequencies for modeling. Then, the transfer function between the floorpan vibration and the resulting interior cavity noise was determined by aligning the shakers to the previously used attachment points. From these studies, interior airborne noise at driver ear level was related to floorpan vibration.

### Optimization Using Finite Element Analysis

Once the transfer function was understood, a finite element technique was used to study the vibration response of the vehicle floor. This technique identifies the "noisy" region in the

undamped floorpan. Confidence in the finite element model came from comparison to the original vibrometer measurements and an understanding of the acoustic attenuation properties of the sprayable damping material. Then, the model was used to design the optimal application of damping material to suppress interior noise levels.

### Validation Testing

The improvement in performance predicted by the FE modeling was verified by repeating the vibrometer measurements. In Figure 3, the average FRFs are shown for all measurement points on the floorpan based on the laser vibrometer data. A comparison of the vibration level with and without damping material indicates an improvement of up to 15 dB is realized with the current damping treatment beyond 100 Hz.



Figure 2: Points measured in laser test.

The optimized layout determined by FEA was created by removing or adding material to a vehicle body applied with the current layout. In Figure 4, the vehicle body is shown with material removed in areas of low vibration and material added in areas of high vibration. The vehicle was then tested using the laser vibrometer to measure the vibration level.

The optimized damping material layout results in a vibration reduction of about 1 dB for the front shaker location and a reduction of about 3 – 5 dB for the rear shaker location (Figure 5). This performance increase was achieved while reducing the damping material

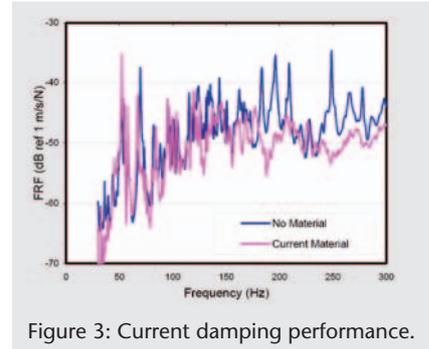


Figure 3: Current damping performance.



Figure 4: Vehicle body with optimized damping material layout.

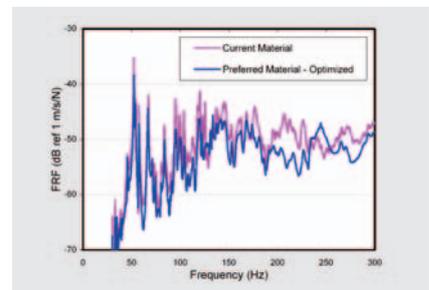


Figure 5: Optimization results.

mass by 0.8 kg (10%) and the wet volume by 0.24 gal (10%).

### Conclusions

This study demonstrated the ability to improve the performance of liquid-applied damping material while simultaneously reducing its usage. Through optimization, the average vibration level was reduced by 1 to 5 dB while providing a 0.8 kg mass savings. This volume reduction of 0.24 gallons per vehicle results in a savings of approximately \$ 215,000/year to the auto body manufacturer. Ideally this optimization should be part of the initial design and placement of the damping material prior to a vehicle launch.

# Faster, Higher, Stronger

## *Dynamic Valvetrain Analysis with Rotec's Rotational Analysis System and Polytec's High Speed Vibrometer*

By combining Rotec's Rotation Analysis System and Polytec's High Speed Vibrometer, development engineers can measure and analyze dynamic and high-speed valvetrain motion, even on racing engines, ensuring that valvetrain components satisfy strength, durability and accuracy requirements.

### Introduction

Modern valvetrain systems must provide both large cross sections for the gas exchange process and high-speed opening and closing of the valves. This combination results in high structural excitation and component stresses from the fast changes in valve velocity and acceleration combined with large lift values. Development programs must

assure that valvetrain components satisfy strength and durability requirements and that they operate within tight specifications and tolerances.

With the increasing complexity of valvetrain systems, the requirement for comprehensive valvetrain testing can be addressed through application-specific test and analysis protocols in customized valvetrain motion software. In response to this need, Rotec

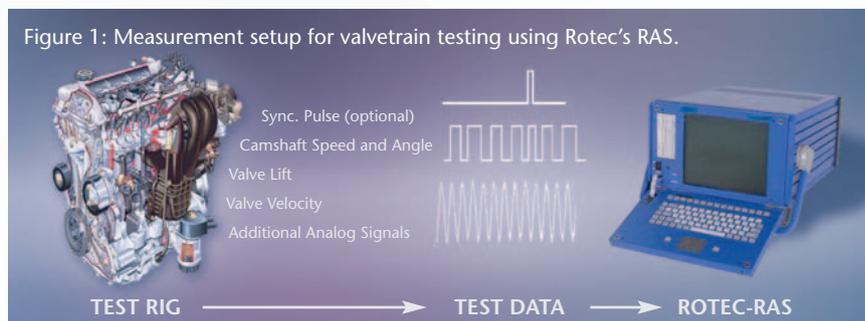
GmbH has developed a PC-based Rotation Analysis

System (RAS) to perform signal acquisition and noise and vibration analysis on engines and transmissions. A large number of these systems are used worldwide by automotive testing and development departments.

### Measurement Setup

In Figure 1, a typical measurement setup for valvetrain testing is shown. Camshaft speed and angle are measured by either fitting an incremental encoder to the shaft or by scanning a toothed wheel with a magnetic pickup. On both fired engines and non-fired test benches the valve lift is generally measured with inductive or capacitive displacement sensors.

Polytec's High-Speed Vibrometer (HSV) system is an excellent sensor to measure valve velocity on motored test benches. The advantages of the HSV include non-contact, high-resolution measurement up to 30 m/s and linear output signals. Valve velocity is measured at frequencies up to 50 kHz and valve lift can be



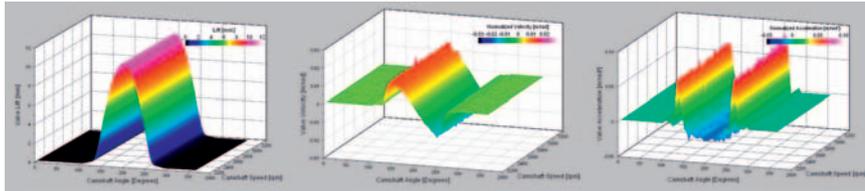


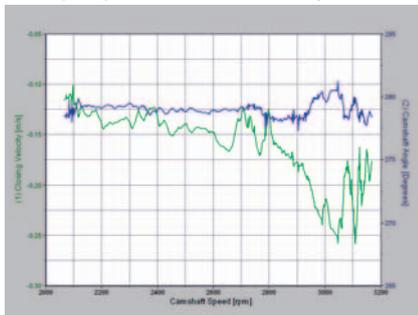
Figure 2: a) Valve lift versus cam angle and speed; b) Valve velocity versus cam angle and speed; c) Valve acceleration versus cam angle and speed.

measured up to 250 kHz. Differential measurement compensates for unwanted vibration and movement (see information box).

By combining both the RAS and HSV systems, engineers can make demanding dynamic measurement and analysis of valvetrain motion, even on high performance racing engine test rigs. Synchronous to the camshaft speed and valve lift and velocity signals, additional test data such as valve spring loads can be acquired.

The RAS rotational speed channels require square-wave TTL level signals as input. The time interval between rising (or falling) edges for each pulse period is recorded using a 10 GHz/40-bit high-speed counter/timer. The RAS analog channels sample at 400 kHz with 16-bit resolution. In valvetrain testing, the speed signal is used for transforming the time equidistant sampling of the lift and velocity signals into angle equidistant data. Consequently, a toothed wheel and proximity probe (instead of rotary encoders) may be used for measuring camshaft speed and angle. Signals from gear wheels with missing teeth may also be processed, a significant advantage of the RAS software.

Figure 3: Valve closing velocity (green) and closing angle (blue) versus cam speed.

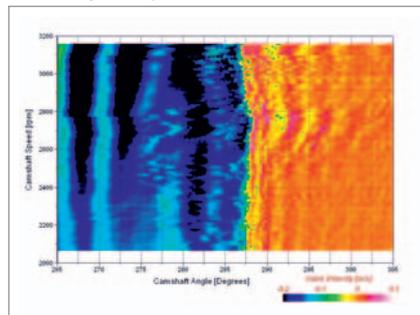


### Exemplary Results

The RAS valvetrain software offers a variety of options for analyzing valve motion versus speed and angle. In Fig. 2, a speed run-up measurement is plotted in 3-D. The valve lift signal which determines the valve lift versus cam angle and speed is measured by the Polytec HSV and shown in Fig. 2a. The valve velocity (Fig. 2b) is also measured by the HSV. However, since the camshaft speed changes over the course of the measurement, it is more meaningful to represent valve speed in m/rad instead of m/s. This option is integrated into the RAS software. The normalized valve acceleration in m/rad<sup>2</sup> is shown in Fig. 2c. This is the 1st derivative of the measured valve velocity (HSV) sampled by the RAS. The software allows for low-pass filtering before differentiating.

There are several methods of calculating valve closing velocities and closing angles. In general, a threshold value of lift during the closing sequence is specified. Then, beginning at maximum lift and looking along the cam angle, the closing velocity and angle are found when the valve lift falls below the threshold lift. Alternatively, having located a specified lift threshold and looking along the cam angle, the first

Figure 4: Valve bounce while impacting the seat.



Polytec Product Information



## HSV High-Speed Vibrometer

The HSV copes with high vibration speeds up to 30 m/s and provides single or differential velocity and displacement measurement capabilities for high-speed applications like valve train testing on performance engines, power tools and impact testing.

[www.polytec.com/highspeed](http://www.polytec.com/highspeed)



local maximum of valve acceleration is found. The valve closing velocity and cam angle are then determined at this position (Fig. 3).

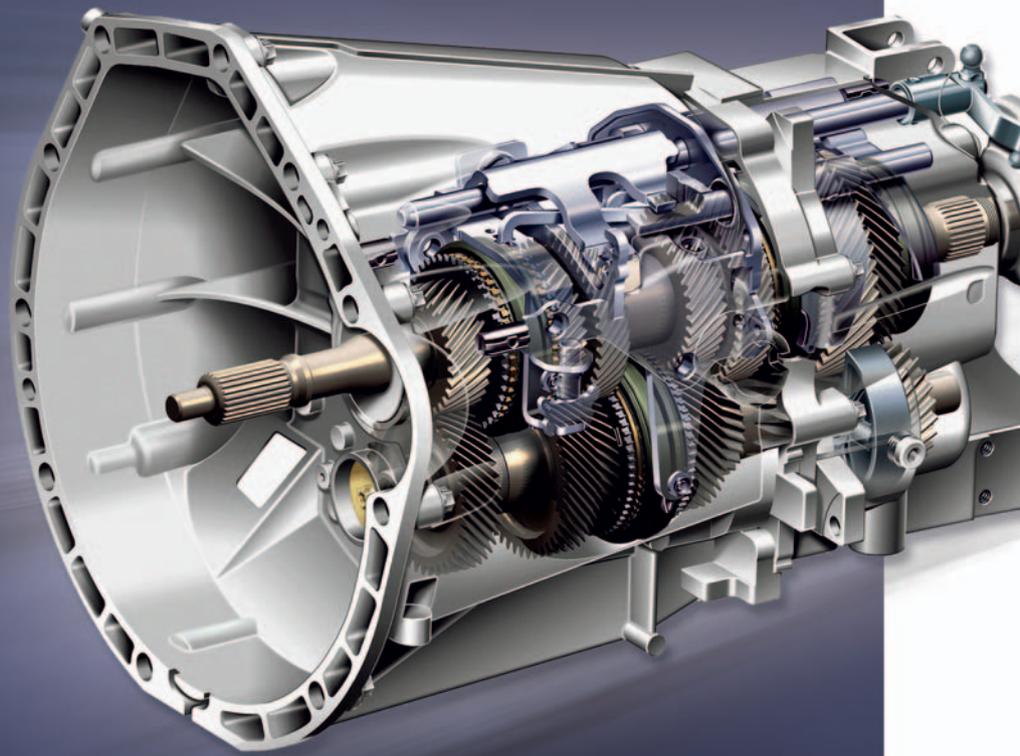
The contour plot (Fig. 4) shows valve velocity versus cam speed in the closing angular range where valve bouncing is apparent. The valve seats at approx. 288 degrees cam angle. The alternating red and green colors show the valve impacting the seat before finally coming to rest.

### Conclusion and Outlook

The RAS valvetrain software offers many other capabilities such as comparing measured 3-D plots with theoretical curves or determining lift loss normalized to angle during the opening and closing phases. Valve open and close duration is also of interest. Valvetrain material and geometrical parameters may be used to investigate cam and tappet component strains (Hertzian stress). In conclusion, the use of high-resolution measuring equipment and application-specific analysis software help satisfy the demands for meaningful results and shorter development cycles.

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# Drive Trains Under Test

## *Rotational Vibrometers Help Determine the Transmission Behavior of a Dual Mass Flywheel*

Vehicle drive trains equipped with a combustion engine experience torsional oscillations caused by the crankshaft. Considerable amplitudes can occur at various positions of the crankshaft affecting the mechanical stability and acoustic properties of the drive trains. To provide a design that avoids or minimizes such phenomena, engineers need knowledge of the dynamic properties of the drive train components. Using Polytec Rotational Vibrometers, a dual mass flywheel can be characterized, demonstrating how the dynamic transmission behavior can be determined on a test rig for drive elements installed at the University of Kaiserslautern.

### High-dynamic Test Rig for Drive Elements

A sophisticated dynamic test rig for drive elements (Figure 1) is available at the Institute for Machine Elements, Gears, and Transmissions at the University of Kaiserslautern. This system

allows the vibrational testing of drive trains and their components under the special influence of torsional excitations and the derivation of the dynamic transmission behavior at various loads, rotational speeds, excitation frequencies and amplitudes.

The test rig uses a twisting motion produced by a high-dynamic electric machine that drives a braking motor via the test item. The braking motor is

operated as a generator so that a torsional momentum is generated that loads the drive element under test. The driving torque can be superimposed on a well-defined oscillation momentum at an excitation frequency  $f_{exc} > 450$  Hz. With a high-resolution measurement of both torsion angle and torque momentum, the dynamic response behavior can be determined.

### Measurement of Torsional Vibration Using Rotational Vibrometers

For the measurement of the torsional vibration, two rotational laser vibro-



Figure 1: Dynamic test rig for drive elements.

Prof. Dr.-Ing. Bernd Sauer and Dipl.-Ing. Andreas Nicola, University of Kaiserslautern, Germany, [megt@mv.uni-kl.de](mailto:megt@mv.uni-kl.de)

meters are used. The measurement procedure is highly precise, robust and mobile. The setup allows the measurement of drive speed  $n$ , dynamic fraction of the rotational speed  $\Delta\omega$ , and dynamic oscillation speed  $\Delta\varphi$  without contact during operation. A detailed description of the operating principle of the Rotational Vibrometer can be found at [www.polytec.com/rotvib](http://www.polytec.com/rotvib).

### Example: Dual Mass Flywheel

In every combustion engine, a fly wheel is used as energy storage to keep the piston motion running even when there is no work cycle. At the same time, it smooths out the torsional excitation of the crankshaft and avoids vibrations. In the majority of cases, this is accomplished solely with flywheel mass. An alternative method is to use a dual mass flywheel (DMF). In the DMF, the flywheel mass is split into two masses that are torsional linked by elastic springs. By varying the ratio between inertias and spring stiffness, a desirable low Eigenfrequency can be found. The DMF acts as a mechanical low-pass filter at the transition to the drive train.

In the title image, the test setup for determining the dynamic transmission behavior under various conditions is shown. The DMF is driven from the left side by a motor at stationary speed while superimposing a torsional oscillation. On the right side, it is loaded by the generator with a constant torque momentum. Between specimen and electric machines, the momentum is measured by the torque sensors

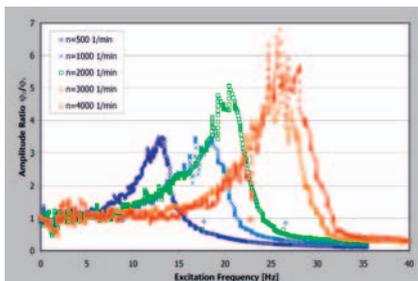


Figure 2: Rotational vibrometers and dual mass flywheel on the test rig.

and the dynamic oscillation angle is measured by the two rotational laser vibrometers.

The experimentally acquired response behavior of the dual mass flywheel at various revolution speeds during a frequency sweep between 0 Hz and 40 Hz is shown in Fig. 2. The excitation was done with a constant angle amplitude. A speed of 500 rpm corresponds to an Eigenfrequency of 13 Hz at a maximal amplitude ratio of  $\varphi_2/\varphi_1 = 3.5$ . The Eigenfrequency moves to higher frequencies with higher speeds. The amplitude amplification also grows with higher speeds.

Assuming that the modal masses are constant, the increase of the Eigenfrequency is due to a stiffening of the existing springs. The reason for the change in stiffness is supposed within the radial deformation of the spring. Apparently, this deformation presses the spring to an external contact surface so that friction is induced at the contact points, decreasing the effective number of springing turns and increasing the stiffness. The increasing amplitude at higher speeds shown in Figure 4 is caused by a decrease in system damping, a fact that could be confirmed by further investigations.

### Conclusions and Prospects

The potential to investigate torsional vibrations with the institute's drive element test rig in combination with rotational laser vibrometry is exciting. Because of the flexibility of the test facility and data acquisition equipment, it is possible to gauge other drive train components such as torsionally stiff and flexible couplings, cardan shafts, and vibration dampers and absorbers. It is also possible to perform acoustic investigations of gearboxes (e.g. rattle behavior) and to acquire knowledge about the dynamic stiffness and frequency attenuation of gears. The equipment is mobile so that measurements can also be made on-site with customers' test rigs and running engines.

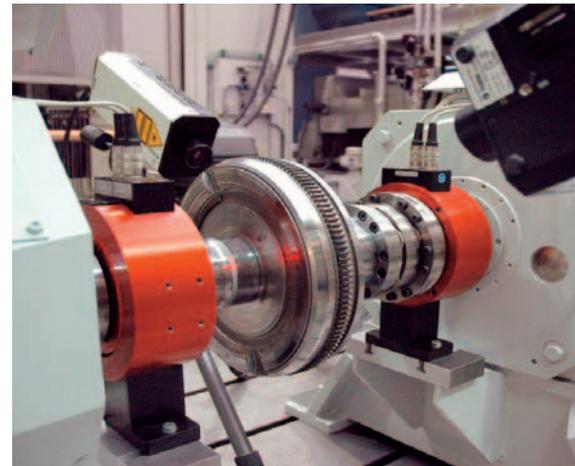


Figure 2: Dual mass flywheel on the test rig.



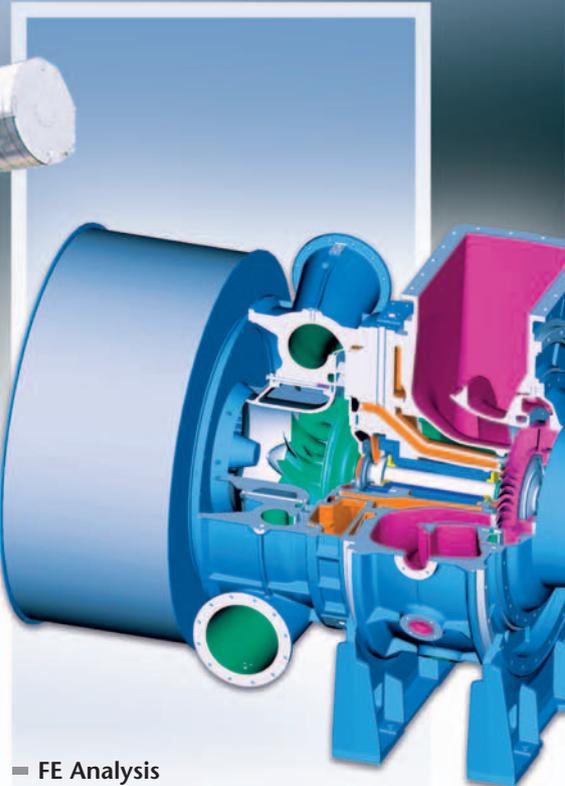
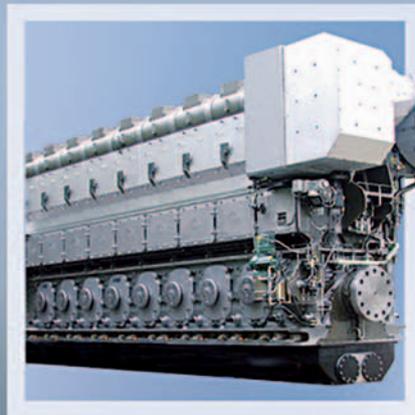
Polytec Product Information

## RLV-5500 Rotational Laser Vibrometer

Polytec's rotational vibrometers are advanced non-contact angular velocity and displacement sensors, perfect for measuring rotating structures such as crankshafts, axles and pulleys. As proof of its success, automotive design and test engineers have skillfully used rotational vibrometer data in both research and development to reduce engine noise and to increase product durability. The new RLV-5500 Rotational Laser Vibrometer features an expanded rpm range of up to 20,000 rpm, an excellent optical sensitivity and S/N ration due to digital decoding techniques, and a very compact sensor head that can be flexibly mounted.

[www.polytec.com/rotvib](http://www.polytec.com/rotvib)

# Turbo Power for Large Diesel Engines



## *Modal Analysis of Turbocharger Compressor Wheels for Large Diesel Engines*

Extremely high pressure ratios and volume flow rates are now achieved in turbochargers for large diesel engines. The protection of rotating components against high-cycle fatigue is extremely important to reduce early failures. The combination of modern techniques such as laser vibrometry and modal analysis allows an exact insight into the vibration behavior of compressor wheels at ambient temperature. Combining modal analysis with measurements carried out on the rotating component provides the basis for the determination of the loads during operation.

### **Introduction**

The maximum power rating of large diesel engines currently used in ships or power stations is about 21,000 kW in the 4-stroke range and 97,000 kW in the 2-stroke range. These engine powers can only be achieved by using turbochargers with the optimum utilization of the compression process, enabling increases in performance of 300 %. Manufacturers of large diesel engines realized this fact at an early stage; MAN Diesel SE has developed and built turbochargers for more than 70 years.

The compression process is repeatedly subjected to conditions where an excitation frequency caused by interferences in the air inlet and outlet (e.g. guide baffle, etc.), and the natural frequencies of the compressor wheel lead to an increased vibration response. The resulting dynamic alternating load must not exceed the fatigue strength in order to ensure a reliable operation of the compressor wheel.

The following steps are used in the development of compressor wheels to prevent fatigue:

### ■ FE Analysis

Finite Element Analysis (FEA) provides approximate modal parameters describing "natural frequency" and "natural mode" values which enable a rough assessment of the loads occurring during operation. Additional experimental investigations are necessary since the damping and the mistuning caused by manufacturing deviations are not exactly known.

### ■ Experimental Modal Analysis

The experimental investigation of the real structure for the determination of the modal parameters primarily serves for the comparison with the results of the Finite Element Method. Additionally, further influences on the vibration behavior can be determined, e.g. caused by the preparation with sensors for operational vibration analysis.

### ■ Vibration Analysis During Operation

Adding to the results from the FE or modal analysis, the strain is determined at selected points of the compressor wheel at different operating points by means of strain gauges in order to measure the load of the component.

By unifying the results of the individual steps, the vibration behavior and stress occurring at the component at different operating conditions are discovered.

### Tests for Experimental Modal Analysis

The dynamic behavior of linear structures can be described by three modal parameters: natural frequency, damping and natural mode. They are specified from any number of Force Response Functions (in short FRF) by means of curve fitting (Fig. 1).

The PSV-400 Scanning Vibrometer has proven to be an exceptional tool for the measurement of these FRF's. It's advantages over contact transducers include adjustable measuring ranges that match the excitation intensity and system response, and elimination of mass loading at the measuring points (Fig. 2).

In addition, the PSV-400 enables the scanning of a great number of measuring points within a very short period of time and the import of FEM meshes as measuring points for a simple verification of natural modes (Fig. 3).

When measuring the modal parameters, a shaker is used for the excitation of the structure to measure the excitation force necessary to determine the FRF's. A comparison with the system response when using a loudspeaker for non-contact excitation ensures that the mechanical connection of the shaker to the compressor wheel does not influence the vibration mode.

Compressor wheels with  $n$  blades generate the same number,  $n$ , of very close and hence strongly coupled

vibration modes. The modes have very similar blade deflection shapes and can be distinguished by the fact that the individual blades oscillate opposite in phase.

The measured FRF's show the strong coupling of the individual modes. In order to separate the individual modes (Fig.4), the data is exported to the modal analysis software Visual Modal Pro by ME'scope. The PSV software supports simple methods to export data to external modal analysis software. For an intuitive graphical presentation the natural modes can be re-imported into the PSV software after the modal parameters have been successfully identified.

### Summary and Outlook

The PSV-400 Scanning Vibrometer provides data allowing a fast and high-quality verification of FE models. The determination of modal parameters of delicate structures is possible without any mechanical influence, a significant advantage over traditional contact transducers such as accelerometers that can have a substantial mechanical influence.

Future use of the PSV-400 with MISO (Multiple Input Single Output) should enable a better separation of superimposed modes. This will be a further step in the continuous process towards understanding and developing complex radial-flow compressor structures.

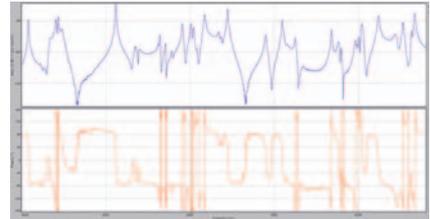
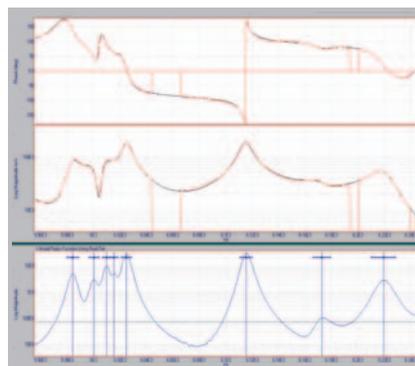


Figure 1: Force Response Function of the vibration amplitude (above) and the phase (below).

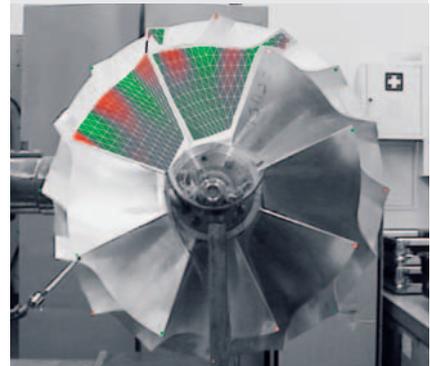


Figure 2: Experimental setup for the measurement of modal parameters with superimposed scan grid and operational deflection shape.

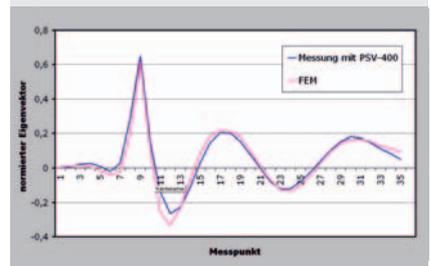


Figure 3: Comparison of a mode using selected measuring points and nodal points from FEA.

Figure 4: Separation of the modes by means of an ME'scope curve fit. Upper diagram: Bode diagram of the measured curve (black lines) and result of the curve fit (red lines). Lower diagram: separated modes.

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# Product News



Polytec's rotational vibrometers are advanced non-contact angular velocity and displacement sensors, perfect for measuring rotating structures such as crankshafts, axles and pulleys. Controlling drive train torsional vibrations is critical to designing reliable vehicles, electric power generators and aircraft propulsion systems. Rotational vibration data used in the early stages of product development has enabled automotive design and test engineers to skillfully reduce engine noise and to substan-

## Measure Rotational Vibrations

### New RLV-5500 Rotational Laser Vibrometer

tially increase product durability. A large standoff distance makes positioning the laser probe fast, safe and convenient and enables the precision measurement of operating machinery at several locations without interruption. The RLV-5500 Rotational Laser Vibrometer is a new class of instrument that benefits from digital decoding techniques, an improved S/N ratio and an expanded rpm range of up to 20,000 rpm. The sensor head design is new, more compact, and small enough to get closer to the measurement object. An integrated air purge system protects the optics from production oil spray and dust. Even onboard measurement of an operating drivetrain in a moving vehicle is now possible.

#### Features and Benefits

- Compact, fiber-coupled sensor head
- Precision measurement of rpm, angular velocity and displacement
- Expanded rpm range to 20,000 rpm at 10 kHz bandwidth
- Data independent of shaft geometry
- Improved S/N ratio through digital demodulation and filtering
- Compatible with all data acquisition systems
- Integrated air wipe to cool and protect the optics

📄 [www.polytec.com/rotvib](http://www.polytec.com/rotvib)

## Non-Contact Curvature and Flatness Measurement Made Simple and Efficient

### New TopMap Metro.Lab Topography Measurement System

The TopMap Metro.Lab is a high-precision white light interferometer with a large z-dynamic range and nanometer resolution. This non-contact topography measurement system is designed to characterize flat and curved surfaces. The Metro.Lab can measure flatness and general topography on hard or soft, robust or delicate surfaces and determine parallelism of two or more surfaces separated by as much as 70 mm. By combining increased throughput, simple operation, precision measurement and an affordable cost, Polytec is changing traditional contact metrology. The Metro.Lab is a complete measurement station for characterizing the topography of large surfaces

without contact. Complex parts can have many precision flat and curved surfaces that must be measured and compared to design specifications. The Metro.Lab's wide field-of-view is a critical advantage when fast throughput is desired. With a large vertical dynamic range of 70 mm and telecentric optics, the measurement of flatness, ripple and parallelism is simple even under traditionally difficult circumstances such as comparing the top and bottom surfaces of a blind hole. Classic surface parameters currently measured with touch probes can also easily be investigated with the Metro.Lab. Since the complete measurement area is captured in one measurement run instead of

composing it from individual lines, measurements are often completed in just a few seconds.

#### Key Features

- Non-contact, non-destructive, optical interferometer
- Measurement on surfaces near steep edges (e.g. drilling holes) is possible due to telecentric optics
- Increased flexibility due to large 70 mm z-dynamic range
- Fast measurement over large field-of-view
- Large 80 mm x 80 mm field-of-view available

📄 [www.topmap.info](http://www.topmap.info)



Compact, Digital, Versatile

## New Compact Vibrometer adds to the Family

Polytec's CLV-2534 Compact Laser Vibrometers and OFV-2500 Vibrometer Controllers are designed to meet the needs of sophisticated industrial vibration measurement. A series of new versions is now available that benefit from digital decoding technology and feature a wide number of new functionalities and improvements.

### Expanded Choices in OFV-2500 Vibrometer Controllers

The digital OFV-2500-3 Vibrometer Controller features 0.02  $\mu\text{m/s}$  resolution limit at 350 kHz bandwidth. An analog, large-bandwidth OFV-2500-2 version complements the digital model by featuring high measurement velocities up to 10 m/s and bandwidths up to 3.2 MHz. Engineered for value, the OFV-2500-2 model replaces the retiring OFV-2500-1 model with better specifications but at same sales price. The OFV-2500-2 can be ordered with an additional integrator for direct displacement output.

For displacement-only measurement, the OFV-2510 is the best choice for lower bandwidth measurements and is based on proven fringe counting technology. All OFV series sensor heads (also legacy versions) can be connected to OFV-2500.

### More CLV-2534 Compact Laser Vibrometers

The OFV-2500 series sensor heads are also evolving. The CLV-2534-2 Compact Laser Vibrometer is a 350 kHz high resolution digital version and the CLV-2534-3 is a 3.2 MHz high bandwidth system with a velocity limit of 10 m/s, offering optional direct displacement output. The main applications are end-of-line production testing, hard disk inspection and general R&D.

### New Optical Accessories

In addition to the camera option, which offers a video image of the object under test, there are many new accessories available for both the OFV-534 Sensor Head and the CLV-2534 Sensor Head, helping to increase the range of possible



applications.

Combining the sensor head with the new VIB-A-510 LED Illumination Unit and a microscope objective (e.g. VIB-A-20xLENS) turns the CLV-2534 or the OFV-534 into a measurement microscope for microstructures. With a spot size of only 1.5  $\mu\text{m}$  and the camera option, the laser is always positioned and focused correctly. These accessories are easily mounted onto the sensor head.

Where a large stand-off distance and small field-of-view are required, the VIB-A-520 telescopic objective replaces the standard objective, making the OFV-534 and CLV-2534 Sensor Head a perfect tool for hard disk drive component measurements and quality tests, featuring a 320 mm working distance and a spot size of only 15  $\mu\text{m}$ .

For measurement locations requiring a turn to get access, two 90° Deflection Units (for laser only and for both laser and video image) are available.

 [www.polytec.com/vibrometers](http://www.polytec.com/vibrometers)

Version 2.4 Now Available

## New PMA In-Plane Vibration Measurement Software Released

Stroboscopic Video Microscopy measurements provided by the MSA-400 Micro System Analyzer are now even easier with the software release of PMASoft version 2.4. A wide number of new functionalities and improvements makes this release the best software yet for in-plane measurements. Featuring a whole series of new benefits, the PMA software can now

- Display and save evaluation results with the video window, without starting a measurement, to give a first impression

- Display a Sine fit for periodic signals and a curve fit to specified peaks
- Provide extensively enhanced peak analysis with a band cursor providing statistical parameters and harmonic oscillator curve fitting and a harmonic cursor that plots additional cursor lines at higher orders of the base frequency
- Import PSV scan grid points from out-of-plane measurements to evaluate a micro device in all three dimensions

 [www.polytec.com/microsystems](http://www.polytec.com/microsystems)



# Trade Shows Technology Seminars Training Classes

May 02 – 03, 2007	2007 US Vibrometer Users Conference	Ann Arbor, MI
May 07 – 10, 2007	AISTech 2007	Indianapolis, IN
May 08 – 10, 2007	Automotive Testing Expo Europe	Stuttgart, Germany
May 08 – 11, 2007	Control 2007	Sinsheim, Germany
May 15 – 17, 2007	Noise and Vibration	St. Charles, IL
May 22 – 24, 2007	Sensor & Test	Nuremberg, Germany
May 12 – 16, 2007	METEC 2007	Düsseldorf, Germany
Jun 18 – 21, 2007	LASER 2007	Munich, Germany
Jul 09 – 12, 2007	14 <sup>th</sup> International Congress on Sound and Vibration	Cairns, Australia
Sept 12 – 14, 2007	Automotive Testing Expo China	Shanghai, China
Sept 19 – 20, 2007	Diskcon USA 2007	Santa Clara, CA
Sept 25 – 27, 2007	MESUREXPO	Paris, France
Sept 25 – 28, 2007	ILMAC	Basel, Switzerland

Reference our web site [www.polytec.com](http://www.polytec.com) for the most up-to-date information and links on trade shows, technology seminars and training classes!

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## Seminars and Training Classes

For a more in-depth view of our technology, register for a complimentary Technology Seminar. Current users should consider attending specialized Training Classes designed to improve their understanding and effectiveness in using their Polytec equipment.

For more information please contact your local sales manager or email us at [info@polytec.com](mailto:info@polytec.com) (North America) or [LM@polytec.de](mailto:LM@polytec.de) (all other regions).



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