



Performance and quality enhancement of automotive components by utilizing non-contact vibration measurements by Laser Doppler Vibrometry

By Martin Johansmann & Chris Chia

Agenda

- Where do we measure and why do we measure vibration optically?
- How does Laser Doppler Vibrometry (LDV) work?
- What can Scanning Laser Doppler Vibrometry (SLDV) do?
- LDV for different applications:
 - Quality control in production (inline & sample testing)
 - Product development and NVH
 - Modal analysis and FEM validation
 - Braking systems
 - Rotating parts
- Conclusions

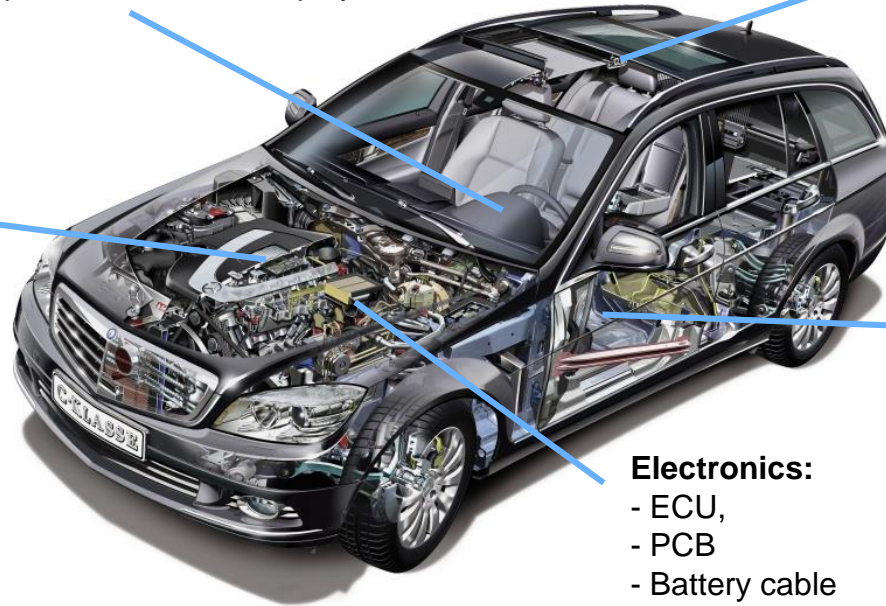
1. Monitor manufacturing quality

Cockpit

- Air condition & heating units
- Fans
- Haptic switches and displays

Engine:

- Components
- Turbo charger
- End-of-line test



Electrical Motors

- Windows
- Sun roof
- Many other functions

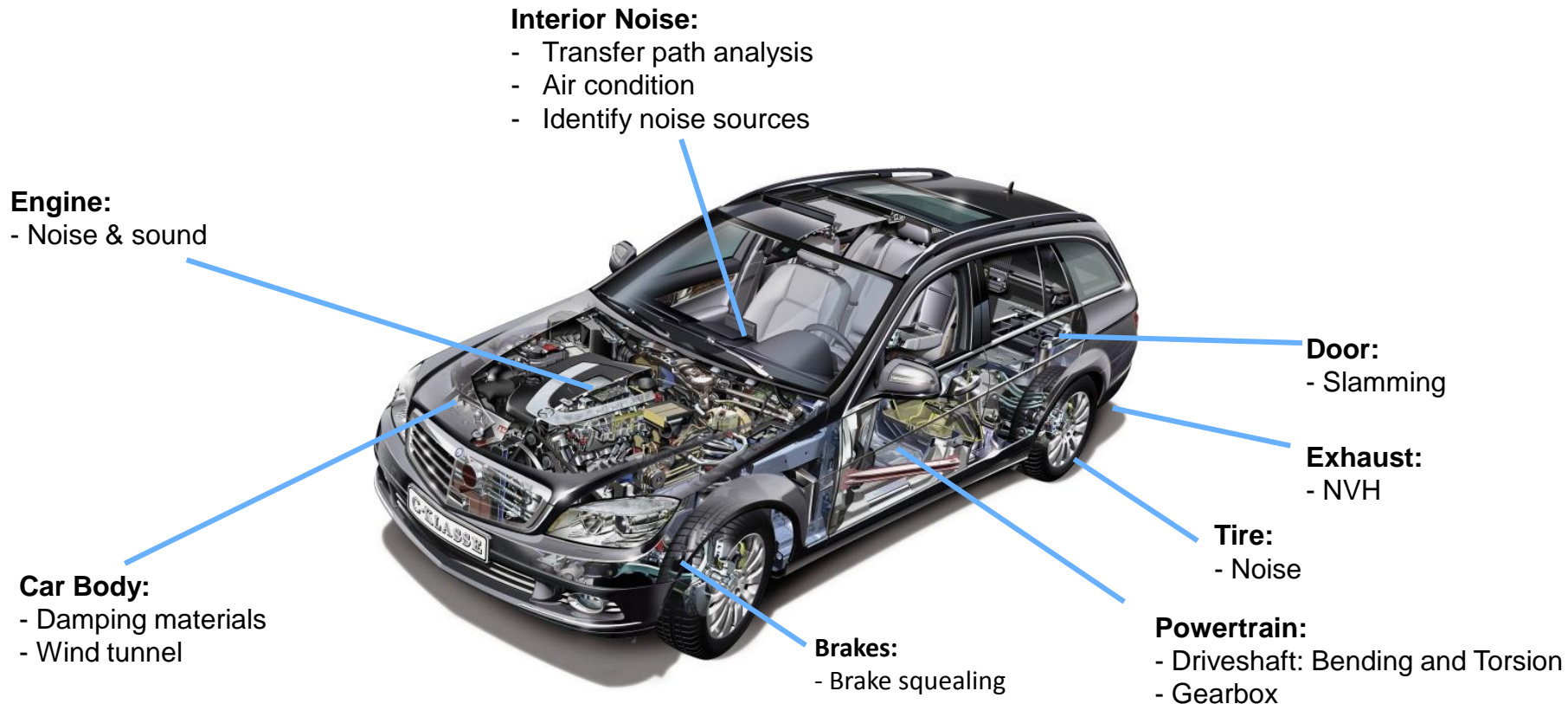
Steering & Power Train

- Gearbox
- Steering System

Electronics:

- ECU,
- PCB
- Battery cable

2. Improve NVH



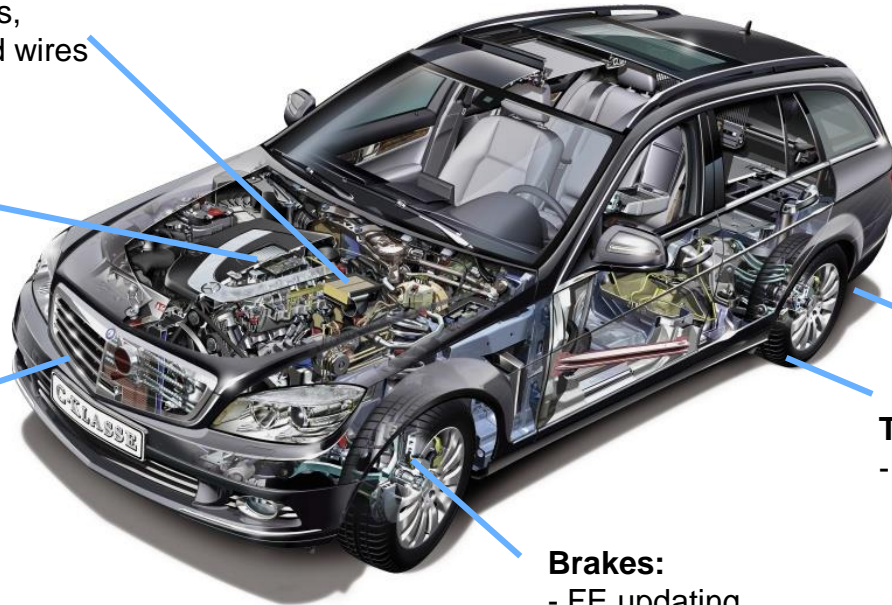
3. Product development / Modal Tests & FEM Validation

Engine:

- Valve train
- Components
- Turbo charger

Electronics:

- ECU,
- PCBs,
- Bond wires



Car Body:

- Structural dynamics
- Modal testing

Exhaust:

- FEM validation (hot)

Tire:

- Model update (rotating)

Brakes:

- FE updating

Measurement Challenges

- Lightweight structures
 - Aluminum and composite materials
 - Need for reduced weight to meet fuel efficiency targets
 - Maintain NVH characteristics and acoustic quality
- Environmental conditions
 - Heat, rotating, wind
- New Technologies
 - EV with higher frequency noise
 - Haptic technologies



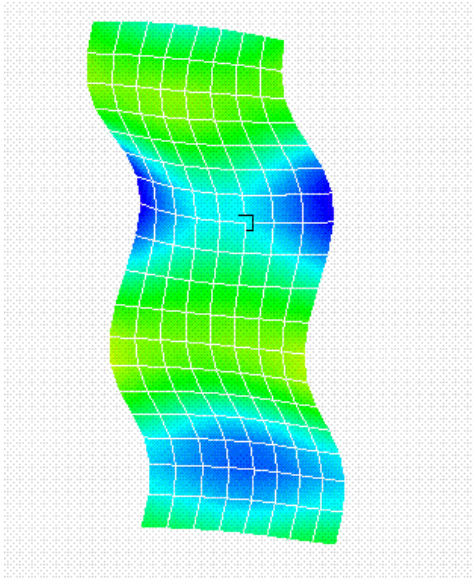
Why do optical testing?

Traditional methods have certain limitations:

- Limited number of test points
⇒ Wrong results, poor FEM correlation

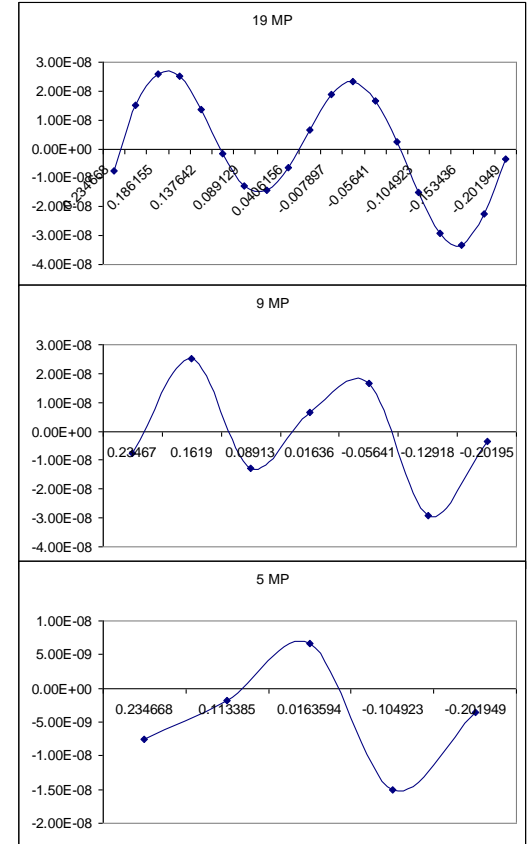
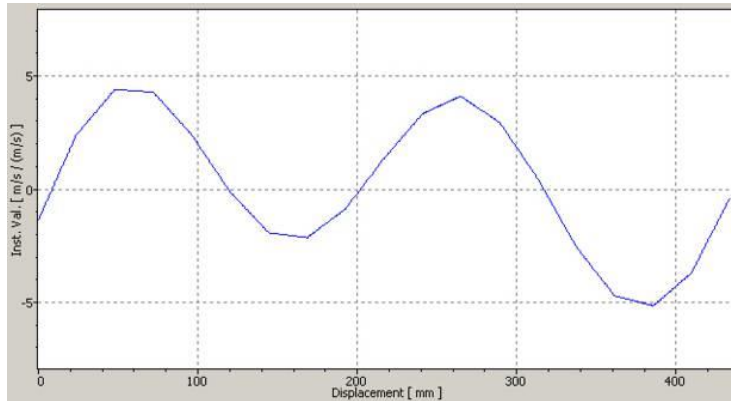


Why do optical testing?



Spatial aliasing:
Deflection shape at 514 Hz

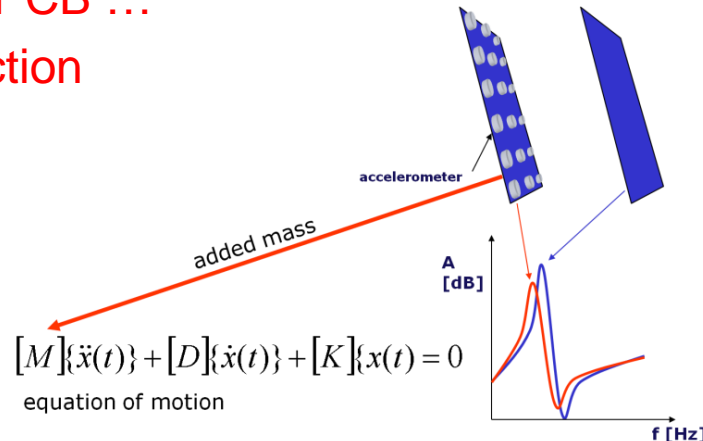
- Low point density causes:
 - amplitude error
 - distorted or wrong shape



Why do optical testing?

Traditional methods have certain limitations:

- Limited number of test points
- Mass and damping are changed \Rightarrow **General problem**
- Bandwidth limited \Rightarrow **EV...**
- Foot print \Rightarrow **Switches, PCB ...**
- Need contact \Rightarrow **Production**



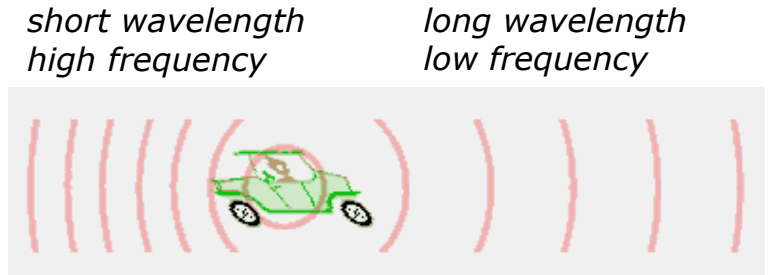
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- **How does Laser Doppler Vibrometry (LDV) work?**

What is Laser Doppler Vibrometry

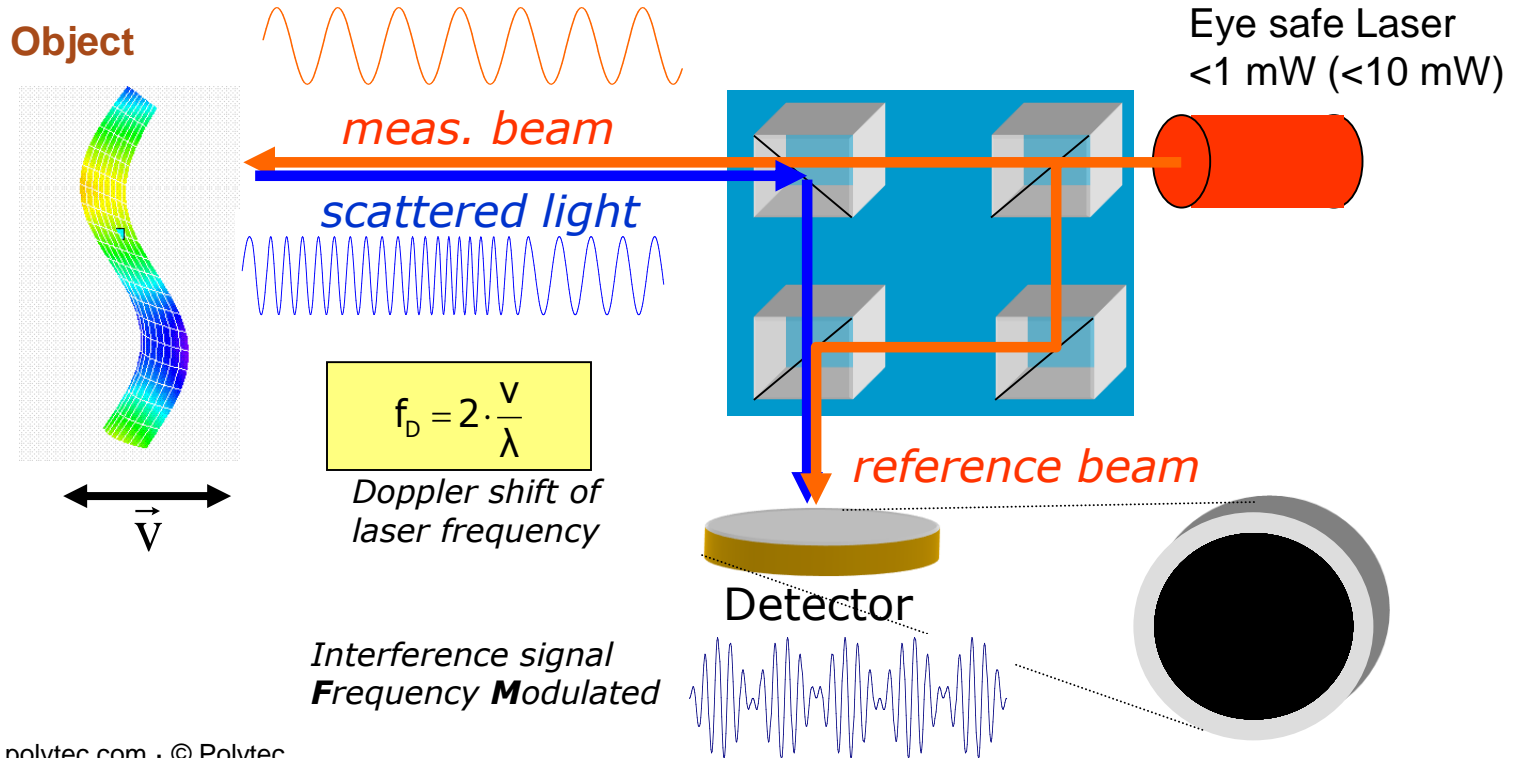
Laser Doppler Vibrometry (LDV):

- non-contact
- direct measurement of
 - velocity
 - displacement
- Physical effect:
 - Doppler Effect
 - frequency modulation of back scattered light
 - Modulation effective in direction of laser beam



Analogy: acoustic Doppler effect

LDV: Operating principle



LDV: Operating principle

The relationship between Doppler frequency, Laser wavelength and velocity is:

$$f_D = 2 \cdot \frac{v}{\lambda}$$

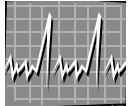
For the He-Ne Laser this can be expressed as

$$f_D = 3.16 \cdot 10^6 \left[\frac{\text{Hz}}{\text{m/s}} \right] \cdot v \left[\frac{\text{m}}{\text{s}} \right]$$

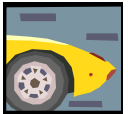
$$\lambda = 632,8 \text{ nm}$$

LDV Measurement Ranges

The measurement ranges cover almost all technical relevant mechanical vibrations:



Frequency: 0 Hz – 1200 MHz



Velocity: 50 nm/s – 40 m/s (9 Decades)

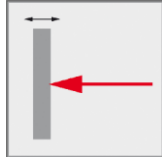


Displacement: 0.1 pm – 10 m (13 Decades)

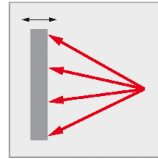


Acceleration: 10^{-8} g – 10^7 g (15 Decades)

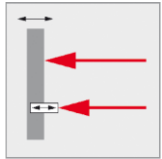
LDV: Many different types



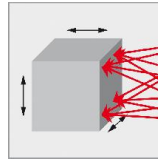
Out-of-Plane



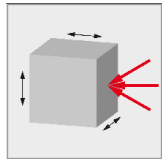
Scanning



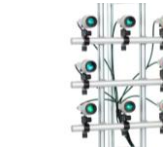
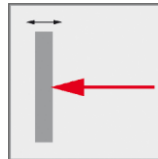
Differential



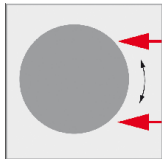
Scanning 3D



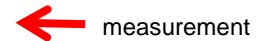
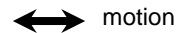
Inplane



Multi point



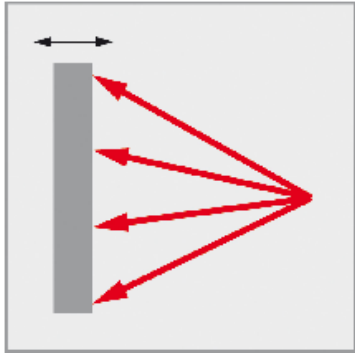
Rotational



Agenda

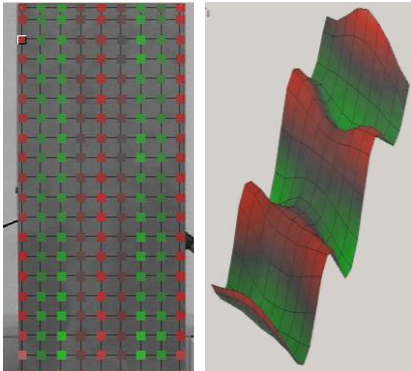
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Scanning Vibrometer (SLDV)

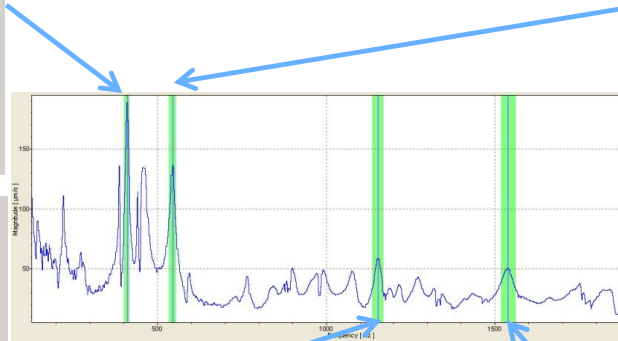
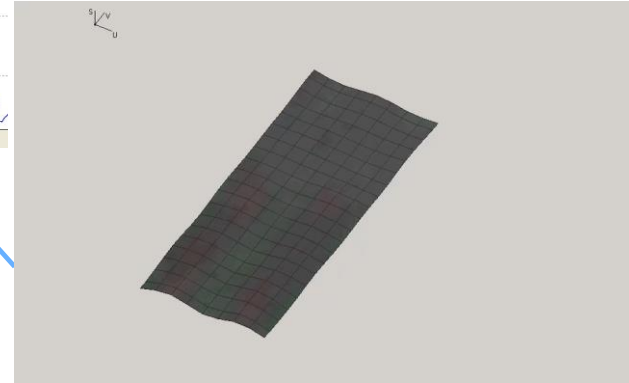
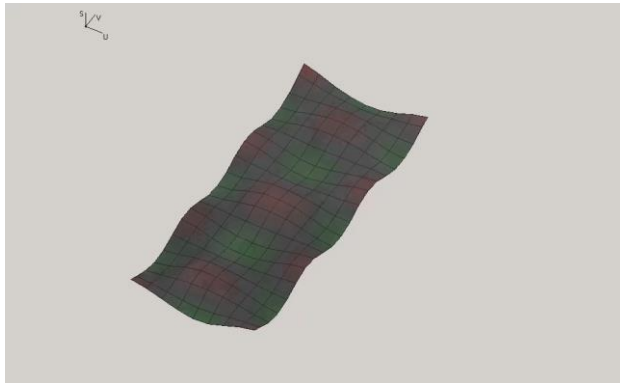
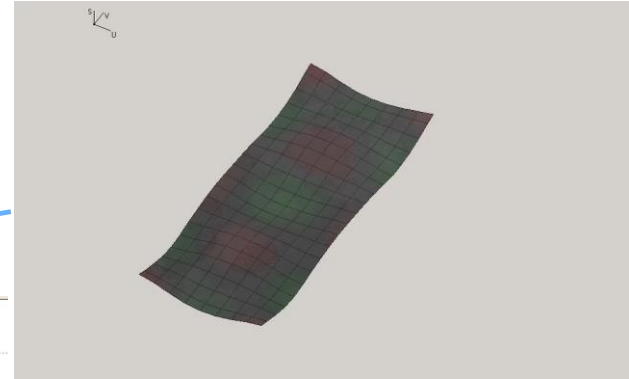
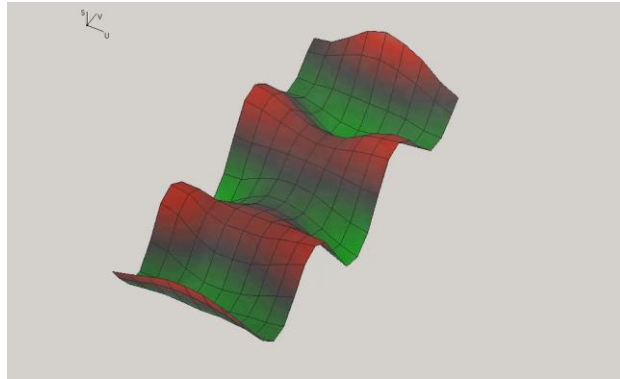


Full-field vibration measurement and mapping

- Scanning the test object point after point on a predefined grid.
- Acquire for each point FRF, amplitude and phase
- Knowing the phase relation among the sample points by simultaneous acquiring of a reference signal the objects deflection shape is constructed by mapping the single point data

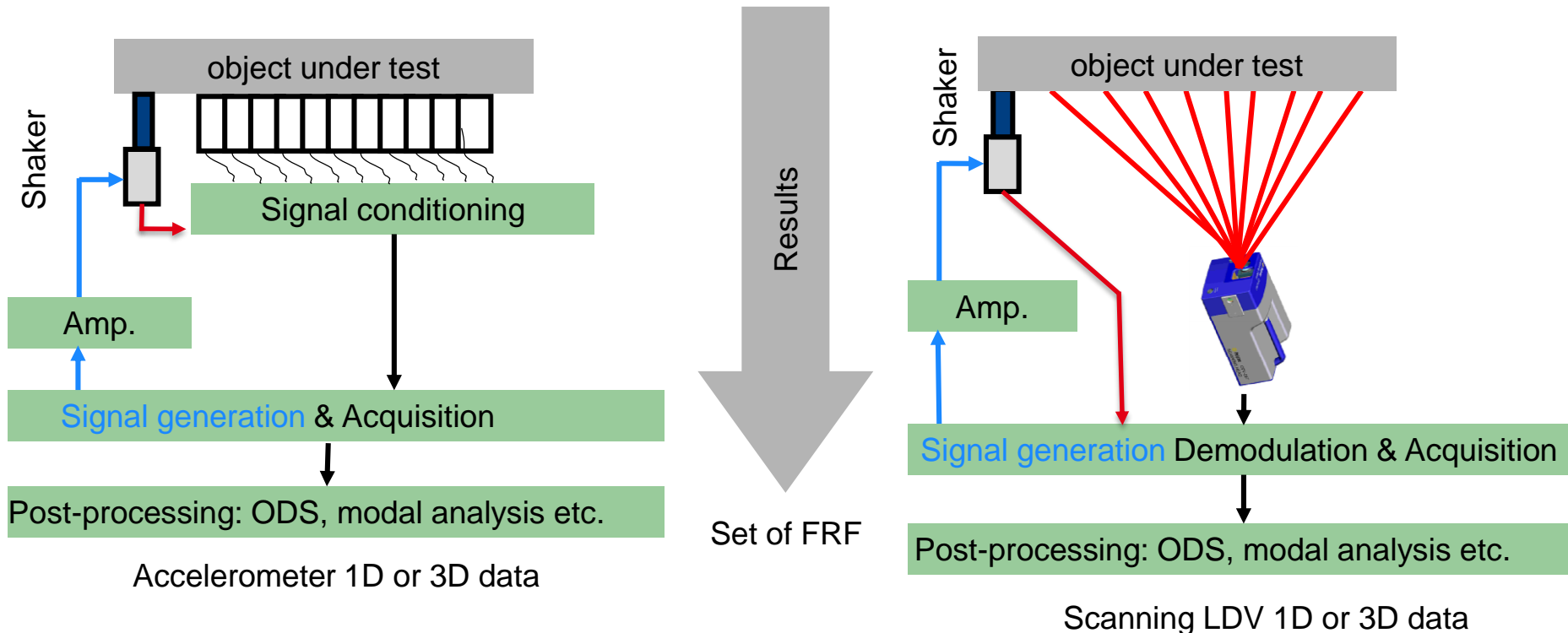


Scanning Vibrometer (SLDV)



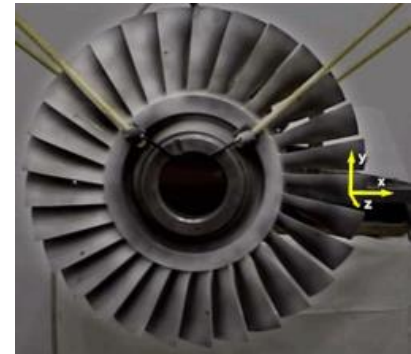
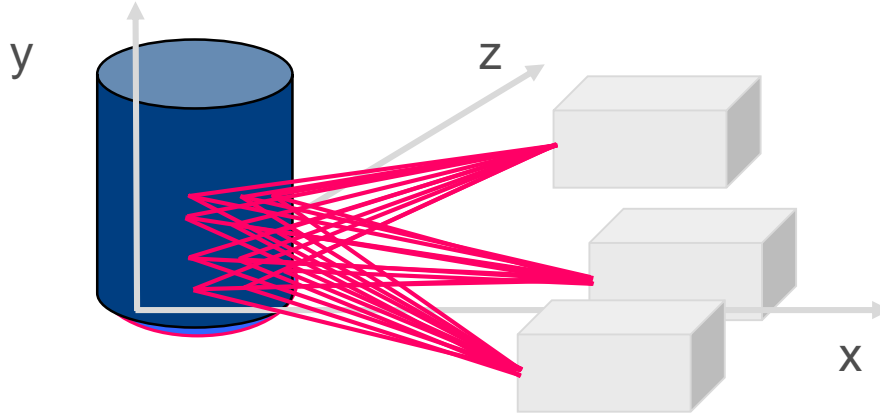
Scanning Vibrometer (SLDV)

Comparison between accelerometer based vibration acquisition and SLDV



3D Scanning LDV

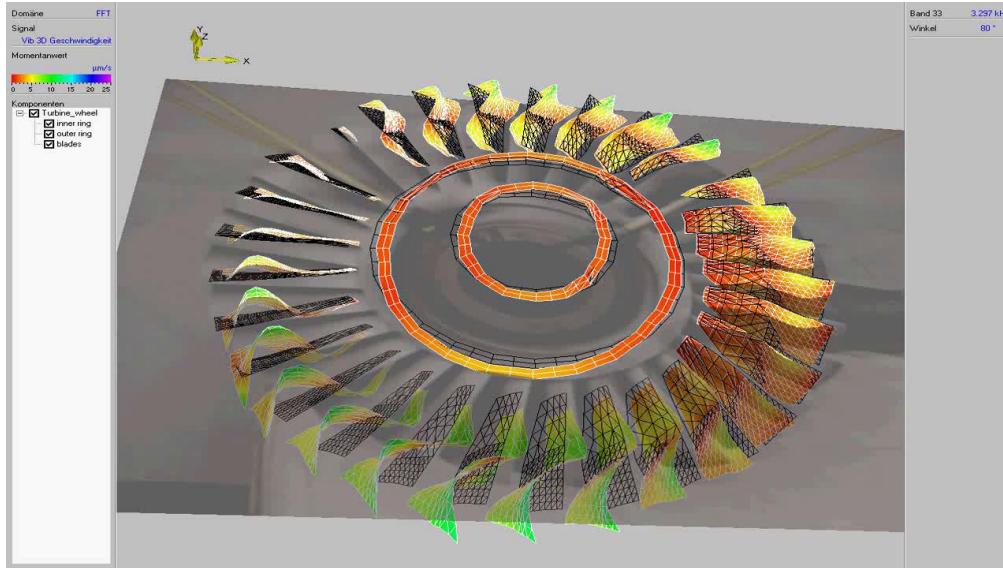
- 3 synchronized laser scanner with common control
- laser beams intersect at surface
- geometry is imported or measured
- simultaneous measurement of 3 vibration components
- coordinate transformation in object coordinate system



3D alignment

3D Scanning LDV

Very complex vibration shape requires 3D



- Panel Vibration
- Acoustic optimization
- ODS analysis

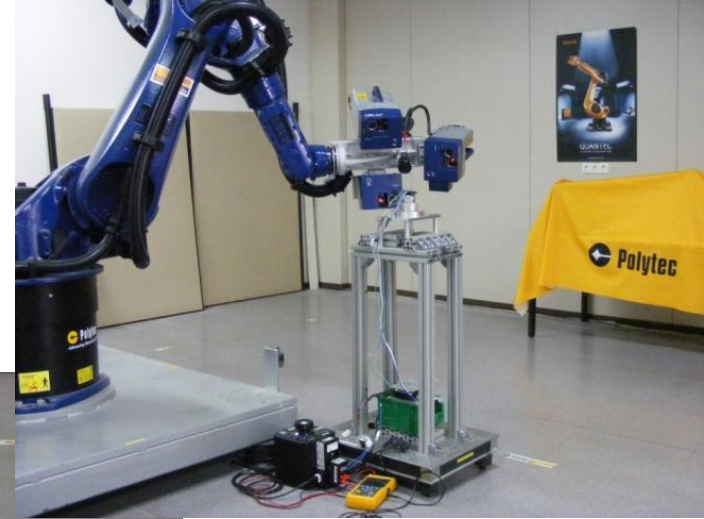
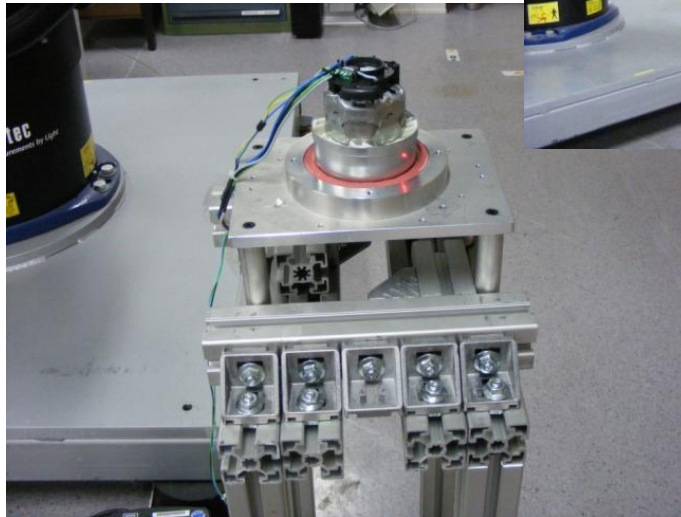
- Structural Dynamics
- FEM Validation
- ODS Analysis of complex shaped objects
- Strain & Stress Analysis

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 - **Quality control in production (inline & sample testing)**

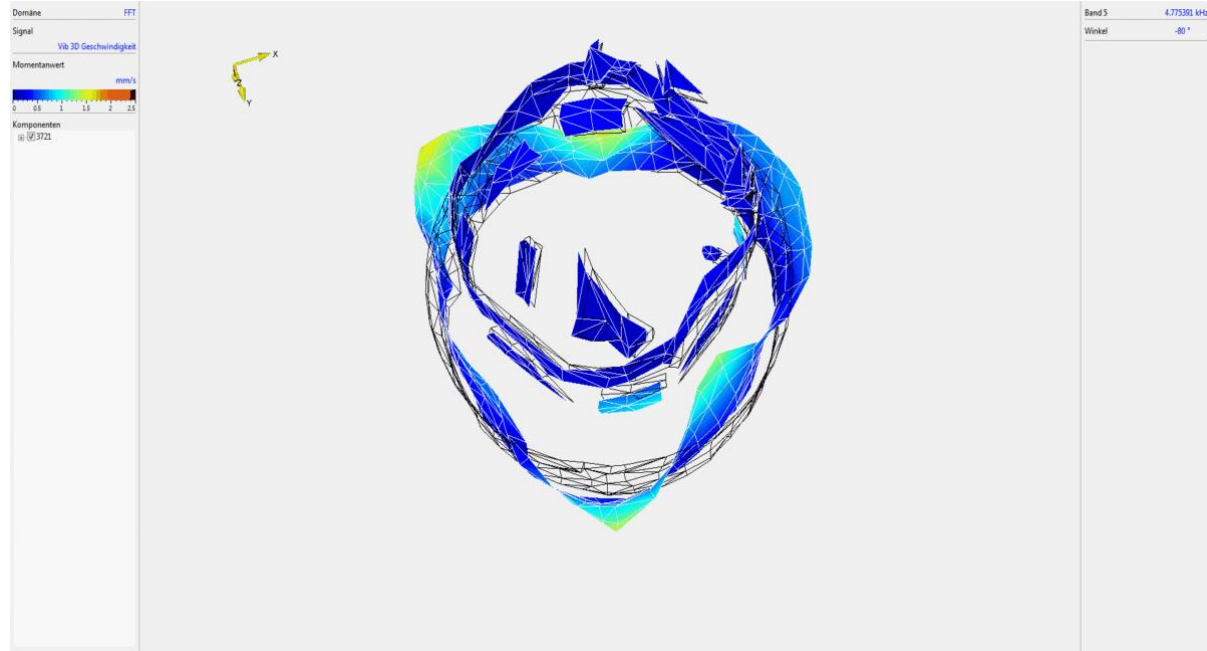
Electrical Motors

- Customer Vorwerk (vacuum cleaner motors)
- Optimisation of sound and vibration as application job carried out by Polytec
- 3D Vibration measurements of the motors



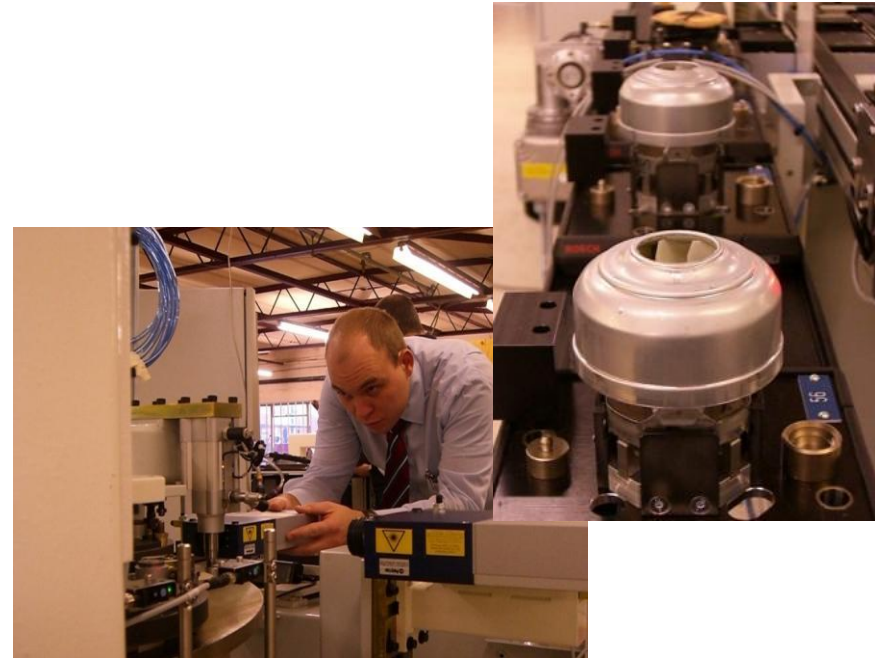
Electrical Motors

- Analysis of Deflection shapes
- Sound and vibration optimization
- Evaluation of best measurement locations for the end of line (EOL) test



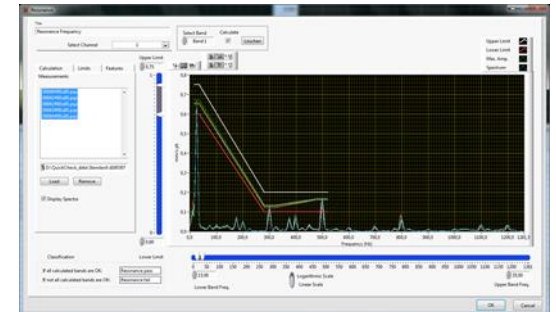
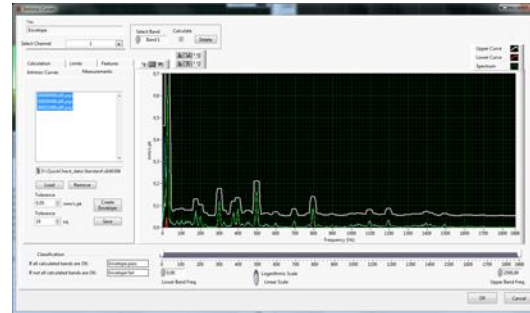
Electrical Motors

- Quality control by single point Vibrometer
- Complete new production line for electric motors for vacuum cleaners
- Noise and vibration test with 3 IVS-400 in three axes
- Measurement and classification by Polytec QuickCheck software
- Failure messages from QuickCheck directly linked to the repair station



LDV for automotive production testing

- Laser Vibrometer IVS-400 with digital and analog output
- Eye safe class 2 laser product
- Data processing by dedicated software (QuickCheck, LabView etc.)



Sun Roof Motor

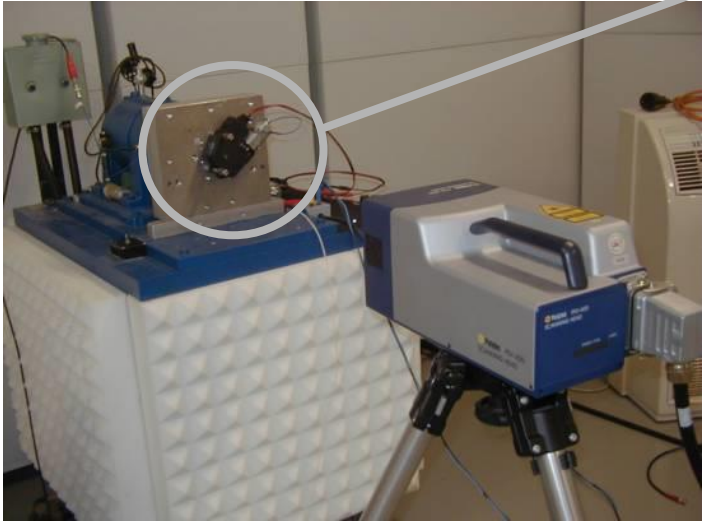
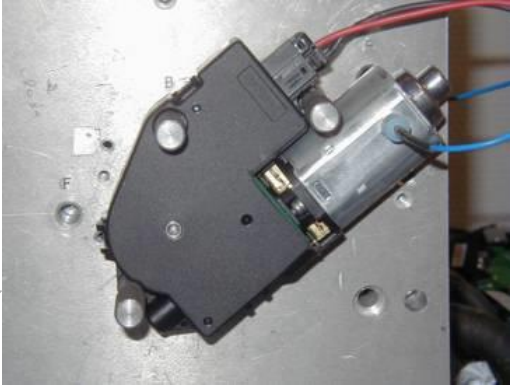
Motor noise of the sun roof drive

- Noise identified by microphone
- Find suitable measurement locations for the end of line (EOL) test



Source: Webasto

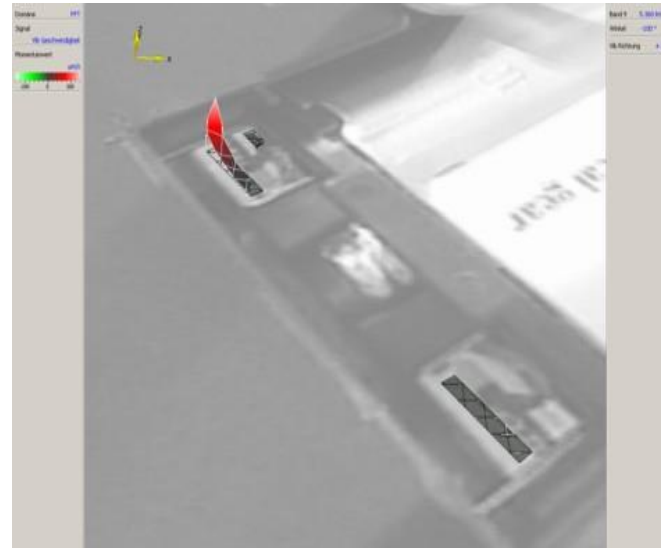
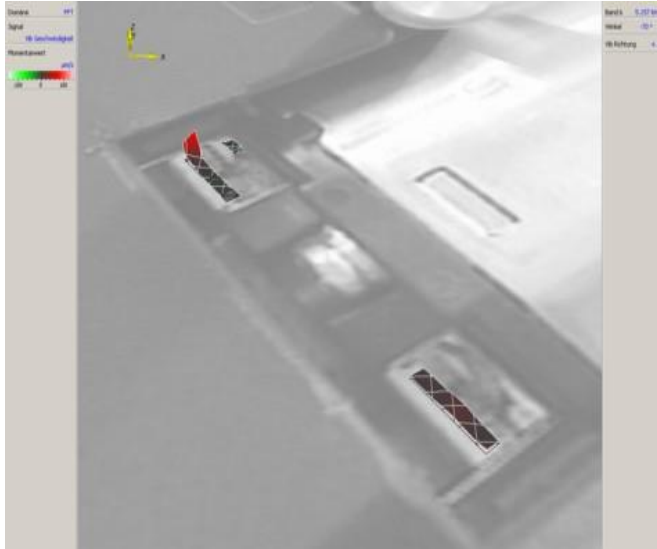
Sun Roof Motor



SLDV measurement of good and noisy motors

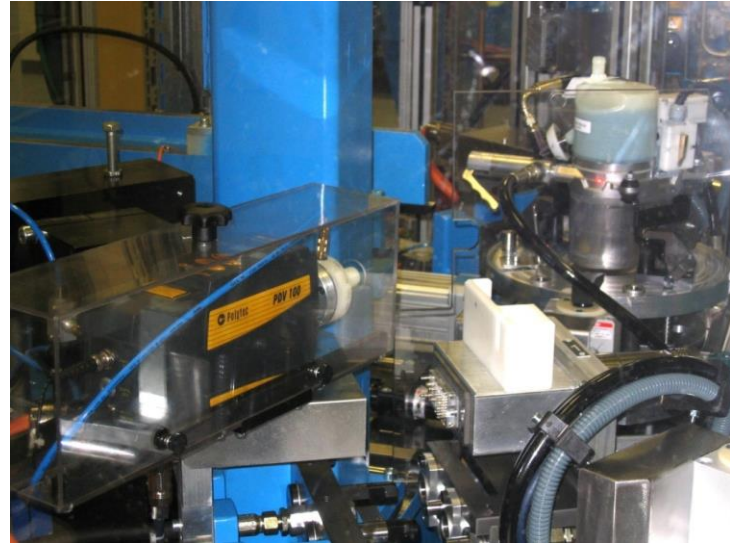
Sun Roof Motor

Good (left) versus bad (right) motor
Representive measurement location found



Quality Control of Steering Gears

- 100% vibration analysis of motor pump assembly
- Vibration measurement at two critical positions with LDV
- Test at different speed and pressure
- Identification of faulty components by order analysis



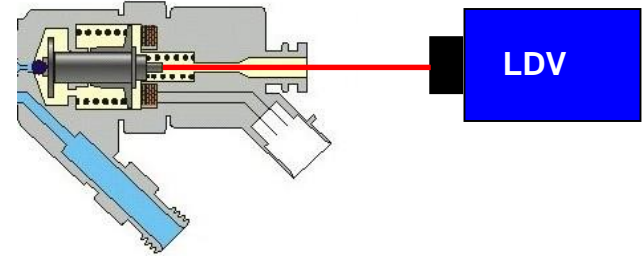
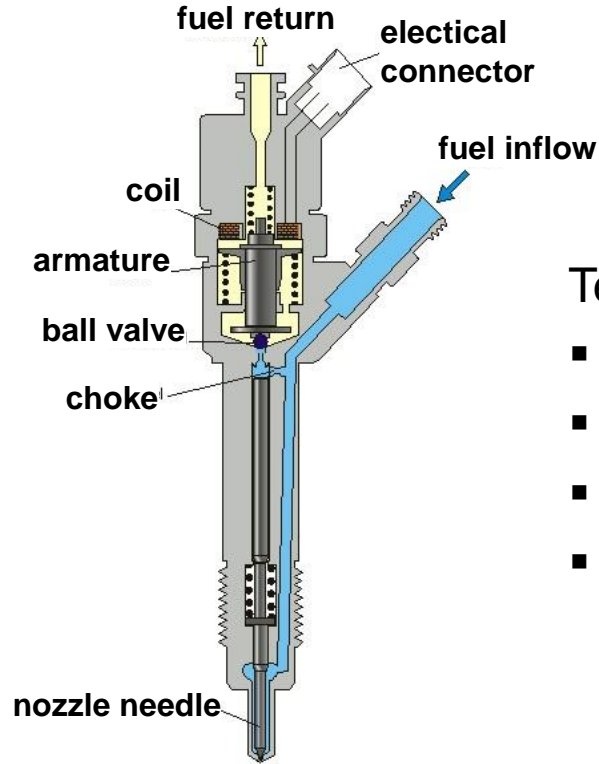
Cold Engine Test

Detect deviations and faults of components such as

- camshaft
- big end bearings
- valves
- cylinder & pistons
- cam shaft drive chain



Fuel injectors



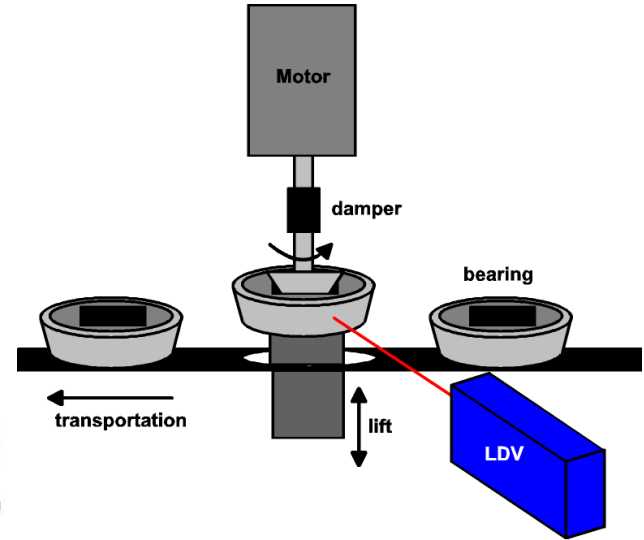
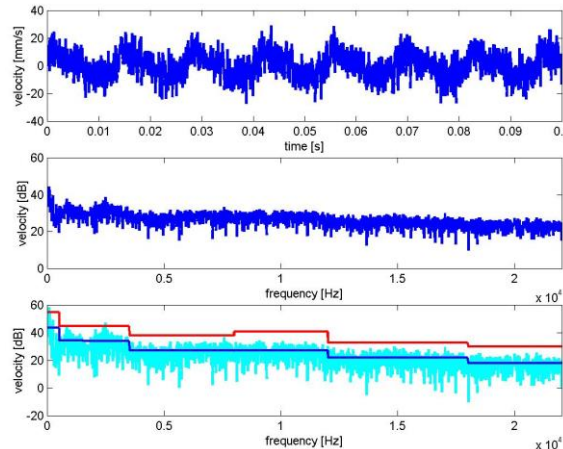
Testing electro-magnetic and piezo type injectors

- Displacement correlates with injected amount of fuel
- Response time correlates with injection time
- Velocities from 6 m/s to 20 m/s
- LDV is worldwide standard for this measurement in Germany, UK, Turkey, India, Thailand, Japan, Mexico and US

Fault Detection of Bearings

100 % testing of all products

- Cycle time about 500 ms
- speed-up to 4000 RPM by a motor
- Evaluation of band power



Fault Detection of Steering Unit

Assisted by 4 robots

- 2 testing lines with 2 x 2 LDV's mounted to 4 robots
- Allows test in different locations
- Easy switching between different models (left drive/ right drive car)

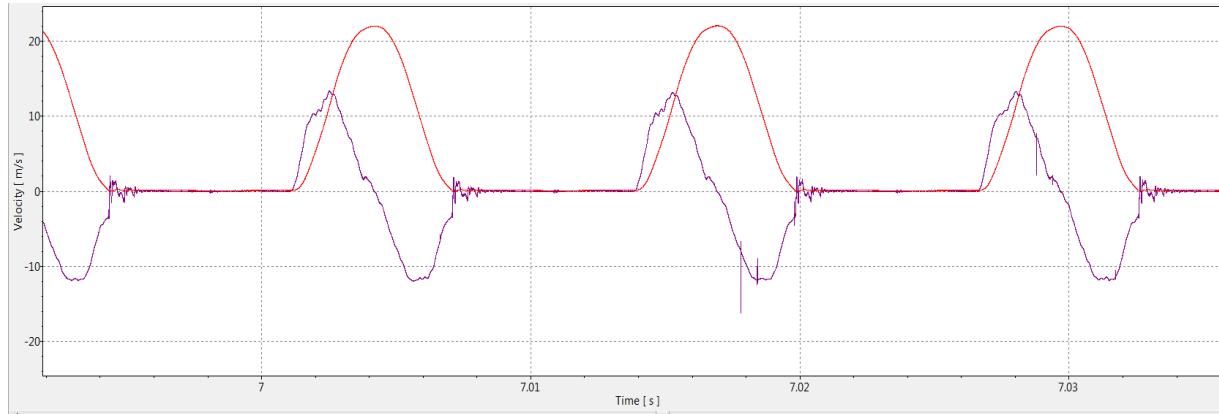


Valvetrain measurement

Valve closing essential for performance and emissions



Valve velocity and displacement



- Valve bouncing visible only in velocity signal
- Relatively high frequencies
- Bouncing has low displacements

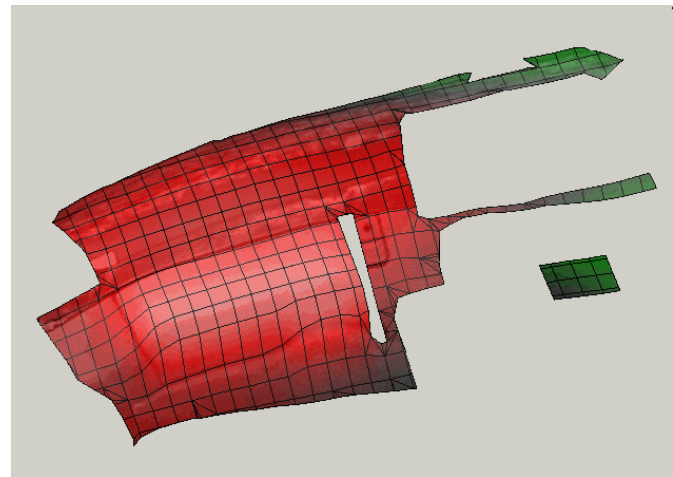
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Car interior – Squeak and Rattle

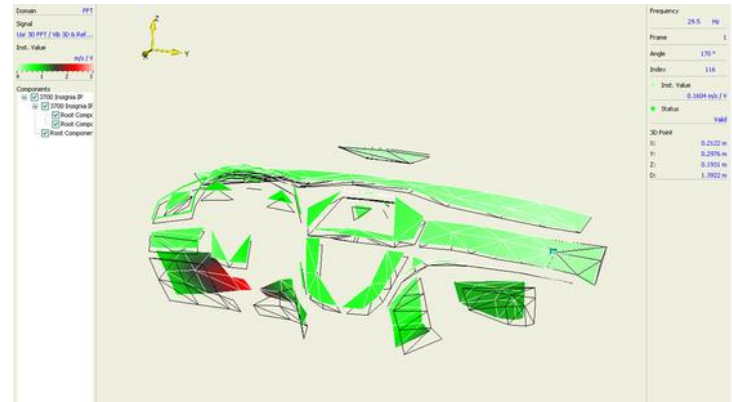
Example from GM (Opel)

- S&R is very complex vibration phenomena
- **Caused** by relative displacement between 2 parts/components
- Other noise sources are fans, AC etc.
- High special resolution of measurement points is needed:
 - To visualize complex movement of components and to find relative movements between parts



Car interior – Squeak and Rattle

- Measurement of the car interior in segments
- Engine excitation or shaker excitation
- Advantages:
 - High number of scan points
 - No mass loading

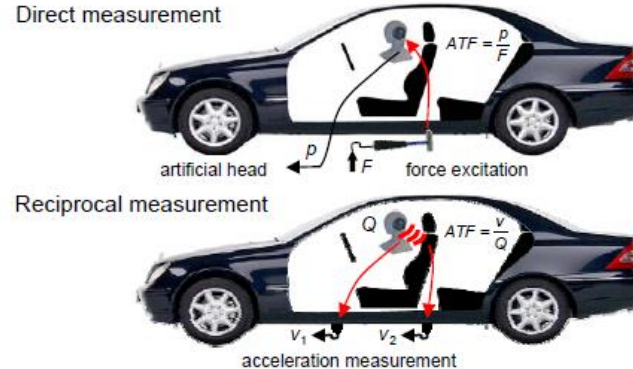


Reciprocal method to find noise sources

Transfer Path Analysis

Measurement Procedure:

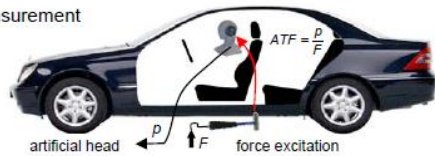
- Measure the noise inside the car caused by vibration e.g. under real driving condition or on a test stand
- Excite the measured noise with speaker and measure with 3D-SLDV the vibration that causes the noise – on car door, engine, exhaust...
- Knowing the vibration sources and where the noise is coming from the design can be modified and improved



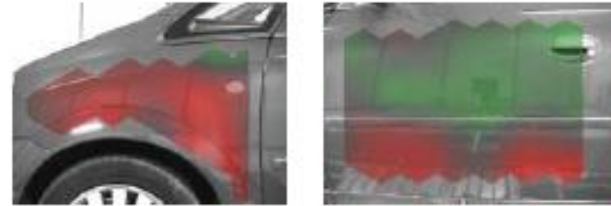
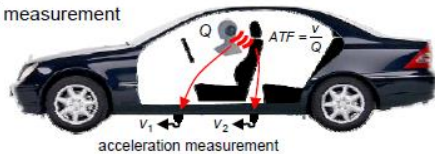
Reciprocal method to find noise sources

Transfer Path Analysis

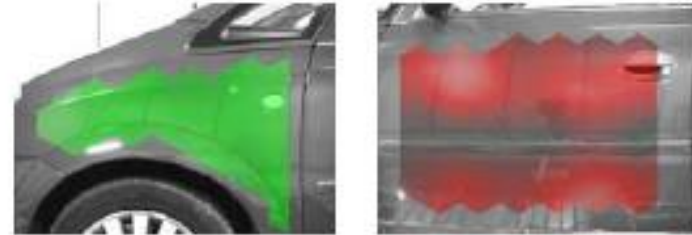
Direct measurement



Reciprocal measurement



Mean surface velocity for engine excitation



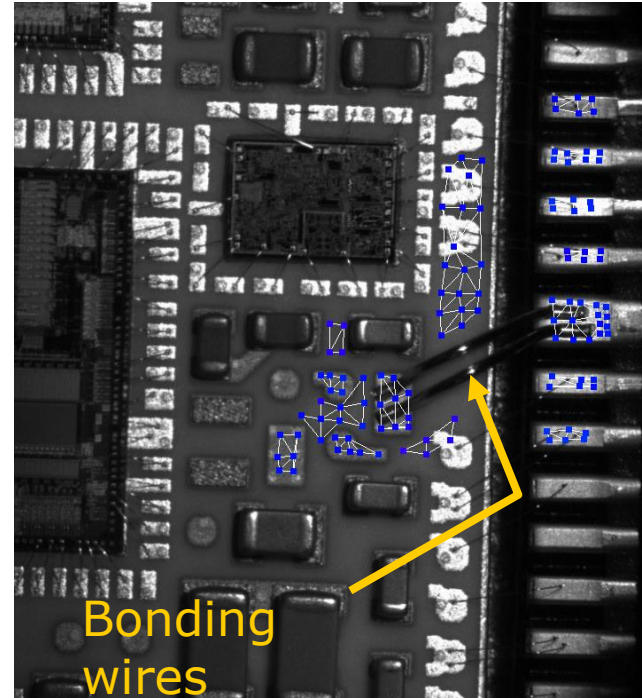
Mean surface velocity for excitation with the binaural sound source in the vehicle interior

Noise source in car door even the mudguard vibrates more when engine is running!

ECU improvement – PCB

PCB with failure under vibration stress:

- 3D measurement on opposite bond pads
- Measurement area 4 cm²
- Pad size typically 1mm²
- Several 3D points on one pad



ECU improvement – PCB

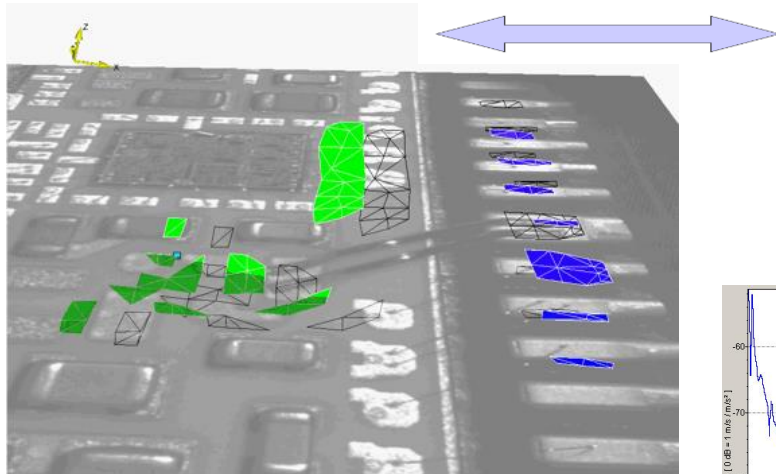
Test Conditions:

- Shaker excitation
 - white noise
 - 10 –250 Hz, ≈ 1 g
 - 10 –5000 Hz, ≈ 5 g
- Phase reference: accelerometer



ECU improvement – PCB

Results



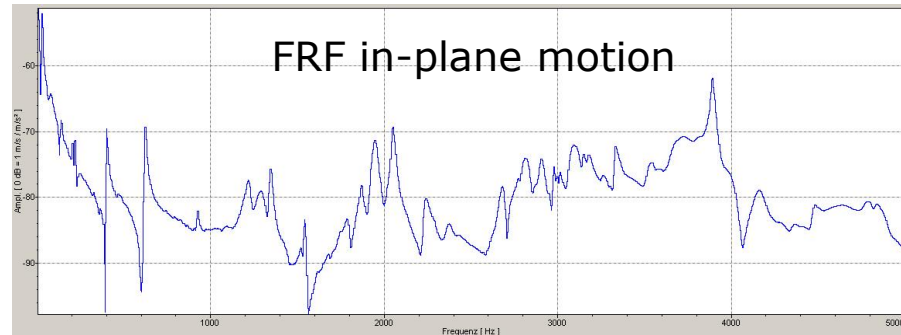
ODS bond pads

Deflection shape:

- Opposite phase in-plane motion between bond pads

Reason for failure:

- In-plane motion causes bending of bond wires



Damping material car chassis

- Car underbody measurements
- Many scan points needed to localize local modes that make noise
- Position damping material just where local modes have big amplitudes



Damping material car chassis

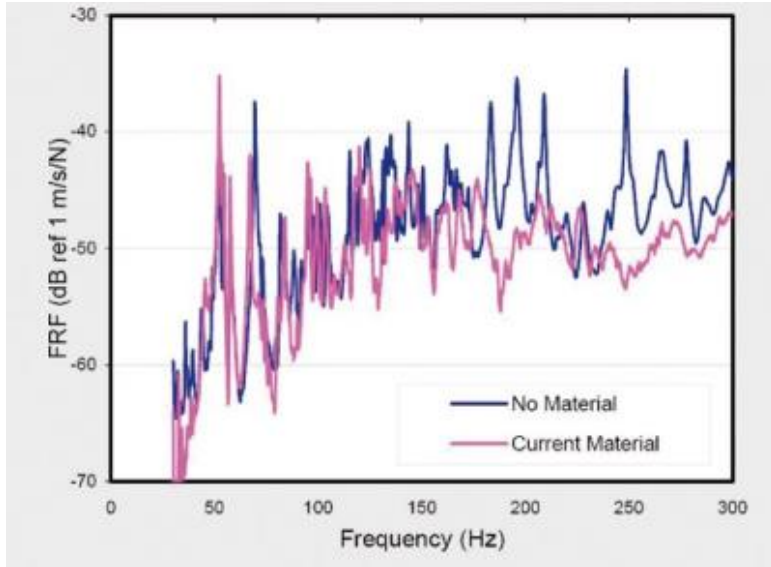
Car platform

- Measurements of vibration shapes with 3D-SLDV
- Damping materials applied according to the amplitude distribution (ODS)
- 0.8 kg reduction in weight
- 1 – 5 dB reduction in SPL especially > 100 Hz

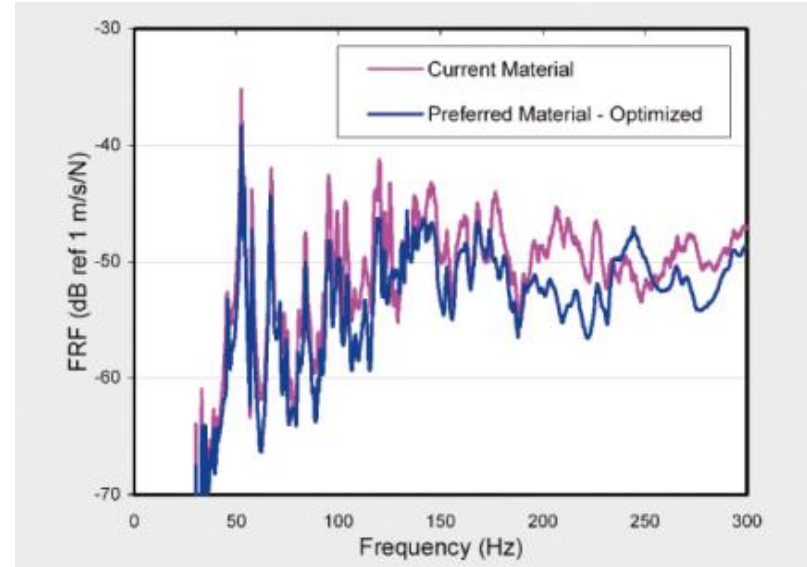


Courtesy: The Dow Chemical Company

Damping material car chassis

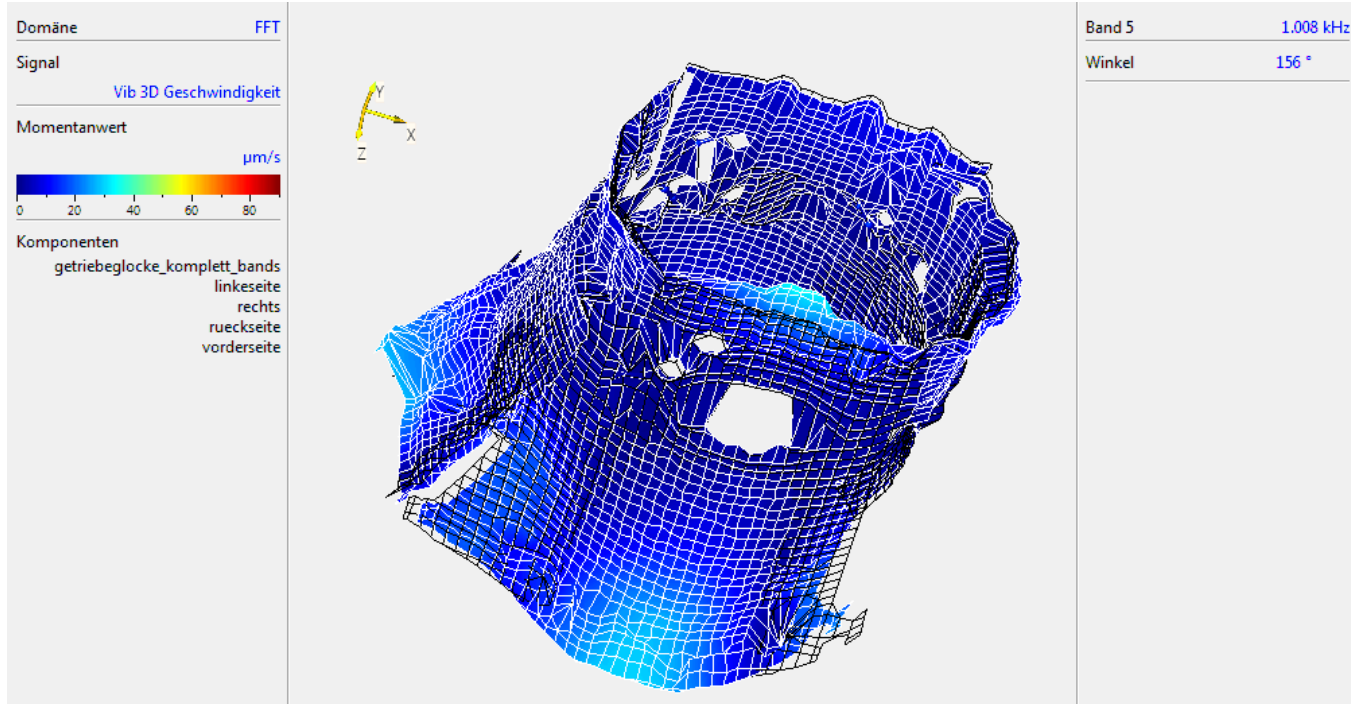


Before optimization



After optimization: slight reduction in the lower freq. area. Significant reduction in the areas above 100 Hz

Other Applications: Gear box mode shapes



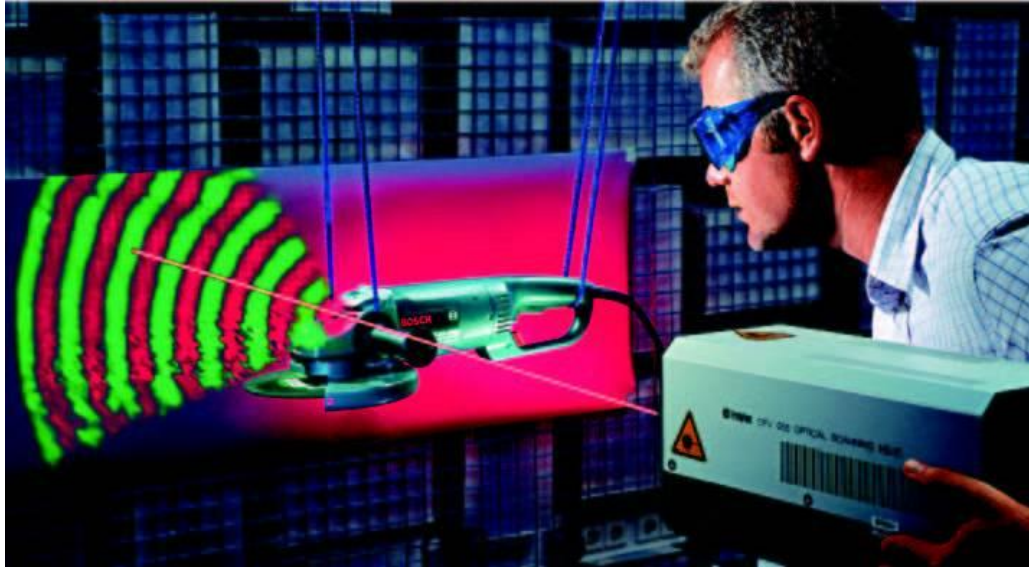
Other Applications: Wind tunnel

- Structural vibration induced by turbulences
- Transducers would influence aero dynamics
- Very popular in Germany



Courtesy AUDI AG

Other Applications: Sound field visualization



Source: BOSCH *Research Info* issue 4/2004

Refracto-Interferometry

- SLDV can be used to visualize sound fields
- Utilized for development of ultrasonic parking sensors

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 - Product development and NVH
 - **Modal analysis and FEM validation**

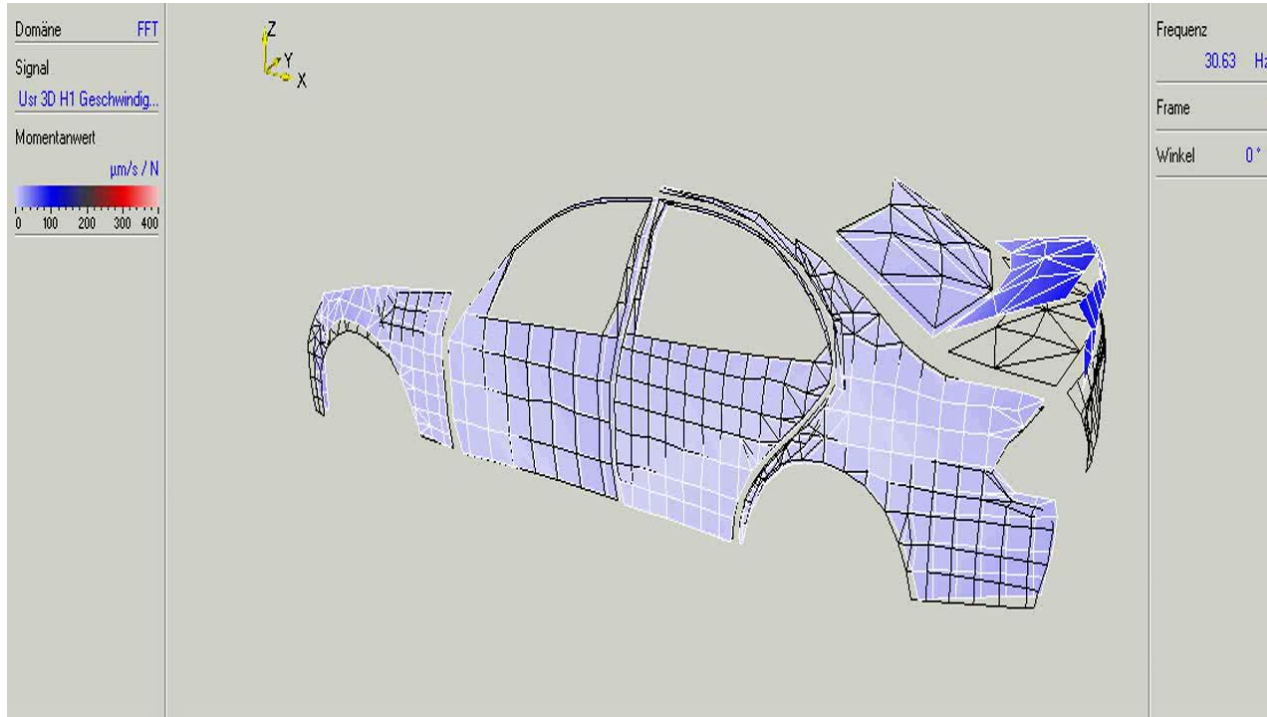
Car body Modal Test & FEM Update



3D SLDV

- Set-up with 3 individual tripods
- Points that can optically not accessed measured with accelerometers
- Main motivation for using LDV is not time saving but the high density of points

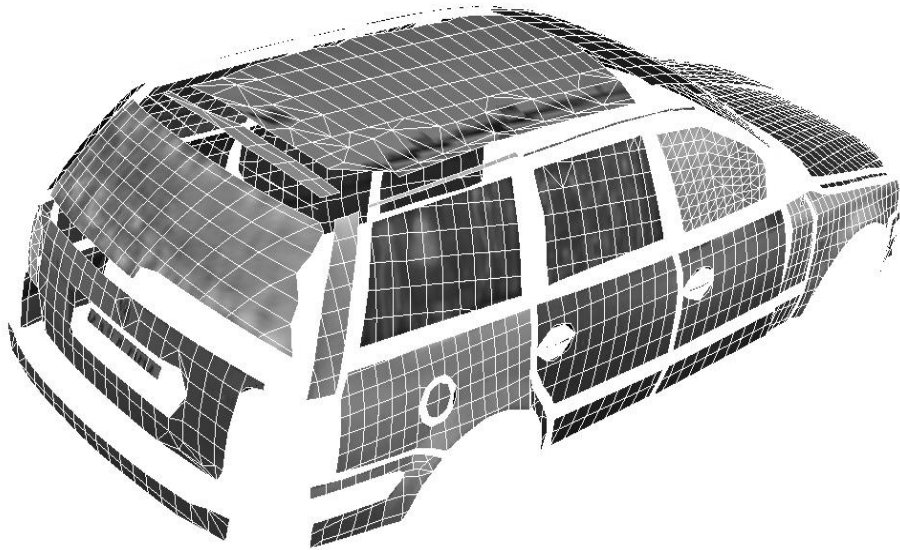
Car body Modal Test & FEM Update



Result

- Data from several measurement positions are combined (stitched) to one data set.

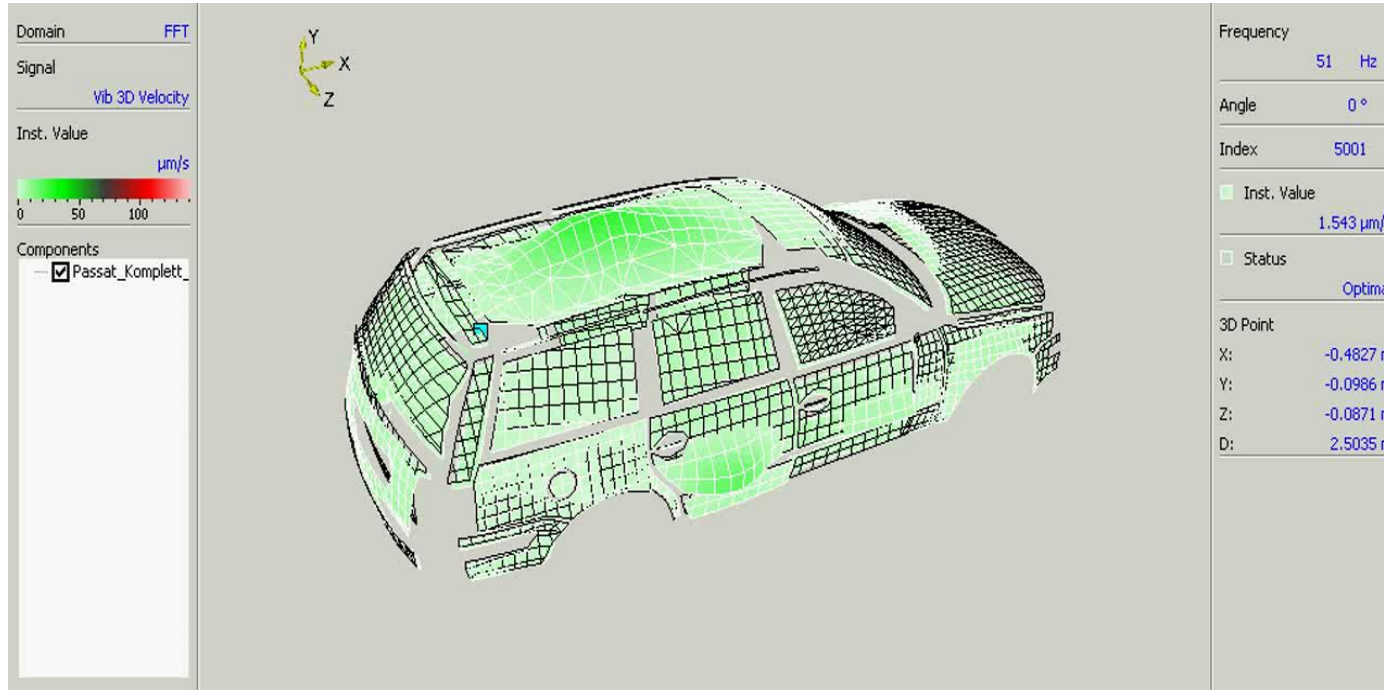
Car body Modal Test & FEM Update



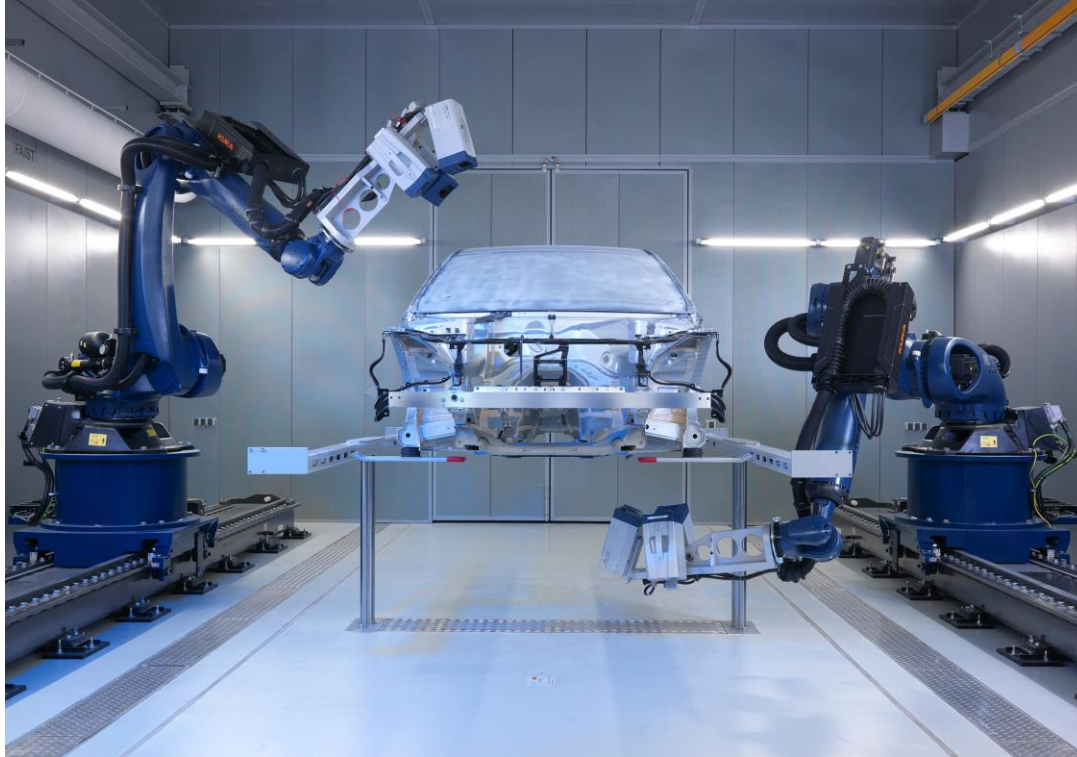
Another example:

- Car body excited by shaker
- Larger number of individual measurements combined to one data set

Car body Modal Test & FEM Update



Car body Modal Test & FEM Update



RoboVib Lab Germany:

- At Polytec in Germany equipped with 2 robots mounted to 6 m linear stages

Car body Modal Test & FEM Update



RoboVib Lab Michigan:

- At Polytec Inc. equipped with 1 robots mounted to linear stage
- Another installation is at Polytec Japan with 2 robots

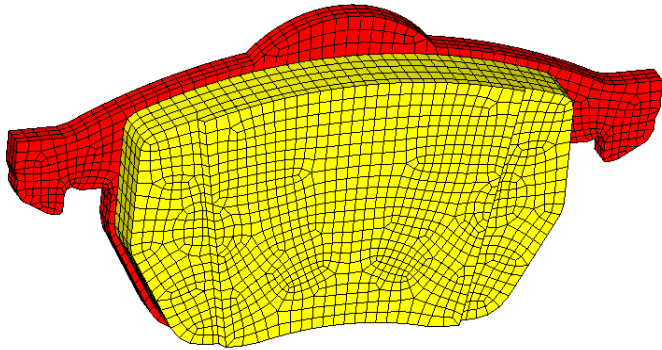
Agenda

- Where do we measure and why do we measure vibration optically?
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Automotive Brake Testing

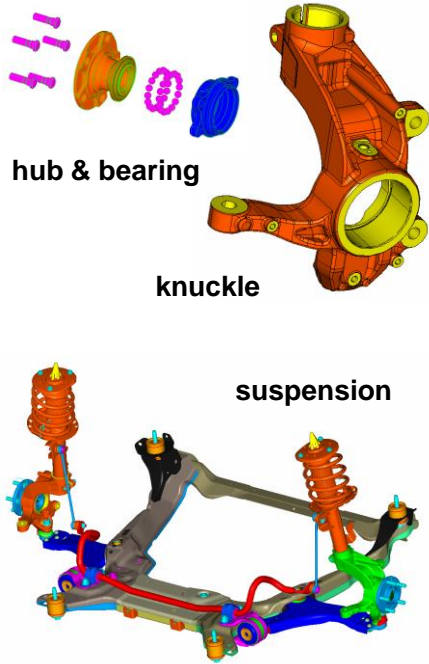
Brake Measurements by SLDV

- Top application for Laser Doppler Vibrometer
- Non-contact, no mass load

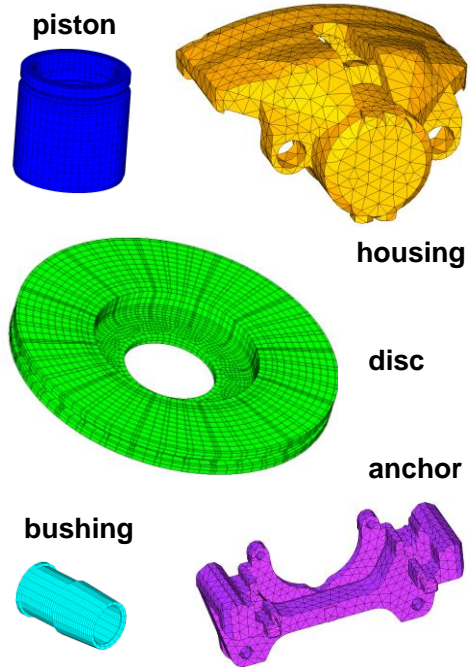


Automotive Brake Testing

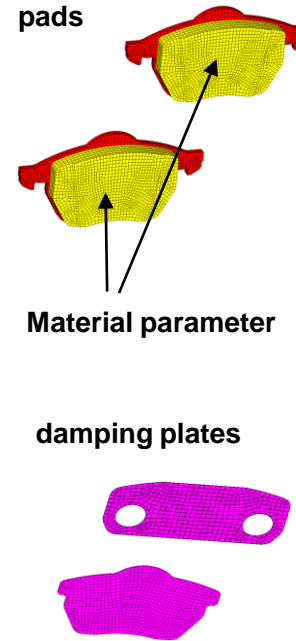
OEM



Brake manufacturer



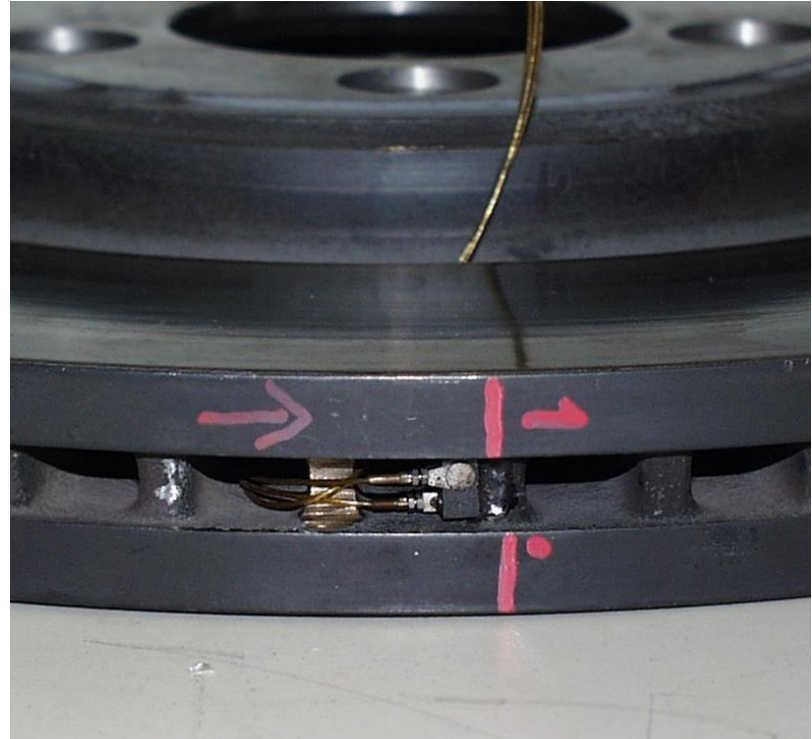
Pad manufacturer



Automotive Brake Testing

Brake Measurements by SLDV

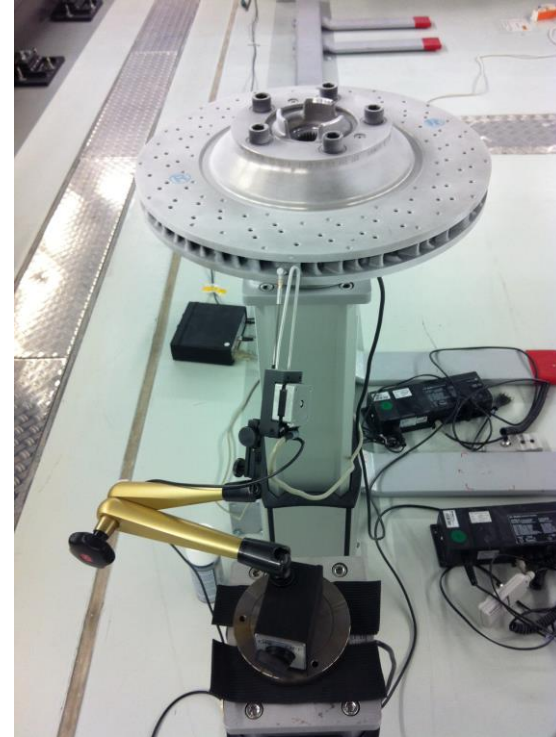
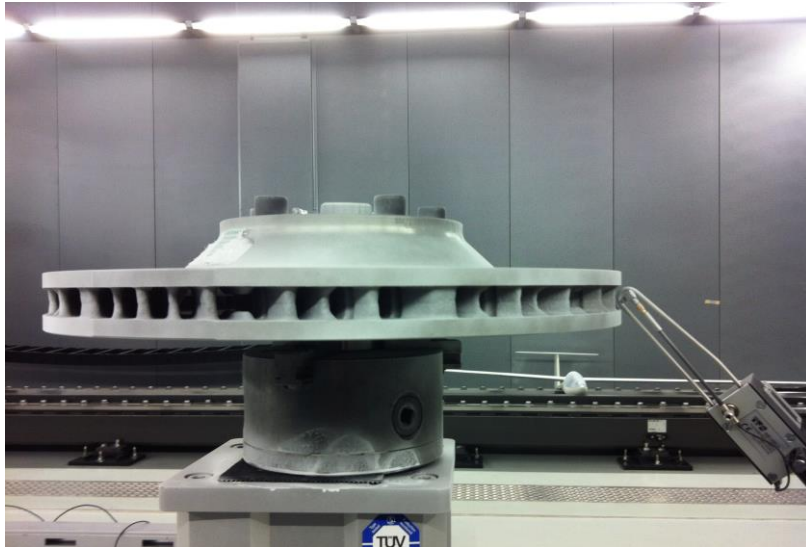
- Top application for Laser Doppler Vibrometer
- On the rotating brake disc: Installing a larger number of accelerometers is extremely time consuming.



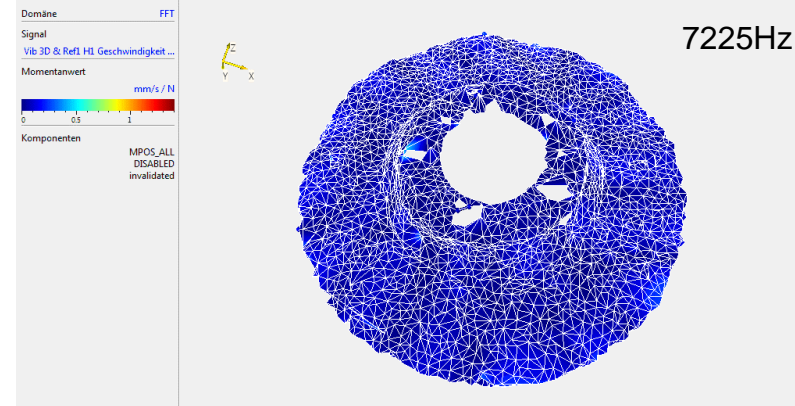
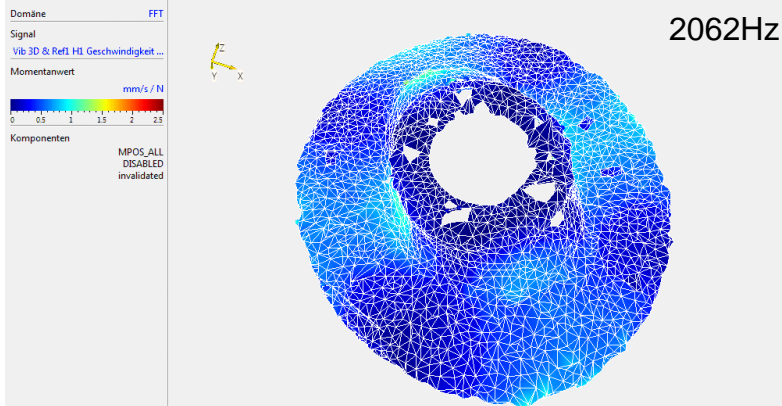
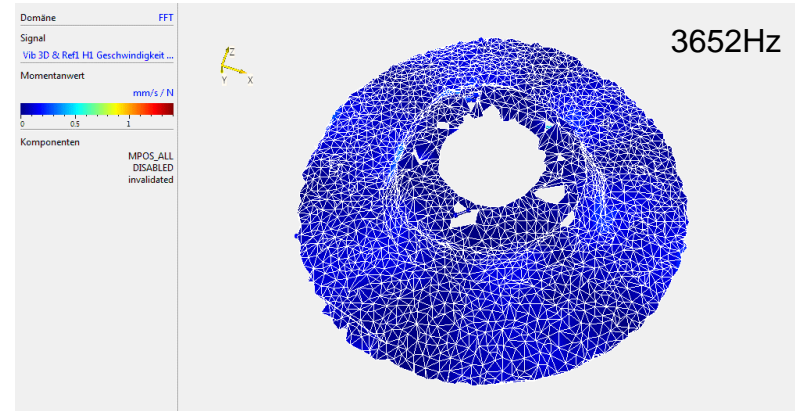
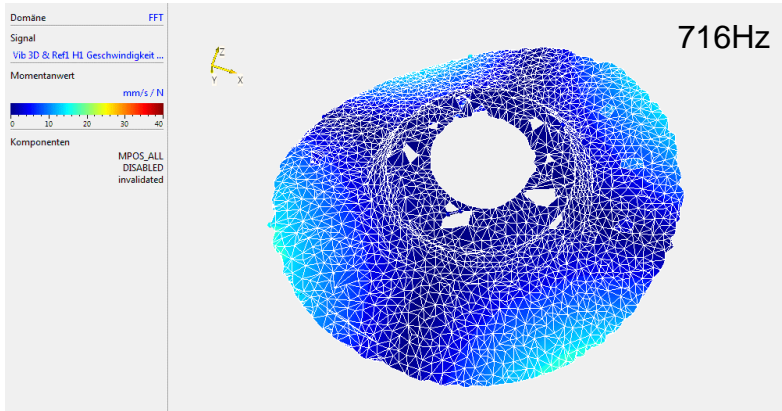
Automotive Brake Testing

Component Test (stationary condition)

- The brake disc is excited with an automated modal hammer



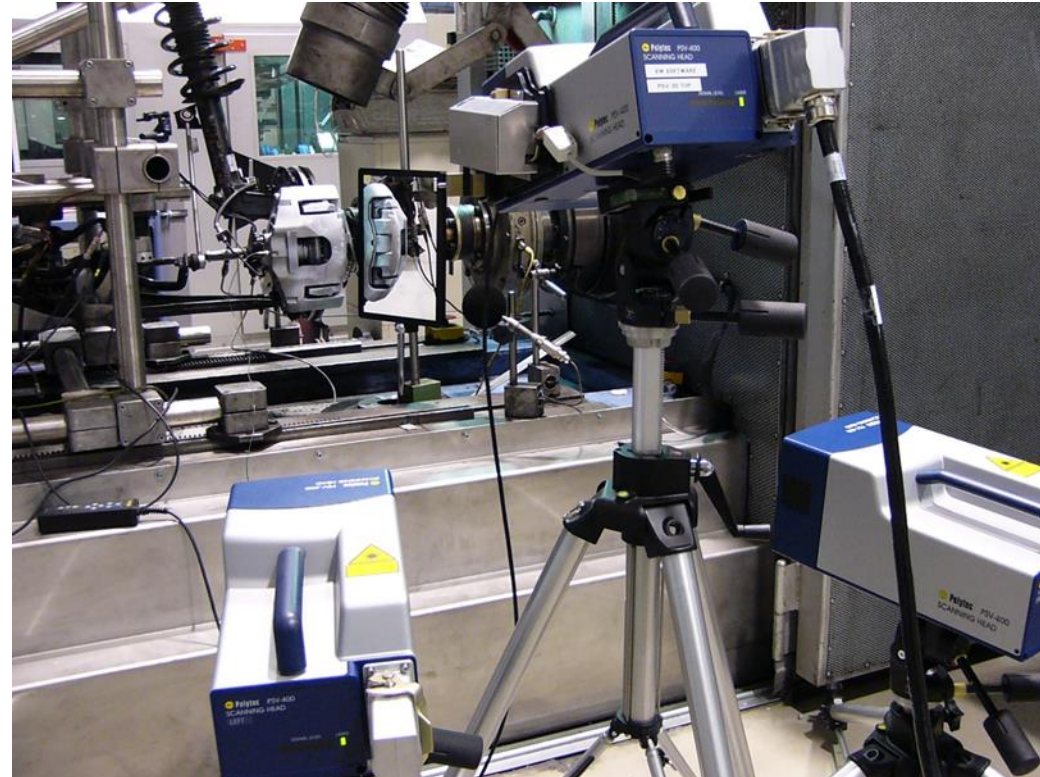
Automotive Brake Testing



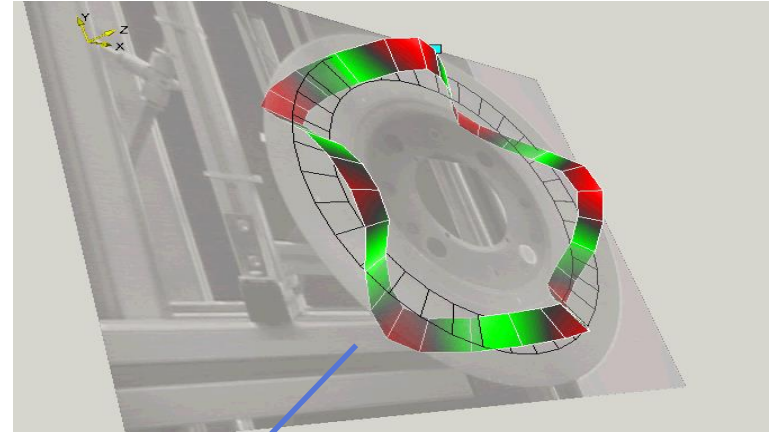
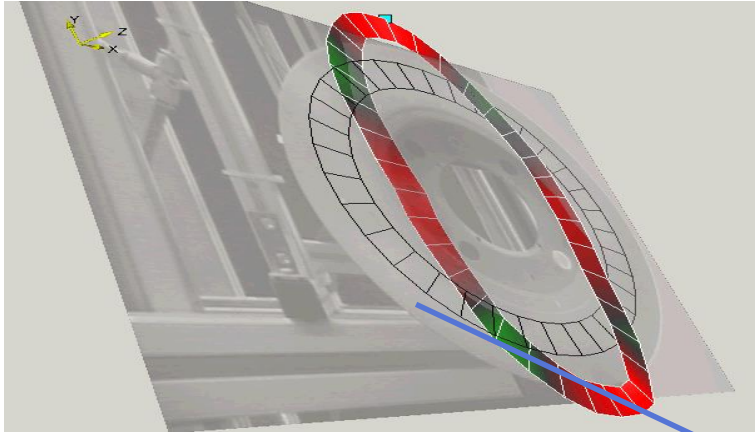
Automotive Brake Testing (Rotating)

Brake squeal

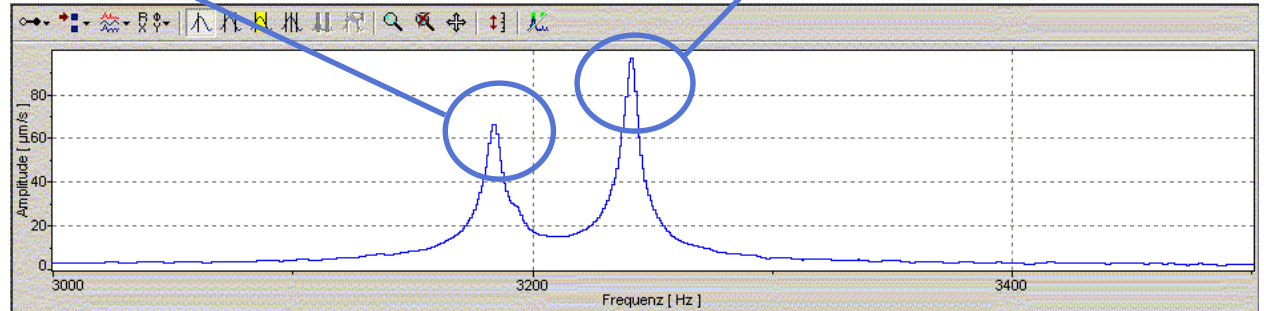
- Occurs only for short time and depends on velocity, brake pressure, temperature and other parameters
- As optical access is limited mirrors are used to measure hidden areas
- The measurement is acoustically triggered, i.e. only when brake squeal is present data are taken



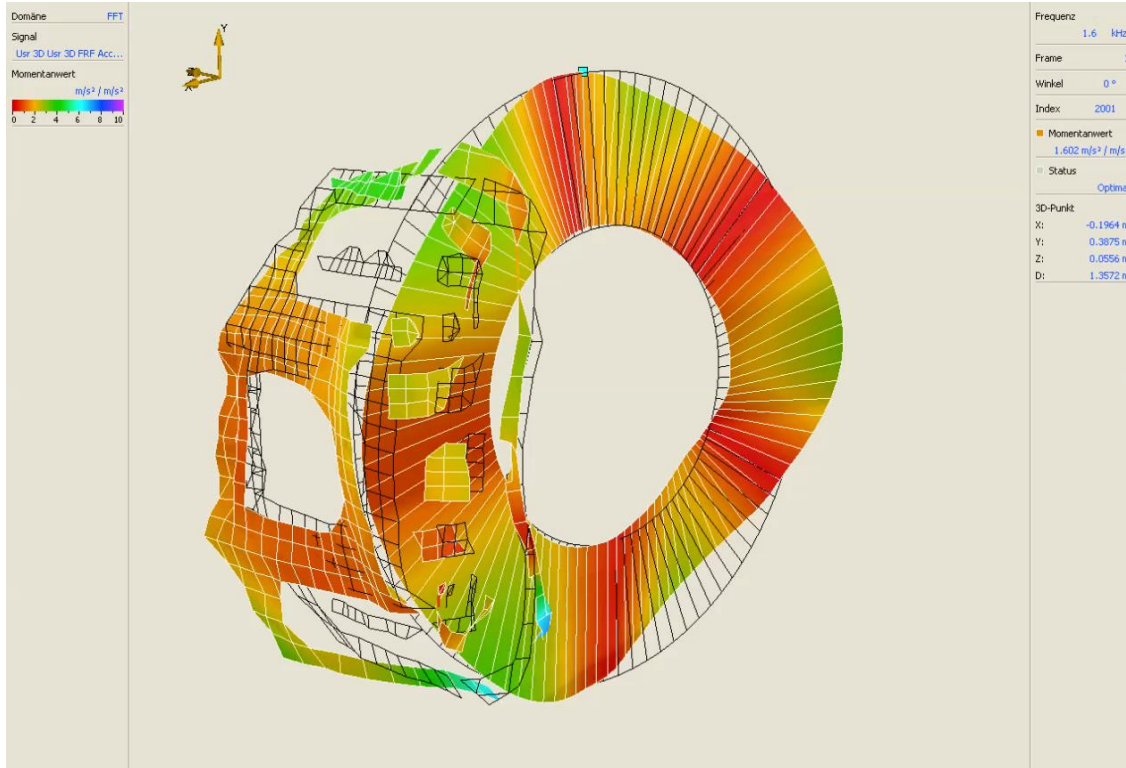
Automotive Brake Testing (Rotating)



- Coupling of an inplane (left) and out of plane mode (right) is one cause for squealling



Automotive Brake Testing (Rotating)

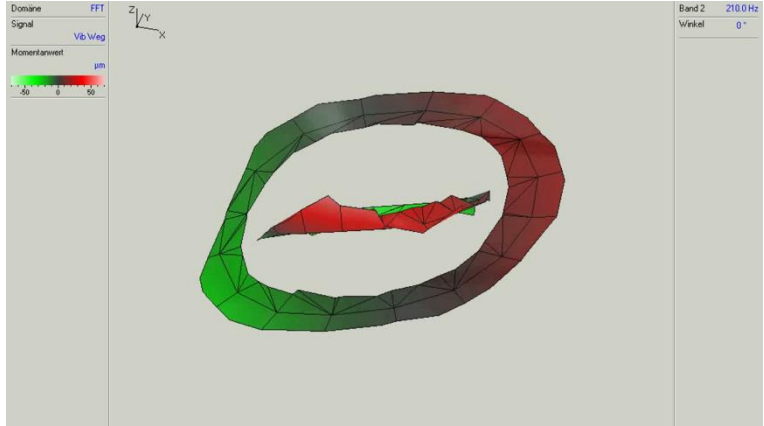
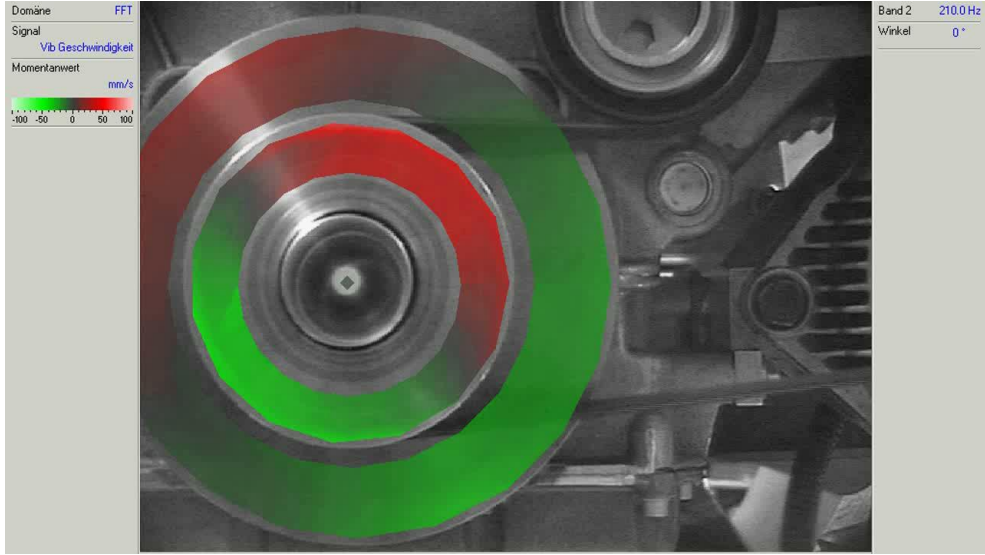


- Operational deflection shape (ODS) during squeal

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Testing Rotatings Parts



Vibration damper at 4100 rev/min

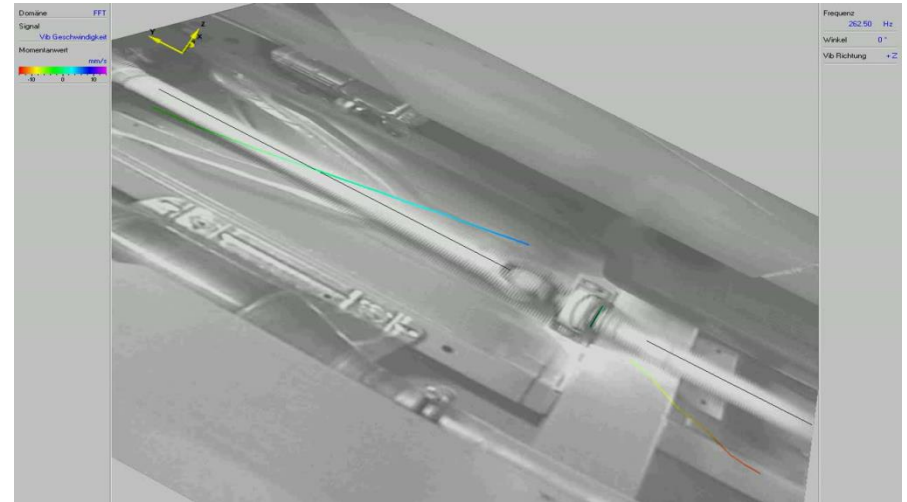
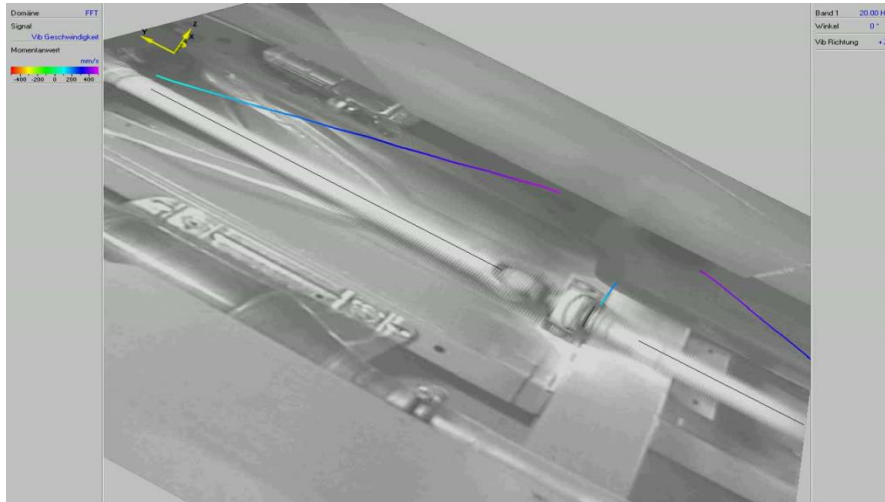
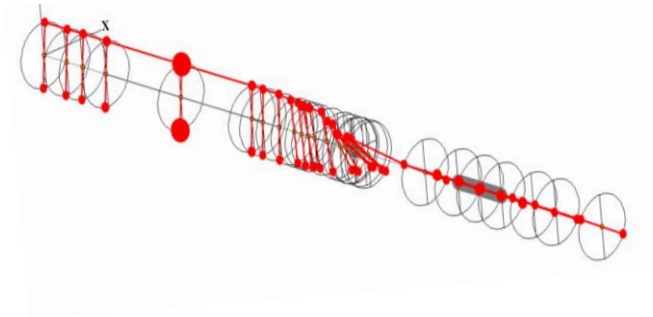
Tires

FE simulation results from Abaqus	Measurement results from the 3-D laser vibrometer
Turning mode 2: 93.9 Hz	Turning mode 2: 91.3 Hz

Testing Rotatings Parts

Passenger car drive shaft

- scanning at fixed RPM along shaft
- bending modes are visible



Testing Rotatings Parts II

With SLDV the laser beam is stationary with respect to the rotating object

- How to measure fans and bladed discs?



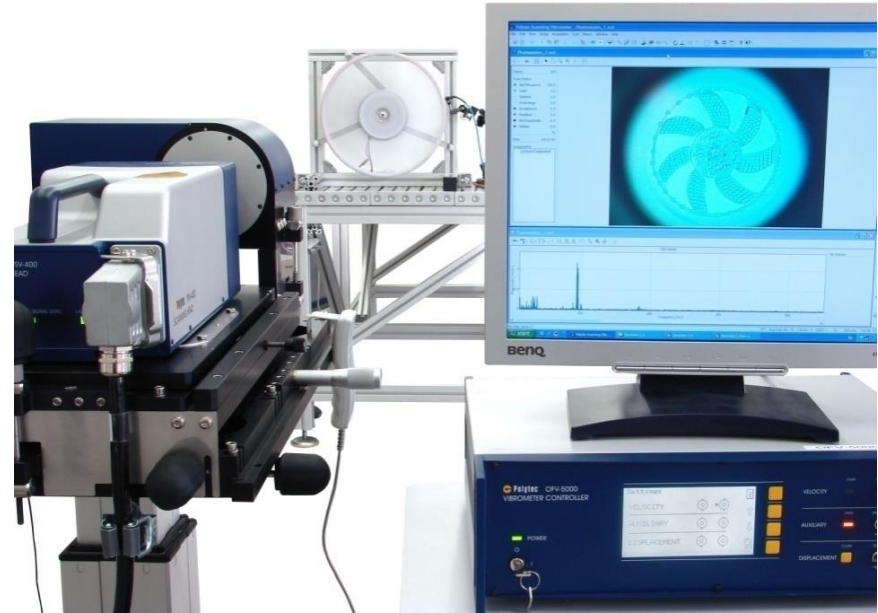
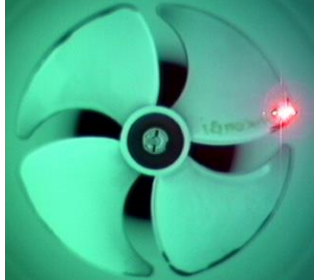
- How to measure in the rotating system of the test object?



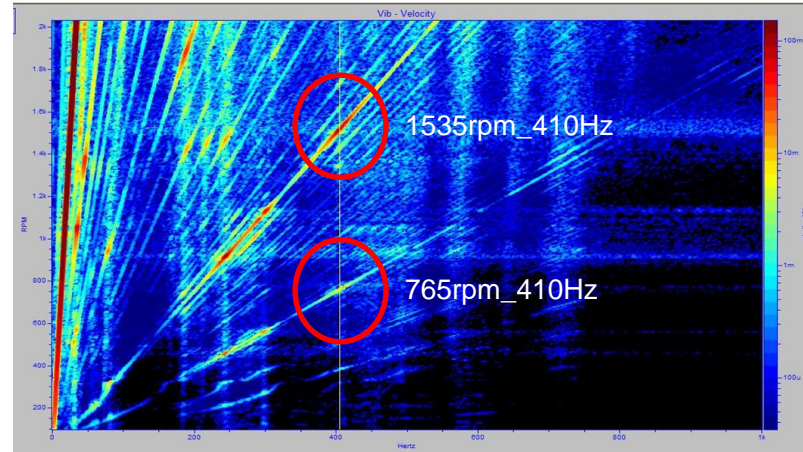
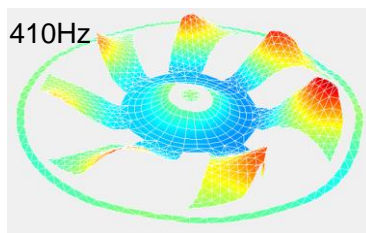
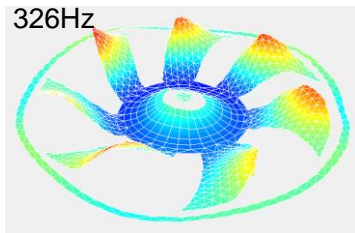
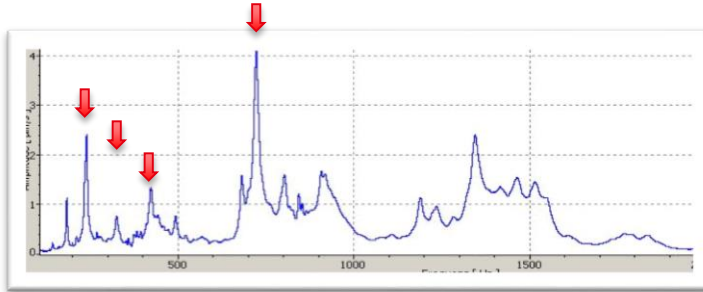
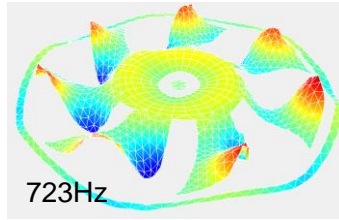
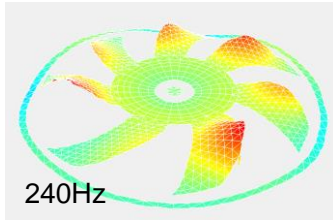
Testing Rotating Parts II

“De-rotating” a rotating object

- Utilizing an optical Derotator
- Synchronized with the rpm of the object. Requires encoder or similar.



Testing Rotating Parts II



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- **Conclusions**

The background of the slide features a dark, industrial setting with a prominent red laser beam cutting across the scene. A bright yellow light source is visible at the bottom center, creating a lens flare effect. The ASDEC logo is rendered in a large, red, outlined font, with a red sine wave graphic integrated into the right side of the 'E'. Below the logo, the text "Measuring Composite Material" is written in a white, bold, sans-serif font with a slight drop shadow.

ASDEC

Measuring Composite Material

Thank you very much for your attention