Laser Doppler Vibrometry

Non-contact Vibration Measurement for Research, Development and Production

Laser 2005

Dr. Heinrich Steger
Polytec GmbH, Waldbronn

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Agenda

- Company Overview
- Basics of Laser Doppler Vibrometry
- Key Features of LDV
- Product Overview
- Scanning & 3D Scanning Vibrometry
- Exemplary Applications
- Conclusions

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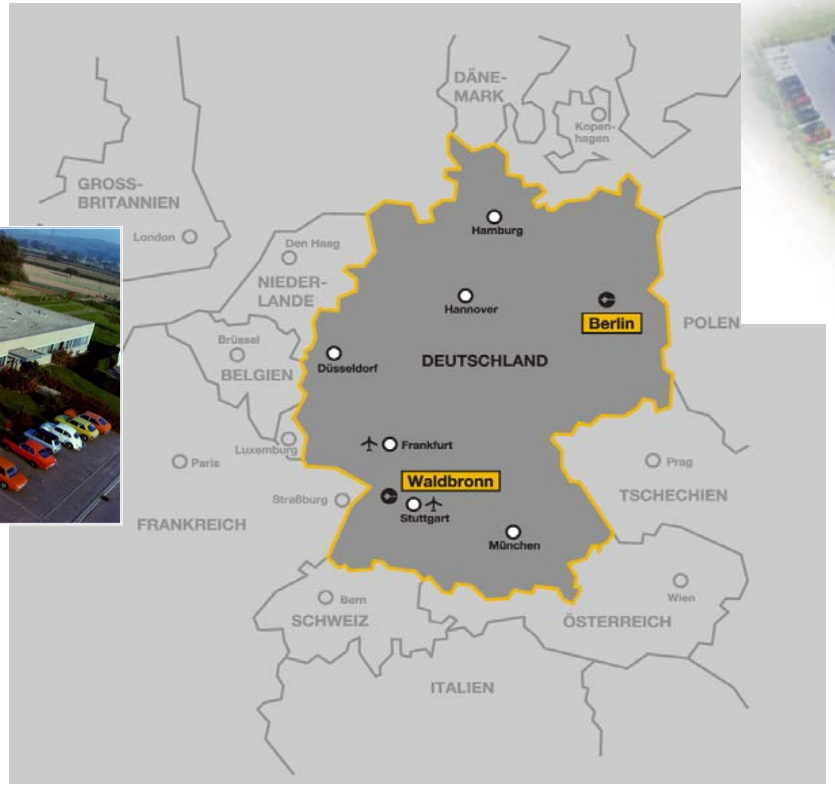
1967 Foundation



Polytec today

250 employees globally

40 employees R&D

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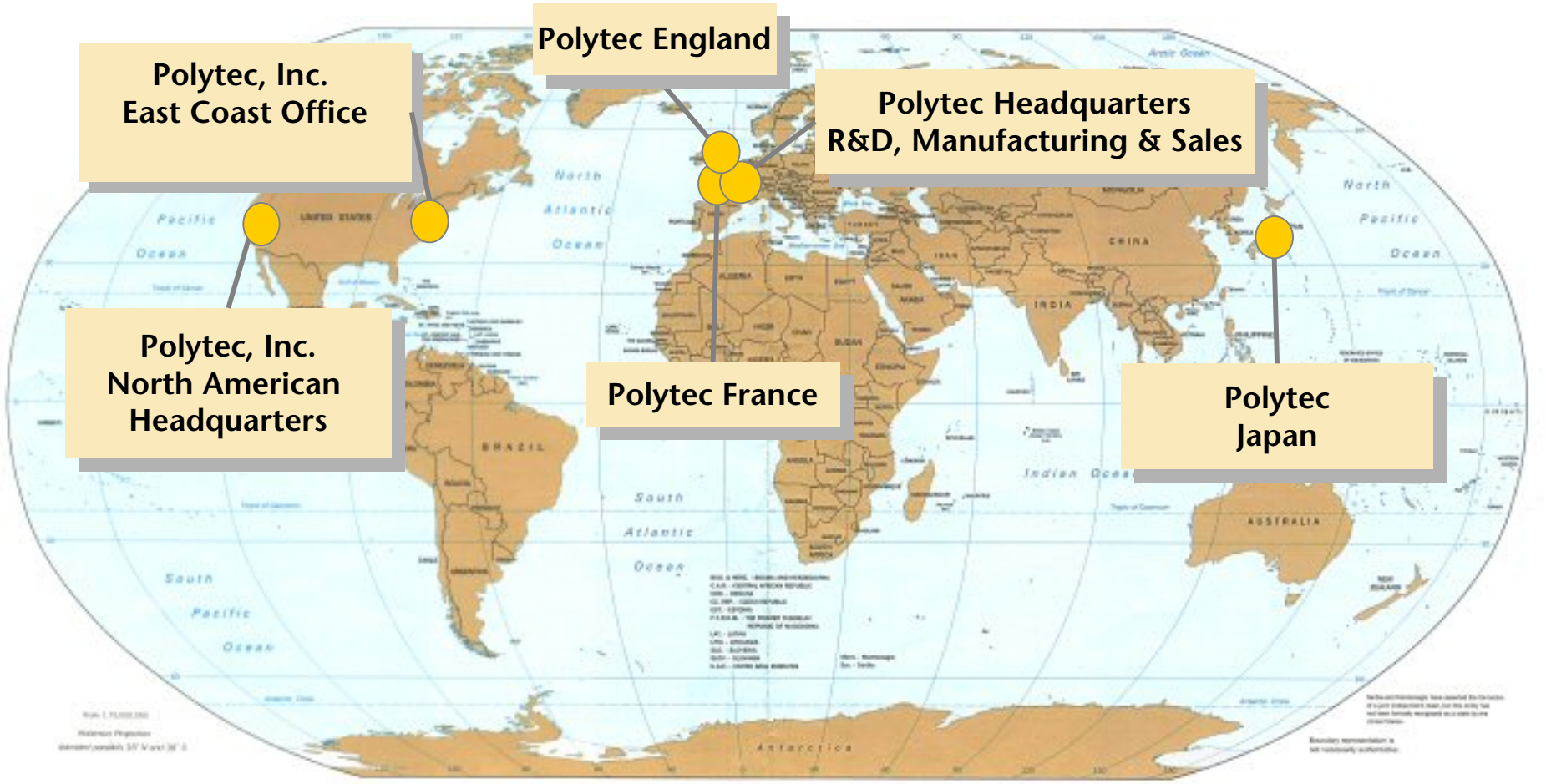
The Polytec Group



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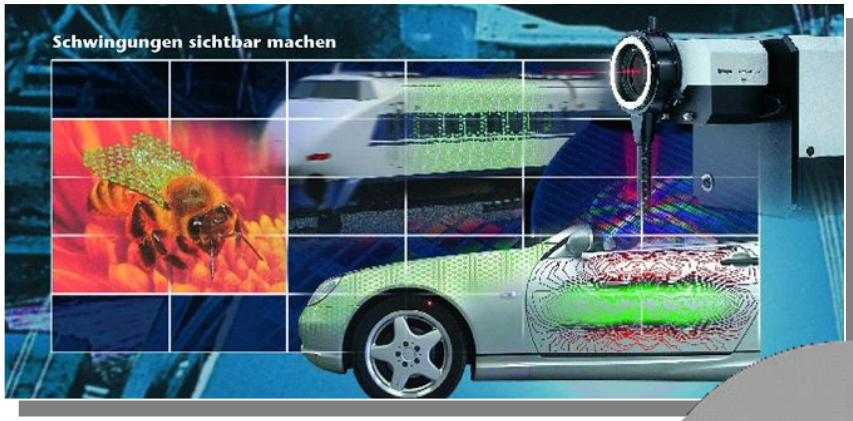
Business Units

Laser Measurement Systems



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Spectral Technologies

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Laser Measurement Systems

- **Laser Doppler Vibrometer** Non-contact Vibration Measurement
- **Laser Surface Velocimeter** Measurement of Speed and Length
- **PNA Polytec Noise Analysis** Production Line Monitoring and Control
- **Surface Metrology**

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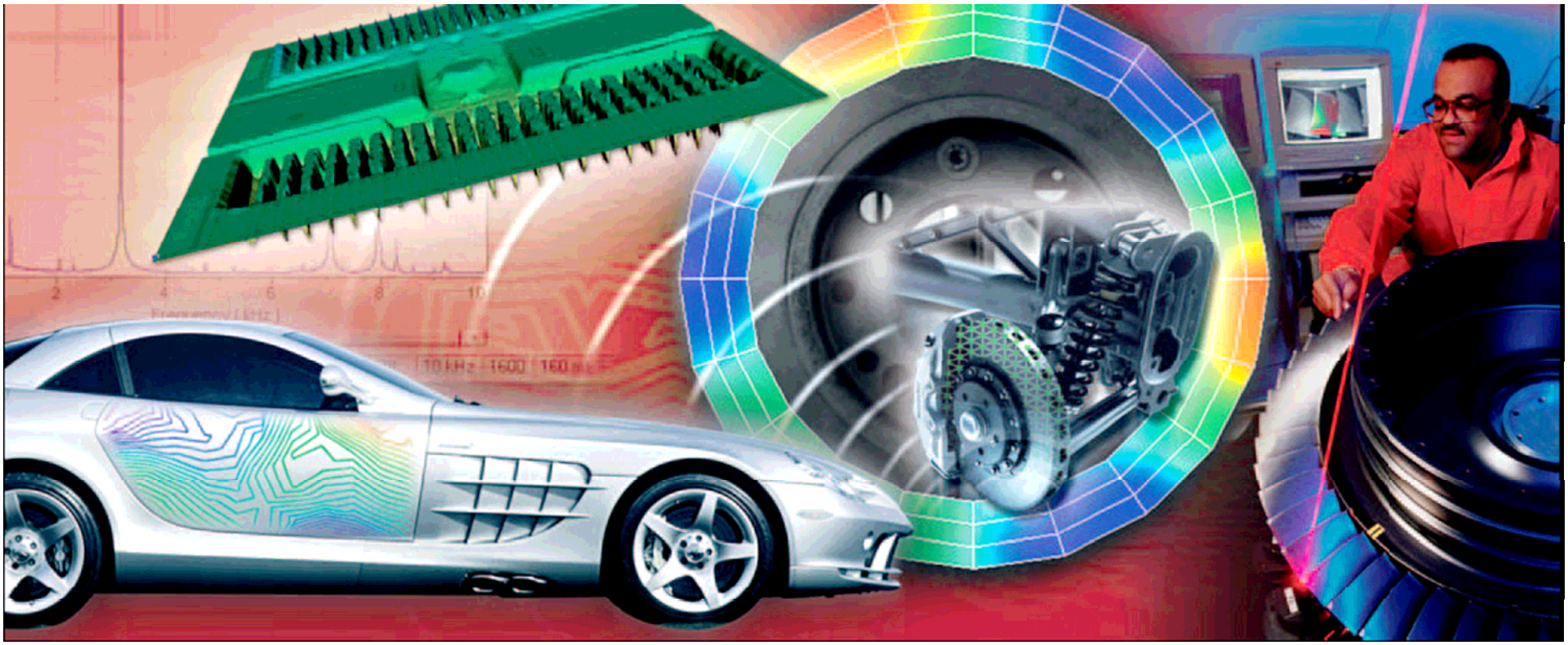
Laser Measurement Systems



Measuring Vibrations

- Single Point or Full Field Scanning
- 1- or 3-dimensional
- on Macro- and Microstructures
- in R&D and Production Environments

Applications

- Automotive
- Aerospace
- Data Storage
- Microsystems
- Transportation
- Engineering
- Audio and Acoustics
- Biology and Medicine
- ... and your field!

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What Advantages does non-contact optical Vibration Measurement offer?

- **Optical**
  - ➡ Non-contact laser sensor
- **Non-contact**
  - ➡ Be independent from object and material properties, especially suited to measure on critical objects, like soft, filigran, fissured, hot or hazardous structures
  - ➡ Reactionless measurement
  - ➡ No cabling
- **Sensor: Light**
  - ➡ Arbitrary number of channels: Scanning
  - ➡ Enormous frequency badwidth
  - ➡ Extreme sensitivity: ➡ nm ➡ pm
  - ➡ Far-distance measurements
  - ➡ Measure at locations difficult to access

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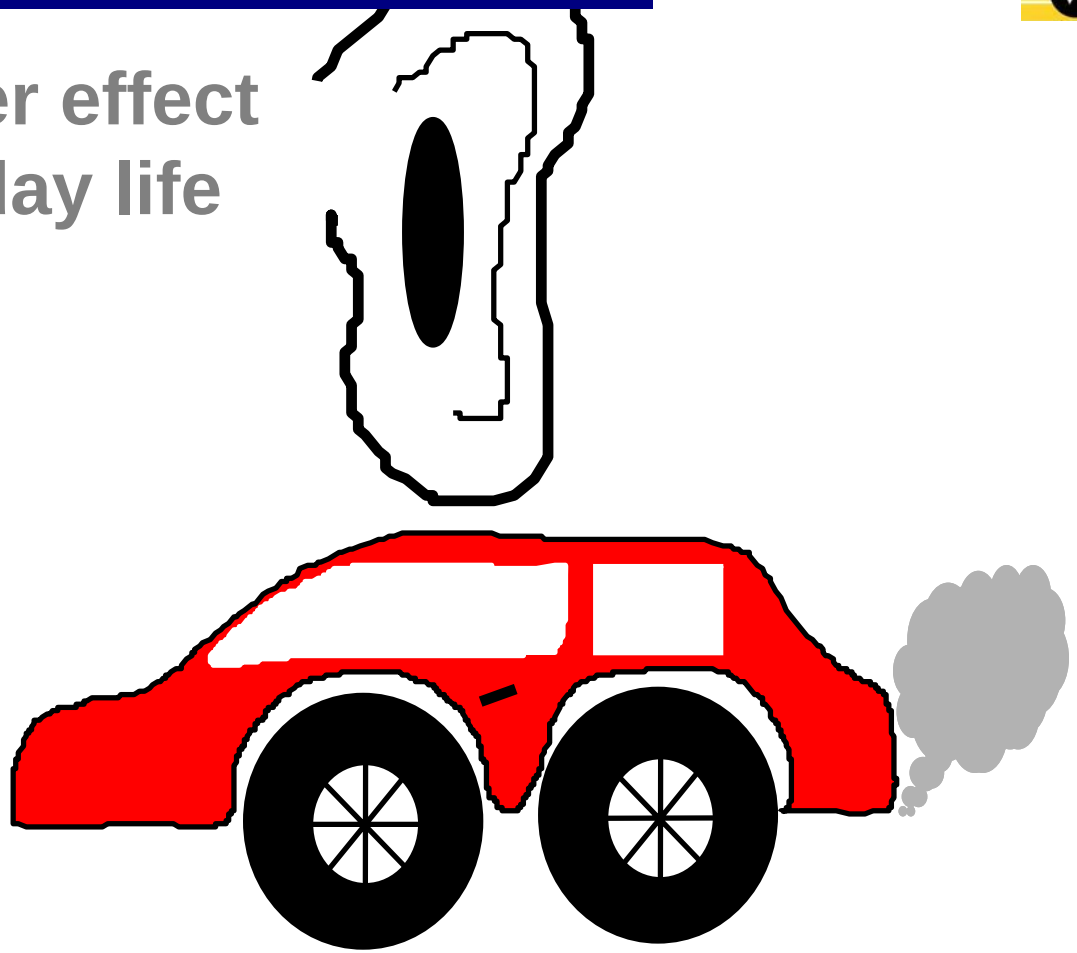
The Doppler effect in every day life



Frequency shift can be heard directly

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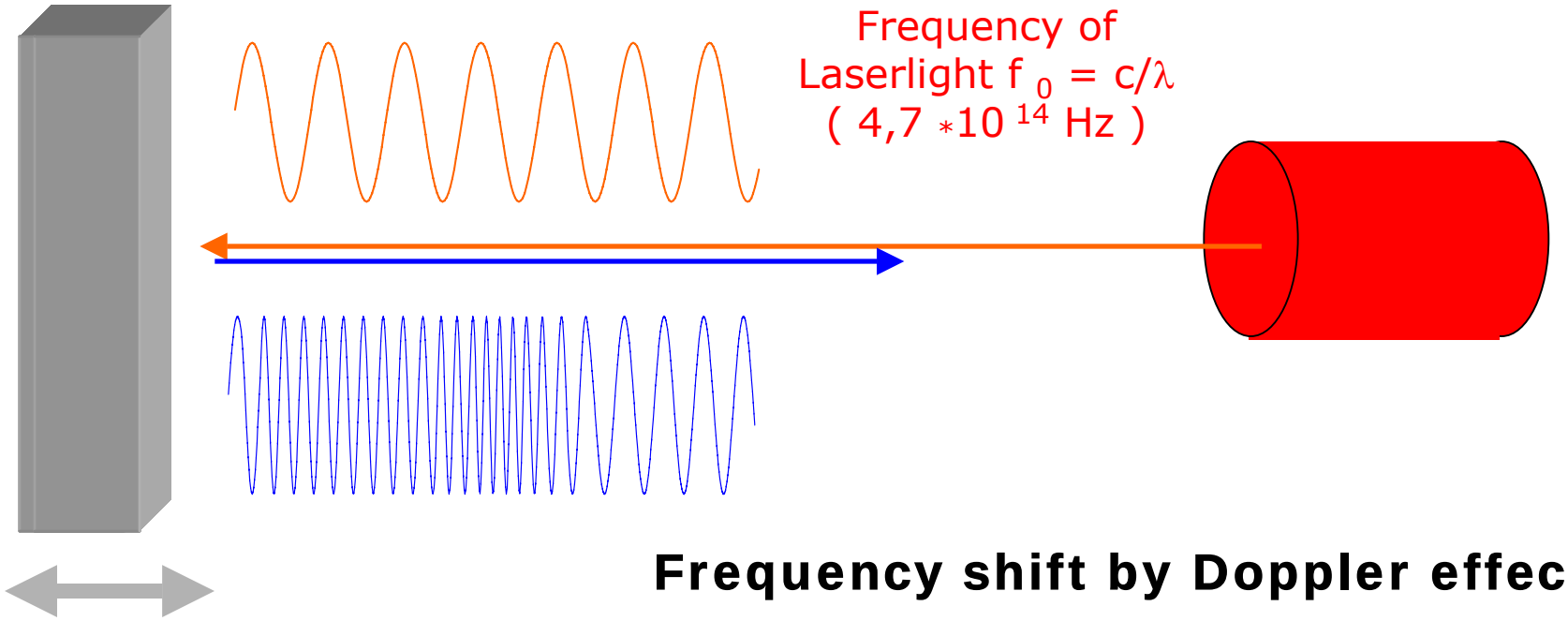
The Doppler Effect with Laser Light

vibrating object

He-Ne Laser
<1 mW (633 nm)



Frequency shift by Doppler effect

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The relation between Doppler frequency, Laser wavelength and velocity is

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

For the He-Ne Laser this can be written as

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

λ= 632,8 nm

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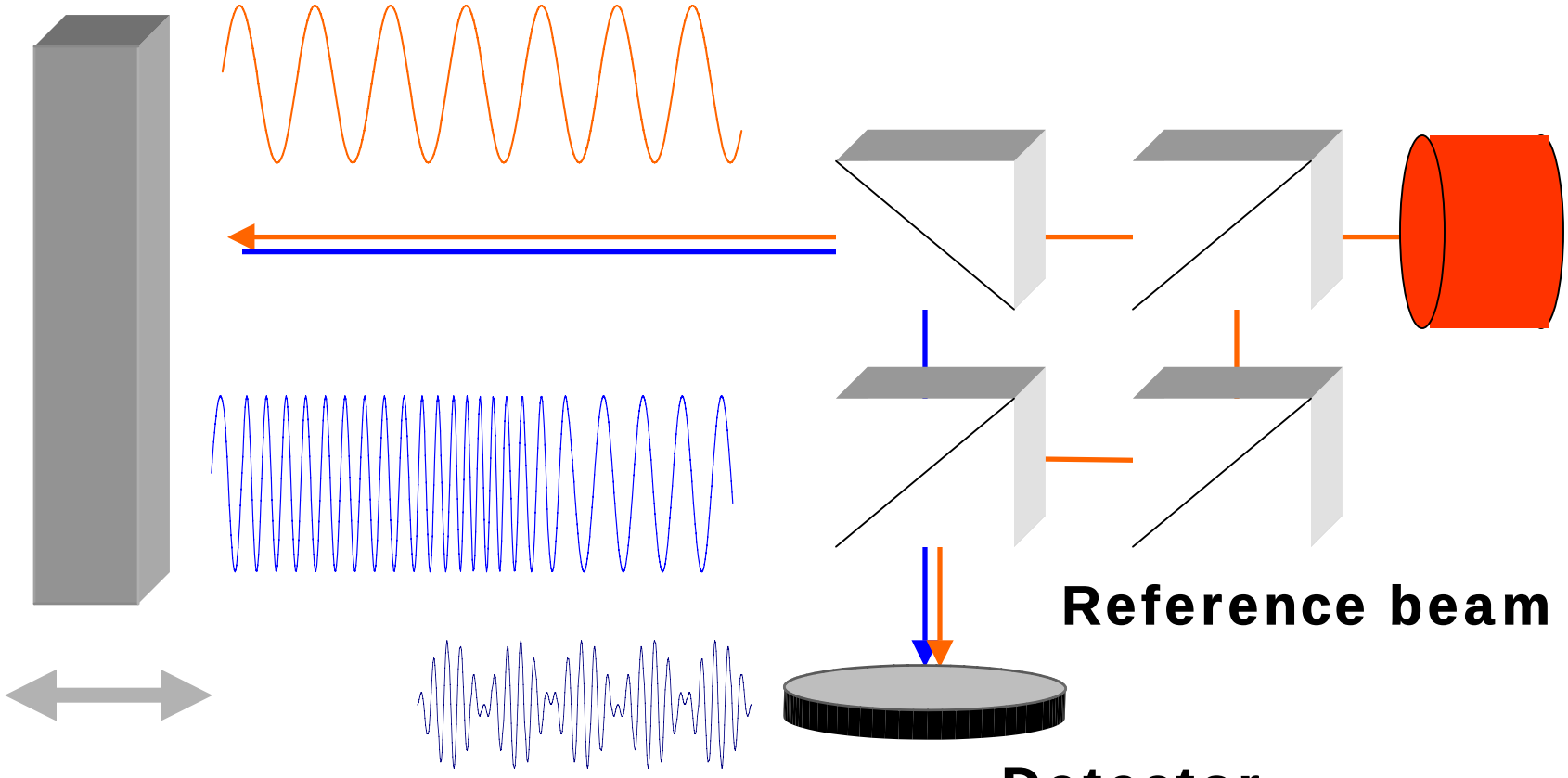
How does a Vibrometer operate?



$$\cos[2\pi(\pm f_D)t]$$

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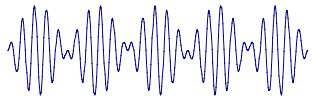
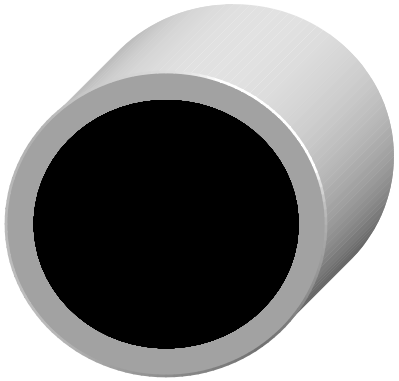
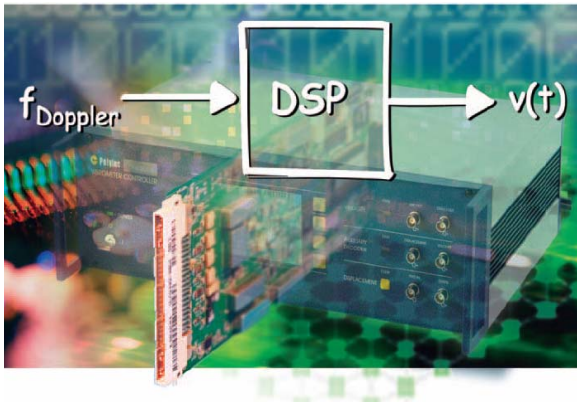




On the **detector** occurs a **bright-dark signal** which has exactly the Doppler frequency

The **detector** converts the **optical signal** to an **electronical signal,** this is demodulated by the **decoder**

On a BNC connector a voltage signal **proportional to the vibration velocity** is available



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The bright-dark modulation signal at the detector can be evaluated in two different ways:

- **Velocity measurement (analog or digital)**

Electronic signal processing converts the Doppler frequency shift - which is proportional to the velocity - into a proportional voltage signal.

- **Displacement measurement (digital process)**

The displacement of the structure changes the optical length of one interferometer arm and introduces a phase shift, proportional to the displacement.

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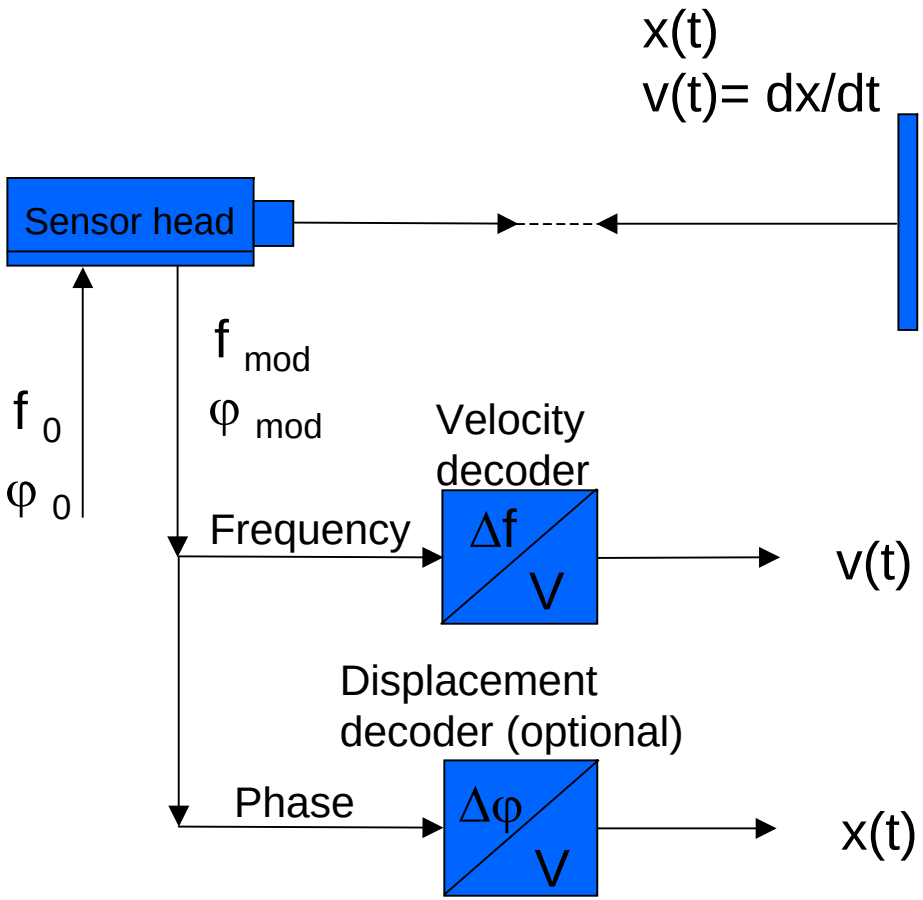
Signal Demodulation



The interferometer compares phase φ_{mod} and frequency f_{mod} of the object beam with those of the internal reference beam (f_0 and φ_0). Displacement is derived by measuring the phase change and velocity by measuring the frequency.

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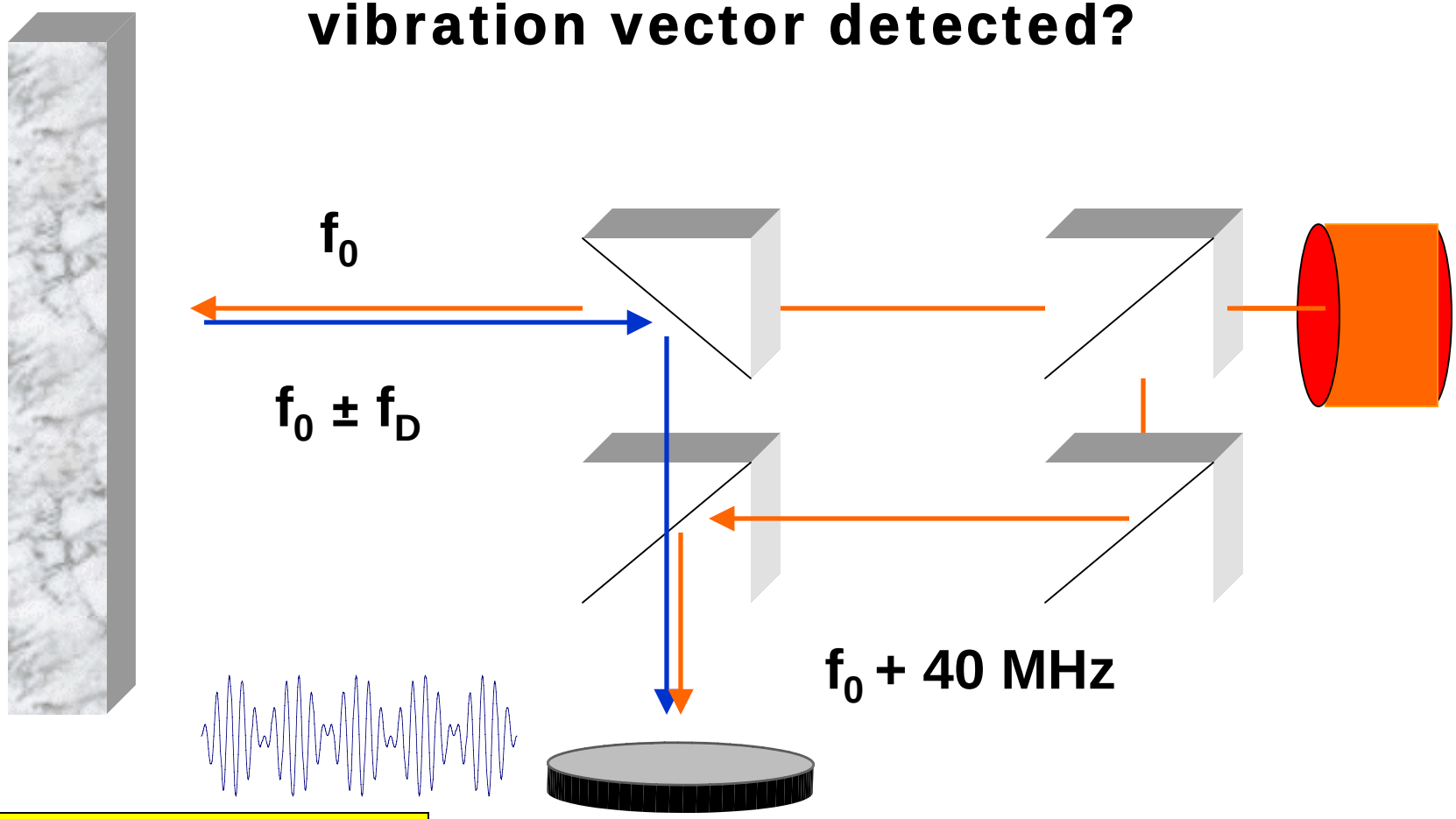
What happens at object velocity v = 0 and how is the direction of the vibration vector detected?



$\cos[2\pi(\pm f_D)t]$

detector with carrier signal

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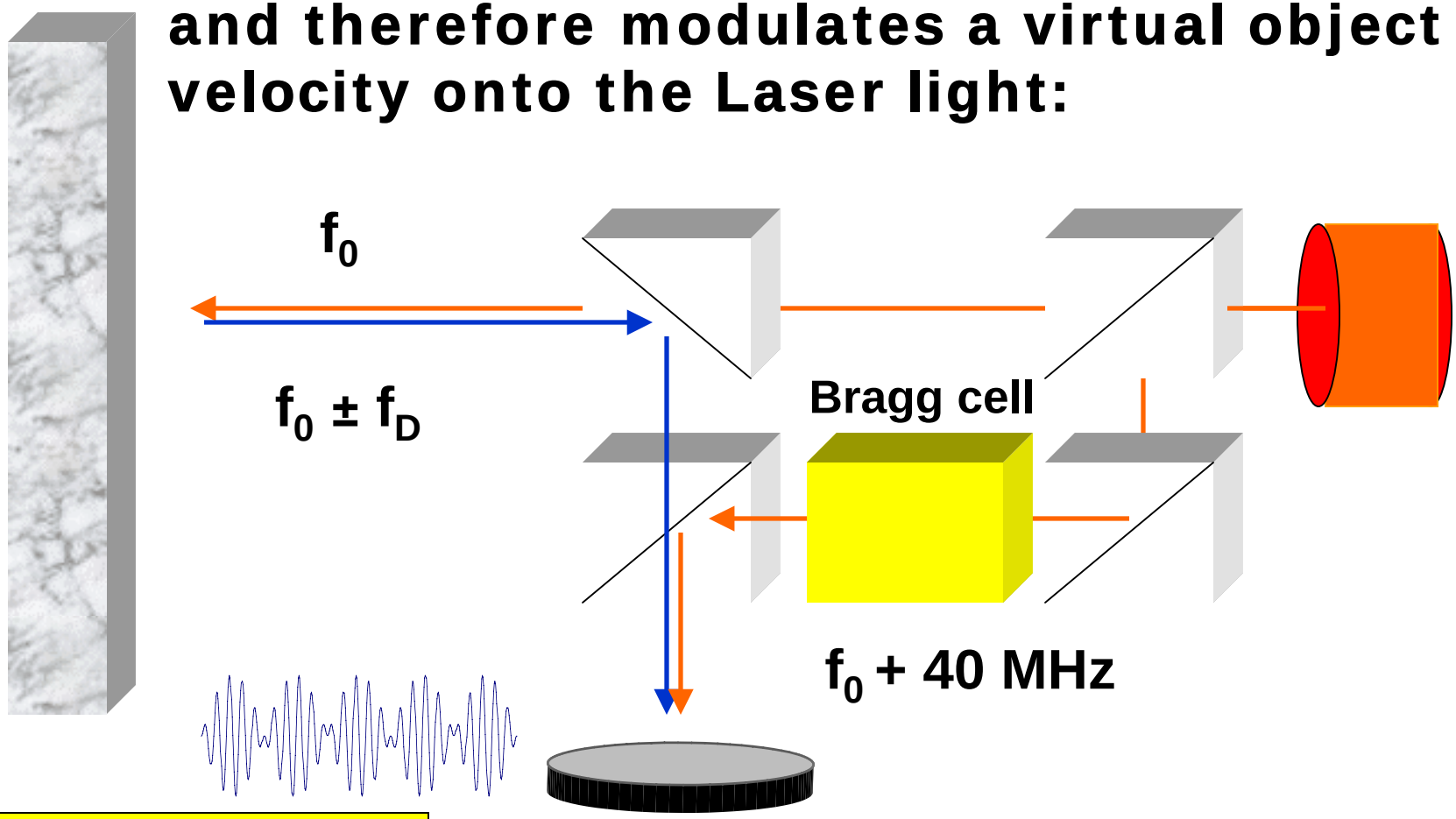
A Bragg cell introduces a constant frequency shift f_B in the reference beam and therefore modulates a virtual object velocity onto the Laser light:



$$\cos[2\pi(f_B \pm f_D)t]$$

detector with carrier signal

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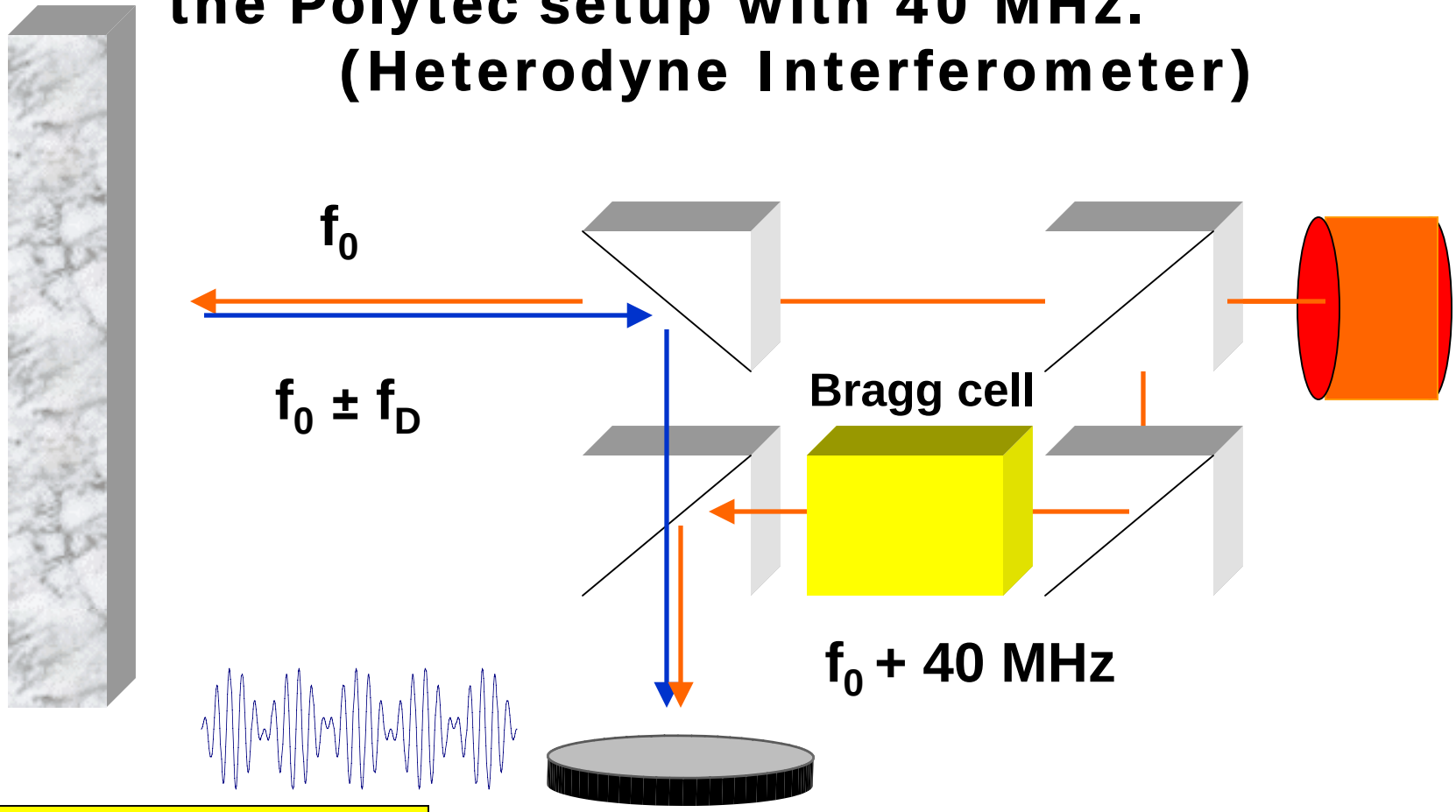
The Bragg cell is positioned in the path of the reference beam and is modulated in the Polytec setup with 40 MHz. (Heterodyne Interferometer)



$$\cos[2\pi(f_B \pm f_D)t]$$

detector with carrier signal

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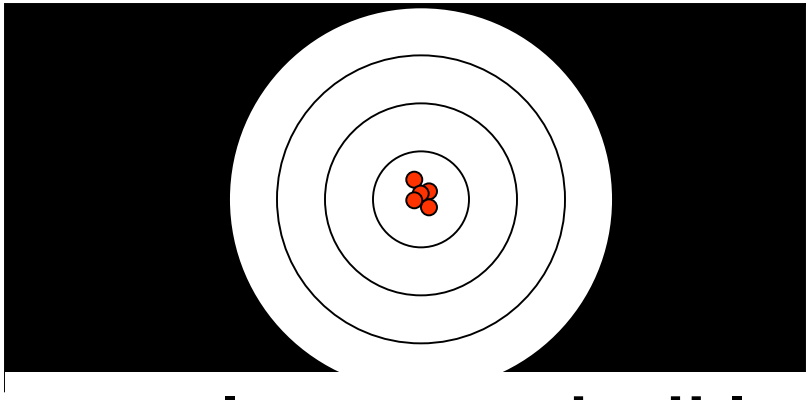
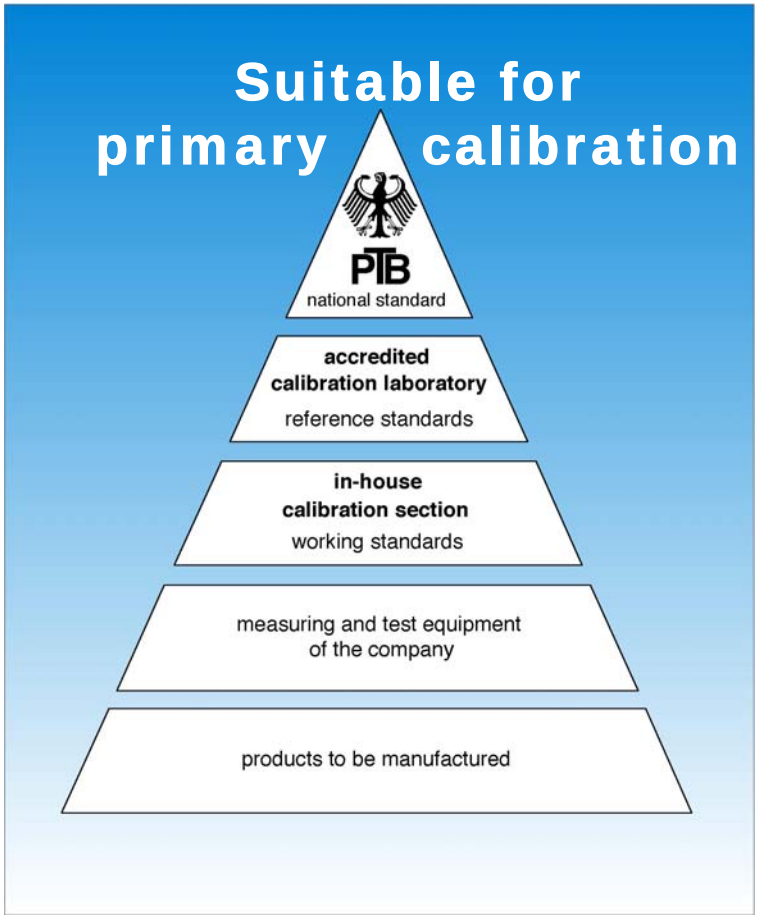
Key Features



exactly + reproducible



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Where is Vibrometry used?

The applications are unlimited!

The measurement ranges cover almost all technical relevant mechanical vibrations.

f	**Frequency:**	0 Hz – 30 MHz	
$dr(t)/dt$	**Velocity:**	50 nm/s–30 m/s (9 Decades)	
$\Delta r(t)$	**Displacement:**	2 pm – 10 m	(13 Decades)
$d^2r(t)/dt^2$	**Acceleration:**	10^{-8} g – 10^{7} g	(15 Decades)

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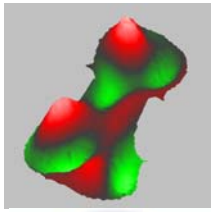
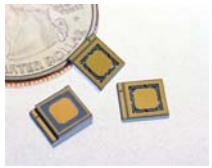
Where is Vibrometry used?

Laser vibrometry is especially beneficial where tactile sensors can not be used :



- Precise measurement of structural dynamics and structure borne sound
- No massloading, reactionless measurement
- Measurement of many sample points in a short time

- Measuring on sample points difficult to access
- Measurement on soft, filigran, jagged or hot structures



- Measurement on microstructures
- Acquisition of high frequencies

- Measurement from large distances
- Independent from material properties

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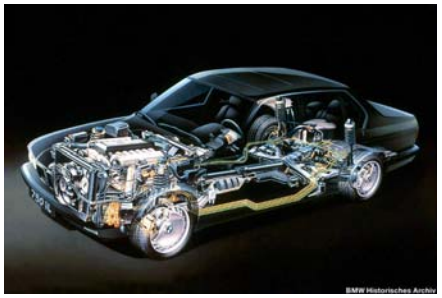
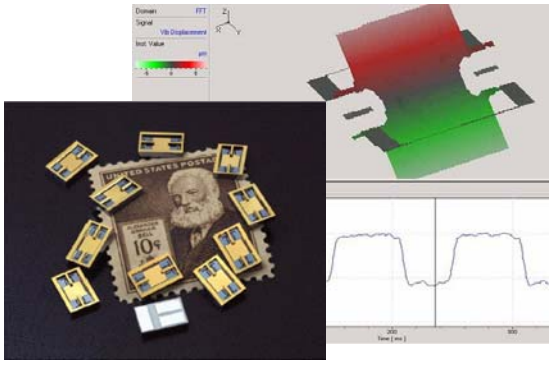
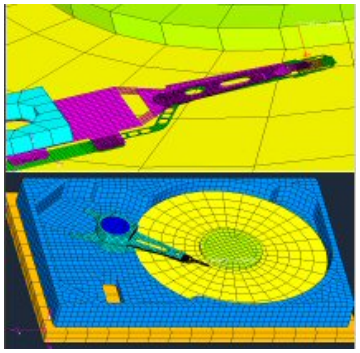
Where is Vibrometry used?



Here, and in many other application areas !





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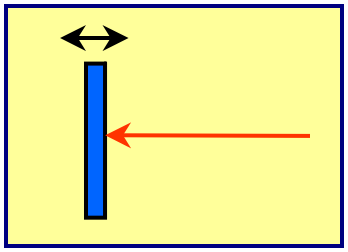
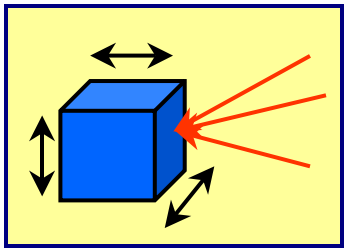
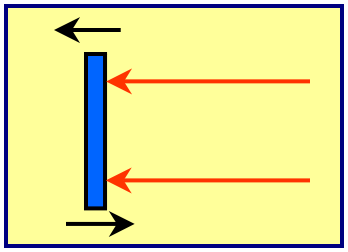
Vibrometer - Typology



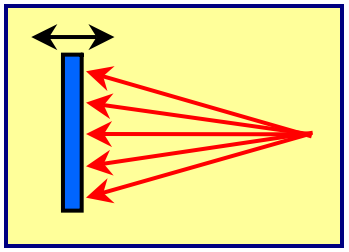
Out-of-Plane



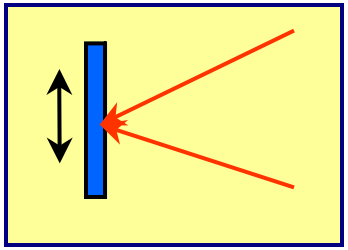
3D Vibrometer



Differential

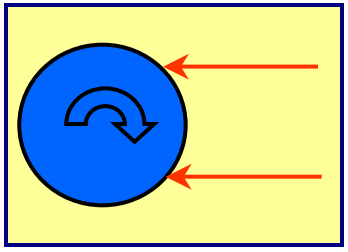


Scanning



In-plane

Scanning 3D



Rotational

↔ Motion — Measurement

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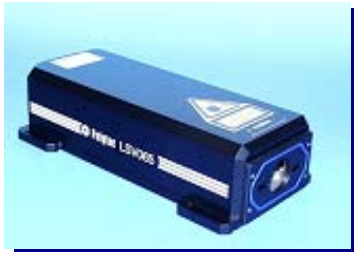
Vibrometer - Typology

Out-of-Plane

3D Vibrometer

Differential

Scanning



In-plane

Rotational

Scanning 3D

↔ Motion ← Measurement

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Modular Vibrometer Platform

OFV-5000

Modular Vibrometer Controller

OFV-505

Single-Point Sensor Head

OVF-551/552

Fiber-Optical Interferometer

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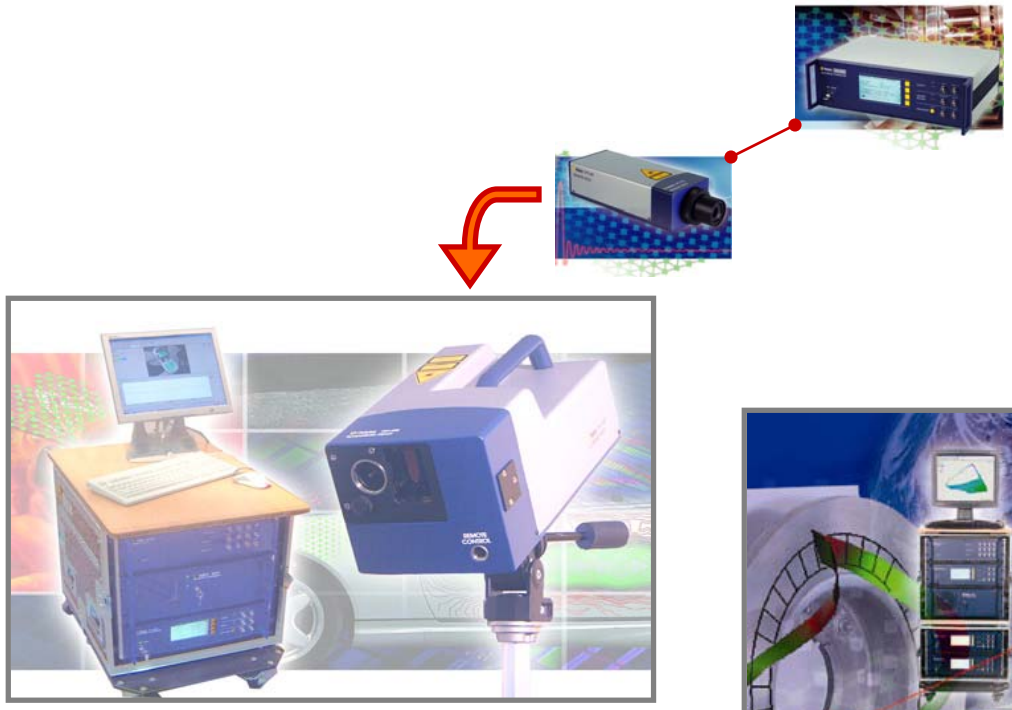
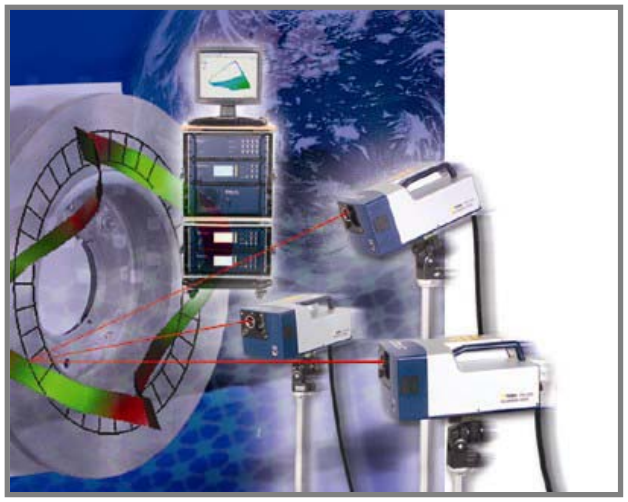
Scanning Vibrometer



PSV-400

Polytec Scanning Vibrometer



PSV-400-3D

3D Scanning Vibrometer

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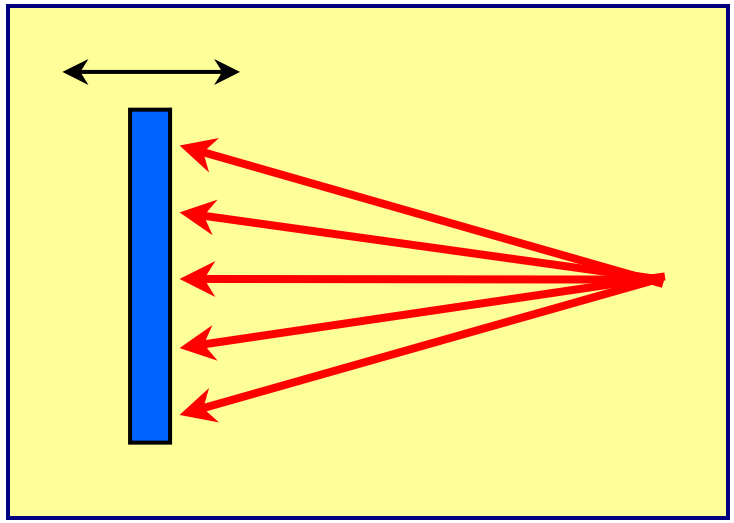
Scanning Vibrometer

Gain insight into structural dynamics and structure borne sound through full-field vibration measurement and mapping



- The measurement beam of the scanning vibrometer scans the testobject on a predefined grid.
- At each sample point a complete measurement is performed within milliseconds.
- The phase relation among the sample points is established through the simultaneous measurement of a reference signal (e.g. excitation).

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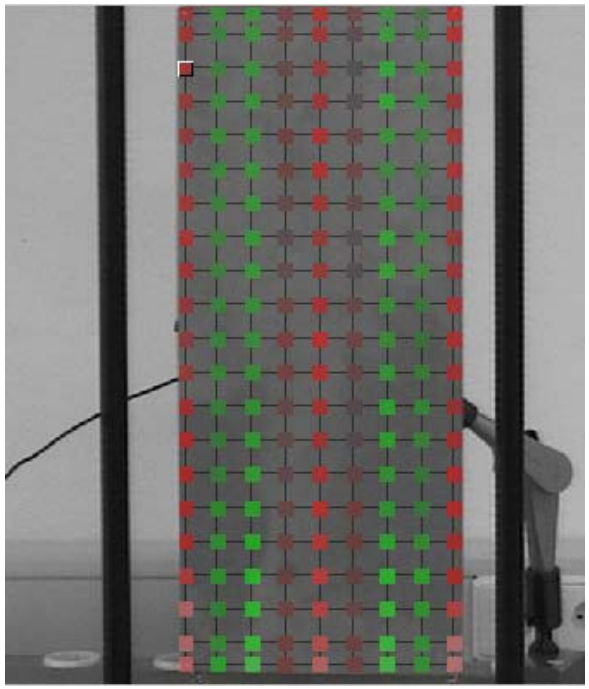
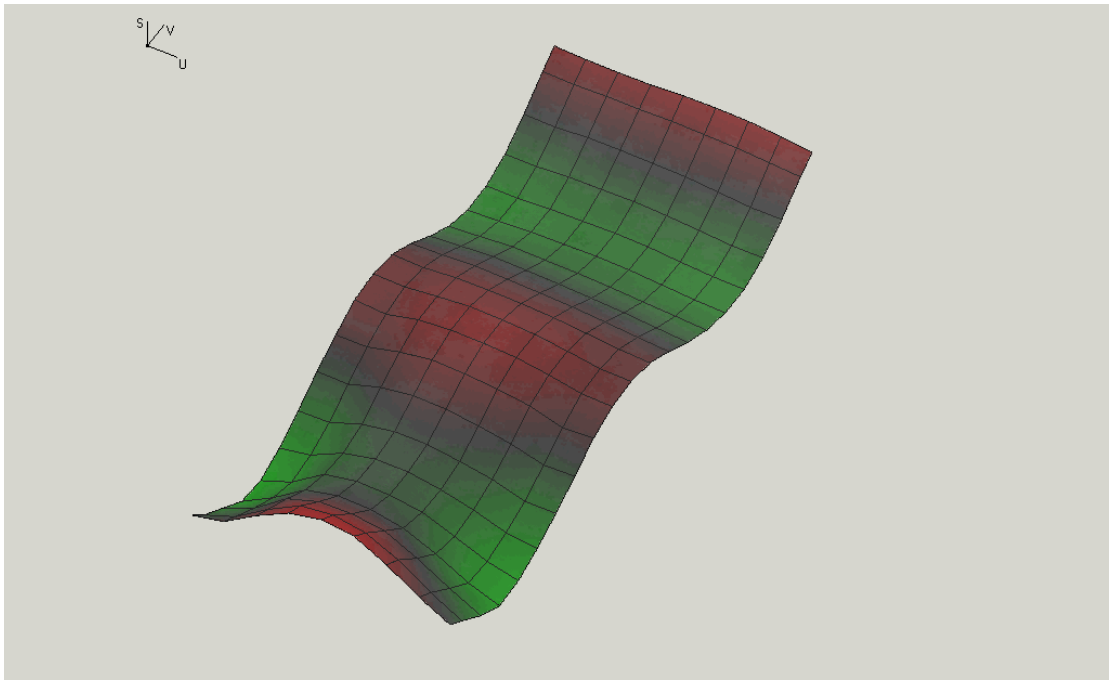
Full-Field Vibration Measurement





- Sample many scan points in a short time
- Up to 512 x 512 sample points in a grid
- Animated visualization of deflection shapes
- Intuitive and simple Operation

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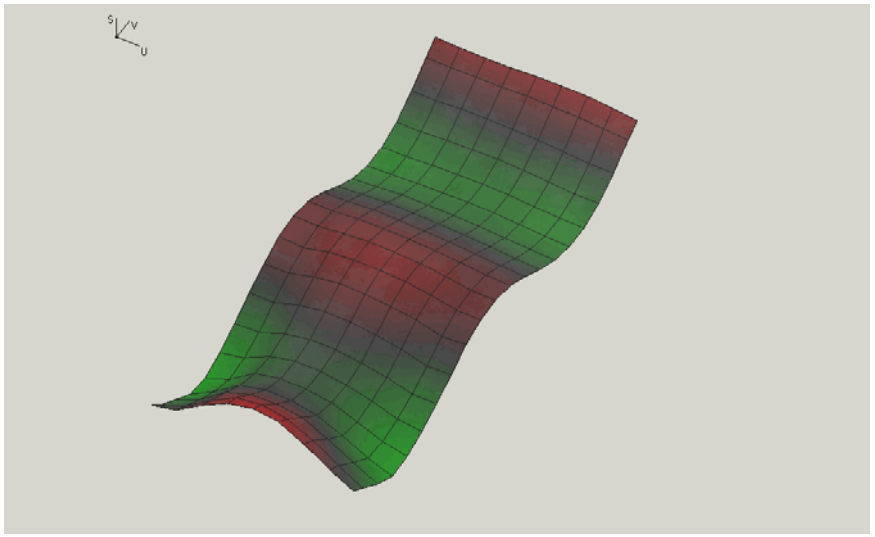
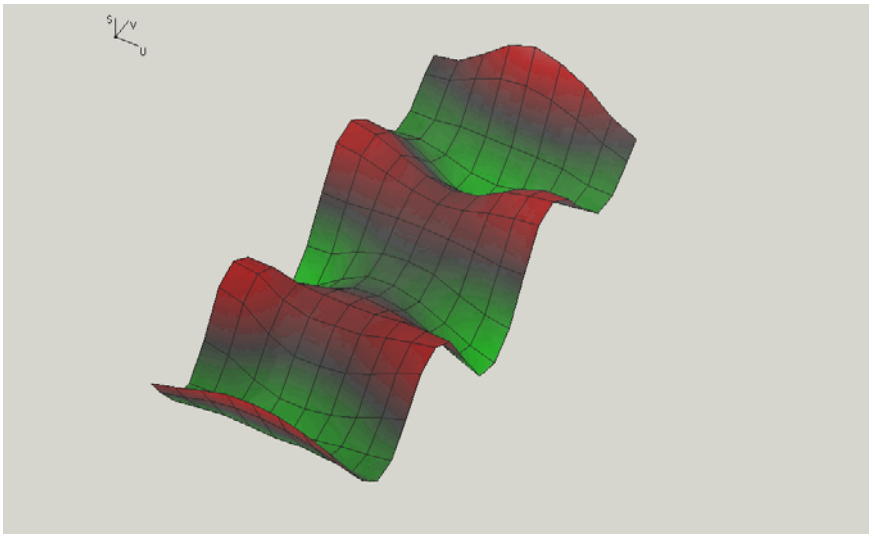
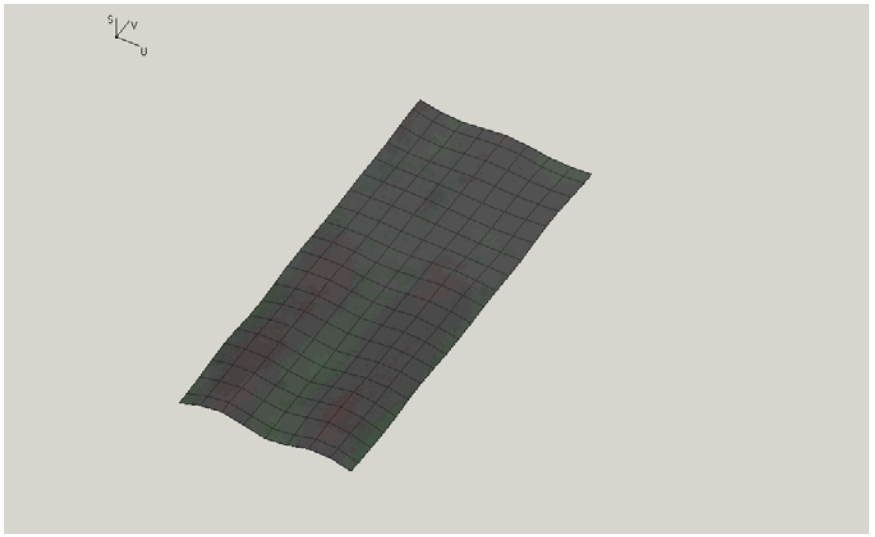
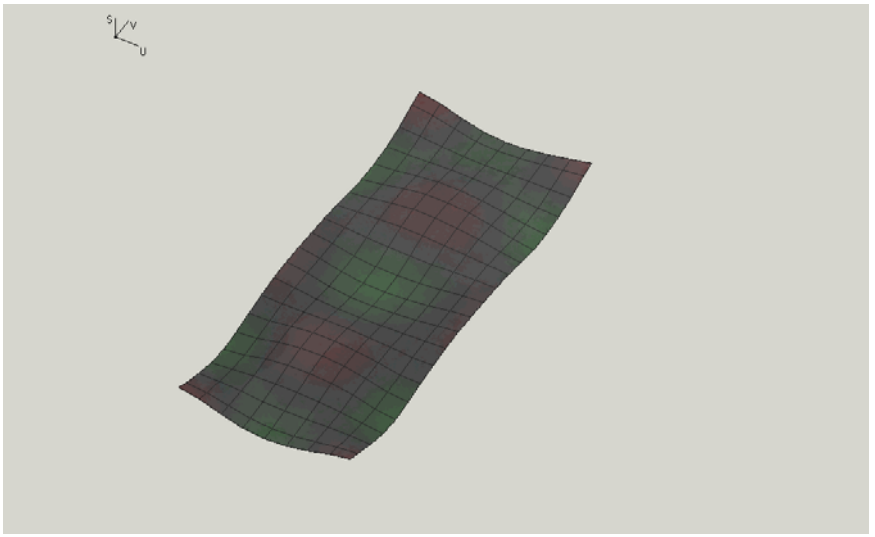
Operating Deflection Shapes









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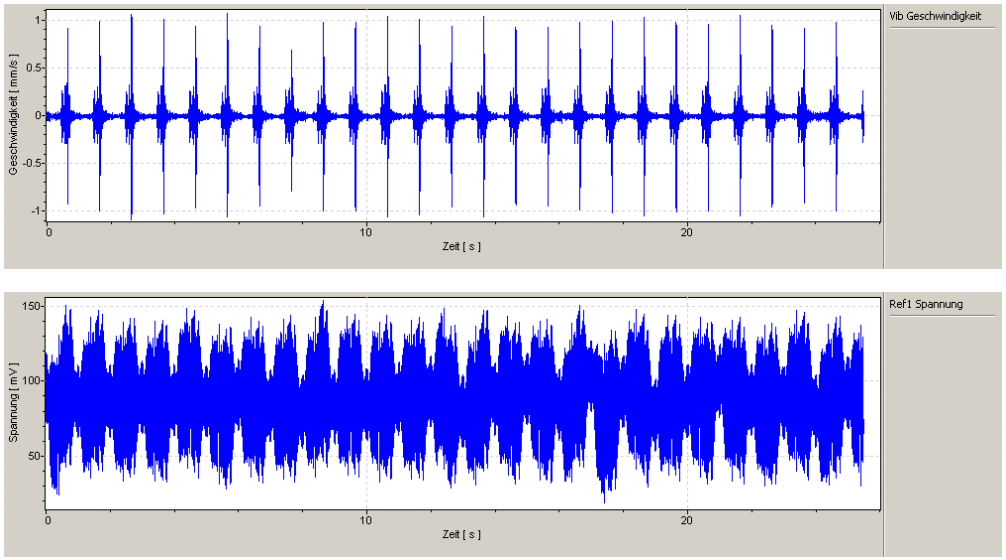
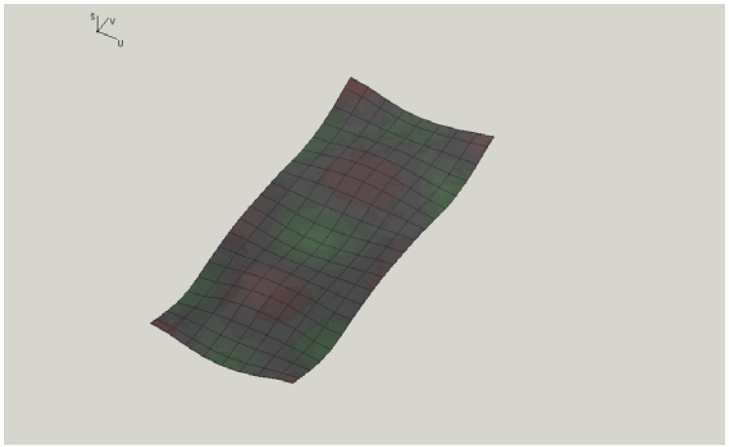
Principle of Operation





- **Measurement of v(t) at all scan points and subsequent FFT transformation**

- **Amplitude and *rel.* Phase at each sample point**
- **Deflection of the surface of the test object**

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Setup and Components

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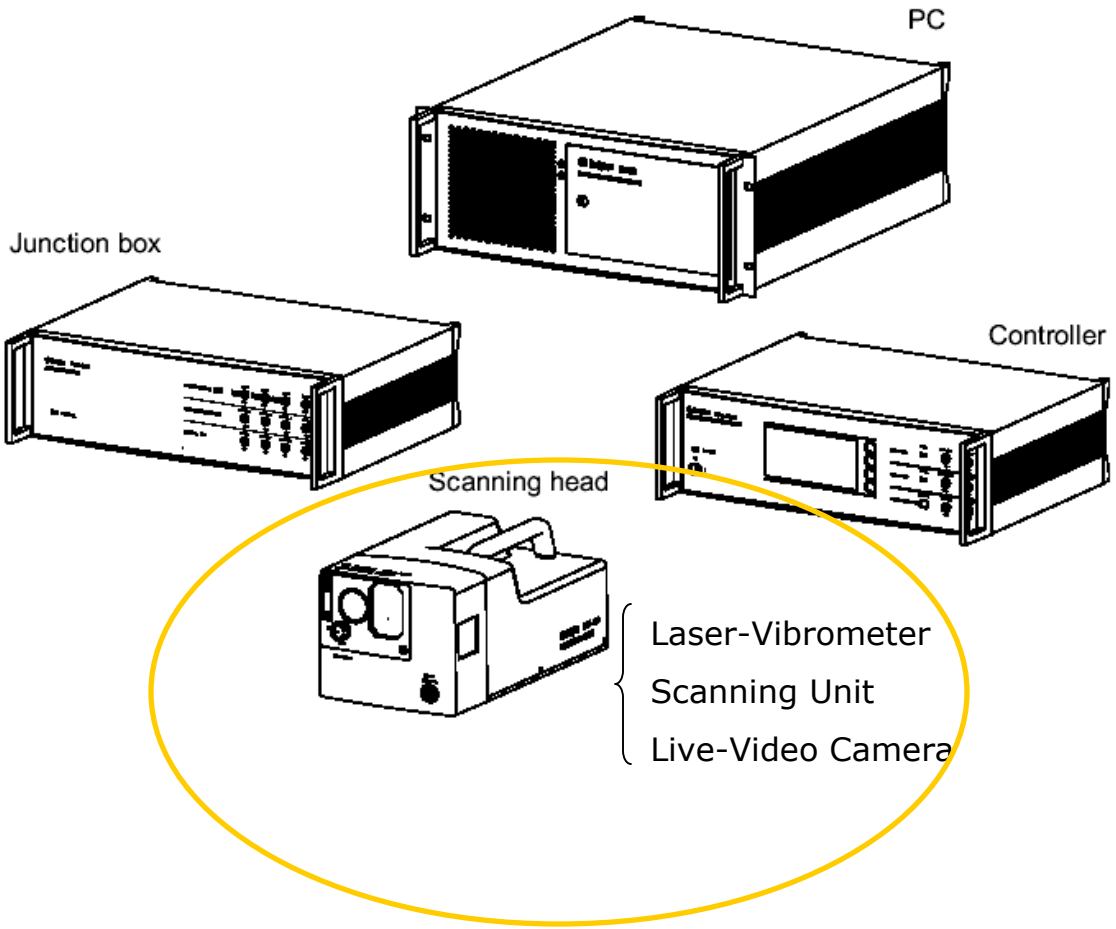
Setup and Components



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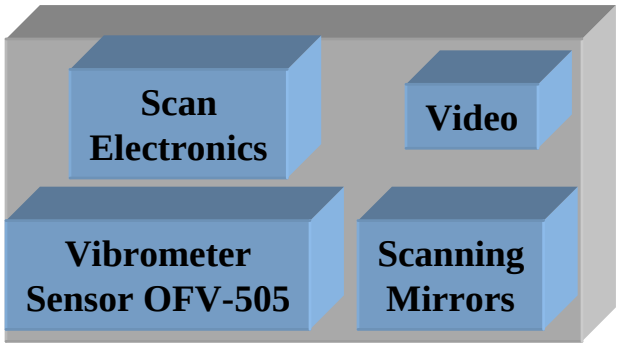
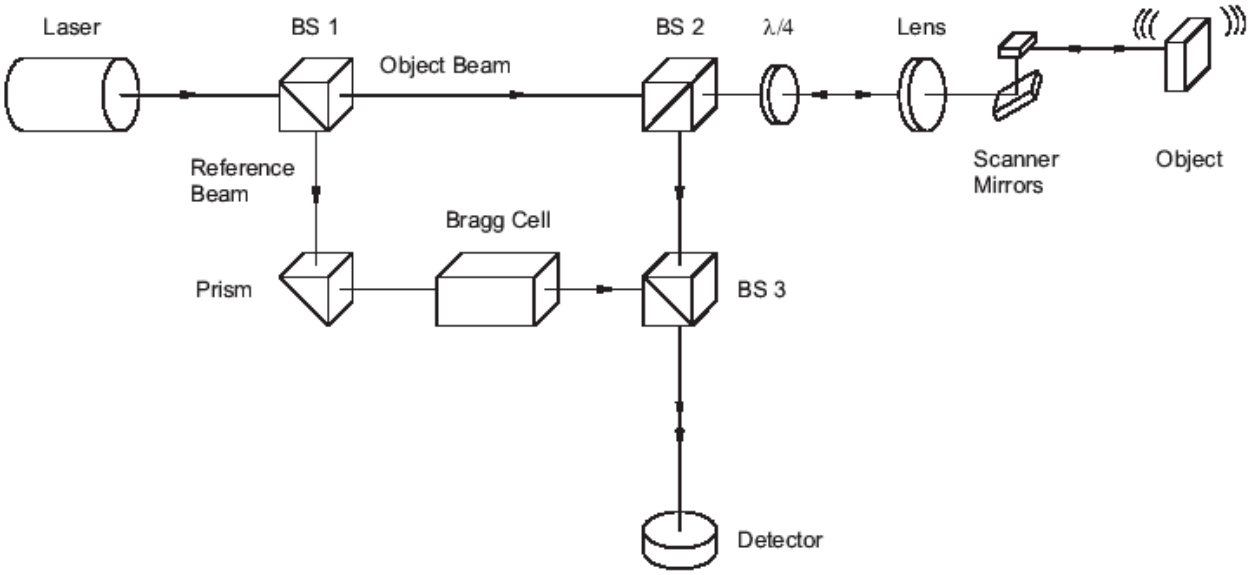
Setup of the PSV-I-400 Sensor





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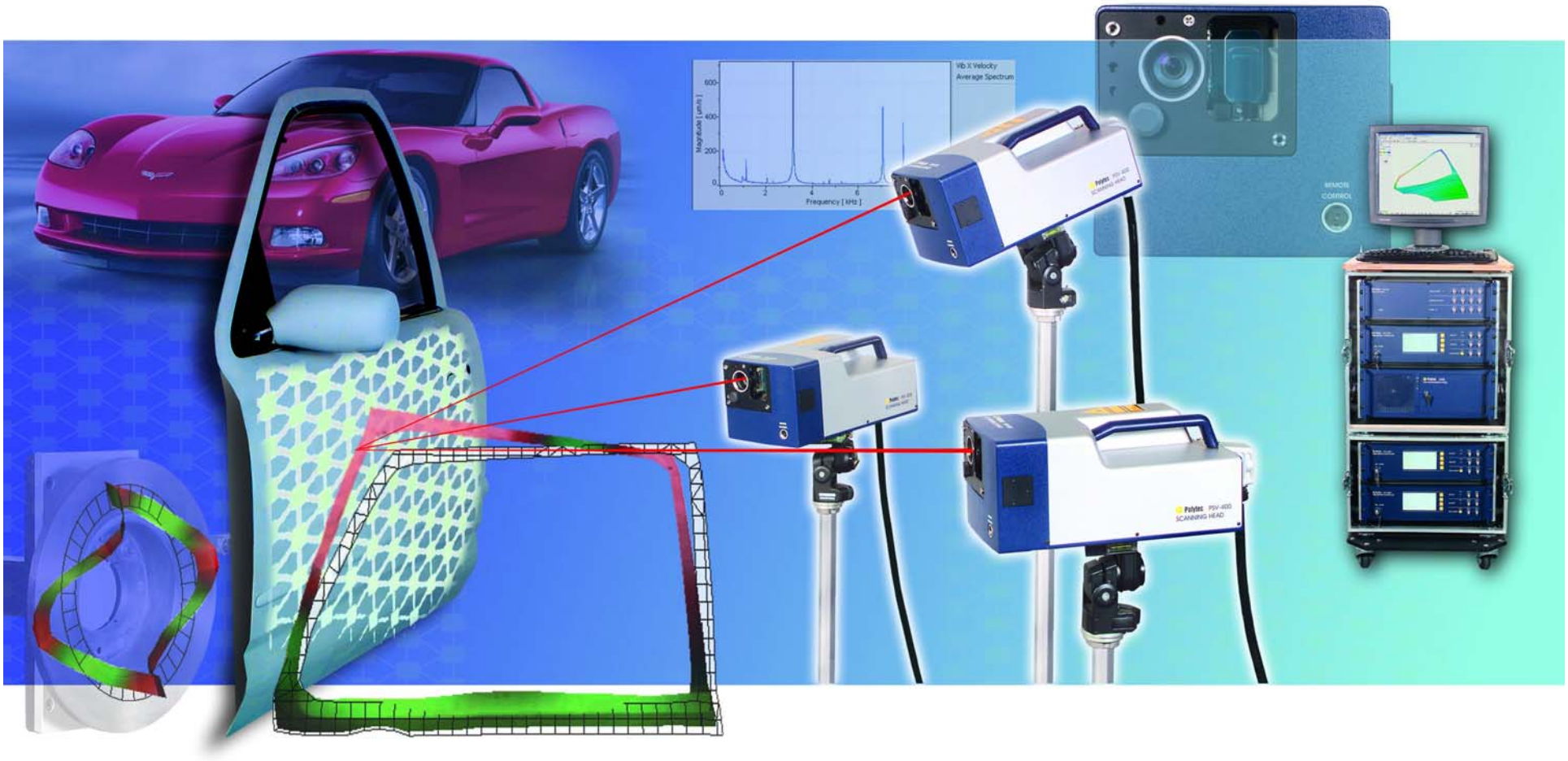
3D Scanning Vibrometer System



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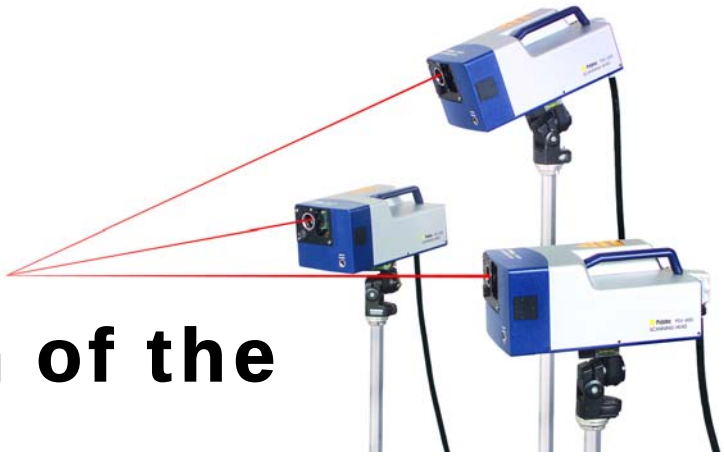
Benefits of a 3D Scanning System

- 3D data output for modal analysis
- Separation of in- and out-of plane results
- Simple sensor-to-object alignment
- High spatial resolution
- Fast
- No mass loading
- Intuitive 3-D animation of the measurement results



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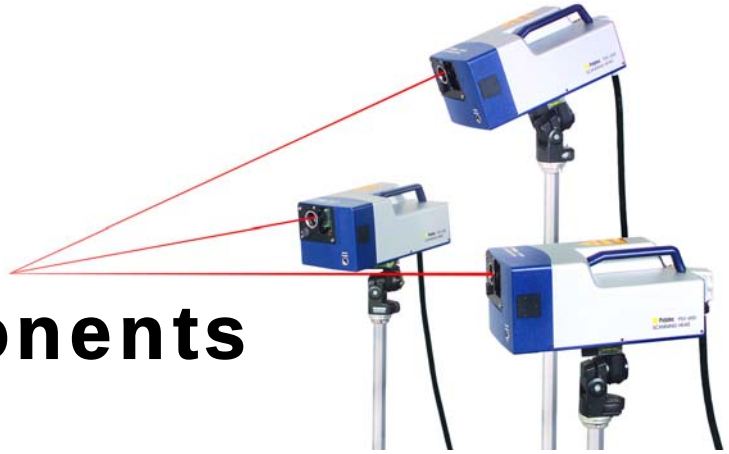
Function Principle of the 3D-SLDV

- 3 Vibrometers measure on the same point, each from a different direction



- Acquisition of all components of the vibration vector
- Measured data is transformed into the Cartesian coordinate system of the measured object

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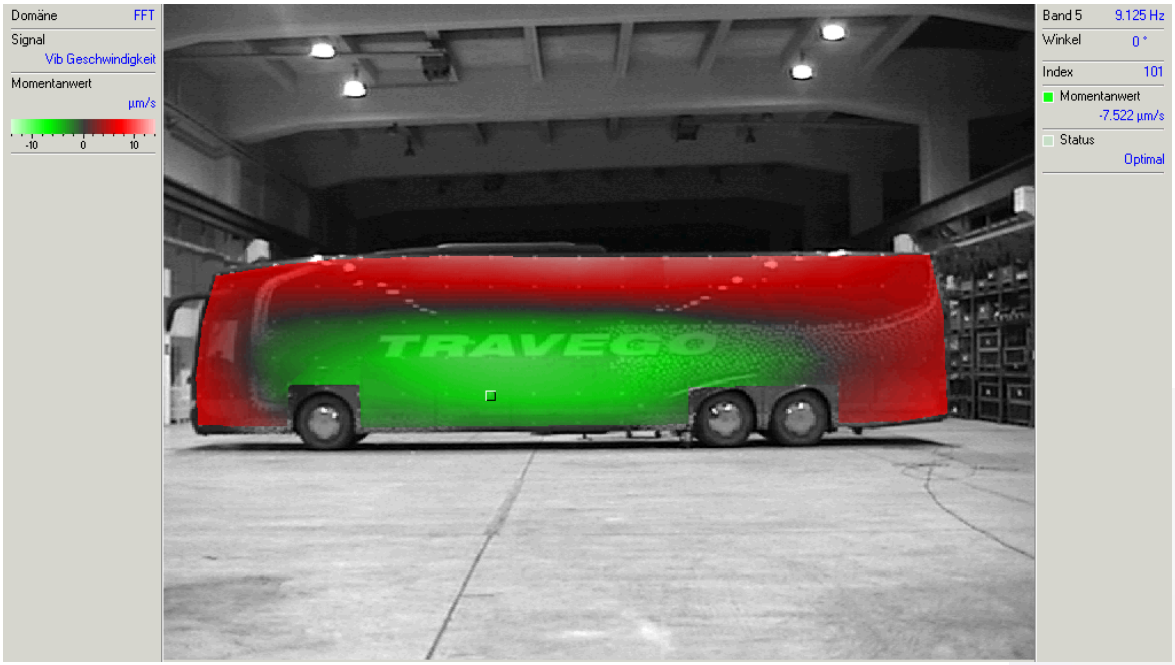
Car Body



PSV-400 Polytec Scanning Vibrometer

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Modal Test on Car Body

Excitation with electro dynamical Shaker
3D-Vibration Measurement with PSV-400-3D

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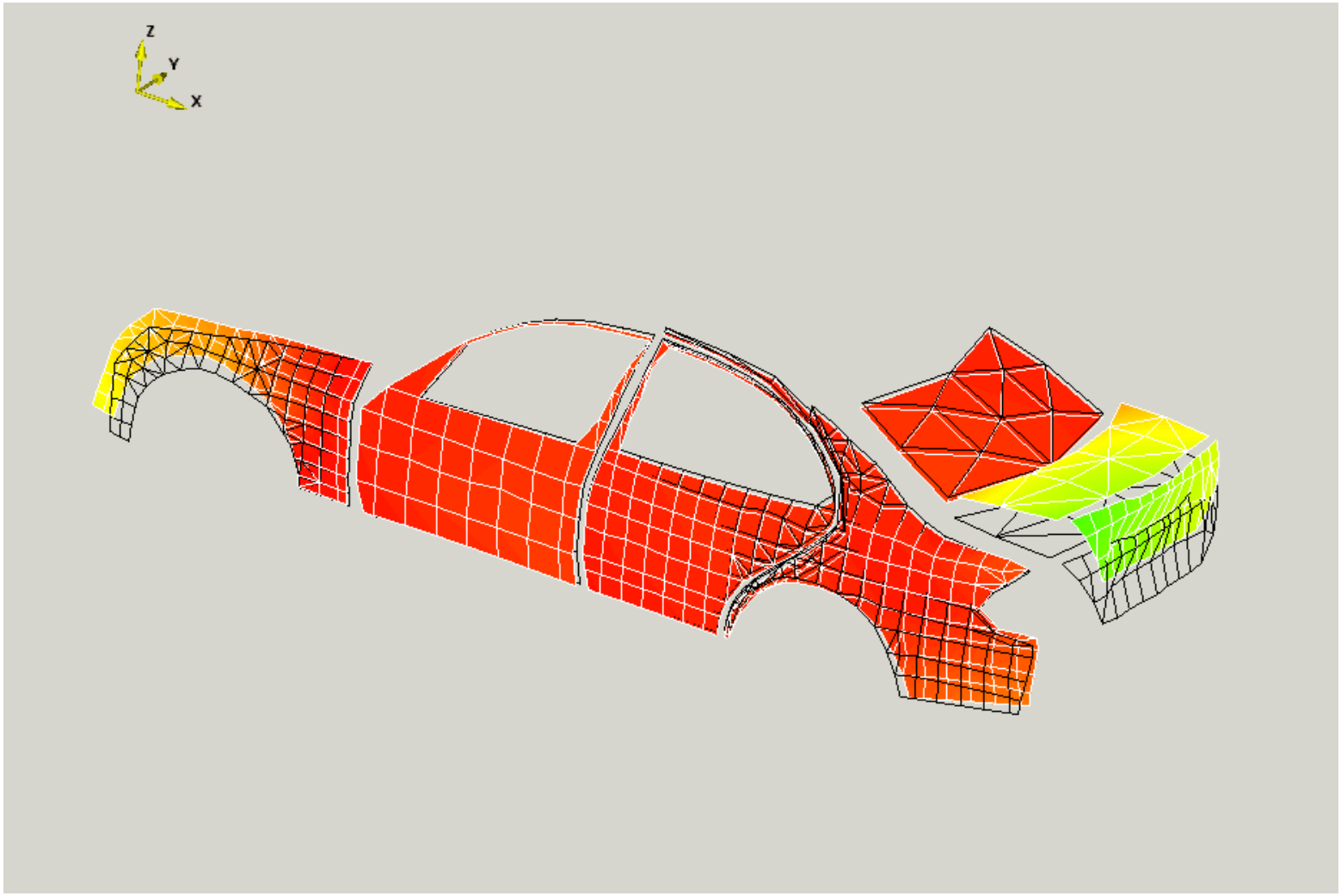
Deflection shape



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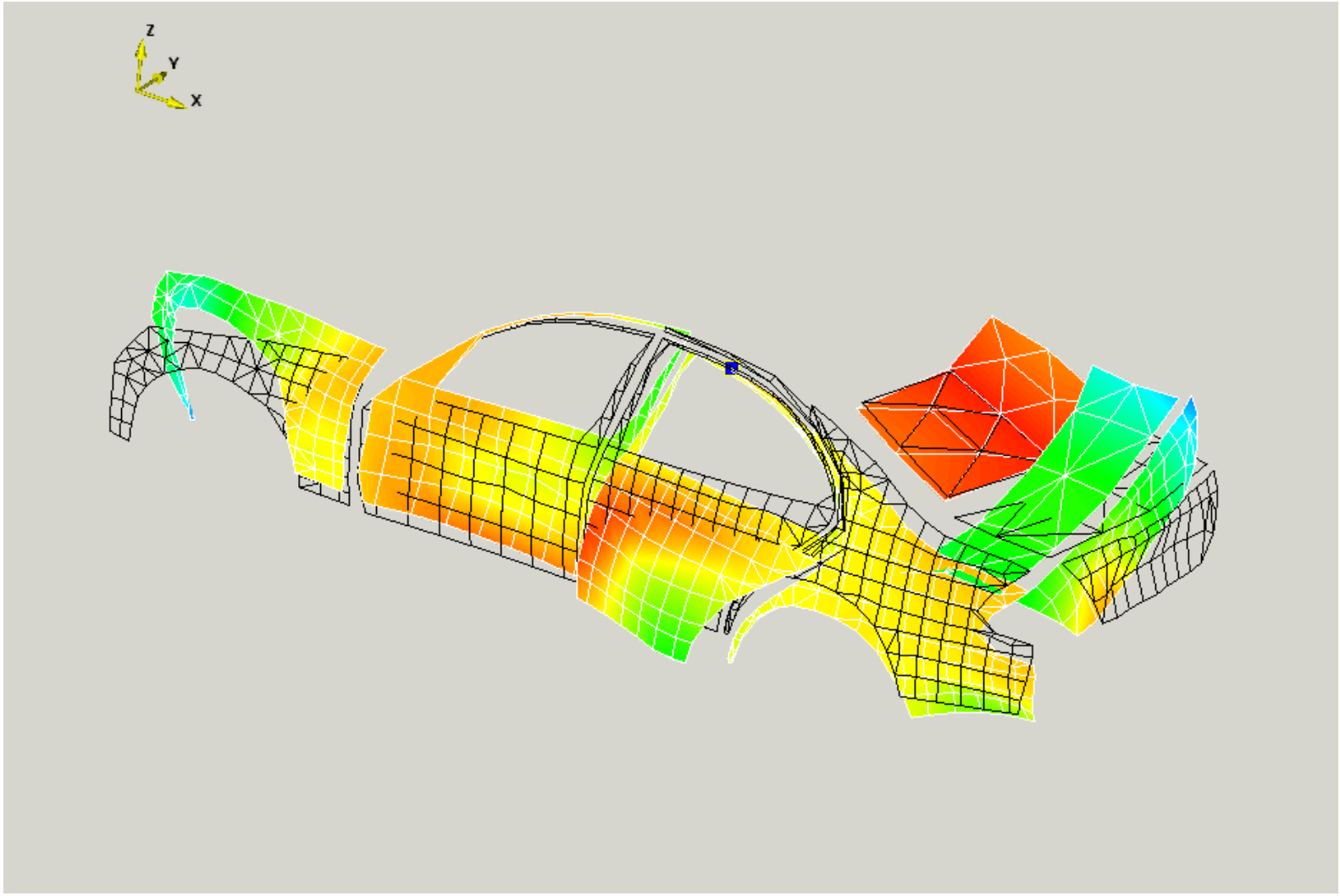
Deflection shape



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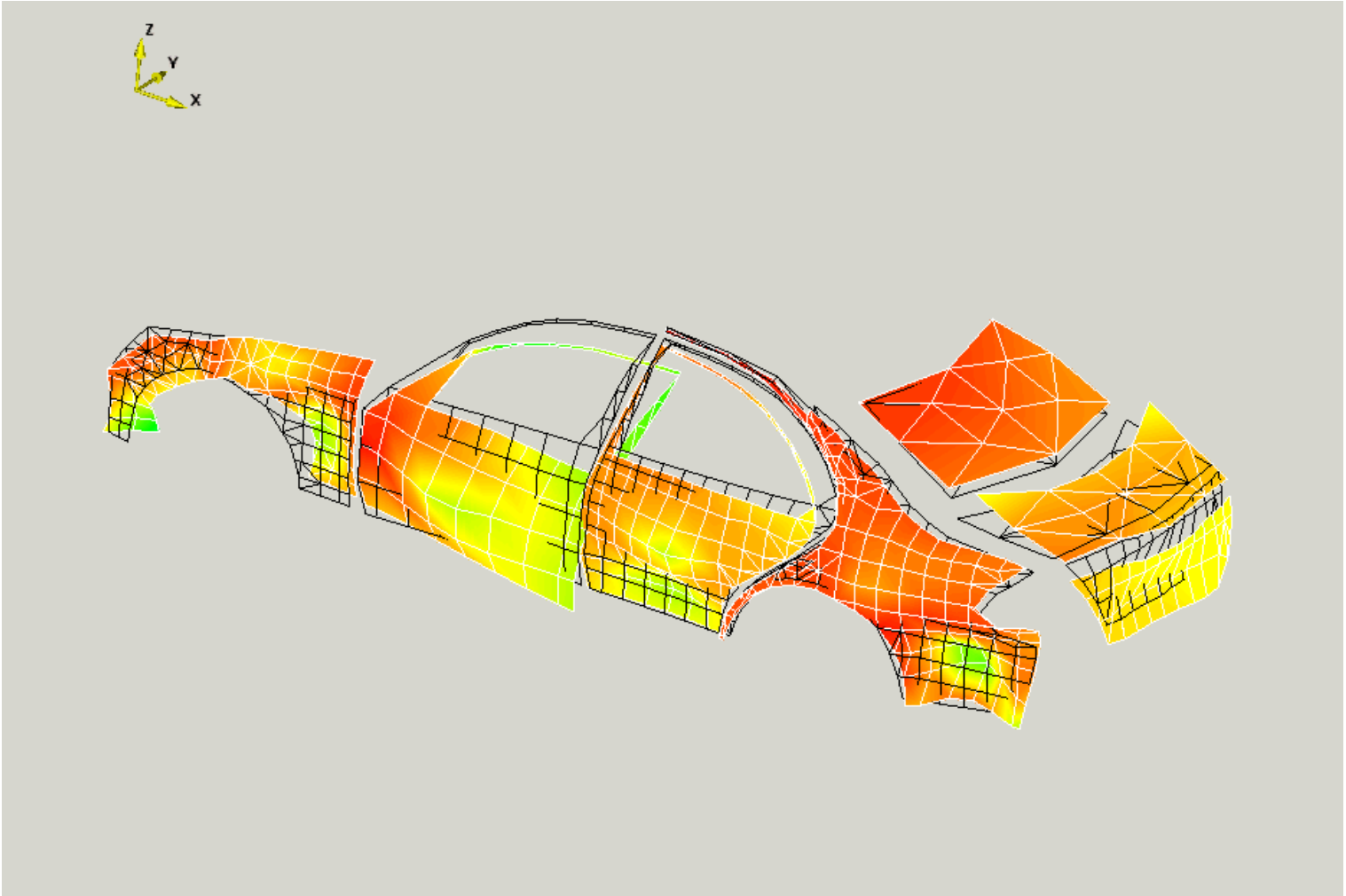
Deflection shape



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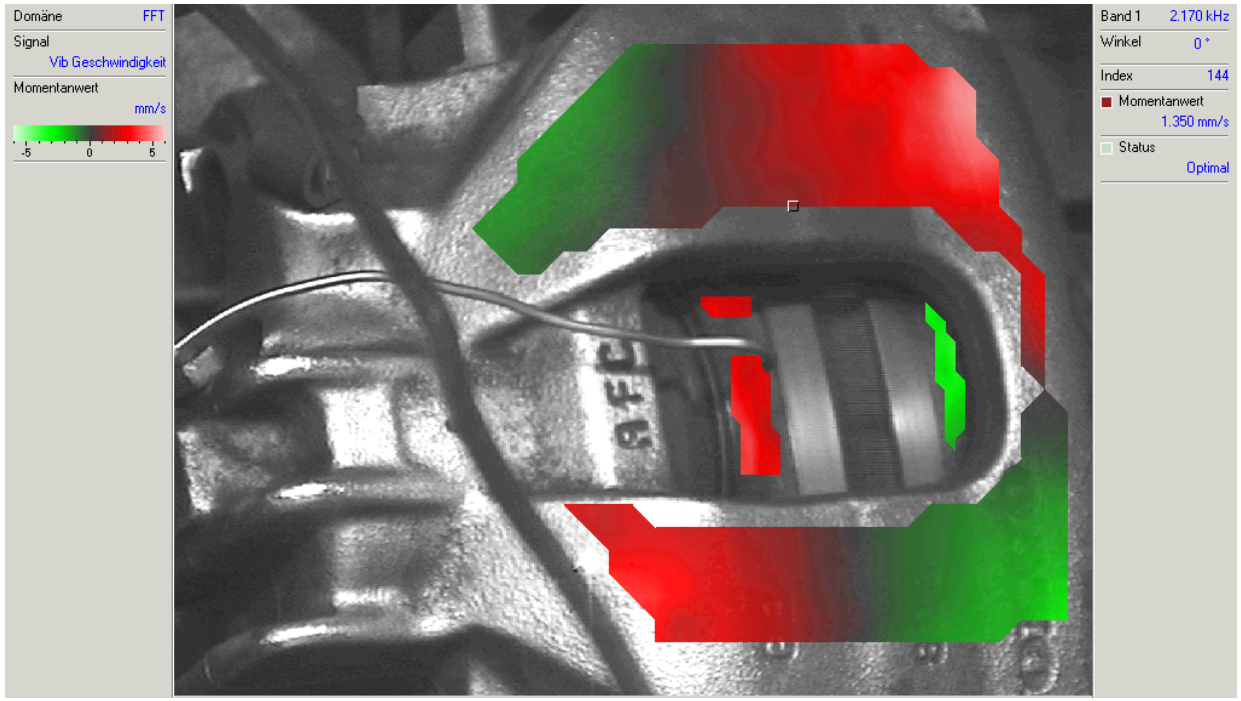
Operating Deflection Shape Analysis

- Brake squealing and related measurement tasks are alway important development activities.
- Measurements can be performed on any substructure as well at standstill as in rotating state.

Example:

Measurement under stationary operating conditions on a caliper



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Operating Deflection Shape Analysis

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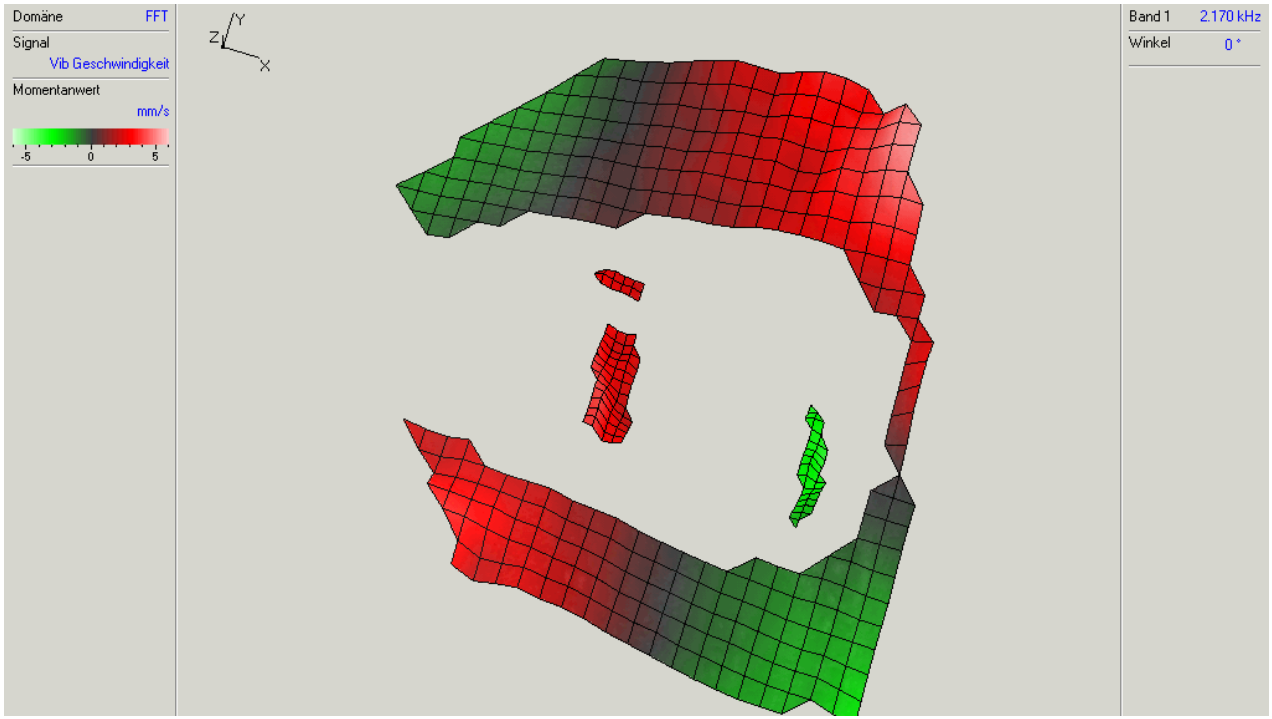

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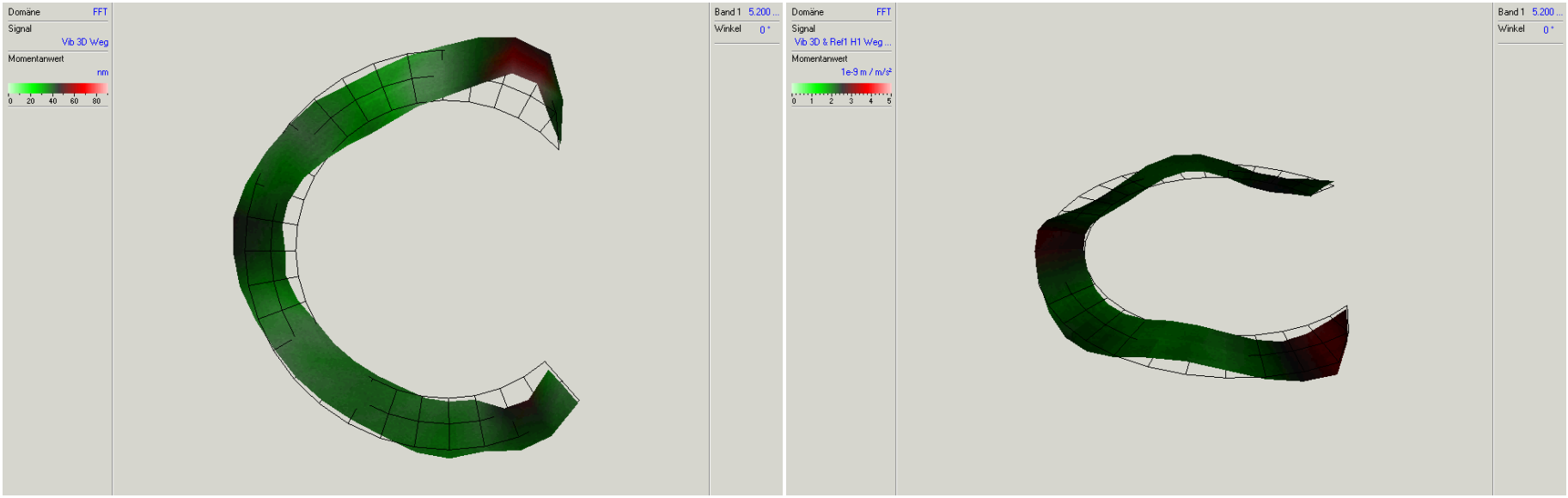
Operating Deflection Shape Analysis

- **Measuring the 3D dynamics**
  under operating conditions(4 rpm; p = 5 bar)



Mode 1: In-Plane **Mode 2: Out-of-Plane**

Result: Mode 1 and 2 are shifted towards each other in the frequency domain, instable state at 5 kHz causes squealing!

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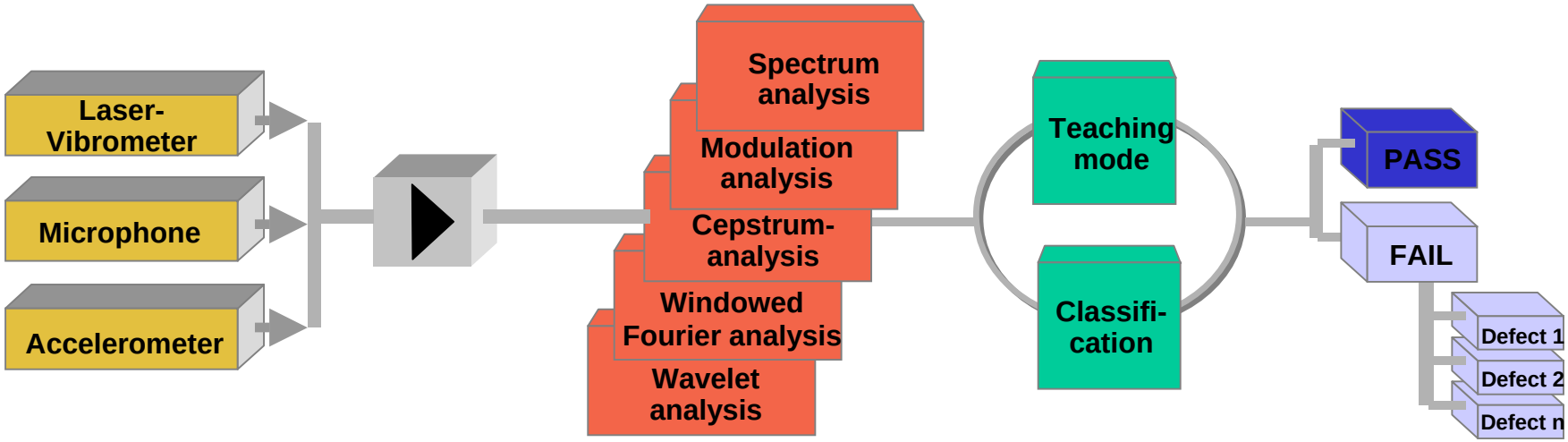
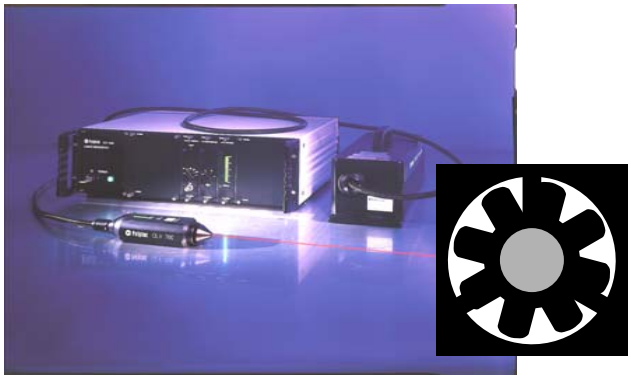
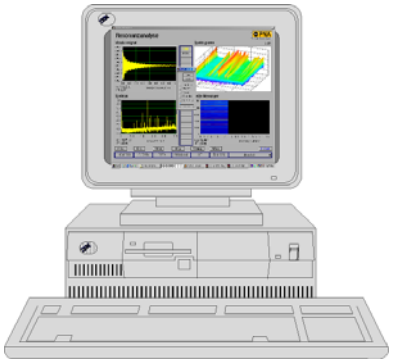
Vibro-Acoustic Defect Analysis



Vibro-Acoustic Sensing

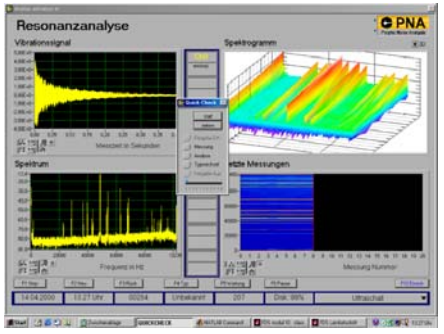


Feature Extraction



Feature Selection & Classification

Result



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Benefits of Laser-Doppler Vibrometry

- **Non contact, optical structure-borne sound measurement**
  - **Immunity to Interferences (e.g. Microphone)**
    No sound insulation necessary
  - **No mechanical contact to the test sample (e.g. Accelerometer)**
    No abrasion of mechanical Parts, no special handling equipment, no magnetic contact needed, measurement on soft materials
  - **Short cycle time (< 500 ms)**
    (handling, measurement and analysis)
  - **Reactionless**
    No interference of the vibration signal
  - **Optical Method**
    Measurements in or through optical transparent materials

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Vibro-Acoustic Defect Analysis

Acoustic crack testing of cam rings

100% End-of-line test

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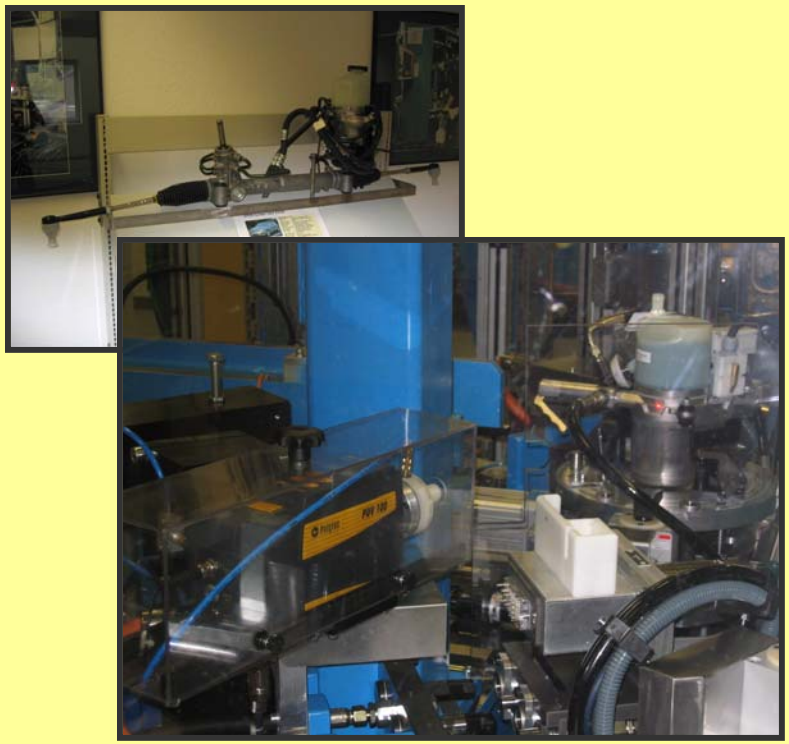
Vibro-Acoustic Defect Analysis

Vibrational testing of steering gears

100% End-of-line test



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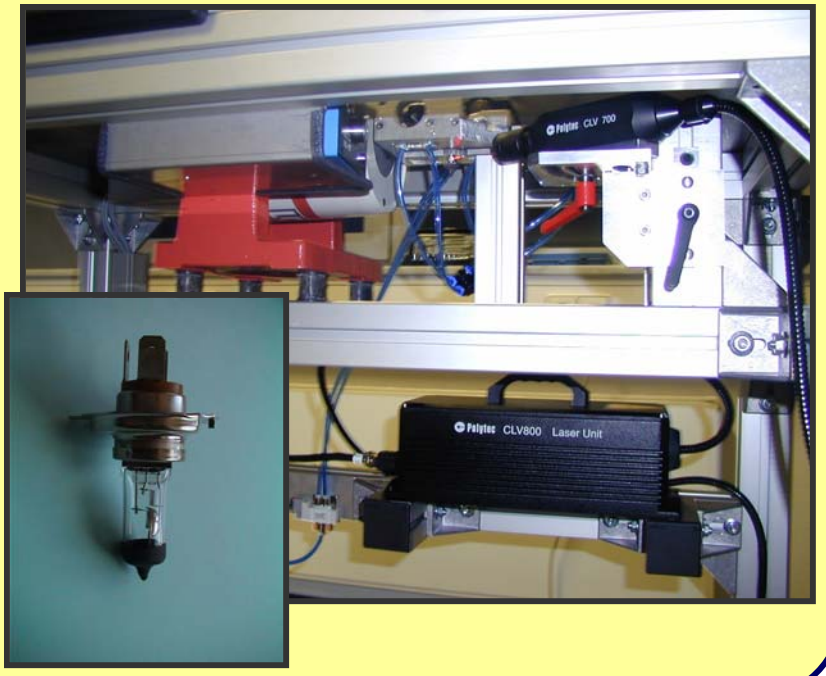
Vibro-Acoustic Defect Analysis

Vibrational testing of light bulbs for cars
100% End-of-line test



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Polytec

MEMS

Micro-
Electo-
Mechancal
System

Micro Mirror

↓

Manipulation
of Light

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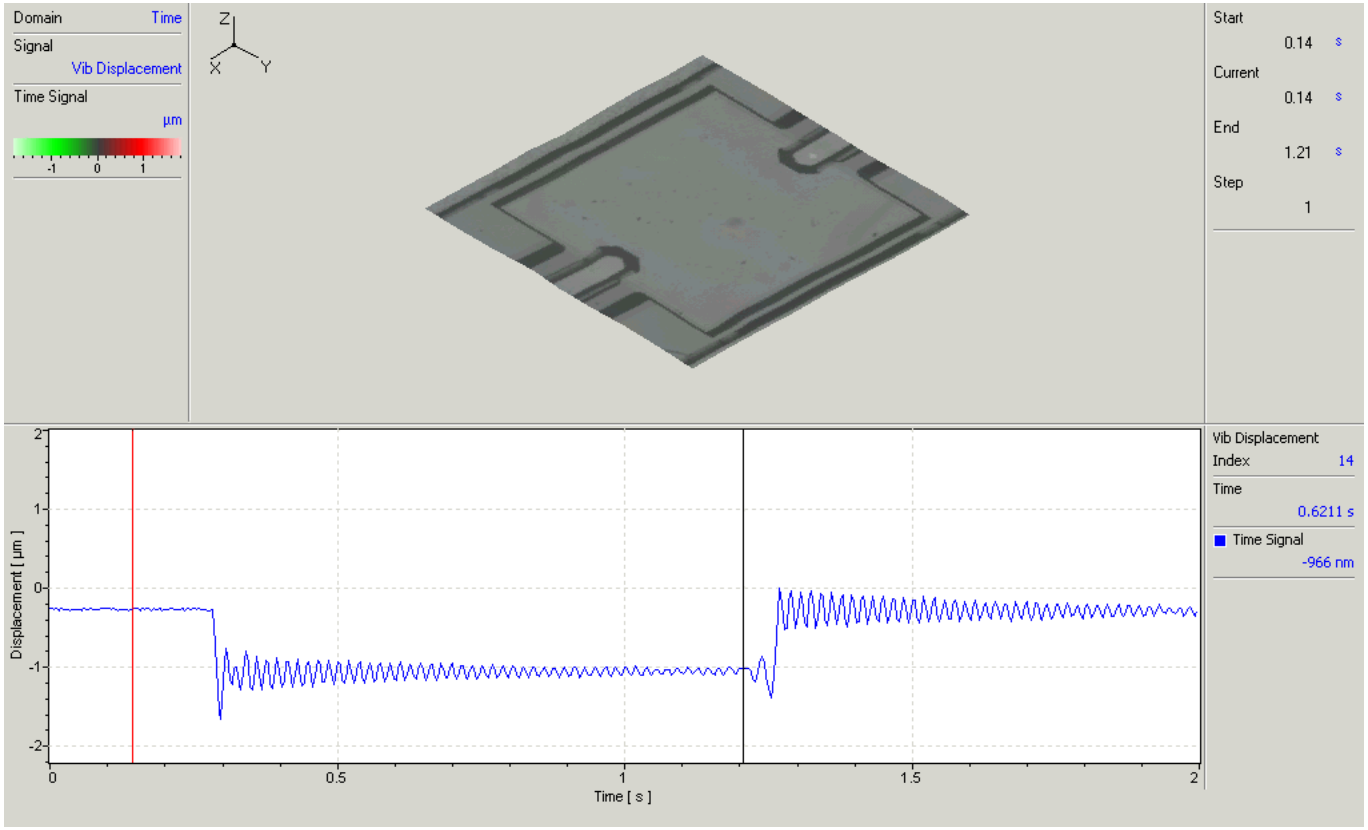
Optimization of Step-Response



Response on 100 Volt step function

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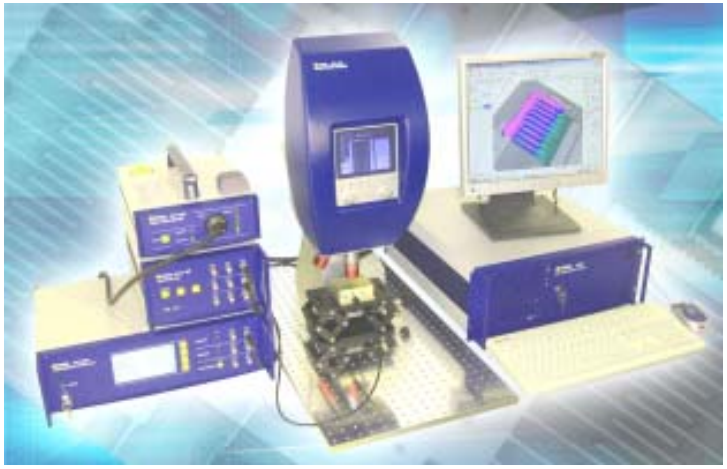
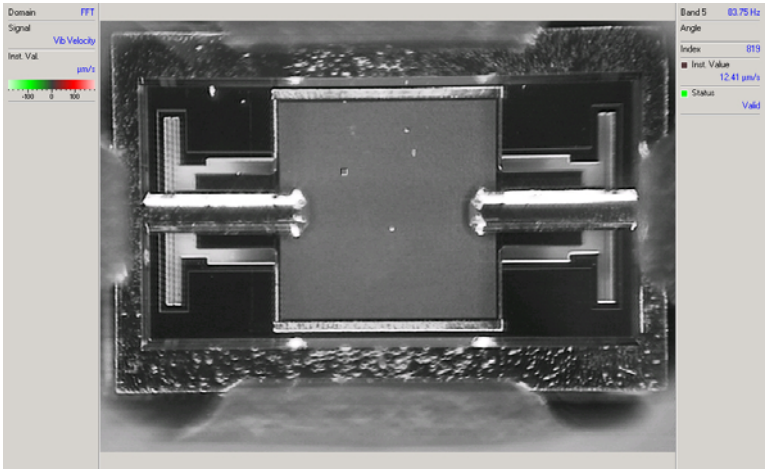
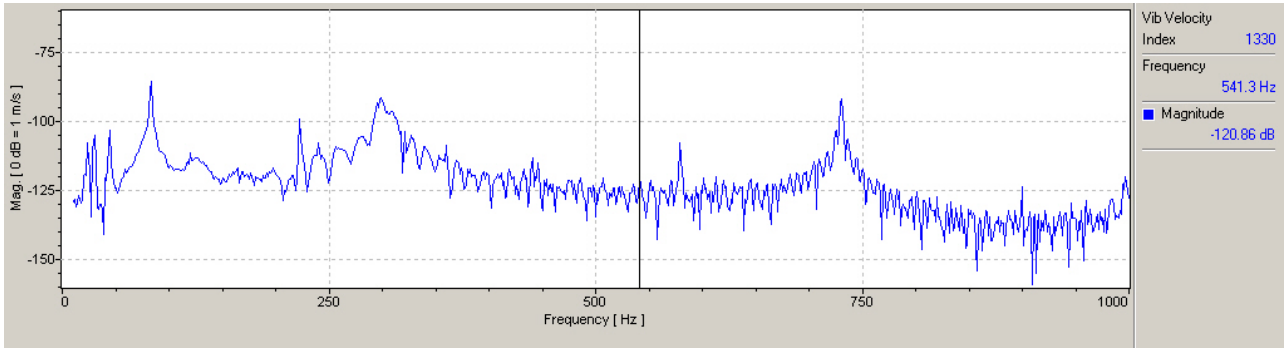
MSA-400 Micro System Analyzer







frequency spectrum

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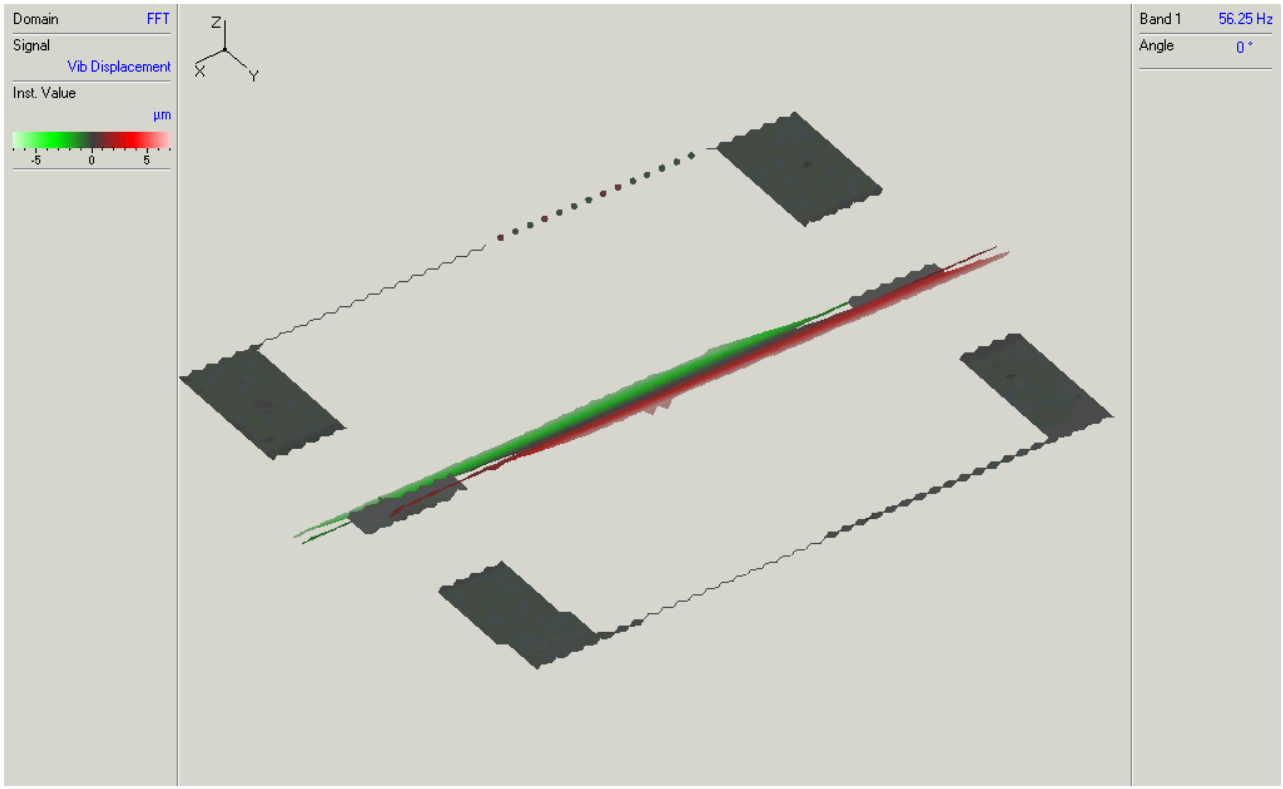
Micro Scanning Vibrometer Measurement

1. order rotational deflection shape @ 55 Hz



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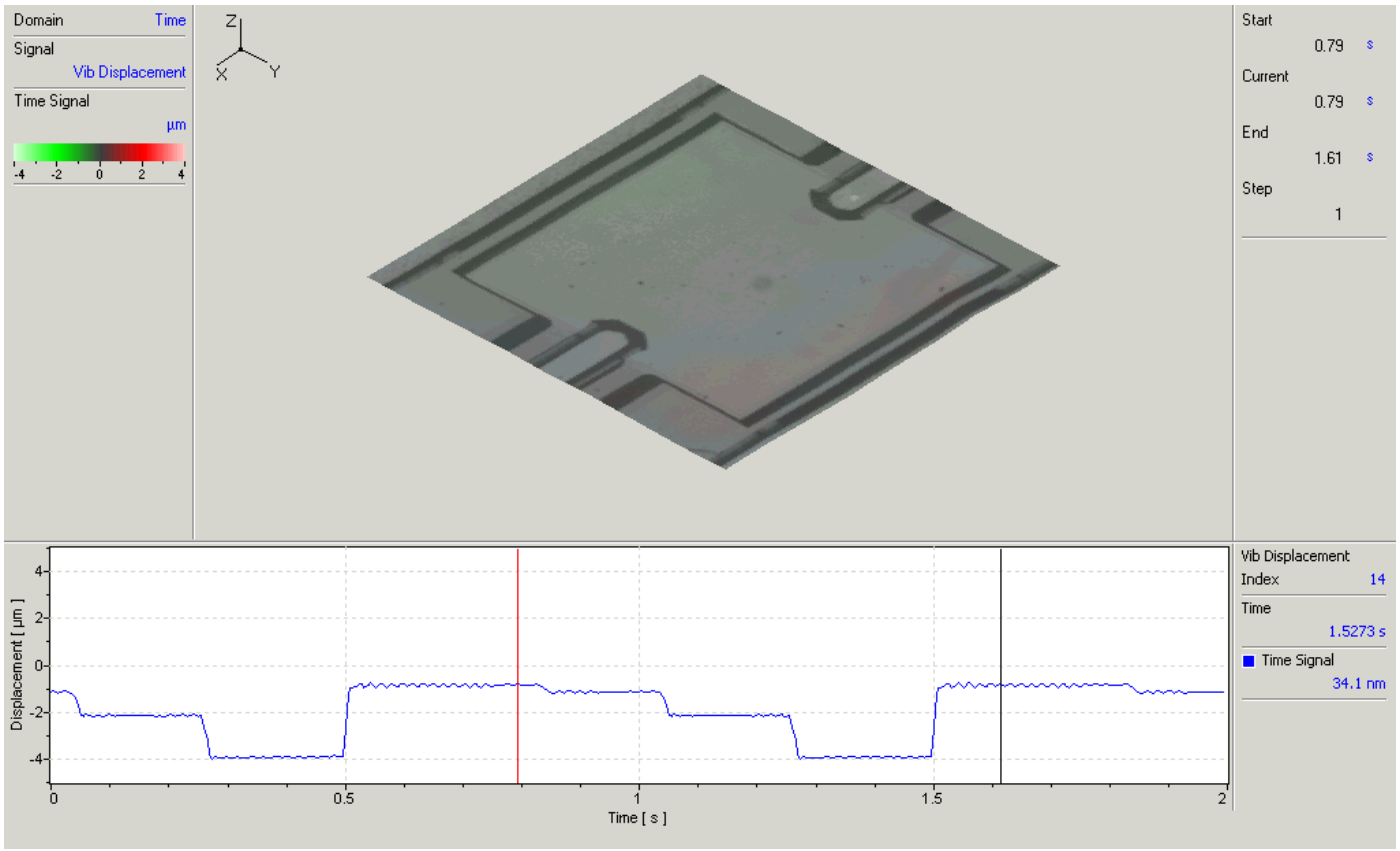
Optimization of Step-Response

‘Input Shaping’ removes resonance



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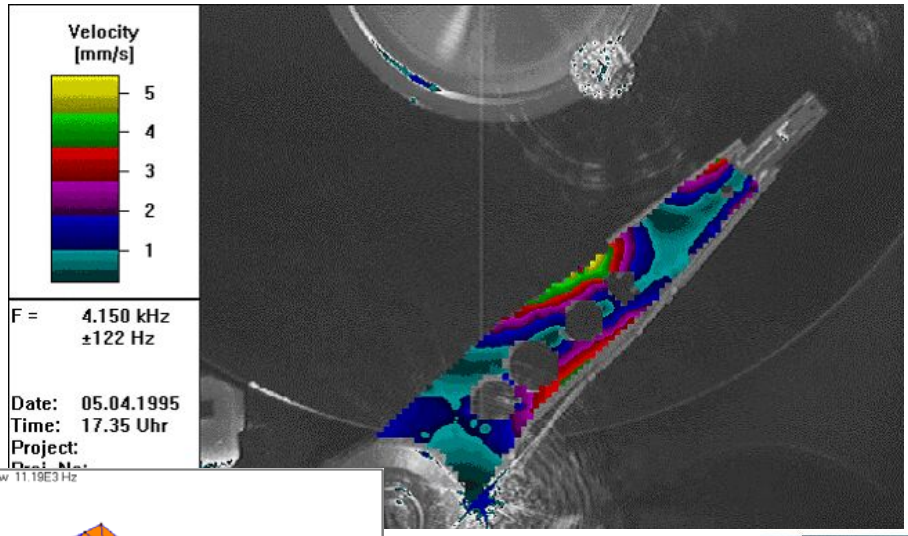
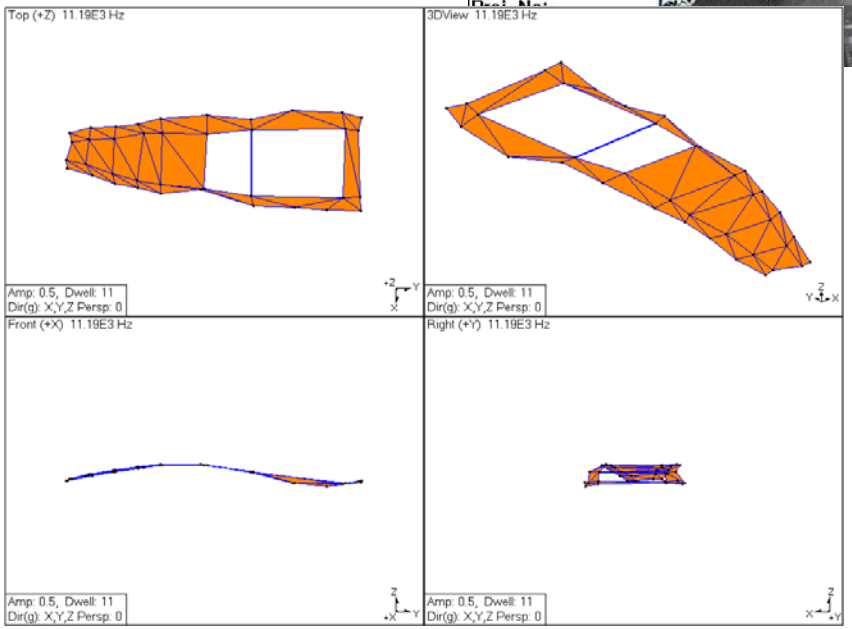
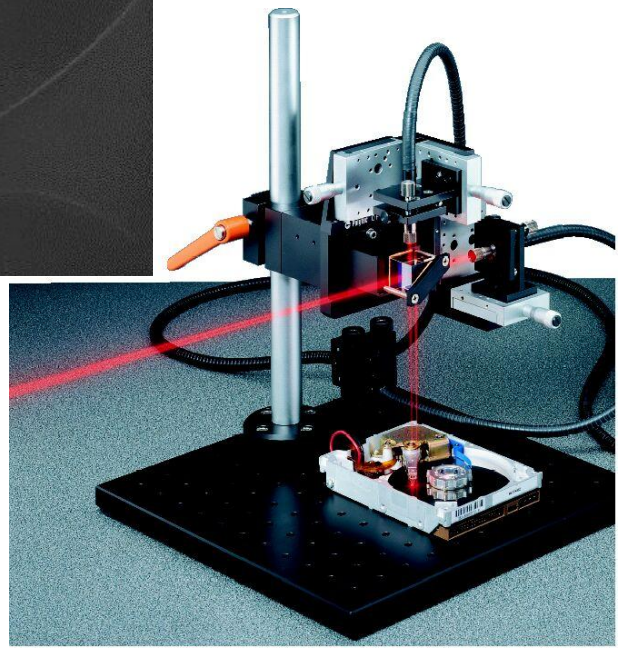
Hard Disc Drives







OFV-551/552 Fiber-optic Vibrometer

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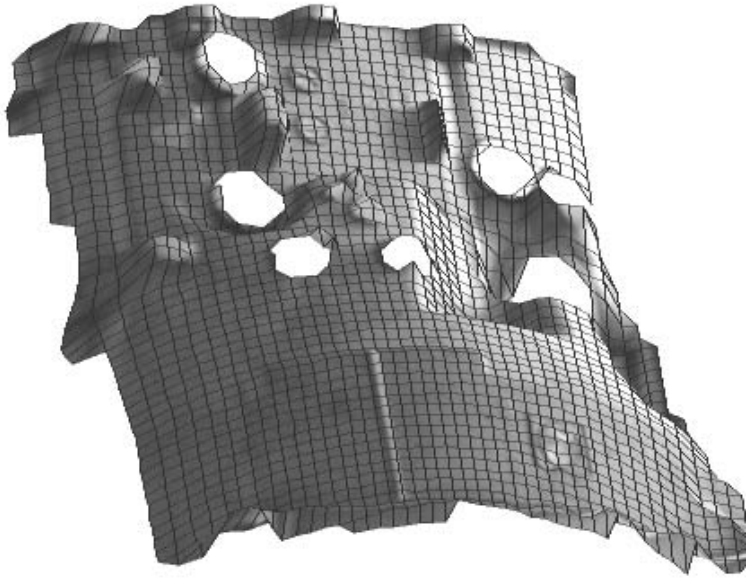
PSV Geometry Scan Unit

Benefit:

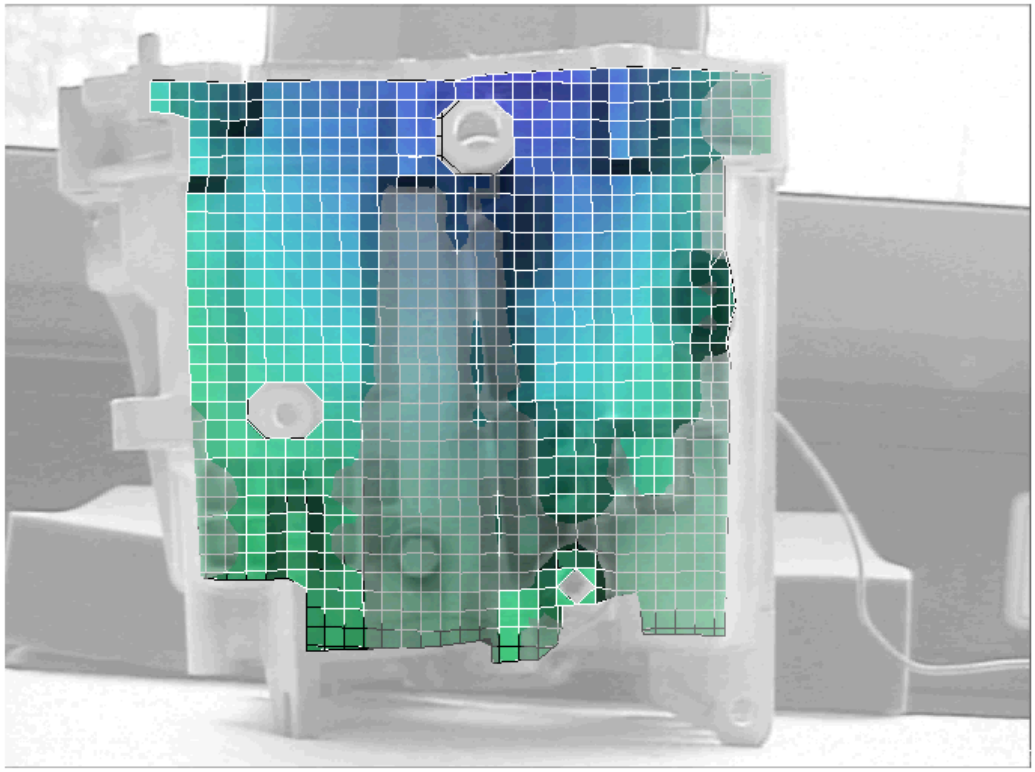
- Direct and fast acquisition of the geometry of the measurement object with the Scanning-Vibrometer



Domain FFT
Signal
Vib & Ref1 CP Voltage * ...
Inst. Value
1e-9 V * m/s
-50 0 50

X
Z Y

572 Hz



Band 1 571.9 Hz
Angle 0 °
Vib Direction -Z

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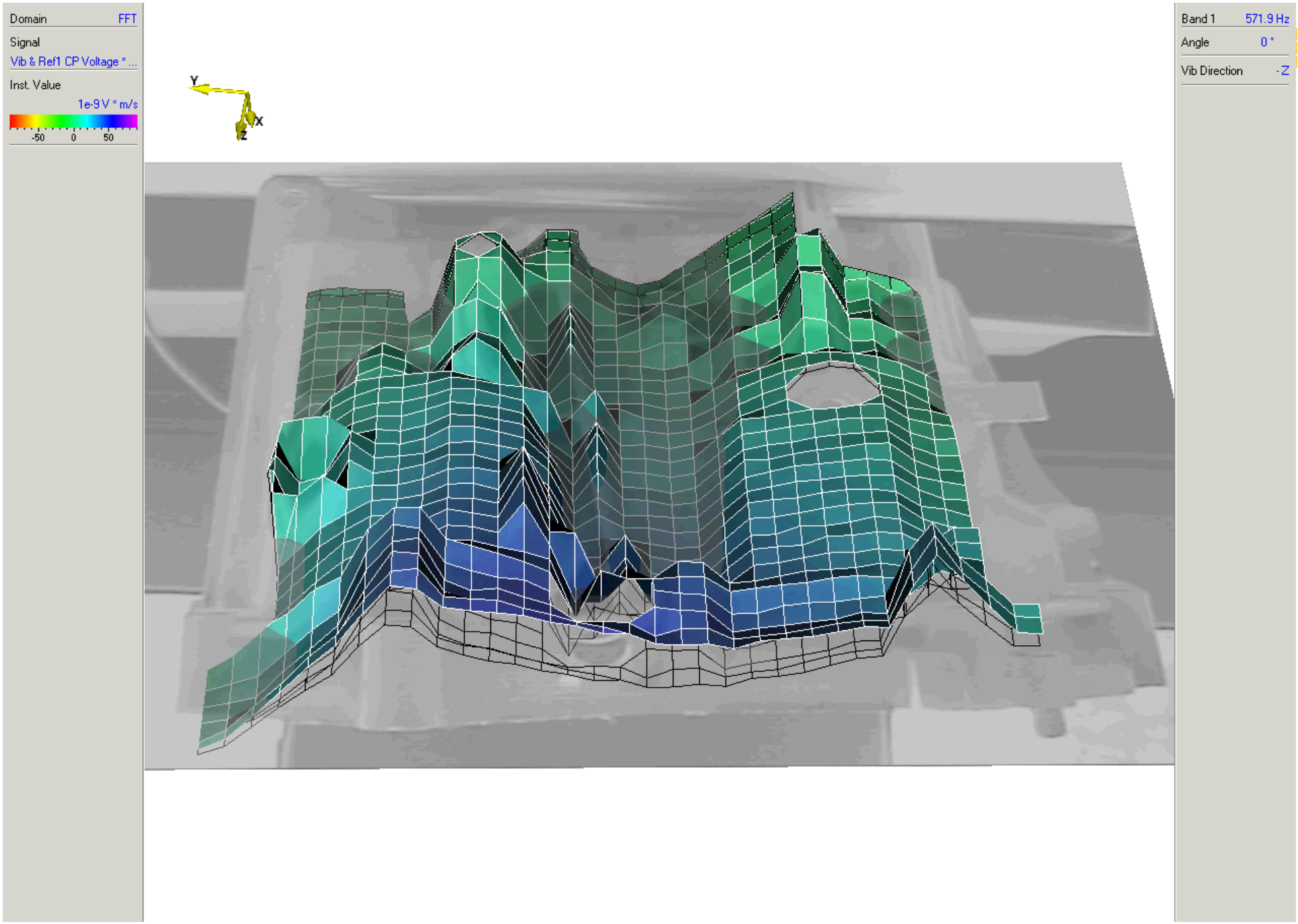
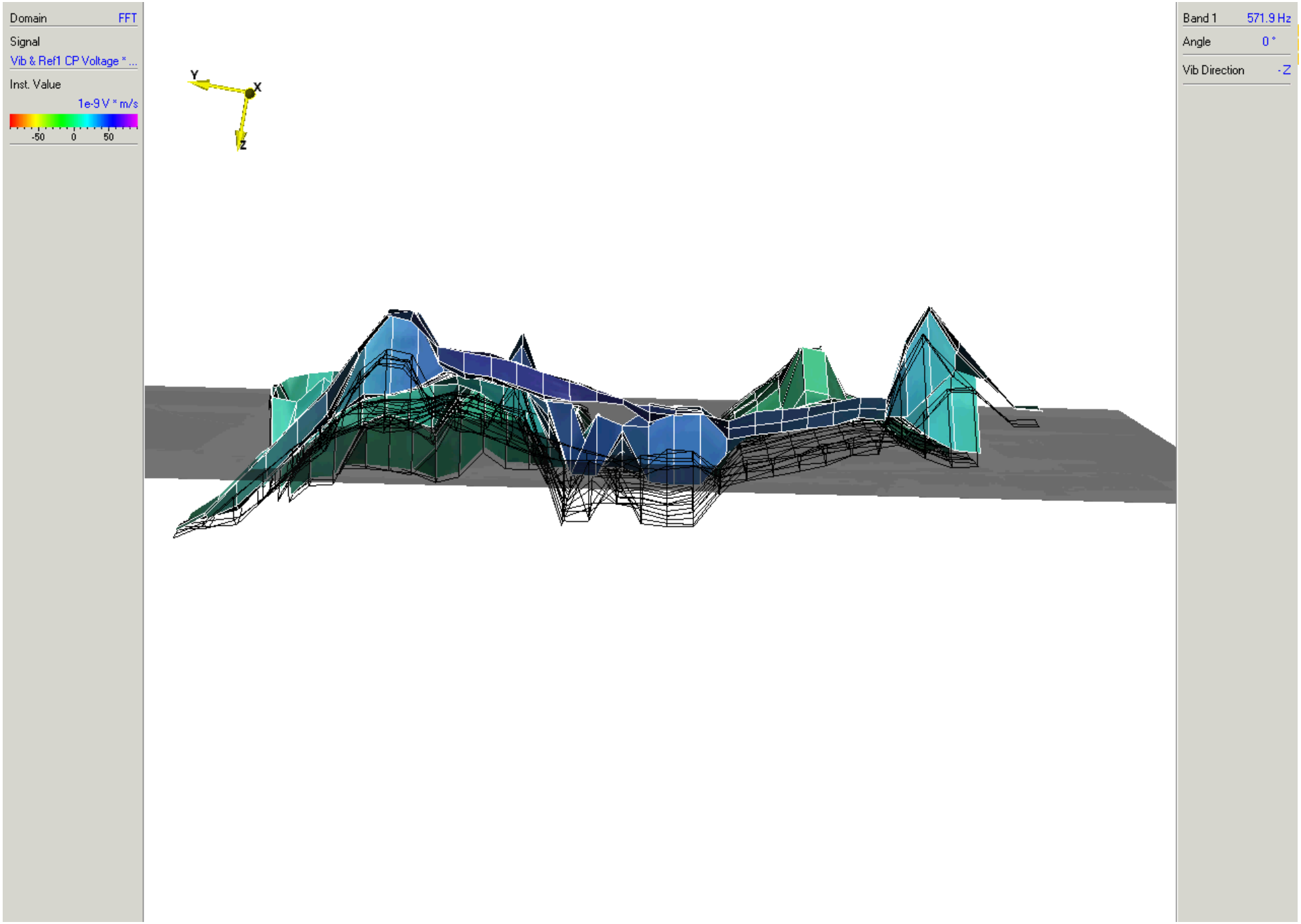

Domain FFT
Signal
Vib & Ref1 CP Voltage * ...
Inst. Value
1e-9 V * m/s
-50
0
50
Y
X
Z
Band 1 571.9 Hz
Angle 0 °
Vib Direction -Z



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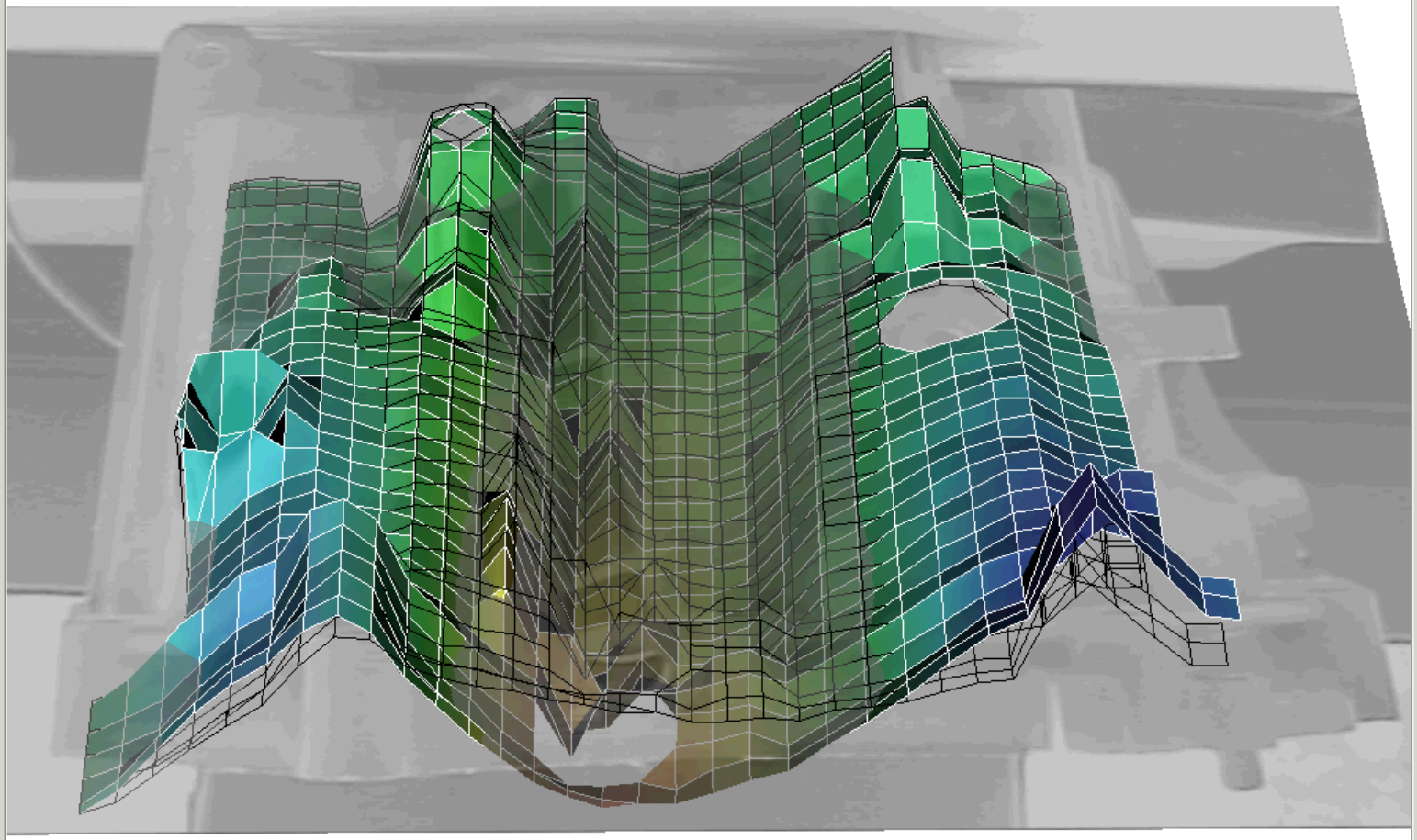
Domain FFT
Signal
Vib & Ref1 CP Voltage * ...
Inst. Value
1e-9 V * m/s
-100 -50 0 50 100

Y
X
Z

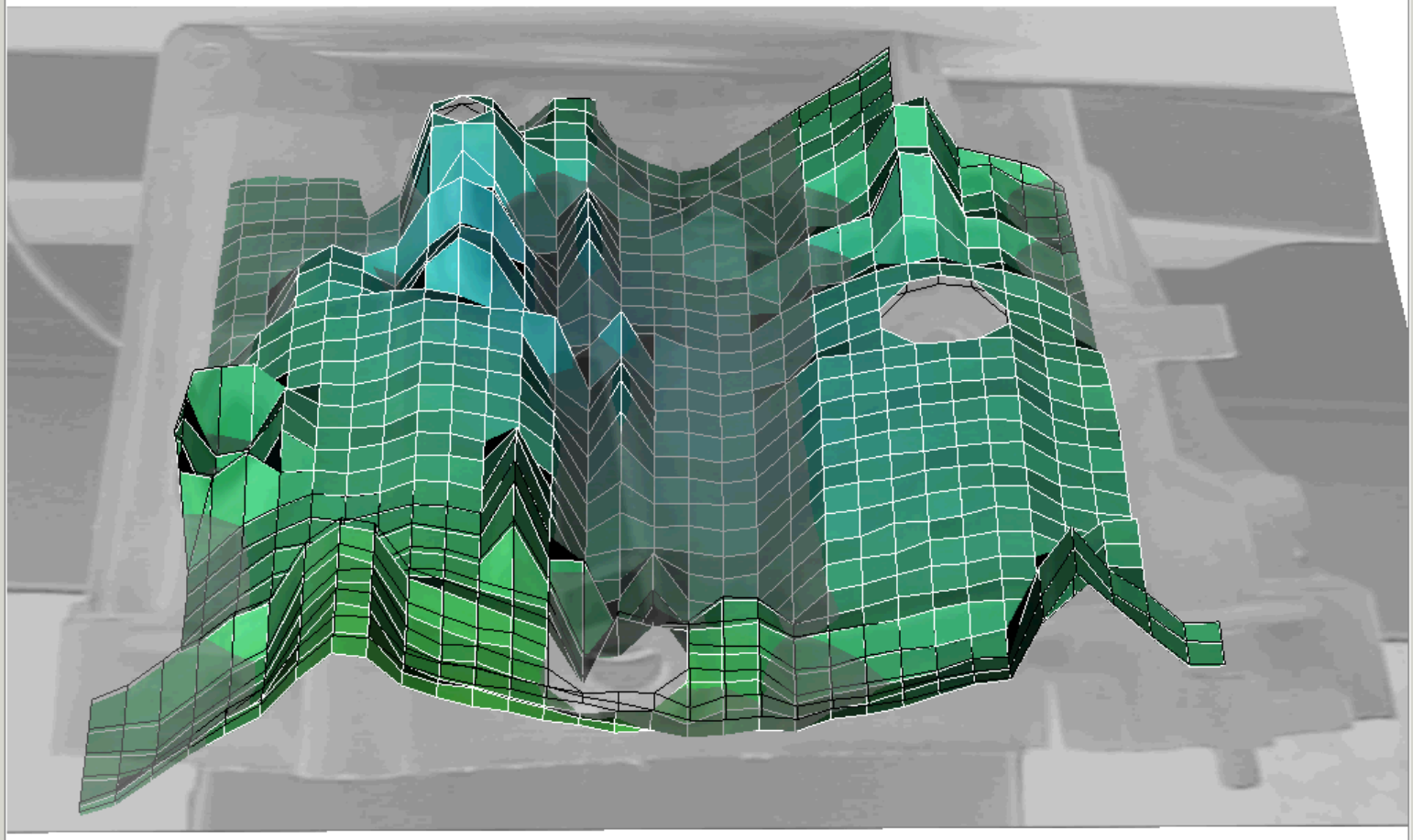
1672 Hz



Band 4 1.672 kHz
Angle 0 °
Vib Direction -Z

Domain FFT
Signal
Vib & Ref1 CP Voltage * ...
Inst. Value
1e-9 V * m/s
-200 -100 0 100 200

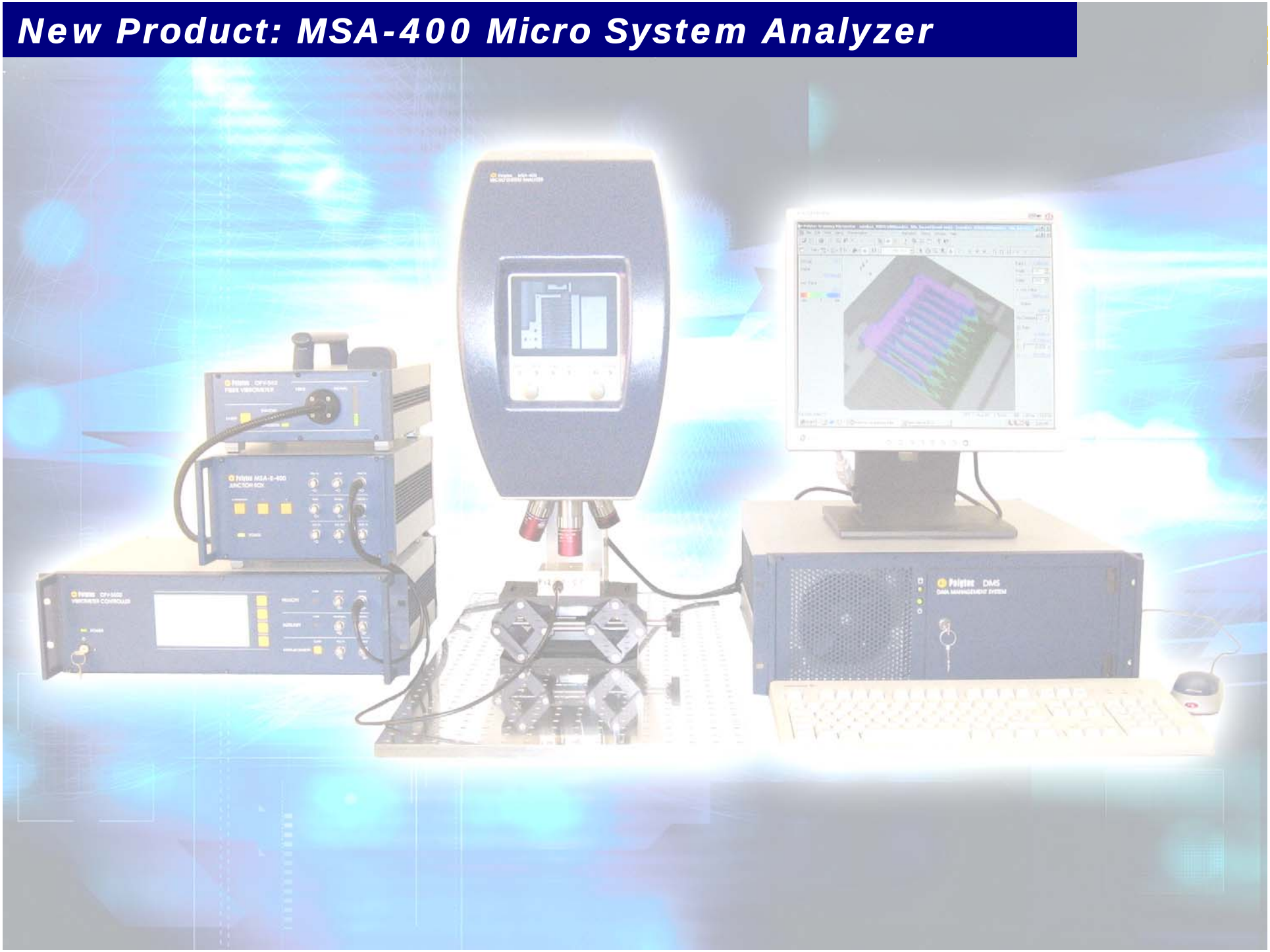
2112 Hz



Band 6 2.112 kHz
Angle 0 °
Vib Direction -Z


Polytec OFV-552
FIBER VIBROMETER
Polytec M3A-E-400
JUNCTION BOX
Polytec OFV-5000
VIBROMETER CONTROLLER
Polytec DMS
DATA MANAGEMENT SYSTEM

New Product: MSA-400 Micro System Analyzer



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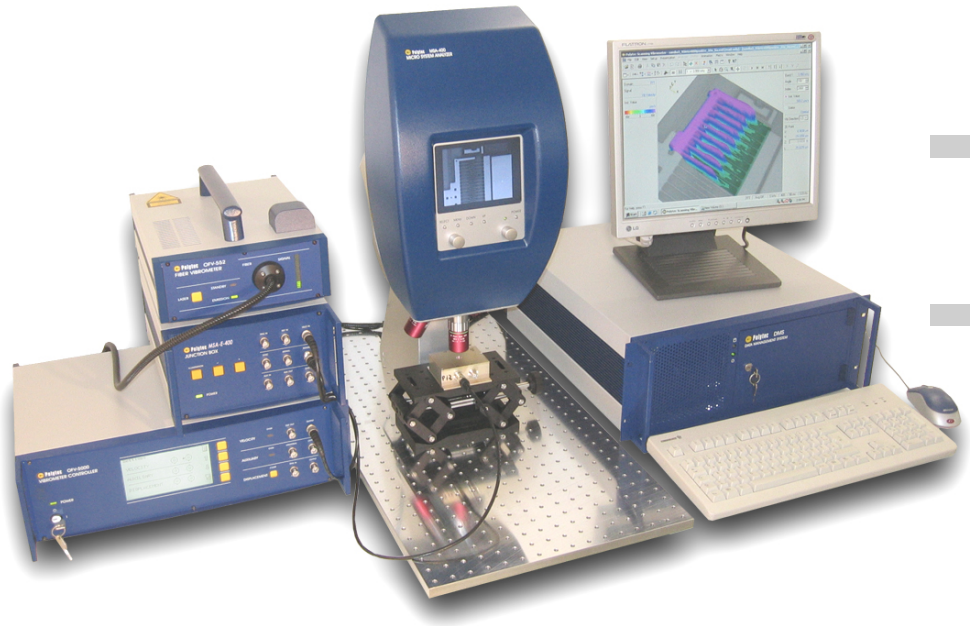
MSA-400 – The Features



- Measures in-plane (IP) and out-of-plane (OOP) motions of micro structures
- Displays frequency and time domain data
- On-line live-video monitoring of the measurement processes,
  no distracting fringes in the video image

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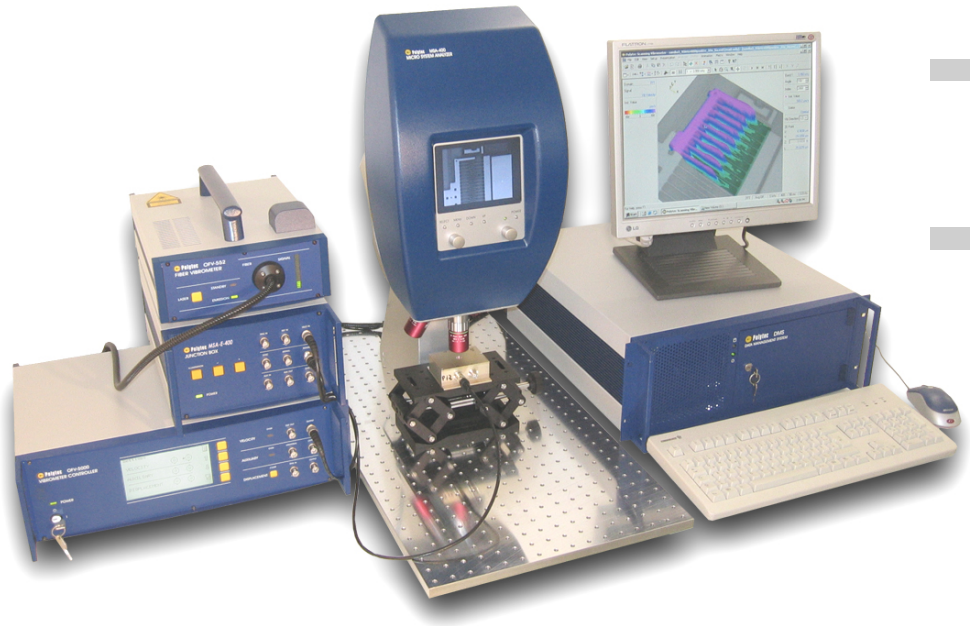
MSA-400 – The Features



- Measurement probe uses sub micron laser spot (0.7 µm for 50 x lens)
- Scripting control for automation
- Standard export formats for measurement data, graphics and animations facilitate postprocessing and reporting

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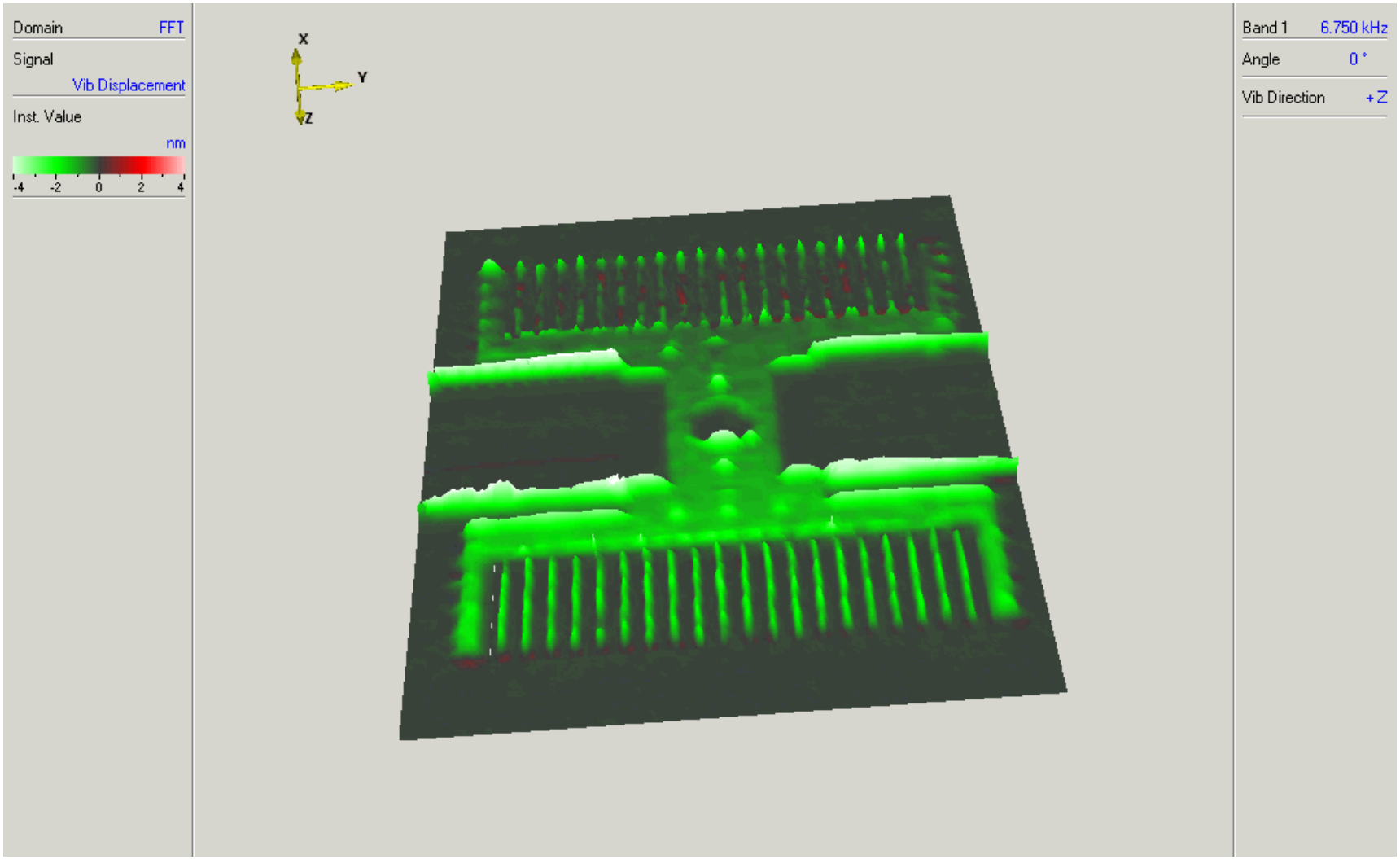
Out-of-plane Motion Analysis



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Out-of-plane Motion Analysis

- using Microscope Scanning Laser Doppler Vibrometry
- Benefits:
  - Full frequency response in one single measurement
  - Very fast identification and visualization of all system resonances

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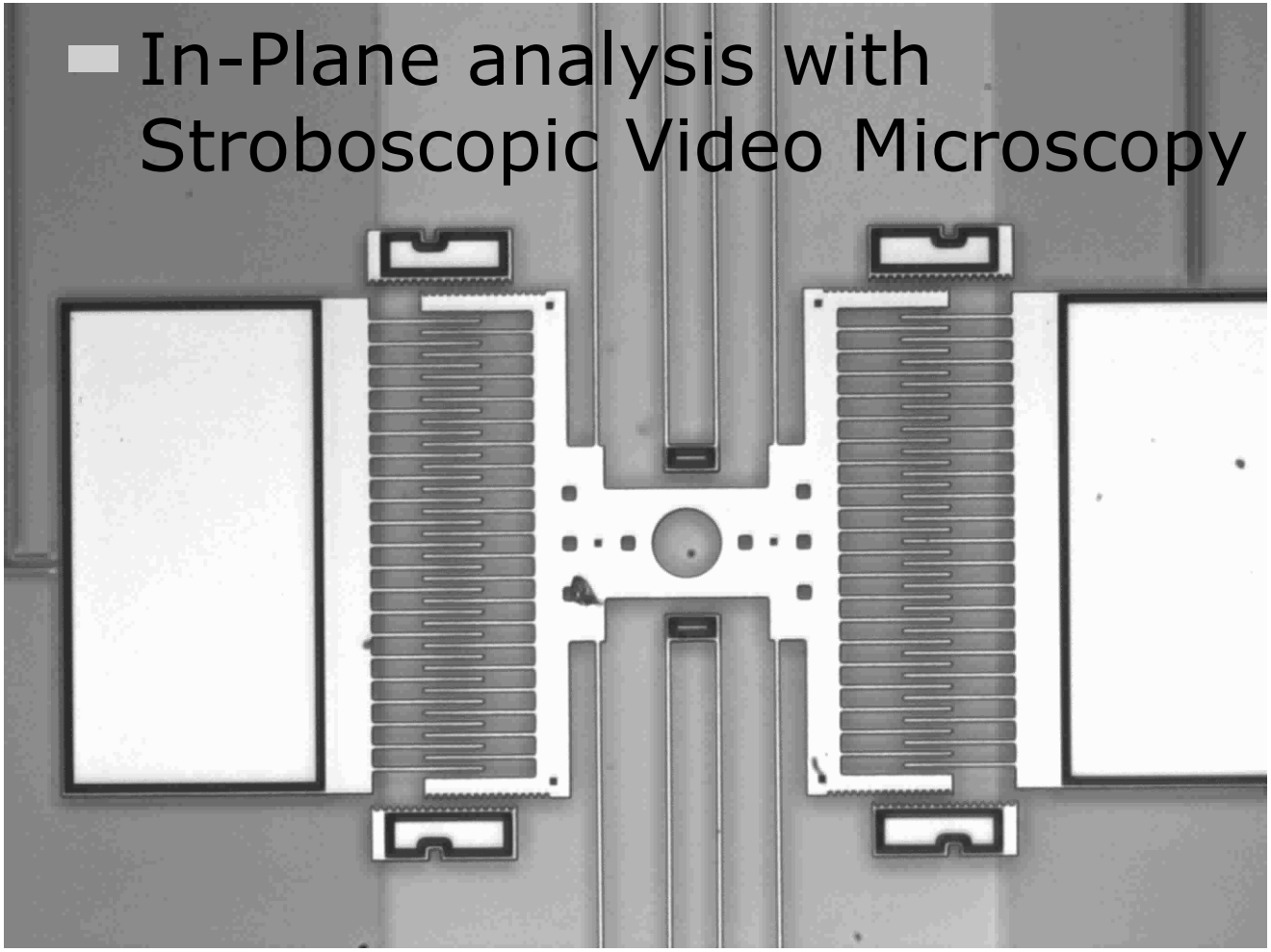
In-plane Motion Analysis

- In-Plane analysis with Stroboscopic Video Microscopy



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In-plane Motion Analysis

- In-Plane analysis with Stroboscopic Video Microscopy
- Benefits of the combined OOP and IP system
  - The extreme OOP sensitiviy (pm) allows to identify also the in-plane resonances through their spurious OOP contribution
  - The subsequent in-plane analysis can be limited to the resonance regions identified in the OOP measurement

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Conclusions

- The non-contact Laser Vibrometry measurement principle without any mass loading facilitates reactionless measurements for highly reliable vibration data in an enormous field of applications
- Scanning and 3-D Scanning Laser Vibrometry is an indispensable tool for fast and efficient experimental modal analysis
- The quick system setup without any cabling on the testobject contributes to a significant reduction of development time

For more information and practical product demonstrations please visit our booth or

http://www.polytec.com

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