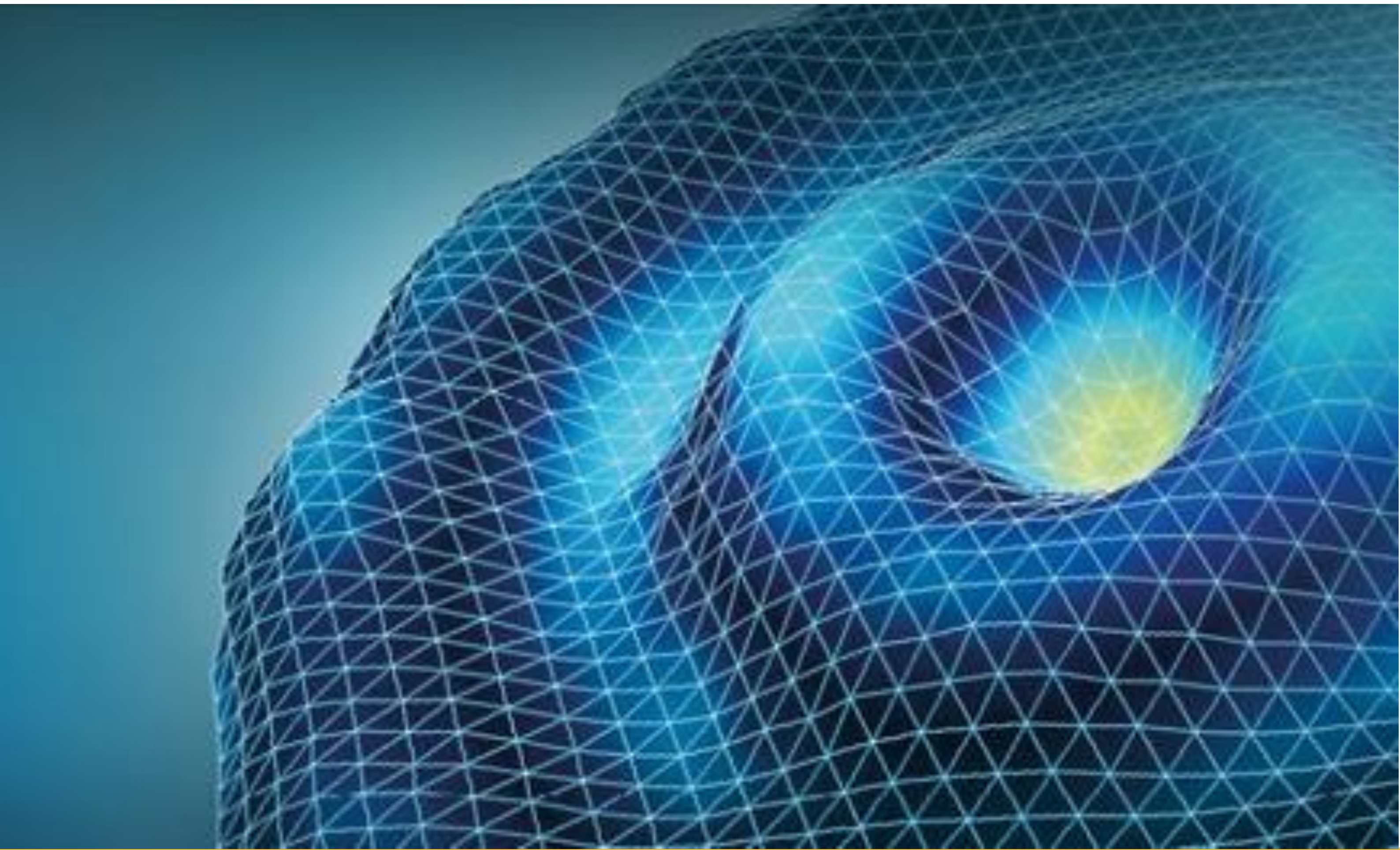

Advanced Optical Vibration Measurement Using Laser Doppler Vibrometry

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A pumping heart, wings vibrating, sounds are emitted and detected – life without vibrations is hard to imagine. Understanding vibrating systems in nature and technology requires sophisticated, flexible, and ideally non-invasive measurement tools. Here, non-contact laser vibrometry proves to be the highest performing method. Recent innovations further push the limits.

In industrial research and development, vibrometers are used to study objects of many different sizes, ranging from entire car bodies, airplane components, engines and buildings to tiny micro-machines and hard drive components. Countless other research applications exist in mechanical engineering, acoustics, and many other engineering-related disciplines. Measurements can even be taken of glowing hot objects, rotating surfaces, ultrasonic tools, and complex, delicate structures.

Measuring with light – fundamentals of Laser Doppler Vibrometry

Laser vibrometers (Figure 1) rely on the principle of laser interferometry, using an eye-safe laser (e.g. HeNe with λ = 633 nm, P < 1 mW) as a light source. Inside the vibrometer, an optical beam splitter separates the laser beam into two components: a reference beam and a measuring beam. The measuring beam hits a spot on the vibrating surface and the backscattered light is frequency-shifted because of the Doppler effect. This light then mixes with the reference beam and a beat frequency is produced.

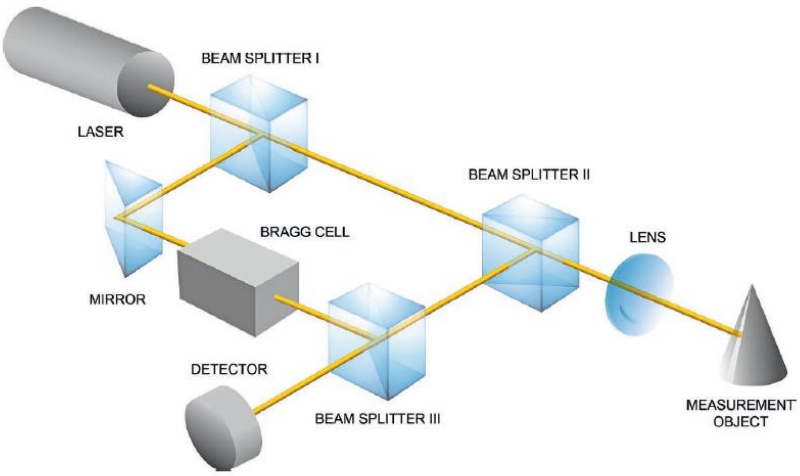

Figure 1: The principle optical construction of a laser vibrometer

This frequency modulation of the light intensity is proportional to the vibration velocity. Whenever the measured object moves by half a wavelength of the HeNe laser (λ = 316 nm), the intensity will run through a full light-dark cycle. A light-sensitive sensor converts the changes in light intensity into an electronic signal. The frequency fD of these light-dark cycles is proportional to the speed v of the measured object as follows:

$$f_D = 2 \times v / \lambda$$

Currently, the shot-noise-limited vibrometers achieve an amplitude resolution far below a picometer during displacement demodulation.

Laser vibrometry today has almost unlimited potential and is used in a wide range of applications. Vibration measurement data can therefore now be obtained with greater precision and efficiency, even for applications where conventional sensor technology cannot be used.

Vibrometer types

The fundamental principle shown in Figure 1 of contactless, non-intrusive, high-resolution optical vibration measurement forms the foundation, not only for standard vibrometers, which measure one point on a vibrating structure, but also for a series of more versatile and specialized measuring devices.
Special double-beam interferometers facilitate optical differential measurement when, for example, it is necessary to remove disruptive background environmental vibrations.

A similar twin beam concept forms the basis for the in-plane vibrometer: Two beams that cross to create a measurement volume enable vibrations to be measured perpendicular to the optical axis.
In the case of 3D vibrometers, three beams merge to enable the detailed recording of X, Y, Z vectors of motion.

And rotational vibrations can be detected by using a double interferometer, applying it for example to study run-ups of vehicle drive trains.

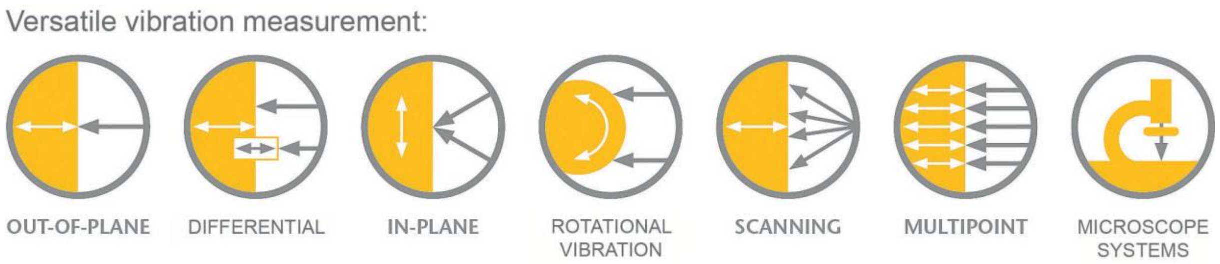

Figure 2: Overview of the different vibrometer types

In addition to these single-point sensors, there are also vibrometer systems for areal measurement. A scanning vibrometer combines an interferometer, precision scanner optics, an integrated video camera and a high-performance data acquisition system. A grid of measurement points can be defined to facilitate the full-field measurement of operational deflection shapes by sequentially scanning the entire surface of interest. The next evolutionary step is to combine three synchronized scanning heads to gather 3D vibrational data from complex structures: the ultimate 3D scanning vibrometer.

Multipoint vibrometry

Non-stationary vibrational phenomena require synchronous measurement of dynamic behavior at a number of points in real time. Examples of automotive applications include fluid induced dynamics, valves, gear boxes, switching operations, run-ups of electrical drives or combustion engines and exhaust systems. In aerospace, applications include: rocket stage ignition, as well as the settling and decay of any structure subjected to impact events. In many of these areas there are challenging conditions, such as high temperatures, high voltage, sensitive structures, where conventional, contact-based sensors are limited. The multipoint vibrometer gets around these limitations thanks to its flexible configuration with multiple fiber-optical sensors.

This system enables synchronized and simultaneous measurement from any given direction (Figure 3), with up to 48 individually adjustable fiber-optic sensors enabling measurements from different perspectives, for example around a complex shaped object. The multipoint vibrometer can be configured to provide three-dimensional vibration vectors. High optical sensitivity results in a low noise level even on uncooperative surfaces, without the need to prepare the sample surface.

The modularity of a multipoint vibrometer now allows us to measure more efficiently, and in many instances more precisely than conventional accelerometers and in cases where adequate test methods had simply not been available.

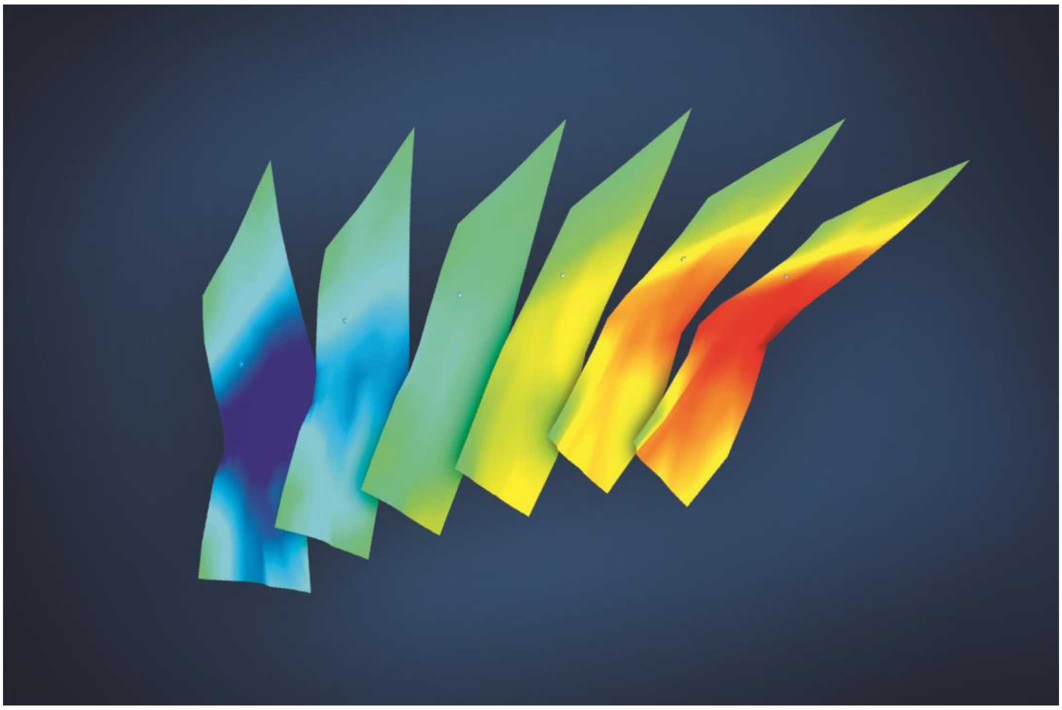

Figure 3: The multipoint vibrometer measures synchronously with up to 48 fiber optics, and illustrates the transient vibration phenomenon in frequency and time-dispersed vibration forms.

The potential to capture time-sensitive, non-stationary transient events and derive time- and frequency dependent deflection shapes without contact opens up a whole realm of new opportunities.

Microsystem Analyzers

Enhanced by microscopic optics, vibrometry allows to measure the dynamical behavior of micro-structures, such as micro-electro-mechanical sensors and actuators and has been firmly established in the development of MEMS and other microsystems. Combined with a surface topography option the so called Micro System Analyzer allows a full static and dynamic characterization of a MEMS device

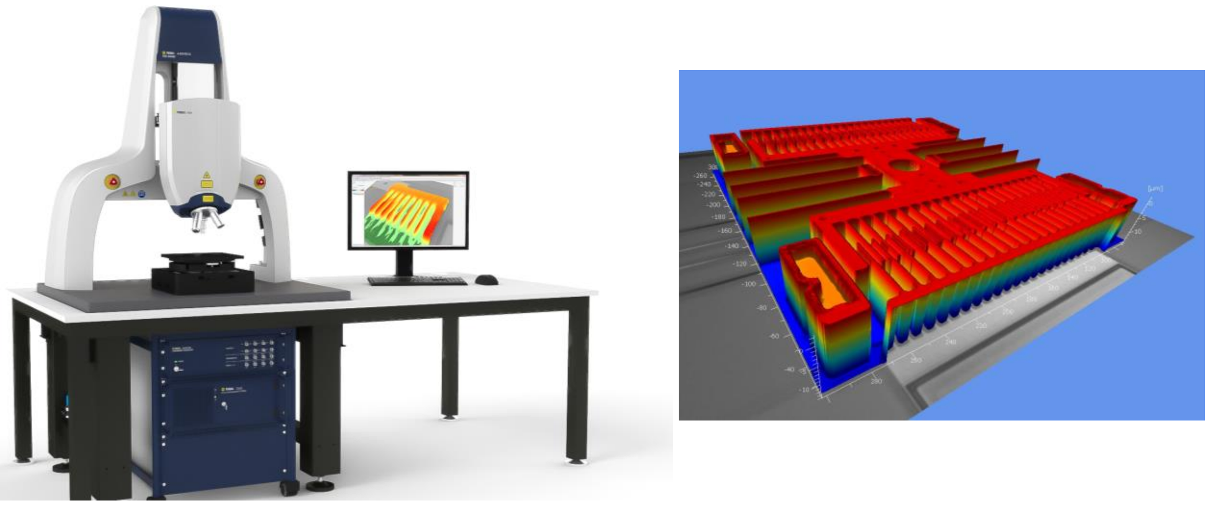

Figure 4: Micro System Analyzer for a complete static and dynamic characterization of micro systems (left).
3D topography of an electrostatic comb drive (right).

Product development in the automotive industry

In the automotive industry in particular, the optimization of vibration behavior and acoustics has become a top priority for product development, since the dynamic and acoustic properties of an automobile are essential quality indicators (Figure 4, 5). This can also be seen in the increasing demand for analysis tools and sophisticated metrology.

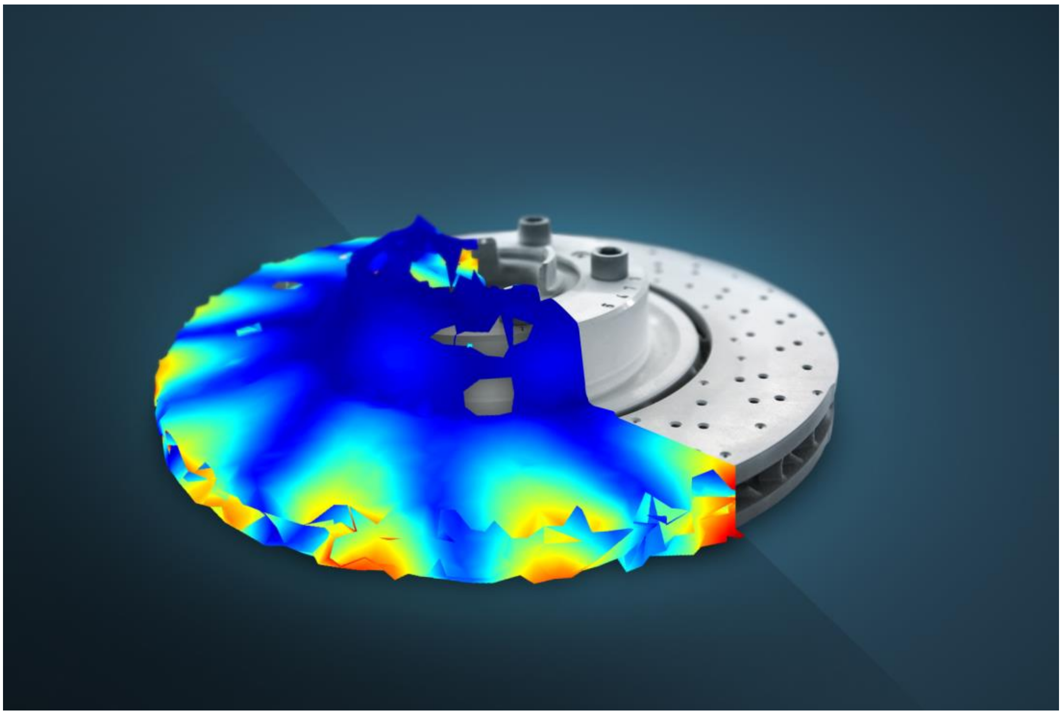

Figure 4: Measuring results for a disc brake system visualized as a vibration form. Concrete measures for design improvement to eliminate unwanted brake squeaking can be derived from the combined results of the experiment and simulation.

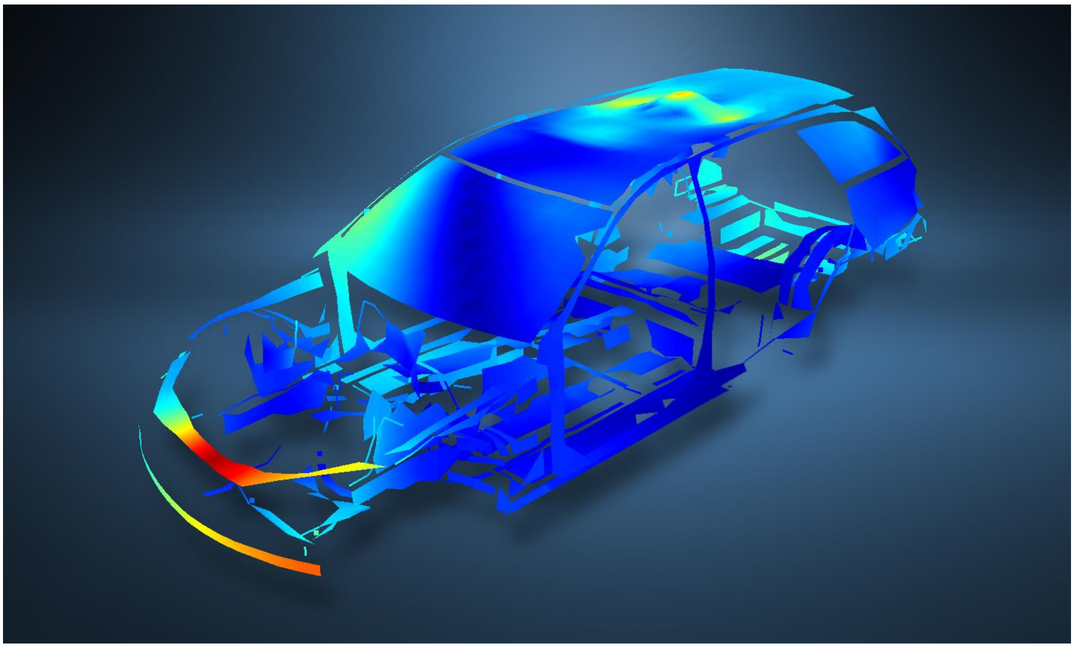

Figure 5: Vehicle bodywork measured with the Polytec RoboVib Structural Test Station and the measuring results for a selected frequency obtained using this equipment. Here the customer benefits first of all from the extremely high measuring point concentration, which is superior in magnitude to conventional measuring technology, and secondly, from the reduction of the total experiment duration from weeks to hours.

Non-contact optical measurement with laser vibrometers has become well-established for many applications in recent years, such as for modal testing, FE model updating or NVH optimization (noise, vibration, harshness). Reasons include the high productivity, ease of use and high precision of this test method, as well as its capacity to solve challenges like red-hot surfaces, complex or microscopic structures. Vibrometers can also handle large objects where access with non-optical methods would be difficult or expensive (Figure 5, 6).

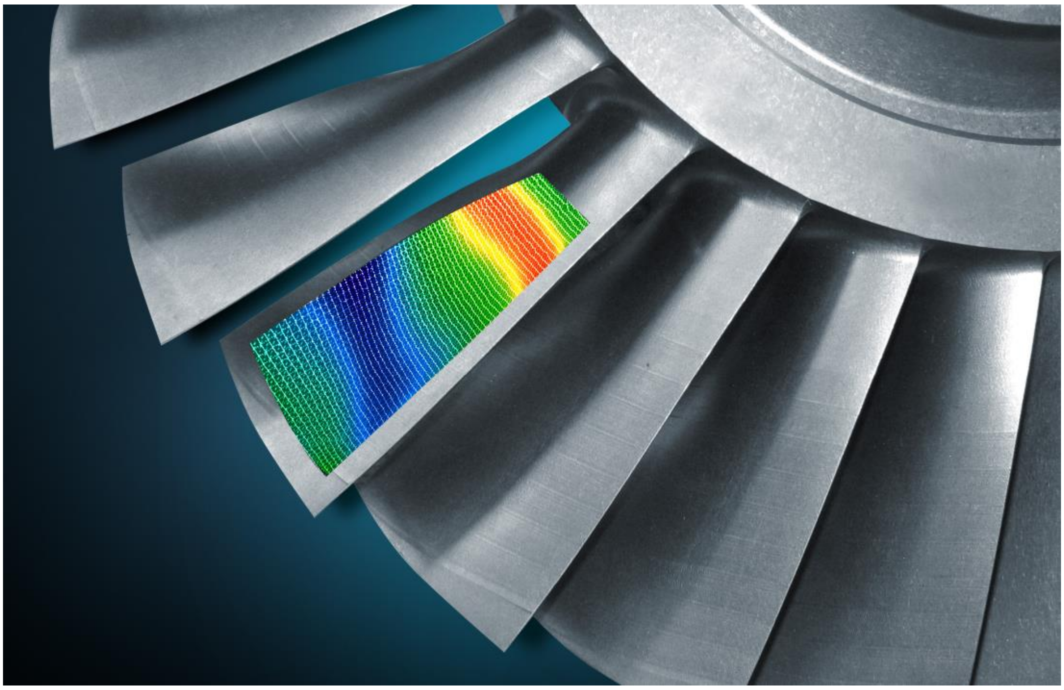

Figure 6: An airplane turbine with its typical vibration form measured on a compressor blisk not shown here. 3D Scanning Vibrometry can be extended to dynamic strain and stress analysis.

Measurement of ultra-high-frequency mechanical vibrations

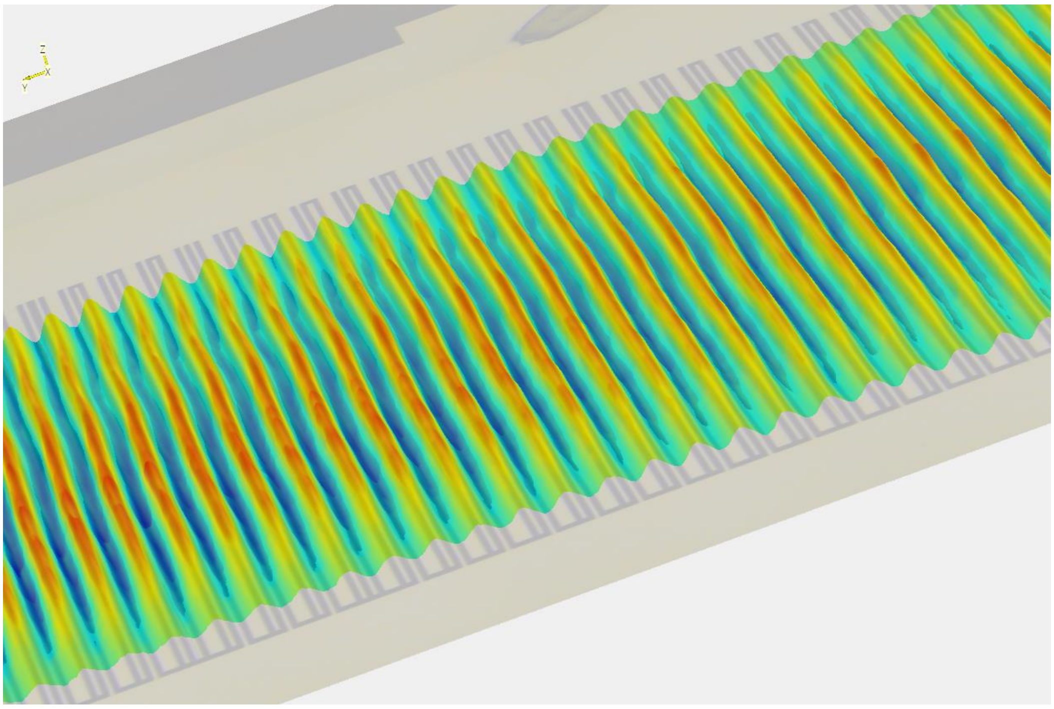

Figure 7: Spread of surface waves on a SAW component at 114 MHz, amplitudes are in the range of < 200pm.

For microsystem technology, microscopically small devices with ultra-high-frequency mechanical movements pose great technological challenges when it comes to examining them directly and without contact. This includes GHz frequencies, sub-picometer amplitudes, and mechanical dimensions in the range of a few micrometers.

An innovative interferometer design enables easy non-contact measurement of such movements at frequencies of up to 2.4 GHz and amplitudes in the sub-pm range, as well as its visualization in "slow motion" (Figure 7). The wide frequency range of such a measuring system makes it possible to examine high-frequency RF MEMS as well. The high lateral resolution is crucial for examining and characterizing the system dynamics with short vibrational wavelengths, such as SAWs or BAWs. Vibration measurement systems of this kind are also suitable for characterizing high-performance ultrasound transducers with high precision due to their wide velocity range.

Introducing VibroFlex:

The new Polytec VibroFlex laser Doppler vibrometer is a modular high-performance solution for non-contact vibration measurement.

It offers unrivalled measurement performance and versatility for solving pressing vibration issues in both R&D and industrial quality control.

The VibroFlex family includes the front-end VibroFlex Connect and a selection of non-contact laser sensor heads. Integrated with the VibSoft data acquisition and analysis software, the vibration measurement system is ready to go. Study acoustics, dynamics and vibrations on nano to macro structures without contact and with laser precision.

Benefits:

- High-performance non-contact vibration measurement solution
- Flexible, modular sensor solution that adapts to your needs
- Sub-pm displacement resolution and vibration velocities up to 30 m/s
- Configurable bandwidth from DC to 24 MHz with highest time resolution
- Sensor heads with auto- and remote focus for excellent signal quality
- Compact sensor head with integrated camera for precise laser positioning and sample monitoring
- Differential fiber optic sensor head for separating relative motions
- Reliable measurement even on challenging surfaces (dark, oily, shiny, hot)
- Digital data interface for convenient setup and best SNR

Learn more about at: www.polytec.com/vibroflex

Conclusion

Laser vibrometers are an indispensable and reliable tool for understanding vibrational behavior in countless applications ranging from the characterization of microstructures to high-performance, fully automated measurement of entire vehicle bodies. Its non-contact and therefore non-invasive characteristics often mean that vibrometry is the only possible solution for challenging measuring tasks, and its ease of use and efficiency easily exceed conventional methods in a wide range of applications.