Polytec

Optimization of Ultrasonic Instruments

Field of Application

- A Aerospace
- B Audio & Acoustics
- C Automotive
- D Data Storage
- G General Vibrometry
- M MEMS & Microstructures
- P Production Testing
- S Scientific & Medical
- T Structural Testing
- **U Ultrasonics**

Improving the Safety, Reliability and Performance of Ultrasonic Instruments for Medical Use

Ultrasonic imaging methods have been in use for many decades and are now an indispensable standard diagnostic tool in hospitals and in almost all doctors' practices and medical clinics. The next step is the use of ultrasound-supported or ultrasonics-based instruments in the operating theater and during outpatient treatment.

The Aim: Verifiably Safer Design and Performance Optimization of Medical Ultrasonic Instruments

Two different applications can be distinguished from one another:

1. Invasive instruments providing direct mechanical contact
2. Instruments with an indirect mode of action focusing ultrasound energy for either imaging or treatment of a condition

The first group includes ultrasonic scalpels, coagulators, aspirators and instruments for intravenous thrombus removal, liposuction and dental plaque removal[1]. Common to all of them is that they come into direct contact with the tissue. If an instrument fails, for example due to fatigue, instrument fragments or detritus can remain inside the patient and cause acute or long-term injury. This must be absolutely avoided by the correct design and application of the instrument.

The second group includes instruments for shock wave therapy and for the application of focused ultrasound energy (HIFU). Here the site of the generation of the ultrasonic energy and its intended effect are spatially separated from each other. Efficiency and spatial precision play a greater role. The risk due to mechanical failure of the ultrasound generator is much smaller.

Use of Laser Doppler Vibrometers

The following properties of laser-based vibration measurement are highly advantageous regarding the development of ultrasonic instruments in medicine:

- Complete freedom from the effects of contact feedback: The vibration of the test object is not influenced by the measuring instrument.
- High spatial resolution: Due to the high frequencies and often filigree-type structures, it must be possible to precisely spatially resolve deflection shapes in measurements. For example, the laser, with its few µm diameter beam is able to measure thin cuts or wires.
- The possibility to measure in transparent media, for example when considering the influence of damping

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- The ability to measure high frequencies: In principle there is no frequency limitation. Currently the highest mechanical vibration frequency that can be measured is 1.2 GHz.

Verification of Finite Element Models using Scanning Vibrometry

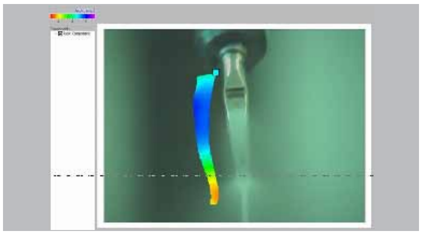
A simulation model is generally used when designing an ultrasonic tool. It is then verified during the prototype phase. The ultrasonic cutting process works at high energies, therefore non-linear behavior is to be expected when cutting, which testing can confirm.

Scanning vibrometry is ideally qualified for verification of these FE models

- The method is point-oriented. A laser (or in the 3-D-process, three lasers) automatically scans the surface of the measurement object at specified points and measures the local vibration. The point measurements are then combined to represent a deflection shape.
- The measurement grid is taken directly from an FE mesh. If the prototype is subjected to broadband excitation, then a deflection shape (amplitude and phase) is obtained for all excitation frequencies. After mode extraction using a modal analysis program, the agreement with the model is determined, for example as a MAC value (Modal Assurance Criterion).

Example: Dental Scaler Instrument

The laser of the scanning vibrometer measures the surface of a dental ultrasonic scaler.



Snapshot of the 3-D animation, together with the video image of the scaler tip.

Application Examples for Invasive Instruments

FE Model Update

As the measurements are taken directly at the nodes of the FE mesh, a highly effective model update is possible by inputting certain measured parameters, for example the damping values.

A great advantage here is that the vibrometer can also reveal characteristics that are difficult to model. For example with thin components, such as wire actuators or blades, there is a risk of mode coupling, i.e. the actually desired longitudinal mode of the actuator excites a parasitic mode (e.g. a bending mode), which then leads to high stresses in the component and consequently to an early failure.

It is difficult to model the coupling because it is dependent on the damping properties. Measurements with the scanning vibrometer illustrate this behavior directly and thus provide insight for component optimization.

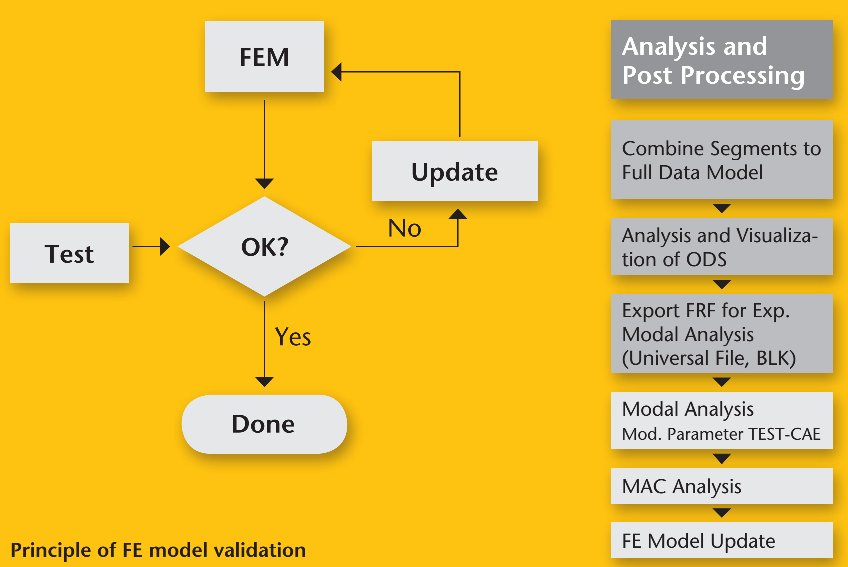
Efficiency Optimization

The optimal operating frequency can be determined based on the distribution of amplitudes of the various modes. First, conclusions can be drawn about the uniformity of the deflection shape. Second, it can be seen directly whether for a certain frequency the maximum energy can be directed to the desired location, for example to the blade's cutting surface. This will determine if the active surface is located at an anti-node or not.

Reliability

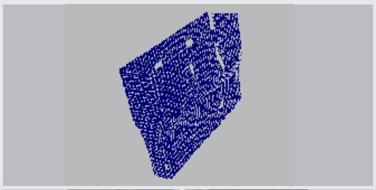
Where medical devices are concerned, safety is priority one. The fracture of a blade during an operation can have fatal consequences and dire financial repercussions for the instrument manufacturer. Hence reliability and with it a determination of the maximum stresses during operational conditions is an essential task. It is also important to document this step so that in the ever-increasing numbers of compensation claims, evidence can be provided that the product was designed according to the state of the art.

3-D scanning vibrometry also offers the possibility to measure dynamic stress and

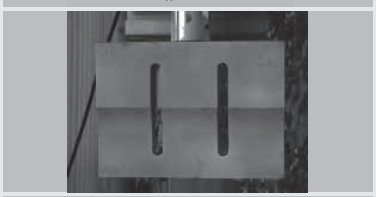


Principle of FE model validation

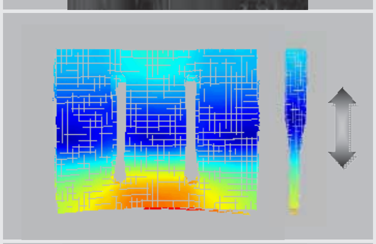
Method Toolbox: Integration of 3-D Measurement Grids



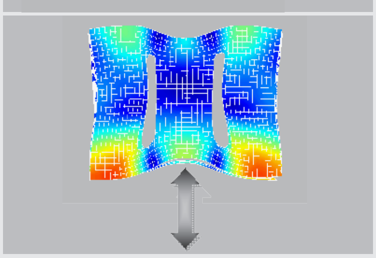
The measurement mesh of an ultrasonic tool tip in this case is determined by precise geometry measurement using triangulation of the three PSV-3D laser beams.



Alternatively the mesh can be imported from the FE program into the measuring system and then aligned with the measurement object using a number of reference points.



Example of a desired deflection shape: The deflection shape measured at 20 kHz largely corresponds to the vibration necessary for the desired process (arrow direction). The movement is fairly uniform over the whole length of the active surface.



Example of an undesired deflection shape: At a somewhat higher frequency, another mode occurs in the foreground, which superimposes a bending eigenmode on the active movement. This means that unsatisfactory results can be expected.

strain distributions and compare them with calculated values. To do this, the relative elongation between measurement points is calculated from measured dynamic displacements using measurement mesh geometry, thus presenting the stress and strain distribution.

Verification of Specifications

Design parameters such as frequency and amplitude can be simply and reliably verified using single point laser vibrometers. This applies both during the development phase as well as during production, so that 100% proof of specification is possible for every part.

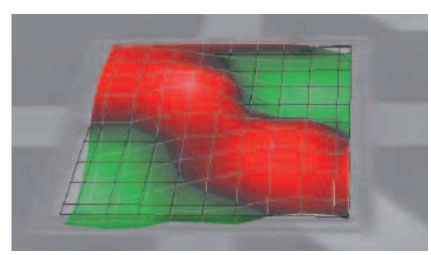
Application Examples for Instruments with an Indirect Mode of Action

In contrast to invasive instruments, diagnostic ultrasonic instruments and imaging processes are generally equipped with transmitter and receiver units, the vibration behavior of which can be characterized.

Typical transmitters are micro-fabricated ultrasonic transducer arrays (PZT ceramic, capacitive cMUTs or piezoelectric pMUTs). Here laser vibrometry provides detailed recordings of the temporal behavior, which can be used for wavefront correction and provide information about the crosstalk behavior[2] between elements.

Experimental testing is being carried out in various work groups with the aid of laser vibrometers as a step to a faster FE model update. The realistic measurement values obtained in this way mean the effects of ambient parameters and fabrication deviations can be more easily estimated[3].

The higher frequencies of transducers that are now being developed with the aim of higher spatial imaging resolution present no obstacles. The UHF-120 ultra-high frequency vibrometer system from Polytec, with its maximum bandwidth of 1.2 GHz, permits the analysis of primary actuators in the high MHz range plus their harmonics. The scanning approach means that the vibration modes of an array are measured over a surface.

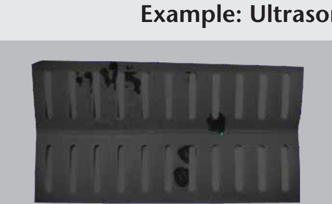


Vibration measurement of a pMUT[4] using the MSA-500 Micro System Analyzer

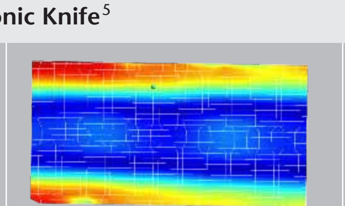
The spatial resolution obtained with this approach is less than one µm.

The sound field originating from ultrasonic transducers can be measured using scanning laser vibrometers as can wave propagations using time domain animations of for example pulses generated by a ultrasound imaging transducer array. It can also be used to determine the influence of the ultrasound energy focused through or on to the surface being treated by measuring the vibration of a phantom.

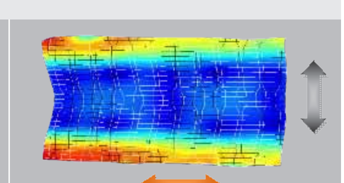
Example: Ultrasonic Knife[5]



Blade of an ultrasonic knife.



RMS distribution (effective amplitude values) of the vibration after measurement with the 3-D Scanning Vibrometer.



Deflection shape at 22.4 kHz: The motion is almost entirely in the direction of the orange arrow, perpendicular to the cutting direction (gray).

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Instruments

Depending on the application, various measuring instruments are available. Single-point vibrometers permit measurement of the amplitude at one point and are used in the verification of specified characteristics (amplitude, frequency). They vary in terms of bandwidth and the direction of the measurement (in-plane, out-of-plane or all three components, 3-D).

Scanning vibrometers are used to measure complete deflection shapes dependent on the frequency. Due to the surface-based measurement principle, the data obtained are suitable for the validation of FE calculations. Out-of-plane systems (PSV-400) and three-dimensional measuring systems are available for this purpose, and their measurement data can also be used to calculate the dynamic stress and strain distributions.

Vibrometer model	PSV-400	PSV-400-3D-M	OFV-534 / OFV-5000	OFV-3320	UHF-120-SV
Property					
Out-of-plane measurement	•	•	•		•
In-plane measurement		•		•	
Surface measurement	•	•			•
Point measurement	•	•	•	•	•
>1 MHz vibration frequency	•		•		•
>24 MHz vibration frequency					•
Laser spot size <2 µm			•		•
Measurement in liquids	•	•	•	•	•
Application					
FE comparison	•	•			•
Mode coupling		•			
Parameter verification (amplitude, frequency)	•	•	•	•	•
Timing	•	•	•	•	•
Imaging arrays (PZT ceramic, cMUT, pMUT)	•		•		•
Sound field visualization	•				
HIFU (high vibration amplitudes)	•				•

Summary

Laser vibrometry is ideally suited as a tool for the verification of FE simulations both for invasive and diagnostic medical ultrasonics instruments. Thanks to its linearity well into the high MHz range and the complete lack of feedback effects, coupled with high lateral resolution, this technology is suitable for nearly all structural dynamic tasks. Calculation methods derived from the basic technology for sound field visualization and for fatigue strength (strain/stress) add further applications.

Consequently laser Doppler vibrometry is a tool suited to the development of efficient, reliable and effective instruments for the doctor and surgeon.

References

1 Lea, S., Laser vibrometry helps to improve the effectiveness of dental ultrasonic instruments. LM INFO Special 2/2005, Polytec, Waldbronn, 2005.

2 Zhuang et al., “Biocompatible coatings for CMUTs in a harsh, aqueous environment”, J. Micromech. Microeng. 17 (2007) 994–1001

3 Dooby et al., Modeling and characterization of CMOS-fabricated cMUTs, Journal of Microelectromechanical Systems, Vol. 20, No. 1, Feb. 2011

4 Chou et al, Vibrational Analysis of Ultrasonic Transducers for Medical Imaging, InFocus – Optical Measurement Solutions, Issue 1/2010 – ISSN 1864-918

5 W. Littmann, J. Twiefel, „Modellierung und Messung von Dämpfung in der Ultraschalltechnik“, 2. VDI-Fachtagung Schwingungsdämpfung, VDI-Berichte 2164, S. 81 ff. (2011)

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