Tutorial

Validating complex models accurately and without contact Using Scanning Laser Doppler Vibrometry (SLDV)

Vibrometry best practices guide and illustration for relevant application examples

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ABSTRACT
The need to validate simulation models of complex mechanical structures has grown in importance for efficiency in the design process. This is especially true for non-linear structures (such as composite panels and jointed components) where it is critical to use an accurate full-field measurement method. This tutorial covers a how-to-guide and use-cases of Scanning Laser Doppler Vibrometry (SLDV) as a non-invasive technology to efficiently characterize critical mechanical structures.

KEYWORDS: vibrometry, non-contact, FE model validation, vibration measurement, quality control

INTRODUCTION

All mechanical structures fail sooner or later if the applied forces exceed the structural limits. What are these limits? How can they be established? What types of forces can be tolerated? These are questions design engineers ask themselves continuously. For example, this is important for aerospace, automotive, for the development of medical devices, civil engineering, consumer electronics and many other applications.

Simulation models that predict the dynamic behavior of critical structures are the bread and butter for the design engineer. These models not only enable safe designs but also give the engineer the capability to optimize for weight, efficiency and performance. Needless to say, the models require accuracy. But how accurate do they need to be? How many prototype iterations need to be tested and evaluated until the final product can be released? Polytec provides state-of-the-art metrology to help the design engineer of today to test and optimize their designs. Non-contact laser Doppler vibrometers have been used in many industries for over 30 years and are continuously adapting to the ever-changing needs of the research and development process. The ability of laser vibrometry to provide fast, accurate measurements and map full-field responses as deflection shapes is instrumental for the short development time frames required in industry.

The diversity of vibrometer applications becomes evident when considering the versatile nature of laser light. Measurements are possible up to several GHz frequencies and down to the sub-Hz range with a flat frequency response and no mass loading. Any surface can be measured as long as there is visual access (even through glass and in water). Large objects like bridges and buildings can be targeted from as far as several 100 meters. Microstructures can be characterized underneath a microscope. There are no measurement restrictions due to an object’s surface color, texture and curvature as long as there is some light being reflected back into the optics of the vibrometer. Furthermore, since the Doppler shifts are sensitive to variations of the refractive index of the medium, vibrometers are capable of directly measuring sound field distributions in water or in air using a technique called Vibro Refractometry.

The purpose of this tutorial is to provide general guidance to the user for making effective, accurate measurements using vibrometry. The tutorial also helps the user gain a basic understanding of the working theory of vibrometers that will enable him/her to generate test data efficiently. A best practices guide and measurement examples are included.

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TEST CASE SCENARIOS FOR VIBROMETRY

Choosing the correct vibrometer system as well as the best setup and measurement parameters can be straightforward once the purpose of test is defined. The most common test scenarios are as follows:

1. **Finite element (FE) model validation**. Finite Element models are compared side-by-side with full-field 3D vibration data to see how well they match. This requires a high fidelity of the data. In order to compare the experimental modal parameters with the simulation, the vibration data needs to be curve fitted. For most accurate curve fitting, not only the resonance peaks need to be resolved clearly but also the response behavior of the anti-nodes, which, by nature, exhibit a much lower vibration amplitude. Some examples of model verification are shown in the following sections for turbine blades.
2. **Non-destructive evaluation (NDE)**. The location of defects can be determined by sending traveling ultrasonic waves through a material and seeing how they interact. A very high sensitivity vibrometer is required as the surface displacement of ultrasonic waves are very small (nm or even pm level) and a large amount of points needs to be measured for visualization. Lack of sensitivity can be compensated by averaging, however, that will result in longer measurement times. Please see application example 2 for more details on NDE applications.
3. **Troubleshooting**. Finding an unwanted vibration for complicated structures can be difficult if you don't know where to look. For example, in the case of electronic circuit boards, the acoustic noise emission can be excessive or damage the board. Vibration data quality is not as critical as in the case of modal validation as long as the vibration signature of the disturbing behavior is evident. A 1D scanning measurement and in some cases, spot checks with a single point vibrometer at only a few locations is sufficient.
4. **Performance validation**. Determining if the design performs as expected is a critical aspect of R&D. For instance, verifying the efficiency of ultrasonically driven devices like an imaging arrays, cutting tools or surgical tools can be critically important. Model validation is required in some cases but mostly it is the performance parameters like frequency and vibration amplitude that are critical.
5. **Quality control**. Verifying that a product does not have defects for in-line manufacturing can improve yield. This can be true for mechanical structures such as bearings, motors, pumps, etc. In quality control usually only one location and one measurement is acquired. Measurement speed is of the essence to allow for maximum throughput.
6. **Basic research / learning from nature**. Vibrometry is used widely by many university labs and institutes for research. Often the mechanical behavior of a structure is typically not known beforehand. Thus, vibrometer systems provide important insights into the complex mechanical vibrations of experimental structures.

MEASUREMENT PRINCIPLE OF A VIBROMETER

A laser Doppler vibrometer uses the light-based Doppler effect to determine the frequency and amplitude of an object's motion in velocity, displacement and acceleration. It is a point-and-shoot approach allowing for instant reading and recording of a vibration signal wherever the laser beam is pointed at.

Figure 1 depicts the optical layout of the laser Doppler vibrometer sensor head with laser source, interferometer and photo-detector. The measurement beam is pointed at the vibrating sample while the reference beam stays within the vibrometer head. The reflected light from the sample is captured by the photodetector where it is re-combined with the reference beam. The returned light is Doppler shifted in frequency by f_D, which is directly proportional to the object's instantaneous velocity v according to the relationship in equation (1) below.

$$f_D = \frac{2 \cdot n \cdot v}{\lambda}, \qquad (1)$$

where λ is the wavelength of the laser source and n the refraction index of the medium the sample is contained in. Due to the simplicity of the optical design, vibrometers are accurate and versatile. The vibrometer is based on interferometry (measured against the wavelength of light) and is calibration free. In fact, it is used for primary calibrations of accelerometers. The interferometer is heterodyned by means of an acousto-optic modulator (Bragg cell) as depicted in ***Figure 1***. The vibrometer measures directionality of movement and achieves highest possible SNR even at low frequencies.

The electronics portion of the laser Doppler vibrometer takes the modulated carrier signal from the photo-detector and demodulates it for displacement using the ArcTan(I/Q) method. From this, velocity and acceleration can be derived easily. Since the demodulation occurs in the frequency domain, any amplitude fluctuations in the returned light intensity will not introduce any noise onto the vibration signal, similar to the benefits of FM radio versus AM radio.

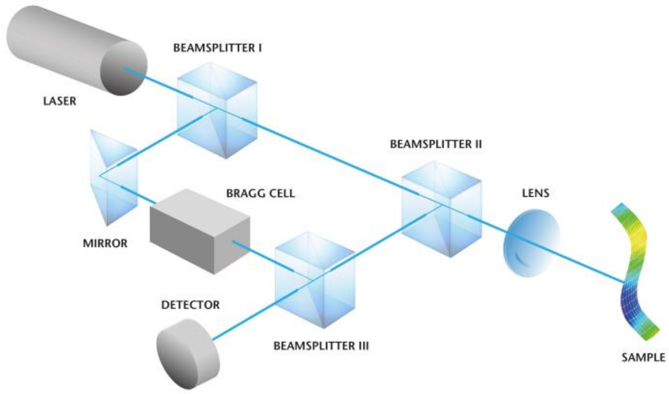

Figure 1: Optical layout of a laser Doppler vibrometer.

In contrast to the heterodyne approach, as described above, a homodyne laser Doppler interferometer does not include a Bragg cell. The Doppler shift in frequency will be positive no matter in what direction the sample is moving, thus a homodyne vibrometer will not be able to inherently provide directionality information. Also, the noise floor of a homodyne based vibrometer is typically higher at low frequencies. Yet another approach is the so called self-mixing interferometer. With the advent of solid-state diode lasers, a compact setup became possible: the light reflected from the sample interferes in the laser cavity leading to a modulation of the properties of the diode laser. This modulation can be detected and decoded to derive the displacement information. The phase noise for this technique tends to be higher compared to homodyne or heterodyne interferometers using external laser sources. For the purpose of this tutorial, only heterodyne laser Doppler vibrometers as depicted in ***Figure 1*** are considered.

There are two basic vibrometer types based on laser wavelength: 1) Helium-Neon (HeNe) laser based vibrometers (633nm) and 2) infrared (IR) solid state laser based vibrometers (1550nm). Each type has it strength and weaknesses. The following overview shall provide the user with a guideline on when to choose which one:

1. Due to a short wavelength and very low phase noise of the HeNe laser tube, HeNe based vibrometers have excellent sensitivity on surfaces with high reflectivity. They also work very well on submersed structures as long as the liquid is transparent. Visible laser based vibrometers are recommended for applications requiring high beam positioning accuracy. Microscope based vibrometers provide a submicron laser spot diameter, which is necessary for characterizing many microstructure devices.
2. IR laser based vibrometers operate with a longer wavelength, which are less sensitive when compared to the HeNe based design. However, the IR laser based vibrometer performs better on surfaces with low reflectivity or at long stand-off distances. This is due to higher laser power (while still being eye-safe) and lower shot-noise on the photo-detector. IR laser based vibrometers require a pilot laser for positioning which makes for a more complex vibrometer design. IR based vibrometer are not able to measure on submersed structures as the absorption of IR light is too high.

There are some applications where either vibrometer system would work and the HeNe based vibrometer is preferred due to its lower price point. Both vibrometer types employ the highest power laser possible while being eye-safe. Increasing laser power to a non- eye safe laser class is not advised for lab environments, although it would theoretically provide even better signal-to-noise ratio (SNR).

CHOOSING A VIBROMETER CONFIGURATION

In order to serve a wide range of applications, a variety of vibrometers are available. Single point vibrometers measure at one location only while full-field vibrometers measure a grid of measurement points upwards to 1000s of locations.

A single point vibrometer measures the vibration behavior of the test structure at a single laser spot location and in the direction of the laser beam. If the vibration vector is not parallel to the laser beam, the vibrometer will measure the component of the vibration vector that is projected onto the vector pointed along the direction of the laser beam. Complex structures move in multiple axes that need to be characterized with a 3D vibrometer. A 3D vibrometer, also called a tri-axial vibrometer, consists of 3 single point vibrometers, which are pointing towards the same measurement location but at different angles. Using a coordinate transfer the orthogonal x, y and z vibration components can be calculated. Durability tests of small PCB-mounted components or bonding wires are a typical application for 3D vibrometry.

A rotational vibrometer measures the rotational dynamics of rotating objects (such as a shaft or a spindle). The rotational vibrometer consists of two vibrometers in parallel and is aligned perpendicularly to the rotation axis. This unique design measures RPM, dynamic angle and angular velocity independent of the shape of the object or linear background vibration.

Full-field vibrometers measure a grid of points across a surface either sequentially using beam steering mirrors or simultaneously using a multi-sensor arrangement. In the case of a SLDV, a phase reference needs to be established to correlate the phase of the measurement points and to animate the deflection shapes. The phase reference can be the waveform driving the source of vibration, a voltage pulse from an impact hammer or a trigger signal. When working with complex structures, the SLDV requires geometry measurements for each point in the measurement grid. Alternatively, the SLDV can import a given mesh of points from a model and align itself with the coordinate system of the test structure. Maintaining a consistent coordinate system is critical especially when measuring an object from different sides and stitching scan data together.

OPTIMIZING SETUP AND TEST PARAMETERS

Measurement quality and noise floor are directly related to the amount of return light captured by the vibrometer. This doesn't mean that measurements with low return light are invalid. Vibrometer accuracy is not affected by the amount of return light unless the SNR is low. Every vibrometer is equipped with a return signal indicator called RSSI (Received Signal Strength Indicator). During the measurement setup it is advised to maximize the RSSI as a first priority. This can be done by properly focusing the beam, choosing an appropriate stand-off distance and optimizing angle of incidence.

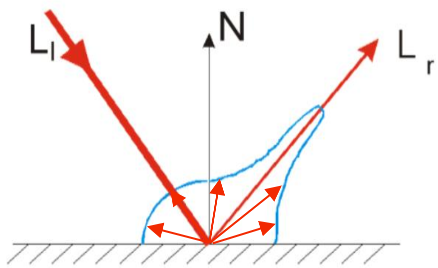

Figure 2: Light scattering distribution on a rough surface.

Figure 2 above depicts a typical light scattering distribution on a rough surface. L_l is the incident light beam and the blue outline represents a typical light scattering distribution over all angles. As is obvious intuitively from ***Figure 2***, the preferred scattering direction (L_r) is at equal angle as the incoming beam. Measurements at an angle are possible with the IR vibrometer. However, a normal incidence provides the best SNR. All surfaces (including black surfaces) reflect light back. The following rule of thumb can be applied: if the laser spot can be seen by eye, the vibrometer is able to capture enough return light for a valid vibration signal in most cases.

The second priority of the setup is the optimization of the demodulation bandwidth. The demodulation bandwidth is directly correlated with the frequency range and the amplitude of the vibration. Minimizing frequency and velocity range on the demodulation side will automatically optimize the SNR.

Although laser light works well for vibrometry, speckle movement is a physical limitation that has to be considered when the test object exhibits large lateral movements. This is not a limitation of the vibrometer design but it is inherent for laser light scattering off a rough surface. For coherent light, constructive and destructive interference of reflected light generates a speckle pattern in the image plane. As the test object moves laterally, the speckle pattern moves as well, which can lead to temporary dropouts that manifest themselves as spikes in the measured vibration signal. In the early days of vibrometry, spikes in the velocity signal used to dramatically reduce the SNR, but current state-of-the-art technology doesn't exhibit dropouts for most applications. Polytec's upcoming generation of vibrometers will allow measurements without dropouts even under extremely challenging measurement conditions.

As mentioned above, measurement speed is affected by the number of required averages during the signal acquisition if a higher SNR is required. In order be able to minimize measurement time, let's first understand the contributing factors. The total scan time t is calculated in equation (2):

$$t = T * n_p * n_{ave} * OL + t_{add}, \tag{2}$$

where the variables are defined as

T	length of one time record
n_p	number of scan points
n_{ave}	number of averages
OL	overlap factor in percent (applies to frequency domain measurement only)
t_{add}	additional time factors (scanner movement, software processing time, etc.)

T is determined by the required frequency resolution Δf of the test. The relationship is inverse proportional as show in equation (3).

$$T = \frac{1}{\Delta f} \quad (3)$$

A high number of measurement points can be required for the validation of FE models. If the behavior is not known a priori when troubleshooting a part, the optimal number of points needs to be determined experimentally. Averaging helps lower the noise floor and thus improves the SNR but increases the measurement time. Optimizing the vibrometer configuration first will ensure best raw data quality and lessens the need for averaging. Additional time factors like the movement of the scanning mirrors and software processing can usually be neglected. Current scanning mirror technology allows for scanning up to 30 points per second. Completing scans of several thousand measurement points within a few minutes is possible, especially at high frequencies.

In a typical NDE scenario for measuring an ultrasonic traveling wave, scan grids using up to 1000's of points are often used. For a 100kHz ultrasonic transducer, an FFT measurement with a frequency resolution of 10Hz should be sufficient. Using 5 averages and a 50% overlap, the estimated measurement time is 500 seconds, which is equal to 8 minutes. In the case of a modal test of a large structure, 250 points are often sufficient. With a required frequency resolution of 1Hz (e.g.) and 5 averages, the measurement time would be 10 minutes.

In contrast to scanning vibrometry, image-based techniques for capturing vibrations, like e.g. digital image correlation (DIC), capture the entire area at once. However, post-processing times can be significant. The displacement resolution of a DIC measurement depends on the field of view. In case the vibration amplitudes are in the µm range DIC usually achieves sufficient SNR. However, DIC requires surface preparation with a speckle pattern to resolve deflection shapes. Importantly, the latest advances in vibrometry make it possible to measure successfully without any surface treatment.

APPLICATION EXAMPLE 1: MODAL TEST ON A TURBINE WHEEL [1]

During the design phase of turbine blades, a FE model is created using material parameters and boundary conditions. Once the first prototype is built, a modal test is performed allowing the design engineer to update the FE model. SLDVs provide the same high fidelity of FE modeling regarding the number of actual FRFs as the response can be measured at a high density of points. This eliminates the need for data interpolation. As laser Doppler vibrometry doesn't add mass to the structure, the measured frequency response functions (FRFs) represent the actual behavior of the blade and do not need to be corrected for any mass loading effects. The IR vibrometer is the ideal choice as no surface treatment is necessary for the measurement.

Figure 3 depicts a turbine wheel with 17 individual blades. The measurement grid was derived from the FE grid and coarsened to the necessary number or nodes for the test. As the wheel is lightly damped, accurate modal testing requires special care during the setup. Instead of attaching a shaker for excitation, an excitation method without mass loading is recommended. In this experiment an automated impact hammer from NV-Tech was used. The hammer head contained a force cell measuring the input force for each measurement point. Calculating the FRFs from the vibrometer response and the input force provides a normalized result. When exciting non-linear structures like composite panels or jointed structures, it is critical that the impact force is consistent during a scan such as to obtain high-fidelity FRF results and clean deflection shapes.

Figure 4 shows the average FRFs in the x, y and z directions across all measurement points. The narrow resonance peaks are a clear indication of low damping. ***Figure 5*** shows the deflection shape of the entire wheel at 700Hz. The modal assurance criteria (MAC) in ***Figure 6*** confirms that there is a good correlation between simulation and measurement.

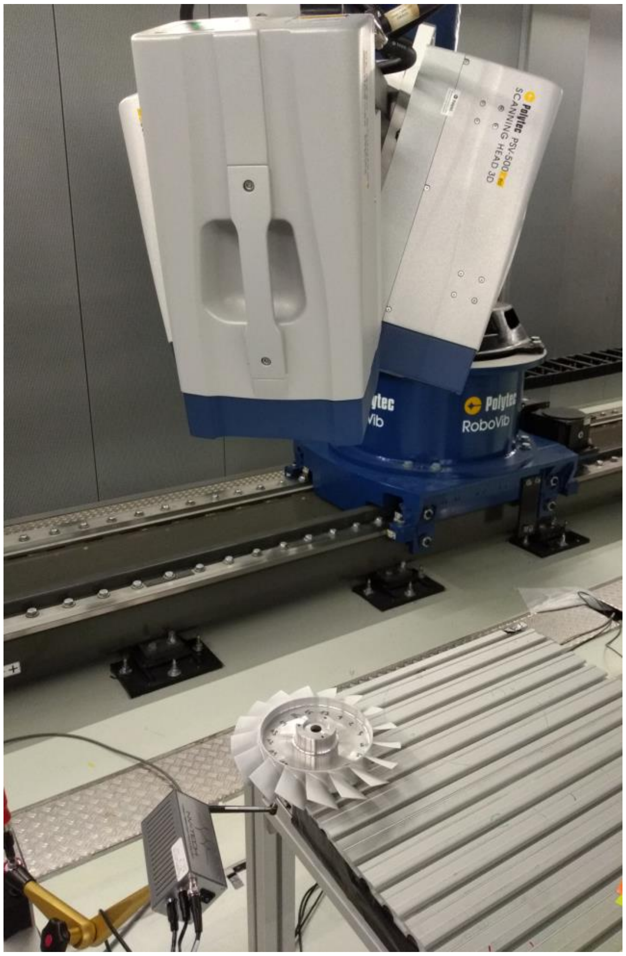

Figure 3: Experimental setup of a 17-blade turbine wheel with PSV-500-3D SLDV.

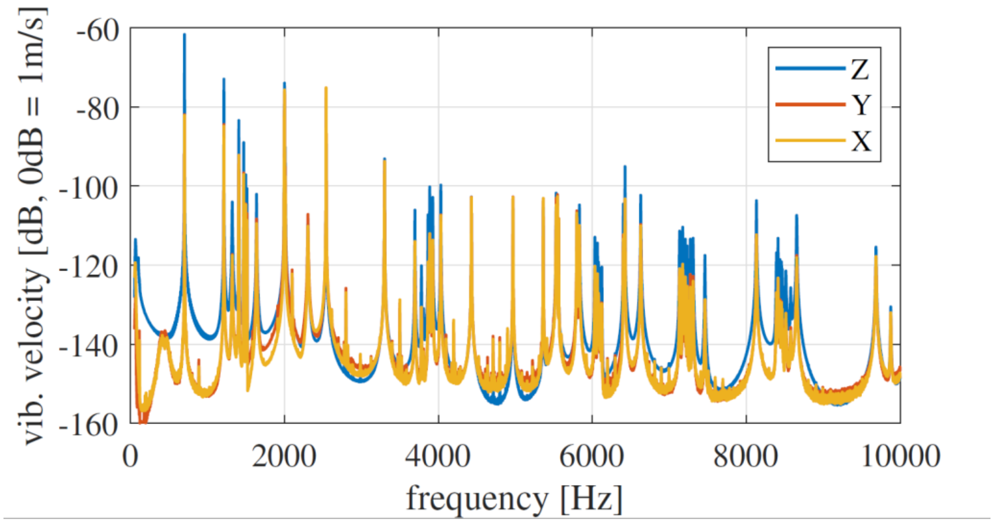

Figure 4: Average FRF for X, Y and Z across all measurement points.

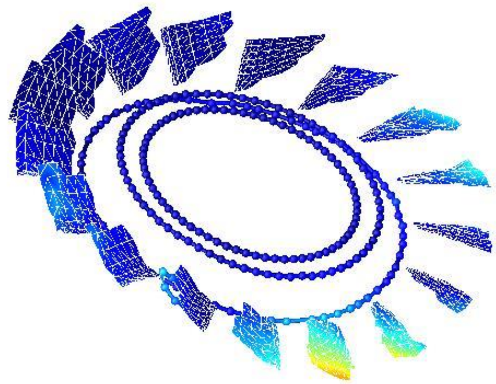

Figure 5: Operational deflection shape (ODS) @ 700Hz.

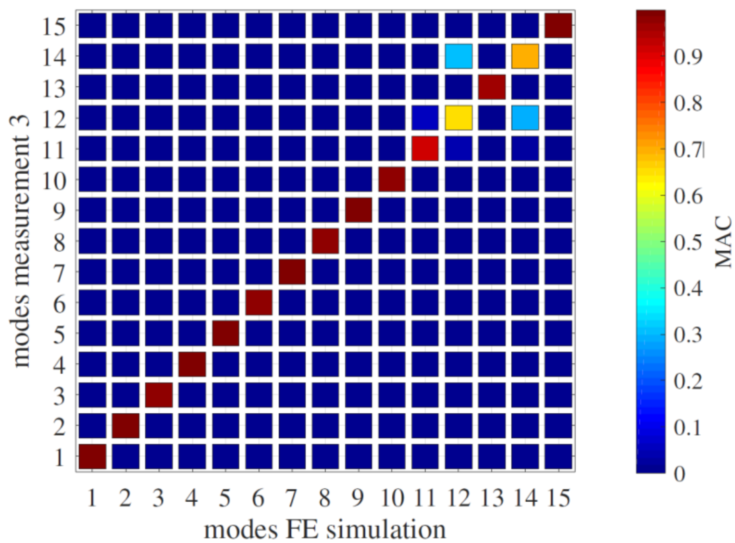

Figure 6: MAC shows good agreement between model and test.

APPLICATION EXAMPLE 2: TRAVELING ULTRASONIC WAVE ANALYSIS

Composite panels are used as lightweight materials for aerospace and automobiles. Defects on composite panels (like impact damage), weaken the structure, although the defect is not necessarily visible upon inspection by eye. For critical composite structures, sensor networks are embedded into the material for real time monitoring. Understanding the ultrasonic wave characteristics is critical for accurate interpretation of the sensor data. ***Figure 7*** shows the impact damage of a panel caused by a wrench being dropped on it. The defect was not visible by eye but could be visualized by capturing a Lamb wave traveling across the plate.

Figure 8 shows a side-be-side comparison of a measured and a simulated ultrasonic wave field across a thin metal plate. The simulated model was created by OnScale, the first Cloud Engineering Simulation platform, combining powerful multiphysics solver technology with the limitless computational power of cloud supercomputers. Zooming into the area of the hole in the center of the plate (***Figure 9***) shows that the ultrasonic wave is perturbed by the presence of the hole. The wave-hole interaction is weak because the wavelength of the ultrasonic wave is quite a bit larger than the diameter of the hole.

In another example, a traveling wave was measured across an aluminum plate that had a crack machined in the back side (***Figure 10***). This measurement allowed the prediction of the wave-crack interaction based on crack length and orientation as can be seen in ***Figure 11***.

The IR SLDV is the best choice for these measurements to improve surface reflectivity. Since the surface displacements can be very small (order of nm), it is critical to set up the vibrometer for best SNR.

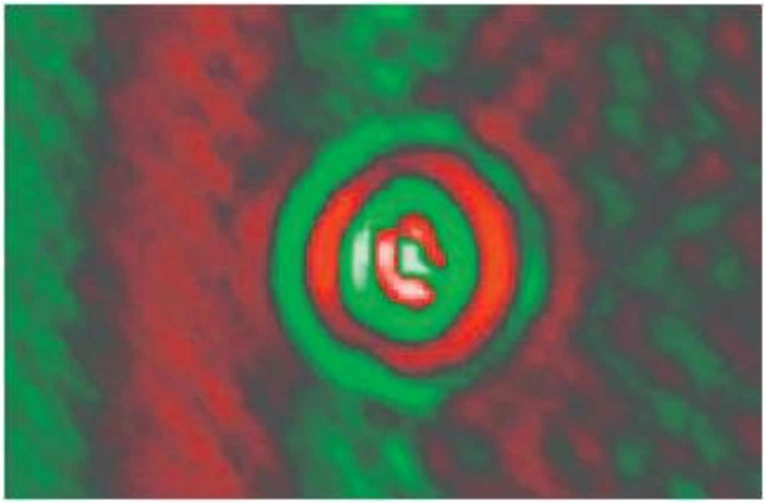

Figure 7: Impact damage on composite panel, visualized by Lamb wave excitation using scanning vibrometry.

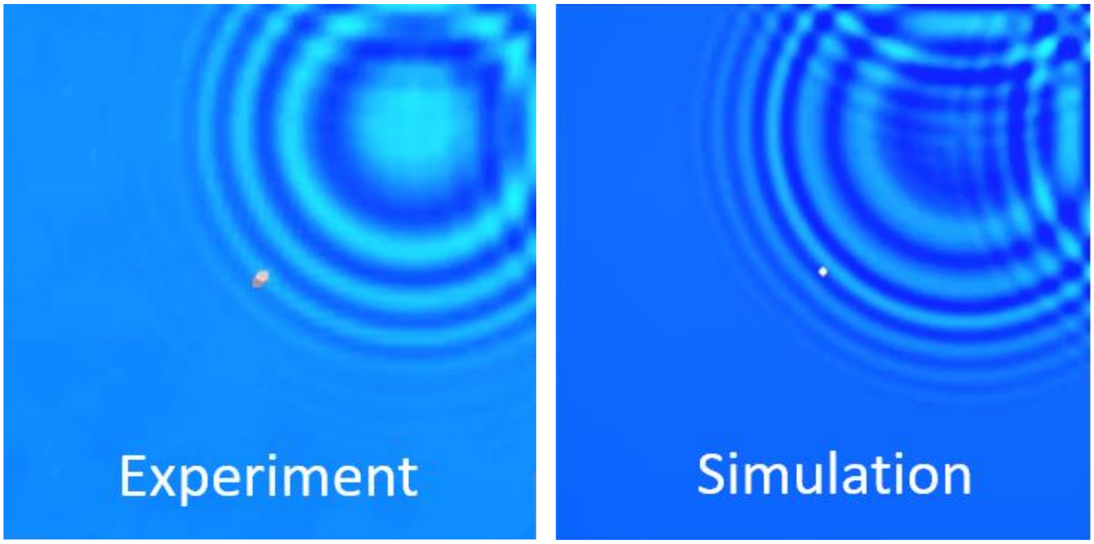

Figure 8: Traveling ultrasonic wave visualization. Measured response (left) vs simulation by OnScale (right).

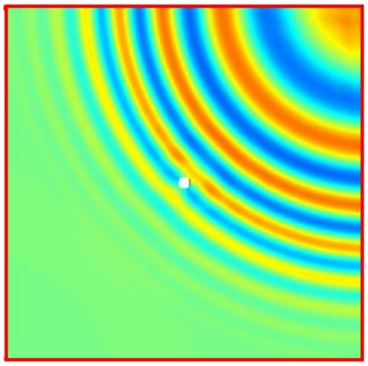

Figure 9: Zoomed in area demonstrating wave interaction with the hole in the center of the plate.

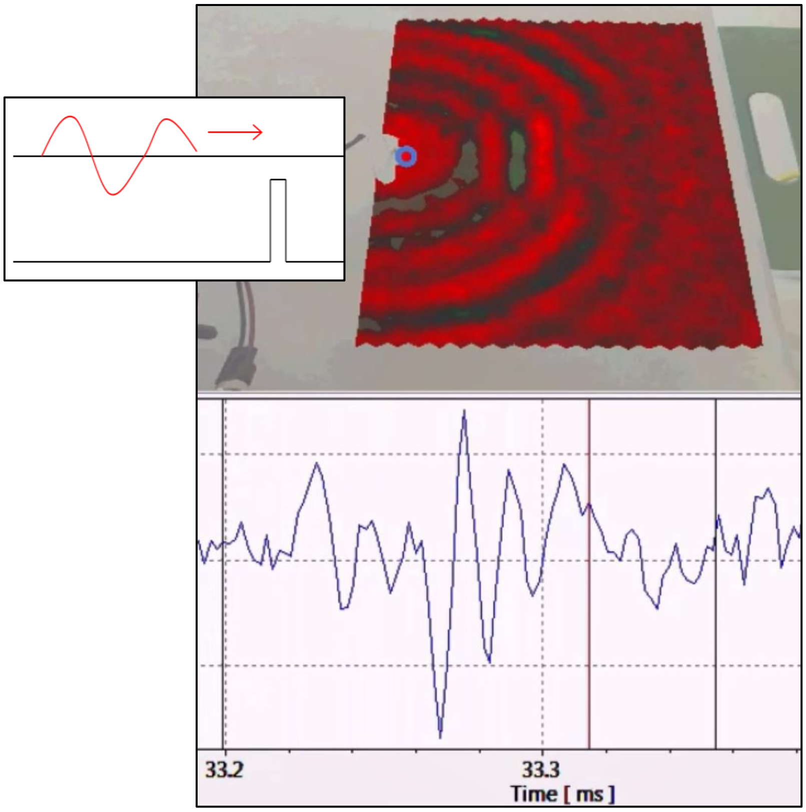

Figure 10: Traveling wave measurement across aluminum plate with crack on opposite side.

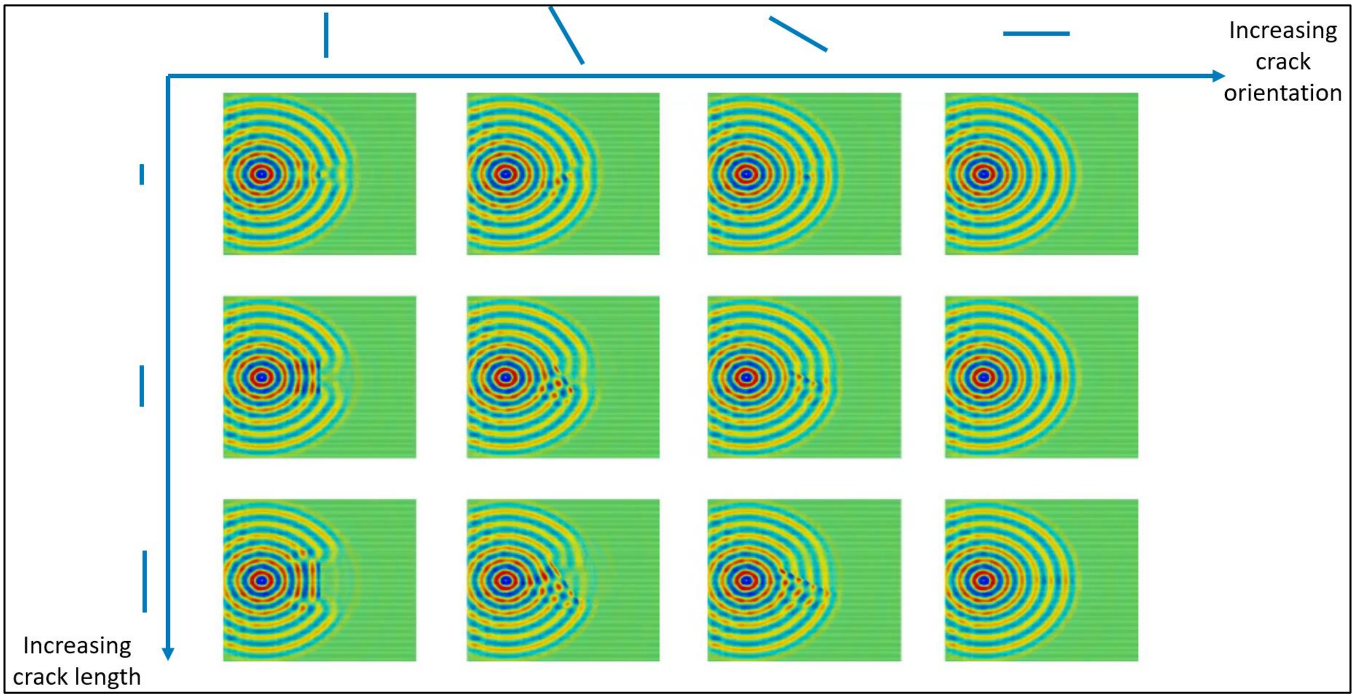

Figure 11: Traveling wave measurement on hidden crack, as simulated by OnScale, allows simulation of various crack configurations.

APPLICATION EXAMPLE 3: DYNAMIC STRESS AND STRAIN CHARACTERIZATION

Three dimensional SLDV data can be used to validate durability simulation models. Determining the location of the maximum stress is essential for the life time of components. In aerospace, turbine blades are conventionally instrumented with strain gauges (
Figure 12) in order to validate strain and stress models and for performing fatigue tests. In contrast to gluing strain gauges to the blade, non-contact vibrometer data can be used to obtain the dynamic strain distribution. As in the case of FE model validation, measuring without contact allows for a direct measurement of the response without having to correct for any mass loading effects.

Because of a small laser spot dimeter (25 – 80 µm depending on stand-off distance) and very accurate beam positioning mechanics of the 3D SLDV, a deflection shape with high spatial density can be measured. By extracting the localized in-plane vibration component, strain values can be calculated for groupings of adjacent points. Overlaying the obtained strain values with an image of the part allows for the visualization of a strain distribution across the object surface. Linear as well as shear strain can be obtained. From the material properties, stress distributions can be calculated as well.

For strain measurements, exact overlap of the 3 laser beams is crucial. For that reason, alignment aides (like the machine vision procedure VideoTriangulation) are available to the user to ensure adequate spot overlap and thus reliable vibration data for the strain calculation. Equally important is the accuracy of the geometry measurement as the distance between adjacent measurement locations factors into the strain equation.

Figure 13 shows the image of an aluminum cantilever beam and the corresponding simulated model. The simulation was performed in a tool called Calculix by Klaus Wittig and measured under shaker excitation using a chirp signal. Strain and stress distributions of that beam are shown in ***Figure 14***, and compared with simulation. The quantitative comparison with a strain gauge (mounted on that cantilever beam at a few select locations) shows good agreement as shown in
Figure 15.

Figure 12: Instrumented turbine blade (courtesy of Vrije Universiteit Brussel, S. Vanlanduit).

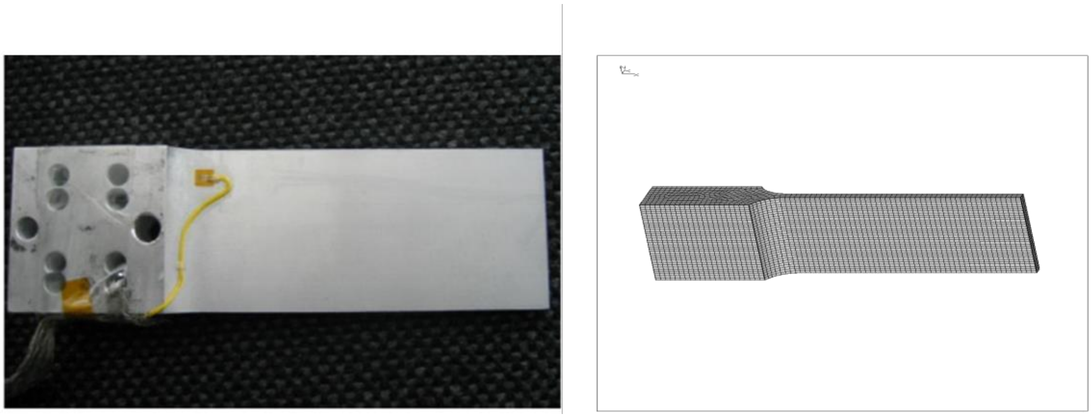

Figure 13: Cantilever sample (left) and the corresponding model (right).

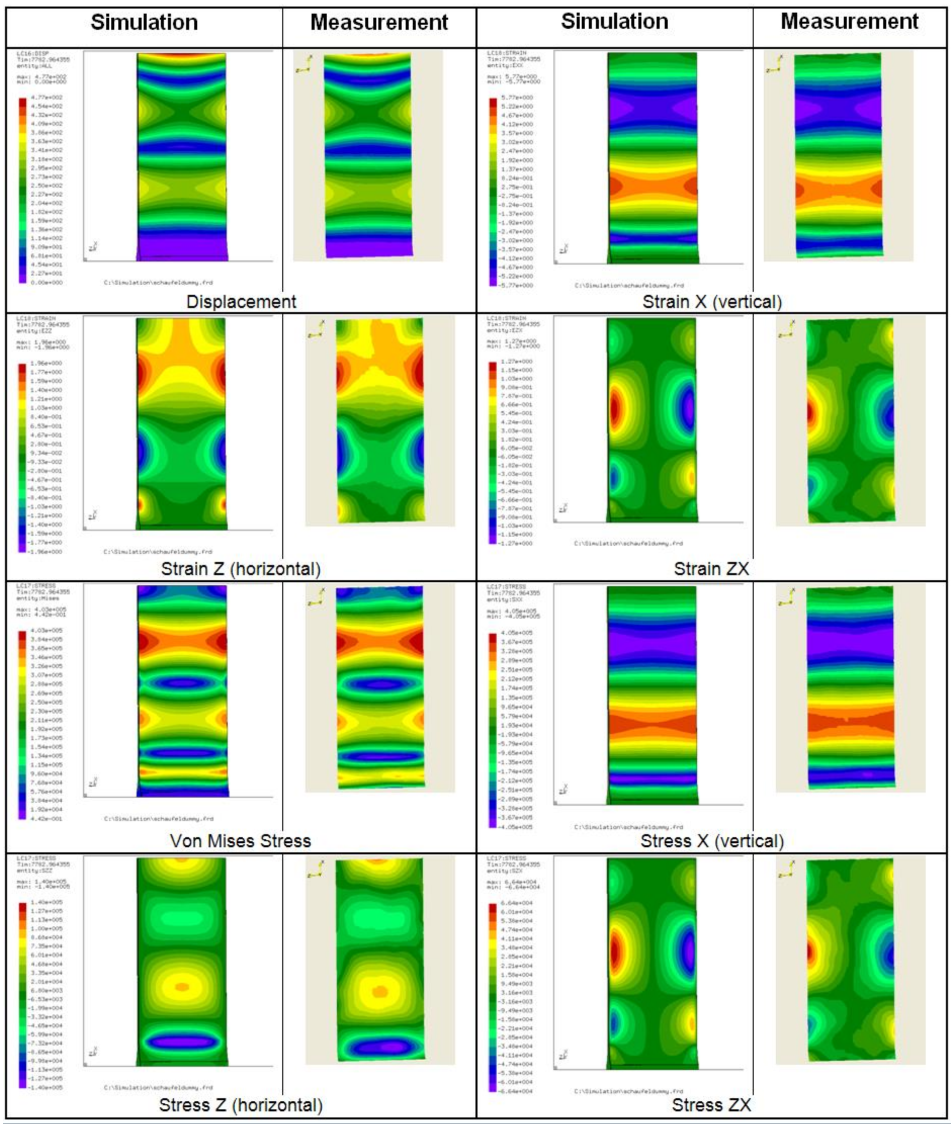

Figure 14: Stress comparison of FEM and test.

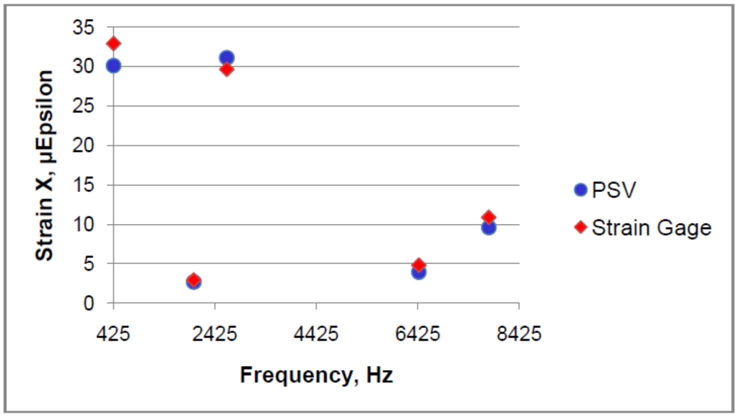

Figure 15: Quantitative agreement of strain gauge data and vibrometer based test results for a few select locations on the cantilever beam.

CONCLUSION

Scanning laser Doppler vibrometry (SLDV) is a unique measurement method that is used across a wide range of industries for FE model validation, NDE, troubleshooting, performance validation, quality control or just basic research. The versatility of SLVD is evident when considering the myriad of applications for characterizing structures. This includes: very large structures down to microscopic ones, frequency ranges from quasi-DC up to GHz, surfaces that are shiny or a dark, hot or cold objects, curved or flat structures, or from close-up or far away. As discussed in this tutorial, choosing the correct vibrometer configuration is critical for obtaining accurate measurement data and fast, effective results.

Polytec offers PolyLab educational program free of charge with the goal to enable students to learn concepts such as vibration testing and modal parameters (natural frequency, damping, and mode shapes) and much more in a fun and exciting experiment. Learn more at www.polytec.com/us/polylab

REFERENCES

[1] Buchwald, P. et al., Experimental and Numerical Modal Analysis of an Axial Compressor Blisk, APVC Sydney 2019
[2] Weisbecker H., Cazzolato, B, Surface Strain Measurements Using a 3D Scanning Laser Vibrometer, 2010 DOI: 10.1007/s11340-011-9545-5
[3] Reyes, J, Avitabile, P., Use of 3D Scanning Laser Vibrometer for Full Field Strain Measurements, DOI: 10.1007/978-3-319-15236-3_19