



Chapter 1

Introduction to Multipath Doppler Vibrometry (MDV) for Validating Complex Models Accurately and Without Contact

Jerome Eichenberger and Joerg Sauer

Abstract The need to validate simulation models of complex mechanical structures continues to grow in importance to increase efficiency in the design process. This is especially true for nonlinear structures (such as composite panels and jointed components) where it is critical to use an accurate full-field measurement method. Multipath Doppler vibrometry (MDV) embodies the most recent breakthrough in dynamic characterization. It delivers high-quality vibration data consistently even for the most adverse environments and provides the test engineer with a reliable tool that is fast and easy to set up. The test object is measured in its unaltered form as it is not necessary to apply any surface treatments. MDV can be applied to a single point measurement and for 1D as well as 3D scanning vibrometry tests. The benefits are illustrated in this paper by various application examples.

Keywords Multipath Doppler vibrometer · MDV · QTec · Vibrometry · Noncontact · FE model validation · Vibration measurement · Quality control

1.1 Introduction

All mechanical structures fail sooner or later if the applied forces exceed the structural limits. These limits need to be understood in depth so breakage can be avoided. Depending on the structure, the failure of just one component could result in the catastrophic breakdown of an entire system. Therefore, design and test engineers work closely together in product development to safely achieve a fast time-to-market. Simulations are valuable in evaluating many design iterations quickly; validation tests, on the other hand, are instrumental in making sure the model reflects the real-world scenario. This is important for critical components in aerospace, automotive, medical devices, civil structures, consumer electronics, and many other products.

Previous work introduced laser Doppler vibrometry (LDV) and its benefits to various applications [1]. In the current paper, the focus is on multipath Doppler vibrometry (MDV), which carries the trademark QTec at Polytec. MDV is revolutionary, and it supersedes LDV in its core design allowing the user to obtain reliable data more quickly.

The purpose of this paper is to demonstrate the benefits of MDV in different applications. Additionally, considerations about the test setup and the excitation method will be touched upon because they are equally critical for performing successful model validations. Experimental modal analysis and operational modal analysis (EMA and OMA) are discussed, and guidance is provided for how to pick the most efficient excitation method.

J. Eichenberger
Polytec, Inc., Irvine, CA, USA
e-mail: j.eichenberger@polytec.com

J. Sauer
Polytec GmbH, Waldbronn, Germany
e-mail: j.sauer@polytec.de

1.2 MDV for Real-World Applications

Multipath Doppler vibrometry (MDV) is a novel technology and overcomes the limitations of optically uncooperative surfaces. It supersedes conventional LDV in the following manner:

1. **MDV is more reliable.** There is minimal risk of signal artifacts (like dropouts) due to low signal return. Consistent results with superior optical sensitivity can be expected even in the most difficult setups like steep incidence angle, low reflectivity, and speckle motion. The data traces in the time domain are free of artifacts enabling accurate interpretation of the data.
2. **MDV is easier.** Setting up an MDV is easy as no surface treatment needs to be applied to the test object.
3. **MDV is faster.** In addition to faster setup times, the superior optical design eliminates the need for averaging in most applications, leading to dramatically reduced measurement times.
4. **MDV enables new applications.** New applications and use cases are emerging like measurements on biological tissue in uncontrolled environments such as the human skin of a patient who is in motion. Another example is continuous scanning LDV (CSLDV) where the laser beam is continuously moving across a test surface. Employing MDV technology for this application, expected to be called continuous scanning MDV (CSMDV), is promising to be substantially more sensitive and faster.

MDV is designed for real-world applications in potentially adverse environments, where the optical properties of the test surface are not well controlled. Reliable performance of the MDV gives the test engineer confidence in the data while making the acquisition process efficient and hassle-free on the most challenging test articles.

The robustness of MDV measurements is illustrated on a hand that is moving back and forth (Fig. 1.1). Human skin is typically a poor optical reflector and represents one of the most challenging optical surfaces for vibrometry especially when there is significant amount of movement. The time trace of the hand motion is displayed in real time via a laptop screen. Figure 1.2 shows the comparison of recorded time traces representing a standard LDV (top image) and an MDV (bottom image). Both measurements were acquired with an MDV one after the other; however, in the top image, the multipath vibrometer feature was turned off making the MDV act like a standard LDV. Nonetheless, the comparison is very compelling as the MDV shows a clear time trace whereas a high number of dropouts are visible with a standard LDV leading to a reduced signal-to-noise ratio (SNR).

In another illustration, 3D LDV and 3D MDV time traces were analyzed on a composite panel that was excited by an impact hammer. Hammer excitation is common practice for modal testing as will be explained in the section Excitation Methods. The hammer impact on a softly suspended test object (also common practice) will cause some rigid body motion. Such rigid body motion doesn't negatively affect the modal test but can be a challenge for optical measurements. In case of a standard LDV, the lateral component of the rigid body motion causes dropouts in the vibration signal (see left plot in Fig. 1.3). The MDV prides itself as dropout-free in this application as well (right plot of Fig. 1.3).

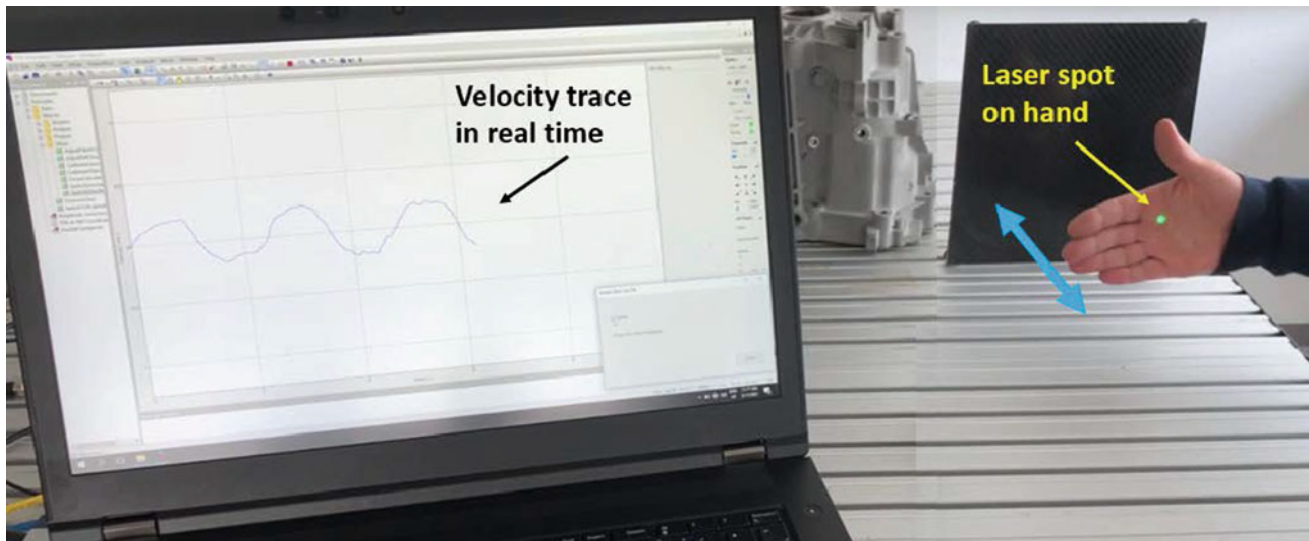


Fig. 1.1 MDV measurement on a hand that is moving back and forth (blue arrow). The velocity trace of the hand motion is displayed in real time

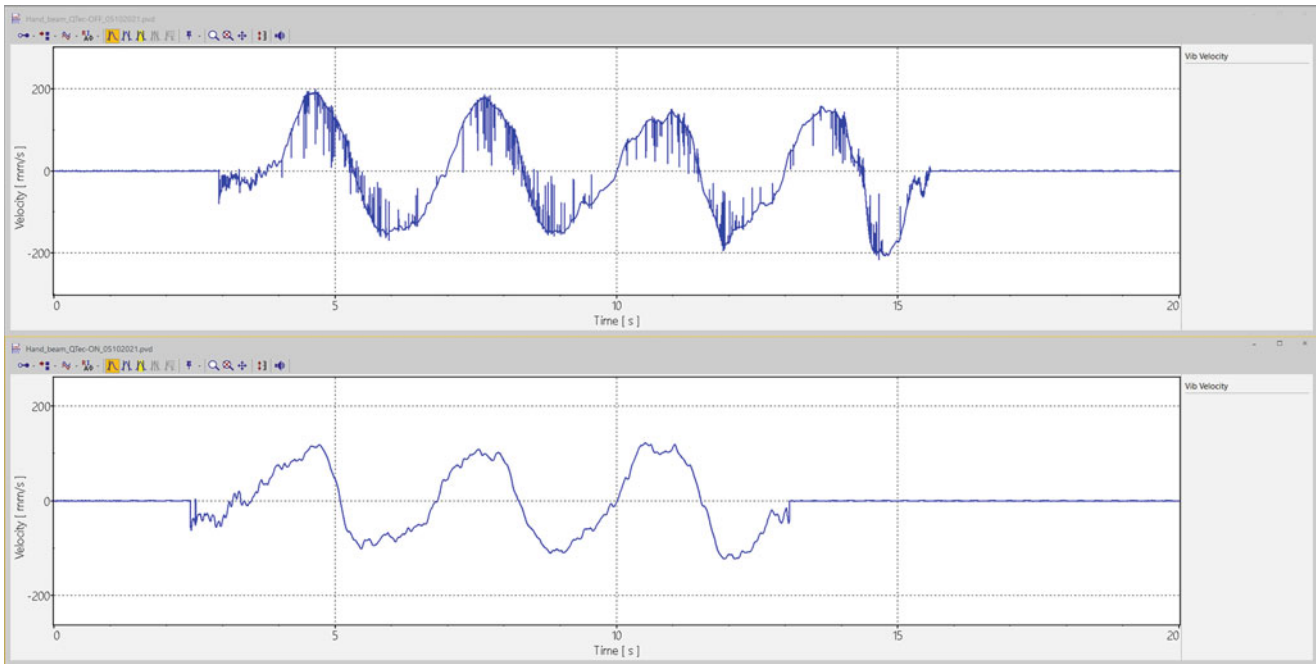


Fig. 1.2 Time trace in velocity of a hand moving along the laser beam. Top image represents standard LDV. Bottom image represents MDV

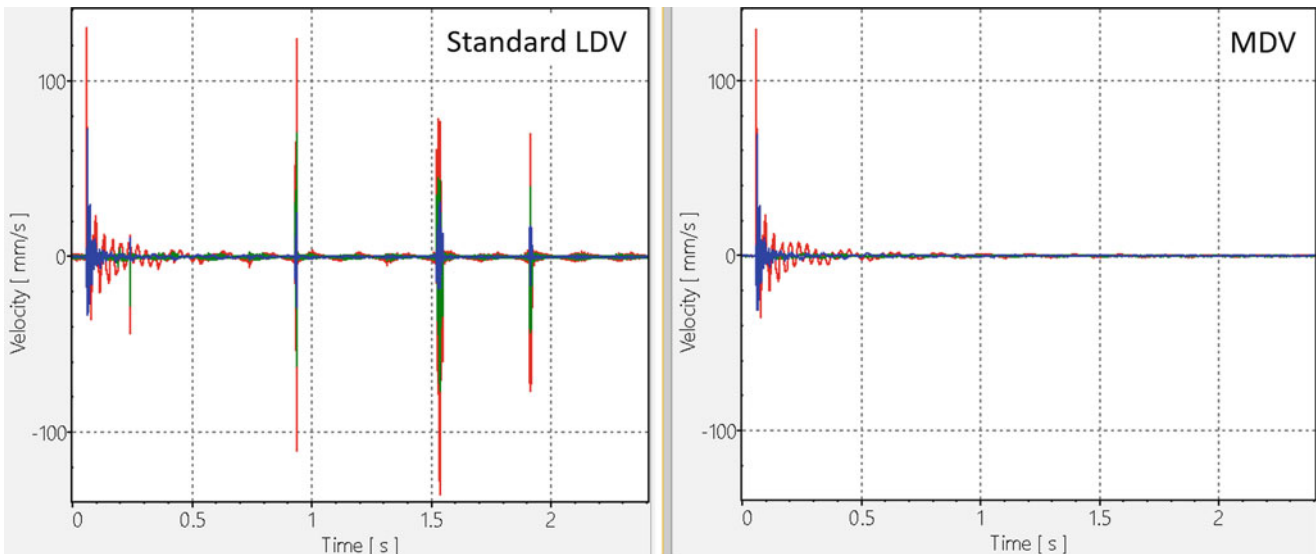


Fig. 1.3 Time trace on a composite panel upon hammer excitation. The left plot represents a standard LDV; the right plot represents an MDV. The traces in blue, red, and green correspond to the vibration responses in Z, X, and Y, respectively

1.3 MDV: A Novel Approach

MDV is a novel approach in its core technology, the optical interferometer. The interferometer is the source of the modulated carrier signal comprising the vibration information in the form of a Doppler shift in frequency or phase. The demodulation electronics are downstream from the interferometer where the vibration information is extracted and then output digitally or via an analog voltage signal. Despite the constantly improving demodulation electronics, it is key to overcome any shortcomings from the optical interferometer raw signal. The MDV is a novel approach removing the shortcomings before reaching these demodulation electronics. Like with any data stream, it is most efficient to improve the data quality at the front end rather than downstream.

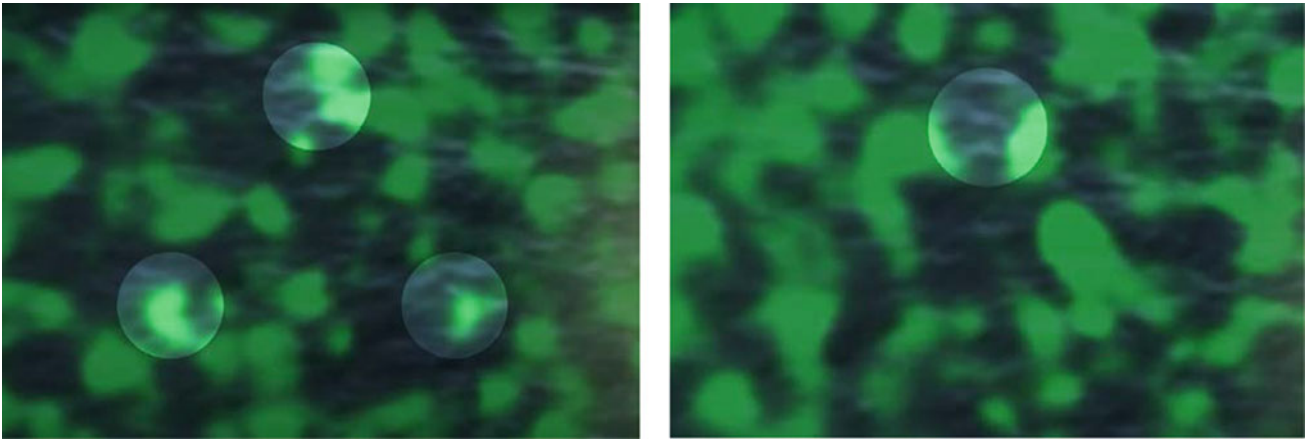


Fig. 1.4 Image plane of the optical interferometer of a conventional LDV (right image) and of a MPV (left image). In this example, the MPV comprises three separate PD

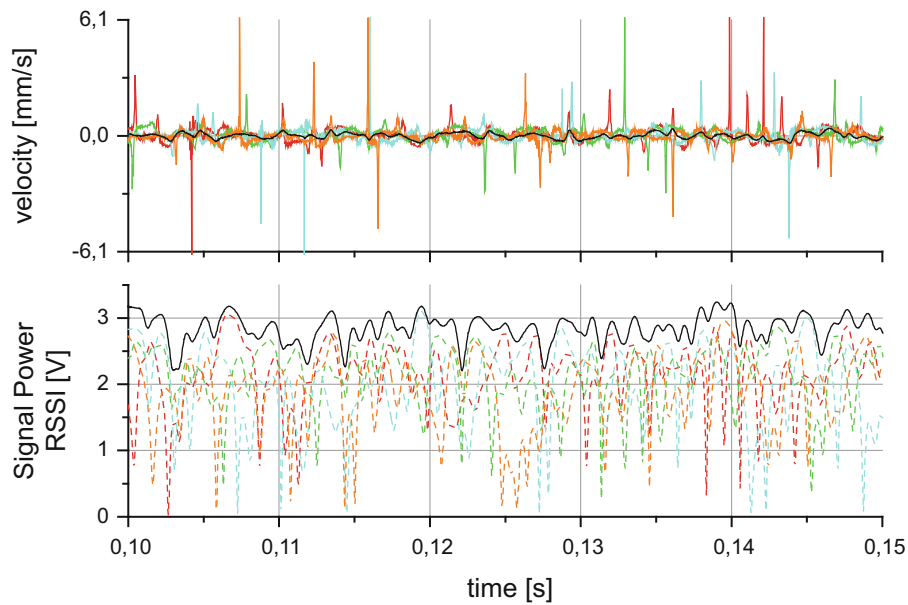


Fig. 1.5 Velocity signal (top) and signal strength (bottom). The colored traces are from individual PDs, and the black trace is a combined signal as it is generated in the MDV

Due to the coherent nature of a laser beam, the reflected light is always speckled unless the laser beam is pointed at a mirrored surface. The speckle nature of light puts an intrinsic limitation on any interferometer setup as the amount of return light strongly depends on the alignment to the speckles. Since speckle alignment cannot be controlled, a new optical arrangement is used that makes the vibrometer insensitive to any speckle effects. Instead of capturing the returned light with only one photodetector (PD), multiple PDs are integrated into the interferometer each capturing light from a slightly different angle.

In conventional vibrometry, using only one PD (see right image in Fig. 1.4), speckle movement causes the signal return strength to fluctuate significantly, directly affecting the signal-to-noise ratio (SNR) of the vibration data. In multipath Doppler vibrometry, using multiple PDs (see left image in Fig. 1.4), the return signal strength is strong continuously despite speckle movement as one of the PDs is always aligned to a bright speckle. Having a consistently strong signal return ensures clean time traces without dropouts on all surfaces.

In addition to the effective removal of deep dropouts (Figs. 1.2 and 1.3), the MDV eliminates small signal spikes that are not obvious right away but can affect signal quality significantly. Movement of speckles on the PD causes phase changes in the Doppler signal that do not represent the actual motion of the object but are an optical artifact. These artifacts show up as small spikes in the vibration velocity signal and appear even with a high signal return like in the case of retroreflective tape.

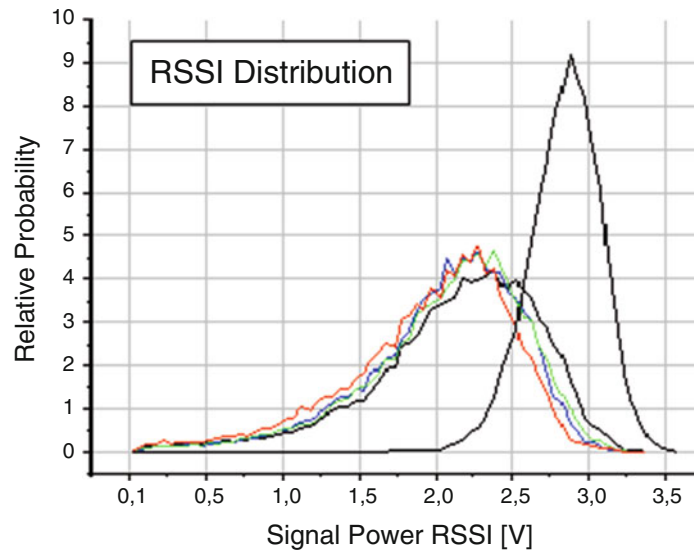


Fig. 1.6 RSSI distribution of single PD vibrometers (colored traces) and MDV (black trace)

Figure 1.5 shows a typical vibration signal in the presence of speckle motion caused by lateral movement of the test object. The velocity signal is displayed in the top plot, and the return signal strength indicator (RSSI) is displayed in the bottom plot. The colored traces represent signals from a single PD within the MDV, whereas the black trace represents the combined trace. The MDV removes all the small spikes efficiently and the RSSI is consistently strong. The RSSI distribution of the above measurement (Fig. 1.6) shows that the MDV maintains a strong signal even in the presence of speckle movement.

Integrating multiple PDs into the interferometer requires a careful and intricate optical design. An integrated FPGA weighs and evaluates the response of all the PDs in parallel and outputs the best-quality signal in real time. The proof of concept for this approach was first published in 2014 [2] and subsequently patented.

Real-time output is one of the beneficial properties of scanning vibrometry in contrast to image-based techniques for capturing vibrations, e.g., digital image correlation (DIC). DIC on the other hand carries the benefit of capturing the dynamic response of the entire object surface at once. However, extensive post-processing is necessary, and surface preparation with a painted speckle pattern is required. Both aspects add significant time to the measurement process and in some cases even exceed the measurement time of a sequential test such as is done by a scanning vibrometer. The displacement resolution and accuracy of DIC measurements depend on the field of view and are orders of magnitude lower compared to interferometric methods. Incidentally, LDVs are used for primary and secondary calibration of accelerometers. DIC vibration amplitudes depend on the interpretation of the raw images. Although algorithms are continuously advancing, they are still not standardized. DIC calibration and measurement results are not NIST traceable, not to mention that rigid body motion during a modal test poses additional challenges on a DIC test. As the saying goes, there is a tool for every job. It is thus crucial to evaluate each measurement task thoroughly to choose the optimal measurement method.

1.4 Quantifying Performance

To choose the most suitable vibrometer model for each application, it is important to know the performance specifications. The most relevant performance metrics of a vibrometer are frequency range, amplitude range, accuracy, and resolution. Each vibrometer model offers a set of ranges providing flexibility to optimize the measurement setup. Typically, the resolution is best for a low frequency and amplitude range. It is therefore advised to adjust the range for each measurement condition accordingly. Accuracy is usually independent of measurement range and is $\pm 1\%$ for most vibrometers. Specialized vibrometers for calibration of other sensors typically exhibit an accuracy down to $\pm 0.1\%$.

The noise-limited resolution (NLR) depends, as described in the previous section, on the amount of return light. Currently, most vibrometer specifications are defined on retro-tape at a 1 m standoff distance, which describes an ideal situation with a very high signal return. Considering real-world applications with low signal return and speckle movement, the current resolution specification method is not adequate. Polytec has therefore introduced a new metric, called spike rate (SR), for

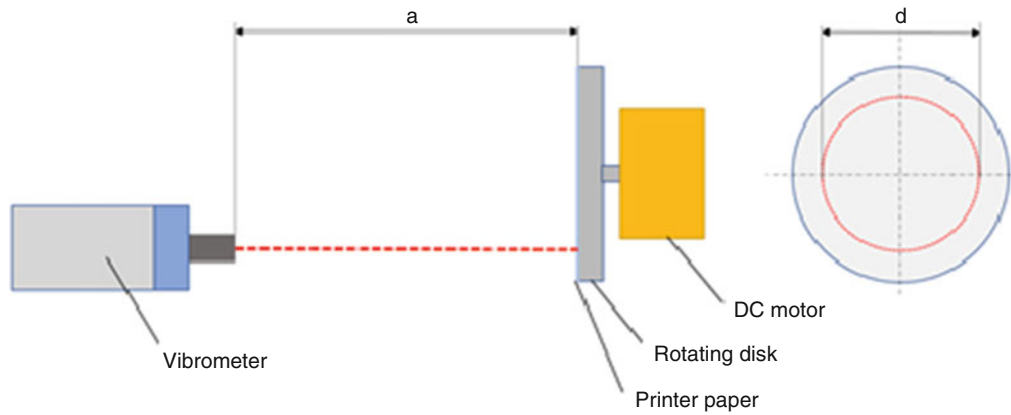


Fig. 1.7 Test setup for measuring the spike rate (SR) of a vibrometer model

Table 1.1 Application categories based on NLR and SR and corresponding performance for MDV and LDV

Application	Visible laser LDV	Standard IR LDV	MDV
Mirror surface	Best	Good	Good
Close up, highly reflective	Best	Good	Good
Machined surface up to 5'	Good	Good	Best
Machined surface > 5'	Not optimal	Good	Best
Composite panels and under angle	Low SNR	Not optimal	Best
Laterally moving composite panel	Low SNR	Low SNR	Best
Traveling wave imaging	Not optimal	Good	Best
Under water tests	Best	Not possible	Not possible

quantifying the vibrometer performance under challenging conditions. Spikes in the vibrometer signal will automatically increase the background noise floor above the NLR. Therefore, the lower the SR, the more resilient the data quality on a rough and moving target surface. SR together with NLR provides a reliable method for comparing different vibrometer models with each other.

The setup for determining the spike rate (SR) is depicted in Fig. 1.7. A slowly rotating disk is used as a target. White printer paper is used as target surface, which provides sufficient surface roughness for generating speckles and, at the same time, is reflective enough to keep the signal level (RSSI) at a medium level. Please refer to application note [3] for a more detailed description of this test setup.

Considering SR and NLR, vibrometers can be categorized into different classes of measurement conditions. Table 1.1 shows a list of the most common conditions and how each vibrometer fares against the others comparing the MDV with the standard LDV in either IR or visible laser light. The classifications of best, good, not optimal, and low SNR are based on the SR and NLR values for each vibrometer type in each measurement condition.

As shown in Table 1.1, there is no measurement scenario where the performance of the standard IR vibrometer exceeds the performance of the MDV. MDV is replacing standard IR LDV technology. On the other hand, LDVs with a visible laser beam will continue to be used for various applications as explained in the next section.

Besides NLR and SR, measurement time is an equally important performance metric, especially for scanning vibrometer measurements. The pressure to shorten the development cycle is increasing in many industries. Thus, it is not only measurement accuracy that is most important but also the shortest possible measurements times. As discussed in the previous work [1], the measurement time t is calculated as follows in Eq. (1.1):

$$t = T * n_p * n_{ave} * OL + t_{add} \quad (1.1)$$

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.)

As the MDV makes it possible to capture vibrometer data without averaging or with only a small number of averages, measurement times are significantly reduced. This is critical especially for larger, high-density measurement grids (e.g., traveling wave analysis). Additional time factors (t_{add}) are usually negligible for vibrometer measurements.

1.5 Applications for Visible Laser-Based Vibrometer

For modal validation of a submersed structure, IR-based vibrometers are unable to measure as the laser light is absorbed by water. For such measurement scenarios, the vibrometer laser needs to be in the visible range. In a recent publication of Krishnan, Malladi, and Tarazaga [4] with the topic of the validation of a multiple-input and multiple-output (MIMO) multiphysics vibroacoustic measurement, a PSV-400 Scanning Laser Vibrometer was used, which houses a HeNe laser source at 633 nm. Polytec released a specific application note providing an overview of vibrometer measurements in water [5].

A related field of vibrometry is refracto-vibrometry, where a vibrometer is used to measure a sound pressure field in air or in water. Incidentally, sound field measurements in water require a visible laser-based vibrometer as is nicely demonstrated in the work of Huber and Huber [6].

HeNe laser-based vibrometers typically have a lower noise floor when compared to IR-based vibrometers if the amount of reflected light is high. This is due to the shorter wavelength and the low phase noise of the HeNe laser tube. Please see previous work for more details on the difference between HeNe- and IR-based vibrometers [1]. The high SNR performance of HeNe-based vibrometers on highly reflective surfaces causes operators to switch from the IR to HeNe at times when displacement amplitudes are very low.

Yet other vibrometer applications where visible laser sources are used are microstructures and microelectromechanical systems (MEMS) in particular. Polytec's Micro System Analyzer (MSA) employs a solid-state laser with a wavelength at 532 nm. A short wavelength is critical as a small laser spot diameter is required. For the characterization of features down to one μm , an IR-based vibrometer would be at a clear disadvantage.

For Polytec's product families, HeNe and IR vibrometer optical heads can be used interchangeably with the same system. In the case of a scanning system, the product family is called PSV (Polytec Scanning Vibrometer). A standard MDV PSV (called PSV QTec) can be equipped with an additional HeNe optics head if a specific application calls for it. In the case of single-point vibrometers, the product family is called VibroFlex. The controller box can be used interchangeably with a HeNe- or an IR-based optics head.

1.6 Test Setup for Modal Analysis

In modal validation the setup and the excitation method are critical. The dynamics of the test object needs to be studied without the influence of any environmental factors. The modal model is a numeric representation of the object under investigation, typically based on assumptions and idealizations. If the test fixture, the excitation, or any other environmental factor influence the dynamic behavior, the modal test will be incorrect, which would in turn have a detrimental effect on the simulation model. In some cases, adjacent structures need to be integrated into the model; however, this makes the simulation unnecessarily complicated.

The dynamic behavior of a structure is represented by the resonance frequencies, damping coefficients, and mode shapes. The modal parameters are like a "fingerprint" of a structure when it comes to the dynamic behavior, and it dictates how it will respond under operating conditions. Dynamic characterization is typically performed on a shaker table. In the case of experimental modal analysis (EMA), the excitation locations and signal pattern are chosen to excite all the critical modes of the structure. In the case of operational modal analysis (OMA), the excitation locations and signal pattern are chosen to

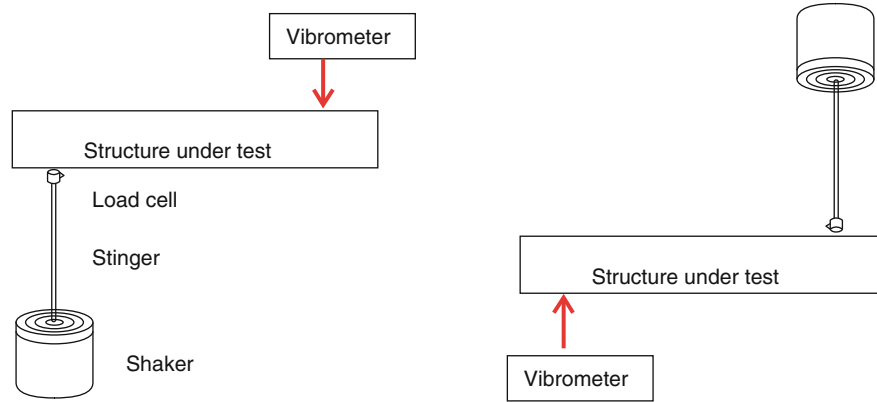


Fig. 1.8 Setup for a reciprocity test

reflect real-world operation. For OMA, instead of using a shaker, the structure is self-excited like in the case of a running engine.

In any modal test, it is critical that the results are independent of the setup. The excitation method of measurement technique must not interfere with the dynamic behavior of the test object. The noncontact nature of MDV and consequently not needing to apply surface treatment ensure that each measurement is “objective.” Along the same lines, the excitation must not alter the dynamic “footprint” of the structure either. It is therefore advised to perform a reciprocity test for each measurement setup. In a reciprocity test, a vibration test is repeated where excitation location and measurement are switched. If both measurements yield the same result, accurate modal data can be expected.

Figure 1.8 shows a schematic of a reciprocity test. The structure is measured twice switching measurement and excitation location in between tests. Reciprocity is proven when both results are the same. If a shaker adds mass loading to the test structure, the reciprocity test would show a difference between the two tests. As an alternative to shaker excitation, an impact hammer can be used, which doesn’t add any mass or stiffness to the test structure.

1.7 Excitation Methods

Even though scanning laser vibrometry is a fast measurement method for acquiring full-field response data, it is still sequential, as described previously. In case of nonlinear structures, e.g., jointed structures or composite panels, the frequency response function (FRF) changes with varying input excitation force. See Fig. 1.9 for example.

Therefore, to measure accurate deflection shapes, the excitation force levels must be consistent across the entire measurement grid. Even the smallest variation in force during the scan will alter the phase response and distort the deflection shape. This is true especially for highly resonant structures.

Keeping the excitation force constant can be achieved with electrodynamic shakers; however, mass loading introduces errors into the modal data especially for lightweight test objects. Mass loading is caused by the impedance head (containing a force and an acceleration sensor), which is glued to the structure. The impedance head adds additional mass, hence the term mass loading, which alters the dynamic response as would be expected by the model.

Hammer excitation doesn’t introduce mass loading and is therefore preferred in many modal testing scenarios. NV-TECH specializes in automated excitation hammer designs with bandwidths up to 40 kHz and achieves repeated impacts with very consistent force and contact time. The contact time (t_c) is the time the hammer is in contact with the test structure, and it determines the excitation bandwidth f , which $f = 1/t_c$.

1.8 Application Example 1: Characterization of Biological Tissue

The characterization of biological samples requires a noncontact approach in many cases. Surface treatment is often not possible either. The natural reflectivity of biological samples is inherently poor and has been causing poor signal quality especially for in vivo measurements where the object is moving. MDV overcomes these challenges as demonstrated

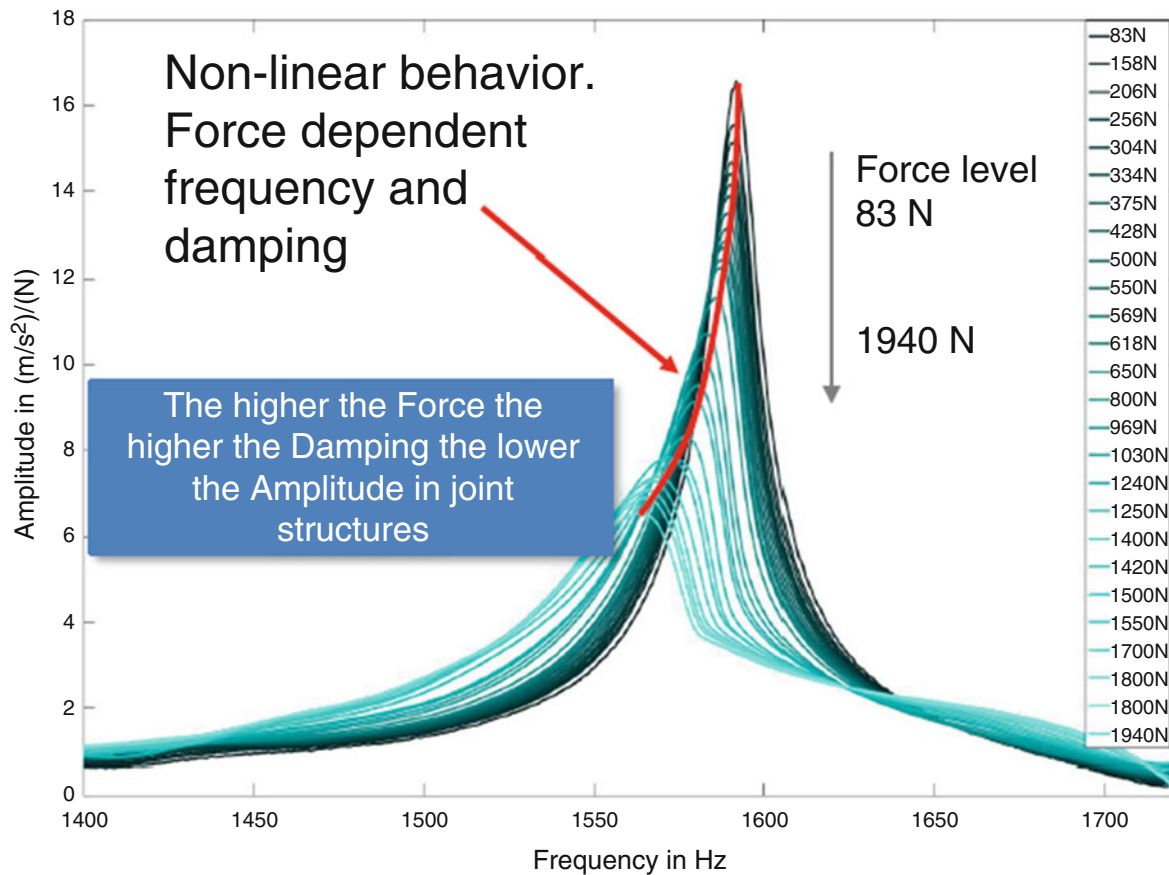


Fig. 1.9 FRF at different force levels for a jointed structure. (Courtesy of P. Blaschke, NV-Tech design)

in Fig. 1.2. Typical biomedical applications are the dynamic characterization of ossicles and the tympanum in otological research. Measurements on muscle cells in vitro or vibrocardiology are performed on the skin of the neck artery or the thorax. Even the slightest movements of a patient will cause speckle movement leading to dropouts with a standard LDV but showing clean time traces using MDV. Tissue engineering is a growing field and will continue to benefit from advancements in vibrometry [7, 8].

Optical vibrocardiography is a technique to obtain medical parameters of the heart. The study by Mignanelli and Rembe shows that 3D response measurements are required to obtain accurate displacement amplitudes, which is crucial in determining the condition of the patient's health [9]. In 3D vibrometry the incident laser beams are angled, and thus lower return light is achieved as compared to 1D measurements where the laser is aligned at normal incidence. The unique speckle handling capability of MDV is promising to solve many measurement challenges in this field. Faster measurements are possible, which is critical for in vivo applications because of fewer averages required to achieve the same SNR.

1.9 Application Example 2: Modal Test on a Composite Panel

Carbon fiber-reinforced plastic (CFRP) is a popular material for critical structures in many industries because it is strong and lightweight. As CFRP is an engineered material, its material properties such as damping and stiffness can be customized for each application individually. Validating simulation models, however, is much more difficult than for conventional materials such as steel and aluminum. Components made from CFRP are anisotropic, and their behavior is highly nonlinear, especially when the geometry is complex. Dynamic testing is essential for updating the simulation models accurately. High spatial resolution is necessary to characterize the material parameters across the entire structure and detect any local deviations from the design.

Fig. 1.10 Setup of curved CFRP panel with automated hammer excitation

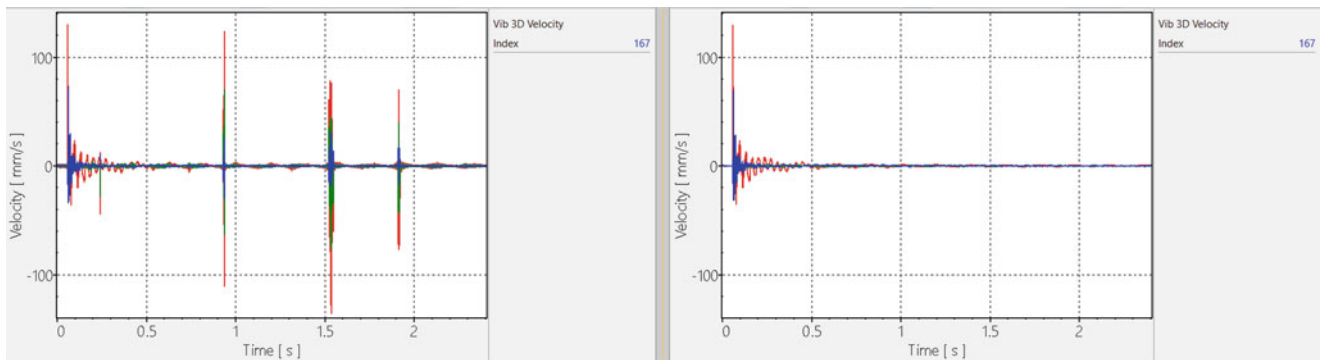
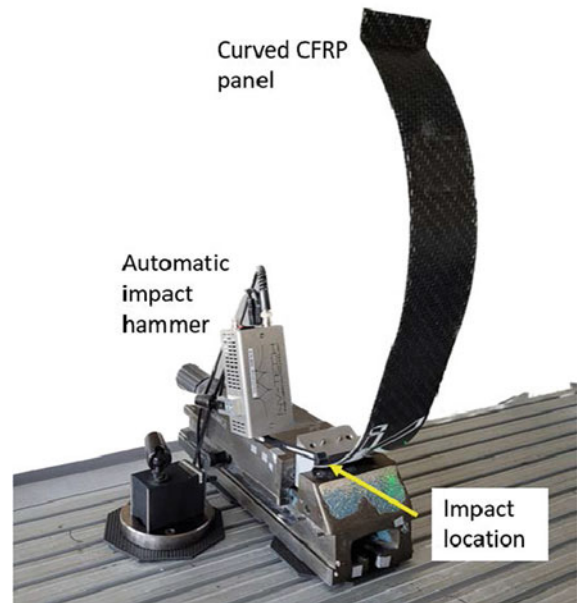


Fig. 1.11 Time domain velocity data on CFRP panel. Standard LDV (left) and MDV (right)

In the following example, a curved CFRP structure was measured to determine the modal parameters. The structure was clamped on one end and excited near the base with an automated hammer (Fig. 1.10). The complex geometry implied complex deflection shapes, which required the modal test to be performed in 3D. The angles of incidence of the laser beams were unfavorable due to the curvature at the perimeters of the scan grid. A shallow angle of incidence coupled with the low optical reflectivity of the CFRP material makes for a challenging vibrometer setup. CFRP material is not only a poor optical reflector; the scattering of light from the carbon fibers and the resin is unpredictable.

In 3D vibrometry the in-plane vibration component is obtained from the three individual scanning heads. The sensitivity and resolution of the in-plane component depends not only on the resolution of the individual signals but also on the angle separation between the three lasers. In a 3D setup, on a curved part, small angle separation can sometimes not be avoided and pose an additional challenge for vibrometry. MDV has proven to address all these challenges successfully as shown below. High SNR was achieved across the entire area without the need of surface treatment.

Figure 1.11 shows a comparison between standard IR LDV and MDV as already indicated in Fig. 1.3. Standard LDVs are prone to show dropouts in the time signal (left), whereas MDVs are clear of dropouts (right).

In the FRF (Fig. 1.12), representing a measurement near the edge of the scan grid, the difference is also obvious. The standard LDV data (left) shows a higher background noise floor, which makes it impossible to resolve the antinodes. Being able to resolve antinodes in a modal test is critical for accurate modal analysis.

In contrast to Fig. 1.12, a measurement at the center of the part is shown in Fig. 1.13, where the incidence angles and the angle separations were more favorable. In this case, the performance of standard LDV and MDV is comparable, although the antinode above 200 Hz (green trace) is only resolved clearly with the MDV. This reemphasizes, as illustrated in Table 1.1, that LDVs perform well in ideal measurement situations. MDV is completing the picture by maintaining excellent performance even in the most challenging measurement conditions.

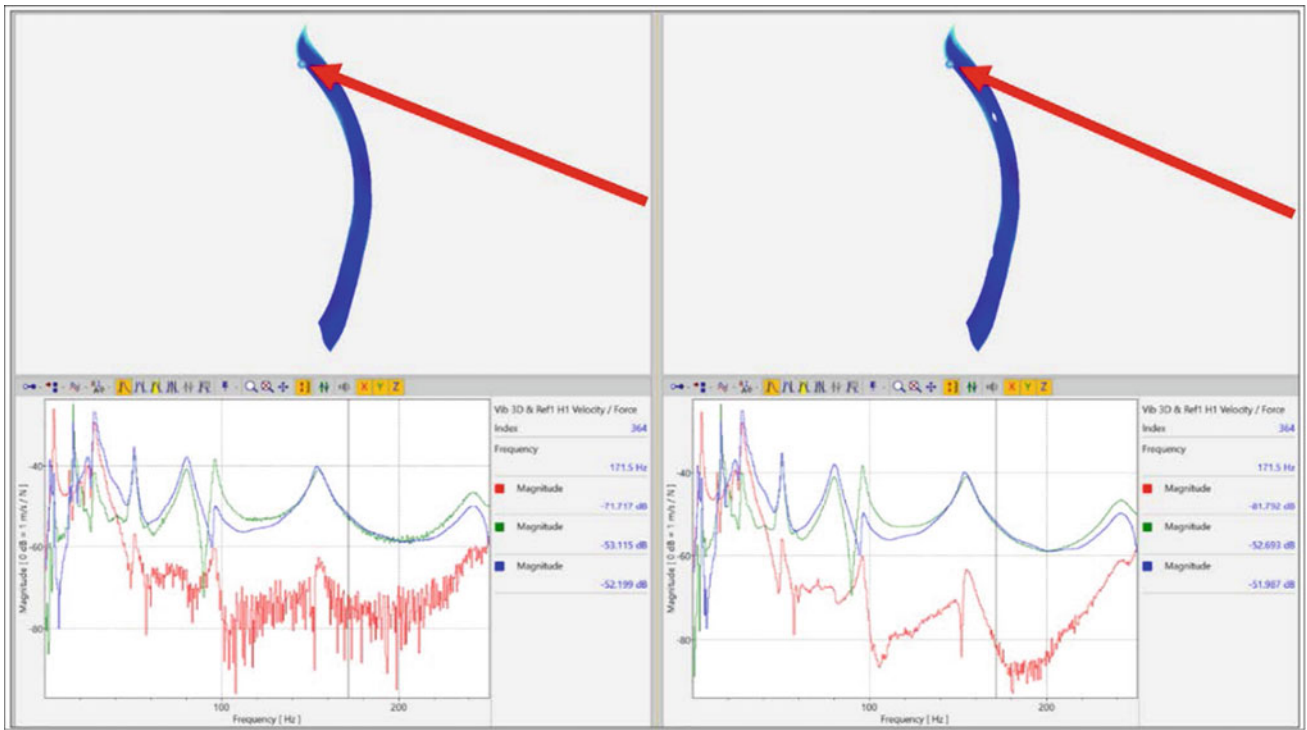


Fig. 1.12 FRF comparison. Standard LDV (left) and MDV (right). This measurement was acquired toward the edge of the scan grid where incident angles were not favorable

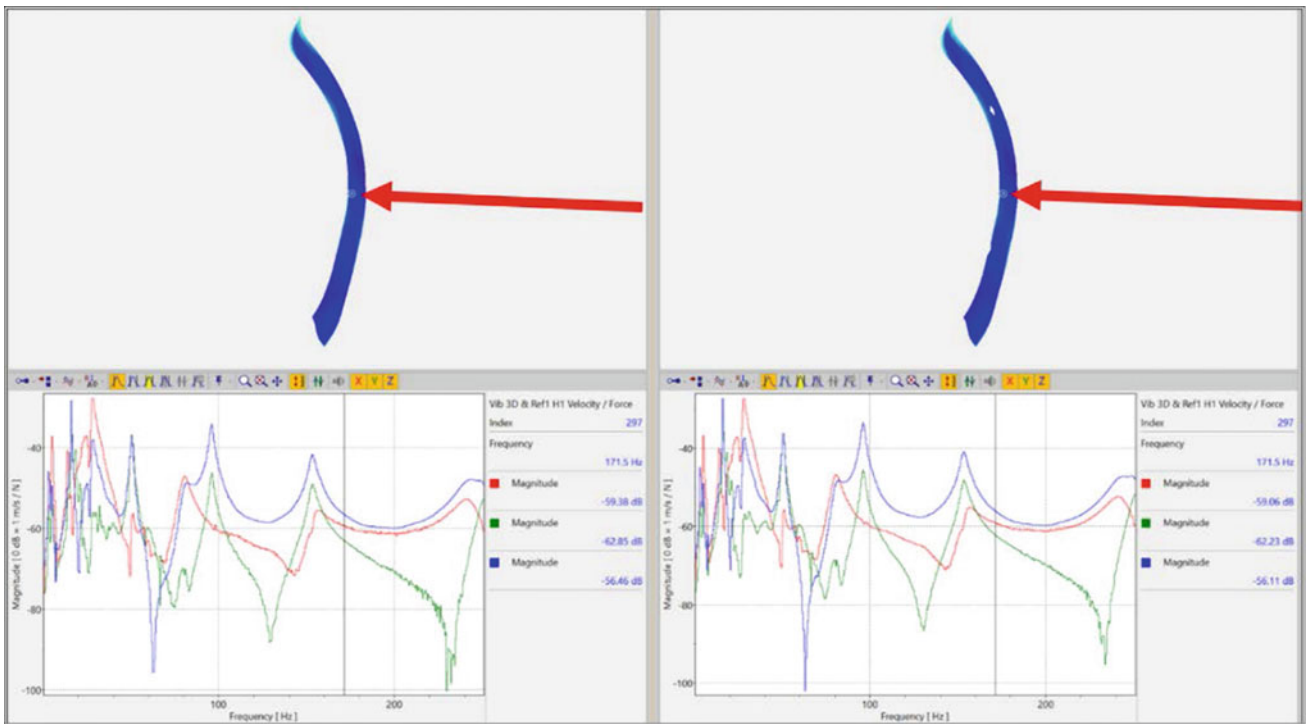


Fig. 1.13 FRF comparison. Standard LDV (left) and MDV (right). This measurement was acquired in the center of the scan grid where incident angles were favorable

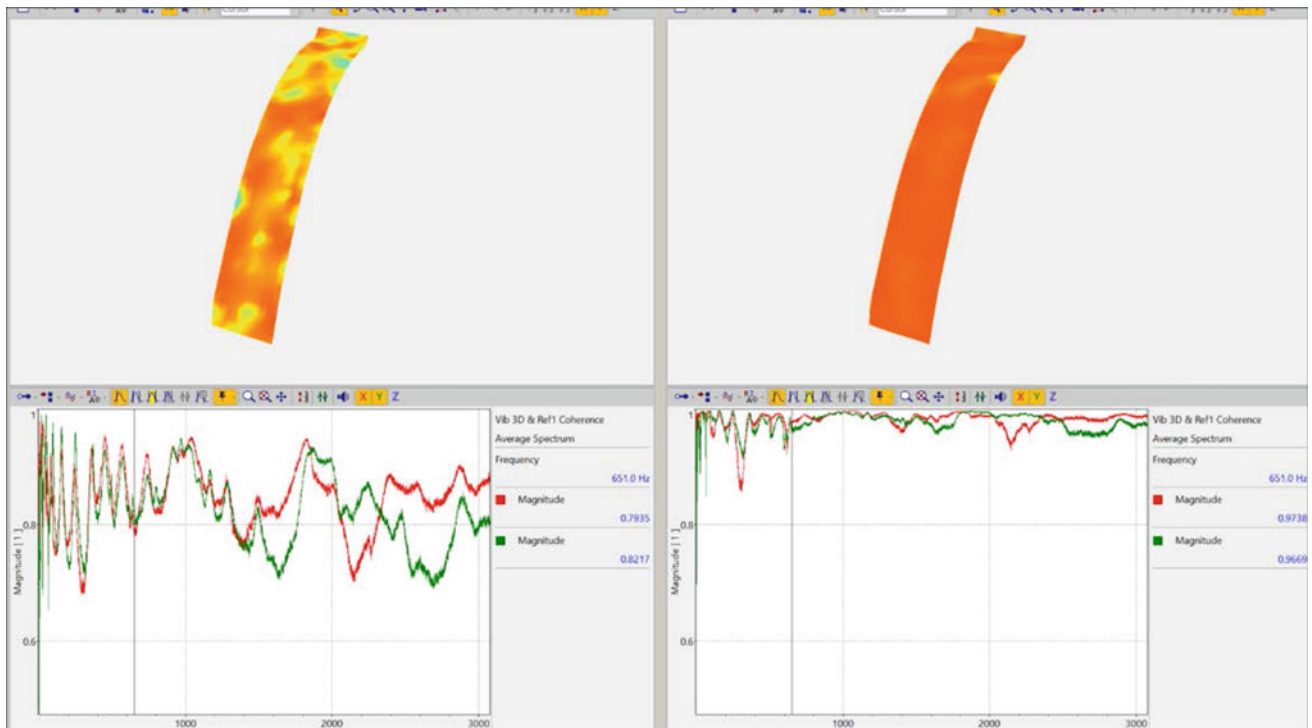


Fig. 1.14 In-plane coherence of modal test (X and Y components only) at an antinode at 651 Hz. Coherence distribution across scan grid (above), average coherence value (below). Standard LDV (left) and MDV (right). Red trace represents X component and green trace represents Y component

The coherence function in modal analysis is a measure of confidence in the FRF results. It is a dimensionless parameter that indicates the correlation between input excitation and vibration response. A coherence of 0 indicates no correlation and only noise is displayed in the FRF. A coherence of 1 indicates perfect correlation. The difference between standard LDV and MDV is evident in the coherence function and is easily quantifiable. Figure 1.14 depicts the coherence of the in-plane components. It is poor for the standard LDV (left) and high for MDV (right).

1.10 Application Example 3: Noncontact Strain Monitoring

As discussed in previous work [1], 3D scanning LDV data can be used to validate the strain value in durability simulation models. In contrast to gluing strain gauges, noncontact 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.

For strain measurements, the quality of the in-plane response is even more critical than for 3D modal tests as the strain value is derived from the local in-plane vibration component. The derivative tends to amplify noise and worsen the SNR in a data set. Therefore, vibration data with high SNR is essential for strain measurements. Figure 1.15 shows the relationship for typical displacement amplitudes between in-plane (IP) and out-of-plane (OOP). The in-plane displacement differential (IP-Diff) is typically three orders of magnitude smaller than the out-of-plane displacement amplitude.

Figure 1.16 shows a comparison of a strain distribution across an aluminum cantilever beam with the standard LDV result on the left and the MDV result on the right. Figure 1.17 shows the corresponding FE simulation. MDV clearly shows higher-quality strain data. In particular, the obvious errors in the strain value at the corners were mitigated using MDV.

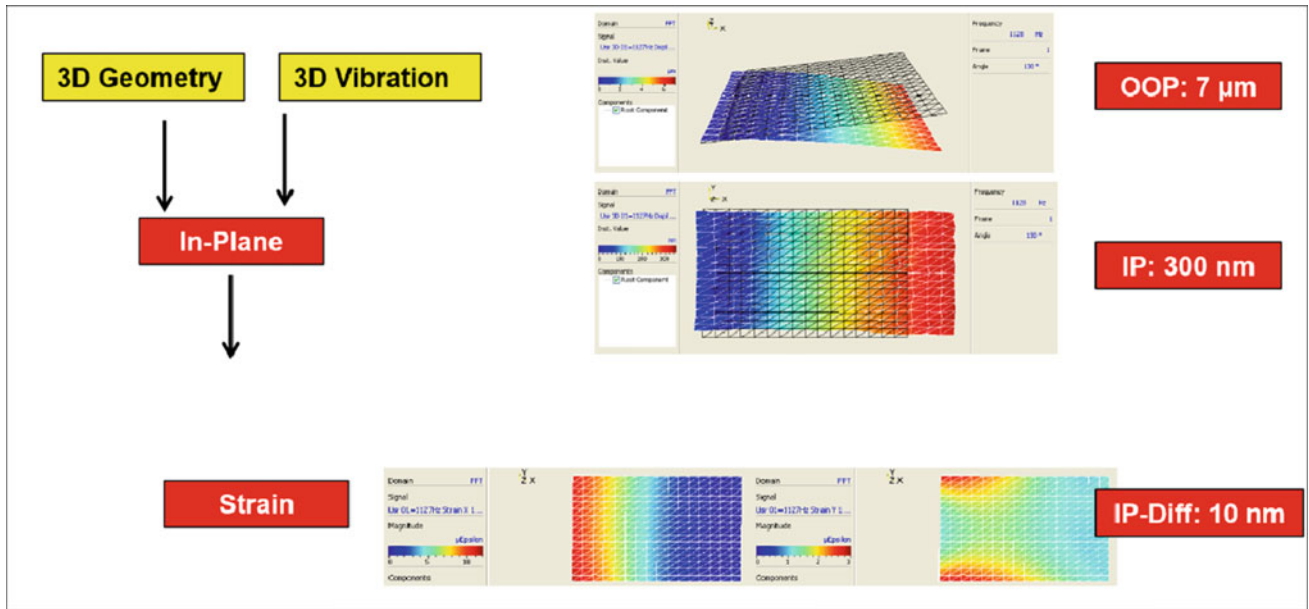


Fig. 1.15 In-plane data for strain calculation is typically three orders of magnitude lower than out-of-plane amplitudes

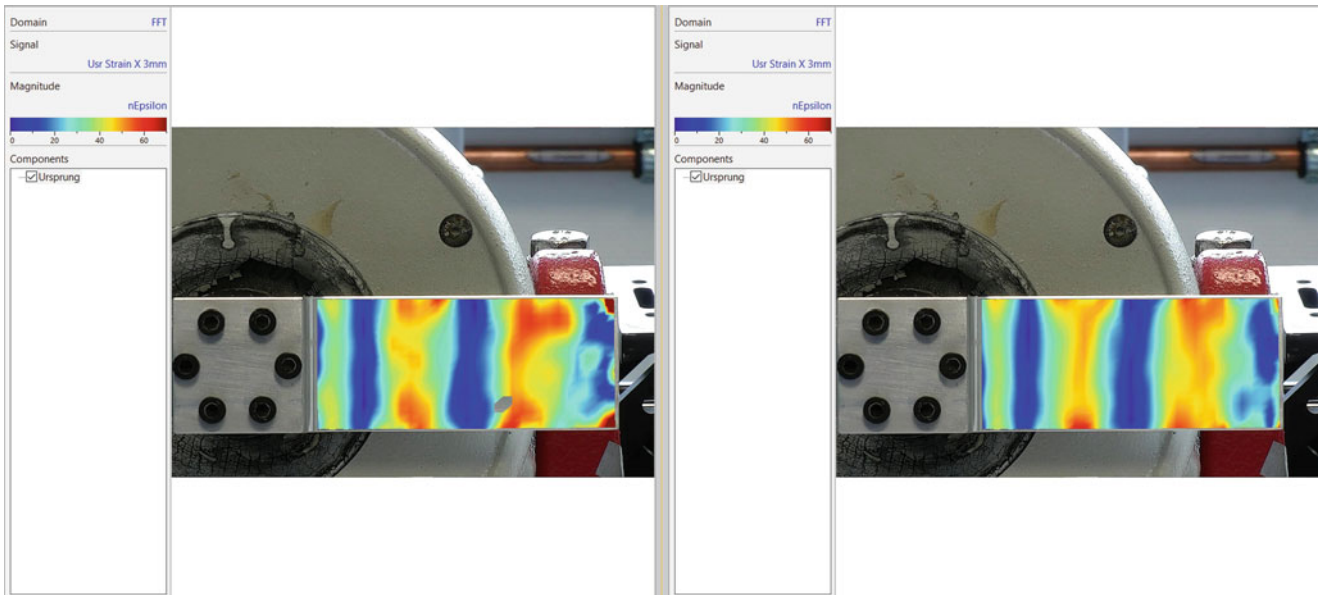


Fig. 1.16 Strain distribution in X (longitudinal direction). Standard LDV (left) and MDV (right)

1.11 Conclusion

As structures and materials become more complex, the need for accurate validation methods is increasing. Scanning vibrometry has been helping design engineers meet time-critical product development cycles for many years. The novel multipath Doppler vibrometry (MDV) promises to make modal testing more reliable and faster even on optically uncooperative surfaces. Various application examples were discussed with respect to relevant improvements in signal quality.

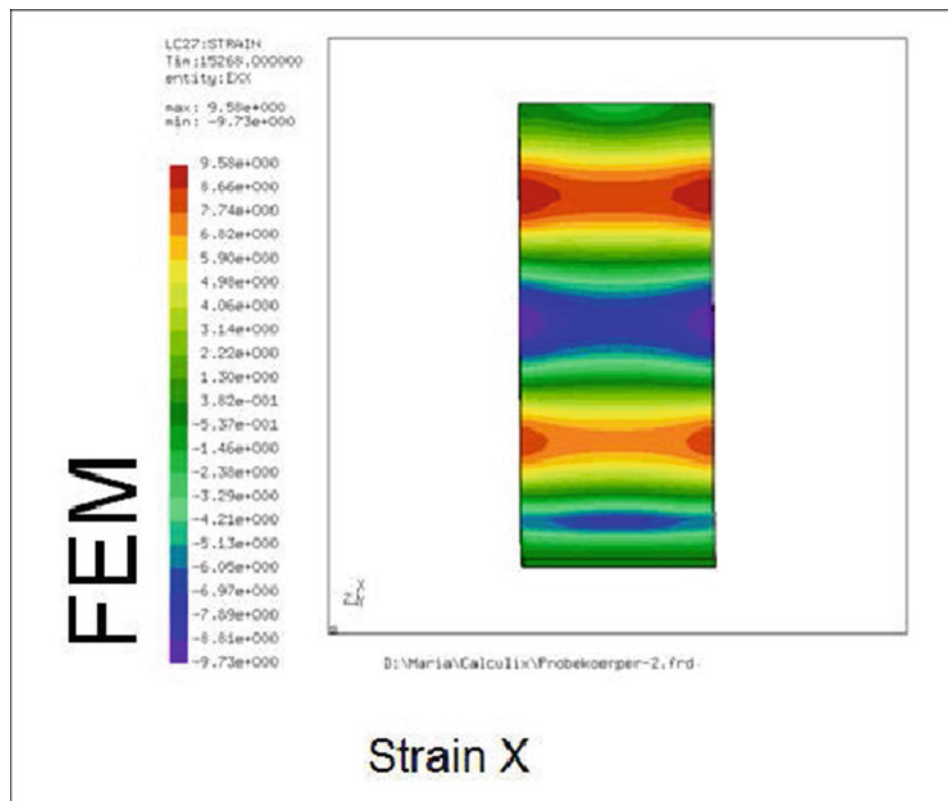


Fig. 1.17 FE simulation for strain in X direction

References

1. Eichenberger, J., Sauer, J.: Validating complex models accurately and without contact using Scanning Laser Doppler Vibrometry (SLDV). In: Di Maio, D., Baqersad, J. (eds.) Rotating Machinery, Optical Methods & Scanning LDV Methods, Volume 6. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-76335-0_11
2. Dräbenstedt, A.: Diversity combining in laser Doppler vibrometry for improved signal reliability. AIP Conf. Proc. **1600**, 263 (2014). <https://doi.org/10.1063/1.4879592>
3. Polytec application note VIB-G-030: Characterization of the robustness of Laser Vibrometers in respect to speckle noise (2021). www.polytec.com/qtac
4. Krishnan, M., Vijaya, V.N., Malladi, S., Tarazaga, P.A.: Leveraging a Data-Driven Approach to Simulate and Experimentally Validate a MIMO Multiphysics Vibroacoustic System. 0888-3270/© 2021 Elsevier Ltd (2021). <https://doi.org/10.1016/j.ymsp.2021.108414>
5. Application note VIB-G-028: Under water measurements with laser vibrometers. https://www.polytec.com/fileadmin/website/vibrometry/pdf/OM_AN_VIB-G-028_Under_water_measurement_52019.pdf
6. Huber, N.R., Huber, T.M.: Optical imaging of propagating Mach cones in water using refracto-vibrometry. J. Acoust. Soc. Am. **141**(3) (March 2017). <https://doi.org/10.1121/1.4977099>
7. Schwarz, S., Hartmann, B., Sauer, J., et al.: Contactless vibrational analysis of transparent hydrogel structures using Laser-Doppler Vibrometry. Exp. Mech. **60**, 1067–1078 (2020). <https://doi.org/10.1007/s11340-020-00626-0>
8. Espinosa, M.G., Otarola, G.A., Hu, J.C., Athanasiou, K.A.: Cartilage dynamic mechanics from non-destructive vibrometry correlates with quasi-static properties. J. R. Soc. Interface. In Revision
9. Mignanelli, L., Rembe, C.: Uncertainty contribution of the laser-beam orientation for laser Doppler vibrometer measurements at the carotid artery. J. Phys. Conf. Ser. **1149**, 012025 (2018). <https://doi.org/10.1088/1742-6596/1149/1/012025>. <https://iopscience.iop.org/article/10.1088/1742-6596/1149/1/012025>