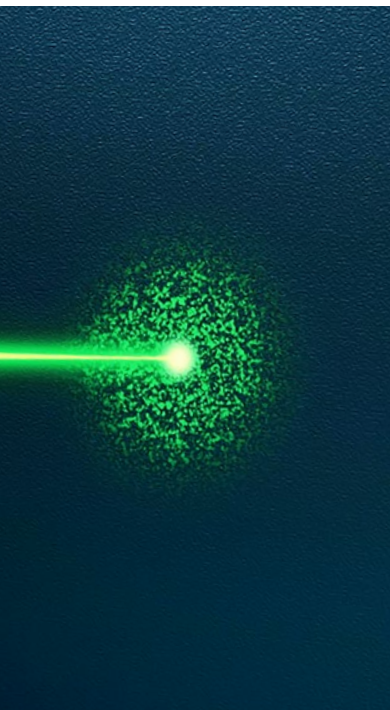


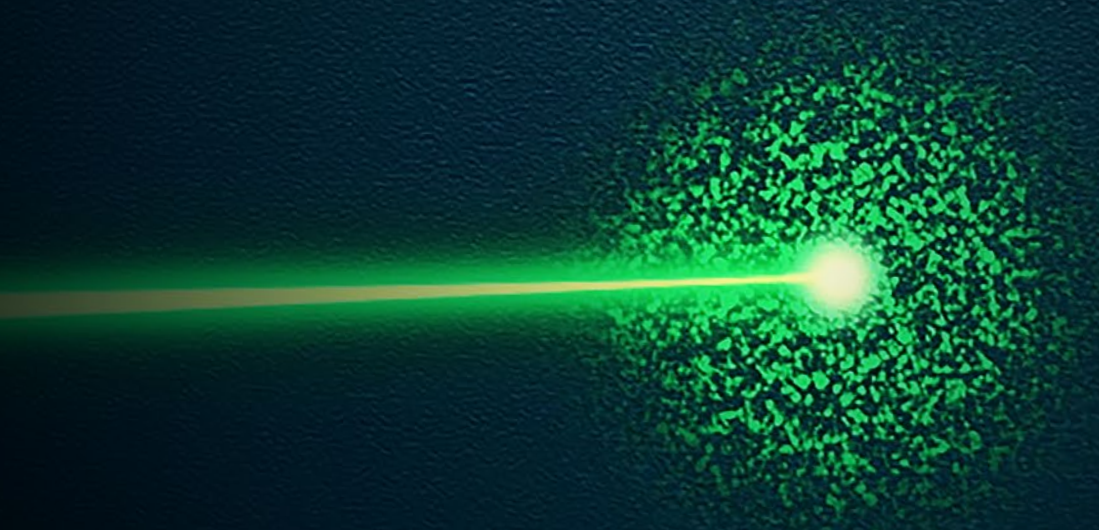
Robustness of LDV in respect to speckle noise



Robustness of laser Doppler vibrometers in respect to speckle noise

Application note





Introduction

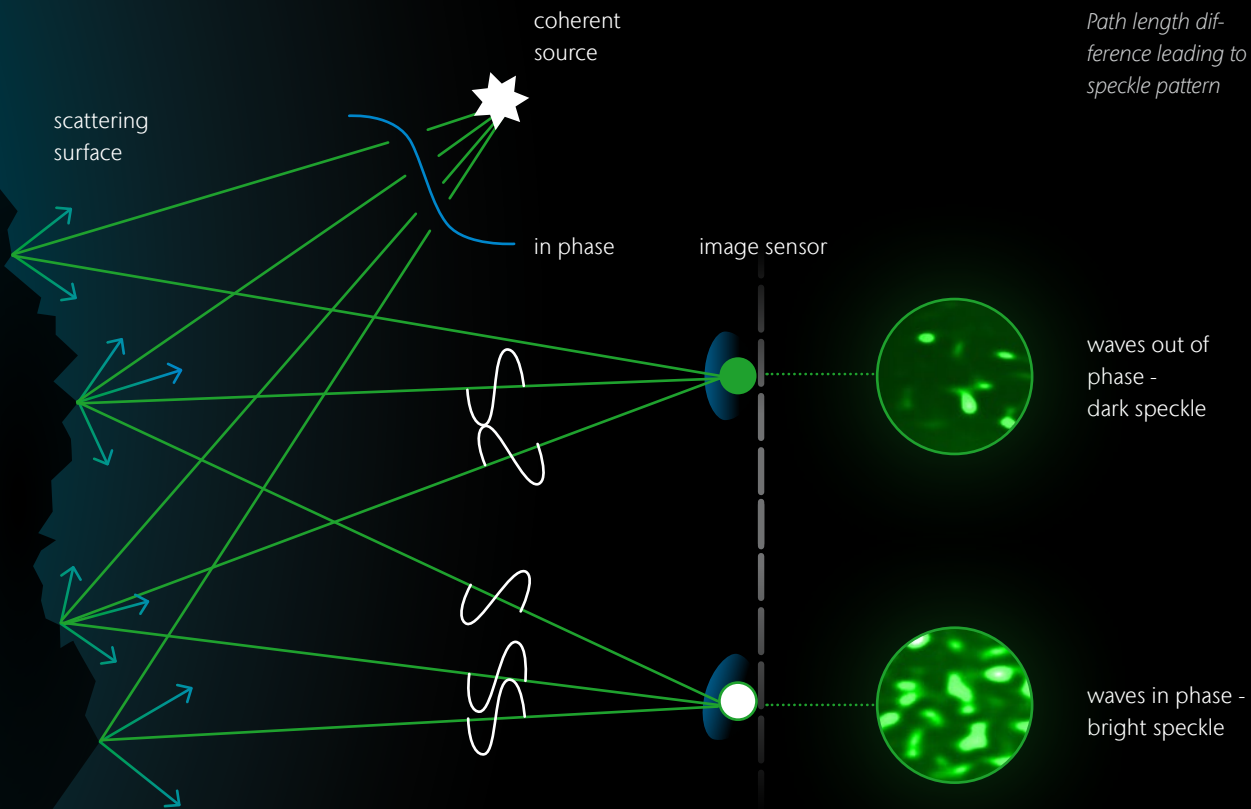
One of the most important parameters when determining whether a measurement instrument is appropriate for a defined measurement task is the noise limited resolution (NLR) of the instrument. This is also valid for laser Doppler vibrometers (LDV), which are widely used for non-contact vibration measurements. The NLR reflects the resolution of the instrument, which is dependent on the settings of the vibrometer such as bandwidth and maximum velocity. To characterize the instrument independently from specific measurement object properties the NLR is determined using well defined object surfaces such as mirrors or retroreflective tape. With this approach, the NLR reflects the resolution under optimal conditions.

In real life, the situation is more complex. In many cases, for example when measurements are done on engineered surfaces, the NLR specification given for ideal conditions becomes less relevant as other effects dominate the noise performance of the instrument. Particular surface properties of the specific measurement object such as reflectivity, roughness or even

small lateral displacements of the measurement object can significantly influence the achievable measurement resolution and in the worst case make reasonable measurements impossible. One of the most relevant practical effects in this context comes from laser speckles, which are unavoidable when a laser beam is directed onto optically rough surfaces. Typically, the received amount of light and therefore the measurement resolution depends on the exact position the laser beam hits the measurement object. Spurious peaks (“dropouts”) in the measurement signal occur when the measurement object moves laterally relative to the laser beam, either accidentally, from intentional object movement or from the vibration of the measurement object itself.

This application note proposes a method for quantitatively measuring the robustness of laser Doppler vibrometers against dropouts in the measurement signal. Different vibrometer models featuring different wavelengths and laser output powers are compared, including the latest innovative multi-path laser Doppler vibrometers utilizing reception diversity for data evaluation (QTec®).

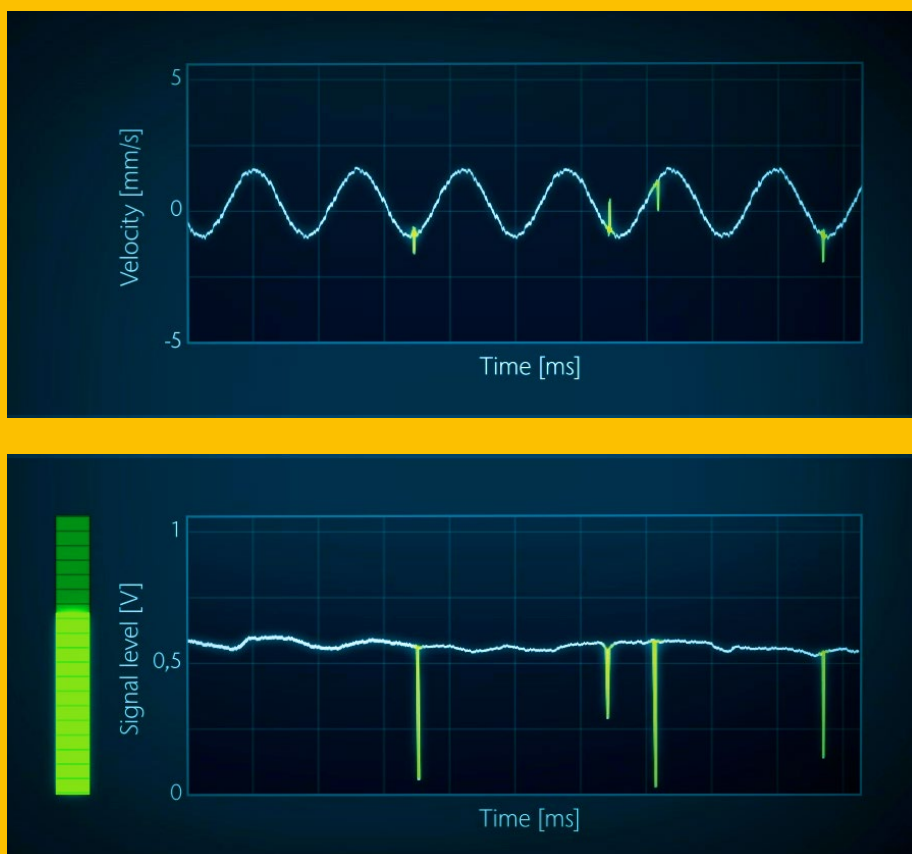
1
Path length difference leading to speckle pattern



Theory of speckles. Speckles occur when coherent light is scattered from an optically rough surface. The path length difference between each point of the surface hit by the laser and an observer leads to a specific intensity distribution from the perspective of the observer

2

Time history with dropouts and corresponding signal level (RSSI) on a single-path laser Doppler vibrometer



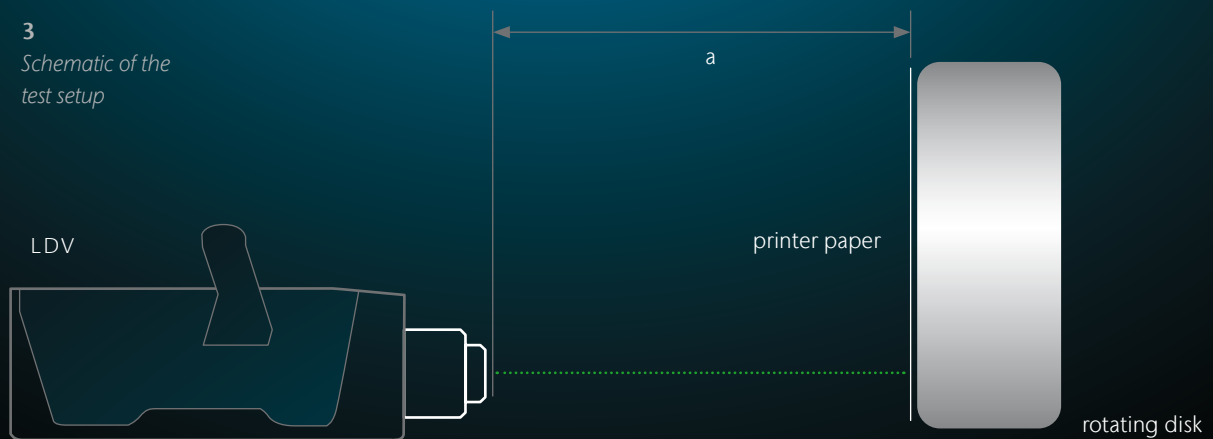
In a single-path laser Doppler vibrometer the size of one speckle is imaged on the photodetector. With a lateral movement of the measured surface, the speckles are exchanged. From speckle to speckle the phase changes in a random way. Dropouts occur due to the phase change, even with excellent average signal level (RSSI), such as when using retroreflective tape. The received signal level depends on the laser power, working distance, surface reflectivity, laser wavelength, focal length of the optics and on a stochastic factor caused by speckle effects. Additional dropouts can occur if the signal level drops below the so-called FM-threshold (Figure 2). The FM-threshold depends on the chosen velocity and bandwidth settings.

The influence of speckles on dropouts in the vibrometer signal is practically eliminated by Polytec's patented multi-path laser Doppler vibrometry utilizing reception diversity (QTec®). QTec® uses several photodetectors and an optical setup where for every photodetector a different spot of the speckle pattern is imaged. Real time signal processing ensures that only signals from photodetectors with bright speckles are used while those which receive low light are suppressed. This technology effectively assures a continuous signal without dropouts. With single-path interferometers it is not foreseeable if a bright speckle or a region with low light hits the photodetector(s). Therefore, the quality of the vibrometer signal varies randomly.

Test setup and assumptions

In order to characterize the robustness of laser Doppler vibrometers with respect to speckle noise, a simple experiment is performed. A measurement is made with a pure lateral movement of the measured object. The theoretically expected result is a flat line, as the vibrometer only measures out-of-plane movement and the object does not perform any out-of-plane movement. However, dropouts in the signal may occur due to the constantly changing speckles on the photodetector. The proposed test setup counts the dropouts and uses it as a measure for the robustness of the signals obtained from the vibrometers.

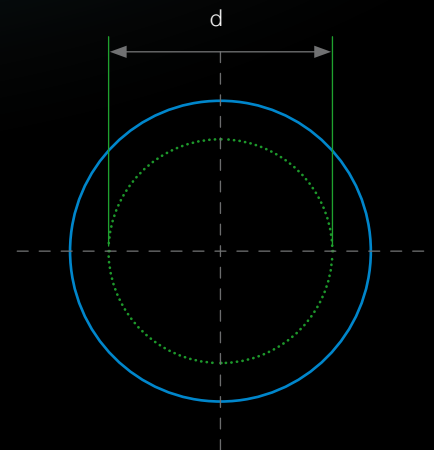
3
*Schematic of the
test setup*



Setup and basic assumptions

A slowly rotating disk is used as a target. For the target surface a commonly available white self-adhesive CD label for ink-jet printing (Avery 8691 or similar) is used. It provides enough surface roughness to cause speckles and has a reasonably high reflectivity to keep the signal level (RSSI) at a medium level. This setup has proven very repeatable in terms of speckle generation.

To analyze optical artifacts in the vibrometer signal, dropouts are counted with an algorithm. To compare vibrometers, the statistical lateral movement in mm between two dropouts is determined.



Setup details

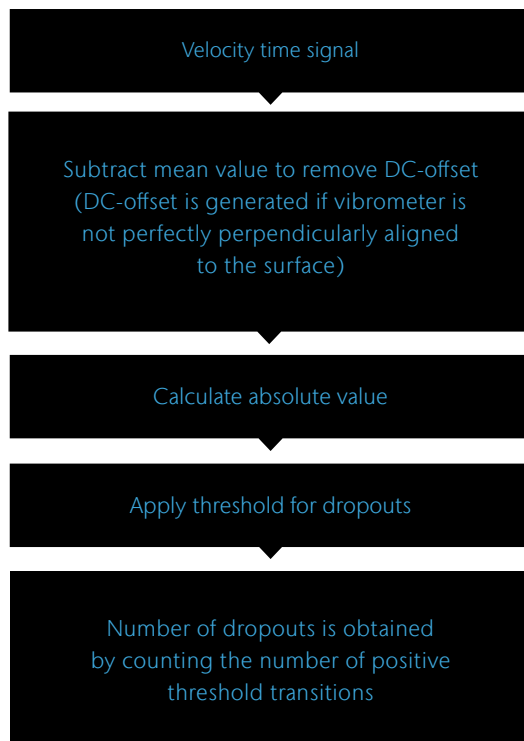
The disk is driven by a DC-motor. The laser Doppler vibrometer is focused perpendicular to the disk.

- Circumferential / lateral speed: $\omega \sim 0.093 \pm 5\%$ cps (cycles per second)
- Measurement diameter: $d = 116$ mm
- Stand-off distance: $a = 1000 \pm 50$ mm
- Bandwidth: 20 kHz
- Sampling frequency: 50 kS/s
- Measurement time: 30 s

Measurement time, diameter and circumferential speed were chosen such that 1 m lateral distance during the measurement time is achieved. The stand-off distance a is kept constant in all experiments. A short distance was chosen to accommodate for a wide range of vibrometer models to be included in the test. A slight variation is allowed to compensate for periodic coherence minima of the HeNe laser.

Algorithm

The achieved time velocity signal of the vibrometer output is processed with a dropout counting algorithm.



Influence of the angle of incidence

If the angle of incidence between the laser and disk is kept in a $\pm 5^\circ$ deviation from the perpendicular position, the error is in the range of the general repeatability of the test and can be neglected.

Statistics

To include the influence of the specific test setup and variations in the individual vibrometers in the results the following measures were performed:

- Every measurement was repeated 10 times
- For every vibrometer model, 3 different individual vibrometers were tested

The resulting uncertainty is given as the standard deviation of the results.

Obviously, the obtained number of dropouts directly depends on the chosen threshold. An appropriate threshold can be defined with the average phase change between two speckles. The phase change between two speckles is in the range of $\pm\pi$. The average absolute phase change between two speckles corresponds to $\pi/2$.

A phase change generates a pseudo displacement depending on the wavelength λ . With $\lambda/2 = 2 \cdot \pi$, the average absolute displacement value d_{average} between two speckles is:

$$d_{\text{average}} = \lambda / 8$$

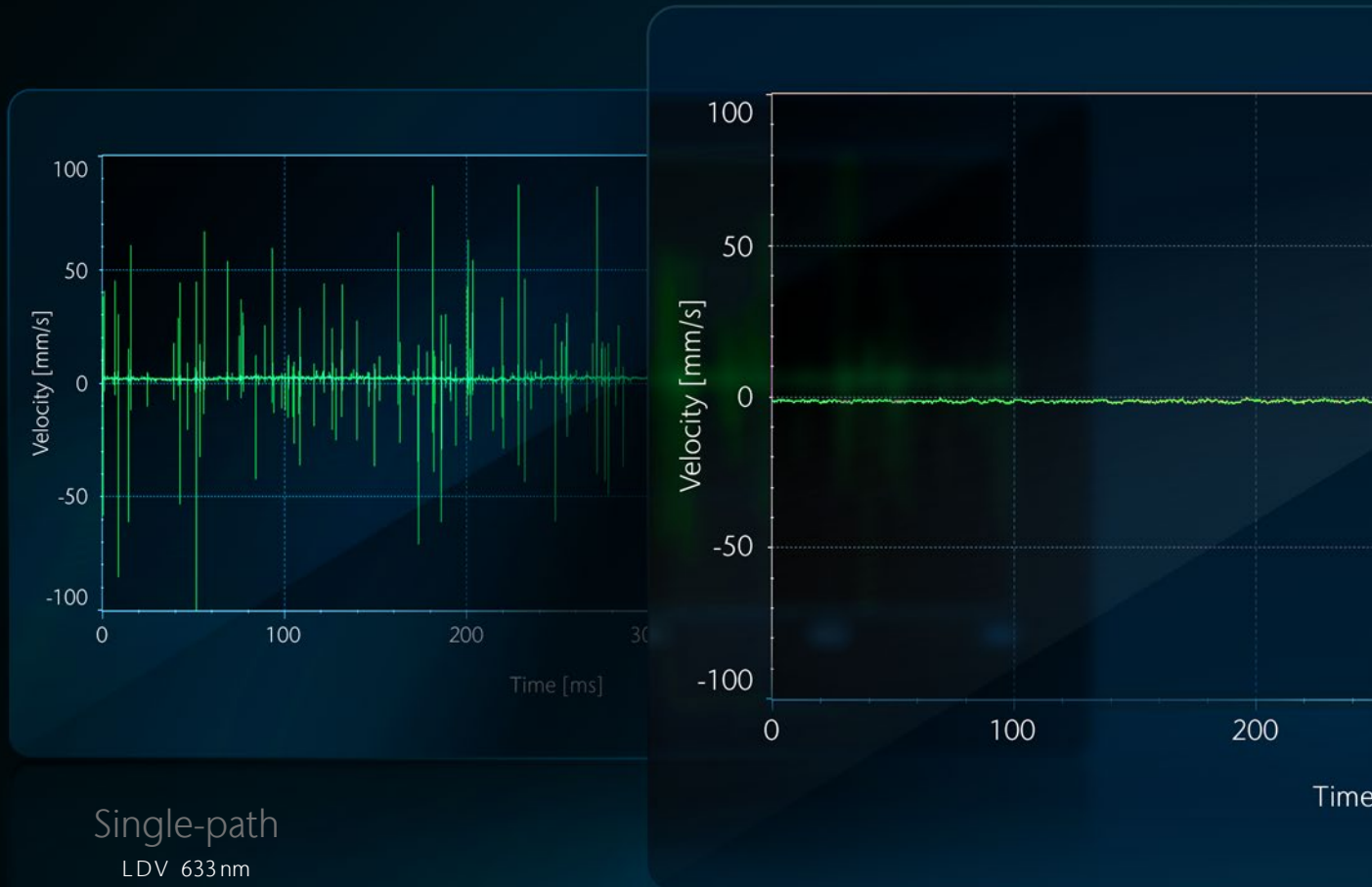
In the velocity domain, we assume that the phase change will be immediate and therefore corresponds to a delta function. Under this assumption, the velocity value can be calculated from the displacement value with the chosen bandwidth BW:

$$v_{\text{average}} = d_{\text{average}} \cdot \text{BW}$$

The threshold is (deliberately) set to v_{average} . Therefore, the threshold is:

$$\text{threshold} = \lambda / 8 \cdot \text{BW}$$

Results for different vibrometers



Introduction to investigated vibrometers

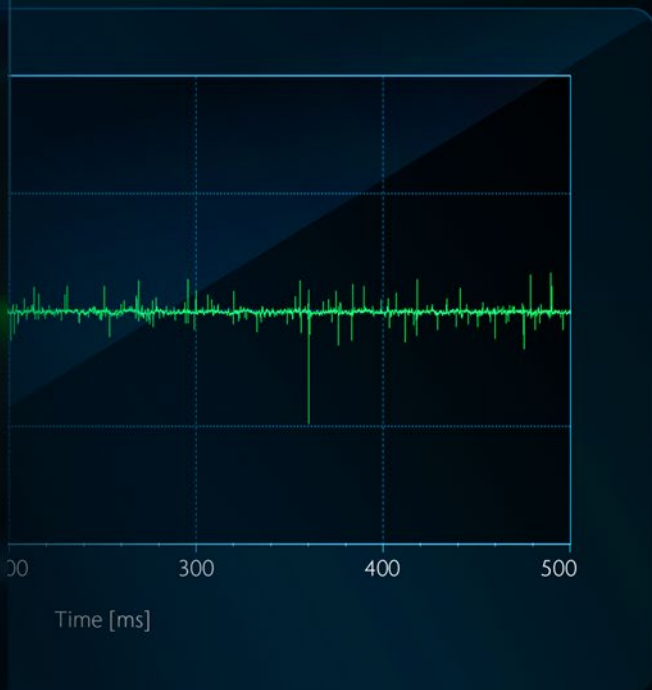
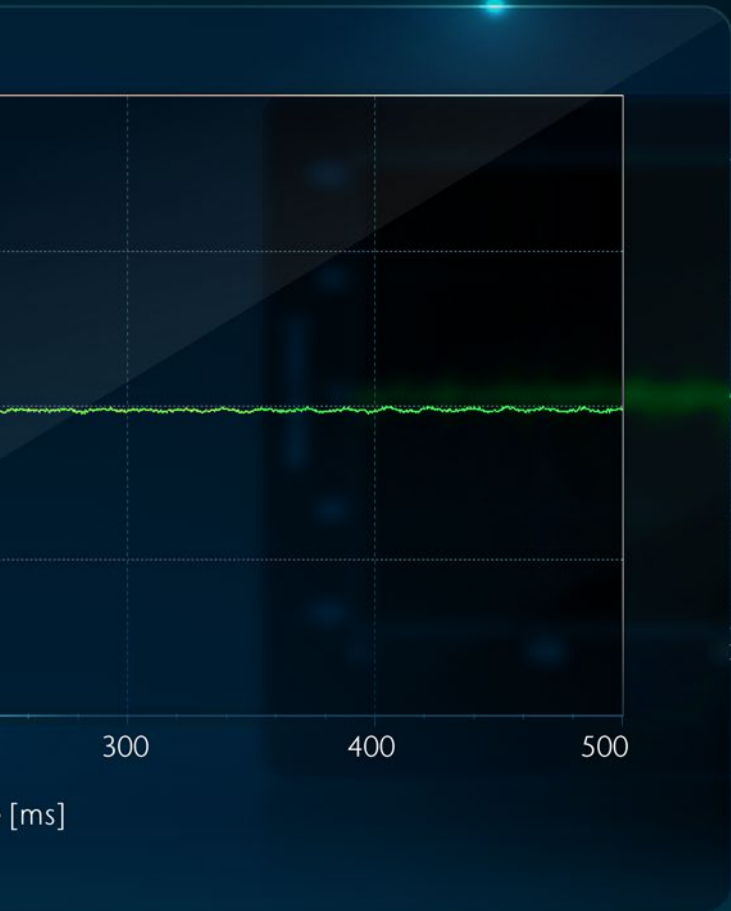
As a proof-of-concept, different laser Doppler vibrometer systems were tested with the proposed setup. Various models were tested to assess the influence of laser wavelength and focusing optics that determine the spot size. The laser wavelength and the output power are dictated by the requirements of laser safety. Visible Helium-Neon lasers (633 nm) are limited to 1 mW while infrared lasers can go up to 10 mW and be classified in the laser class 2, which is regarded as being operationally safe.

Results

The raw time data in velocity already shows the difference in performance between different models. In Figure 4 sample time traces are shown.

As a result, the optical signal robustness OSR, defined as distance lateral movement in mm over the number of dropouts, was calculated from the raw data based on the algorithm described above.

Multi-path
LDV QTec®

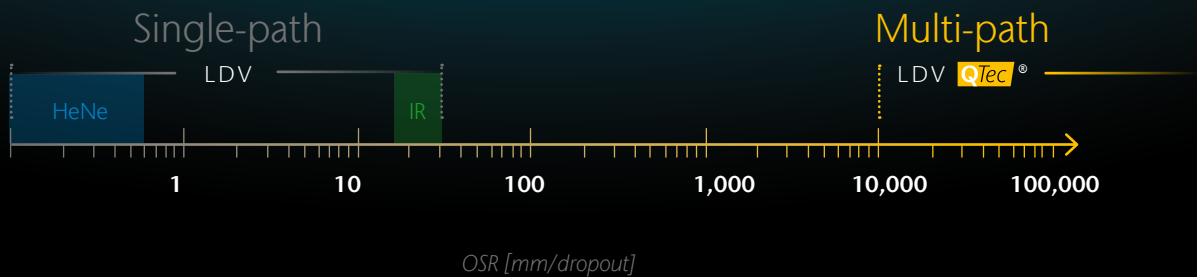


Single-path
LDV 1550nm

Technology	Wavelength [nm]	Output power [mW]	Optical signal robustness [mm/dropout]	Standard deviation mean [%]
Single-path LDV	633 (HeNe)	<1	0.1 ... 0.6	18
Single-path LDV	1,550 (IR)	<10	15 ... 29	19
Multi-path QTec® LDV	1,550 (IR)	<10	>> 10,000	n.a. ¹

1) Standard deviation could not be stated as no dropouts were detected during repeated measurements

Influencing param-
eters and resulting
average optical
signal robustness



The higher the OSR value, the more robust the LDV design is against surface induced noise effects and the closer one can get to the specified NLR in real world measurements.

The optical signal robustness is meant to be an indicator for a good SNR performance on rough, technical surfaces. The unique properties of visible, especially low noise HeNe laser-based designs on the other hand will be the better choice for shorter stand-off distances on smooth, reflective surfaces due to its better NLR and for measure-

ments trough water due to the low absorption. Considering optical signal robustness and NLR, vibrometers can be recommended for specific measurement conditions. The table shows a list of the most common conditions and how each vibrometer fares against the others comparing the QTec based LDV with the standard LDV with

Application categories based on NLR and optical signal robustness and corresponding performance.

Application	Single-Path LDV (HeNe) visible	Single-Path LDV (IR)	Multi-Path LDV (IR) QTec®
Mirror surface	● Best	● Good	● Good
Close up, highly reflective	● Best	● Good	● Good
Machined surface up to 1.5 m distance	● Good	● Good	● Best
Machined surface > 1.5 m distance	● Not optimal	● Good	● Best
Composite panels	● Low SNR	● Not optimal	● Best
High angle of incident, e.g 3D measurements	● Low SNR	● Good	● 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

either IR or visible HeNe laser light source. The classification of best, good, not optimal and low SNR are based on the optical signal robustness and NLR values for each vibrometer type in each measurement condition. The higher the OSR value, the more robust the LDV design is against surface induced noise effects and the closer one can get to the specified NLR in real world measurements.

As shown in the table of applications, there is no measurement scenario where the performance of the standard IR vibrometer exceeds the performance of the QTec. Furthermore QTec is superior to standard IR LDV technology in most cases. On the other hand, LDVs with a visible laser beam will continue to be used for various applications as listed above.

Discussion

Theoretical considerations show a dependency of the optical signal robustness OSR on the working distance and on the numerical aperture of the vibrometer. The smaller the spot size, the higher the theoretical speckle exchange rate and therefore the optical signal robustness is expected to be lower. Conversely, the smaller the spot size, the more light is collected by the vibrometer, which is favorable in producing fewer dropouts. Both are opposing effects and therefore, it is not easy to make theoretical predictions as to the net results for single-path vibrometers.

However, for QTec®, the measured optical signal robustness is close to infinity (zero dropouts) and accompanying experiments show that it remains at this value over a wide variation of working distances. Therefore, compared to single-path laser Doppler vibrometers, the multi-path laser Doppler vibrometer sits in a class of its own. As a consequence, sensors with QTec® achieve performance values that are closest to the specified NLR for most real-world applications.

In this application note, a test setup and an evaluation procedure are proposed. It is important to state, that no signal enhancement algorithms were applied to the processed signal to determine the optical signal robustness towards surface effects. Post-processing of the decoded signal is another way to eliminate speckle dropouts from

the signal. There are two reasons why post-processing can only mitigate the noise effects, but not remove them. First, in the presence of dropouts, a part of the raw signal is missing and cannot be reconstructed without loss. QTec® receives a continuous signal and is therefore a favorable lossless technology. Secondly, the phase changes are encoded in the signal as displacement noise. Removing the noise in post-processing would require information about the phase distribution. As it has a stochastic distribution, noise removal will affect the signal as well. For a true reconstruction, the root cause of noise (speckles) must be removed at its source as it is done by QTec®.

Conclusion and outlook

With the proposed setup a classification of the robustness towards surface effects can be performed with non-proprietary methods and a comparison between different laser Doppler vibrometers can be made. The results can be replicated using the simple setup of a rotating disk. The significance of this test is that information about the suitability of a certain instrument for measurements on rough technical surfaces can be predicted. Dropouts in the signal are unavoidable with standard single-path laser Doppler vibrometers and can be quantitatively measured as described in this application note. The only method for avoiding the described signal quality loss due to the speckle effect in laser Doppler vibrometer measurements on a given real surface is to use a multi-path laser Doppler vibrometer with diversity reception. This is available in the latest innovative QTec® vibrometers from Polytec.

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