Chapter 2
Continuous Scanning LDV: Comparison among different Vibrometer configuration and technologies

Milena Martarelli, Alessia Caputo, Joerg Sauer, and Paolo Castellini

Abstract Laser Doppler Vibrometry (LDV) is a mature measurement technique with numerous applications in civil, industrial and research fields. Despite this, developments in the technique are continuously progressing, both in terms of the measurement system and hardware, and in terms of measurement strategies and data processing. Compared to traditional point-by-point scanning, the technique of continuously moving the laser beam across a surface has the inherent potential for high spatial resolution combined with high scanning speed, opening up new applications beyond structural dynamics evaluation. In this paper, the Continuous Scanning strategy was applied using vibrometers with different wavelengths and technologies in order to evaluate the effects on the measurement results. In particular, results were compared with interferometers utilizing red and infrared wavelengths, along with traditional demodulation methods and multi-path interferometry (QTec). The findings highlight that the activation of QTec significantly improves the signal-to-noise ratio and reduces phase jumps, thus enhancing measurement stability and accuracy. The results obtained were carefully compared, focusing on the measurement uncertainty of the operational vibrational modes.

Keywords Laser Doppler Vibrometry · Continuous Scanning · QTec · Signal Quality · Operational Modal Analysis

Introduction

Measuring vibration without contact using a laser based on the Doppler effect is a technique already proposed 1964 [1]. Since the Doppler shift f_D expressed for reception in direct reflection

$$f_D = \frac{2nv}{\lambda} \tag{1}$$

where n is the index of refraction (1 in air) and v is the instantaneous velocity of the target and λ the laser wavelength, is in real world experiments eight orders of magnitude smaller than the laser light frequency. An interferometer has proven to be the best method to precisely determine the Doppler shift. Building upon this principle, Laser Doppler Vibrometer (LDV) equipped with a couple of moving mirrors automate the positioning of the laser beam on the surface of the object under test, allowing the reconstruction of the vibration spatial distribution of the object by scanning over a dense grid of points in a fast way. This vibration measurement strategy is named Scanning LDV (SLDV) and is widely used for modal analysis.

A strategy that overcomes this limitation is the so called Continuous SLDV (CSLDV) that consists of using the mirrors moving continuously in order to make the laser beam sweeping across the surface of the object under test. By means of this technique the vibration spatial distribution is therefore measured in one shot and, consequently, in a limited time [2]. Unfortunately the scanning of the laser beam over a rough surface exacerbated the well-known drawback of optical interferometry which is the speckle noise [3]. In the case of beam like structures, the CSLDV is typically exploited in the line scan mode, e.g. the laser beam is made to scan back and forward along a line, see Figure 1 (a). In this circumstance

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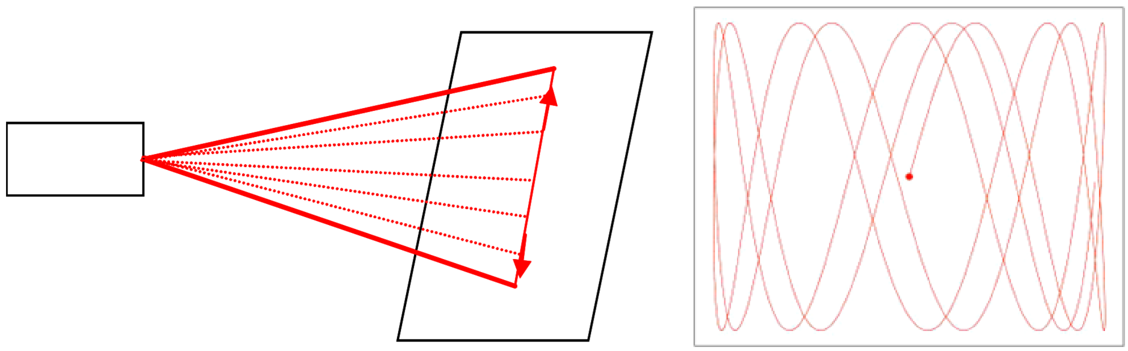
the laser beam passes periodically on the same speckle and therefore the effect of the speckle noise is boosted. In the case of plate like structures, the adopted CSLDV strategy is the area scan, see Figure 1 (b), that consists of driving the mirrors moving the laser beam with two sinewaves at frequencies mutually prime. The laser beam will then move along a curvilinear line, i.e. a Lissajous pattern, and it will never pass through the same point [4]. In this circumstance, opposite of the line scan, the speckle noise will be reduced. Despite this, techniques aimed at mitigating the effect of speckle noise make it possible to improve the quality of data collected via CSLDV.



(a) Line scan **(b)** Area scan

Fig. 1 Schematic representation of CSLDV strategies: **(a)** Line Scan – back-and-forth laser movement increases speckle noise; **(b)** Area Scan – Lissajous pattern reduces speckle effects by avoiding repeated points.

The CSLDV philosophy is based on the fact that when the laser beam scans continuously along a trajectory over a vibrating structure at a known excitation frequency with a motion low known, the LDV output is modulated in amplitude by the Operational Deflection Shape (ODS) of the structure itself at that excitation frequency. The easiest method for recovering the ODS from the LDV output is demodulation. The conventional and most diffuse method is instead the polynomial reconstruction. This latter is founded on the hypothesis that the ODS can be expressed by an analytic formulation based on a polynomial series. The polynomial coefficients are linked to the LDV output spectrum which has a shape typical of modulated signals. In practice it consists of a series of sidebands equi-spaced and centered to the excitation frequency. The polynomial coefficients can be calculated from the amplitude and phase of those sidebands by applying a Chebeyshev transformation matrix. There are several alternative methods for reconstructing ODSs from CSDLV data, like re-sampling the time history synchronously with the fundamental period (i.e. the scanning frequency) in order to recover a sort of "lifted" time histories at a finite number of points on the structure [5], [6]. Another method is the so called mode matching strategy which is based on the fact that mode shapes of the structure under test are known a priori (from a numerical model, an analytical formulation or previous measurements). It is then possible to settle a procedure that searches for similarities between those known mode shapes (the candidate mode shapes) and ODSs that actually modulate the signal measured and identify the actual mode shapes excited and the corresponding frequency [7]. Another strategy deserving to be mentioned is a blind identification of the polynomial coefficients based on the solution, in least square sense, of a set of linear equation defining the relations between the contributions of each cluster of frequencies (central frequency + sidebands) potentially defining the spectral pattern of a certain ODS to the complex spectrum measured [8]. In this paper the conventional method founded on the polynomial reconstruction of ODS by applying the Chebeyshev transformation matrix will be applied to demonstrate the efficacy of the Qtec technology in improving the ODS reconstruction from CSLDV data. The improvement of CLSDV technique open up new field of application of the method not only in modal analysis but also in structural damage detection where the measurement noise can compromise and sometimes invalidate the detection of defects as they typical have a minimum contribution to the overall vibration of the whole structure [9],[10].

Material and Methods

The experimental set up

The experimental setup consists of a rectangular aluminum plate of dimensions of 180x350 mm and thickness of 2 mm and clamped at one of the shortest sides. The plate was forced to vibration by means of an electrodynamic shaker (TIRA model TV 50009) connected to the structure via a stinger and a force cell (PCB model 208C01) for measuring the force transmitted to the plate. The vibration measurement was performed while the structure was forced at one single resonance; the resonances of the plate has then been measured in advance via a sine sweep test. The shaker has therefore been set to provide sinusoidal excitation at the resonance frequencies in sequence from mode 1 to mode 6, see Table 1. The table reports also the Modal Participation (MP) factor of each mode to the overall vibration. For the sake of synthesis, in the following only the mode shapes 2, 3, 5 and 6 will be considered whose spatial distribution is visualized in Figure 2 which represents the modes nodal lines. The vibration has been measured via an SLDV (Polytec model PSV-500 with selectable QTec option) in continuous scanning mode. Specifically the laser beam was made to sweep over the entire surface of the plate by piloting the driving mirrors with two sinewaves at 1.1 Hz, in the shortest direction, and 20 Hz, in the longest one. The experimental setup is shown in Figure 3; the shaker and the force cell are not visible because they are behind the plate but the driving point (the connection of the stinger attached to the shaker and the plate) is noticeable as the black dot on the surface of the plate.

Table 1 Natural frequency and mode participation of plate

	Frequency [Hz]	MP [%]
Mode 1	12.8	18.4
Mode 2	53.6	6.4
Mode 3	74.8	13.2
Mode 4	80.6	13.5
Mode 5	168.2	7.3
Mode 6	196.8	13.8

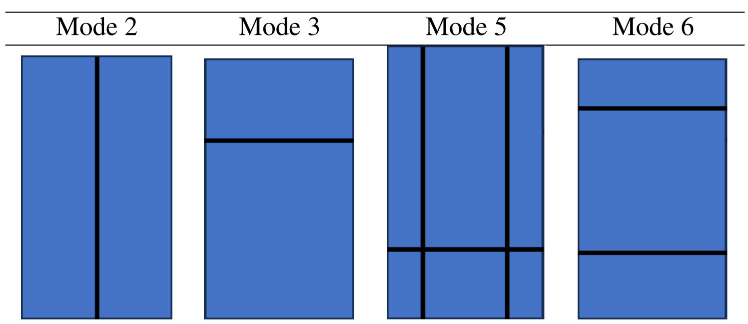


Fig. 2 Nodal lines of mode shapes considered in the analysis.

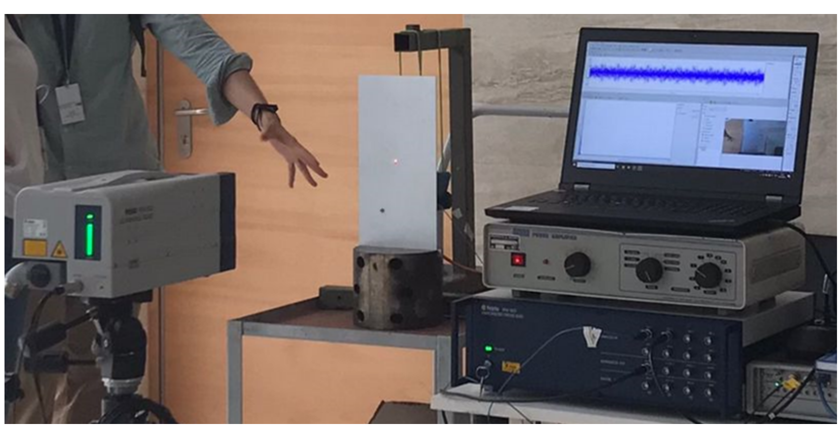


Fig. 3 Experimental set up for vibration measurement

ODS reconstruction from CLSDV data

Consider a line scan in the x-direction along a beam like structure. If the vibration is measured while the structure is forced at one resonance ω_j, and if the laser beam is moving along the structure, the LDV output is modulated in amplitude by the ODS of the structure itself at the excitation frequency ω_j. Consider that the ODS analytic formulation is a polynomial, as equation 2:

$$v(x) = \sum_{i=1}^{N} \mathrm{V}_i \mathrm{x}^{(i-1)} \tag{2}$$

being v the vibration velocity at the resonance frequency ω_j, V the polynomial coefficients, x the linear coordinate and N the polynomial order. The coefficients of such polynomial can be recovered from the amplitude and phase of the sidebands of the LDV output spectrum Si by applying the Chebeyshev transformation matrix $[T]$ as in equation 3:

$$\{\mathrm{V}\} = [\mathrm{T}]\{\mathrm{S}\} \tag{3}$$

QTec technology

For unambiguous detection of the sign of the velocity, the LDV is equipped with an optical-acoustic modulator (Bragg-cell) that adds a constant offset to the Doppler shift. This system allows to improved phase accuracy and signal-to-noise [11]. The most prominent noise source are "pseudo vibrations" caused by speckle transitions or changes of the speckle pattern caused by the coherent illumination of an optical rough surface (Figure 4) [12].

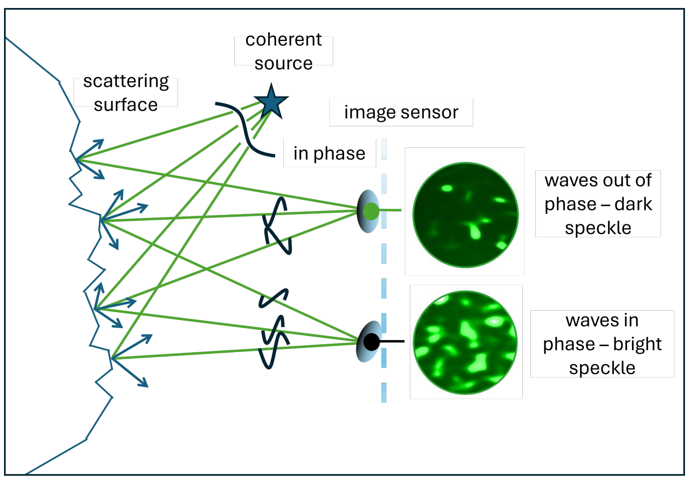


Fig. 4 Constructive and destructive interference depending on the observer position

Changes of speckle patterns cause signal drop-outs which express themselves in spikes in the velocity signal and phase jumps in the order of the wavelength λ in the displacement signal (Figure 5). At the same time the received signal strength (RSSI) drops. Due to a destructive interference little or no light arrives at the photo detector.

Speckle pattern changes are occurring with practically all real would measurements. Scanning Laser Doppler vibrometers in point-by-point scanning mode where the laser position is determined by galvo driven mirrors are exposed to speckle pattern changes while the scanning mirrors are moving or in decay. This makes wait times between each point mandatory if the SNR shall be optimized. This leads to the conclusion that the measurement time for scanning LDV could be drastically reduced if the speckle noise can be avoided. Inherent and not avoidable with the above-described interferometer configuration is speckle noise with rotating measurement samples like shafts and with continuous scanning laser Doppler vibrometer experiments. Since the speckle pattern is depending on the observer position relative to the illumination direction with coherent light adding observer position (multi-path) and using the received signals from all positions to recombine a speckle-drop-out free signal (Figure 6) [11].

The basic principle is used in WiFi receivers for a long time successfully and is called diversity reception. The implementation of a multi-path interferometer was proposed in the study of Martarelli et al. and is today implemented in the Polytec QTec® Laser Doppler Vibrometers used for generating the data for this paper [2]. The phase jumps and corresponding spikes of speckle changes are completely avoided with multi-path diversity combining if the RSSI signal is above the general FM threshold that allows signal detection and demodulation.

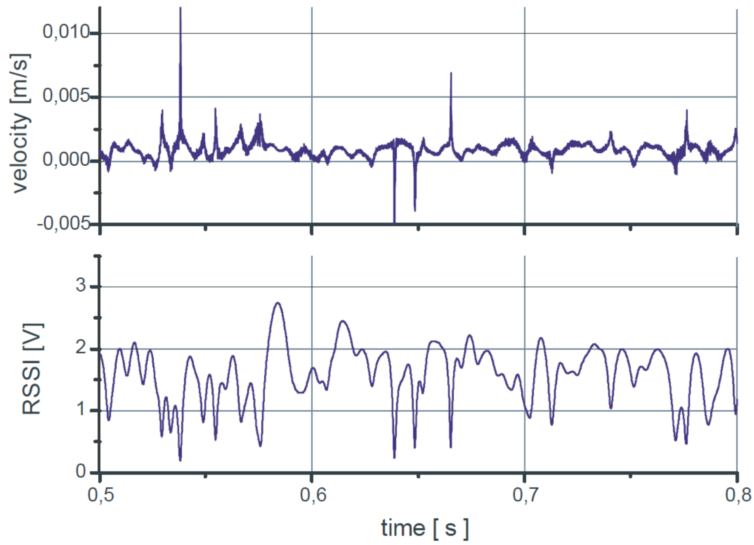


Fig. 5 Velocity signal spikes and corresponding RSSI signal drop a dark speckle

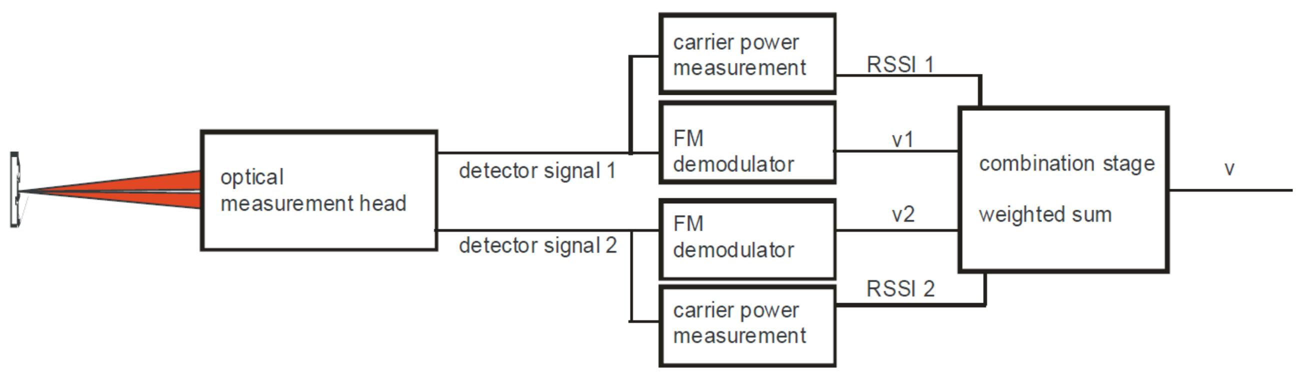


Fig. 6 General signal flow for a dual-path optical diversity system

Table 2 Increase in SNR and phase shift produced by the activation of the QTec option.

Mode	SNR [dB]		Phase shift θ [rad]		
	QTec off	QTec on	QTec off	QTec on	$\Delta\theta$
2	64.3	64.8	1.92	-0.04	1.96
3	26.4	34.5	1.48	2.73	1.24
5	13.4	14.2	2.07	2.94	0.87
6	20.31	20.92	-1.75	1.62	3.38

Results

In Figure 7 it can be observed the time histories and relative amplitude spectra measured by the CSLDV at the fourth resonance frequencies considered (the ones corresponding to the 2^{nd}, 3^{rd}, 5^{th} and 6^{th} ODS). Examining the signals related to the 2^{nd} excitation frequency (53.6 Hz), it can be remarked that the time history is slightly more noisy when the QTec is off while the main difference is in the phase spectrum around the sideband frequencies. Observing the signals at the 3^{rd} excitation frequency (74.8 Hz) the increase of noisiness in the time history acquired when the QTec is off is even more evident. The phase spectrum is instead less observable. The same can be said for the other two signals at the highest excitation frequencies. In order to express those differences in a synthetic way, two condensed metrics have been identified: the Signal

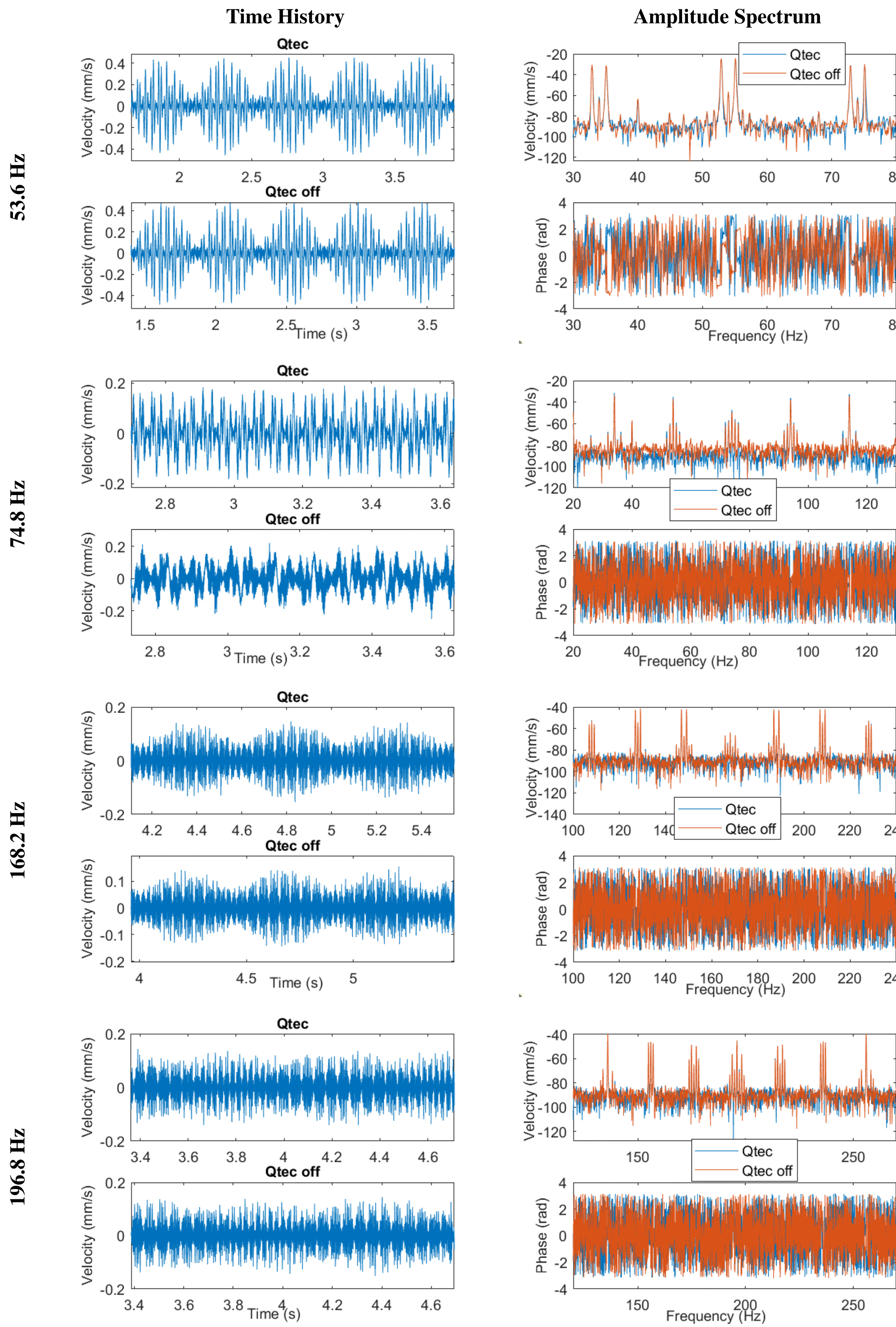


Fig. 7 CLSDV time histories and amplitude spectra at four excitation frequencies

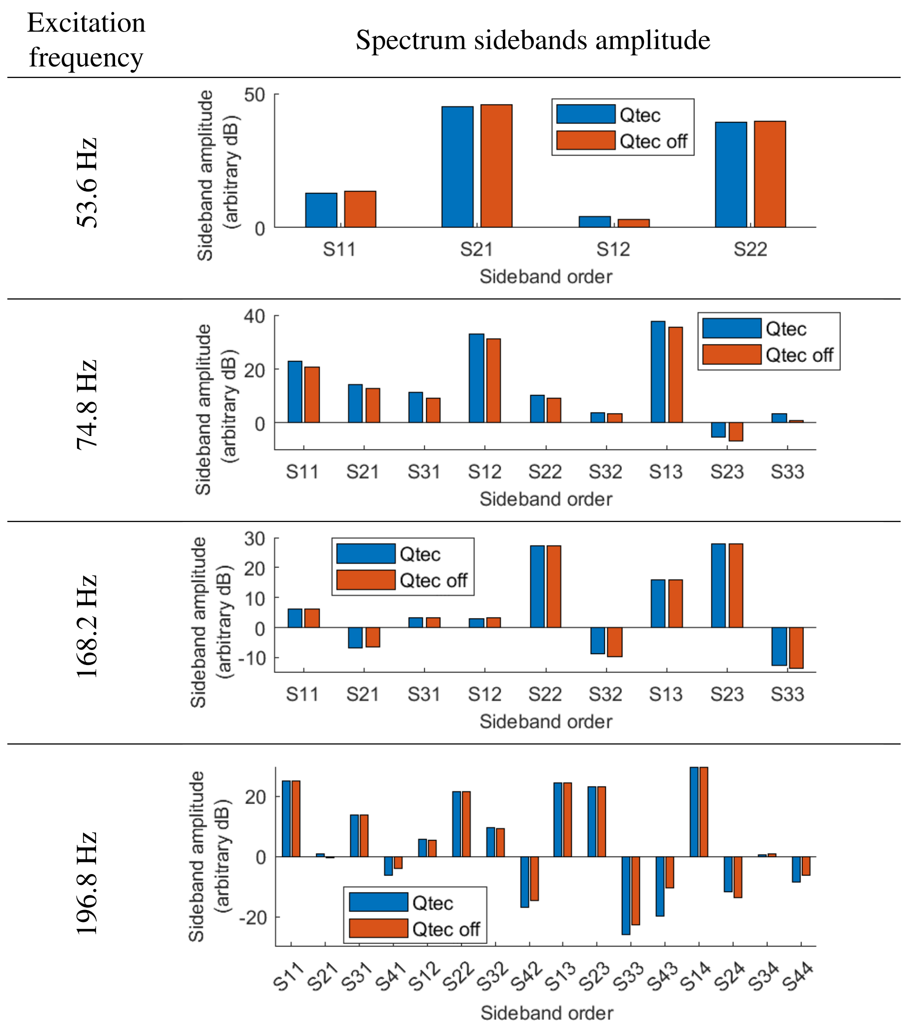


Fig. 8 Spectrum sidebands amplitude with Qtec activated and deactivated at the four excitation frequencies

to Noise Ratio (SNR) and the phase shift ($\Delta\theta$). The SNR of the signals acquired with the QTec activated and deactivated has been calculated as the ratio between the amplitude of the spectrum at the excitation frequency ωj and the mean value of the spectrum at all the frequencies except the excitation frequency and its sidebands. The phase shift has been determined as the difference between the phase of the spectrum acquired with the QTec option activated at the first sideband frequency and the same phase of the spectrum acquired with the QTec option deactivated. Those metrics are reported in Table 2, from which it can be deduced that the QTec does not reduce SNR which is always extremely high, except for the mode 3 there an increase of almost 8 dB is observed if the QTec is active. Concerning the sideband phase instead it is evident that the QTec modifies it of about 1 rad for the majority o the modes but for the 6th mode a phase shift higher than 3 rad is observed. It is expected that this phase variation will affect the mode shapes. Another way to highlight the effect of the QTec option is to observe the amplitude of the sideband spectra at the different excitation frequencies as reported in Figure 8. For modes 2 and 5, the torsional ones, the spectrum sidebands amplitude are almost not affected by the QTec mode. For mode 3 instead the sidebands calculated from the CSLDV data acquired with and without QTec differ the most and this confirm also the fact that the SNR in this case is 8 dB less when the QTec is deactivated. Considering mode 6, the sideband amplitudes are again different between the conditions of QTec on and off. This effect is very evident at the highest sidebands orders, which is justified by the fact that the high order sidebands are small and therefore more influenced by noise.

The final comparison can be done by observing the ODS reconstructed applying the Chebeyshev transformation to recover the 2D polynomials, which are reported in Figure 9. As evidenced by the previous analysis the ODSs suffering the most the QTec deactivation are the 3^{rd} and the 6^{th} ones. When the QTec mode is deactivated is visible in the ODS a not expected concavity along the x-direction that is due to high order sidebdnds distortion.

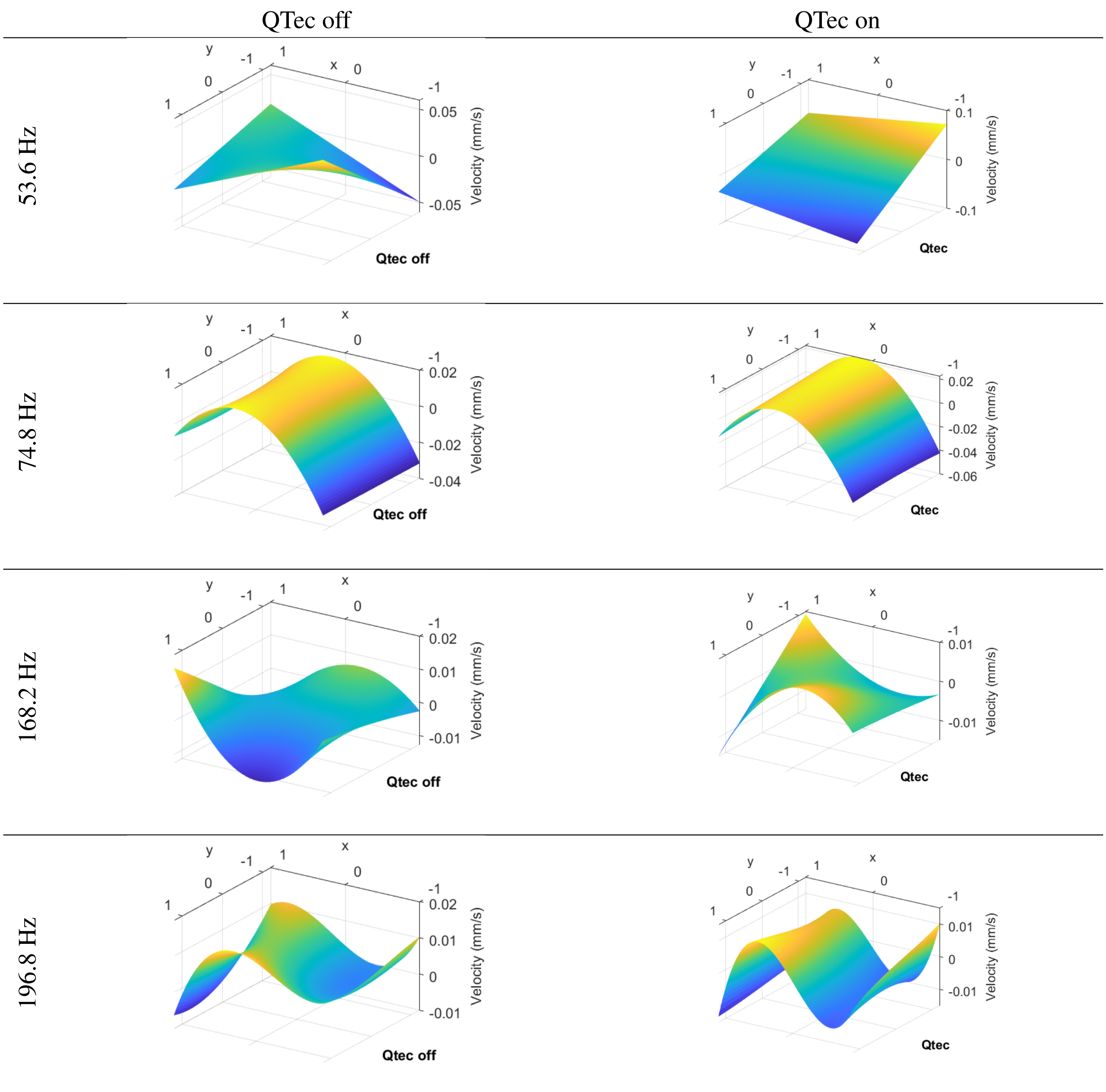


Fig. 9 Comparison of ODSs with QTec activated (right) and deactivated (left) at various frequencies

Conclusion

The experimental analysis demonstrated the advantages of QTec technology in vibration measurements using CSLDV. The observed improvement of the SNR with QTec engaged for the 3^{rd} mode meets the expectation from experimental modal analysis experiments in point-by-point scanning mode. The SNR influence in the other modes was thus not as expected, indicating that QTec's effectiveness in suppressing phase jumps varies across different modes. The suppression of the actual phase jumps between speckles is effective also at the high speckle exchange rates of several 100 kHz as they occur at higher scan rates (Figure 10). While SNR is generally high without QTec, the technology is crucial for mitigating phase fluctuations, especially in the 3^{rd} and 6^{th} modes, which are sensitive to distortions. The analysis of ODS confirmed that QTec improves the accuracy of modal shape reconstruction, minimizing errors in structural analysis. Future work will address theoretical assumptions related to phase changes within the speckle that may limit SNR improvements. Overall, integrating QTec technology enhances measurement reliability and data integrity in complex vibration analysis.

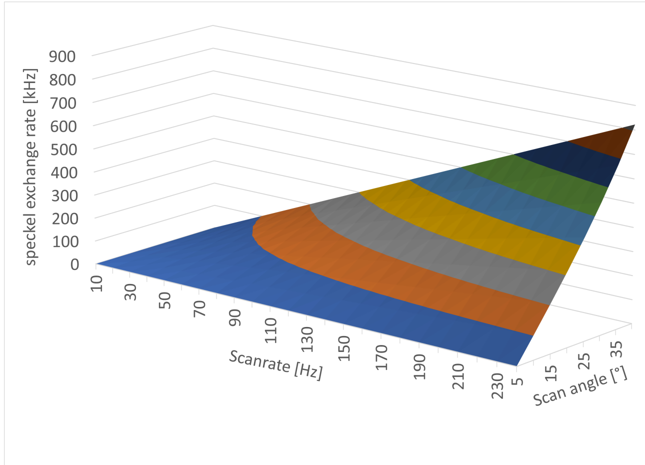


Fig. 10 Speckle exchange rates in CSLDV experiments depending on scan rate and angle for the PSV QTec with 1550 nm wavelength at 1m distance

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