DOI 10.5162/sensor2015/D1.1

Speckle-Insensitive Laser-Doppler Vibrometry with Adaptive Optics and Signal Diversity

Christian Rembe[1,2], *Alexander Dräbenstedt*[2]
[1] *TU Clausthal, IEI, Clausthal-Zellerfeld, Leibnizstraße 28, Germany*
rembe@iei.tu-clausthal.de
[2] *Polytec GmbH, Polytec Platz 1-7, Waldbronn, Germany*

Abstract:
Phase noise and signal drop-outs by laser-speckle are the dominant limitations for the resolution of laser-Doppler vibrometers while measuring on rough surfaces of mechanic-engineering parts. For a long time laser-speckle effects have been accepted to be an unsolvable problem that can only be treated with bandwidth limiting signal-processing filters. Recent publications show now that this perception can be conquered with methods from adaptive optics and signal diversity. The paper discusses the possibility to introduce adaptive optics with spatial light modulators in order to maximize the signal strength of a laser-Doppler vibrometer. The other solution discussed in this paper is based on signal diversity as it is known from radar technology. Several sub-apertures which detect different angular speckles and a special polarization detection scheme allow obtaining different signals from independent speckles. The possibilities and limits of the two approaches are explored. The conclusion of the paper is that speckle-insensitive laser-Doppler vibrometry is feasible.

Key words: Laser-Doppler vibrometry, speckle-insensitive vibrometry, adaptive optics, signal diversity.

Introduction

The Laser-Doppler Vibrometer (LDV) has become the gold-standard for non-contact vibration analysis of macroscopic (e.g. buildings) and microscopic (e.g. MEMS) structures [1, 2, 3] due to its easy handling without wires, high flexibility, high resolution, and its absence of retroaction to the specimen compared to tactile acceleration sensors. However, a drawback of this technology compared to acceleration sensors is its sensitivity to the laser-speckle effect on rough surfaces [4, 5, 6]. Although the high-dynamic intensity range of more than 120 dB has made signal-strength variations by speckle effects acceptable for most applications, a real speckle-insensitive LDV is desirable.

For a long time it has been assumed that signal-drop outs and phase noise by laser speckle can only be treated in the demodulated velocity signal. Recent research results show new approaches which address speckle effects already in the optical domain. Serafine et al. have demonstrated an adaptive solution with the galvo-scanner system of a laser-scanning vibrometer by implementing a search algorithm for an optimal measurement point [7]. Rembe and Haist have proposed to reduce speckle effects by adaptive optics based on digital holograms [8], Mayer et. al. have demonstrated the compensation of signal-loss by laser-speckles based on the proposed setup [9] and Polytec has developed and patented a technique based on sub-aperture and polarization-sensitive detection [10]. Diversity combining makes use of the distribution of bright and dark speckles over two perpendicular polarizations and spatial segments of the detection aperture. Since the total power of the scattered light is contained, a dark speckle in one channel increases the probability slightly for a bright speckle in any other channel. An intelligent approach to combine the information of independent channels enables high insensitivity to laser-speckle effects. Dräbenstedt has demonstrated a dramatic reduction of signal-dropout probability by employing diversity combining with a sophisticated algorithm which combines the demodulated signals of several channels optimizing the signal-to-noise ratio (SNR) of the combined signal [11].

This paper gives an overview of the state-of-the art of speckle treatment in LDV and compares the different approaches to overcome speckle noise.

Laser-Doppler Vibrometry

The key component of a LDV is an interferometer with a broad-bandwidth detection of the interference signal. Although also homodyne detection schemes have been utilized in the past, the superior properties [2] of the heterodyne interferometer have superseded all other approaches to measure vibrations optically. The typical setup of a heterodyne interferometer is shown in figure 1.

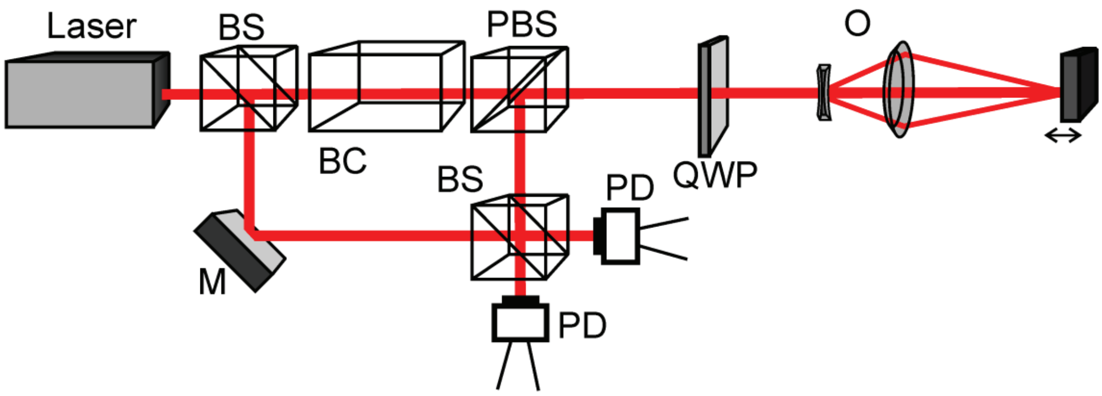

Fig. 1. Schematic of a heterodyne interferometer. BC is Bragg cell, BS is beam splitter, PBS is polarisation beam splitter, QWP is quarter wave plate, A is aperture, PD is photo diode, O is an objective lens, and M is a mirror.

The Bragg cell shifts the laser frequency and generates an intrinsic frequency offset in respect to the reference beam. The photo detector arrangement consists usually of a balanced detector pair and converts the dynamic light intensity at the detector in a current signal which is amplified by a trans-impedance amplifier to a voltage signal. The detector signal has a carrier frequency which corresponds to the frequency shift generated by the Bragg cell. All phase modulations on the electrical field vector through the vibration of the sample are down-mixed to phase modulations of the heterodyne detector voltage-signal [3]

$$u(t) = K\left(P_r + P_m + 2\varepsilon\sqrt{P_r P_m}\cos(\omega_h t + \varphi(t))\right) \quad (1)$$

with K the amplification of the detector, P_r the reference-light power that impinges the detector, P_m the measurement-light power that impinges the detector, ε the heterodyning efficiency, ω_h the heterodyne carrier frequency, and

$$\varphi(t) = \frac{4\pi}{\lambda} s(t) \quad . \quad (2)$$

Here, λ is the laser wavelength and $s(t)$ is the time dependent displacement of the vibrating surface. The demodulator electronics of a LDV reveal the phase modulation and, therefore, the displacement with high bandwidth. Actually, the value of the heterodyne frequency ω_h and the relation described by the Carson equation [12]

$$\omega_h > \dot{\varphi}_{\max} + \omega_m \quad (3)$$

limit the detectable vibration bandwidth if the detector bandwidth B is $B \geq 2\omega_h$. $\dot{\varphi}_{\max}$ is the maximum Doppler shift and ω_m is the maximum modulation frequency

Influence of Laser Speckle

The influence of laser speckle to the signal of a common single-beam LDV is discussed in detail in reference [5]. However, the speckle effect introduces dark and bright patterns with random phase in the scattered light field. The typical angular diameter of a bright pattern corresponds to the diffraction limited light cone which coincides to the aperture angle of the measurement beam that impinges the sample. The random phase has usually the largest gradients in the dark sectors of the speckle fields between two bright areas.

These properties result in two effects to the LDV signal. Effect (1) originates from the fact that the measurement beam can impinge on a surface point where a dark speckle is scattered to the detection aperture. This would reduce the measurement-light power P_m and, therefore, would increase the noise of the displacement signal. A signal drop-out occurs if the heterodyne carrier power drops down to the noise power in the demodulation bandwidth. Effect (2) results from transverse vibrations which would change the position of the laser spot on the surface and, thus, the speckle field. Especially, crossings of dark speckles generate substantial phase noise $\varphi_n(t)$ because the random phase of the laser speckle field $\varphi_{speckle}(\vec{r})$ at surface positions $\vec{r}(t)$ shows phase jumps at dark speckles. Two techniques have been explored recently which will be discussed and compared in the following.

Speckle Treatment with Adaptive Optics

Method number 1 accesses on a correction of the speckle field with wavefront alteration of the measurement beam. This requires a spatial light modulator (SLM) in the measurement beam to change the wavefront. Proper SLM for LDV can be either realized by micromirror array or by liquid crystal display (LCD) phase modulators. It is not favorable to measure the wavefront of the returning measurement light which would reduce the valuable returning light power. On the other hand, the available strength of the heterodyne carrier depicted in equation (1) under the condition that a spread or movement of the measurement spot is minimal can be optimized with the SLM phase modulation. A proper cost function for an adaptive optics optimization or control loop can be defined on this basis. Figure 2a) shows the schematic of a possible arrangement and Figure 2b) demonstrates an algorithm which has been developed to simulate the working principle of the approach.

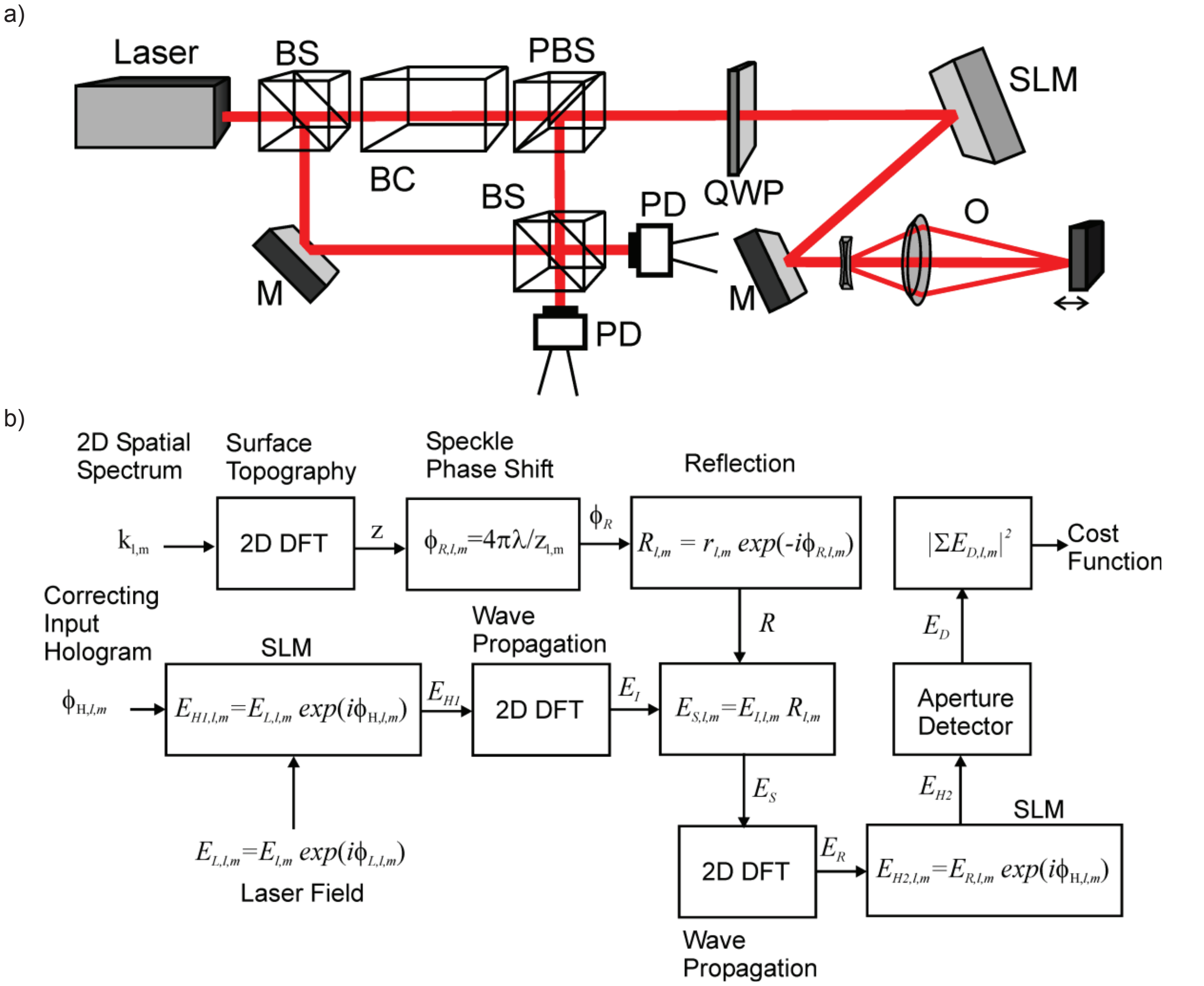

Fig. 2. Schematic of a heterodyne interferometer with an SLM to utilize adaptive optics for speckle treatment (a). The abbreviations of Fig 1 are used. The principle of the proposed adaptive optics algorithm is depicted in (b).

The input of the simulation is a speckle field which impinges the aperture defined by the reference beam wavefront. The wavefront scattered from a random rough surface on this aperture which lies in the Fourier plane can be simulated with a 2-dimensional discrete Fourier transformation (2D DFT). The light power collected by the aperture plus integrated power of the difference between the distorted laser focus and the uncorrected laser has been used as merit function for an optimization procedure performed by Matlab®. Figure 3 demonstrates how rather tiny aberrations with minimum influence on the laser spot position and size can dramatically increase the detected light power.

Polytec has realized the demonstrator setup to perform experimental investigations on this approach during the research project Holovib (BMBF grant number 13N9338). Polytec has realized the experimental setup with an IVS 300

DOI 10.5162/sensor2015/D1.1

LDV shown in Figure 4. The received signal strength indication (RSSI) of the heterodyne detector signal is recorded and is accessible in the PC to calculate an improved hologram which could be displayed on the SLM. The partner University of Stuttgart has implemented an interface to alter the coefficients of the Zernike polynomials introduced as aberrations with the SLM [13].

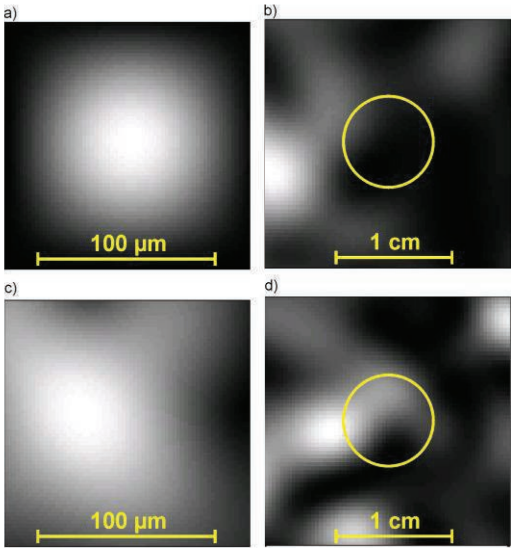

Fig. 3. Simulated laser-spot size of the measurement laser focus on the sample when no aberration were introduced by the SLM (a) and the resulting speckle intensity field of a randomly chosen example rough surface. After the optimization procedure the received light power is increased.

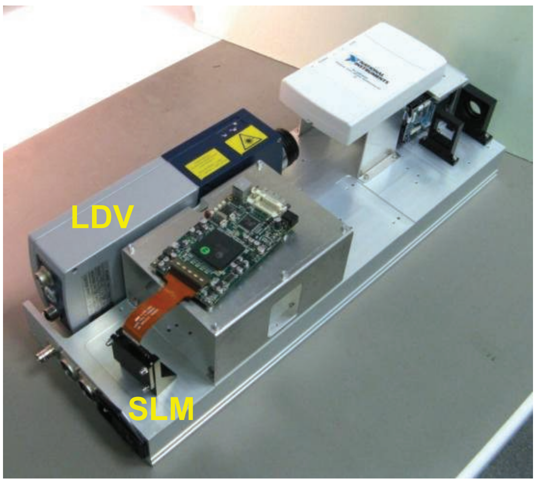

Fig. 4. Photograph of the experimental setup to explore the utilization of adaptive optics in LDV to reduce speckle effects. The SLM alters the wavefront of the measurement beam as depicted in Fig. 2.

The partner University of Wuppertal has investigated algorithms to find a proper optimum after a minimum number of iterations and they have demonstrated a sophisticated control algorithm [14] which has gained in average approximately 7 dB SNR of the heterodyne detector carrier strength. The main result of the investigations within the Holovib project can be summarized such that it is sufficient to change the defocus term and the x- and y- tilt terms of the Zernike polynomials for the optimization to achieve nearly the same performance as with a higher number of Zernike coefficients (e.g. 7). In a control loop the adaptive optics holds the LDV on a bright speckle and, therefore, minimizes in addition speckle phase noise.

However, this technique can only compensate speckle effects during transverse motion if the in-plane displacements are rather small compared to the spot size or if the bandwidth of the adaptive optics control is larger than the measurement bandwidth of the in-plane displacements. Since LCD modulators and adaptive optics mirrors have a rather low frame rate or control bandwidth the technique is limited to rather small in-plane displacement bandwidths considering nowadays available technology and components. Consequently, although it has been demonstrated that this technique can improve LDV performance its application in commercial sensors is currently rather limited. Extremely fast steering and focusing elements are required for a successful realization in an industrial LDV sensor.

Speckle Treatment with Signal Diversity

An alternative approach has been explored at Polytec which is based on the basic concepts of signal combining and it has been demonstrated that this technique is suitable to handle rapid alterations of the speckle field which corresponds to fast in-plane velocities and large transverse displacement of rough targets. In fact it has been shown that this technology makes possible a speckle-robust LDV. The basic setup of a demonstration setup can analyze two correlated speckle fields by evaluating light from two detection apertures. A schematic of an interferometric setup with 2 detection apertures [11] is depicted in Figure 5.

However the optical setup for diversity is realized, the total scattered light power remains constant for a given surface reflectivity whatever roughness topography the surface may have. Therefore, the received power of two channels is uncorrelated or in case of a directional scatter with only a view speckles rather anticorrelated. However, the probability to receive dark speckles in all detection channels at the same time is a much rarer event than receiving a dark speckle in just one detection channel. Due to this fact it can be concluded that a weighted sum of the demodulated signals of each channel

DOI 10.5162/sensor2015/D1.1

$$s_{com}(t) = \sum_{i=1}^{N} a_i(RSSI_i)s_i(t) \Bigg/ \sum_{i=1}^{N} a_i(RSSI_i) \quad (4)$$

will result in a substantially improved combined signal $s_{com}(t)$. The weighting factors $a_i(RSSI_i)$ are strictly increasing functions from the current RSSI value of channel i. Therefore, the stronger the signal, the higher the weight of that channel.

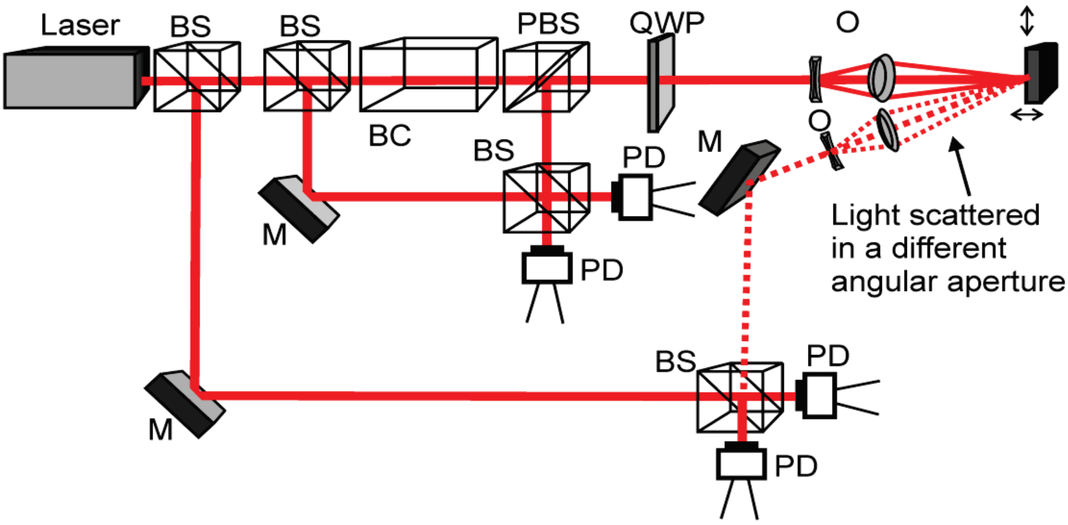

Fig. 5. Schematic of a heterodyne interferometer with 2 sub-apertures for speckle treatment with signal diversity (a). The abbreviations of Fig 1 are used.

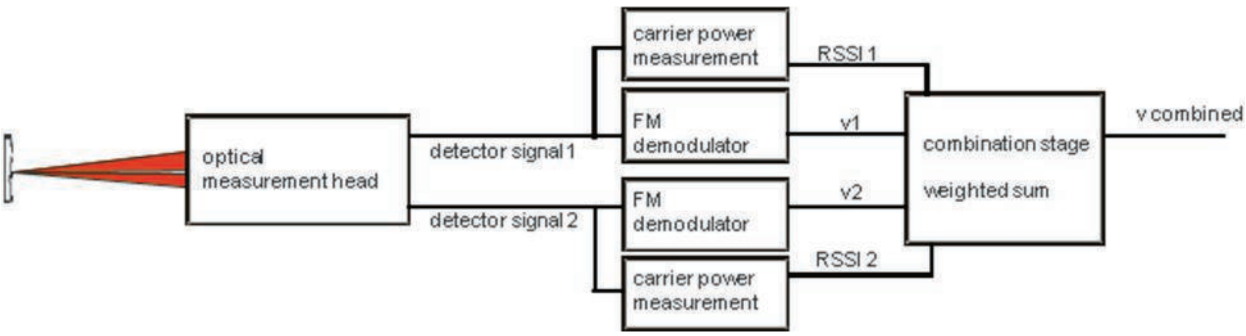

Fig. 6. Schematic of the signal-processing scheme of a two-channel diversity combining LDV.

Figure 6 shows the schematic of a two-channel demodulation scheme for generation of a velocity signal. A demonstrator setup has also been developed at Polytec for the diversity combing approach. Noise measurements have been performed by pointing the measurement laser beam on a rough rotating structure generating a fast alternating speckle field. The demonstrator can demodulate two separate channels and can compute in real time a combined signal in respect to equation 4. Measurements have been performed on a disk rotating with 9.9 RPM.

Since the computation is performed in real time, the combined signal is slightly delayed but remains its full bandwidth. This is a major advantage against the adaptive-optics approach where the adaptive-optics modulation of the wavefront introduces disturbances to the measurement signal within its control bandwidth. Speckle effect 1 is the occurrence of signal drop-out. It depends on the probability that the RSSI drops below a certain value. Figure 7 shows the cumulative probability of the occurrence of a RSSI voltage defined on the x-axis for the 2 original signals and the combined signal. A signal drop-out appears at a certain RSSI value in dependence on the demodulation bandwidth and is reduced by just 2 channels already by a factor 30 [11] and a factor above 2000 can be achieved with 4 channels. Speckle effect 2 introduces phase jumps at dark speckles. Since dark speckles are suppressed by diversity combining, velocity spikes are reduced and, thus, phase noise by laser speckles is reduced dramatically.

DOI 10.5162/sensor2015/D1.1

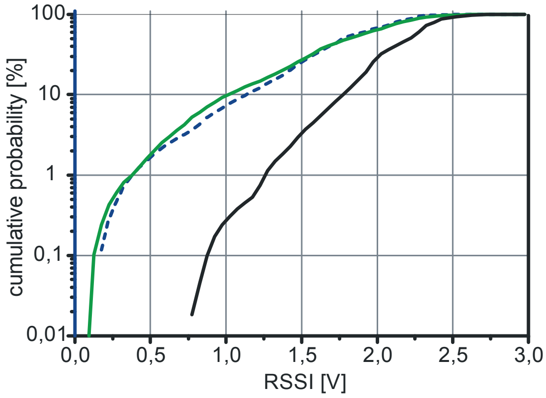

Fig. 7. cumulative probability; channel 1 dashed blue (dark grey) line, channel 2 green (light grey) line, equivalent combined signal strength black

Figure 8 shows the effect of signal diversity to the noise level of a velocity vibration spectrum with transverse movement of the rough surface.

Conclusion

Adaptive optics and signal diversity techniques can reduce the effects of laser speckles on rough surfaces substantially. However, in direct comparison, signal diversity enables a more robust suppression of speckle-induced noise with no negative influence to the measurement signal. Diversity combining with just two channels reduces the probability for signal drop-outs already by a factor of 30.

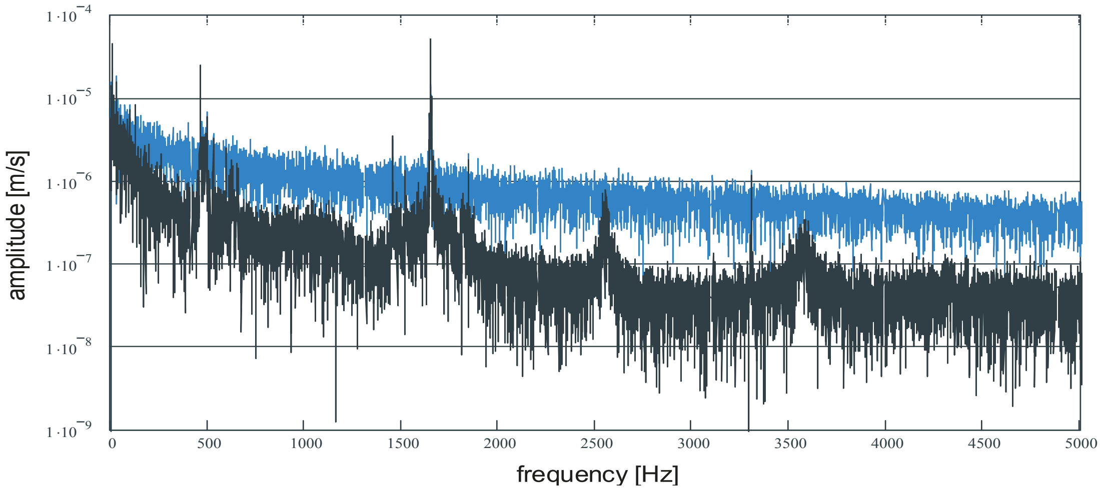

Fig. 8. Vibration velocity amplitude spectrum of the previous measurement, blue (gray) is the average spectrum of both raw channels, black is the spectrum of the combined channel with a much lower noise level.

References

[1] G.A. Massey, An optical heterodyne ultrasonic image converter, Proc. IEEE, **56**, 2157(1968).

[2] M. Bauer, F. Ritter, G. Siegmund, High-precision laser vibrometers based on digital Doppler-signal processing, Proc. SPIE, **4827**, 50(2002).

[3] C. Rembe, G. Siegmund, H. Steger, M. Wörtge, "Measuring MEMS in motion by LDV", in Optical Inspection of Microsystems, Ed. W. Osten, Boca Raton, Taylor & Francis, (2007).

[4] S. J. Rothberg , B. J. Halkon, Laser vibrometry meets laser speckle, SPIE **5503**, 280 (2004).

[5] A. Dräbenstedt, Quantification of displacement and velocity noise in vibrometer measurements on transversely moving or rotating surfaces, SPIE **6616**, V, 661632(2007).

[6] R. Kuschmierz, N. Koukourakis, A. Fischer, J. Czarske, On the speckle number of interf. velocity and distance measurements of moving rough surfaces, Opt. Lett. **39**(19), 5622(2014).

[7] S. Serafini, N. Paone, and P. Castellini, Agent-based station for on-line diagnostics by self-adaptive laser Doppler vibrometry, Rev. Sci. Instrum. **84**, 121703(2013).

[8] C. Rembe, T. Haist, Interferometer for optically measuring an object, US000007808646B2, (2010).

[9] S. Mayer, B. Tibken, C. Rembe, A new approach for signal loss compensation in a vibrometer, Proc. ACC, June 29 -July 1, San Francisco, CA, 2645(2011).

[10] A. Dräbenstedt, S. Boedecker, C. Rembe, M. Schüssler, Matthias, T.-H. Xu, DE102012211549B3, (2013).

[11] A. Dräbenstedt, Diversity combining in laser Doppler vibrometry for improved signal reliability, AIP Conf. Proc. **1600**, 263 (2014).

[12] J.R. Carson, "Notes on the theory of modulation", Proc. IRE, **10(**1), 57-64(1922).

[13] S. Zwick, M. Warber, T. Haist, F. Schaal, W. Osten, S. Boedecker, C. Rembe, Advanced scanning laser-Doppler vibrometer with computer generated holograms, AIP Conf. Proc. **1253**, 279(2010).

[14] R. Dehnert, S. Mayer, B. Tibken, Extremum seeking control to avoid speckle-dropouts in a vibrometer , SPIE **8789**, 87890B-11(2013).