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SPECTRUM ENHANCEMENT OF LASER VIBROMETER SIGNALS USING A NEW SPECKLE NOISE REDUCTION TECHNIQUE AND ANGULAR RESAMPLING

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Abstract

In this paper, a new method to enhance vibration signals measured by Laser Doppler Vibrometry (LDV) is proposed. The method consists of two stages of processing. The first stage is intended to reduce the speckle noise, an inherent problem of LDV when rough surfaces are measured. The speckle noise causes amplitude dropouts, resulting in undesired "spikes" on the waveform of the velocity signal. It is shown that the presence of the speckle noise depends on the optical level signal (a DC voltage proportional to the amount of backscattered light from the object under investigation). Whenever the optical level is critically low, a new spike is generated and persists until a sufficient value of the optical level is reached. Therefore, speckle noise reduction is achieved by removing all periods of the velocity signal that correspond to the optical level below a specified threshold. The remaining periods are then "connected" using zero crossings in order to form a denoised velocity signal. The second stage is based on an order tracking method recently developed by Bonnardot et al. This method requires no tachometer signal since the instantaneous shaft speed is extracted from the instantaneous phase of a demodulated vibration signal. After the resample times are determined, the denoised signal is resampled in the angular domain by using linear interpolation. As a result, fluctuations of the shaft speed are removed, which reduces smearing of discrete frequency components and thus contributes to sharper peaks in the order spectrum. Finally, spectrum enhancement is also illustrated using the power spectral density and the envelope spectrum. The results indicate that the method can reveal spectral peaks buried in the noise, and thus improve detectability of mechanical faults. The method has been applied to LDV signals measured on washing machines for the purpose of quality control in production lines.

1. INTRODUCTION

Laser Doppler vibrometry (LDV) is a non-contact measurement technique used to acquire the velocity (or displacement) of vibrating objects. Due to the non-invasive character of LDV, the measurement process does not affect the object of interest, particularly its natural stiffness and damping [1]. LDV measurements can be also automated, which significantly reduces the testing time and makes LDV particularly attractive for quality control in production lines. For example, LDV has been recently employed in detection of manufacturing defects in washing machines [2] and electric motors [3, 4].

Despite the advantages of LDV, vibration measurements on rough surfaces can be distorted by speckle noise which is the most important limitation of LDV [5]. Hence this paper presents a new method for reducing the speckle noise (Sec. 2), followed by an applied order-tracking technique (Sec. 3). The improvement obtained by each step is demonstrated in Sec. 4.

2. SPECKLE NOISE REDUCTION

Vibration data are acquired using a testing station for quality control of washing machines. Specifically, vibration velocity is measured on the surface of the drum by an industrial single-point vibrometer [6], which also provides an additional output signal referred to as *optical level* (level of the optical signal). The optical level is a measure of the amount of light scattered back from the object under investigation. The signal is provided as a DC voltage proportional to the logarithm of the optical signal level [6]. It is often used for optimising the focus of the laser beam, which can be manually adjusted by a focusing ring.

Reduction of speckle noise is based on thresholding the optical level signal and removing all periods of the velocity signal which are critically distorted. The remaining periods are then "joined" together to form a new denoised signal. This method can be used only during the steady state, where the removed periods carry similar information as the periods to be preserved. On the other hand, the frequency content is changing during the run-up and run-down of the washing machine, hence the removal would cause a loss of information. The method operates as follows.

2.1. Zero crossings of the sinusoidal signal

The steady-state velocity signal $x_{\text{ss}}(m)$ is band-pass filtered in order to extract a sinusoidal signal $s_{\text{ss}}(m)$ for detection of zero crossings. This procedure consists of five steps and is shown in Fig. 1. First, the amplitude spectrum of $x_{\text{ss}}(m)$ is computed using the discrete Fourier transform (DFT). Second, the shaft frequency f_0 is detected as the maximum peak in the range 0–30 Hz. Third, the lower and upper edge of the filtered band are computed as 0.8 f_0 and 1.2 f_0, respectively. Fourth, band-pass filtering of $x_{\text{ss}}(m)$ is performed in the frequency domain. Fifth, zero crossings of $s_{\text{ss}}(m)$ are detected in a standard way.

The filtered band is from 11.6 to 17.4 Hz, which is necessary for preserving fluctuations of the shaft speed. Fig. 1(b) depicts the waveform of the original signal $x_{\text{ss}}(m)$ and the filtered sinusoidal signal $s_{\text{ss}}(m)$ with its zero crossings. These crossings represent the "true" (noise-free) zero crossings of $x_{\text{ss}}(m)$ and are thus used to separate this signal into individual periods.

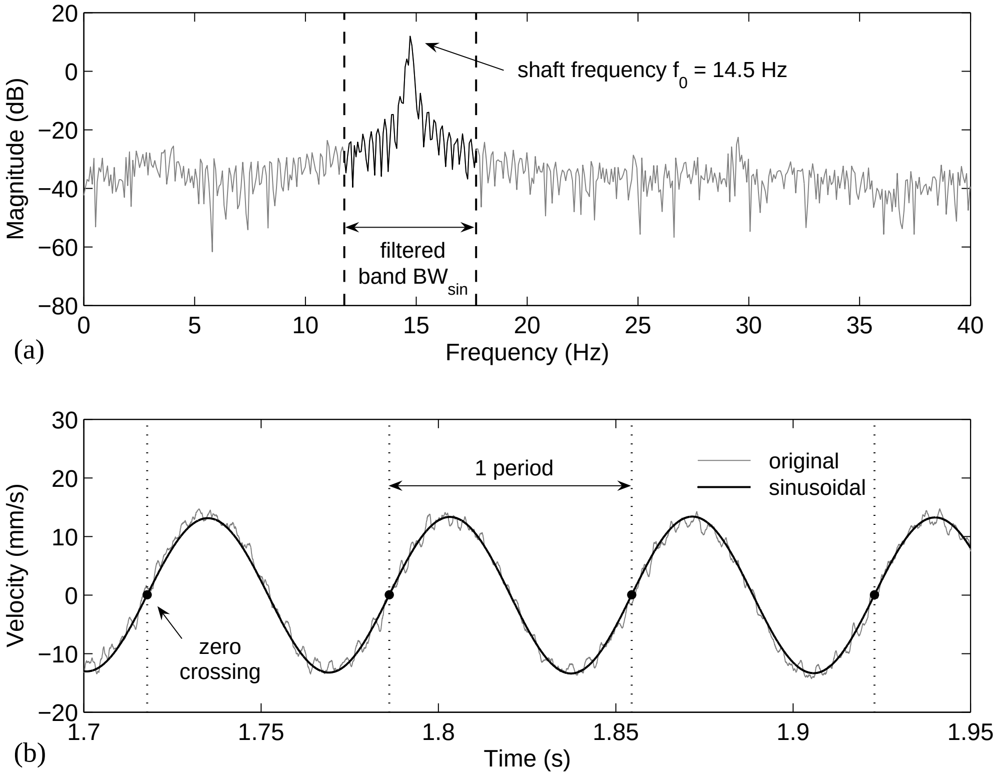

Figure 1. Extraction of the sinusoidal signal: (a) selected band for band-pass filtering, (b) detail of the waveform with detected zero crossings.

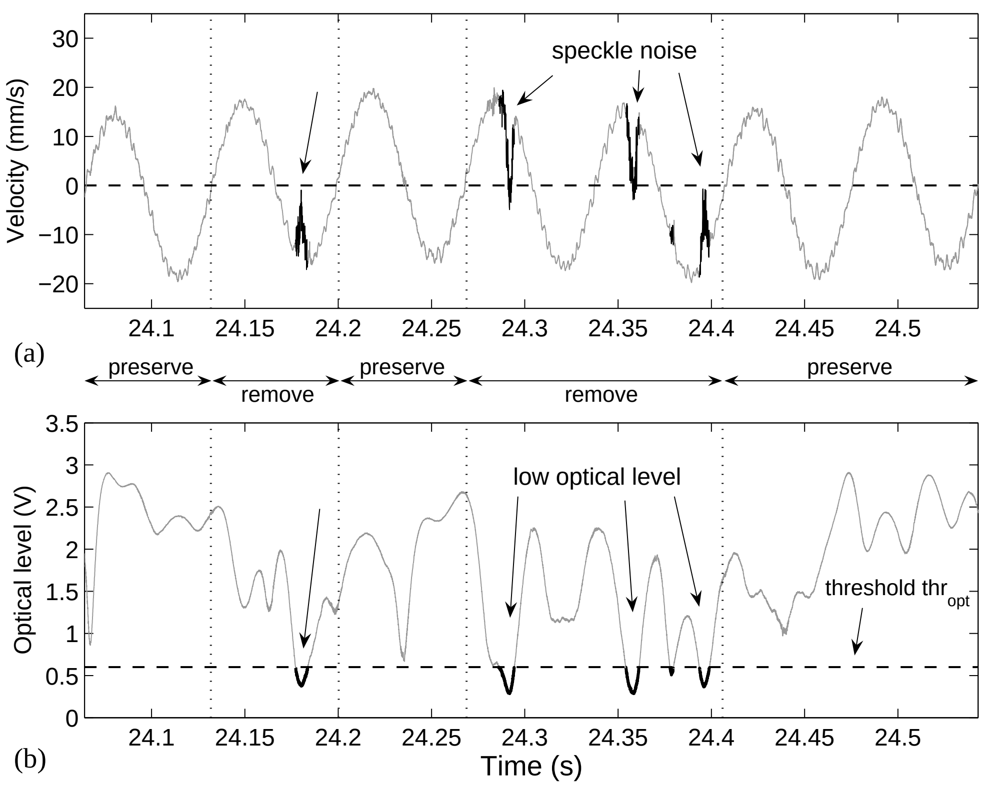

Figure 2. Removal of periods distorted by critical amount of speckle noise.

2.2. Removal of periods with speckle noise

Fig. 2 shows an example of speckle noise which indicates that this noise generates "spikes" on the waveform of the velocity signal. The direction of these spikes is always towards zero, which implies that the speckle noise causes dropouts of the signal amplitude. The waveform of $x_{\text{ss}}(m)$ is practically the same as the speckle noise model proposed by Gasparetti and Revel [7].

It has been observed that the presence of the speckle noise is dependent on the steady-state optical level signal $q_{\text{ss}}(m)$. Whenever the value of $q_{\text{ss}}(m)$ is critically low, a new spike is generated and persists until the optical level returns to a sufficient value. Based on this observation, the denoising procedure operates as follows. The signals $x_{\text{ss}}(m)$ and $q_{\text{ss}}(m)$ are processed period by period using the detected zero crossings. If the optical level for a current period drops below a threshold thr_{opt}, this period is regarded as distorted and is removed from the signal (notice the labels 'remove' and 'preserve' in Fig. 2). The goal of this procedure is to remove the most severe speckle noise, since a small amount of the noise is present in the whole signal.

The periods to be preserved are then "connected" to form a new signal $x_d(n)$, as illustrated in Fig. 3. A new time index n is used to emphasise that $x_d(n)$ has a different time basis than $x_{\text{ss}}(m)$. The signal $x_d(n)$ has been termed the denoised signal, although this method does not reduce noise in the classical sense. Indeed, this approach is feasible only due to the simple waveform of $x_{\text{ss}}(m)$, which allows the periods without speckle noise to be connected using the zero crossings. As a result, the speckle noise is efficiently removed without introducing any non-stationarities, while the length of the remaining signal is maximised. On the other hand, the corresponding optical level $q_d(n)$ is discontinuous, hence it is not further used. It is depicted in Fig. 3(d) only for illustration that $q_d(n)$ is always greater than thr_{opt}.

The initial value of the threshold thr_{opt} is 0.8. However, if the denoised signal $x_d(n)$ is too short, thr_{opt} can be progressively reduced in steps of 0.05 and denoising of $x_{\text{ss}}(m)$ repeated. This can be performed iteratively until a sufficient length of $x_d(n)$ is reached. This length is specified as a *required number of signal periods* n_{per}. For example, if n_{per} = 20 (recommended value), the length of the denoised signal is approximately 1.38 s (= 20 / 14.5 Hz). The final value of thr_{opt} in Fig. 2 and 3 is 0.6 and 0.55, respectively.

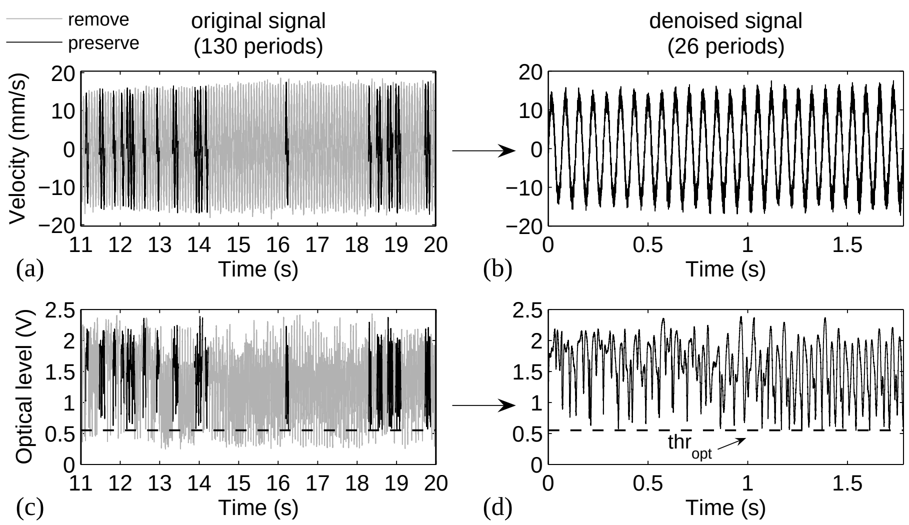

Figure 3. Connecting the periods without speckle noise to form the denoised velocity signal.

3. APPLIED ANGULAR RESAMPLING

Order tracking is a vibration analysis technique in which multiples of machine speed (*orders*) are used instead of absolute frequencies. *Computed order tracking* (COT) is a resampling-based technique introduced in 1989 by Potter and Gribler [8] and further studied by several authors, e.g. in [9]. In this method, both vibration and tachometer signals are acquired using the normal sampling mode (with a fixed sampling frequency), resulting in samples spaced at uniform time increments. Digital interpolation techniques are then used to post-process the data in order to obtain a new vibration signal sampled at constant increments of the shaft angle.

In 2005, Bonnardot et al. [10] proposed an alternative approach to resampling-based order tracking, referred to in their paper as *angular resampling*. This method requires no tacho signal, since the speed information is extracted from the instantaneous phase of a demodulated vibration signal. Specifically, the instantaneous shaft speed is extracted from the gearbox acceleration signal by using a band-pass filter centered on the meshing frequency (or one of its harmonics). It has been recommended to compare speed estimates obtained from several harmonics and then select the best ones. This method cannot be used during the run-up or run-down of a machine, as only small speed fluctuations can be compensated (such as during the steady state).

In this paper, angular resampling is applied to the velocity signal $x_d(n)$, resulting in the order-tracked signal $x_{\text{ot}}(n)$ (the signal has been converted from the angular domain back to the time domain). Extracting the instantaneous speed is much easier than in [10], since the shaft speed is readily available as shown in Fig. 1(a). The sampling frequency of $x_d(n)$ is much higher than necessary, hence linear interpolation is sufficient for both angle and signal interpolation.

Fig. 4 presents a comparison of DFT order spectra before and after angular resampling. The spectra are zoomed to highlight the range from -60 to 0 dB, hence the peak at the first

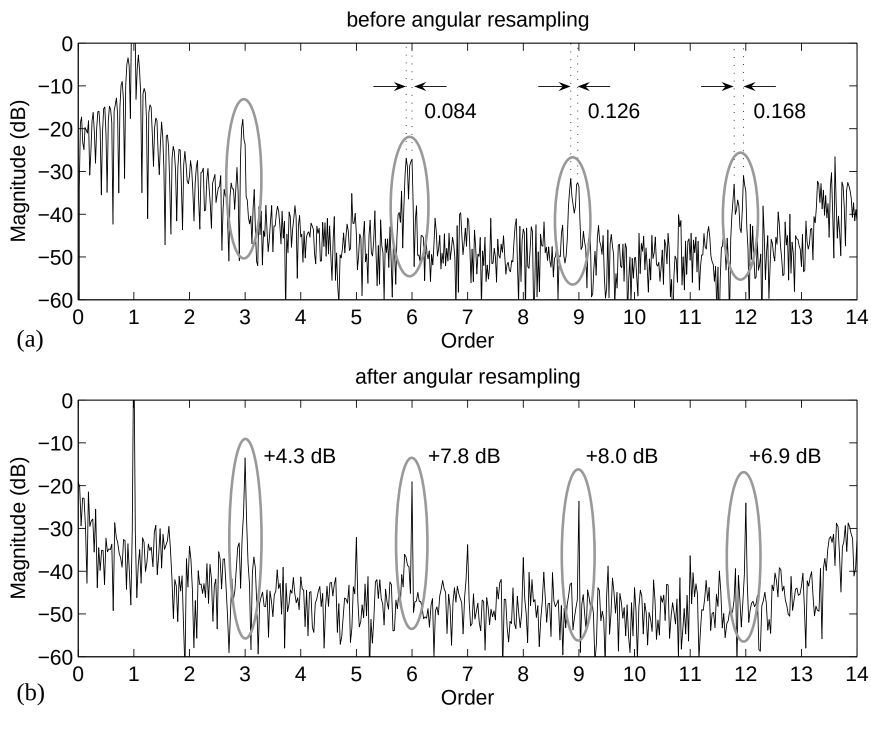

Figure 4. Order spectrum of the denoised signal before (a) and after (b) angular resampling.

order is clipped. As can be seen, angular resampling contributes to sharper peaks in the amplitude spectrum and thus operates as a "spectrum sharpener" [10]. The main improvement is that pairs of smaller peaks merge into a single peak with an increased magnitude, typically by 4–8 dB. The spectrum in Fig. 4(a) exhibits two individual peaks at the 6th, 9th and 12th order, separated by the distance of 0.084, 0.126 and 0.168 order, respectively. Frequency spacings are obtained after multiplication by f_0 = 14.5 Hz, yielding 1.218 Hz, 1.827 Hz, 2.436 Hz, respectively. These spacings can be divided by the order number to obtain the spacing for the first order, e.g. 2.436/12 = 0.204 Hz. Since 0.204 Hz is comparable to the frequency resolution, the corresponding peak at f_0 appears as a single broader peak. As the spacing increases towards higher orders, the two peaks become separated, each corresponding to a slightly different shaft speed. The difference is 0.204 · 60 = 12.24 RPM and is the result of a lower speed in the beginning of the steady state and a higher speed at the end. On the other hand, order tracking results in a constant "speed" within the whole signal, thus only one peak at each order can be observed in Fig. 4(b).

4. ENHANCEMENT OF THE ENVELOPE SPECTRUM

Envelope analysis is an established diagnostic technique in which a specific frequency band is demodulated in order to shift modulation effects at high frequency into the low-frequency range [11]. Here the envelope signal is obtained using the Hilbert technique [11] and is squared before computing its spectrum by the DFT. The demodulated band is chosen from 500 to 2000 Hz.

Fig. 5 presents an improvement of the envelope spectrum obtained by each preprocessing stage. The corresponding signal was measured on a washing machine with a faulty motor, the detail of this signal is shown in Fig. 1(b). The labels "original", "denoised" and "order-tracked" correspond to $x_{\text{ss}}(m)$, $x_d(n)$ and $x_{\text{ot}}(n)$, respectively. The enhancement of the envelope spectrum is a direct consequence of the changes in the power spectral density (PSD) shown in Fig. 5(a). As can be seen, reduction of the speckle noise decreases the overall PSD level by several dB, particularly in the range from 1300 to 2000 Hz. As a result, the peak at 1839 Hz has been partially extracted from the speckle noise, which represents a special case of random masking [11]. Angular resampling yields an additional PSD improvement, resulting in a further emphasis of the peak at 1839 Hz. Several other peaks are also enhanced, particularly at 613 and 1226 Hz. Notice that the peaks are more visible because the power at the surrounding frequencies has been significantly decreased. As a consequence, the peaks protrude above the baseline although their actual magnitude remains almost the same.

The PSD is estimated using the Welch's method of averaged periodograms. The window length is selected as $2spr$, where spr = 1500 is the number of samples per rotation in $x_{\text{ot}}(n)$. This means that the window length is matched to the signal period and the resampled data are thus "perfectly" periodic within each segment (there are no discontinuities on the borders). As a result, no leakage can occur in the amplitude spectrum, hence the rectangular window is used (i.e. no window). This window is the best window for analysing discrete frequency components due to the minimum mainlobe width, which explains why the peaks in Fig. 5(a) are revealed. Angular resampling can thus be regarded as a technique of adjusting the signal for the desired window length. Therefore, the method is useful not only for removing the speed fluctuations, but also for effectively solving the general problem of choosing an appropriate window length.

The spacing between the significant PSD peaks is 613 Hz, hence this frequency is visible

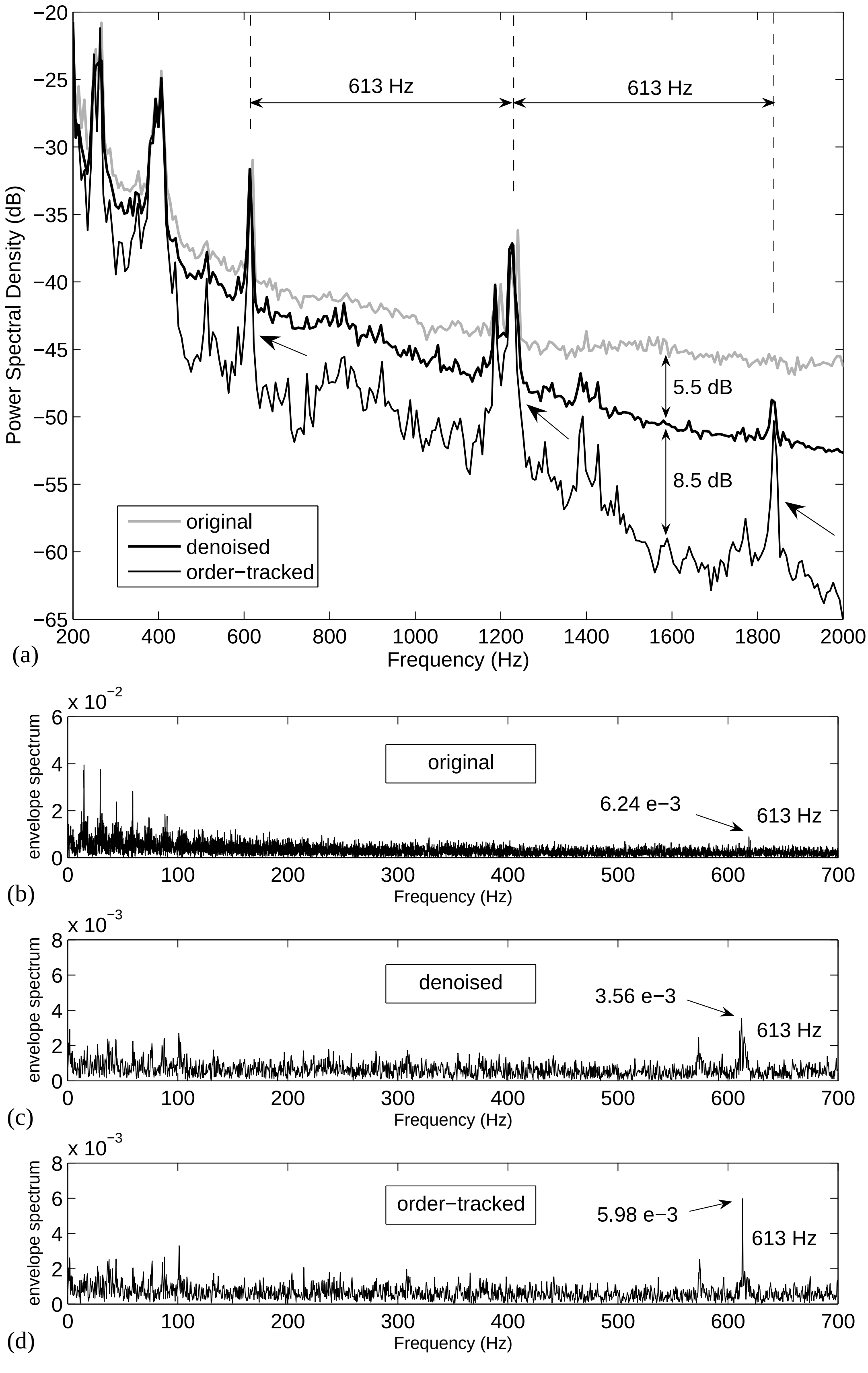

Figure 5. Enhancement of the PSD and the envelope spectrum by the proposed method.

in the original (b), denoised (c) and order-tracked (d) envelope spectrum in Fig. 5. Specifically, the amplitude at 613 Hz in each envelope spectrum is 6.24 e-3, 3.56 e-3 and 5.98 e-3, respectively. The peak in Fig. 5(b) is thus larger than the peaks in Fig. 5(c) and (d), but is negligible in the original envelope spectrum in comparison with the peaks below 100 Hz. On the other hand, the peak at 613 Hz becomes dominant in the preprocessed envelope spectra, in accordance with the relative increase of the corresponding PSD peaks in Fig. 5(a). The frequency of 613 Hz is very close to $3f_r$ = 615 Hz, where f_r = 12300 / 60 = 205 Hz is the rotation frequency of the motor. This feature is used as a fault indicator since it occurs in all measurements with a faulty motor and is absent in the remaining signals.

5. SUMMARY

This paper presents a new approach to reducing the speckle noise in LDV signals, combined with a recent order tracking method of Bonnardot et al. [10]. Experimental results indicate that a significant spectrum enhancement can be achieved, which is illustrated using the order spectrum, the envelope spectrum and the PSD.

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