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To cite this article: Yang Jin and Zili Li 2021 *J. Phys.: Conf. Ser.* **2041** 012007

View the article online for updates and enhancements.

A new method for eliminating speckle noise from Laser Doppler Vibrometer signals

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Abstract.   As the durability and stability of structures in operation are required, effective technologies are necessary to monitor the structural health. Laser Doppler vibrometer (LDV) is a non-contact and non-destructive vibration detector suitable for acquire broadband signals remotely and continuously. The significant signal issue is speckle noise mainly by LDV scanning from moving platforms (LDVom). This paper presents a novel approach based on ensemble empirical mode decomposition for eliminating speckle noise. The instantaneous frequency in intrinsic mode functions (IMFs) corresponds to the instantaneous vibration that is acquired by LDVom, and the signal is continuous in a sole IMF. In numerical simulations, the EEMD-based approach can effectively reveal the true vibration despite intensive noise. The correlation coefficient remains over 0.9 when the initial signal-to-noise ratio decreases to -15 db.   In experiments, the 500 Hz vibration is almost revealed by EEMD regardless of the noise intensity and the vibration strength. Therefore, our approach is applicable in eliminating speckle noise.

1. Introduction
Nowadays, vibration detection and modal analysis are playing increasingly important roles in characterizing structural health conditions [1, 2]. Contact transducers are effective and the mainstream technologies adopted in both scientific research and industrial applications [3, 4, 5], but the shortcomings of the contact nature, intermittent sensor distribution, and mass loading that changes the modes have restricted the applications. Therefore, it is significant to develop non-contact and continuously moving measurement systems that can remotely and continuously acquire broadband vibration signals.

In this research, Laser Doppler Vibrometer (LDV), which is a vibration detecting instrument developed based on Doppler frequency shift between the incident and the reflected laser beams [6, 7], is utilized for remote measurement. Equipped with a rotating mirror [8], it constitutes a system of LDV on the moving platform (LDVom), which can continuously scan the vibrating surface to acquire the operational deflection shapes.

The most significant issue that affects LDVom signals is the speckle noise [9, 10]. The noise arises from the variation of speckle patterns produced by the interference of reflected lasers from rough surfaces. The speckle noise is broadband distributed in the frequency domain, with intensive fluctuation and frequent signal drop-outs in the time domain. It is seldom addressed in the literature. In this work, we attempt to fill this gap by removing the speckle noise numerically generated [11] and experimentally acquired with ensemble empirical mode decomposition (EEMD) [12, 13].

2. Methodology

2.1. Ensemble empirical mode decomposition

Since intensive noise buries local waveform in the time domain and frequent noise peaks hide actual vibration energy in the frequency domain, classic signal processing approaches, like band-pass filters and wavelet transform, become less effective [14]. Empirical mode decomposition (EMD) is a self-adaptive approach for signal analysis, with bandwidths determined by the signal itself. The definition of intrinsic mode functions (IMFs) determines that the signal is continuous in a sole mode, suitable for most cases of mechanical systems. The instantaneous frequency in an IMF corresponds to the instantaneous vibration that LDVom acquired, and therefore EMD has the potential to reveal the actual vibration. To overcome the shortcoming of mode mixing, EEMD is developed assisted by Gaussian white noise [13]. The detailed algorithm of EEMD for signal analysis is described in [12] and [13].

Figure 1. The experimental setup of the LDVom system.

2.2. Simulation and experiment

The numerical simulation of speckle noise is based on the algorithm proposed in [11]. The target surface is divided into grids representing speckle patterns, each randomly assigned optical intensity and phase according to the statistical properties. The resultant phase is then calculated inside the photodetector focusing on the vibrating surface, and thus we can obtain the speckle noise according to Doppler frequency shift.

In the numerical simulation, we intended to distinguish the true vibration (which is artificially generated) from the polluted signals. A signal consisting of multi-frequency harmonics (varying from 500Hz to 2500Hz) is adopted as the true vibration and then polluted by the simulated speckle noise. The correlation coefficient δ (Eq. (1)) between the de-speckle result v_d by EEMD and the true vibration v is calculated to evaluate our approach.

$$\delta(v, v_d) = \frac{Cov(v, v_d)}{\sqrt{Var(v)Var(v_d)}} \tag{1}$$

where, $Cov()$ calculates the co-variance and $Var()$ calculates the variance.

In the physical experiments, the LDVom system scans a 540×40 mm^2 cantilever strip artificially excited at 500 Hz. Figure 1 shows the experimental setup. The LDV laser beam is deflected by a rotating mirror onto the target surface. The scanning speed is 0.1 m/s and the sampling frequency is 102400 Hz.

3. Results

3.1. Simulation results

Figure 2 shows in the numerical simulation the actual vibration compared with the polluted signal. The initial signal-to-noise ratio is -5 db. The signal drop-outs appear frequently and reach 15 times the amplitude of the actual vibration. Thus the signal is significantly distorted by the speckle noise.
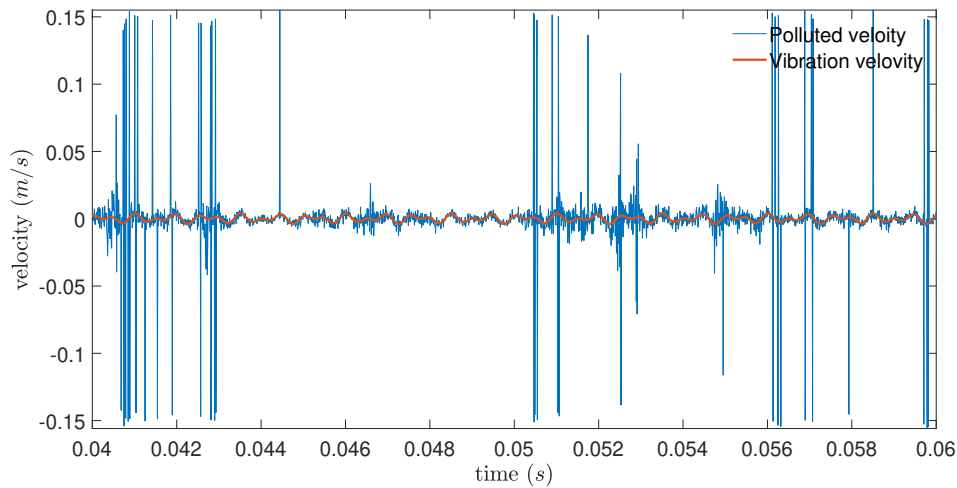

Figure 2. Comparison between the polluted velocity V_m and the true vibration v.

By removing the first few IMFs decomposed by EEMD, the de-speckle result and the corresponding true vibration are presented in Fig. 3. A good agreement is visible between these two time series. The correlation coefficient is over 0.98 after eliminating the speckle noise.

When we reduce the initial signal-to-noise ratio to -15 db, the correlation coefficient remains over 0.9. These results indicate the effectiveness of our de-speckle approach.
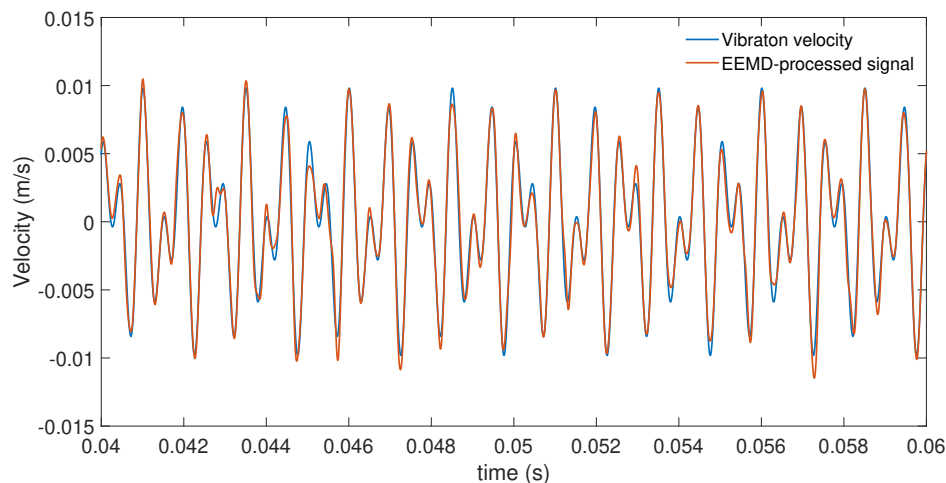

Figure 3. Comparison between the EEMD result and the true vibration with 2000, 2200 & 2500Hz harmonics.

3.2. Experimental results

Promising de-speckle results are also achieved in physical experiments. EEMD is utilized to decompose the signal and then preserve the IMFs centring around 500 Hz. Fig. 4, 5 & 6 present the de-speckle results considering different vibration and noise intensities. EEMD can reveal the true vibration around 500 Hz when the speckle noise is weak. When the noise is intensive and the vibration is weak, the EEMD results preserve small distortions arising from continuously intensive noise (Fig. 6). Nonetheless, EEMD still reveals the true vibration around 500 Hz. Therefore, our approach is applicable in eliminating speckle noise.
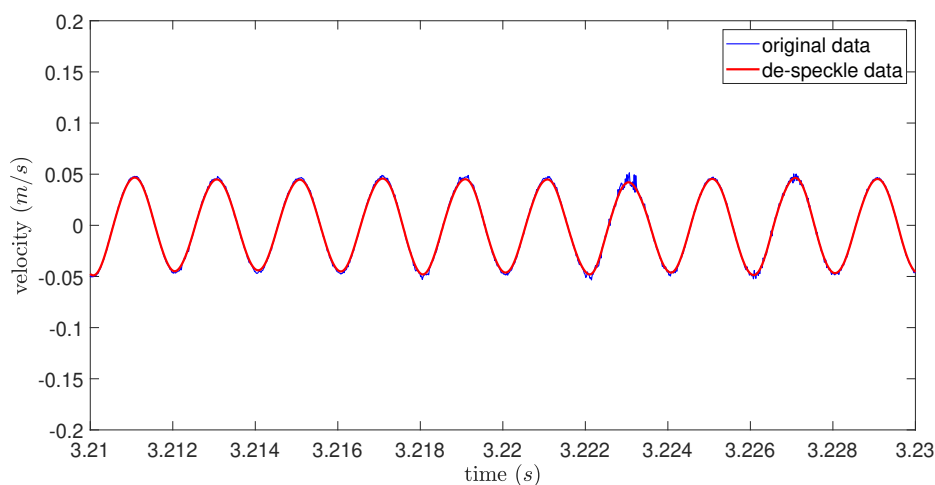

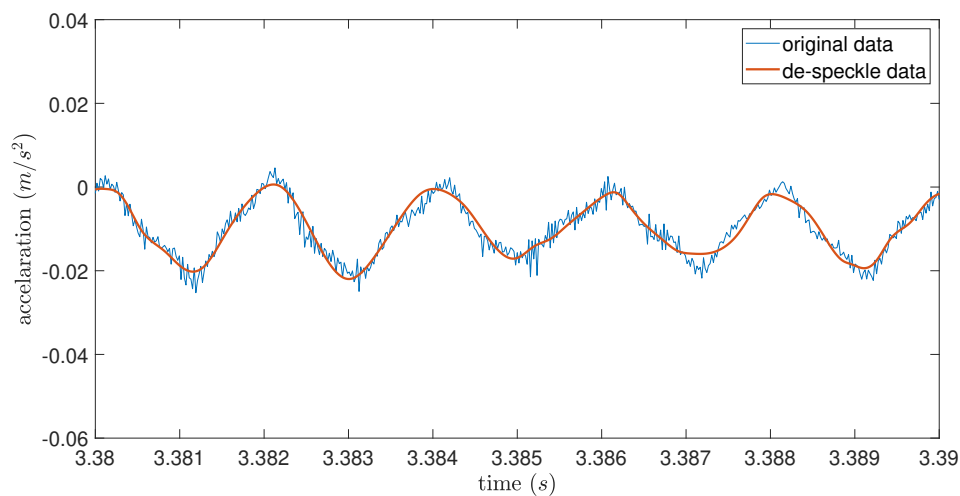**Figure 4.** De-speckle results of the large vibration and weak noise.

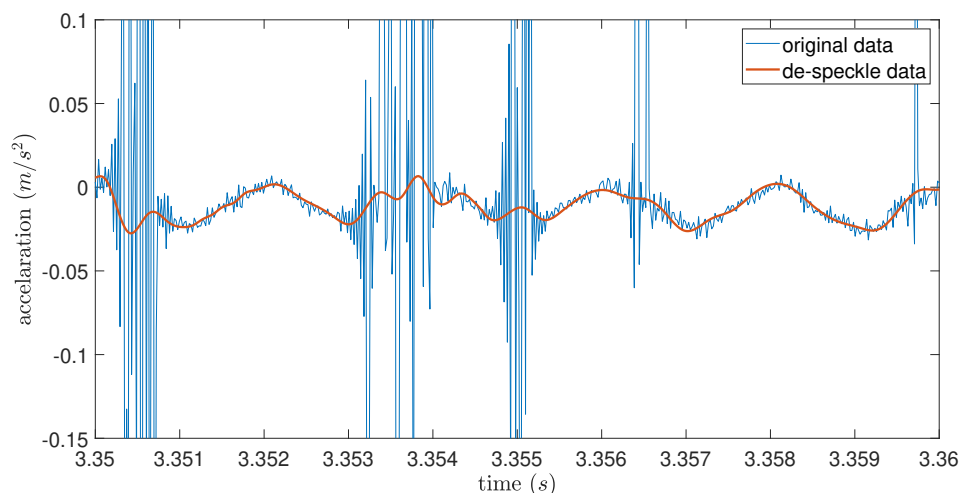**Figure 5.** De-speckle results of the small vibration and weak noise.

Figure 6. De-speckle results of the small vibration and intensive noise.

4. Conclusion

This paper develops an EEMD-based approach for eliminating speckle noises from LDVom signals. The instantaneous frequency in IMFs corresponds to the instantaneous vibration that is acquired by LDVom, and the signal is continuous in a sole IMF. In numerical simulations, the EEMD-based approach can effectively reveal the true vibration despite intensive noise. The correlation coefficient remains over 0.9 when the initial signal-to-noise ratio decreases to -15 db. These results indicate the de-speckle effectiveness. In physical experiments, the 500 Hz vibration is almost revealed by EEMD regardless of the noise intensity and the vibration strength. Therefore, our approach is applicable in eliminating speckle noise.

Further investigations are planned to evaluate the robustness of our de-speckle approach. Different surface properties of the targets and different scanning strategies will be concerned. In the future, the de-speckle approach will be applied to analyze signals for structural health

monitoring.

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