Eliminating Speckle Noises for Laser Doppler Vibrometer Based on Empirical Wavelet Transform

Jin, Yang; Li, Zili

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Eliminating Speckle Noises for Laser Doppler Vibrometer Based on Empirical Wavelet Transform

[1]Yang Jin, [1]Zili Li

[1]Railway Engineering, Delft University of Technology, The Netherlands
Email: J.Jin-3@tudelft.nl

Abstract. *This paper presents a novel approach for eliminating speckle noises in Laser Doppler Vibrometer signals based on empirical wavelet transform (EWT). The moving root-mean-square thresholds are utilized to cut off signal drop-outs and produce noise discontinuity that EWT can identify. The extremum ratio behaves as the criterion to reject or accept the EWT decomposed components. While processing simulated signals, the EWT-based approach outperforms others and presents de-speckle robustness. In experiments, EWT reveals the actual vibration despite low signal-to-noise ratios, which indicates de-speckle efficiency.*

Keywords: Laser Doppler Vibrometer, Speckle Noise, Empirical Wavelet Transform

1. Introduction

Vibration measurement is playing an increasingly significant role in modal analysis and mechanical system diagnosis. Laser Doppler Vibrometer (LDV) is a non-contact and non-destructive vibration detector, which can acquire the signals remotely (e.g., from high-temperature objects) and avoid mass loading that light structures are sensitive to, superior to attached transducers. The speckle noise arising from coherent laser components over the rough surface is an extremely troublesome issue restricting the LDV application extension [1]. Two kinds of the speckle noise distort the actual signal, as the signal drop-outs can reach over 30 times of the vibration amplitudes and the dominant noises with normal amplitudes can reduce the signal-to-noise ratio (SNR) to -15 db. The characteristics of speckle noises are far different from those of the white noises, thereby former de-noise strategies becoming inapplicable. Developing novel approaches for mitigating speckle noises has aroused recent research concerns, such as energy analysis [2], polishing target surface [3], cutting off outliers [4] and moving-averaging signals [5]. These methods are not suitable for extensive practices, e.g., those that require complete time-series analysis, large-scale measurements, or high-speed scanning. Calculating the signal energy is effective in damage inspection but overlooks the waveforms significant for modal analysis; attaching retroreflective tapes can reduce the surface roughness and further the noise amplitude, but not applicable in large-scale measurements; utilizing thresholds can cut off signal drop-outs but preserves the dominant noises with normal amplitudes; the moving average approach requires cyclical measurements with the scanning period far lower than the vibration period. Therefore, an effective post-processing approach for eliminating speckle noises remains to be developed. Empirical wavelet transform (EWT) [6] is an adaptive signal decomposition approach with wavelets adapted to the processed signal. It has the potential to handle speckle noises and mitigate related distortions due to the naturally determined bandwidths and the continuity of decomposed signal components.

In this paper, we develop an EWT-based approach to extract actual vibrations from noisy LDV signals. The moving root-mean-square (MRMS) thresholds are utilized to cut off signal drop-outs and produce noise discontinuity that EWT can identify. The extremum ratio behaves as the criterion to reject or accept the EWT decomposed components. The developed de-speckle approach is evaluated in both numerically simulated and experimentally acquired signals.

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2. Subject and Methods

Empirical Wavelet Transform

Since the actual vibration is time-frequency variant and the speckle noise is not uniformly distributed in the frequency domain, traditional signal decomposition approaches with certain bandwidths, including band-pass filters (BPF) [7] and wavelet transform (WT) [8], become inadequate for analysis. EWT overcomes this disadvantage by adaptively determining the wavelet bandwidths around the maxima of the Fourier spectrum. Therefore the empirical wavelets are adapted to the processed signal and have the potential to naturally extract the actual vibrations. Besides, EWT can avoid artifacts from high-frequency components, specifically the signal drop-outs, superior to empirical mode decomposition that presents similar adaptive properties. The mathematical construction of the wavelet group and scaling functions is described in [6].

De-speckle Algorithm

A specific algorithm is designed to eliminate the speckle noises. The first procedure is to calculate the MRMS thresholds $T_r(t)$ of the signal $v(t)$ with the moving window w, utilizing Eq. 1. It replaces signal amplitudes outlying the thresholds by the MRMS values, thereby reducing drop-outs amplitudes and producing discontinuities that represent the noise locations. Cutting off the signal drop-outs can mitigate the effect of large amplitude distortions in low-frequency components.

$$T_r(t) = v(t) \otimes e_w / w \pm \sqrt{v^2(t) \otimes e_w / w}, \tag{1}$$

where

$\otimes$ convolution calculation

e_w all ones vector with length w

The following procedures are to decompose the signal by EWT and then reconstruct the actual vibration by chosen components. EWT can acquire diverse approximate and detail coefficients that contain noises or actual vibrations. The extremum-number ratio between the decomposed components and the original signal is predefined as a criterion to determine the component belongings. An actual-vibration component should achieve an extremum-number ratio ranging below the frequency ratio (2 times the target frequency divide by sampling frequency).

Simulation and Experiment

The numerical simulation of speckle noises is based on the LDV measurement principle, Doppler frequency shifts. The time variance of the modulated laser phase, which dominantly contributes to the speckle noises, arises from the varying surface roughness. Therefore, the scanning surface is divided into speckle elements that have been assigned optical intensities and phases according to statistical distributions. The mathematical calculations of speckle noises are derived in [9].

In numerical simulations, a nonstationary signal is adopted as the actual vibration, polluted by simulated speckle noises. In order to evaluate the de-speckle robustness, the initial SNR varies in (-5 db, -10 db, -15 db). Other approaches including BPF and WT are compared, and the correlation coefficient between the de-speckle signal and actual vibration can evaluate the accuracy. In experiments, a 540×40 mm^2 cantilever strip is artificially excited at 500 Hz. The LDV system acquires vibration signals along the strip surface with the scanning speed 0.1 m/s and the sampling frequency 102400 Hz.

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3. Results

Figure 1a presents the simulated vibration polluted by speckle noises, with initial SNR = -10 db. The signal drop-outs can reach 100 times the smallest vibration amplitude and the dominant noises significantly distort the vibrations. The corresponding de-speckle results achieved by our developed approach is illustrated in Figure 1b. The de-speckled curve agrees well with the actual vibration, with the post SNR = 17.24 db and the correlation coefficient 0.98. Table 1 outlines the comparison results. The EWT-based approach outperforms others in the de-speckle procedure. BPF and WT approaches fail to achieve promising results with intensive speckle noises. The correlation coefficients of EWT results retain over 0.95 and the post SNRs retain over 13 db with decreasing initial SNRs, which indicates the robustness of the developed approach.

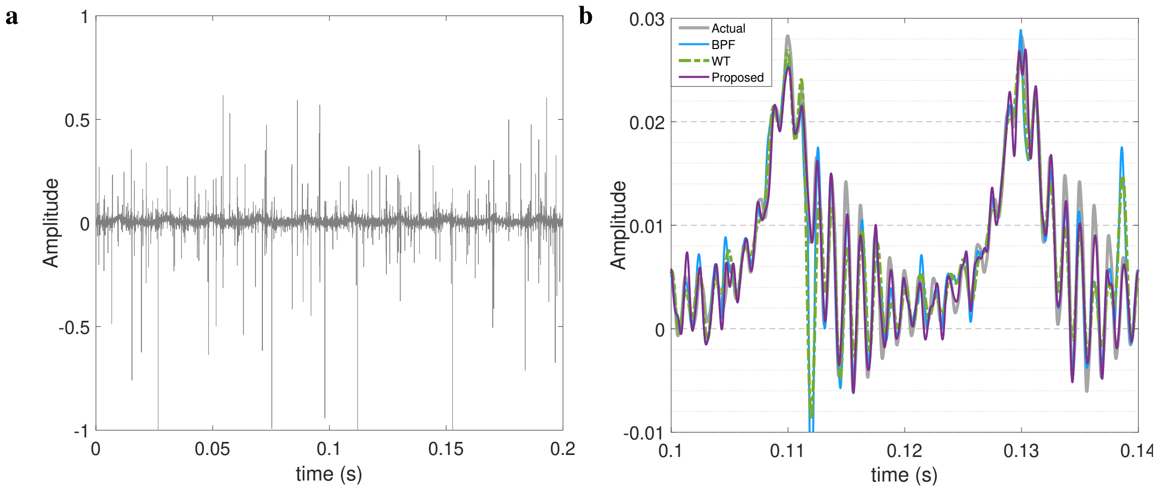

Fig. 1: a. Simulated signal polluted by speckle noises; b. De-speckle results versus actual vibration.

Initial SNR	Post SNR EWT	Post SNR BPF	Post SNR WT	Correlation EWT	Correlation BPF	Correlation WT
-5 db	21.65 db	12.55 db	9.66 db	0.99	0.95	0.94
-10 db	17.24 db	6.97 db	4.50 db	0.98	0.85	0.82
-15 db	13.11 db	2.78 db	0.44 db	0.95	0.71	0.66

Table 1: Post SNRs and correlation coefficients of diverse comparison results.

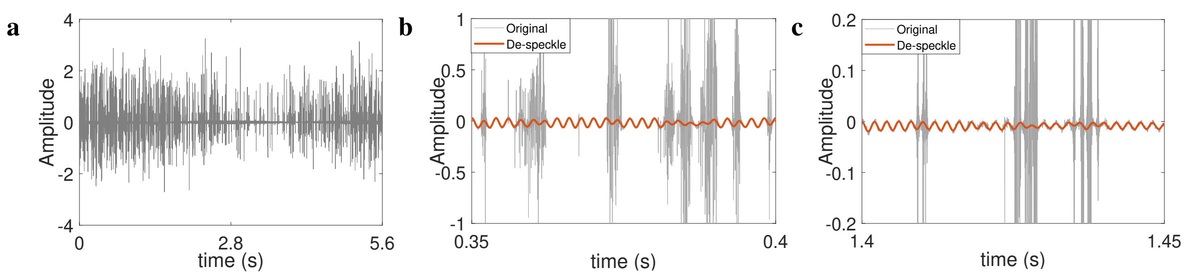

Fig. 2: a. Experimental LDV signal; b. De-speckle results with relatively large vibrations; c. De-speckle results with weak vibrations.

Figure 2a presents the scanning LDV signal from experiments. The 500 Hz vibration amplitude varies from 0.005 to 0.05, lower than 1/40 of the signal drop-out amplitude. The estimated initial SNR is -14 db, which means intensive speckle noises have dramatically polluted the actual vibrations. Figure 2b shows the de-speckle result between 0.35 s and 0.4 s (intensive noise

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duration), where the 500 Hz vibration amplitudes are around 0.05 and the estimated initial SNR is -24 db. The developed EWT-based approach has revealed the 500 Hz vibrations despite some amplitude deformations. Figure 2c illustrates the de-speckle results between 1.4 s and 1.45 s (intensive noise duration), where the 500 Hz vibration amplitudes are around 0.05 and the estimated initial SNR is -25 db. The de-speckle curve presents promising 500 Hz waveforms even at intensively noisy locations. Therefore, the developed approach is applicable in eliminating speckle noises.

4. Conclusions

This paper develops an EWT-based approach for eliminating speckle noises in LDV vibration signals. The MRMS thresholds are utilized to cut off signal drop-outs and the extremum-number ratio behaves as the criterion to reject or accept the EWT decomposed components. In numerical simulations, the EWT-based approach can effectively reconstruct the actual vibrations despite intensive noises, outperforming BPF and WT. The post SNR and correlation coefficient retain promising with the decreasing initial SNR, thereby indicating the de-speckle robustness. In experiments, the speckle noises are intensive in the acquired LDV signals with the estimated initial SNR -14 db. The developed approach can reveal the actual 500 Hz vibrations regardless of how weak the vibration responses are. Therefore, our approach is applicable in eliminating speckle noises.

Further investigations can concern the applicability in mitigating speckle noises acquired from different materials by different scanning strategies. In addition, the de-speckle approach will be applied to process LDV signals for modal analysis and damage inspection.

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