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Research Article

Denoising GPS-Based Structure Monitoring Data Using Hybrid EMD and Wavelet Packet

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High-frequency components are often discarded for data denoising when applying pure wavelet multiscale or empirical mode decomposition (EMD) based approaches. Instead, they may raise the problem of energy leakage in vibration signals. Hybrid EMD and wavelet packet (EMD-WP) is proposed to denoise Global Positioning System- (GPS-) based structure monitoring data. First, field observables are decomposed into a collection of intrinsic mode functions (IMFs) with different characteristics. Second, high-frequency IMFs are denoised using the wavelet packet; then the monitoring data are reconstructed using the denoised IMFs together with the remaining low-frequency IMFs. Our algorithm is demonstrated on a synthetic displacement response of a 3-story frame excited by El Centro earthquake along with a set of Gaussian random white noises on different levels added. We find that the hybrid method can effectively weaken the multipath effect with low frequency and can potentially extract vibration feature. However, false modals may still exist by the rest of the noise contained in the high-frequency IMFs and when the frequency of the noise is located in the same band as that of effective vibration. Finally, real GPS observables are implemented to evaluate the efficiency of EMD-WP method in mitigating low-frequency multipath.

1. Introduction

Structure Healthy Monitoring (SHM) is one of the most popular topics in civil engineering now. It utilizes on-site nondestructive sensor technology to capture structure system features, for example, structural response, and analyzes these features to detect structural damage or obsolescence [1, 2]. Nondestructive sensor technology is built on various instruments, such as accelerometer, stressometer, and anemoscope. In particular, accelerometer is often used in field structural vibration test to obtain the structural vibration modal parameters (e.g., frequency, damping, and vibration mode) as well as the relation between structure and environmental loads. Nevertheless, due to the initial condition issue in double integrating, displacements are not easy to be obtained from acceleration. Structural engineers are trying to seek some new test methods to overcome these challenges. Currently, the technique of Global Positioning System- Real Time Kinematic (GPS-RTK) is widely used in SHM (see, e.g., [3–5]). However, vibration signals collected by GPS-RTK are often embedded in various noises. Some noises related to atmosphere, satellite, and receiver can be removed by differencing technology, whereas the multipath effect could not be removed by applying such a differencing procedure [6]. As a result, multipath is a main obstacle in GPS-based SHM and other high-precision GPS applications [7]. Recently, except for hardware-dependent techniques (e.g., choke ring antennas [8] and Trimble's Zephyr antennas [9]), structural engineers mainly focus on algorithm-dependent techniques for multipath mitigation, for example, Signal-to-Noise Ratio (SNR) [10], Adaptive Filtering [11], Vondrak Filtering [12], principal component analysis [13], and wavelet analysis [14]. Due to the high time-frequency capability, wavelet-based techniques (e.g., wavelet multiresolution (WMR)) are extensively used in processing GPS-RTK data to extract weak vibration features. In this method, field observables are divided into different frequency bands (or scales); then vibration features are reconstructed by using selected coefficients of wavelet decomposition. However, the choice of wavelet parameters (e.g., wavelet basis, scale, and threshold) affects the extraction quality of vibration signal features. Thus, not having a priori knowledge of the signal feature could lead to inappropriate vibration signal features extracted.

In 1998, Huang et al. [15] proposed a new signal time-frequency process method, called empirical mode decomposition (EMD). This method can decompose a given signal into a set of elemental signals called intrinsic mode functions (IMFs), which reserves the nonlinear and nonstationary features well. Since EMD inherits merit of WMR and avoids the issue of wavelet basis selection, EMD has been widely used in civil engineering, geology, and meteorology. However, most high-frequency IMFs are often regarded as noise and are discarded in practices, which may lead to information loss and energy leak of the vibration signal. Moreover, applying asymmetric wavelet basis could cause the issue of phase shift. These issues motivate us to use combined EMD and wavelet for data denoising. Wang et al. [16] proved that EMD-WP performs better than applying either a pure EMD or wavelet in reducing the noise of GPS carrier phase. Du et al. [17] proposed an EMD-based wavelet threshold value filtering denoising solution in low signal-to-noise condition. Li [18] found that temporal feature of the damage can be well identified used EMD combined wavelet. The goal of this work is to discuss the capability of the combined EMD and wavelet packet (EMD-WP) in GPS-based SHM data denoising.

The remainder of the article is structured as follows. Section 2 briefly describes the GPS multipath effect and its features. Section 3 gives the EMD-WP denoising procedure. Section 4 describes the synthetic and real GPS data used in this study and quantifies the performance of our algorithms. Finally, conclusions are summarized in Section 5.

2. GPS Multipath Effect and Its Features

During structural monitoring, real environment is always much more complicated than what we consider. The collected signals in GPS receiver consist of signals from both satellite and various signals refracted or reflected from unexpected objects in the vicinity of the antenna (see Figure 1); such signals cause phase shift in carrier phase observation or satellite signal transmit delay which eventually leads to GPS mistracking. This is called multipath effect.

Although hardware like choke coil embedded in GPS antenna could mitigate multipath effect, those residual multipath effects can still lead to errors as large as in centimeter level when applying short baseline RTK. Huang et al. [6] explored multipath effect in single reflector situation and derived typical periodicity formula of multipath effect. Huang et al. [19] discussed features like frequency, value, and spatiotemporal characterized multipath effect, and they significantly improved GPS dynamic monitoring accuracy by combining filtering and differencing. Dai et al. [20] found that the period of the multipath effect is proportional to the distance between the antenna and refactor, and this relation is very sensitive to the distance change and appeared to be periodical. Other papers [21, 22] also indicated that multipath effect caused by close distance reflection appeared to be in low frequency and periodical and recommended various filtering methods to weaken multipath.

3. EMD-WP Denoising Procedure

The basic idea of EMP-WP denoising is dividing signal into batch of IMFs with different feature scale and partial frequency feature by applying EMD, choosing high-frequency IMFs by Fourier transformation and conducting wavelet packet denoising, and summing up denoised IMFs and most of leftover low-frequency IMF measures to reconstruct the original signal; eventually those valid vibration signals will be extracted. Basic steps are shown in the following:

(1) Initiation: $r_0 = S(t)$, $i = 1$.

(2) Extract ith IMF signal:

 (a) Initiation: $h_0(t) = r_i(t)$, $k = 1$.

 (b) Get the maximum value serial and minimum value serial of $h_{k-1}(t)$.

 (c) Try fitting extremum serials of $h_{k-1}(t)$ by using cubic spline interpolation; get upper and lower envelops: $u_{k-1}(t)$ and $v_{k-1}(t)$.

 (d) Calculate average curve of lower and upper envelops: $m_{k-1}(t) = (u_{k-1}(t) + v_{k-1}(t))/2$.

 (e) Calculate $h_k(t) = h_{k-1}(t) - m_{k-1}(t)$.

 (f) Set $\mathrm{IMF}_i(t) = h_k(t)$ if iteration standard is satisfied; otherwise set $k = k + 1$ and jump to step (b) to continue.

(3) Calculate the residuals: $r_i(t) = r_{i-1}(t) - \mathrm{IMF}_i(t)$.

(4) Run FFT to IMF_i; choose high-frequency and low-frequency IMF by considering signal time-frequency features.

(5) Conduct wavelet packet denoising high-frequency IMF:

 (a) Choose one wavelet function and decompose layer N; then conduct N-layer wavelet decomposition to signal.

 (b) Set entropy standard and deter best tree.

 (c) To each layer's high-frequency coefficient, choose threshold and get soft threshold quantified.

 (d) Reconstruct signal by using the N-layer low-frequency coefficient from wavelet packet division and quantified N-layer high-frequency coefficient.

(6) Sum up denoised high-frequency IMFs and leftover low-frequency IMFs to finish signal reconstruction.

The work flow of EMD-WP is shown in Figure 2.

4. Applications to GPS Data

4.1. Synthetic Example. The dynamic equation of building with multiple degrees of freedom in ambient excitation $F(t)$ can be represented as

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = D_s F(t), \tag{1}$$

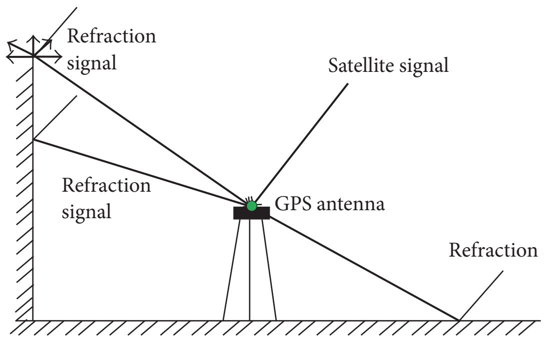


Figure 1: Flowchart of GPS multipath.

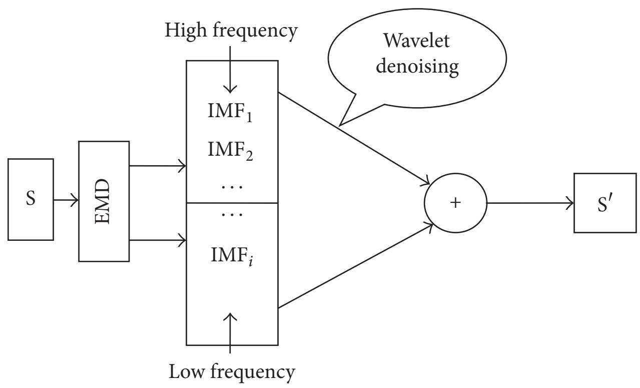


Figure 2: Flowchart of EMD-WP denoising approach.

Table 1: Obtained frequency by simulated displacements and eigenfrequency.

Modal order	Frequency (Hz)	
	Simulated value	Theoretical value
(1)	0.1042	0.1009
(2)	0.3292	0.3318
(3)	0.5500	0.5495

Table 2: Comparison frequency of three tests.

Modal order	Frequency (Hz)			
	Simulated value	Test 1	Test 2	Test 3
(1)	0.1042	0.1042	0.1000	0.1042
(2)	0.3292	0.3125	0.3625	0.3292
(3)	0.5500	0.5875	0.5625	0.5500

where $X(t)$, $\dot{X}(t)$, and $\ddot{X}(t) \in R^n$ are structural displacement, speed, and acceleration vector, respectively; M, C, and $K \in R^{n\times n}$ represent structure mass, damping, and stiffness matrix, respectively; $F(t)$ is ambient excitation vector, $D_s \in R^{n\times r}$ is excitation position matrix; and $X(t_0)$ and $\dot{X}(t_0) \in R^n$ represent initial displacement and initial speed vector.

Figure 3 shows the 3-story framework. Mass of each story $m = 20000$ kg, story stiffness $K = 100$ KN/M, Rayleigh damping is applied (damping constants are 0.1081 and 0.0179), and adjusted El Centro (NS, 1940) earthquake wave (http://www.vibrationdata.com/elcentro.htm) is adapted as ambient excitation. Matlab-lsim function is applied to simulate structural vertex displacement (see Figure 4), sampling rate is 10 Hz, sampling time is 4 minutes, and the comparison between feature frequency and theoretical value is shown in Table 1.

As mentioned before, it is not easy to simulate all kinds of complicated observation environments; nevertheless, a set of Gaussian random white noises on different levels including 20 dB, 10 dB, and 1 dB were added to the simulated displacements in Figure 4. For conveniency, we label them as tests 1, 2, and 3. Following the steps given by proposed EMD-WP method, GPS signals are decomposed by applying EMD (see Figure 5(a)), and the decomposed result is classified by the frequency features of IMFs (see Figure 5(b)). The first three IMFs are chosen for wavelet packet denoising. Default signal threshold value is adapted during denoising, number of wavelet packet decomposed layers is set to 3, and function db4 is chosen as wavelet basis function. Finally, the reconstructed signal is considered as extracted vibration signal feature. Following the same way in test 1, we perform EMD on tests 2 and 3. The comparison between frequency calculated by denoised data and theoretical frequency is presented in Table 2. It is worth to mention that we do not discuss the damping ratio identification here due to the fact that it is very sensitive to error.

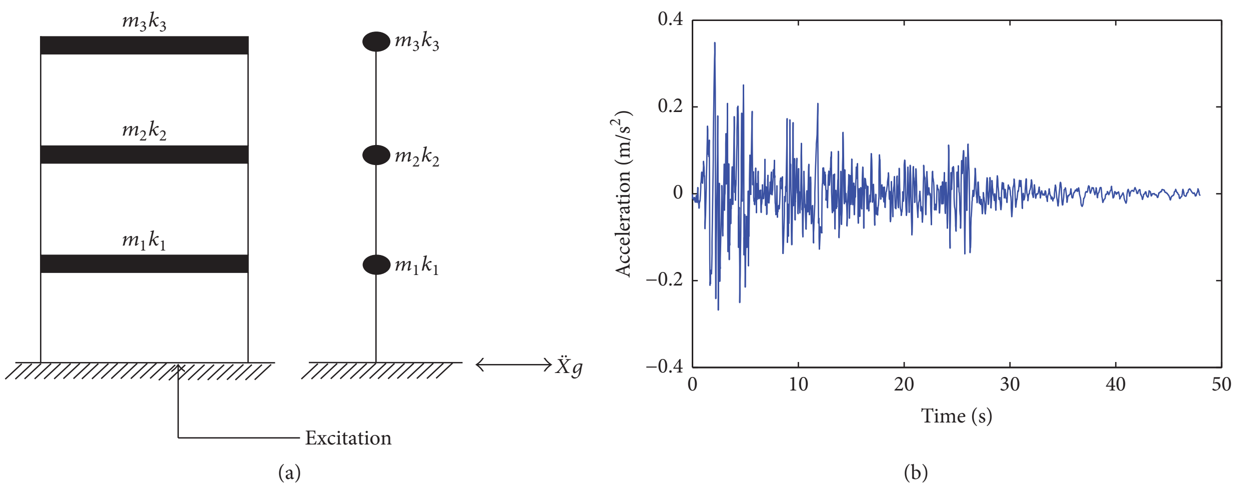


Figure 3: Schematic of 3-story frame (a) excited by El Centro earthquake (b).

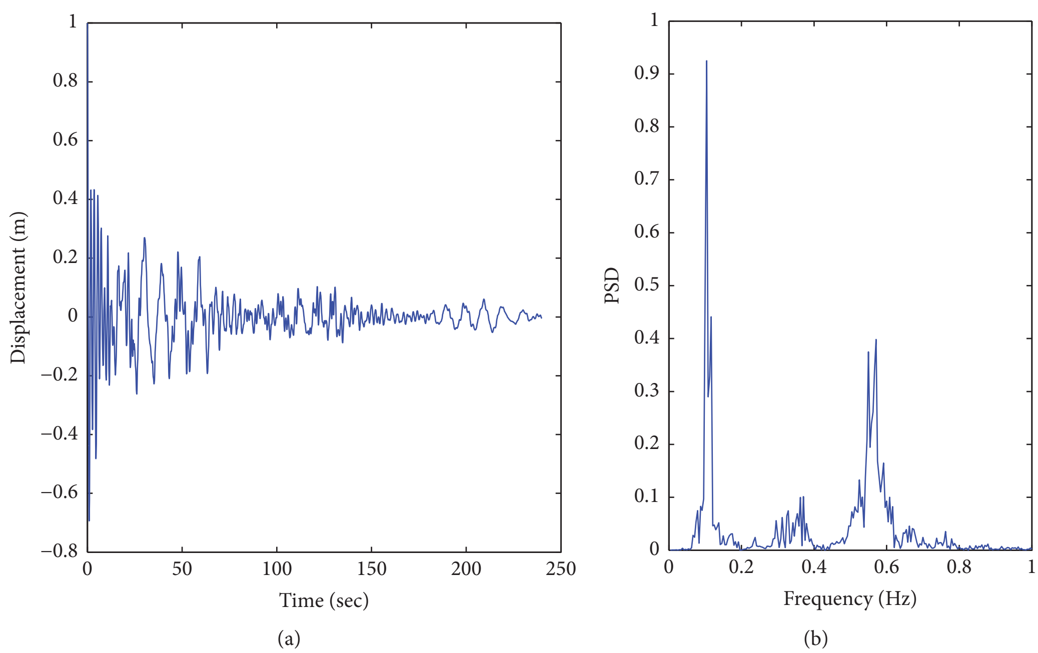


Figure 4: Simulated displacements (a) and FFT results (b).

Figure 6 indicates that EMD-WP could be used to filter out the signal at different noise levels. Particularly, we find that EMD-WP works better for high SNR signals, and most original signal information can be reserved. However, in the case of vibration signal with low SNR, some noises might remain even if they are filtered, part of noises share the same frequency band with vibration signal feature (i.e., frequency mix overlapping), and part are introduced by high-frequency IMF denoising process; these unfavorable scenarios could cause fake modals and also the energy enlargement of the structural vibration. Thus, simply using the peak detection to capture the feature frequency will be inappropriate in these cases and could lead to wrong conclusions. As such, it should be aware during the dynamic feature test for dam or high cable support tower where main vibration frequencies are usually low or ultralow frequency in ambient excitation. Furthermore, readers should bear in mind that it is not easy to simulate all kinds of real monitoring situations and no denoising method is omnipotent. Fortunately, our synthetic example gives some information about possible scenarios in which our method would be less effective. Anyway, in the following section, we apply our method to real GPS data.

4.2. Real GPS Observables. GPS-RTK vibration data (see Figure 7(a)) collected on a bridge girder is used to evaluate our proposed method. The girder is potentially subjected by traffic load and some environmental loads, for example, wind and temperature change. Vibration receiver sample rate is set

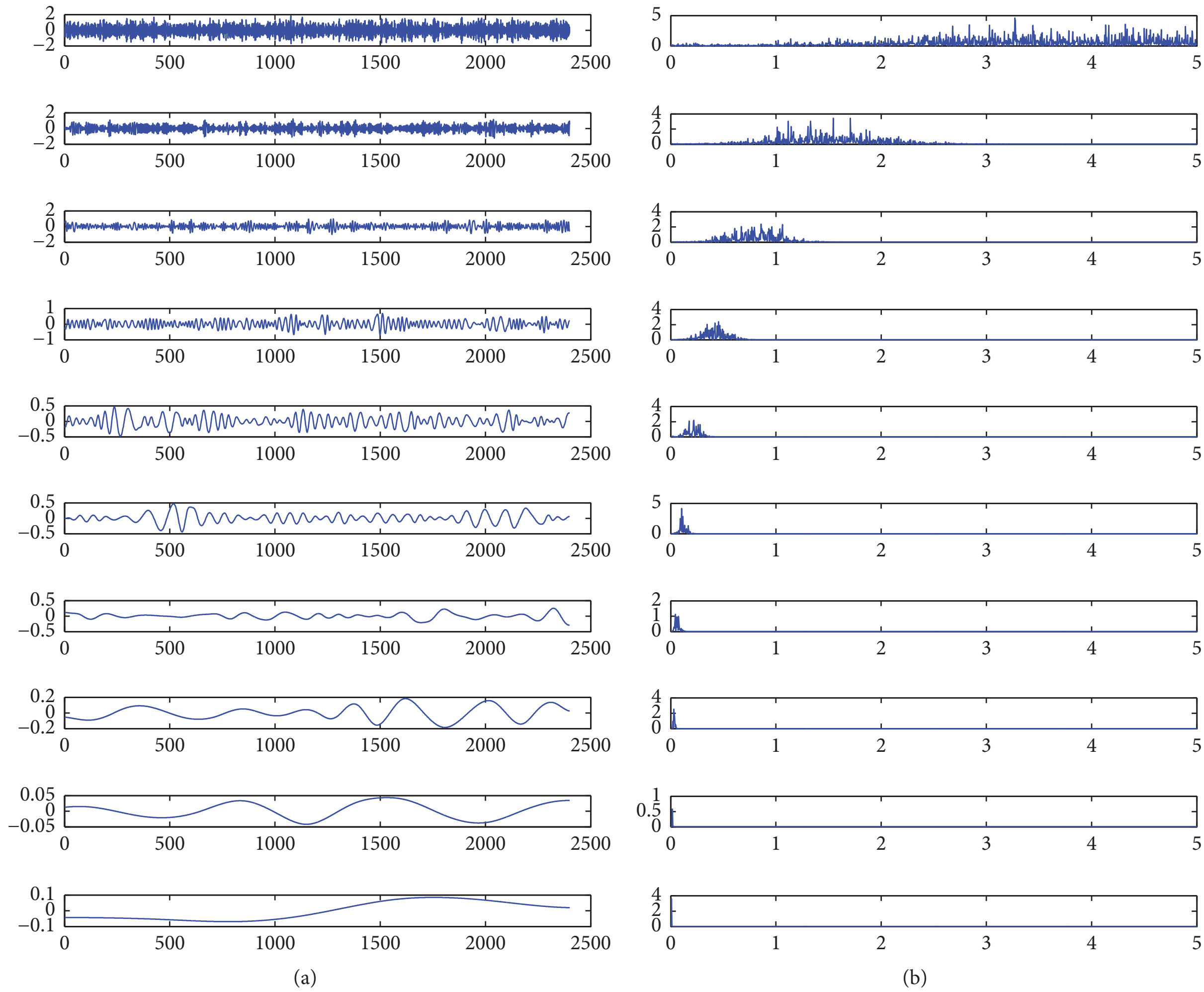


Figure 5: Main IMF components (from line 1 to line 10, they are IMF_1 to IMF_{10}) and corresponding FFT results.

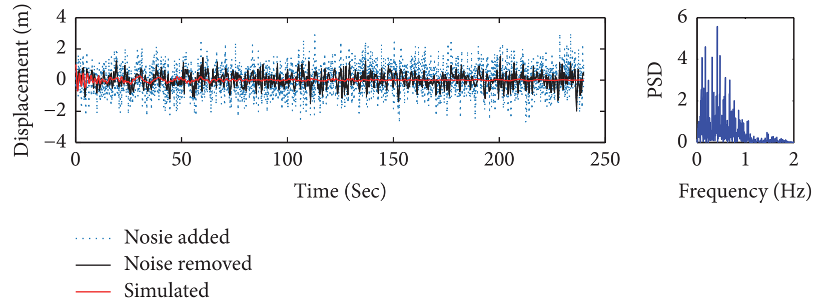
to 5 Hz, satellite elevation limit is 15°, and observation time is 30 minutes. Figure 7(a) shows that the displacement in the vertical component remains around ±2 cm and the maximum value is no more than ±3 cm, which meets the normal accuracy of GPS-RTK. Figure 7(b) provides the extracted vibration feature by applying our EMD-WP method. Figure 8 gives the spectrum features of the raw and denoised GPS data.

According to [23], low-frequency part (0~0.1 Hz) of GPS structural monitoring signal can be generally divided into static, quasistatic, and multipath effect. Static effect is mainly caused by wind load, multipath effect is supposedly caused by short distance refracted signal, and quasistatic effect is mainly caused by environmental factors like temperature change. We find that the absence of low-frequency part meets the fact that the wind is weak when collecting GPS data and vibration mainly caused by microtremor. Moreover, as noticed by power located between 10^{-3} and 10^{-2} Hz frequency band, not only the majority of low-frequency multipath effect but also the quasistatic content caused by the temperature gradient and the traffic load is mitigated by EMD-WP. Meanwhile, the high-frequency part of the signal is also removed. Due to the small ambient excitation and observation error, the peak (arrow pointing in Figure 8) located at the low-order model frequency is not obvious.

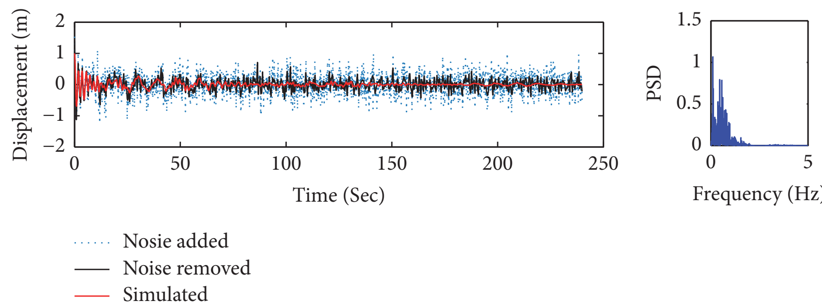
5. Conclusions

This paper explores the application of EMD-WP on data denoising of GPS structural monitoring. A set of simulated noises on different levels are analyzed; the result shows EMD-WP can reserve useful information of original signal and can extract the vibration feature. However, in the case of the vibration signal with low SNR, the noise shares the same band with effective vibration and the remaining noise in high-frequency IMF vector could cause fake modal. A real GPS test also proved that EMD-WP can effectively weaken the multipath effect with low frequency. We should note that our method may fail when processing low sampling rate (e.g., 1 Hz) GPS data due to the problem of frequency mix overlapping.

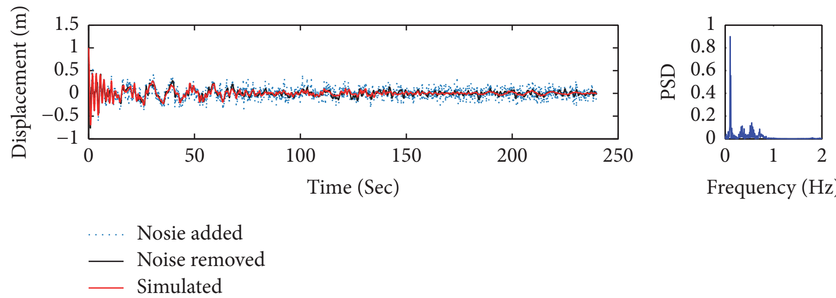
It is not easy to achieve millimeter level in SHM by current GPS-RTK technique. One main challenge is the multipath, which cannot be totally removed by applying single filtering



(a)

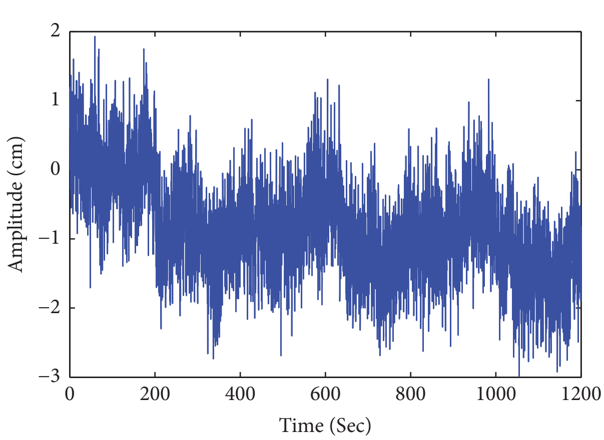


(b)

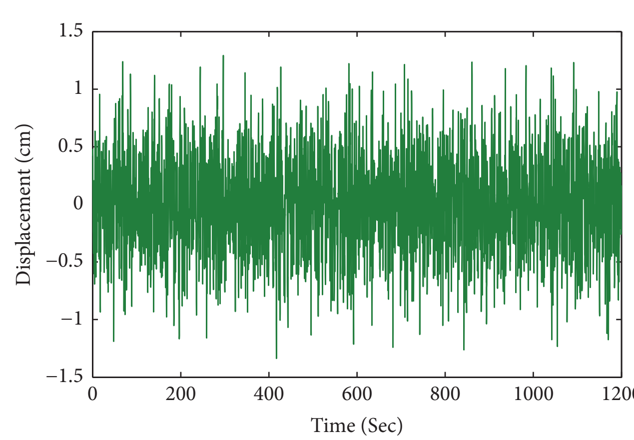


(c)

FIGURE 6: Results of three simulated examples: (a) test 1, (b) test 2, and (c) test 3, respectively.



(a)



(b)

FIGURE 7: (a) Ambient GPS observables and (b) extracted structure vibration.

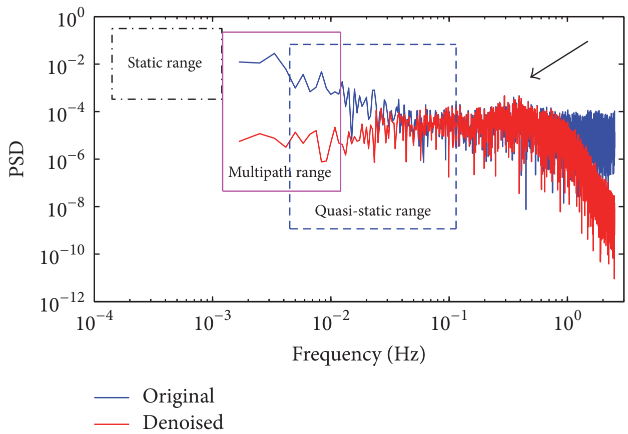


Figure 8: Spectrum of ambient and denoised observables (log-log scale).

after the process. Theoretically, GPS-RTK can collect low-order main frequency of construction; nevertheless, the reliability of GPS-RTK in SHM needs further evaluation. Also, structural damping and vibration type should be concerned for identifying the real structural modal.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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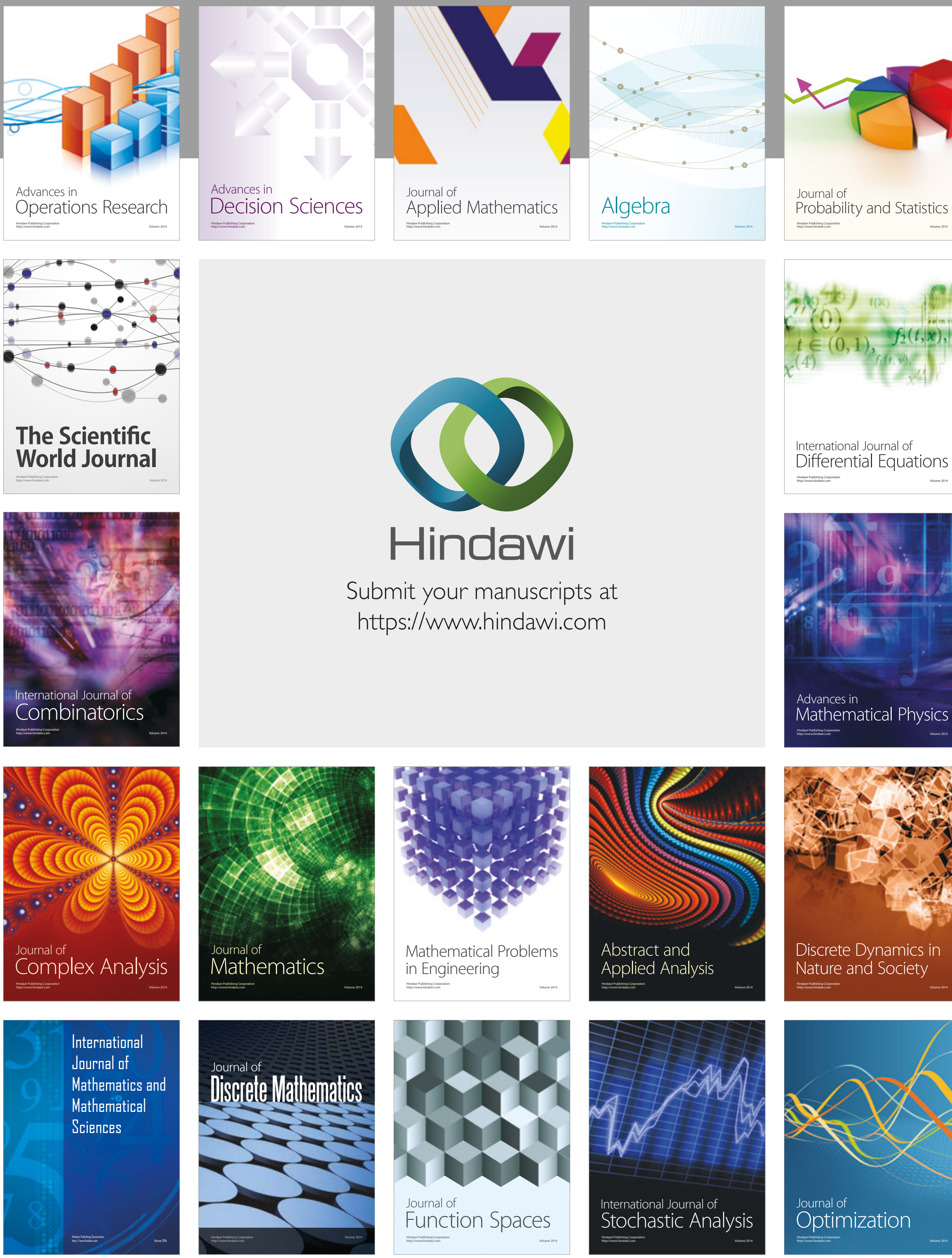
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