On the difference between empirical mode decomposition and Hilbert vibration decomposition for earthquake motion records

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SUMMARY:
In this paper, Empirical mode decomposition (EMD) and Hilbert vibration decomposition (HVD) are employed to process various different types of non-stationary and nonlinear vibration. The properties of these two methods are systematically analysis by comparing the efficacy in some numerically simulated signals. Meanwhile these two methods are used to analyze a Wenchuan earthquake strong ground motion record to capture low-frequency pulse-like as well as high-frequency wave signals. Some improving strategies are proposed to reduce some disadvantages in these two methods. The result of investigation demonstrates that the combination of EMD and HVD may be more effectively in decomposing multi-component signal.

Keywords: *EMD, HVD, Hilbert transform, narrowband signal, mono-component signal*

1. INTRODUCTION

In earthquake engineering, the records of strong ground motions exhibit a time-evolving frequency composition due to the dispersion of the propagating seismic waves, and a time-decaying intensity after a short initial period of development. The temporal-frequency motion energy distribution can improve understanding of earthquake impact on various engineering systems and aid in the seismic-resistant design and retrofit. Characterization of earthquake motion from observed records with the aid of proper data processing and analysis methods, as the input to structural engineering systems, can be used to compute dynamic nonlinear response and evaluate seismic performance of those systems.

According to Huang et al. (1998, 2001), the conventional Fourier-based approaches may yield distorted, indirect, or incomplete information about nonlinear and non-stationary time series, such as ground motion recording. To reveal useful information from signals that might be either hidden or distorted by conventional methods, Huang proposed the Empirical mode decomposition (EMD) method to extract mono-component and symmetric components, known as intrinsic mode functions (IMF), from initial multi-component signal. EMD is an adaptive signal processing method, which provides a powerful tool to extracts intrinsic mode function from wideband signals. However as an empirical method, EMD not only lacks the mathematical theoretical foundation, but also has end effect, overshoots or undershoots, IMF criteria problems during the sifting process. Especially because of the special sift method, EMD always decomposes wideband signal from high frequency to low frequency, but not from high energy to low energy. These characteristics bring on the incapability of separating components which include closely spaced frequencies or weak high frequencies. An enormous number of applications have been presented in the last decade, and many publications have attempted to improve or at least to modify the original methods (Huang 2011). The newest ensemble empirical mode decomposition (EEMD) method (Wu and Huang 2009) largely overcomes the mode mixing problem of the original EMD.

Recently, a different technique, called the Hilbert vibration decomposition (HVD) method, dedicated to the same problem of decomposition of non-stationary wideband vibration, was proposed by Feldman (2006), which can estimate the largest energy component frequency as an average function of the instantaneous frequency of the composition, and can estimate the corresponding envelope by synchronous demodulation. HVD is able to decompose wideband signal from high energy to low energy, also enables decomposition of the narrowband multi-component signals. However, as a global instantaneous frequency estimation method, HVD has to use rather long data records. Furthermore, HVD is not effective for separating non-oscillating signal or intermittent signal.

Feldman (2008) analyzed and compared theoretically EMD and HVD. Braun and Feldman (2011) tested some general behavior of the two methods. In this paper, the two methods are employed to process various different types of non-stationary and nonlinear vibration. The properties of these two methods are systematically analysis by comparing the efficacy in some numerically simulated signals. Meanwhile these two methods are used to analyze the free-field ground motion and to estimate the structural health status during the evolution of a seismic event through the measurement of seismic response record. Some improving strategies are proposed to reduce some disadvantages in these two methods. The result of investigation demonstrates that the combination of EMD and HVD may be more effectively in decomposing multi-component signal.

2. ANALYSIS OF SIMULATED SIGNALS

In this section, we first use a hypothetical wave recording in paper of Zhang et al. (2003) to illustrate features of EMD and HVD analysis in non-stationary signal processing. Then we use a narrowband multi-component free-decay vibration signal in Chen et al. (2003) to discuss the efficacy of the two methods.

2.1. Hypothetical Wave Recording

A numerically simulated signal was shown in Figure 1, which have a non-sinusoidal waveform with sharp crests and rounded-off troughs.

$$x_1 = \cos\left[2\pi t + 0.5\sin(2\pi t)\right]e^{-0.2t} \tag{2.1}$$

$$x_2 = 0.05\sin(30\pi t) \tag{2.2}$$

$$x = x_1 + x_2 \tag{2.3}$$

x_1 is a decaying wave, and x_2 is a noise. x is physically related to one type of water wave in general, and symptomatic of nonlinear responses at the soil sites in earthquake recording that are very close to the sites where liquefaction or strong nonlinearity happens in particular.

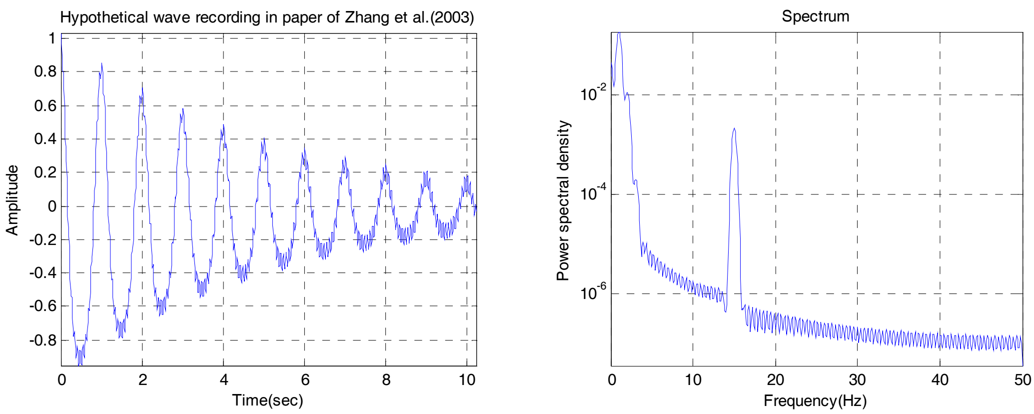

Figure 1. Hypothetical Wave Recording and its power spectra

EMD result:

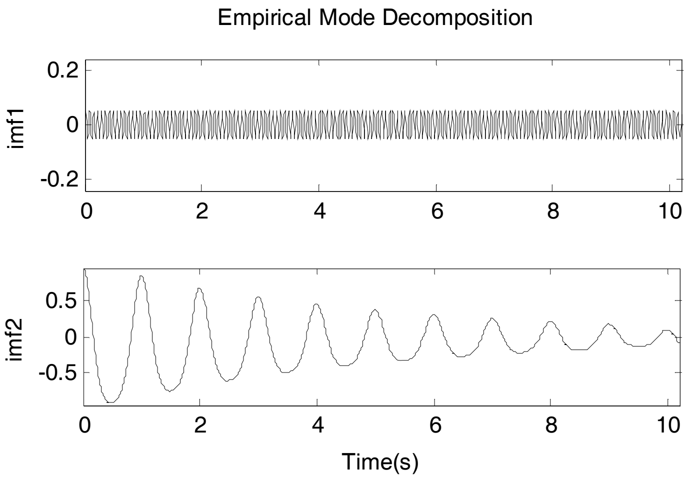

Figure 2. EMD-based high-frequency and low-frequency component of Hypothetical Wave Recording

HVD result:

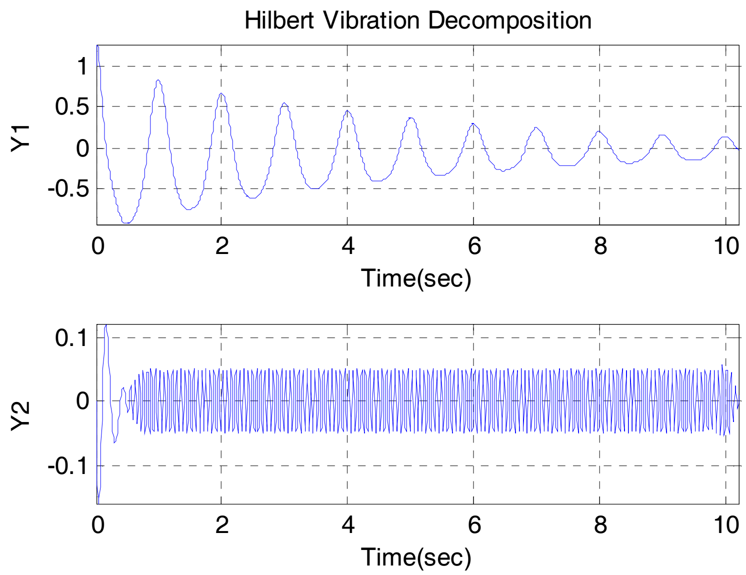

Figure 3. HVD-based low-frequency and high-frequency component of Hypothetical Wave Recording

Both methods can reveal characteristics of waves, but EMD always decomposes wideband signal from high frequency to low frequency, HVD always decomposes wideband signal from high energy to low energy. This is the important difference point between both methods. In general, since of error accumulation, only high frequency component of EMD and high energy component of HVD can be extracted exactly. From above figures, we also can get that HVD did not deal with the end effect. However this is not important, we can improve easily.

2.2. Narrowband Multi-component Free-decay Vibration Signal

Another numerically simulated signal was shown in Figure 4, which contain three narrowband free-decay vibration signals.

$$x_1 = 10\cos(4\pi t)e^{-0.08\pi t} \quad (2.4)$$

$$x_2 = 1.8\cos(8.6\pi t)e^{-0.172\pi t} \quad (2.5)$$

$$x_3 = 0.5\cos(20\pi t)e^{-0.4\pi t} \quad (2.6)$$

$$x = x_1 + x_2 + x_3 \quad (2.7)$$

x_1 and x_2 and x_3 are decaying waves, x is physically related to one type of structural vibration wave in general, and can be seen as a beating phenomena of waves, in which the envelope of the superposition of three waves will be oscillating at the frequency difference of the three waves.

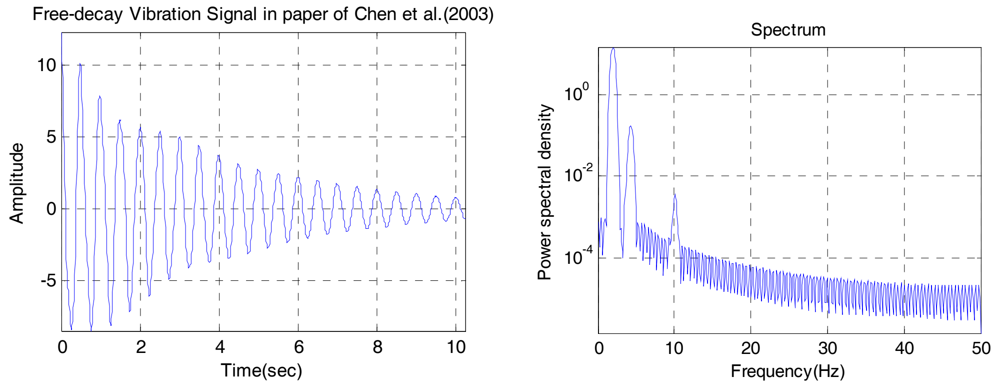

Figure 4. Free-decay Vibration Signal and its power spectra

EMD result:

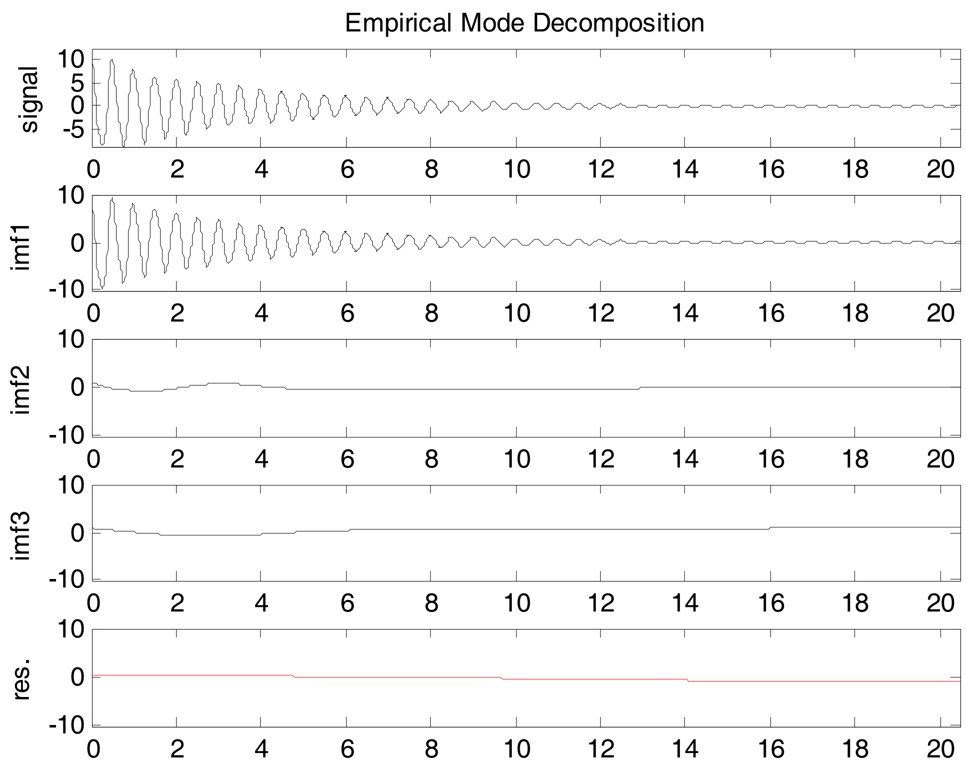

Figure 5. EMD-based high-frequency and low-frequency component of Free-decay Vibration Signal

HVD result:

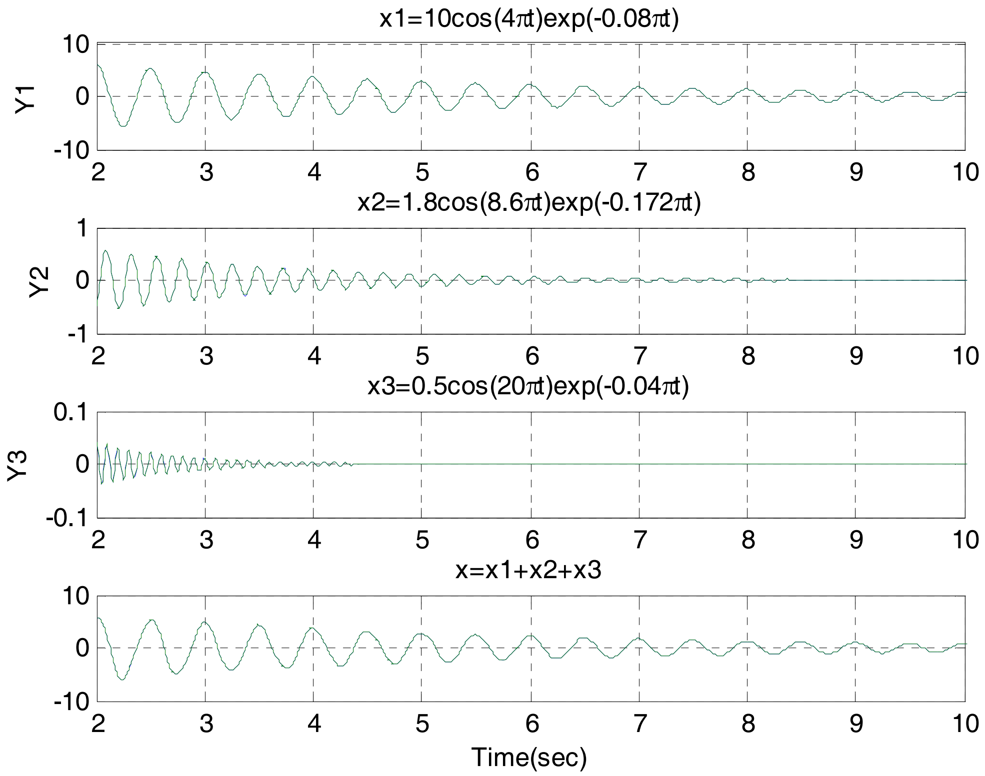

Figure 6. HVD-based low-frequency and high-frequency component of Free-decay Vibration Signal

From above figures, we can get that EMD did not decompose this narrowband multi-component free-decay vibration signal, however HVD did decompose this signal. Because of the special sift method in EMD, it can not separate components which include closely spaced frequencies or weak high frequencies. About this aspect, Braun and Feldman (2011) discussed the theoretical frequency resolution limitations of the two methods.

3. ANALYSIS OF STRONG GROUND MOTION RECORDS

We now demonstrate the rationale for use of EMD and HVD in analyzing ground motion with the acceleration record of the 2008 Wenchuan, China earthquake. The record is the east-west acceleration time history at station Wolong (51WCW) (latitude 31.0° and longitude103.2°), located approximately 30.8 km from the epicentre.

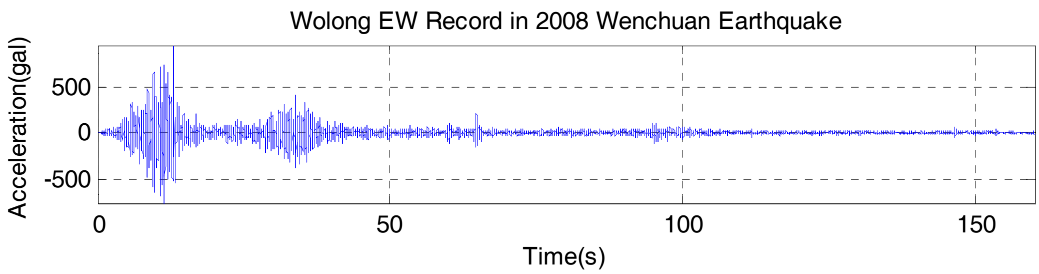

Figure 7. Recorded acceleration time history of EW component at Wolong station

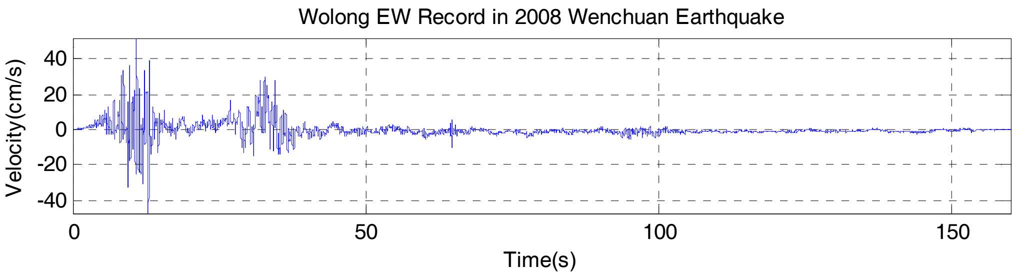

Figure 8. Velocity time history at Wolong station after baseline correction

Figure 7 shows the recorded acceleration time history of EW component at Wolong station. After baseline correction, we can get the velocity time history shown in Figure 8. Figure 8 shows two sets of strong ground motion in the time intervals 3-18 and 26-37 s, respectively. Based on visual observation, the arrival at 3-18 s mainly contains high-frequency energy, while 26-37 s consists of both low-frequency pulse-like wave signals and high-frequency signal. From a seismological perspective, these observations imply two major subevents in the rupture process. From a structural engineering perspective, the second set of wave maybe cause much larger dynamic responses of long period structures than will the first set. For example, a multi-span continuous girder bridge named as Baihua Bridge which situates close to the epicentre (4.2km) was hit by strong ground motion and was severely damaged. The first 10 modes natural periods of Baihua Bridge are 2.175-1.103 s, about 0.4-1Hz.

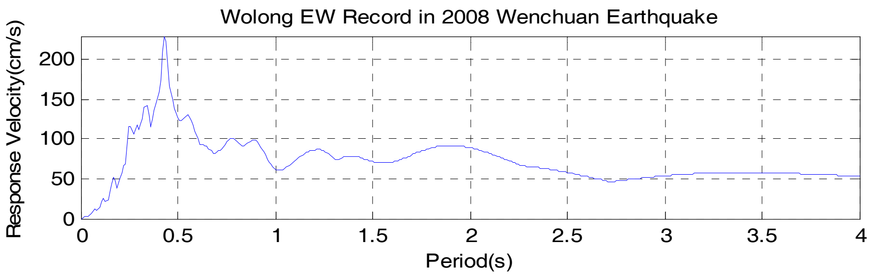

Figure 9. Velocity response spectra at Wolong station after baseline correction

EMD result:

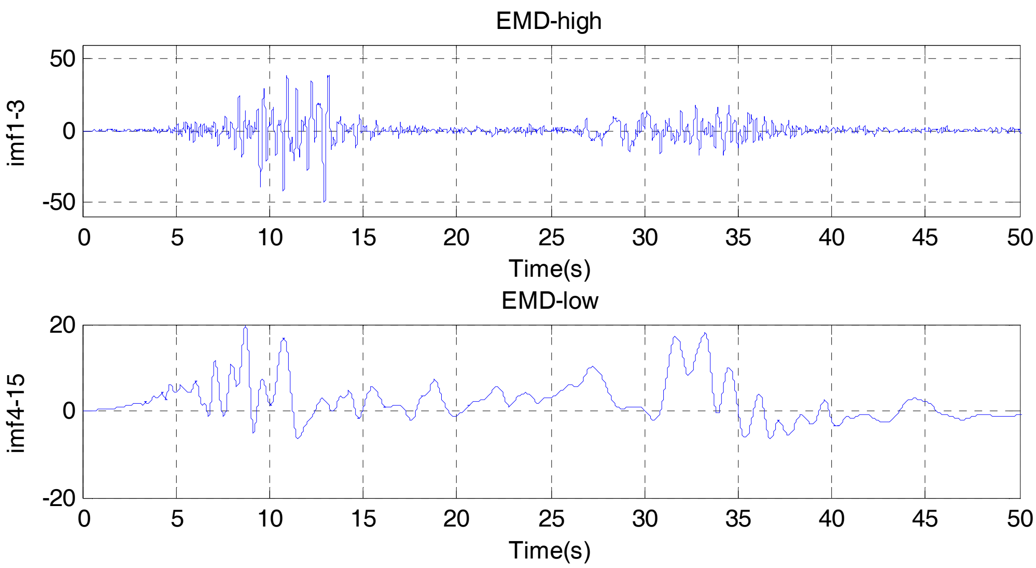

Figure 10. EMD-based high and low frequency component of velocity time history at Wolong station

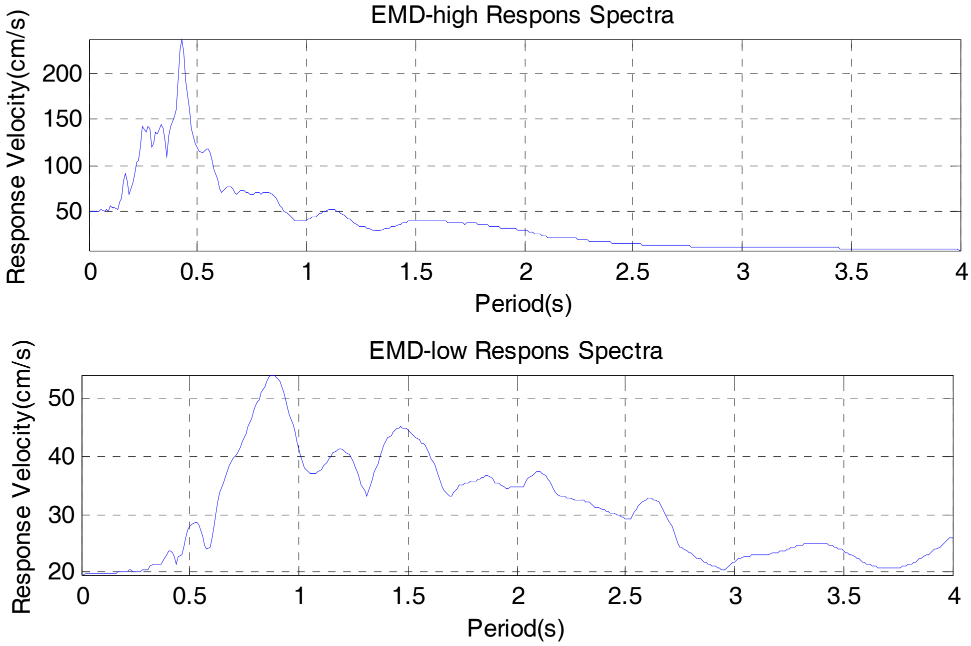

Figure 11. Velocity response spectra of EMD-based high and low-frequency component

By EMD, the high frequency IMF component can be extracted exactly, but for low frequency component, which we care about, because of error accumulation, the reliability is a problem.

HVD result:

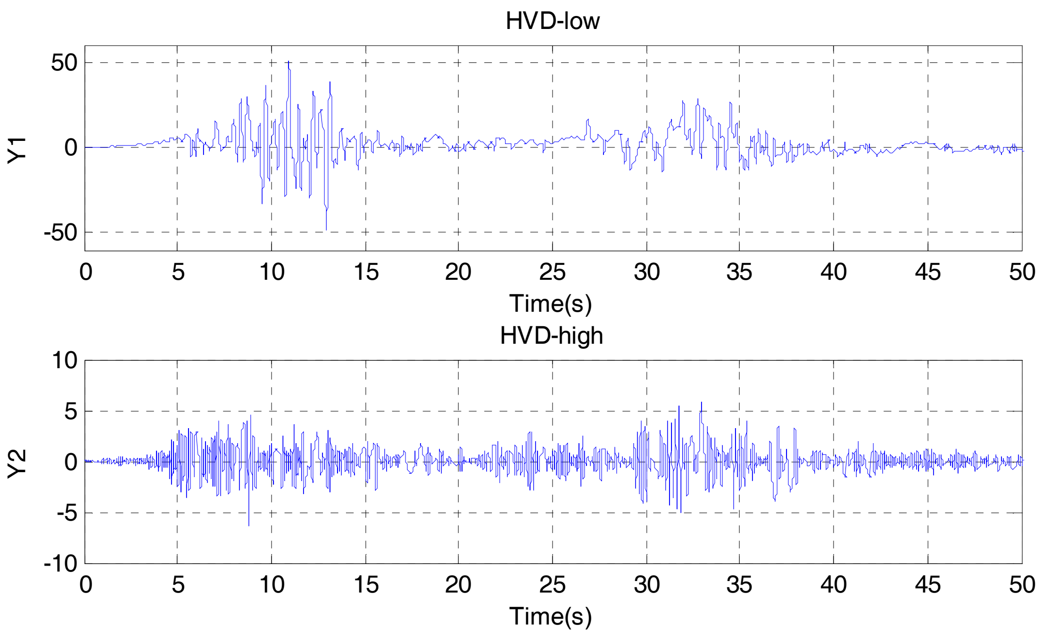

Figure 12. HVD-based low and high frequency component of velocity time history at Wolong station

By HVD, the low frequency and high energy component can be extracted exactly first, so the low frequency components to used structural dynamic analysis are more reliable. However, as the same reason, the high frequency components maybe have error accumulation.

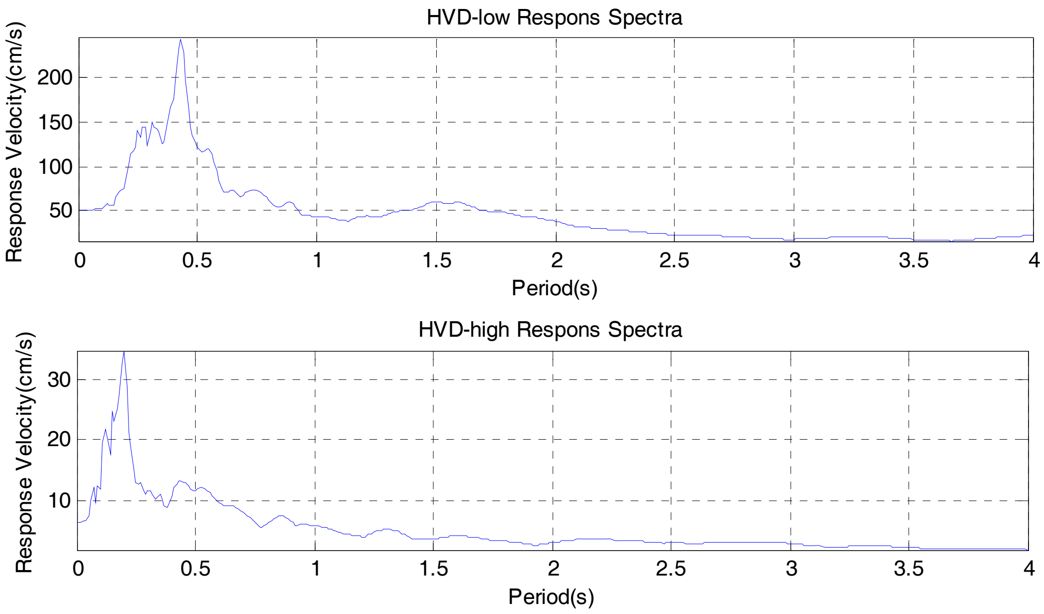

Figure 13. Velocity response spectra of HVD-based low and high frequency component

From above figures, we also can find that both EMD and HVD are found suited for analyzing earthquake motion records, which are better than some conventional Fourier signal processing technique in extracting some features of recordings in studies of seismology and earthquake engineering. EMD can decompose high frequency components and HVD suit for extract high energy low frequency components, so combination of EMD and HVD maybe more effectively. In the light of specific conditions, we can use HVD decompose low frequency component which we care about at first, then use EMD decompose high frequency component which we care about.

5. CONCLUSIONS

This study introduces the methods of EMD and HVD for earthquake data analysis and investigates its rationale for studies of earthquake engineering. It reveals the following:

(1) Both EMD and HVD are found suited for analyzing earthquake motion records, which are better than some conventional Fourier signal processing technique in extracting some features of recordings in studies of seismology and earthquake engineering.

(2) As an empirical method, EMD not only lacks the mathematical theoretical foundation, but also has end effect, overshoots or undershoots, IMF criteria problems during the sifting process. Especially because of the special sift method, EMD always decomposes wideband signal from high frequency to low frequency, but not from high energy to low energy. These characteristics bring on the incapability of separating components which include closely spaced frequencies or weak high frequencies.

(3) HVD is able to decompose wideband signal from high energy to low energy, also enables decomposition of the narrowband multi-component signals. However, as a global instantaneous frequency estimation method, HVD has to use rather long data records. Furthermore, HVD is not effective for separating non-oscillating signal or intermittent signal.

(4) In earthquake ground motion record analysis, EMD can decompose high frequency components and HVD suit for extract high energy low frequency components, so combination of EMD and HVD maybe more effectively.

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