The time-frequency analysis of the train Axle box acceleration signals using empirical mode decomposition

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Received 6 May 2014, www.tsi.lv

Abstract

Rail defects usually result in lots of problems such as affecting the comfort of passengers, increasing the wheel-rail forces, exacerbating the train axle boxes vibration and track wear, even threatening the safe operation of trains. In this paper, the characteristic frequency distribution of the changing axle box acceleration caused by defects is analysed by empirical mode decomposition and Hilbert-Huang Transform is used to analyse the time-frequency changes of axle box acceleration. As a result, rail defects can be effectively positioned and the short wave irregularities within a certain degree can be detected. The research provides timely protection for the maintenance of the track.

Keywords: track detection, empirical mode decomposition, time-frequency analysis, Axle box acceleration

1 Introduction

Condition monitoring of railway tracks, vehicles are essential in ensuring the safety of railways [1]. Early track defects maintenance can not only prevent further deterioration of the state of the track, but also to save the track testing and maintenance costs. Traditional railway track detection methods, special track inspection cars, light rail detection cars do not adapt to the frequent detection of rapid measurement of high-density urban railway lines.

Track detection methods based on the online running vehicles are becoming a key research direction. Li [2] research on early detection of track defects based on the method of axle box vibration acceleration mutations, using validated finite element model to simulate the axle box acceleration changes caused by the track defects to analysis of the type and the location of track defects for early maintenance. Italy M. Bocciolone [3] et al studied vehicular measurement device to collect vehicle axle box acceleration, and study the wear condition of the track by the method of the mean square value of the collected data analysis. The graduate school of Nihon University Mori et al research [4] collected noise signal of the train compartment caused by rail defects by installing the microphone on the train when it running, and combined simulation to detect track status online.

The aforementioned researches on the rail defect detection and data processing have lay a solid foundation for our research. In this paper, Hilbert-Huang transform is used to analyse and process the axle box acceleration signal. And the characteristic frequency distribution of the changing axle box acceleration caused by track defects is analysed to get track irregularity frequency (wavelength)-amplitude time frequency distribution. The rest of this paper is organized as follows. Firstly, the empirical mode decomposition method is discussed in section 2. Then, Axle box acceleration signals are collected in section 3. Based on this, the time-frequency analysis of axle box acceleration is researched in section 4. Finally, conclusions are discussed in section 5.

2 The Empirical Mode Decomposition method

As the acceleration collected on the railway vehicle axle box are non-stationary and nonlinear signals, And Hilbert-Huang Transform [5] is the most effective method to process the signals. This analysis method was a new signal analysis theory, it first proposed by NASA NE Huang et al in 1998. The main innovations include the proposed of the concept of Intrinsic Mode Function (IMF) and the introduction of Empirical Mode Decomposition (EMD). EMD decompose a signal based on the data itself characteristic time scales, it is a kind of self-adaptive and efficient data processing methods, and have very obvious advantage in nonlinear non-stationary signals processing.

EMD decompose the signal into some intrinsic mode functions (IMFs) with different scale features, and the IMFs satisfy the following two conditions:

1) In the whole data set, the number of extreme points and the number of zero-crossings must be either equal or differ at most by one;

2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

To extract the IMF from a given data set, the sifting process is implemented as follows. First, identify all the local extreme, and then connect all of the local maxima by a cubic spline line as the upper envelope. Then, repeat the

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procedure for the local minima to produce the lower envelope. The upper and lower envelopes should cover all the data between them. Their mean is designated as $m_1(t)$, and the difference between the data and $m_1(t)$ is $h_1(t)$, i.e.:

$$h_1(t) = x(t) - m_1(t)\,. \tag{1}$$

Ideally, $h_1(t)$ should be an IMF, for the construction of $h_1(t)$ described above should have forced the result to satisfy all the definitions of an IMF by construction. To check if $h_1(t)$ is an IMF, we demand the following conditions:

(*i*) $h_1(t)$ should be free of riding waves i.e. the first component should not display under-shots or over-shots riding on the data and producing local extremes without zero crossing.

(*ii*) To display symmetry of the upper and lower envelops with respect to zero.

(*iii*) Obviously the number of zero crossing and extremes should be the same in both functions.

The sifting process has to be repeated as many times as it is required to reduce the extracted signal to an IMF. In the subsequent sifting process steps, $h_1(t)$ is treated as the data; then:

$$h_{11}(t) = h_1(t) - m_{11}(t)\,, \tag{2}$$

where $m_{11}(t)$ is the mean of the upper and lower envelops of $h_1(t)$.

This process can be repeated up to *k* times; $h_{1k}(t)$ is then given by:

$$h_{1k}(t) = h_{1(k-1)}(t) - m_{1k}(t)\,. \tag{3}$$

After each processing step, checking must be done on whether the number of zero crossings equals the number of extreme points.

The resulting time series is the first IMF, and then it is designated as $c_1(t) = h_{1k}(t)$. The first IMF component from the data contains the highest oscillation frequencies found in the original data $x(t)$.

This first IMF is subtracted from the original data, and this difference, is called a residue $r_1(t)$ by:

$$r_1(t) = x(t) - c_1(t)\,. \tag{4}$$

The residue $r_1(t)$ is taken as if it was the original data and we apply to it again the sifting process. The process of finding more intrinsic modes $c_i(t)$ continues until the last mode is found. The final residue will be a constant or a monotonic function; in this last case it will be the general trend of the data.

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t)\,. \tag{5}$$

Thus, one achieves a decomposition of the data into n-IMFs, plus a residue, $r_n(t)$, which can be either the mean trend or a constant.

Then using Hilbert transform to every IMF component $c_i(t)$, we get:

$$H\left[c_i(t)\right] = \frac{1}{\pi} P\int_{-\infty}^{+\infty} \frac{c_i(\tau)}{t-\tau} d\tau\,, \tag{6}$$

where *P* indicates the Cauchy Principle Value integral. And the analytic signal can be constructed by $c(t)$ and $H\left[c(t)\right]$,

$$z_i(t) = c_i(t) + jH\left[c_i(t)\right] = a_i(t)e^{j\theta_i(t)}\,, \tag{7}$$

where $a(t) = \left(c^2(t) + H\left[c(t)\right]^2\right)^{\frac{1}{2}}$ is instantaneous amplitude, $\theta(t) = \arctan\left(\frac{H\left[c(t)\right]}{c(t)}\right)$ is instantaneous phase, and the instantaneous frequency can be achieved by $f(t) = \frac{1}{2\pi}\left[\frac{d\theta(t)}{dt}\right]$, therefore, the original signal $x(t)$ can be presented as follows:

$$x(t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)\exp\left[j\int f_i(t)dt\right]. \tag{8}$$

Equation (7) enables us to represent the amplitude and the instantaneous frequency, in a three-dimensional plot, in which the amplitude is the height in the time-frequency plane. This time-frequency distribution is designated as the Hilbert-Huang spectrum $H(\omega, t)$:

$$H(\omega, t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)\exp\left[j\int \omega_i(t)dt\right]. \tag{9}$$

The Hilbert spectrum offers a measure of amplitude contribution from each frequency and time.

3 Axle box acceleration collection

Rail corrugation and sleeper spacing irregularity would cause great changes in the wheel-rail forces when vehicle running, wheel vibration will become more apparent especially the vehicle in the case of a high speed. Axle box and the wheel are rigid connection, axle box acceleration not only able to characterize the state of wheel vibration, but also to reflect the excitation formed by short track irregularity. Acceleration axle box contains larger bandwidth, with a variety of information of track defects. By measuring the acceleration of the axle box and its amplitude frequency variation analysis, we can make a fairly credible judgment for the track status.

Figure 1 is the schematic diagram of the axle box acceleration collection, accelerometer collect the changing axle box acceleration, the collected acceleration and the train GPS data were transmitted to the signal collection devices via the data line simultaneously. Axle box acceleration, GPS data and other information of the train collected by ATS receiver connect with an external computer via data fusion system. Computer process the data to analysis track status. Figure 2 is the sensor layout of the test vehicle.

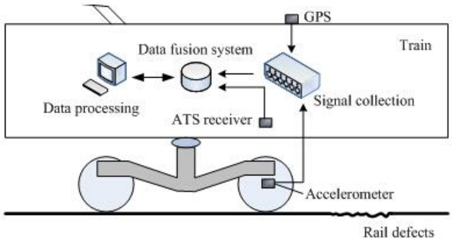

FIGURE 1 The schematic diagram of the Axle box acceleration collection

FIGURE 2 Sensor layout of the test vehicle

4 Axle box acceleration time-frequency analysis

Track irregularity is the main source of excitation of vehicle vibration, different spatial frequency components of the track will effects vehicle running status differently [6]. Shortwave irregularity is one of the main reasons to generate vehicle noise and cause changes in wheel-rail interaction force. Tiny rail surface defects generate huge wheel-rail interaction forces when train at high speed, and it cause axle box vibrate severely. Meanwhile, axle box acceleration can reflect the status of the track. In this paper, EMD and Hilbert transform combined with time-frequency analysis were used to process axle box acceleration.

FIGURE 3 The run line of test vehicle

The red line in Figure 3 is the run line of test vehicle, the train run between the longyang road station (point A) and Zhangjiang High Technology station (point B), in shanghai metro line 2. Vertical acceleration of the axle box collected in 92.5m long track, on a section of track between A and B. The speed of the test vehicle was 33.3Km / h, 270 sampling points per meter, the sampling frequency is 2500Hz. Figure 4 is the vertical acceleration of the axle box processed by a low-pass filter, figure 5 is its corresponding spectrogram.

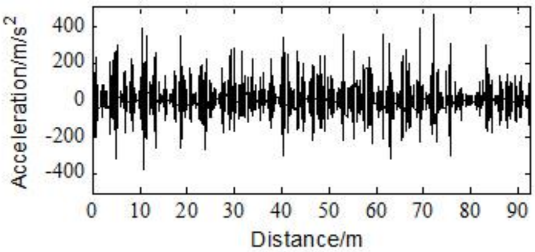

FIGURE 4 The vertical acceleration of the axle box

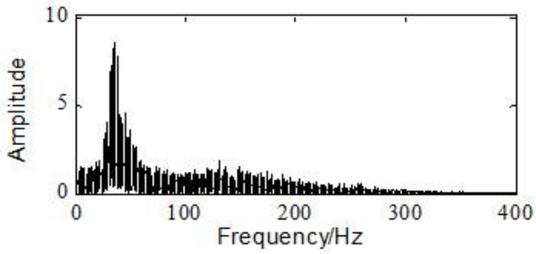

FIGURE 5 Spectrogram of acceleration

Shortwave irregularity wavelength typically distribute in the range of 0.05m-1m, therefore, it will cause vibration frequency distribution in the 9.25-185Hz on the vehicle axle box when the train speed is 33.3Km/h. The frequency distribution of axle box vertical acceleration can be a good reaction in vibration between wheel and rail. Using EMD to decompose the measured vertical acceleration of the axle box, figure 6 is the decomposition results, the acceleration was adaptively decomposed into 14 intrinsic mode function (IMF) based on the EMD algorithm, the last of the IMFs is trend signal. Figure 7 is the corresponding spectrum of IMFs, it is obviously that the frequency of IMFs is descend from high to low. In entire frequency band, the frequency amplitude between 0 and 200Hz are larger and it gradually weakening when frequency over 200Hz. This is because the vertical acceleration of axle box was processed by a low-pass filter before it decomposed by EMD.

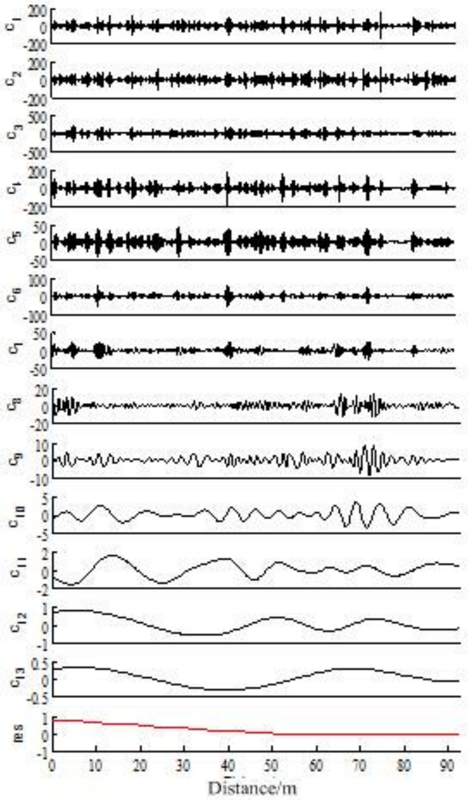

FIGURE 6 The decomposition results

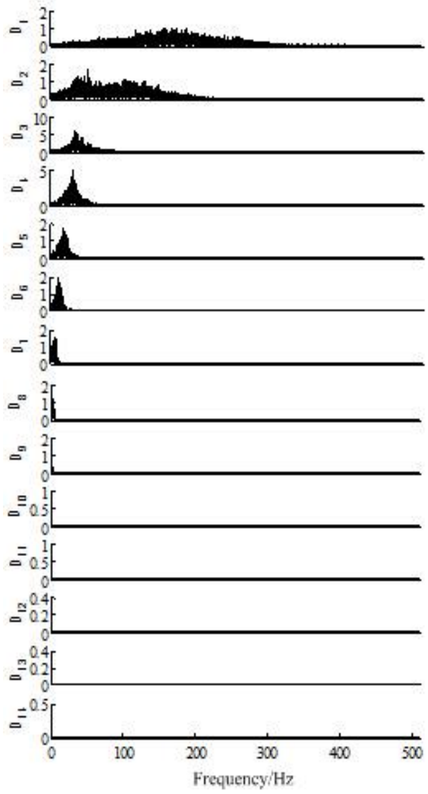

FIGURE 7 The corresponding spectrum of IMFs

The collected axle box acceleration includes not only part of the axle box vibrations caused by shortwave irregularity, but also includes other vibration from mechanical parts itself and surrounding environment. Due to the different vibration intensity, the energy of vibration on the performance of axle box is different, in which the vibration caused by the shortwave irregularity is far greater than any other case vibration. Because the acceleration have non-stationary characteristics and the shortwave irregularity randomness, it may appear that in acceleration sometime the signal intensity and the SNR are small, and another time the signal intensity and the SNR are high. Hilbert-Huang Transform can select the higher signal intensity to process in time series and improve the quality of data processing. It also can characterize random signals time-frequency distribution characteristics at the same time.

Figure 8 is the three-dimensional HHT time-frequency spectrum of axle box acceleration, it is obtained by calculating IMFs shown in Figure 6 by the method of Hilbert transform. Points in the figure indicates the energy, the brighter the colour, which means the higher the energy, and vice versa, the lower the energy. The horizontal axis represents the track mileage, and the vertical axis represents the frequency distribution of acceleration. As shown in figure 8, the frequency of the acceleration mainly within 200Hz, the frequency spectrum with good aggregation, and the instantaneous energy spectrum intuitively and unevenly distributed in several track mileage (Figure 8, points 1-4). We can well identify energy changes with time and frequency.

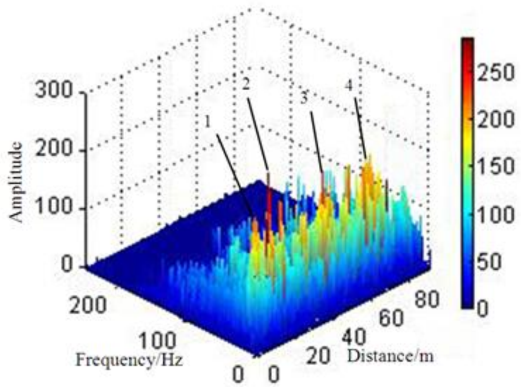

FIGURE 8 Three-dimensional time-frequency spectrum

Observing acceleration spectrum from the three-dimensional in Figure 8, in the frequency range of 10Hz-100Hz, the time-frequency energy spectrum is relatively concentrated obviously, especially in track mileage of 5m, 12m, 41m, 68m (1-4 point) the energy peaks are larger, the corresponding frequency and shortwave wavelength of track are mainly concentrated in the range of 11-27Hz and 0.343-0.841m. Wheel-rail interaction force will cause axle box greater vibration when vehicle running in these track shortwave irregularities, and it will be clearly reflected on energy peaks of axle box acceleration. By comparing the actual situation in the field section of track testing, we found the track shortwave irregularities position and the wavelength range distribution are better match the analysis in this paper. The type of hundreds of millimetres track shortwave irregularities we detected, including sleeper spacing irregularities and rail corrugation, these would be the focus of the track maintenance.

5 Conclusion

This paper pre-processed the collected axle box acceleration, and decomposed the vertical acceleration of axle box using the EMD method to analyse the characteristics frequency distribution of track shortwave irregularity. Hilbert transform was then used to calculate the IMFs to get the three-dimensional HHT time-frequency spectrum of axle box acceleration. By analysing the changes of the frequency of axle box acceleration and its energy distribution variation combined with the trains operating parameters, we can position the distribution of the track shortwave irregularity. It is beneficial for the track maintenance, and ensuring the safety of urban rail transit operation.

Acknowledgements

This work was supported by the Scientific Research Innovation Project of Shanghai Education Commission (12YZ149, 12ZZ184), Shanghai Municipal Natural Science Foundation (12ZR1412300), Key Technology R&D Project of Shanghai Committee of Science and Technology (13510501300) and Construction Project for Transportation Engineering(13SC002)

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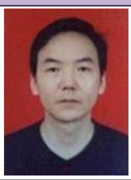

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