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Rotating Machinery Signal Analysis Method Based on EEMD and Spectrum Correction

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Abstract

Aiming at the problems of low accuracy of non-stationary signal spectrum analysis in rotating machinery vibration, this paper puts forward a kind of rotating mechanical signal analysis method based on EEMD and spectrum correction. Firstly, ensemble empirical mode decomposition (EEMD) is used to obtain the intrinsic mode functions (IMF) of the original signal; secondly, do correlation analysis for each IMF component and the original signal separately, and find out the IMF component with the largest correlation coefficient and calculate the frequency spectrum of the IMF; finally, spectrum correction algorithm is employed to get accurate spectrum for quantitative analysis. A practical vibration signal of rotor vibration platform is applied to testing the method of this paper, the EMD method and wavelet analysis method separately. The results show that the proposed new method can improve the precision of spectrum analysis for rotating mechanical signal significantly; therefore, it has a good application prospect.

Key words: EEMD; spectrum correction; Intrinsic mode; signal analysis.

1. Introduction

At present, there are many methods for the analysis of vibration signal of rotating machinery, such as wavelet analysis, empirical mode decomposition (EMD), analytical modal method, envelope demodulation method, etc.

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For the wavelet analysis method [1], because of its own sensitivity to parameters, it is difficult to break down the characteristic signal adaptively, and the time-frequency resolution accuracy is not high, especially for the non-stationary signal. For the EMD method [2], although it can be adaptively decompose the basic model components from the time scale of the original signal itself, but the EMD method itself has such problems as the mode mixing, the end effect, the overshoot or the under impulse, which will affect the final analysis results. For analytical modal method [3], although the time used in analysis process is greatly reduced, the premise is to determine the signal in the various frequency components, so it is very difficult to realize fault diagnosis in mechanical systems with unknown characteristic frequency.

The EEMD is a noise assisted data analysis method that Wu and Huang proposed. This method not only inherits the advantages of empirical mode decomposition but can effectively inhibit the impact of noise in the original signal to prevent aliasing mode, so as to separate the natural modal components with real physical meaning from the original signal. The different components corresponding to different characteristic frequency for some rotating machinery, and the fault will be accompanied by some kind of modulation phenomenon. In this paper, the EEMD method is used to separate the original signal adaptively. Then, the correlation analysis of each IMF component and the original signal is carried out to find out the largest correlation coefficient of the IMF component. If there is a failure in the mechanical equipment, the characteristic frequency of this component is inevitable. Finally, due to the limitation of frequency resolution in the frequency domain analysis, it is difficult to locate the frequency domain. In order to get accurate spectrum information, spectrum correction algorithm is used to correct the spectrum to improve the accuracy of the spectrum.

2. EEMD and the principle of spectrum correction

2.1. Principle of EEMD

If the original signal is x(t), then the decomposition of the EMD algorithm can be expressed as

$$x(t)=\sum_{i=1}^{n}c_i(t)+r_n(t) \qquad (1)$$

Where ci (t) the intrinsic mode function (IMF), and rn (t) is the remainder of the decomposition.

The EMD algorithm can decompose the signal into the IMF based on the time characteristics scale of the signal. But there are several problems, such as the computation of the overshoot and the impact of the extreme envelope, the mode mixing [4], the end effect, etc. And the phenomenon of mode mixing is the most serious, namely the IMF of EMD decomposition contains a number of time scale components.

To overcome the problem of mode mixing, EEMD [5] was introduced based on the statistical properties of white noise, which shows that the EMD method is an effective self-adaptive dyadic filter bank when applied to the white noise, and the noise could help data analysis in the decomposition of EMD. When a signal is added to this uniformly distributed white noise background, the components in different scales of the signal are automatically projected onto proper scales of reference established by the white noise in the background. But the noise in each trial is different in separate trials. Thus it can be decreased or even completely cancelled out in the ensemble mean of enough trials. So after several empirical mode decomposition (EMD) trials, the ensemble mean is treated as the true solution and can effectively suppress the noise of the original signal [6].Then the mode mixing phenomenon can be well suppressed in EMD.

EEMD decomposition steps are as follows:

- Initialize the number of trials in the ensemble, M, the amplitude of the added white noise, and the trial number m= 1;
- Perform the m-th trial on the signal added with white noise,

a. Generate a white noise series with the initialized amplitude and add it to the investigated signal x (t), where nm (t) indicates the m-th added white noise series, and xm (t) represents the noise-added signal of the m-th trial;

$$x_m(t) = x(t) + k \cdot n_m(t) \qquad (2)$$

b. Decompose the noise-added signal xm (t) into IMFs cjm (j=1,2,3…I) using the EMD method, where cjm denotes the j-th IMF of the m-th trial, and I is the number of IMFs;

c. If the trial number is smaller than the number required, i.e. m<M ,then go to step(a) with m=m+1. Repeat steps(a) and (b) again, but with a new randomly generated white noise series each time;

- Calculate the ensemble mean $\overline{c_j}$ of the M trials for each IMF,

$$\overline{c_j} = \frac{\sum_{m=1}^{M} c_{j,m}}{M} (j = 1,2,3...I; m = 1,2,3...M) \qquad (3)$$

- Report the mean $\overline{c_j}$ of each of the I IMFs as the final IMFs.

2.2. principle of spectrum correction

Considering each IMF component of EEMD decomposition includes only a fundamental mode oscillation, and no complicated superposition of wave exists, energy centrobaric correction method is adopted to meet the accuracy requirements of the practical application of spectrum analysis. It is characterized by using discrete spectrum energy center of window function limitlessly approach origin of coordinate for discrete spectrum correction. Although the energy center method theory of discrete frequency correction are suitable for all symmetric window function[7], the Hanning window has a higher accuracy than the university. Due to the spectral energy centrobaric correction method can correct multi segment average spectrum directly, it is widely used in single frequency component signals or signals contain multiple frequency components with larger intervals for it is simple and with high accuracy [8].

The Hanning [9] window energy centrobaric method is used in this paper, and its basic principle can be expressed as

$$\sum_{i=-n}^{n} G(x+i) \cdot x(x+i) = 0 \tag{4}$$

Where G (x) is the power spectrum function of the window function, and the formula (4) shows that the energy center of the Hanning window is close to the center of the energy. Considering power spectrum values of the side lobe of window function is very small, if let x [-0.5, 0.5], it can be used to accurately find the center coordinates of the winner valve by a few lines with a larger power spectrum according to the characteristics of the energy center, expressed as

$$x_0 = \left(\sum_{i=-n}^{n} Y_i \cdot (m+i) \cdot f_s / N\right) \Big/ \sum_{i=-n}^{n} Y_i \tag{5}$$

Eq. (5) is the general formula of energy correction frequency, where x0 is main valve center, Yi is the i-th line spectrum value of the power spectrum, m is peak spectral line number of the main valve, and fs is sampling frequency, n is the spectral points. Let Kt be the energy recovery coefficient (Hanning window for 8/3), then the correction amplitude is

$$A = \sqrt{K_t \cdot \sum_{i=-n}^{n} Y_i} \tag{6}$$

Let the correction rate of the normalized correction frequency be Δx, and it can be got by Eq. (5),

$$\Delta x = (x_0 - m f_s / N) / (f_s / N) \tag{7}$$

According to the characteristic of the phase of the symmetric window, the correction of the phase is

$$\Delta \varphi = -\Delta x \cdot \pi \tag{8}$$

According to Eq. (8), phase correction of the energy method is

$$\varphi = arctan(I_k / R_k) + \Delta \varphi \tag{9}$$

Where Ik and Rk are respectively the imaginary part and the real part of the FFT corresponding to the spectral line number k.

3. Rotating machinery signal analysis method based on the EEMD and spectral correction

Aiming at the non-stationary vibration signal of rotating machinery, there are many analysis methods, such as wavelet analysis method, empirical mode decomposition (EMD), analytical modal method, etc. But there are some drawbacks, which affect the final results of the analysis. In order to accurately locate the fault characteristic frequency in the spectrum analysis, this paper proposes a signal analysis method based on EEMD and spectrum correction.

The specific steps of the method are as follows:

- The original vibration signal is decomposed by EEMD, and get IMFs;
- Correlation analysis between the IMF component and the original signal is obtained, and find out the IMF component with larger correlation coefficient and seek its frequency spectrum;

$$R = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\sum X^2 - \frac{\left(\sum X\right)^2}{N}}\sqrt{\sum Y^2 - \frac{\left(\sum Y\right)^2}{N}}} \qquad (10)$$

- The IMF component spectrum with larger correlation coefficient is processed to get the correct spectrum;
- According to the frequency components and spectral amplitude of the corrected spectrum to determine the operating state of the rotating machinery, and find out whether there is a fault and the fault degree.

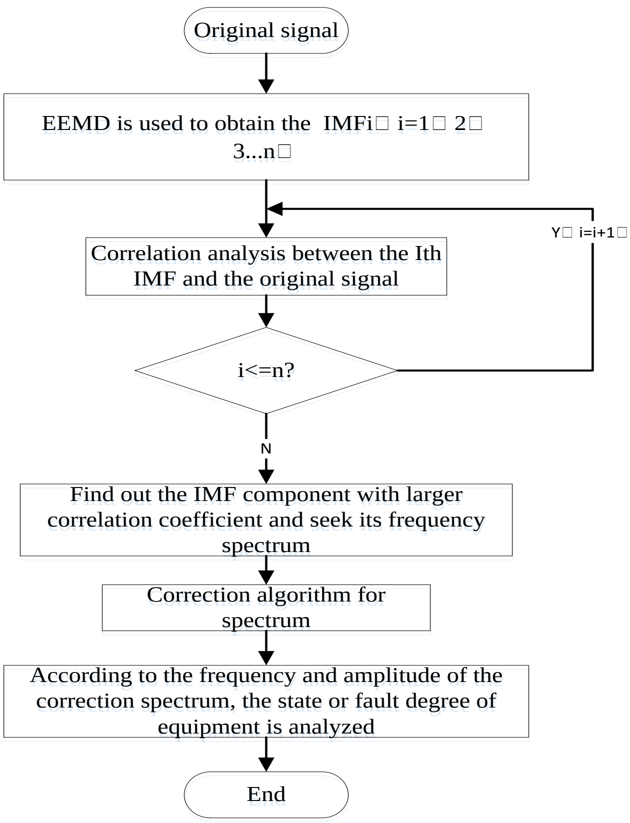

Figure 1: Flow chart of signal analysis of rotating machinery

4. Experiment and analysis

The analysis object is a large rotor platform, and the original data is collected by BENTLY3500 vibration probe. Sampling frequency fs= 2k. The number of rotating shaft of the rotor platform is two, and the main and subordinate rotating shafts are N_1 and N_2, respectively, and their gear teeth are Q_1=9, Q_2=54. Set rotational speed R= 1285 r/min, so the theoretical calculation value of the N_1 rotation frequency is f_1=21.42 Hz, N_2 rotation frequency f_2=3.57Hz, and meshing frequency f_3=192.75Hz. To capture the 2.5s data from the acquisition data as the original data, and the original signal is shown in Figure. 2.

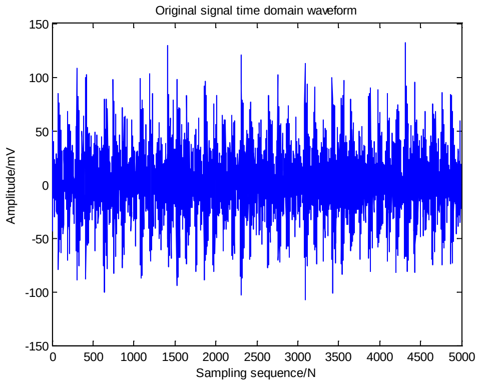

Figure 2: Time domain waveform of the original signal

Wavelet analysis method is used to get the original signal decomposition waveform and wavelet spectrum as shown in Figure. 3 and Figure. 4, respectively. Although the wavelet method can suppress the random noise and pulse interference, the final decomposition waveform distortion is serious. And the method can not extract the true signal characteristics, which can be seen from the decomposition results. In addition, there are many frequency components and features are not related. This is due to the theoretical basis of the wavelet analysis is the Fourier transform, which cannot exactly describe the signal whose frequency changes with time. So in the analysis of non-stationary signals, it is easy to produce false signals and false frequency and other faults.

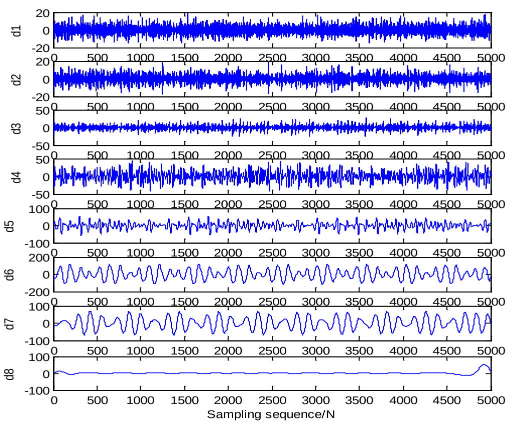

Figure 3: Wavelet decomposition of the original signal

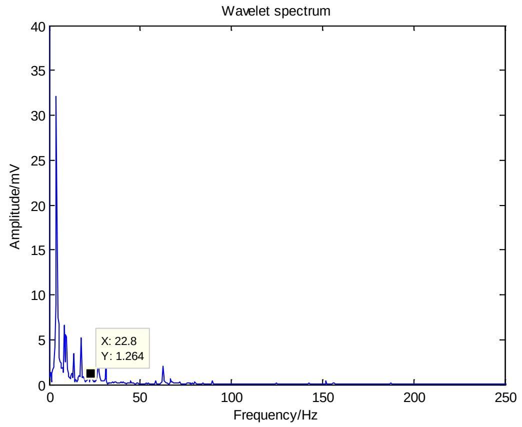

Figure 4: Wavelet spectrum

Using EMD to decompose the signal, and obtain 9 IMF components and one remainder. The decomposition waveform is shown in Figure. 5.

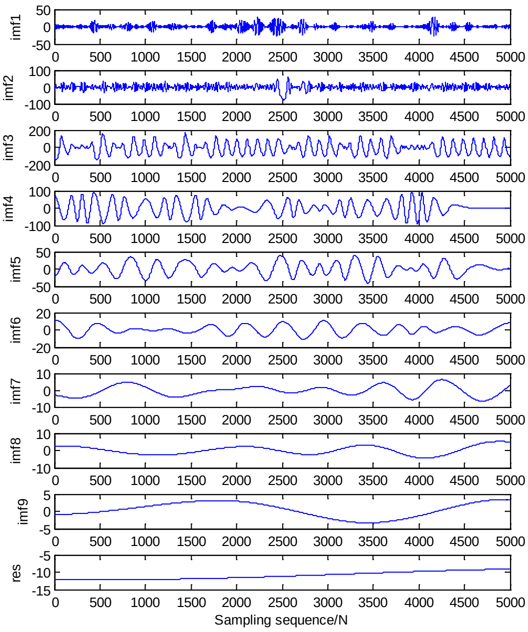

Figure 5: Results of EMD decomposition of the original signal

The results from the EMD decomposition can hardly see any significant signals. After the correlation analysis of the IMF components and the original signal, the correlation coefficients of each IMF are obtained and is shown in table 1. It can be seen from the table that the correlation coefficient is larger for the imf3 component, and its frequency spectrum is obtained. The results are shown in Figure. 6. Due to the impact of the intermittent signal or noise, the mode mixing is generated when the EMD is decomposed, and the useful signal is submerged in other time scale components. And all these factors make the imf3 spectrum contains more frequency components, and make it difficult to distinguish the characteristics of signal frequency.

Table 1: Correlation coefficients of each component after EMD decomposition

component	imf1	imf2	imf3	imf4	imf5	imf6	imf7	imf8	imf9
correlation coefficient	0.0116	0.0225	0.9219	0.2795	0.0063	0.1086	0.0265	0.0623	0.0606

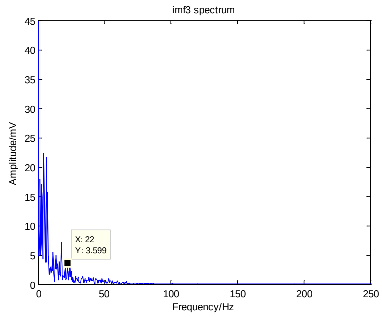

Figure 6: The IMF component spectrum with the larger correlation coefficient in EMD decomposition

The original signal is analyzed and processed by the method proposed in this paper. Firstly, the original signal is decomposed by EEMD and obtained 12 IMF components and a remainder, and the results are shown in Figure. 7. It can be seen from the EEMD decomposition results that IMF1 and IMF6 have complete time scale, and they all have certain physical meanings. In order to make a quantitative analysis, the correlation analysis between the EEMD decomposition and the original signal is done, and the results are shown in Table 2.

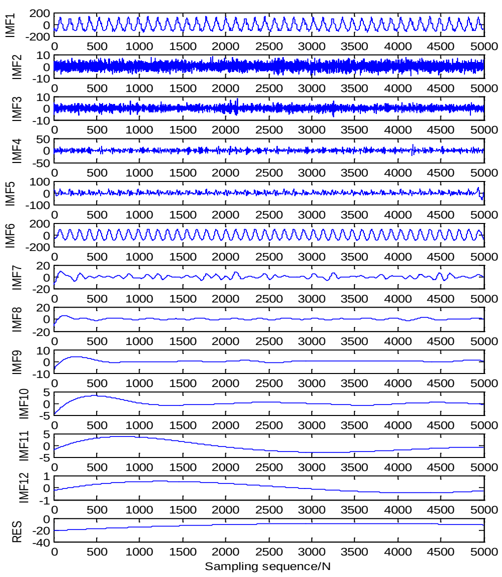

Figure 7: Results of EEMD decomposition of the original signal

Table 2: Correlation coefficients of each component after EEMD decomposition

component	IMF1	IMF2	IMF3	IMF4	IMF5	IMF6	IMF7	IMF8	IMF9	IMF10	IMF11	IMF12
correlation coefficient	0.9896	0.0027	0.0013	0.0157	0.1069	0.8959	0.4932	0.0452	0.1722	0.1172	0.0665	0.0679

Find the spectrum of the component with larger correlation coefficient, as shown in Figure. 8, whose energy is mainly concentrated in 0Hz, 21Hz, 43Hz, 64Hz, 86Hz. The 21Hz spectrum space contains the largest energy, and 0 Hz represents the DC component of the original signal, so the 0Hz component is not considered. And then the spectrum correction is carried out on the basis of Fig. 6. The results are shown in Figure. 9. 21.34 Hz, 42.72 Hz, 64.05 Hz and 85.44 Hz components are obtained, and corresponding to the fundamental frequency, two times frequency, three times frequency and four times frequency respectively. Thus we can know that the rotation frequency of the main shaft of the rotor platform is 21.34Hz (0.16 Hz deviation is produced by the motor drive and other factors). Hence there is a fault in the main shaft of the rotor platform, and the degree of fault can be quantified by the amplitude of the characteristic frequency in the frequency spectrum. In practical application, a threshold value can be set, and the fault or fault severity can be judged if the amplitude exceeds the threshold value in the frequency spectrum.

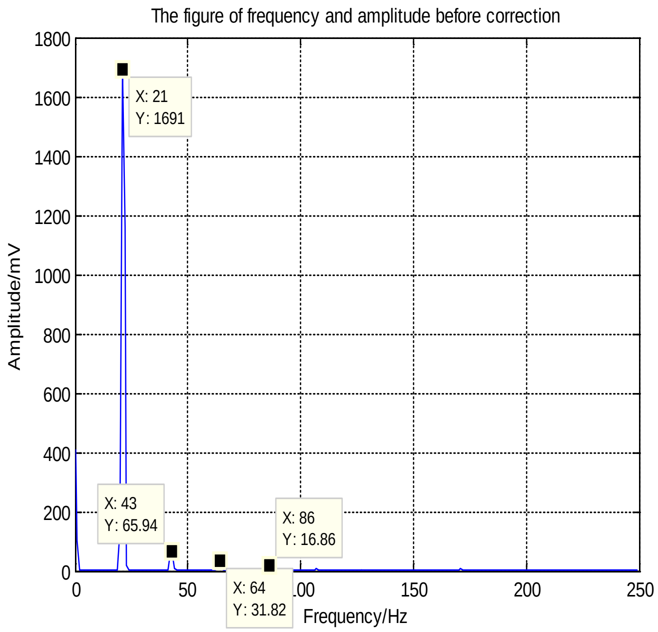

Figure 8: The spectrum of IMF1 component with a larger correlation coefficient in EEMD decomposition

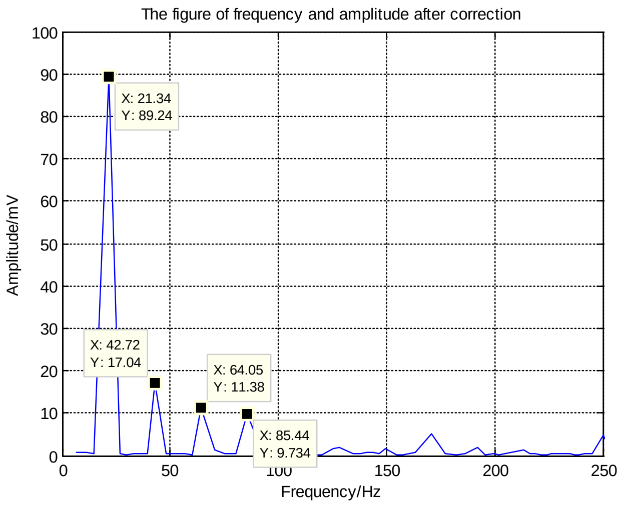

Figure 9: The spectrum after spectrum correction

In summary, the analysis results of different spectrum analysis methods are shown in Table 3.

Table 3: Spectral analysis results of different methods

	Theoretical value /Hz	Measured value /Hz	Absolute error /Hz
Wavelet method		22.8	1.38
EMD method	21.42	22	0.58
Paper method		21.34	0.08

5. Conclusion

Aiming at the problem that the spectrum analysis of the non-stationary signal is not high, this paper proposes a new analysis method of rotating machinery signal based on EEMD and spectrum correction after analyzing the principle of EEMD and spectrum correction. The method proposed in this paper, the EMD method and wavelet analysis method are respectively used on the same large rotor system vibration signal for processing and testing, and the results show that the new method can accurately analyze the characteristic frequency of the original signal, and the results can accord with the actual circumstance. Compared with wavelet analysis and EMD, the frequency components of the vibration signal spectrum obtained by this paper proposed method are more clear, and the spectral accuracy is significantly improved.

References

[1] Wang Qiaohua, Wu Changjun. "Application of wavelet transform in gear fault diagnosis." Coal Mine Mechinery, vol. 33, pp. 272-273, 2012.

[2] Su Cuijiao, Zhao Na, et al. "Fault Diagnosis Method for Rotating Mechinery Based on AMD." Chinese

Mechanical Engineering, vol. 27, pp. 674-679, 2016.

[3] Liu Lijun, Wang Qi, Yang Keji et al. “EMD and spectrum correction-based fault diagnosis method.” Chinese journal of Scientific instrument, vol. 32, pp. 1278-1283, 2011.

[4] Fan Hong. Non stationary signal feature extraction method and its application. Beijing, Chin: Science Publishing company, 2013, pp. 125-134.

[5] Yang Shixi, Cao Chongfeng, Yang will be new. “EEMD noise reduction method for non-stationary vibration signals of large rotating machinery.” Journal of Vibration and Shock, vol. 28, pp. 33-38, 2009.

[6] Dou Dongyang, Zhao Yingkai. “Application of ensemble empirical mode decomposition in failure analysis of rotating machinery.” Transactions of the CSAE, vol. 26, pp. 190-196, 2010.

[7] Wang Bolin. “New method of small deviation correction of spectrum.” Automation of Electric Power Systems, vol. 29, pp. 46-49, 2005.

[8] Duan Huming, Qin Shuren. “A review of the correction method for discrete spectrum.” Journal of Vibration and Shock, vol. 26, pp. 138-188, 2006.

[9] Huang Zhiyun, Xu Xu. “Study on the spectral correction method based on phase difference.” Journal of Vibration and Shock, vol. 24, pp. 77-79, 2005.

[10] Flandrin P, Goncalves P, Rilling G. “EMD equivalent filter Banks, form interpretation to applications.” Hilbert-Huang Transform Introduction and Applications, World Scientific, Singapore, vol. 360, pp. 67-87, 2005.

[11] Heydt G T, Fjeld P S, Liu C C eta. “Applications of the windowed FFT to electric power quality assessment.” IEEE Transactions on Power Delivery, vol. 14, pp. 1411-1416, 1999.

[12] Wu F, Qu L. “An improve method for restraining the end effect in empirical mode decomposision and its application to the fault diagnosis of large rotating machinery.” Journal of sound and vibration, vol. 314, pp. 586-602, 2008.

[13] Chen G, Wang Z. “A signal decomposition theorem with hilbert thansform and its application to narrowband time series with closely spaced frequency components.” Mechanical systems and signal processing, vol. 28, pp. 258-279, 2012.

[14] Feldman M. “A Signal Decomposition or Lowpass Filtering with Hilbert Transform.” Mechanical Systems and Signal Processing, vol. 25, pp. 3205-3208, 2011.