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Nonlinear and Non-stationary Vibration Analysis for Mechanical Fault Detection Using EMD-FFT Method

M. Besanjideh*[a], M. Fooladi. Mahani [b]

[a] *Mechanical Engineering Department, Shahid Bahonar University of Kerman, Kerman-Iran*
[b] *Mechanical Engineering Department, Shahid Bahonar University of Kerman, Kerman-Iran*

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A B S T R A C T

The Hilbert-Huang transform (HHT) is a powerful method for nonlinear and non-stationary vibrations analysis. This approach consists of two basic parts of empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA). To achieve reliable results, Bedrosian and Nuttall theorems should be satisfied. Otherwise, the phase and amplitude functions are mixed together and consequently, the confidence of resultant frequencies are reduced. To prevent such an event, various methods entitled as improved Hilbert-Huang transforms have been proposed. Yet, another method is introduced in this paper that has a high ability to identify the mechanical defects easily. According to this method, the signal is decomposed to its intrinsic mode functions (IMFs) and then each of the IMF is analyzed by fast Fourier transform (FFT). Using the proposed method, which is called EMD-FFT, the mechanical defects of an electromotor have been detected in Kerman combined power plant. In addition, it is shown that the classical FFT method is unable to detect all the defects because of nonlinear and non-stationary properties of the signals, and also use of the HHT method, regardless of satisfying the mentioned theorems, causes invalid results due to incorporation of phase and amplitude functions.

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NOMENCLATURE

$s(t)$	Original signal	f_{or}	Bearing outer race frequency
$A(t)$	Amplitude function	f_{bs}	Bearing ball spin frequency
$f(t)$	Frequency function	f_c	Bearing cage frequency
$\tilde{s}(t)$	Hilbert transform of original signal	N_b	Number of balls
$F(s(t))$	Fourier transform of original signal	B_d	Ball diameter
$F(\tilde{s}(t))$	Fourier-Hilbert transform of original signal	p_d	Pitch diameter of ball bearing
$z(t)$	Analytic signal	ΔE	Error bound function
j	Identity imaginary number	α	Ball contact angle
f_s	Shaft rotation frequency	$\varphi(t)$	Phase function
f_{ir}	Bearing inner race frequency		

*Corresponding Author Email: besanjide@gmail.com (M. Besanjideh)

1. INTRODUCTION

One of the most important techniques that is used in condition monitoring is the vibration analysis. This technique is capable of identifying physical symptoms that cause the disruption in machinery operation.

For many years, fast Fourier transform (FFT) has been used to identify the mechanical systems defects. This method represents a given time domain signal in the form of frequency domain but is less effective in indicating all the characteristic defect frequencies (CDFs); for example, this method is less efficient in determining the defects of the inner race in the rolling bearings [1]. Also, the FFT is not capable of analyzing nonlinear and non-stationary signals.

Distribution wavelet transform (DWT) has been used extensively for signal processing in the last two decades [2]. This method is based on the energy distribution which leads to the frequency band energy leakage. Although the DWT is implemented for nonlinear and non-stationary signals analysis, the problem of energy leakage causes an inaccurate performance. Regardless of trying to improve the DWT [3], one of the major weaknesses of this method is that it uses a fixed decomposition scale for analysis and does not pay attention to the signal characteristics.

The Hilbert-Huang transform (HHT) is a two-step method which consists of the empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA) [4]. The EMD decomposes the signal into a finite set of independent intrinsic mode functions (IMFs) and the HSA extracts the instantaneous frequencies and amplitudes of the signal by using Hilbert transform (HT) of the IMFs. The HHT has attracted considerable attention in recent years; the main reason is its ability to analyze the nonlinear and non-stationary signals. Although the energy leakage problems do not occur in the process of the HHT, satisfying Bedrosian and Nuttall theorems is a challenge that the HHT is encountered with. To solve this problem partially, Huang et al. [5] proposed a normalized HHT method. Also, some models, such as the VARMA, are proposed to calculate the instantaneous frequencies [6]. In this study, another technique is proposed for mechanical system analysis that is called EMD-FFT. Not only this method is simply implemented but also it represents accurate results. Although the EMD-FFT and the HHT are two different techniques, it will be shown that they are not completely separable from each other. Consequently, the EMD-FFT can represent equivalent results in comparison with the HHT; circumvent limitations of Bedrosian, and Nuttall theorems.

Another advantage of the EMD-FFT method is its authorization to concentrate on each of the IMFs. The IMFs contain frequencies in the decreasing order. Thus, the first IMF contains the maximum rate of change of the amplitude; hence, the highest frequency content and the last IMF (residue) is almost without any oscillatory manner. This property of the IMFs does not permit the small frequencies to be omitted during the transmission of signal from time domain to frequency domain. The last property is very noteworthy for mechanical fault diagnosis because several machinery defects, such as cage failure, are indicated in small frequencies.

2. EMPIRICAL MODE DECOMPOSITION (EMD)

To analyze a multi component signal, it is essential to decompose the signal into mono component functions. Huang et al. [4] proposed the EMD method to extrac mono component functions from nonlinear and non-stationary signals, which are known as intrinsic mode functions (IMFs).

The basic concept of the EMD is to decompose the original signal into a collection of the IMF components that satisfy the following two conditions:

(a) Over a data set, the number of exterma and the number of zero-crossing must either be equal or differ not more than by one.

(b) At any point, mean value of the envelopes defined by local maxima and local minima is zero.

To generate the IMFs from original signal, the procdure of the EMD algorithm is described as follow:

1- Estimation of all local exterma of the original signal $s(t)$ that is shown in Figure 1a and then connect all local maxima by cubic spline as the maximum envelope ($e_{\max}$) and repeat the technique for the local minima to produce the minimum envelope ($e_{\min}$) as depicted in Figure 1b.

2- Computation of the local mean function $\mathrm{m}_1(t)$ as:

$$\mathrm{m}_1(t) = \frac{e_{\max} + e_{\min}}{2} \tag{1}$$

This is shown in Figure 1c.

3- The candidate for the first IMF $h_1(t)$ is achieved as:

$$h_1(t) = s(t) - m_1(t) \tag{2}$$

4- If $h_1(t)$ does not satisfy the conditions of the IMFs, set $h_1(t)$ as the original signal and the steps 1 and 2 are repeated until $h_1(t)$ being an IMF.

5- After getting the IMF, remove it from the original signal and obtain residue $r_1(t)$ as follows:

$$r_1(t) = s(t) - h_1(t) \tag{3}$$

This is shown in Figure 1d.

6- Set $r_1(t)$ as the original data and repeat the above process until the n^{th} IMF could be generated and any

IMF could not be extracted from $r_n(t)$. Consequently, Equation (4) can be drawn:

$$s(t) = \sum_{i=1}^{n} h_i(t) + r_n(t) \tag{4}$$

According to Equation (4), the signal is decomposed into n-IMF components and a residue with the aid of a process that use Equations (1-3) and checking the IMF conditions.

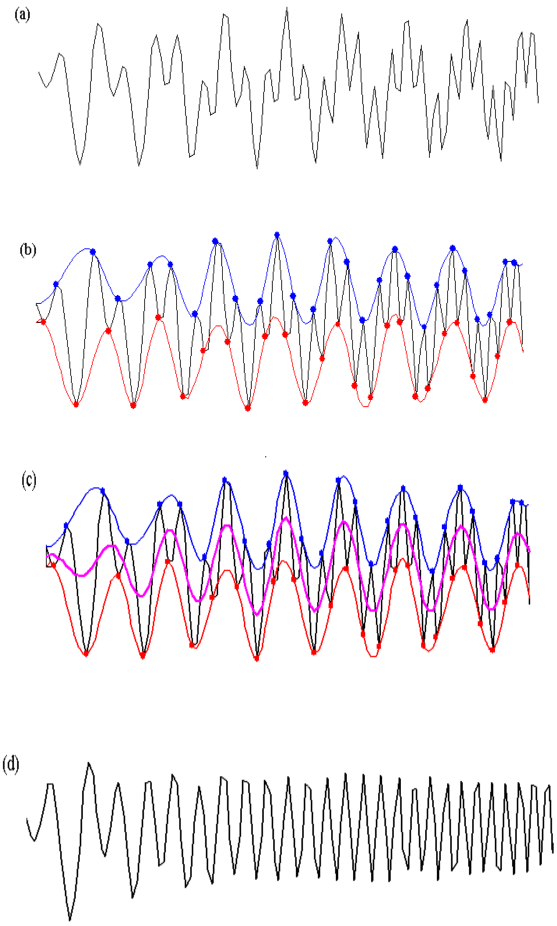


Figure 1. Schematic representation of EMD procedure: (a) Original signal, (b) Maximum and minimum envelopes, (c) Local mean function, (d) Residual signal.

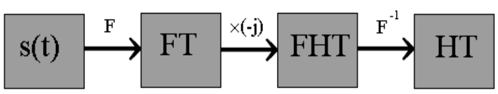


Figure 2. Procedure of obtaining Hilbert transform with the aid of Fourier and inverse Fourier transforms.

3. HILBERT SPECTRAL ANALYSIS (HSA)

Equation (5) is an integral transform that defines the Hilbert transform of a signal s(t) [7].

$$\tilde{s}(t) = s(t) * \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{s(\tau)}{t-\tau} d\tau \tag{5}$$

Using the property of Fourier transform of convolution multiplied, Fourier-Hilbert transform (FHT) is obtained as:

$$F(\tilde{s}(t)) = F(s(t) * \frac{1}{\pi t}) = F(s(t)).\, F(\frac{1}{\pi t}) \tag{6}$$

Fourier transform of signal $\frac{1}{\pi t}$ is:

$$F(\frac{1}{\pi t}) = -j\,\mathrm{sgn}(f) \tag{7}$$

For positive frequencies, Equation (7) is simplified as:

$$F(\frac{1}{\pi t}) = -j \tag{8}$$

Substituting Equation (8) into Equation (6) leads to:

$$F(\tilde{s}(t)) = -jF(s(t)) \tag{9}$$

If the inverse Fourier transform is applied on the Equation (9), Hilbert transform of the signal is obtained. Figure 2 shows how to calculate Hilbert transform of a signal with the aid of Fourier transform and inverse Fourier transform.

The analytic signal corresponding to real signal $s(t)$ is defined as:

$$z(t) = s(t) + j\tilde{S}(t) = A(t)e^{j\varphi(t)} \tag{10}$$

where

$$\mathrm{A(t)}=\sqrt{\mathrm{s}^2(\mathrm{t})+\tilde{\mathrm{s}}^2(\mathrm{t})} \quad \text{and} \quad \phi(t) = \tan^{-1}\left(\frac{\tilde{s}(t)}{s(t)}\right) \tag{11}$$

In Equation (11), $A(t)$ and $\varphi(t)$ are instantaneous amplitude and phase function, respectively. Differentiation of phase function with respect to the time variable leads to obtain of instantaneous frequency $f(t)$ and can be expressed as Equation (12).

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \tag{12}$$

Studying a signal in the form of Equation (10) makes it possible to consider the effect of instantaneous amplitudes and instantaneous frequencies on the Hilbert spectrum.

4. LIMITATIONS OF HILBERT SPECTRAL ANALYSIS

It is possible to rewrite Equation (10) in a new form by:

$$z(t) = A(t)\cos\varphi(t) + jA(t)\sin\varphi(t) \tag{13}$$

Comparing Equations (10) and (13) leads to:

$$s(t) = A(t)\cos\varphi(t) \text{ and } \tilde{s}(t) = A(t)\sin\varphi(t) \quad (14)$$

From Equation (14), it is anticipated that the Hilbert transform does not change the amplitudes but it is essential to a phase change of $\frac{\pi}{2}$. On the other hand, Hilbert transform can be written as:

$$H[A(t)\cos\phi(t)] = A(t)H[\cos\phi(t)] = A(t)\sin\phi(t) \quad (15)$$

Obviously, the HT has no effect on amplitudes and $H[\cos\varphi(t)] = \sin\varphi(t)$. That is, we expect $\frac{\pi}{2}$ change in the phase function exactly. But, the Bedrosian and Nuttall theorems warn that the last statement is not valid indisputably. According to Bedrosian theorem, Equation (15) is immutable only if the Fourier spectrums of $\cos\varphi(t)$ and $A(t)$ are completely separate from each other in the frequency domain and the frequency range of the spectrum of $\cos\varphi(t)$ is higher than that of $A(t)$.

If Bedrosian theorem was not to be satisfied, the amplitude variation would mix with the phase function. In this manner, Equation (15) would not be true and the reliability of Hilbert spectrum would decrease severely.

According to Nuttall theorem, the relation $H[\cos\varphi(t)] = \sin\varphi(t)$ is immutable only if $A(t)$ and $\varphi(t)$ are essentially narrow band functions. Otherwise, there is a discrepancy between the Hilbert transform $\tilde{s}(t)$ and quadrature function $Q_c(t)$ (that shift the phase stringently $\frac{\pi}{2}$). Therefore, the error bound is defined as:

$$\Delta E = \int_{t=0}^{T} |Q_c(t) - \tilde{s}(t)| dt = \int_{-\infty}^{0} s_q(f) df \quad (16)$$

where $s_q(f)$ in Equation (16) is Fourier spectrum of $Q_c(t)$. Thus, Nuttall theorem would be satisfied only and only if $\Delta E = 0$.

To circumvent the limitation of the HSA, Huang et al. [5] proposed a method which is called normalized Hilbert transform that solves the problem of Bedrosian theorem and a variable error bound based on this method tries to solve the problem of Nuttall theorem, but the difficulty in finding an exact quadrature $Q_c(t)$ is unresolved [6].

5. PROPOSED EMD-FFT METHOD

For mechanical fault diagnosis, if Bedrosian and Nuttall theorems are not satisfied, it is recommended to use the FFT on each of the IMFs that are generated from the EMD process. According to Figure 2, Hilbert transform can be achieved in three steps; where the first step is used to calculate the Fourier transform of the signal. But if the mentioned theorems are not satisfied, performing the other two steps causes the incorporation of amplitude and phase functions and because of this fact, the other two steps are left out. In other words, in this method, empirical mode decomposition is joined to the prevalent FFT method.

Rai and Mohanthy [8] conducted some tests on bearings with inner and outer race faults and demonstrated that such analysis has a good performance in detecting bearing faults under nonlinear and non-stationary vibrations.

Although the EMD-FFT method may lead to a large covariance for the first IMFs, it is very useful for mechanical fault detection because we are often looking for specific frequencies (CDFs) and it is important to select a simple method that acts quickly and accurately for mechanical system analysis.

6. CHARACTRISTIC DEFECT FREQUENCIES

One of the most prevalent methods for mechanical system monitoring is the identification of defect frequencies from machine spectrums. The shaft rotation frequency f_s and the ball bearing components frequencies are the most important frequencies which are observed in a faulty machine spectrums. Usually, these cited frequencies are known as characteristic defect frequencies (CDFs). The CDFs are determined by Equations (17-20).

$$f_{ir} = f_s \frac{N_b}{2}(1 + \frac{B_d}{p_d}\cos\alpha) \quad (17)$$

$$f_{or} = f_s \frac{N_b}{2}(1 - \frac{B_d}{p_d}\cos\alpha) \quad (18)$$

$$f_{bs} = f_s \frac{p_d}{2B_d}(1 - \frac{B_d^2}{p_d^2}\cos^2\alpha) \quad (19)$$

$$f_c = \frac{f_s}{2}(1 - \frac{B_d}{p_d}\cos\alpha) \quad (20)$$

Obtained frequencies are very important to identify the ball bearing faults but some other structural defects appear in multiples of shaft frequency. For example, some shaft defects, such as bending and misalignment, are often observed in integer multiples of shaft frequency. Also, non-integer multiples of shaft frequency often indicate inaccurate mechanical clearance between bearing outer race and housing or between bearing inner race and shaft which occur due to incorrect interference. Nevertheless, both integer and non integer multiples of shaft frequency are dominant components in some faulty cases such as pedestal looseness in rotor system [9].

7. RESULTS AND DISCUSSIONS

As displayed in Figure 3, the experimental set up consists of an electromotor which is coupled with an auxiliary water pump in the cooling system of Kerman combined power plant. The electromotor is damaged with high vibrations due to bearing failures and inaccurate mechanical clearance. The shaft is supported on the SKF 6319 series ball bearings and rotates at the speed of 50Hz (f_s). In the following analysis, a piezoelectric sensor with maximum response frequency of 300 kHz was coupled with the system near the shaft and the signals were recorded by a data acquisition system for an interval of 2 seconds in two perpendicular directions. The values of CDFs are given in Table 1. Also, Figure 4 shows the ball bearing vibrations in these two directions.

In order to investigate electro motor failures, both the FFT and HHT techniques are adopted to analyze the signals; where the results are shown in Figures 5 and 6, respectively. As Figure 5 shows, the FFT spectrums were able to capture the shaft frequency (50Hz) and its non-integer multiples (25Hz, 125Hz) that are above the allowable values. Consequently, inaccurate mechanical clearance is detected but not any vestige of the ball bearing failures is detected.

As depicted in Figure 6, it is clearly seen that the phase and amplitude functions are mixed together because the Bedrosian and Nuttall theorems are not satisfied and consequently, none of the CDFs are indicated in the Hilbert spectrums.

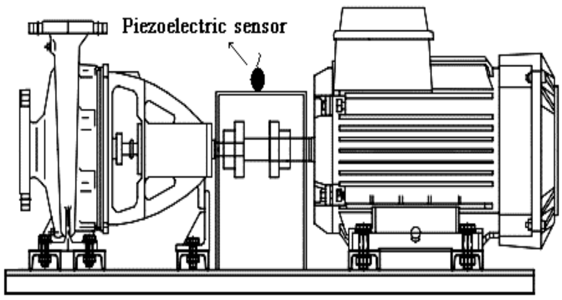


Figure 3. Schematic representation of the experimental set up.

TABLE 1. Characteristic defect frequencies.

f_{ir}	245.10 Hz
f_{or}	154.80 Hz
f_{bs}	105.00 Hz
f_c	19.35 Hz

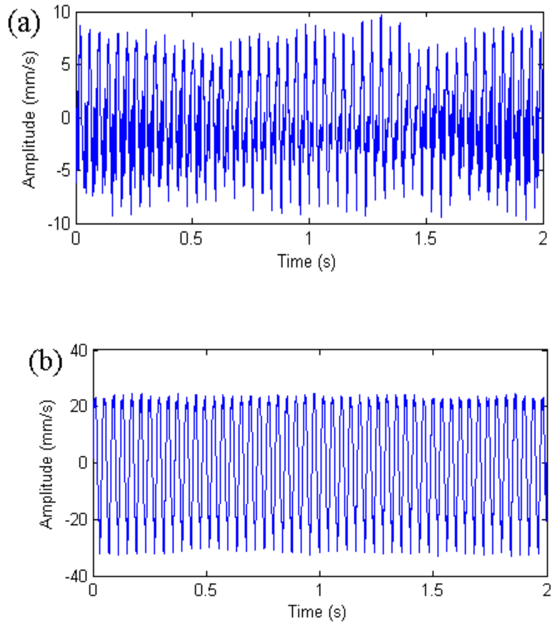


Figure 4. Ball bearings vibrations in two perpendicular directions. (a) Vertical (b) Horizontal.

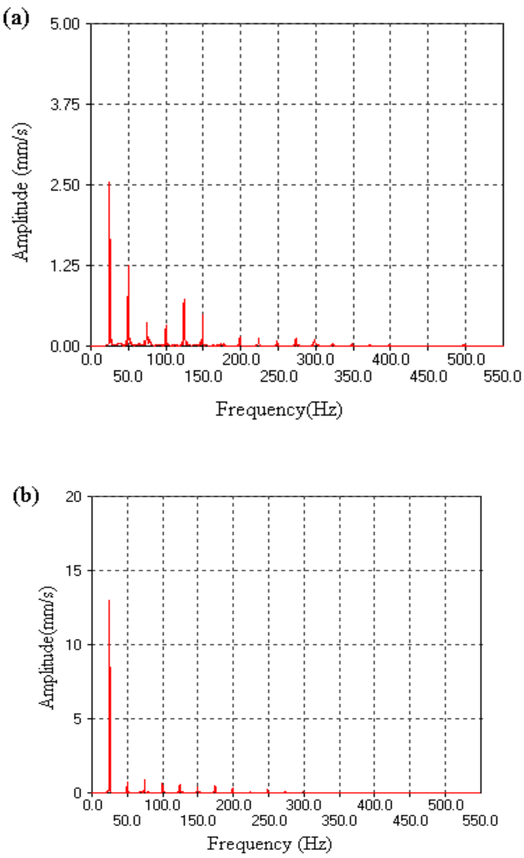


Figure 5. FFT analysis of electro motor signals. (a) Vertical spectrum (b) Horizontal spectrum.

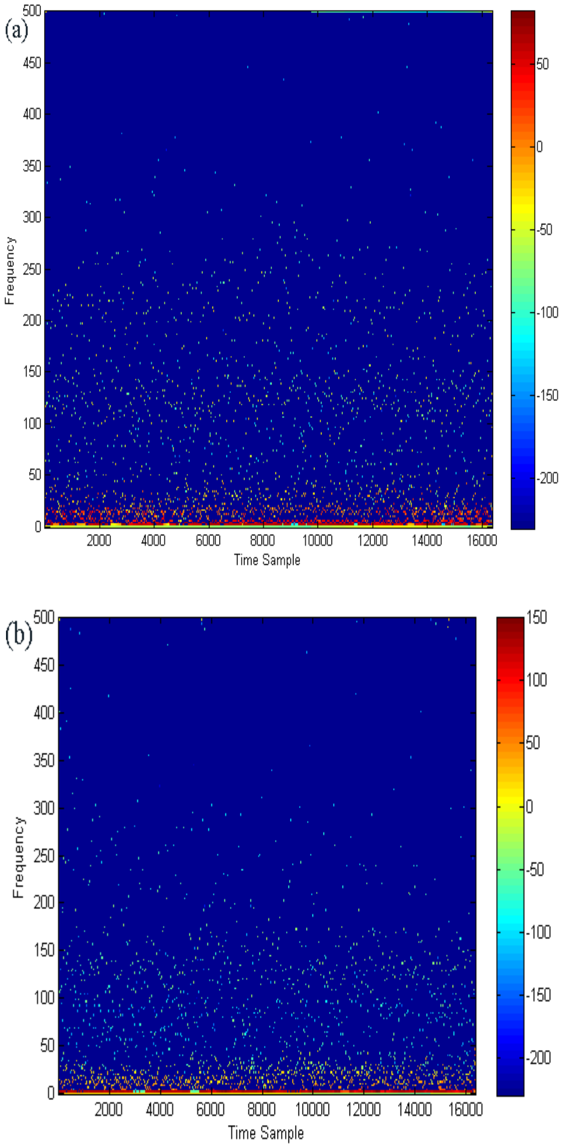
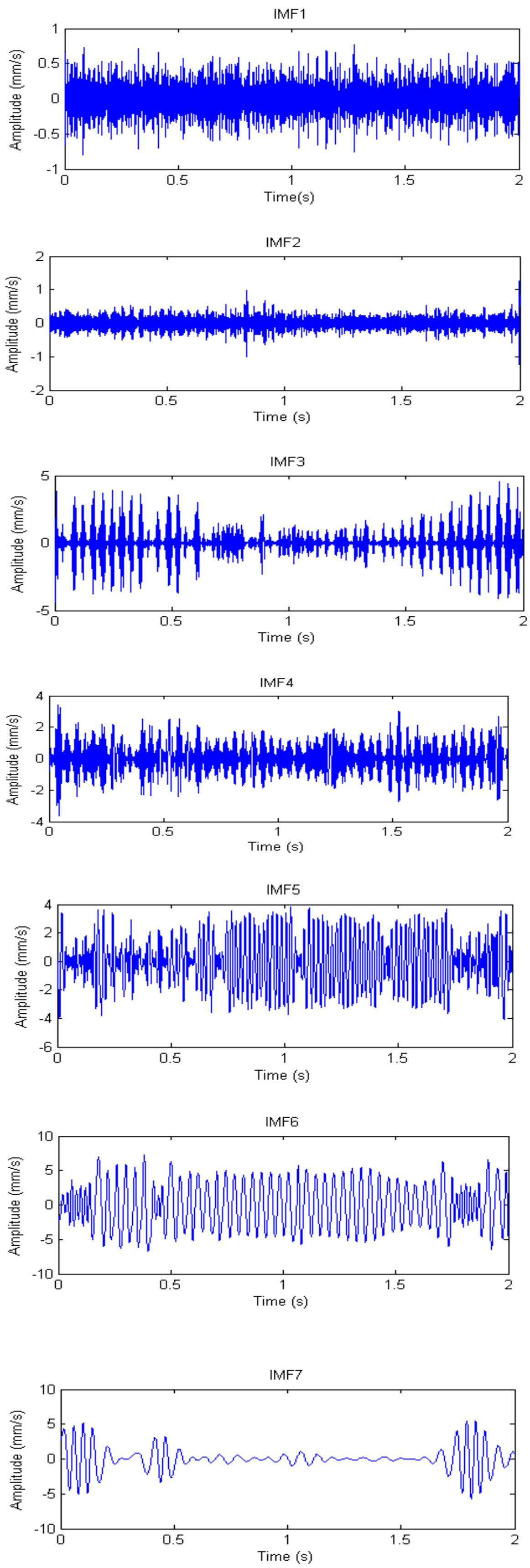


Figure 6. HHT analysis of electromotor signals (a) Vertical signal (b) Horizontal signal

Figures 7 and 8 show the IMFs that are extracted from vertical and horizontal signals, respectively. Also, Figures 9 and 10 represent the result of EMD- FFT analysis for the first three IMFs of vertical and horizontal signals, respectively. According to the results, not only inaccurate mechanical clearance presages have been indicated but also symptoms of ball bearing are shown clearly. As depicted in Figures 9a and 9c, the defects of inner race and cage are inevitable. Similarly, these defects are detected in Figures 10a and 10c. On the other hand, the presence of non-integer multiples of shaft frequency ($0.5f_s$ and $2.5f_s$) in the spectrums of Figures 9 and 10 demonstrate that the inaccurate mechanical clearance occur indisputably.



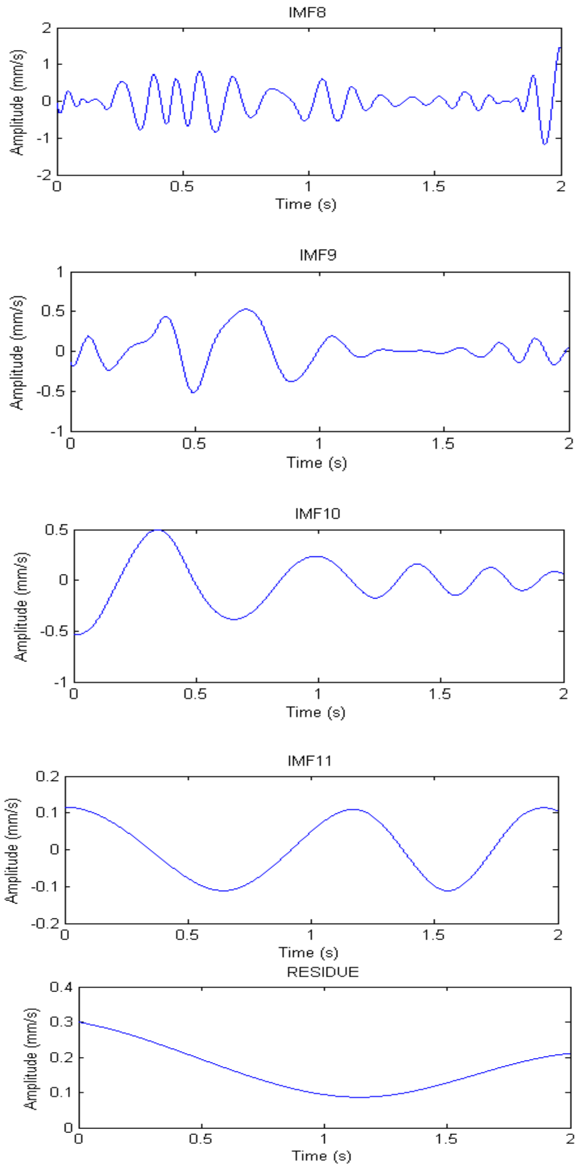
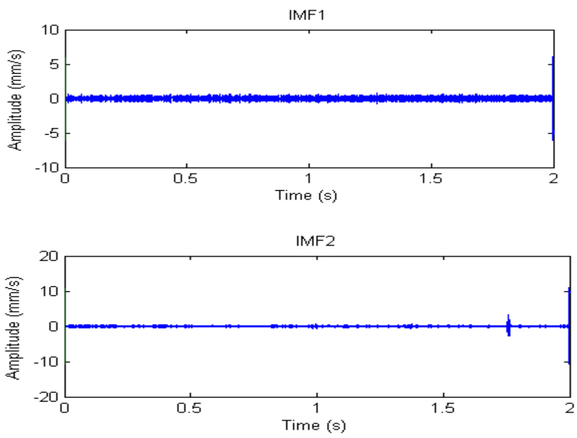
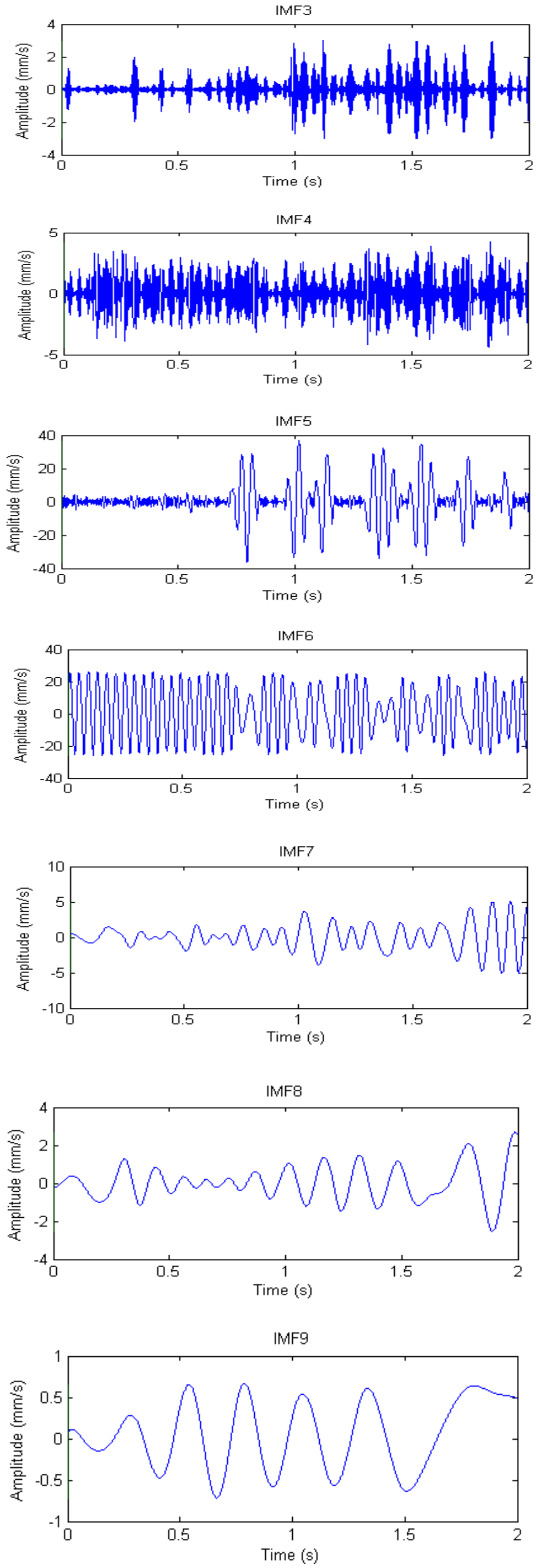


Figure 7. Empirical mode decomposition for vertical signal of electromotor.





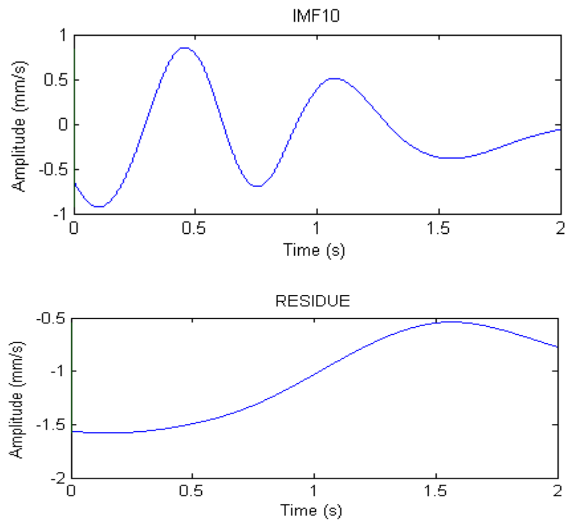
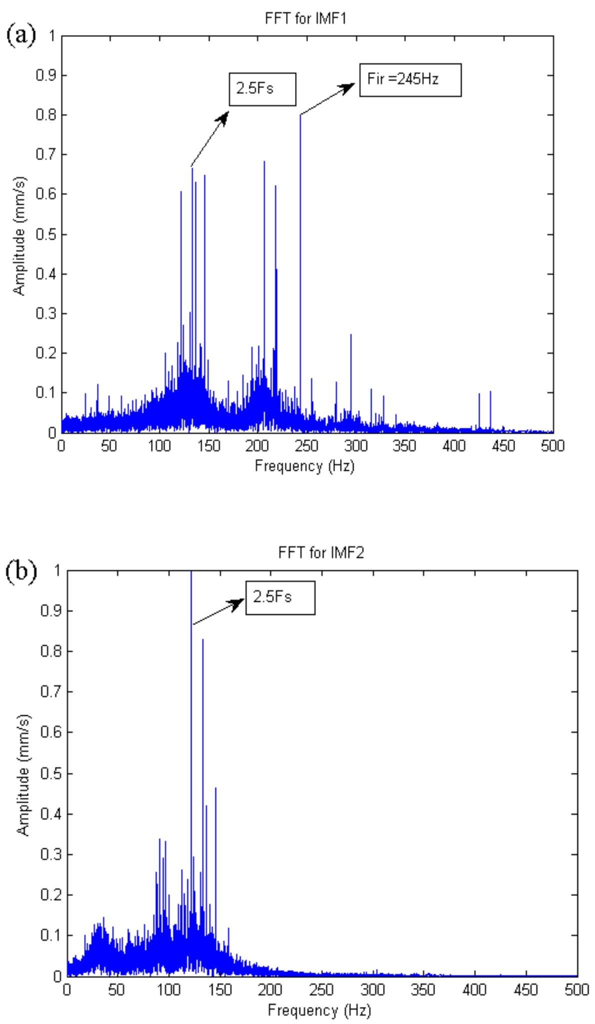


Figure 8. Empirical mode decomposition for horizontal signal of electromotor



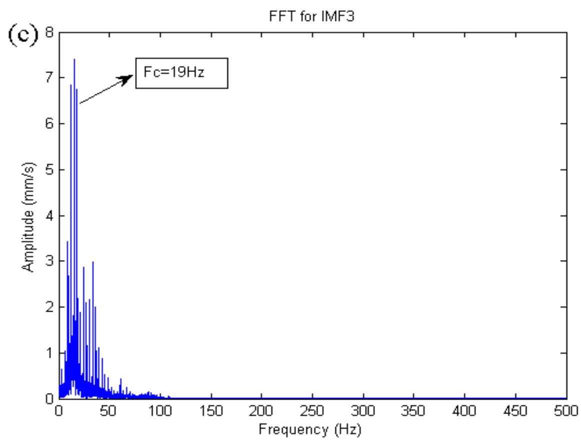
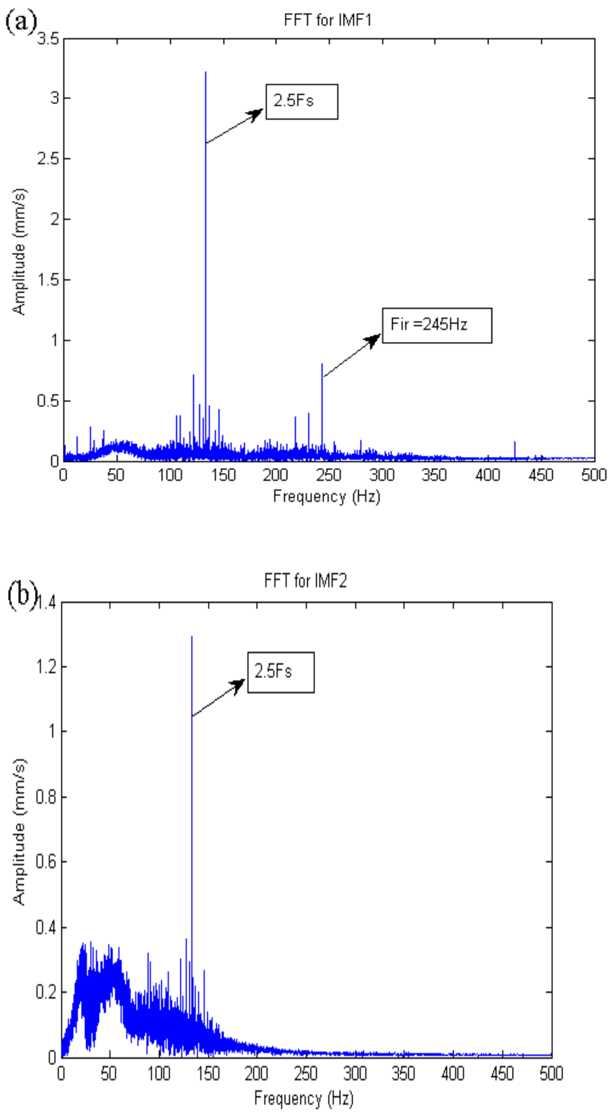


Figure 9. EMD-FFT analysis results for the first three IMFs from vertical signal.



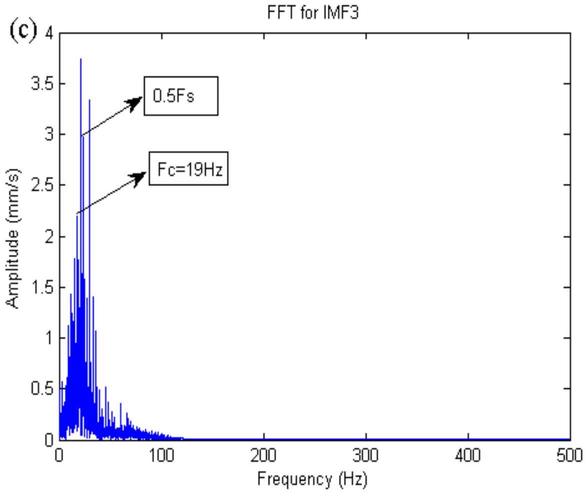


Figure 10. EMD-FFT analysis results for the first three IMFs from horizontal signal.

8. CONCLUDING REMARKS

In order to detect the mechanical defects, a technique based on empirical mode decomposition (EMD) and fast Foureir transform (FFT) was proposed. The notable trait of this method is its ability to analyze the nonlinear and non-stationary vibration. Although the HHT is a powerful method to analyze cited signals, if Bedrosian and Nuttall theorems are not satisfied, the results of analysis will be invalid.

More precisely, in this study, three methods of FFT, HHT and EMD-FFT were used to analyze the vibrations of a defective electro motor. The FFT could not diagnose all the defects successfully because this method is unable to analyze nonlinear and non-stationary signals. Also, the HHT was not successful because without noticing the Bedrosian and Nuttall theorems, the phase and amplitude functions were mixing together. Eventually, the EMD-FFT method was capable to identify all the defects of the electro motor fast and accurately without any specific necessities.

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[a] *Mechanical Engineering Department of Shahid Bahonar University of Kerman, Kerman-Iran*
[b] *Mechanical Engineering Department of Shahid Bahonar University of Kerman, Kerman-Iran*

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چکیده

تبدیل هیلبرت هوانگ (HHT) روشی قدرتمند برای آنالیز ارتعاشات غیرخطی و نامانا می باشد. این روش شامل دو قسمت اصلی تجزیه ی تجربی مودی (EMD) و آنالیز طیفی هیلبرت (HSA) می باشد. برای دستیابی به نتایج صحیح باید قضایای بدروسین و نوتال ارضا شوند؛ در غیر این صورت توابع فاز و دامنه با یکدیگر مخلوط می شوند و در نتیجه از میزان اعتماد به فرکانس های حاصله کاسته می شود. برای جلوگیری از چنین رخدادی روش های گوناگونی تحت عنوان تبدیل های ارتقا یافته ی هیلبرت هوانگ معرفی شده اند اما در این مقاله روش دیگری معرفی می شود که در عین سادگی توانایی بالایی در شناسایی عیوب مکانیکی دارد. در این روش ابتدا سیگنال به مود های ذاتی (IMFs) تجزیه می شود و سپس هر IMF با استفاده از تبدیل فوریه سریع (FFT) آنالیز می شود. با استفاده از این روش که EMD-FFT نامیده می شود، عیوب مکانیکی یک الکتروموتور در نیروگاه سیکل ترکیبی کرمان شناسایی شده است. علاوه بر این نشان داده می شود که روش کلاسیک FFT به علت خاصیت های غیر خطی و نامانای سیگنال ها، در تشخصی تمامی عیوب ناتوان است و همچنین استفاده از روش HHT بدون توجه به ارضای قضایای مذکور، به علت ترکیب توابع فاز و دامنه، منجر به نتایج نامعتبر می شود.

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