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A comparative simulation study between continuous wavelet transform and Hilbert Hung transform for bearing fault detection

Walid Touti, Samira Ben Salem, Khmais Bacha, Abdelkader Chaari
Unit of research: control, monitoring and reliability of the systems
Higher school of sciences and technology of Tunis
Tunis, Tunisia
walid8421@live.fr , Samira-bensalem@voila.fr , khmais-bacha@voila.fr , nabile.chaari@yahoo.fr

Abstract— **In this paper, vibration signal of an outer race fault is simulated, since in practice, vibration signal collected from rotating machine is noisy, continuous wavelet transform (CWT) and Hilbert Hung Transform (HHT) was used to extract fault key from the simulated signal in subject to detect the considered fault. The presented signal processing techniques was compared in term of computing time and fault sensitivity improvement.**

Keywords—Intrinsic mode function, Envelope spectrum, Vibration signal, Empirical mode decomposition, Hilbert Hung transform, Wavelet transform, Bearing defect

I. INTRODUCTION

Bearing damage is one of the most failures in induction machines; this fault can represent a serious problem when industrial process was trained by induction machines. For this reason, bearing fault detection presents an important stage. Vibration analysis is an efficient technique to extract fault characteristic frequency from rotating machines. Vibration analysis in one of the efficient techniques applied in bearing healthy monitoring, [1][2][3] used wavelet denoising for vibration signal in order to extract fault key by applying FFT transform, continuous wavelet transform was combined with Hilbert transform by [4] to obtain a new signal processing technique called multi-scale enveloping spectrogram. Empirical mode decomposition performed to vibration signal by [5][6], EMD is combined with Hilbert transform to obtain Hilbert Hung transform. [7] was studied the effect of Morlet wavelet central frequency and band pass frequency for damaged bearing vibration signal analysis.

II. VIBRATION SIGNAL CAUSED BY OUTER RACE FAULT

Vibration acquired from machines with localized outer race fault is presented in References [8][9] :

$$v(t) = \sum_{k=0}^{L} A_k h(t - kT_v - \tau_i) + w(t) \tag{1}$$

$$h(t) = e^{-\sigma t} \sin(2\pi f_1 t) \tag{2}$$

Where Tv is the period of the impulse signal generated by single impact between rolling element and defective outer race, A_k the amplitude of the impulse, τ_i the initial phase of the impulse. $\omega(t)$ present the noise excited by machine structure, σ the exponential decay frequency and f_1 the carrier frequency. f_{be} is the outer race characteristic frequency, defined by [2][8][9] :

$$f_{be} = \frac{1}{T_v} \tag{3}$$

In reference [10], f_{be} is 86 Hz. Simulated outer race vibration signal parameters are shown in Table I.

TABLE I. Simulated outer race vibration signal parameters

Signal parameters	**Parameters values**
$T_{v\,(s)}$	0.0115
$A_k\,(m/s^2)$	1
τ_i	0
σ	1500
$f_1\,(Hz)$	2000

The simulated signal without noise is presented in figure 1.a and the associated envelope spectrum in figure 1-b can detect the defect frequency while the envelope spectrum presented in figure 2-b which is associated to the noisy signal with signal to noise ratio equal to -1*dB* in figure 2-a don't represent a peak associated to f_{be}. To overcome this limitation of conventional envelope spectrum, EMD and CWT will be performed to the noisy signal to extract outer race and inner race fault characteristic frequencies.

III. BEARING FAULT DETECTION

In this section, we present a theoretical background of CWT and HHT techniques. Two noisy signals will be analyzed by these techniques in way to compare the computing time and the fault sensitivity.

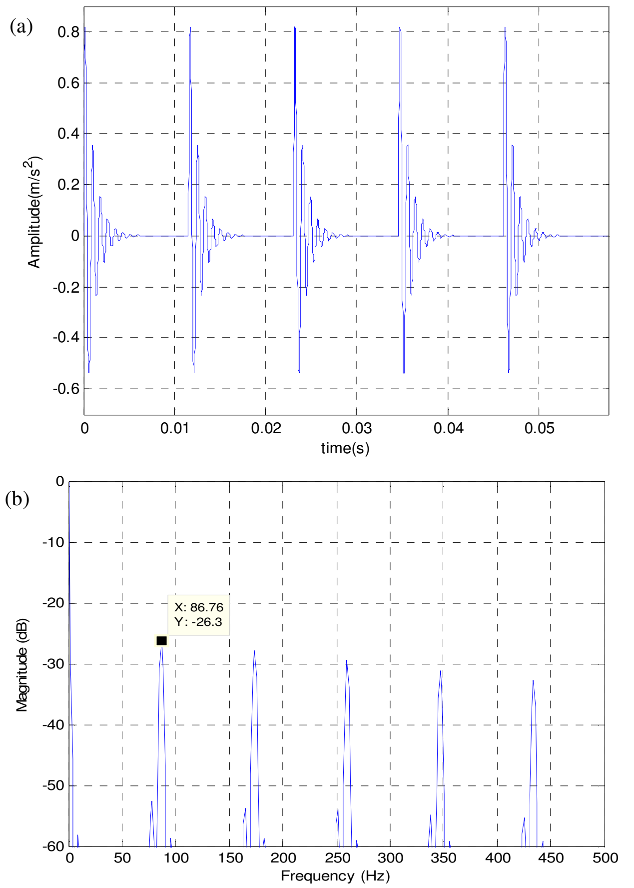

Fig. 1. Simulated outer race fault without noise, (a) vibration signal, (b) Envelope spectrum

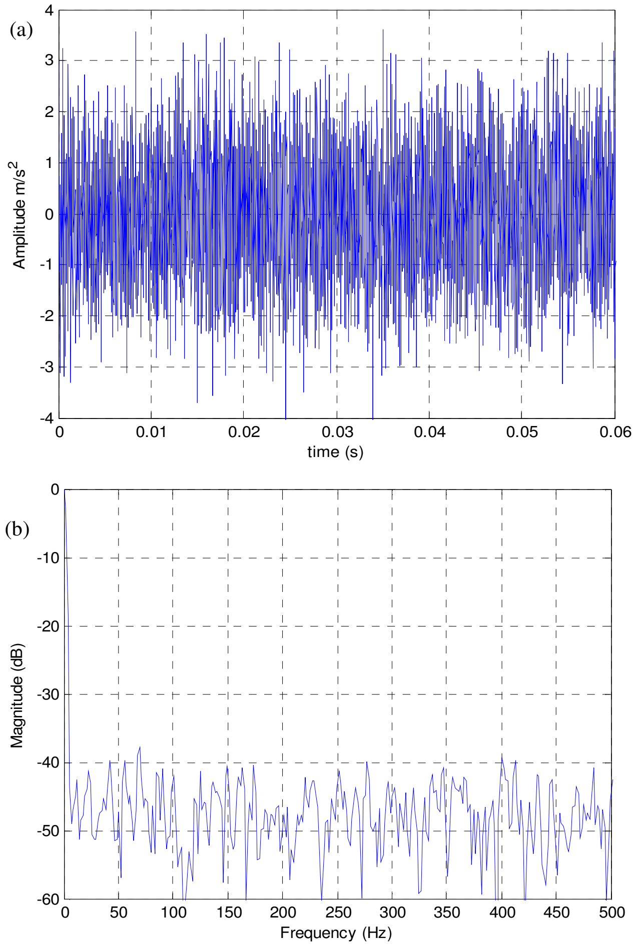

Fig. 2. Simulated outer race fault with signal to noise ratio SNR=-1dB, (a) vibration signal, (b) Envelope spectrum

A. *Continuous wavelet transform approach*

Wavelet transform is an advanced signal processing technique which resolves some limitation of Fourier transform in order to analyze the signal in time-frequency domain since typical peak in vibration signal was disturbed in time domain. CWT use a family of dilated and translated window functions [4][11]. The transformation is given by:

$$wt(\tau,s)=\frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty}x(t)\psi^{*}(\frac{t-\tau}{s})dt \qquad (4)$$

$$\psi_{\tau,s}(t)=\frac{1}{\sqrt{s}}\psi(\frac{t-\tau}{s}) \qquad (5)$$

Where *x(t)* is the noisy vibration signal, $\psi_{\tau,s}$ is the translated mother wavelet by the time parameter τ and scaled by the scale parameter s. In Ref [4], Complex Gaussian wavelet is selected as the best mother wavelet for bearing fault characteristic frequency extraction.[7][11]uses complex Morlet wavelet as the mother wavelet for vibration signal analysis, the analytic formulation of complex gaussian wavelet is mentioned by:

$$\psi_G(t)=c_p\left(e^{-jt}e^{-t^2}\right) \qquad (6)$$

Where *Cp* is such that the second norm of the *Pth* derivative of ψ is equal to 1. Figure 3 illustrate the waveform the complex gaussian wavelet with $p=8$.

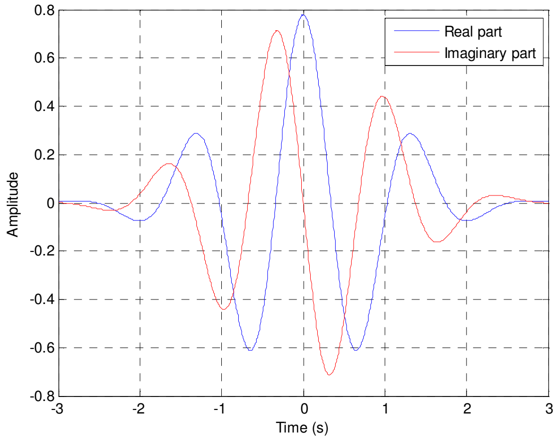

Fig. 3. Complex Gaussian wavelet

We consider a bearing with $N_b=9$ balls, and working with rotating frequency equal to *24.1 Hz* [10]. Outer race fault and inner race fault was presented by [12] in two equations in Table II.

TABLE II. Outer race and inner race fault characteristics frequencies

Outer race fault	Inner race fault
$f_o=0.4. f_r.. N_b=86.76Hz$	$f_i=0.6. f_r.. N_b=130.14Hz$

The simulation is obtained using MATLAB version 7.14 in a personal computer with 2.13 GHz dual core CPU and 2 GB memory and synthetic signal with 50000 samples. As it is concluded in Ref [4], complex Gaussian wavelet is the efficient mother wavelet for bearing fault frequency extraction, this result is affirmed by the present work, where the time scale representation of the CWT envelope of vibration signals witch simulate an outer race fault and inner race fault is presented in fig. 4-a and Fig. 5-a respectively. The typical impulse generated by the simulated outer race fault was clearly detected at the scale 31, and at scale 45 for the inner race fault. The associated spectrogram of the wavelet decomposition for the outer race and inner race fault are presented in fig. 4-b and fig. 5-b respectively.

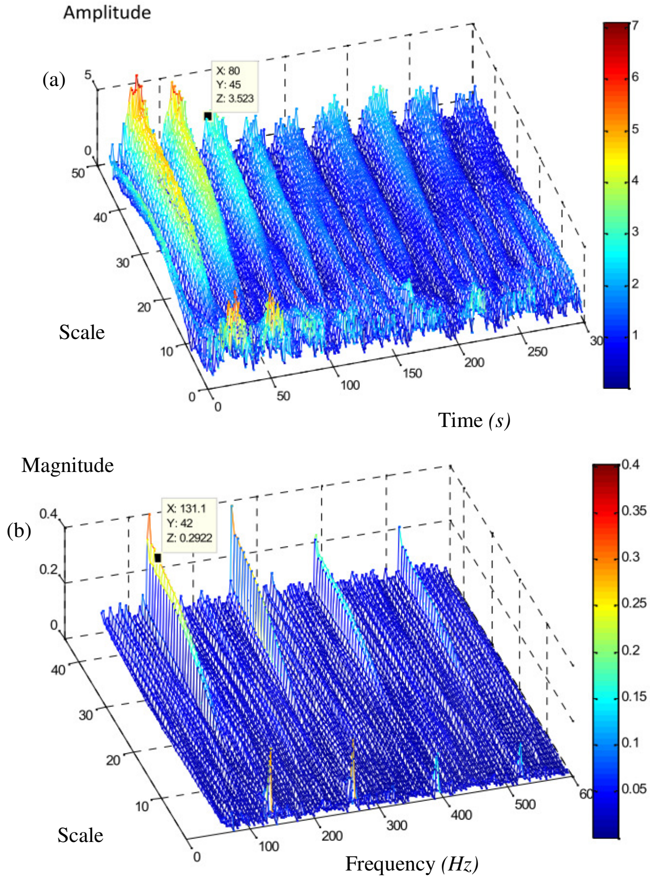

Fig. 5. Inner race fault detection by CWT, (a) *Complex Gaussian Wavelet coefficients envelopes, (b) spectrogram of wavelet coefficient envelopes*

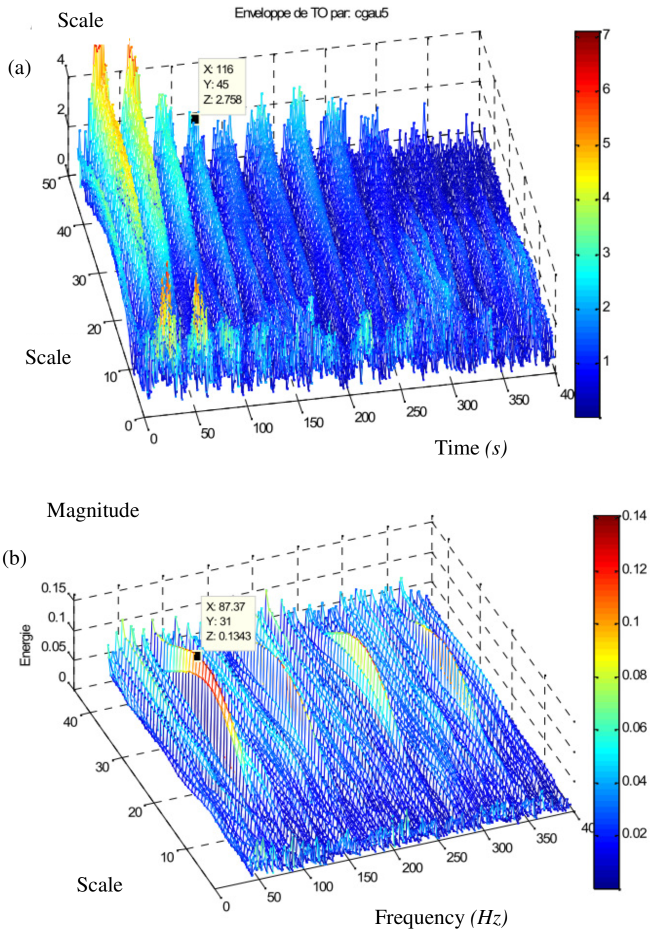

Fig. 4. Outer race fault detection by CWT, (a) *Complex Gaussian Wavelet coefficients envelopes, (b) spectrogram of wavelet coefficient envelopes*

wavelet coefficient at the scale 45 for the envelope spectrum of wavelet coefficient of inner race fault and outer race fault respectively. It can be concluded that CWT is an efficient tools to vibration signal denoising for bearing fault detection in reference to spectrum sensitivity to the studied faults. Table III shows the fault sensitivity improvement using CWT techniques.

TABLE III. Wavelet envelope spectrum versus conventional spectrum for bearing faults sensitivity

Fault case	**Table Column Head**		
	Conventional spectrum magnitude (dB)	***Wavelet coefficient envelope spectrum (dB)***	***Wavelet approach fault sensitivity improvement (dB)***
Outer race	-39	-23.95	15.05
Inner race	-39	-14.48	24.52

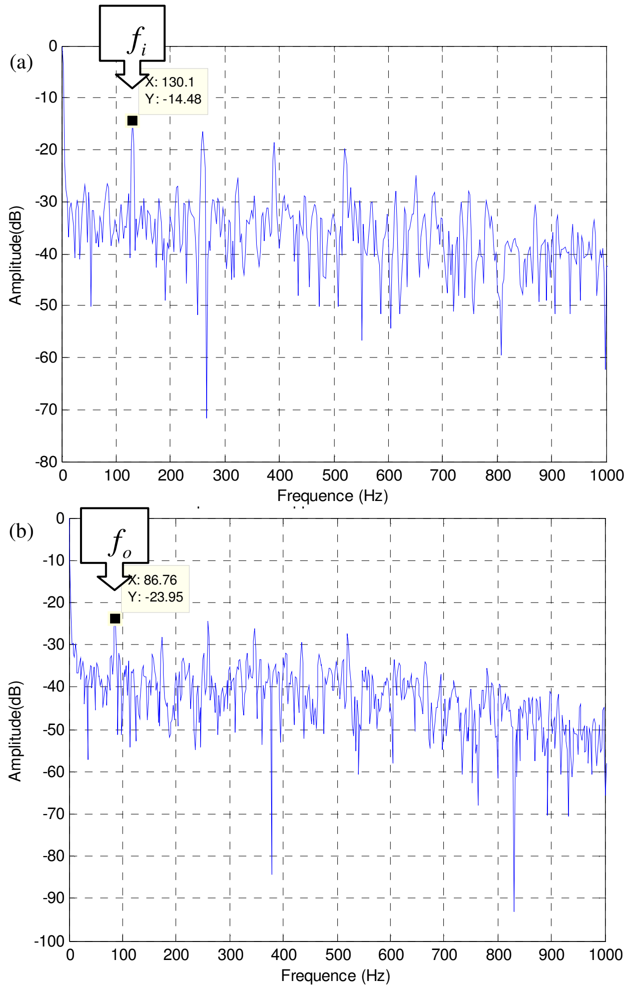

Fig. 6. *Wavelet coefficients envelope spectrum of at the scale 45, (a) inner race fault case, (b) outer race fault case*

B. *Hilbert Hung transform approach*

Empirical mode decomposition (EMD) is an efficient tool to decompose amplitude modulated and frequency modulated signals into finite number of simple oscillator components named intrinsic mode functions (IMF). The theoretical background of this technique is mentioned in [5][14], the envelope analysis of intrinsic mode functions in called Hilbert Hung transform (HHT) [13][14]. In this section, EMD is applied to the same original signals analyzed in III-A. Figure 7 shows the intrinsic mode functions decomposed simulated inner race fault vibration signal and the correspondent envelopes in figure8, it's shown that period T_i=7,7*ms* correspond to the characteristic frequency f_i=130.14*Hz* is detected in time domain and the frequency magnitude of the envelope spectrum of the fifth IMF is clearly detected in figure 11-b.

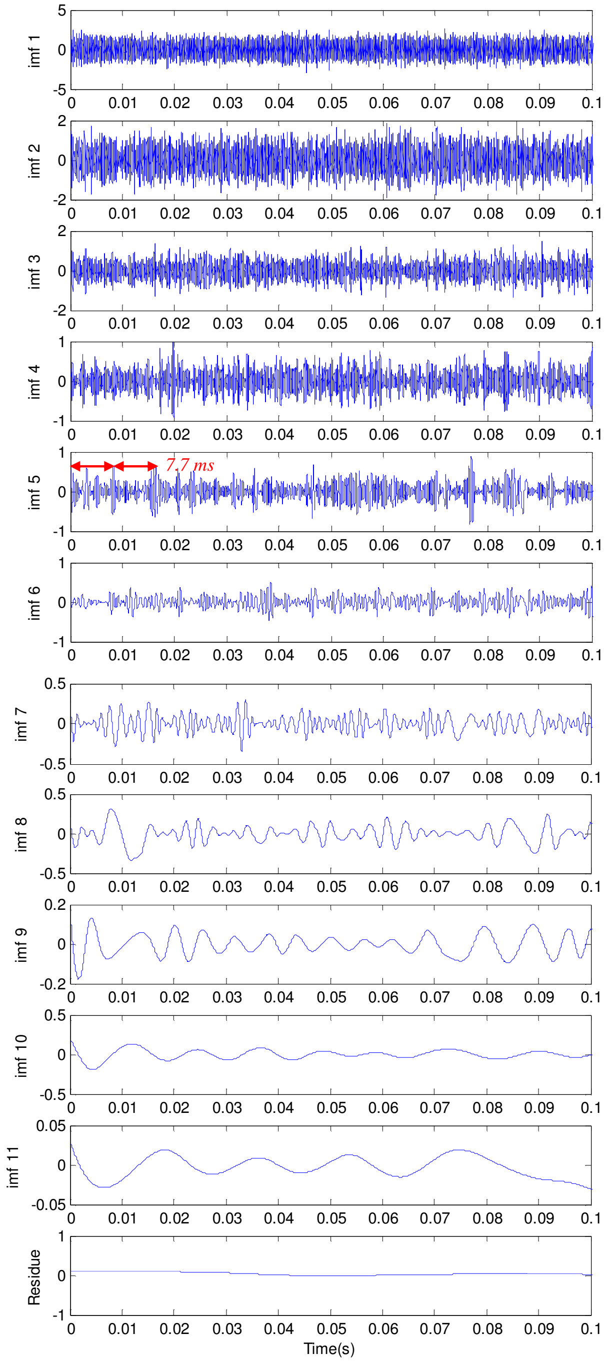

Fig. 7. *The EMD decomposed result of vibration signal of the simulated outer race fault*

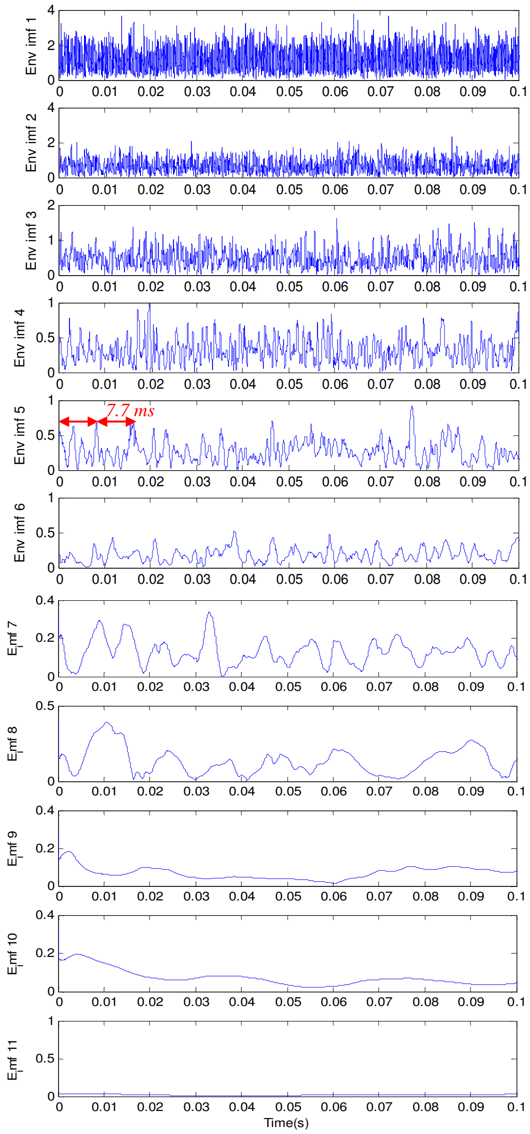

Fig. 8. *Intrinsic mode functions envelopes result of vibration signal of the simulated outer race fault*

In figure 9 we present The EMD decomposed result of vibration signal of the simulated outer race fault with f_o=86,76Hz, T_i=11,5ms is the corresponding period to the characteristic frequency and it's detected in time domain in figure 10 and in the fifth IMF envelope of figure 10. The frequency magnitude of the envelope spectrum of the fifth IMF is clearly detected in figure 11-c.

In Table IV, we present the fault sensitivity using HHT technique for two cases of outer and inner race fault. It can be seen from Table IV that the present technique can identify the characteristic fault frequency with mean sensitivity improvement of *8dB* for the bearing fault vibration signal.

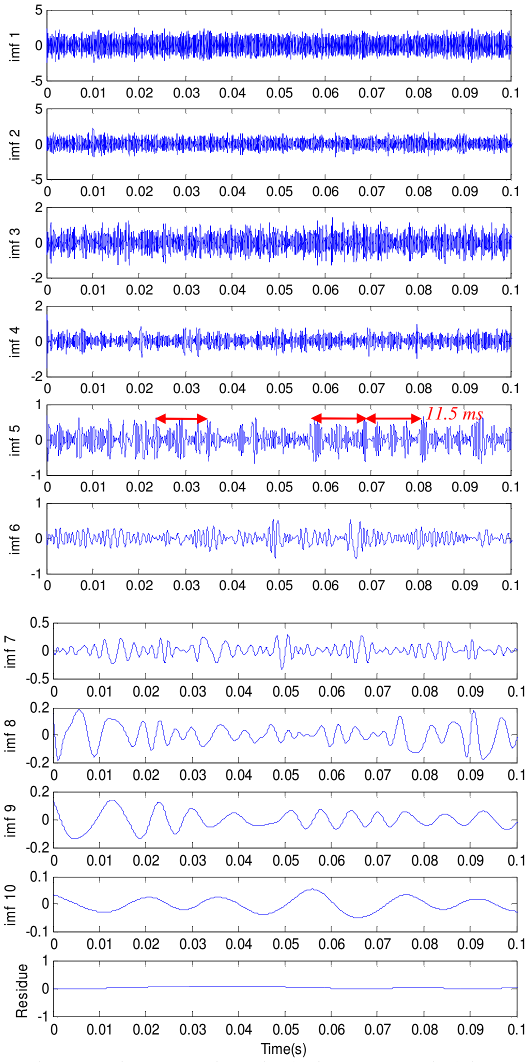

Fig. 9. *The EMD decomposed result of vibration signal of the simulated inner race fault*

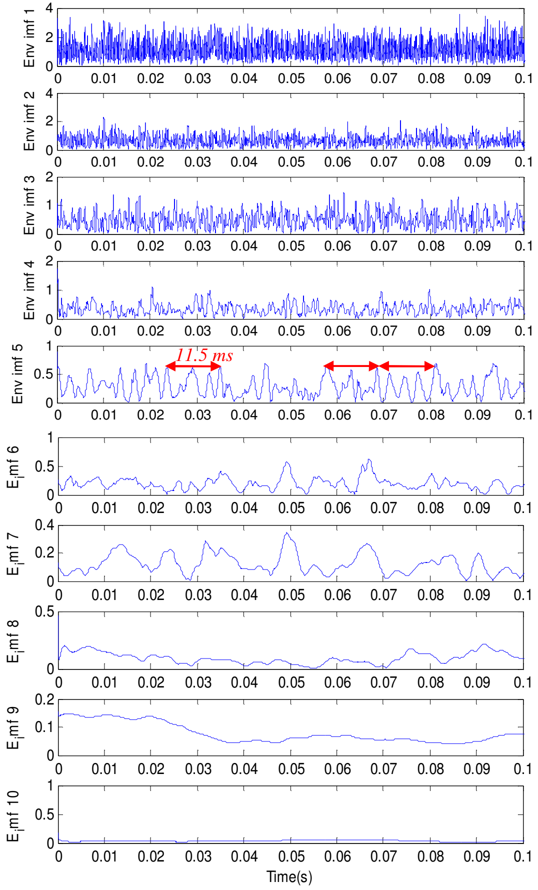

Fig. 10. *Intrinsic mode functions envelopes result of vibration signal of the simulated outer race fault*

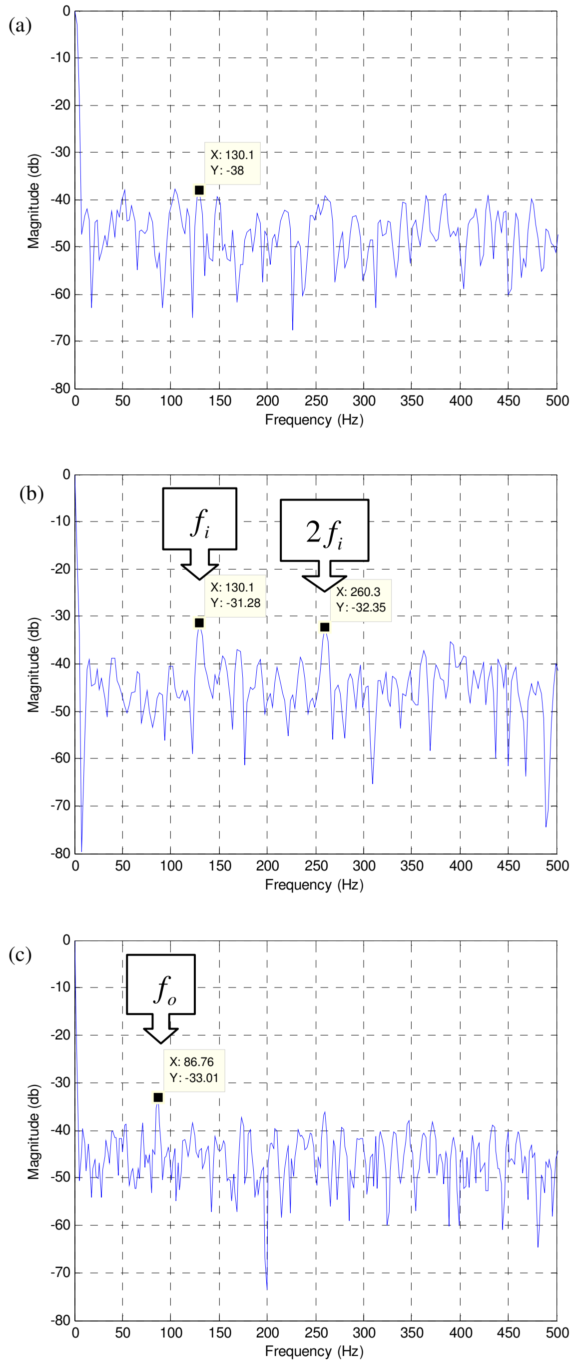

Fig. 11. Simulated bearing faults detection, (a) conventional envelope spectrum, (b) envelope spectrum of the fifth IMF for outer race fault, (c) envelope spectrum of the fifth IMF for outer inner fault

TABLE IV. *HHT technique versus conventional spectrum for bearing faults sensitivity*

	Fault Characteristic Frequency	**Magnitude of conventional Spectrum (dB)**	**Magnitude of the fifth Imf envelope spectrum (dB)**	**HHT sensitivity improvement (dB)**
Outer race	86.76 *Hz*	-40	-33.13	6.87
Inner race	130.14 *Hz*	-42	-33	9

IV. PERFORMANCE ANALYSIS OF CWT VERSUS HHT

Fault characteristic frequency sensitivity improvement and the computing time were illustrated in Table V.

TABLE V. *Comparison of HHT and CWT performance in bearing fault diagnosis*

	Computing time (s)	Disadvantages	mean sensitivity improvement (dB)
C.W.T	40	Choice of : • The analyzing mother wavelet. • Scale vector dimension. • Scale of wavelet coefficient fault key.	20
H.H.T.	70	Choice of fault key Imf level.	8

Both presented methods can detect bearing fault according to vibration signal, CWT have the best sensitivity improvement than HHT method and can be performed in reduced time interval than the second method. But, in other way, CWT techniques present many practical problems. The choice of analyzing mother wavelet and the wavelet coefficient fault key is not evident. [11] Confirms that the analyzing mother wavelet must have the same shape of analyzed signal, and for bearing fault vibration signal, the most appropriated wavelet is Morlet wavelet and complex Gaussian wavelet.

V. CONCLUSION

CWT and HHT was selected the most useful signal processing techniques to extract bearing fault frequencies from noisy and modulated vibration signals. After performing CWT to the simulated two signals presenting outer and inner race fault many times using the selected analyzing mother wavelets mentioned in III-A, Complex Gaussian wavelet is the best appropriate wavelet for outer race and inner race fault detection with fault frequency magnitude sensitivity improvement *20dB*. Hilbert Hung transform is considered as auto adaptative filtering technique, it present less practical problem than CWT, but HHT method have a low sensitivity improvement in fault frequency magnitude. Since wavelet techniques is the more efficient method in this way, bearing fault diagnosis tool can be designed by making experience from a considered mother wavelet database.

REFERENCES

[1] S. Abbasion, A. Rafsanjani, A. Farshidianfar, N. Irani: Rolling element bearings multi-fault classification based on the wavelet denoising and support vector machine, Mechanical Systems and Signal Processing 21 (2007), pp 2933–2945

[2] Robert B. Randall, Jérôme Antoni, “Rolling element bearing diagnostics—A tutorial”, Mechanical Systems and Signal Processing 25 (2011),pp 485–520

[3] Yanxue Wang, Zhengjia He, Yanyang Zi, “Enhancement of signal denoising and multiple fault signatures detecting in rotating machinery machinery using dual-tree complex wavelet transform”, Mechanical Systems and Signal Processing 24 (2010),pp 119–137

[4] Ruqiang Yan, Robert X. Gao, “ Multi-scale enveloping spectrogram for vibration analysis in bearing defect diagnosis”, Tribology international 42 (2009), pp 293-302

[5] Yu Yang , Dejie Yu, Junsheng Cheng, “A fault diagnosis approach for roller bearing based on IMF envelope spectrum and SVM”, Measurement 40 (2007) pp 943–950

[6] Yaguo Lei, Zhengjia He, Yanyang Zi, “Application of the EEMD method to rotor fault diagnosis of rotating machinery”, Mechanical Systems and Signal Processing 23 (2009), pp 1327–1338

[7] Yuh-Tay Sheen, “On the study of applying Morlet wavelet to the Hilbert transform for the envelope detection of bearing vibrations”, Mechanical system and signal processing (2009).

[8] Fidel Ernesto Herna´ndez Montero, Oscar Caveda Medina, “The application of bispectrum on diagnosis of rolling element bearings: A theoretical approach”, Mechanical Systems and Signal Processing 22 (2008), pp 588–596.

[9] Xiaodong Wang, Yanyang Zia, Zhengjia He, “Multiwavelet denoising with improved neighboring coefficients for application on rolling bearing fault diagnosis, Mechanical Systems and Signal Processing 25 (2011), pp 285–304.

[10] Samira Ben Salem, Walid Touti, Khmais Bacha, Abdelkader Chaari, “Induction motor mechanical fault identification using Park’s vector approach”, International Conference on Electrical Engineering and Software Applications (ICEESA), 2013 .

[11] Wensheng Su, Fengtao Wang, Hong Zhu, Zhixin Zhang, Zhenggang Guo, “Rolling element bearing faults diagnosis based on optimal Morlet wavelet filter and autocorrelation enhancement”, Mechanical Systems and Signal Processing 24 (2010), pp 1458–1472.

[12] Jafar Zarei, Javad Poshtan, “An advanced Park’s vectors approach for bearing fault detection”, Tribology International 42 (2009), pp 213–219

[13] R.T. Rato, M.D. Ortigueira, A.G. Batista, “On the HHT its problems and some solutions”, Mechanical Systems and Signal Processing 22 (2008) 1374–1394

[14] S.R. Qina, Y.M. Zhong, “A new envelope algorithm of Hilbert–Huang Transform”, Mechanical Systems and Signal Processing 20 (2006), pp 1941–1952.