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Diagnosis of rotating machine defects by vibration analysis

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ABSTRACT
This work presents the analysis of the vibration signals of a ball bearing, the signals available on the platform Case Western Reserve University in the form of MATLAB files. By proposing an approach for the diagnosis of any rotating machine and detects the failed components in a simple way, the proposed approach consists of several methods and steps each complementary to the other. First on decomposing the signal by the feature mode decomposition (FMD) method and then, according to the Kurtosis values by selecting the useful signals after the selection by computing the sum of the useful signals called the residual of the original signal. The simplicity of the form of the residual makes through the application of band pass filtering and Hilbert transform, but the analysis of the peaks represents the frequency of the failed components.

Section: RESEARCH PAPER

Keywords: Vibration signal; kurtosis; FMD; Hilbert transform; filtering

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1. INTRODUCTION

Rotating machines such as engine and gearbox produce a vibration which characterized by a set of parameters such as amplitude, velocity and acceleration [1]. The measurement of the parameters depends on the frequency of the vibration such as displacement sensor used at low frequency and velocity sensor at medium frequency and accelerometer at high frequency, vibration monitoring is a technique more used in maintenance, which allows the detection of defects [1].

The method of machine monitoring divided into two types: the first is the methods of fault detection based on the creation of an analytical model to correlate the signature and detect the damage parameters such as hidden Markov model (HMM), artificial neural network (ANN) [1]. The second method is the processing and extraction of the characteristics of the vibration signal in the time domain, frequency domain, and time-frequency domain [1].

Data acquisition is an important step in the diagnosis of machine faults and the information collected divided into two types: data from events dependent on installation, repair, but monitoring data collected by measurements such as vibration data, the next step after the acquisition is the analysis of the data through models, algorithms, tools, which ensures a better interpretation [2].

The algorithms of decomposition of a signal are the most used in data analysis, such as EMD, EEMD, CEEMD, empirical mode decomposition (EMD) created by Huang in 1998 but this method presents the problem of mixing modes [3]. Through its EMD improved by Wu in 2009 to ensemble empirical mode decomposition (EEMD) and in 2011 improved by Torres to complete ensemble empirical mode decomposition (CEEMD) [3]. The last decomposition method created by Yonghao Miao in 2022 is called feature mode decomposition (FMD) [4].

In this work, we propose an approach to analyse the real signals of the ball bearing 6025-SKF, the experimental signals available on the platform (CWRU) in the form of MATLAB files, see Figure 1.

2. METHOD

In this study, we propose an approach that allows the processing of vibratory signals of a machine in an efficient way and gives a result that directly indicates the kinematic frequency

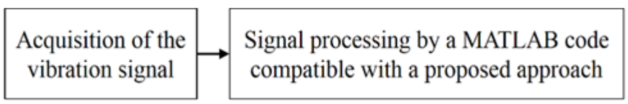

Figure 1. Parts of the proposed approach.

of the failed components. The approach consists of two parts, the first is the experimental part of signal acquisition by a measurement chain and the second part is the processing of the vibration signal by a MATLAB code compatible with a proposed approach that provides the frequencies of defects:

Figure 2 illustrates the proposed approach that consists of several steps each complementary to the other:

- Step1: After insertion of the signal in fact the decomposition by FMD through the use of a finite impulse response (FIR) filter bank the signal decomposes into different modes, the algorithm of FMD consists of the following steps [4]:
  - Enter the number of modes n and the length of the filter L.
  - Initialization of filter banks by a Hanning window using K filter.
  - Obtain the modes (filtered signals) by the following equation:

    $$u_k^i = x * f_k^i \tag{1}$$

    u_k^i: modes, x: signal, f_k^i: filter coefficient, i: iteration, $*$: convolution.
  - Updating the filter coefficients by using the signal x and the modes u and the estimated period T, which chosen as the point where the autocorrelation spectrum reaches the maximum value R_k^i after the point zero crossing.
  - Judges the number of iterations i if it reaches the pre-interaction number by going to the next step.
  - Calculation of correlation coefficient CC, both modes build a matrix $CC_{K\times K}$, then calculating the correlated kurtosis CK using the estimated period.
  - Judges if the number of modes n reaches the specified number.
  - Obtain the final modes.

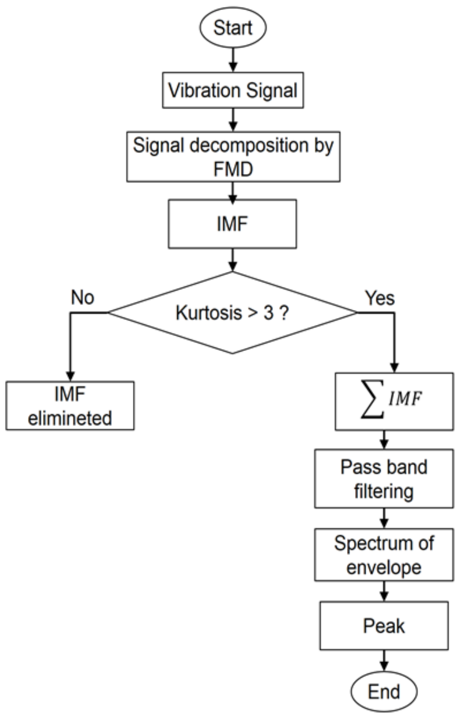

Figure 2. The signal processing approach.

Figure 3 shows the flowchart of the FMD method [4]:
The input parameters to the FMD algorithm are the number of modes n, the length of the filter L and the number of frequency band segments K:

- The filter length L has an influence on the filtering performance, the FMD performance test consists of the variation of the correlated Kurtosis CK values of the filtered signals as a function of the filter length L, and the test result defines the optimal FMD filter length range, $L \in [30; 100]$, [4].
- The parameter K must be greater than n to ensure decomposition, the FMD performance test which consists of the variation of CK values as a function of K defines the optimal parameter interval $K \in [5; 10]$, [4].

However, we in your study propose criteria to define the values of the parameters of FMD:

- The number equals half the number of modes obtained by EMD:

$$n_{(\mathrm{FMD})} = \frac{n_{(\mathrm{EMD})}}{2}\,. \tag{2}$$

- The parameter K is half of the optimal interval:

$$K = \frac{5+10}{2} \cong 8\,. \tag{3}$$

- The number (L) defined according to the variation of cross correlation (C) between the modes obtained by FMD and the original signal, the case that represents a maximum total value (TC) of cross correlation (C) chosen.

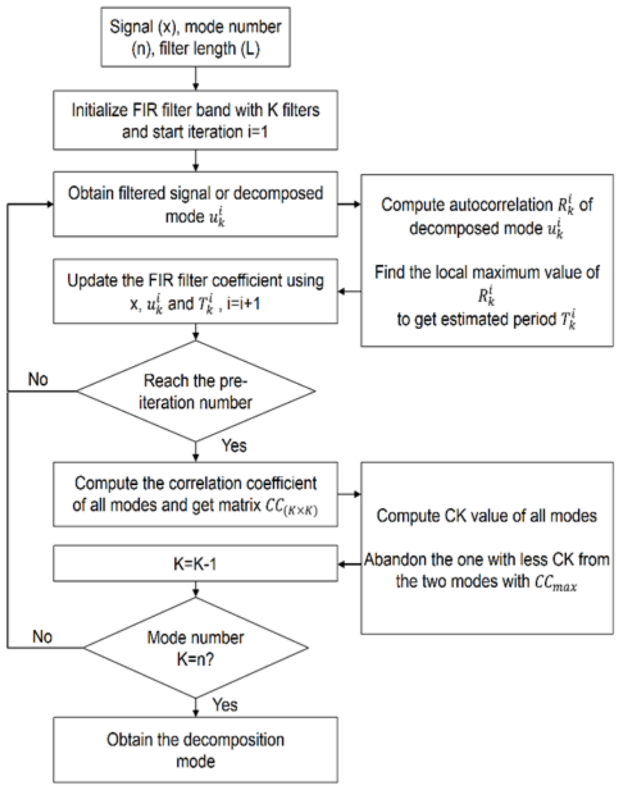

Figure 3. FMD algorithm.

The cross correlation function applied to measure the similarity between two functions and calculated by the following formula [5]:

$$C(\tau) = \int_{-\infty}^{+\infty} x(t)\, IMF_i(t-\tau)\, \mathrm{d}t \tag{4}$$

$i = 1, 2, \dots, n_{(\mathrm{FMD})}$: the number of modes, IMF: the modes, τ: time shift parameter.

$$TC = \sum_{i=1}^{n_{(\mathrm{FMD})}} C_i(\tau)\,. \tag{5}$$

- Step2: the kurtosis is a moment of order 4 and used to identify the non-periodic impacts and operation of a machine, the value there is a threshold in the detection of faults when the kurtosis greater than three the signal is impulsive [6]. As the case of bearing in good condition, the kurtosis is less than three and the distribution of the Gaussian signal [7].

$$ku = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - \bar{x}}{\sigma}\right)^4\,, \tag{6}$$

$\bar{x}$: the mean, σ: standard deviation.

- Step3 : the sum of the IMF that illustrates a kurtosis value greater than three called the signal residual x_{res} [8], after the determination of residual on calculating the kurtogram to define the two pass frequencies of the digital band pass filter, the limits of the interval that illustrate a high value of spectral kurtosis $K(f)$ is the pass frequencies.
  The kurtogram represents the variation of spectral kurtosis values as a function of frequency f and width Δf, [9].
  $K(f)$ is calculated by the following formula, [9]:

$$K(f) = \frac{< H^4(t,f) >}{< H^2(t,f) >^2} - 2 \tag{7}$$

$H(t,f)$: complex envelope of the signal at frequency f, estimated by the short-term Fourier transform [9].

- Step 4: calculation of the envelope spectrum of the filtered signal x_{resf} by the Hilbert $H[x_{\mathrm{resf}}(t)]$ and Fourier transform, the absolute value $E(t)$ of the analytical signal $z(t)$ is the envelope of x_{resf} and $E(f)$ is the spectrum, $E(t)$ and $E(f)$ calculated by the following equations [10]:

$$H[x_{\mathrm{resf}}(t)] = x_{\mathrm{resf}}(t) * \frac{1}{\pi\, t} \tag{8}$$

$*$: convolution product.

$$z(t) = x_{\mathrm{resf}} + j\, H[x_{\mathrm{resf}}(t)] \tag{9}$$

$$z(t) = E(t)\, e^{j\,\varphi(t)} \tag{10}$$

$$x_{\mathrm{resf}}(t) = R\{z(t)\} = E(t)\cos(\varphi(t)) \tag{11}$$

$$E(t) = |x_{\mathrm{resf}}(t) + j\, H[x_{\mathrm{resf}}(t)]| \tag{12}$$

$$E(f) = \int_{-\infty}^{+\infty} E(t) e^{-j\,2\,\pi\,f\,t}\, \mathrm{d}t\,. \tag{13}$$

- Step 5: the peak is the maximum amplitude value of a signal found by the following formula [11]:

$$Peak = \max|E(f)| \tag{14}$$

The relationship between the peak frequency and the kinematic frequency of the components of a machine is the result of the diagnosis that ensures the detection of the faulty component.

3. VIBRATION SIGNALS

In this section, analysing the real vibratory signal of ball bearing type 6025-SKF that supports the shaft of an electric motor at the drive end and subjected to different speeds and loads, among the signals available in the platform CWRU taking two signals of defects, the characteristics of each signal represented in Table 1, [12].

Fault frequencies of bearing components are the multiple of the rotation frequency in Hz with a coefficient as shown in Table 2 [12].

4. RESULTS AND DISCUSSIONS

4.1. Case 1

By applying the proposed approach on the inner race fault signal (107.mat), starting with the estimation of the parameters of the FMD algorithm:

- The number of modes obtained by applying the EMD algorithm on the signal 107.mat equals 13 so $n_{\mathrm{FMD}} \cong 6$.
- The variation of TC as a function of L is represented in Figure 4.
  The maximum value of cross-correlation $TC = 893.8$ has $L = 32$, the step P of variation of the interval L equals two, $P = 2$.

The decomposition of the vibration signal (107.mat) by the FMD method gives six modes represented in Figure 5, and the spectrum of each mode illustrated in Figure 6.
The kurtosis values for each mode shown in the Table 3.
The original signal residual is the sum of the modes $(2, 3, \dots, 6)$:

$$x_{\mathrm{res}}(t) = \sum_{i=2}^{6} IMF_i(t)\,. \tag{15}$$

The spectrum and the temporal signal of $x_{\mathrm{res}}(t)$ are represented in Figure 7.

Table 1. Vibration signals.

Signal	Defect diameter	Sampling frequency
Inner race (107.mat) Load (1491.4 N m/s) Speed (1750 rpm)	0.1778 mm	12 kHz
Inner race (211.mat) Load (1491.4 N m/s) Speed (1750 rpm)	0.5334 mm	12 kHz

Table 2. Defect frequencies.

Components	Coefficients	Frequency (Hz)
Inner race	5.4152	157.94
Outer race	3.5848	104.55
Cage	0.39828	11.61
Rolling element	4.7135	137.47

The residual spectrum is complex and rich with information as shown in Figure 7, the interpretation of $x_{\mathrm{res}}(f)$ is difficult for this reason, in fact the pass band filtering through the Buttworth filter, the two pass frequencies of the filter defined from kurtogram of $x_{\mathrm{res}}(t)$.

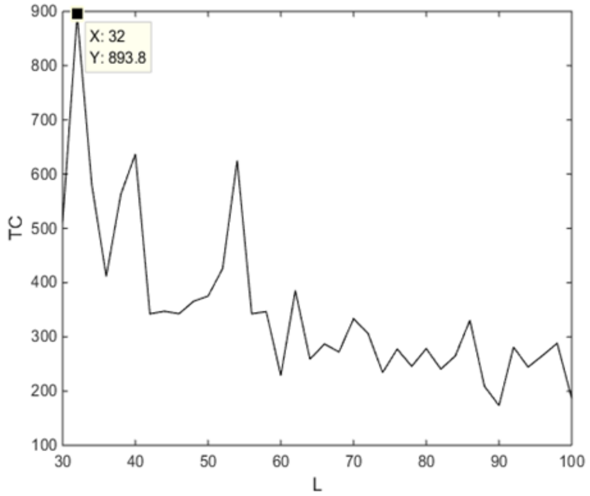

Figure 4. The variation of TC.

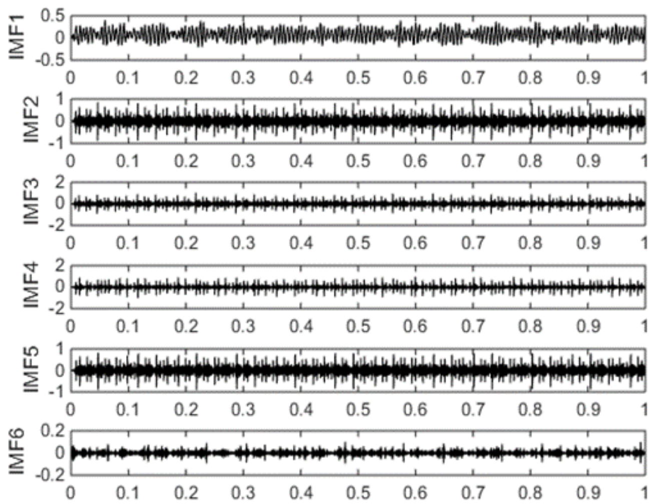

Figure 5. The temporal variation of the modes.

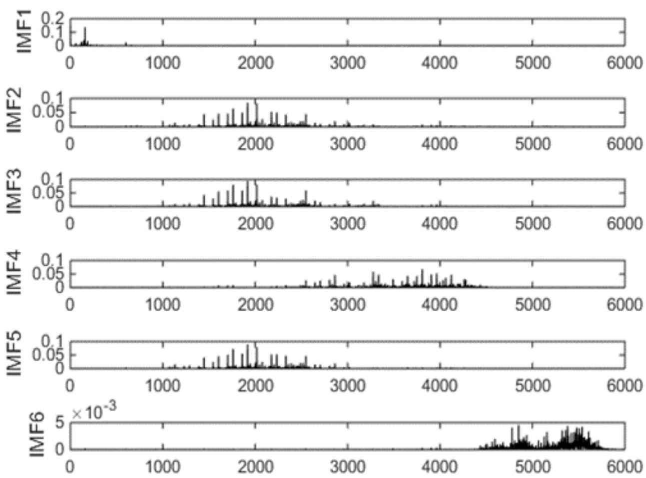

Figure 6. The spectrum of the modes.

Table 3. Kurtosis values.

IMF	Kurtosis
1	2.1
2	5.8
3	6.3
4	8.8
5	5.7
6	5

The kurtogram in Figure 8 shows a maximum value of spectral kurtosis $K_{\mathrm{max}} = 0.5$ at the centered frequency $f_{\mathrm{c}} = 3750$ Hz with a width $Bw = 500$ Hz at the level $l = 3.5$ so the two passing frequencies $Fp = [3250\ ;\ 4250]$ (Hz).

The spectrum of the envelope $E(f)$ of the filtered signal $x_{\mathrm{resf}}(t)$ in Figure 9, illustrates a peak $\max|E(f)| = 0.661$ at frequency $f = 157.5$ Hz, the value of f closer to the fault frequency of the inner race ($F_{\text{inner race}} = f$).

4.2. Case 2

In this case by analysing the vibration signal (211.mat) by the proposed approach, but summarizes the different steps:

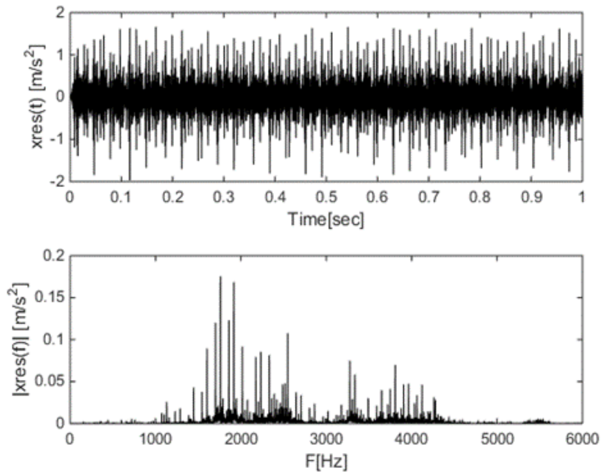

Figure 7. The residual.

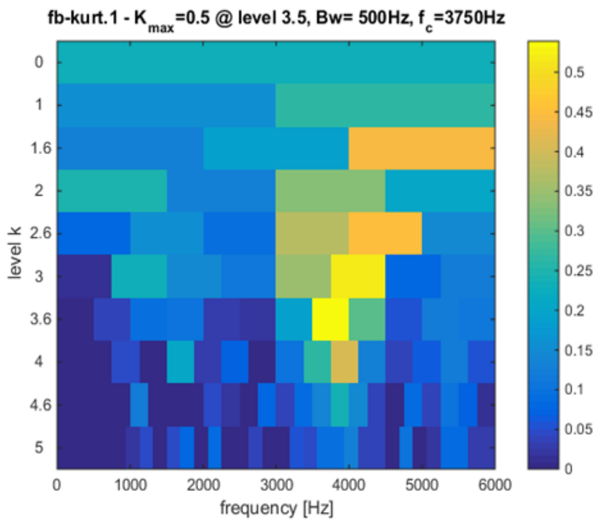

Figure 8. Kurtogram of $x_{res}(t)$.

- The EMD decomposition of the signal yields 14 modes, the maximum cross-correlation value $TC = 329.55$ at $L = 30$ as shown in Figure 10, the estimation of FMD parameters according to the proposed criteria is: $n_{\mathrm{FMD}} = 7$; $L = 30$; $K = 8$.
- The residual is equal to the sum of all modes $(1, 2, \ldots, 7)$ as shown in the Table 4.
- We observe on the spectrum $x_{\mathrm{res}}(f)$ (Figure 11) a very high amplitude peak at the inner race fault frequency.

$$x_{\mathrm{res}}(t) = \sum_{i=1}^{7} IMF_i(t)\,. \tag{16}$$

From the kurtogram of $x_{\mathrm{res}}(t)$ find the two frequencies of passage $Fp = [5375\,;5875]$ Hz.

On the envelope spectrum $E(f)$ (Figure 12), a high amplitude peak is found in the rotation frequency (29 Hz) and the second peak at the inner race fault frequency (157.5 Hz).

Table 4. The values of kurtosis.

IMF	Kurtosis
1	3.5
2	9.7
3	10
4	10.6
5	10.2
6	10.2
7	16

5. CONCLUSION

In this paper, we analyse two fault vibration signals of the inner ring of the ball bearing by a new proposed approach, which consists of a set of signal processing methods organized in the form of steps.

From the final result of the proposed approach, we conclude that the new criteria formulated to estimate the input parameter of the FMD algorithm show a good efficiency since the number of modes and the length of the filter are two essential parameters to ensure the signal decomposition by FMD. As well as the

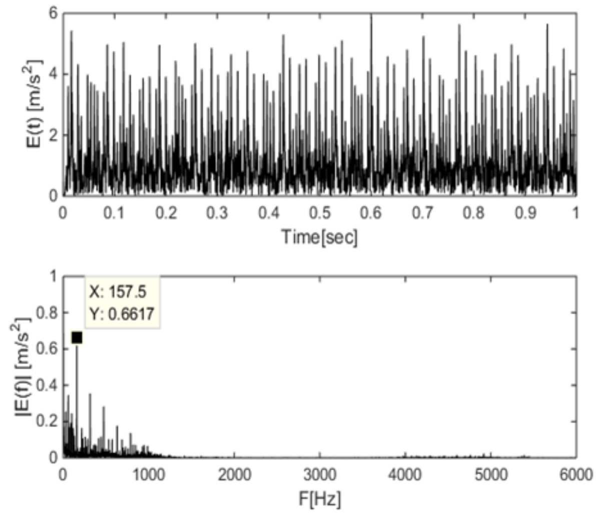

Figure 9. $E(t)$ and $E(f)$.

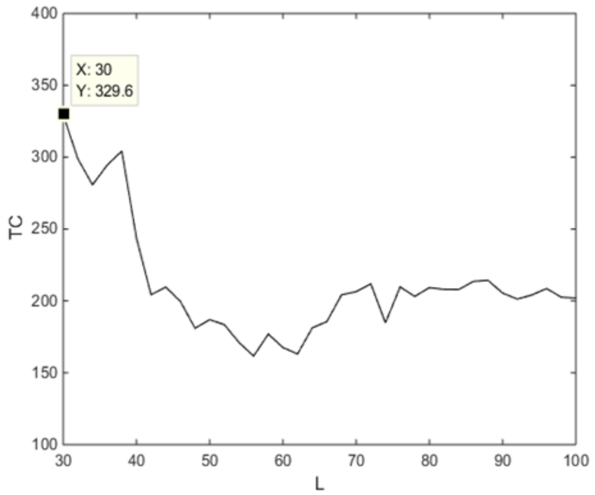

Figure 10. TC as a function of L

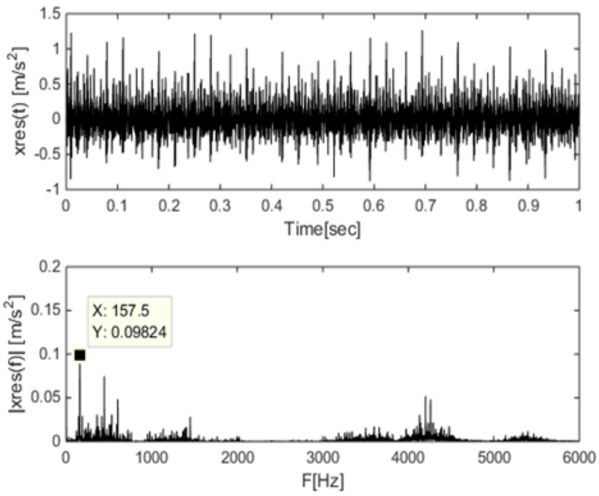

Figure 11. $x_{\mathrm{res}}(t)$ and $x_{\mathrm{res}}(f)$.

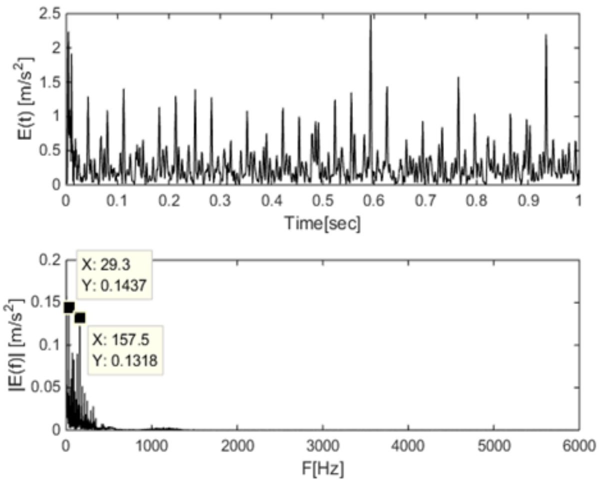

Figure 12. $E(t)$ and $E(f)$.

parameters guarantee the decrease of the equality constraint between the original signal and the set of modes obtained after the decomposition.

The selection of useful modes through the use of parameters such as kurtosis is a very important step to extract the information depends on defects.

The envelope analysis is the last step of the proposed approach that represents the peaks of high amplitudes at the default frequency, envelope analysis is a combination of band pass filtering and Hilbert transform and Fourier transform, in your study the two pass frequencies of the filter defined by the maximum values of spectral kurtosis in the kurtogram.

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