Project Report

On

A Comparative Analysis of Signal Processing Techniques Used for Bearing Fault Diagnosis

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ABSTRACT

A comparative analysis has been performed as an effort to obtain a better idea of how effective various Signal Processing Techniques are in detecting the Bearing Faults.

Various Signal Processing Techniques such as Fast Fourier Transform (FFT), Envelope Detection, Empirical Mode Decomposition (EMD) and Morphological Operators are applied on the Signal and the results are compared

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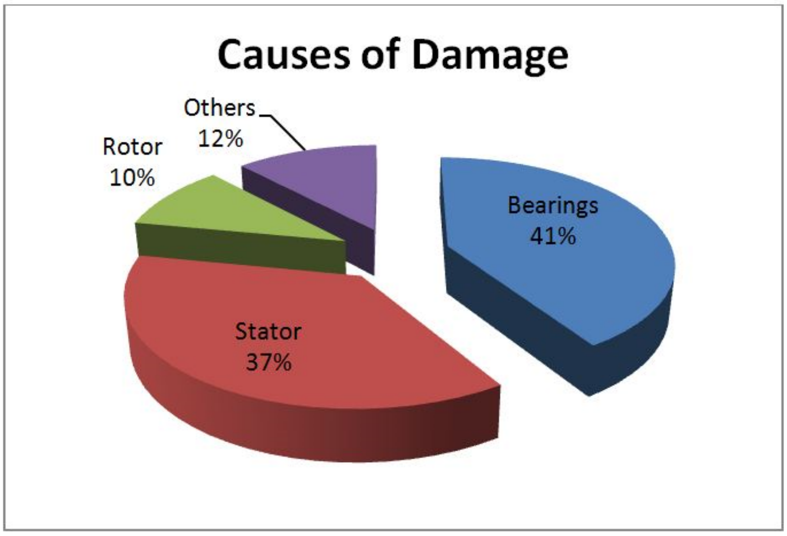
1. INTRODUCTION

Condition Monitoring is the process of monitoring a particular parameter (Vibration, temperature etc.) in order to identify a significant change which is indicative of a developing fault. It is an important component of Predictive maintenance which offers much more cost-saving when compared to Preventive maintenance.

Motors have become indispensable to many industries and hence a lot of research is being done to predict its failure.

Causes	%
Overheating	25
Ageing of windings	5
Earth fault	10
Defective bearing	12
Moisture	17
Oil, grease	20
Chemicals	1
Particles, dust	5

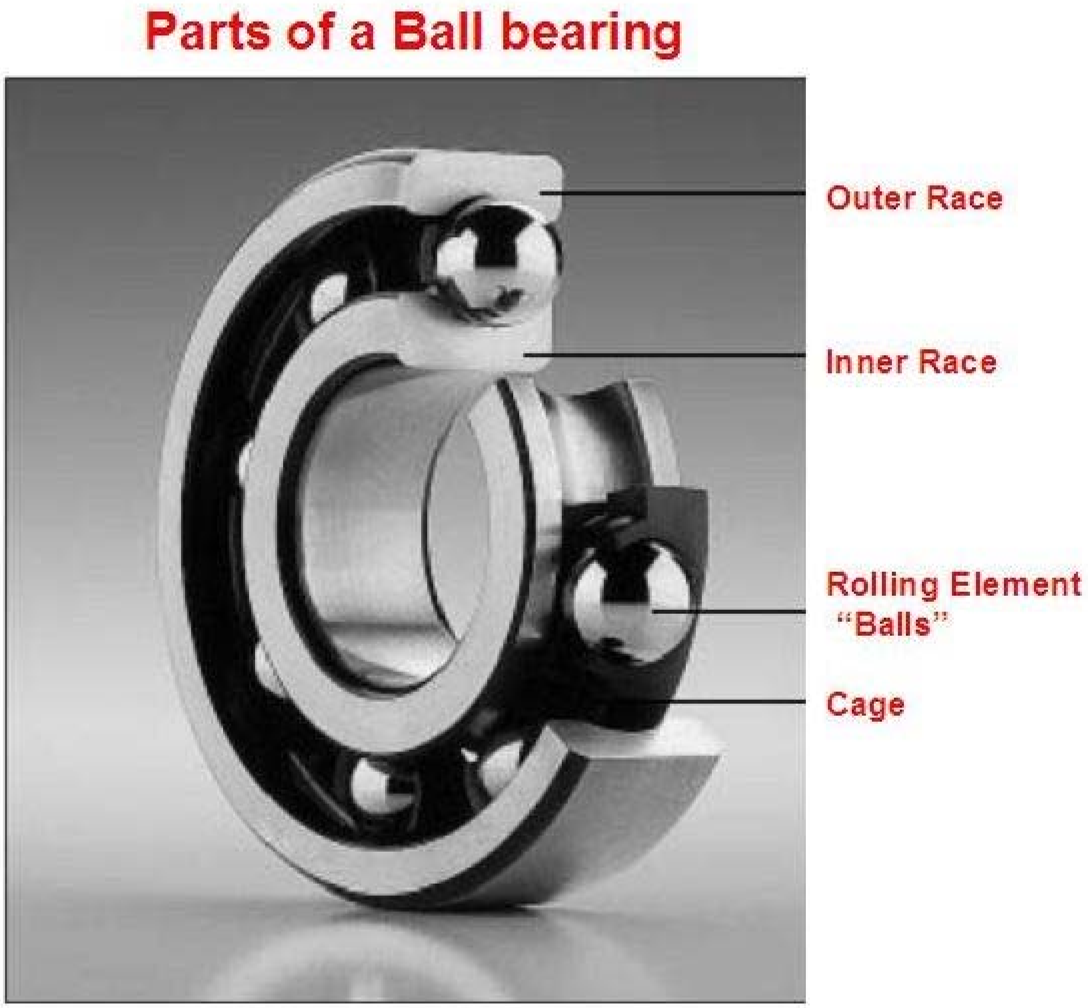


Defective Bearings are one of the major causes of failure in motors. A lot of methods have been used to detect developing bearing faults.

Vibrational Analysis is the most commonly used method for Condition Monitoring.

2. Roller Bearings and Defects

A roller bearing is a bearing which is used to support load and reduce friction. The rolling-elements of a bearing ride on races. The large race that goes into a bore is called the *outer race*, and the small race that the shaft rides in is called the *inner race*.



Defects in Roller Bearings

Bearing Faults can be classified into 3 types based on the element damaged

1. Inner-Race Fault
2. Outer-Race Fault
3. Ball Defect

Each Fault is associated with characteristic frequency called fundamental Fault Frequency. This frequency is dependant on the geometry of the Bearing.

$$BPFO = \frac{N}{2} f_r \left(1 - \frac{d}{D}\cos\alpha\right)$$

$$BPFI = \frac{N}{2} f_r \left(1 + \frac{d}{D}\cos\alpha\right)$$

$$BPF = \frac{D}{2d} f_r \left(1 - \left(\frac{d}{D}\cos\alpha\right)^2\right)$$

Where

BPFO - Ball Pass Frequency Outer-Race
BPFI - Ball Pass Frequency Inner-Race
N - Number of Balls
f_r - Rotational Speed of the rotor (in Hz)
d - Diameter of the ball
D - Pitch Diameter
α - Contact Angle

3. Techniques Used for Fault Detection

3.1 Time Domain Analysis

A time signal/vibration can be analysed based on various parameters such as Peak to Valley Difference, RMS value, crest factor, form factor, Kurtosis etc. However the signal obtained from the accelerometer is too noisy and even a single spike can affect it badly. In addition to this, some of the factors are also dependant on operating speed and load and hence Time-Domain analysis is not very reliable.

3.2 Frequency Domain Analysis

Several Techniques are used such as FFT, Wavelet Transform, Envelope Detection, Empirical Mode Decomposition etc.

3.2.1 Fast Fourier Transform

FFT is an algorithm to compute Discrete Fourier Transform and its inverse. DFT converts equally spaced samples into combination of complex sinusoids ordered by their frequencies (thus converting from Time-Domain to Frequency-Domain).

$$X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(j-1)(k-1)}$$

$$x(j) = \frac{1}{N}\sum_{j=1}^{N} X(k)\omega_N^{-(j-1)(k-1)}$$

where

$$\omega_N = e^{\frac{2\pi i}{N}}$$

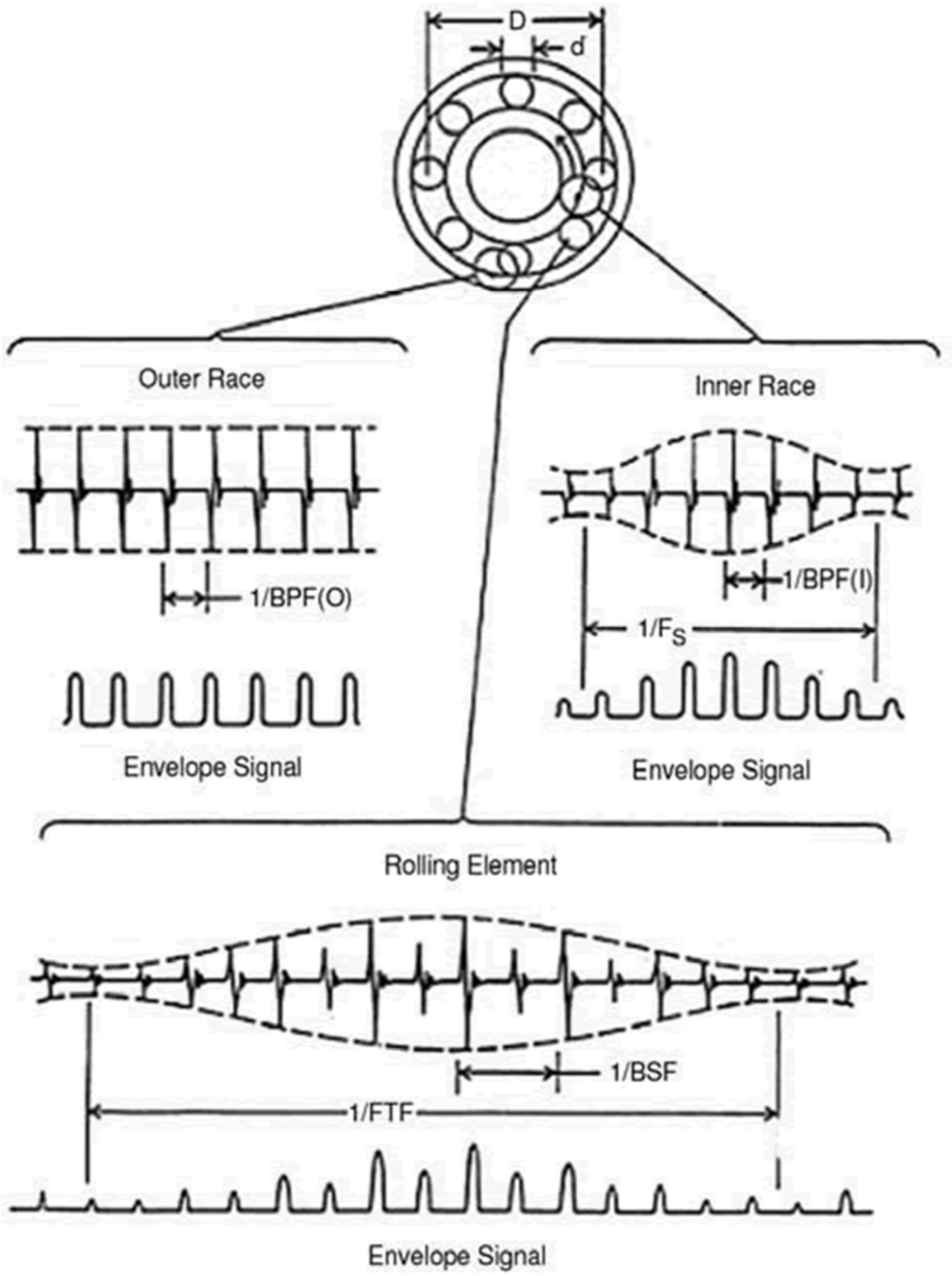
When fault is present in the bearing, a sharp transient accompanied by damped oscillation is captured in the vibrational signal. When this signal is observed in Frequency-Domain, a peak is observed at the respective fault frequency and its harmonics.

3.2.2 Envelope Detection

There are two methods to extract the envelope of the signal.

1. The Signal is squared, passed through a low pass filter and then its square root is taken.
2. By taking the absolute value of Hilbert Transform of the signal.

The FFT of the obtained signals are taken and analysed



3.2.3 Empirical Mode Decomposition

EMD is a method used for analysing non-linear and non-stationary signals. The signals are decomposed into function called Intrinsic Mode Functions (IMF) in the Time-domain itself and are of the same length as that of the signal. This allows varying frequency in time to be preserved.

IMF’s have the following property:

1. The number of extrema and the number of zero crossing are equal or atmost differ by one.
2. The Mean value defined by the envelope of local maxima and local minima is Zero.

The process of extracting an IMF is called sifting. We stop the sifting process if the Sum of the Differences (SD) is less than a pre-given value or if the number of Zero crossings and extrema differ by one or remain equal. The sifting process is as follows.

1. Extract the local minima and maxima. Interpolate the obtained maxima and minima by cubic spline lines to form the upper and lower envelope respectively.
2. Subtract the mean of the envelope from the signal.
3. Check if the obtained signal is an IMF. If not repeat the above till it satisfies the definition of an IMF.
4. Subtract the obtained IMF from the signal and similarly extract the IMF from the remaining signal.

When the stoppage criterion is met, a residue is left. The sum of all the IMFs and the residue give back the original signal.

The FFTs of the IMFs are taken and analysed.

3.2.4 Morphological Operators

Mathematical morphology deals with mathematical theory of describing shapes using sets. It is used to study the interactions between an image and a chosen structuring element using basic operations of erosion and dilation.

Erosion

$$\left(\varepsilon(f)\right)(x) = \min_{s \epsilon S} f(x + s)$$

Dilation

$$\left(\delta(f)\right)(x) = \max_{s \epsilon S} f(x + s)$$

Top Hat operator is a morphological operator used to extract small elements and details from image. Top-hat filtering computes the morphological opening of the image and then subtracts the result from the original image. (The morphological open operation is an erosion followed by a dilation, using the same structuring element for both operations.)

Signals can be considered as a one Dimensional Image and the above morphological operations can be applied with a 1-D structuring element of suitable length.

4. ANALYSIS OF VIBRATIONAL SIGNAL

The vibration data used for analysis is obtained from CWRU Bearing Data Centre

Size (in Inches)

Inside Diameter	Outside Diameter	Thickness	Ball Diameter	Pitch Diameter
0.9843	2.0472	0.5906	0.3126	1.537

Defect frequencies (in multiples of running speed in Hertz)

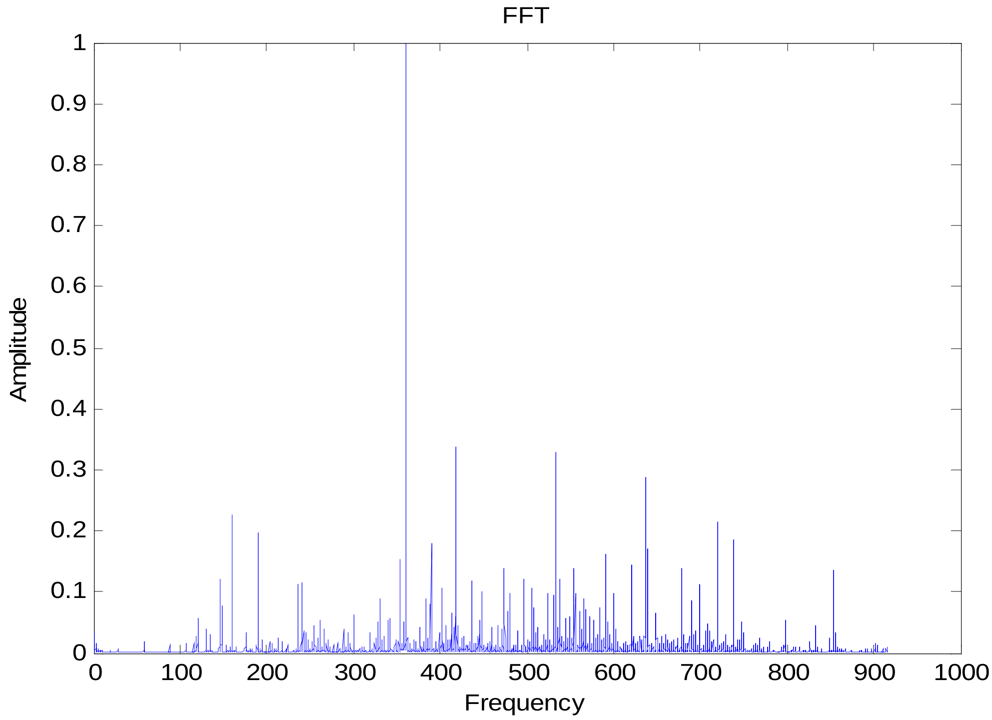
Inner Ring	Outer Ring	Cage Train	Rolling Element
5.4152	3.5848	0.39828	4.7135

Calculated Defect Frequencies

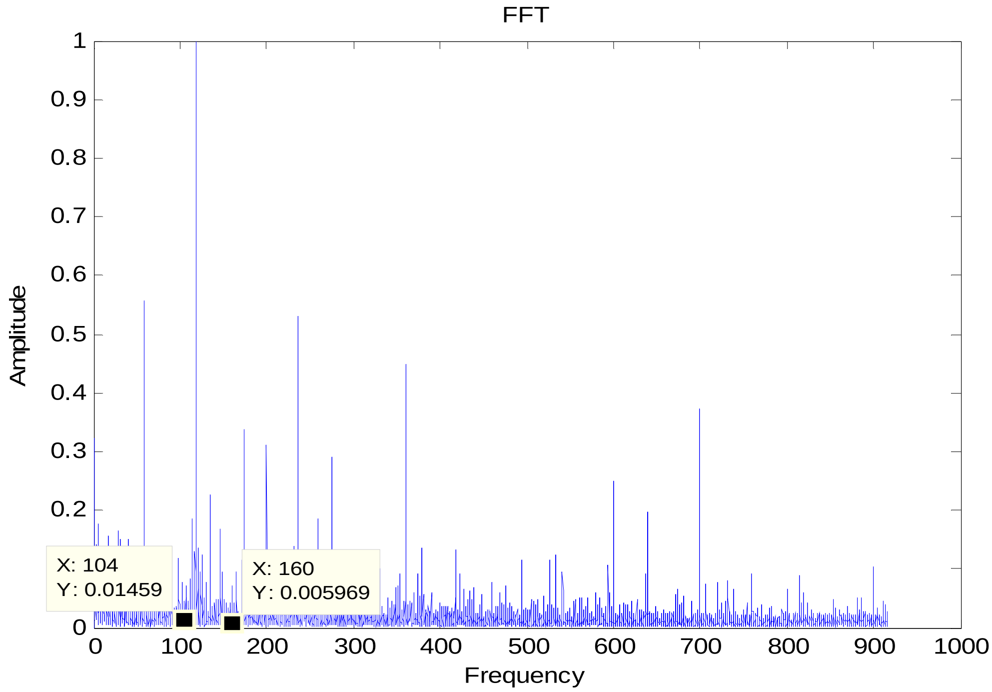
RPM	IR-Fault Frequency (in Hz)	OR-Fault Frequency (in Hz)
1797	162	107
1774	160	105
1752	158	104
1728	156	103

Signal without fault (Normal Baseline condition)

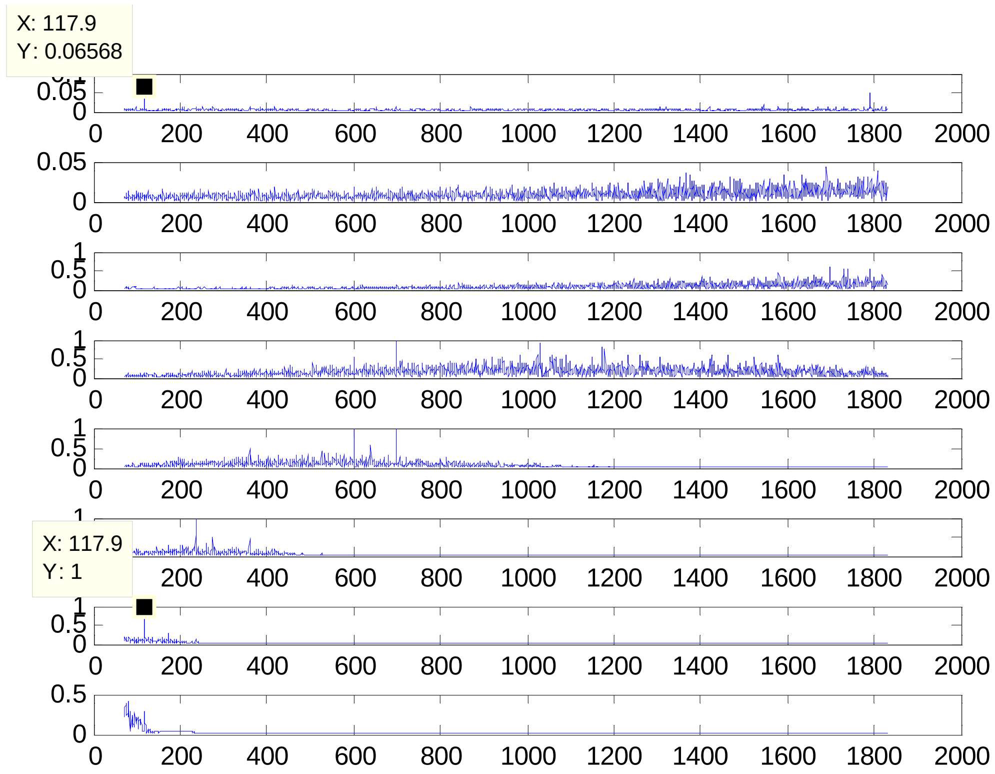
FFT of the Signal



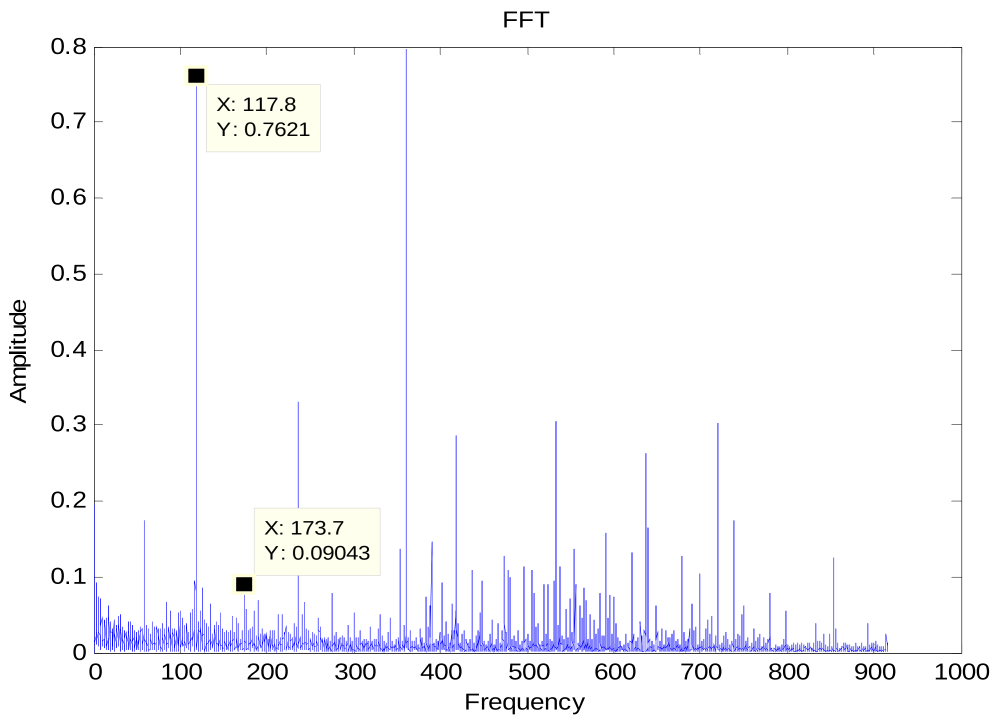
FFT of the envelope



Empirical Mode Decomposition (FFTs of the IMFs)



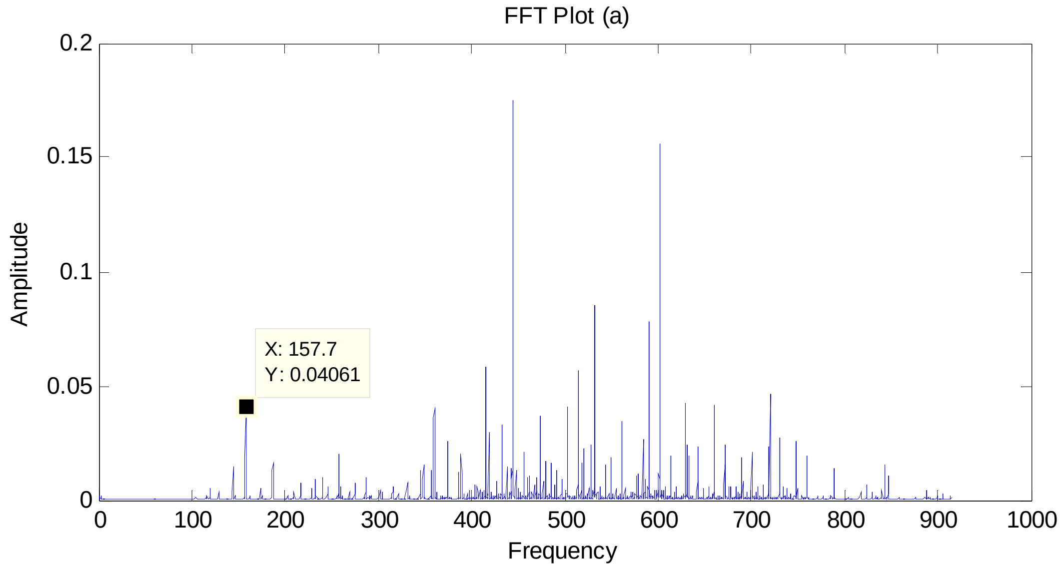
Morphological Operators(Top-Hat Filetring)

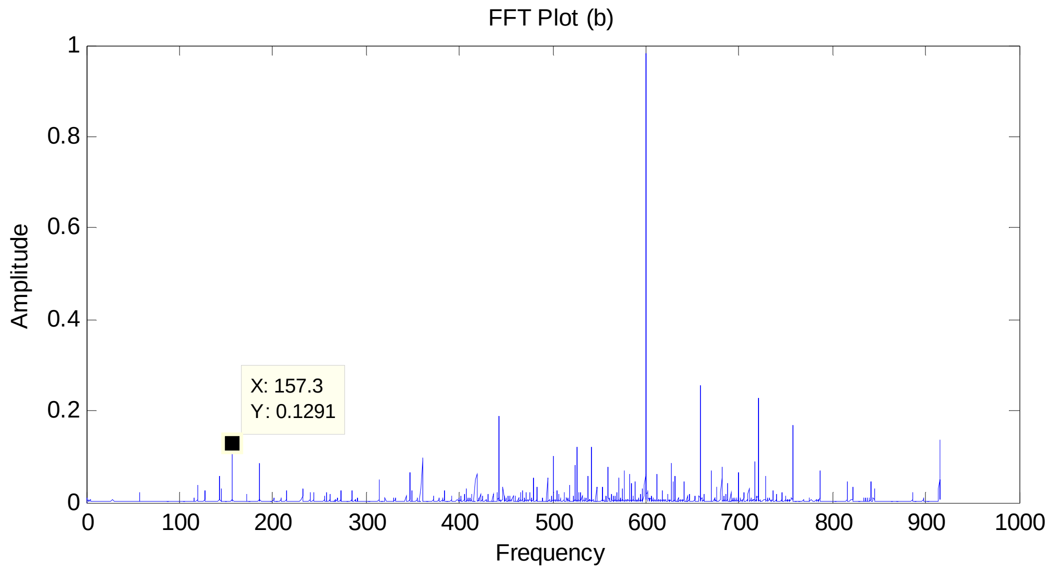


No Peaks are observed at fault Frequencies.

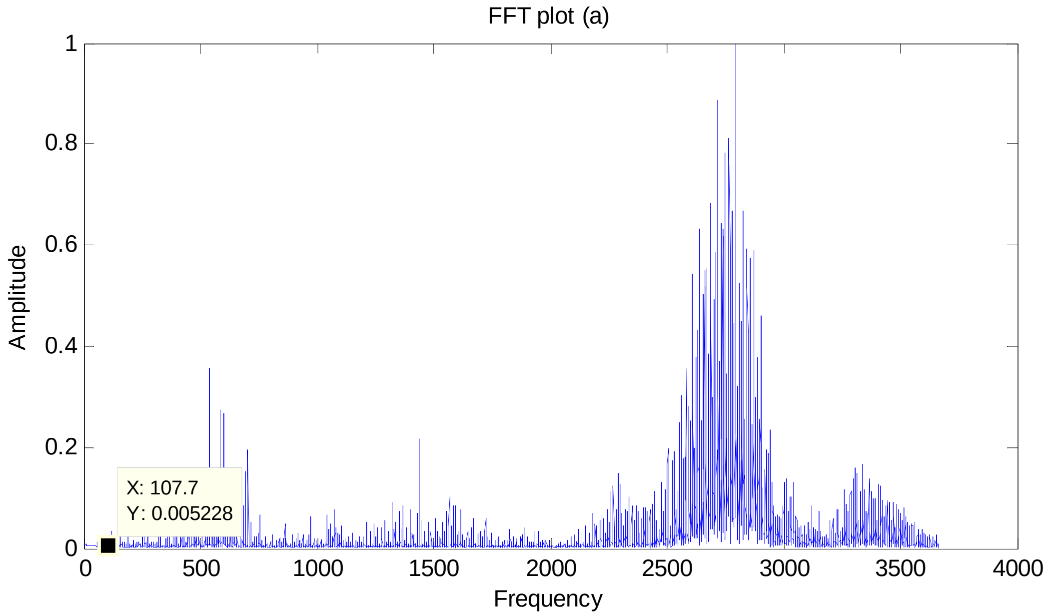
4.1 Analysis Using FFT

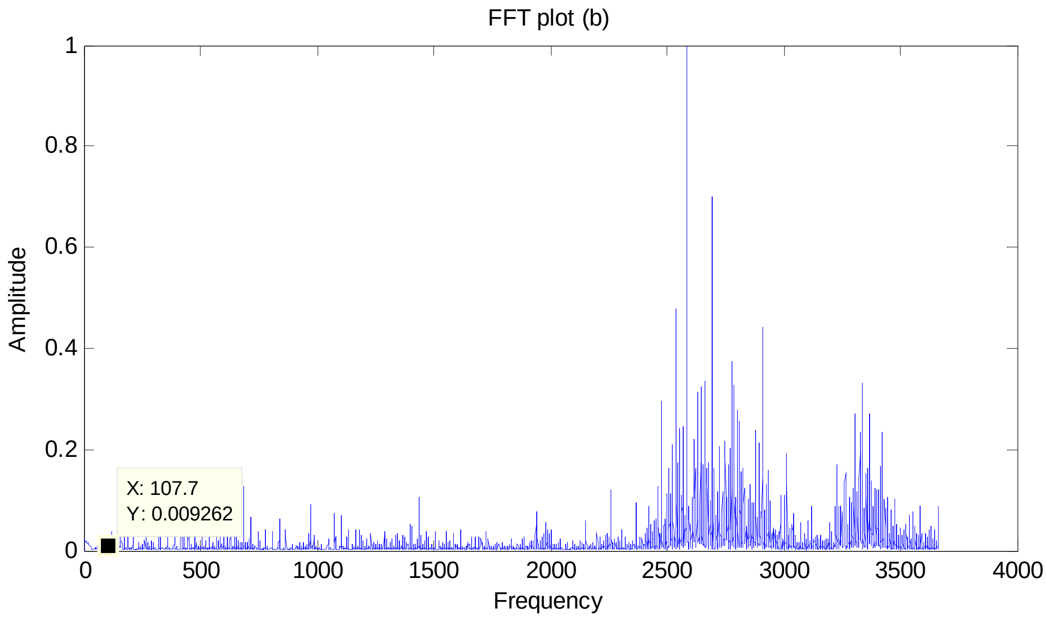
FFT of IR Fault of 0.021’’ (a) and 0.007’’ (b)





FFT of OR Fault of 0.021’’ (a) and 0.007’’ (b)

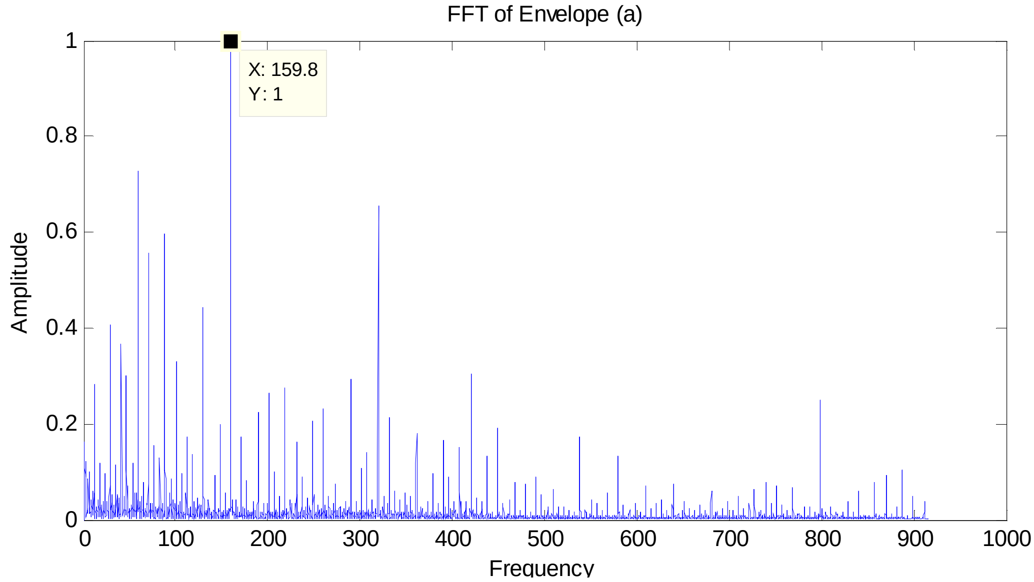


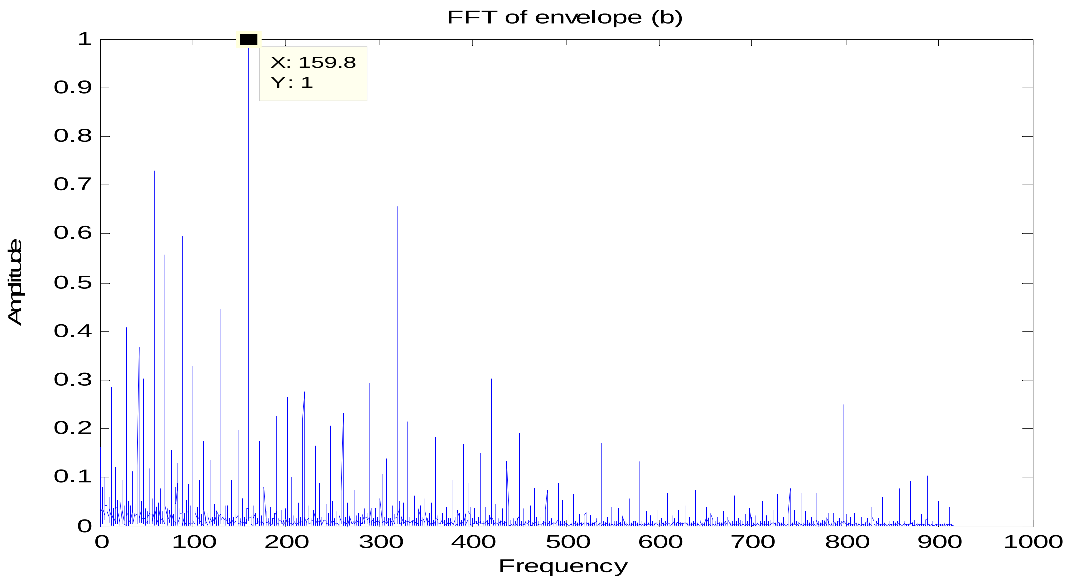


We are able to detect peaks at the IR fault frequencies (~157 Hz) but not at OR-fault frequencies (~107Hz). Also as size of the fault decreases, the peak may not be detectable. It is hard to analyse a signal effectively when the fault signal is weaker than the interfering signal. Hence it can be concluded that FFT doesn't provide proper diagnosis when the signal has a low SNR.

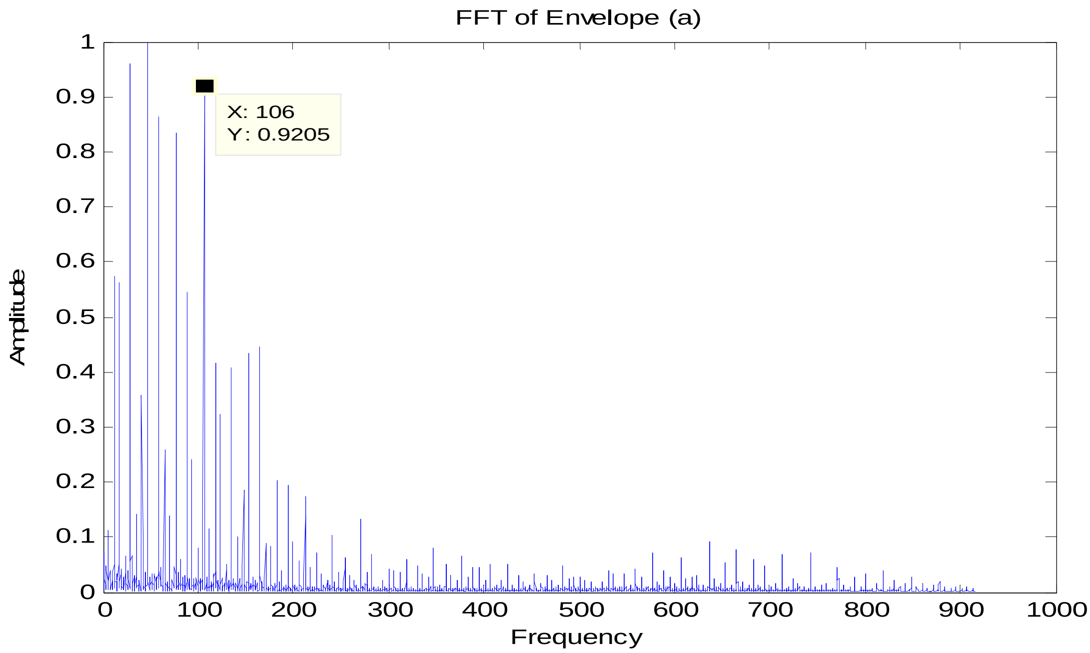
4.2 Analysis Using Envelope Detection

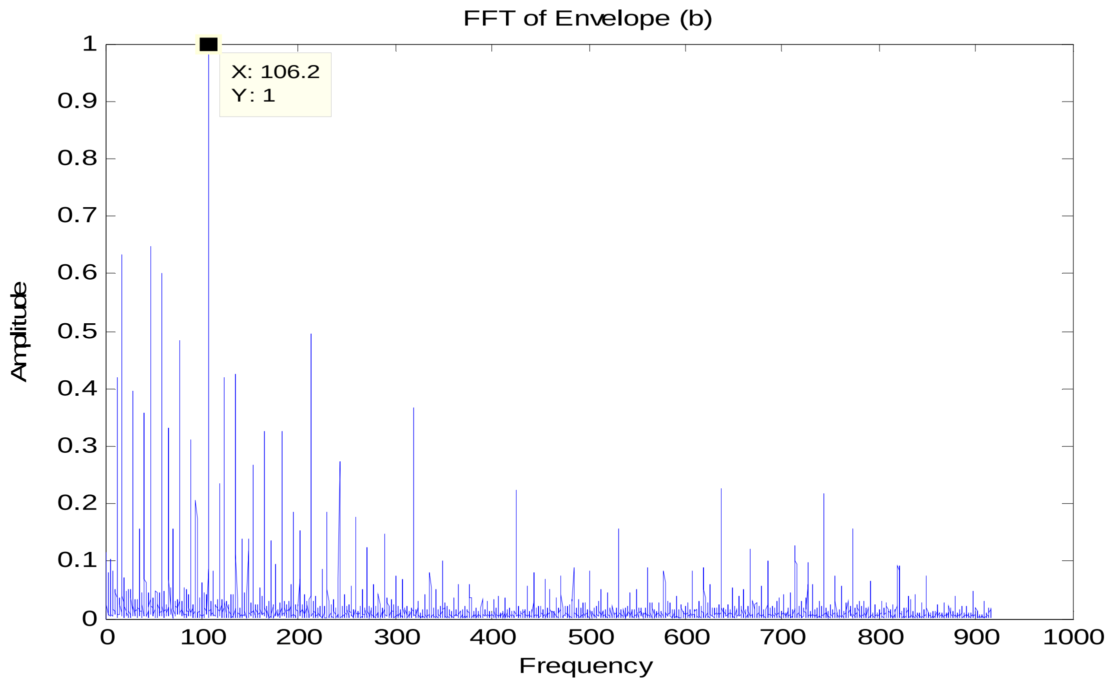
FFT of Envelope of IR Fault of 0.021’’ (a) and 0.007’’





FFT of Envelope of OR Fault of 0.021’’ (a) and 0.007’’



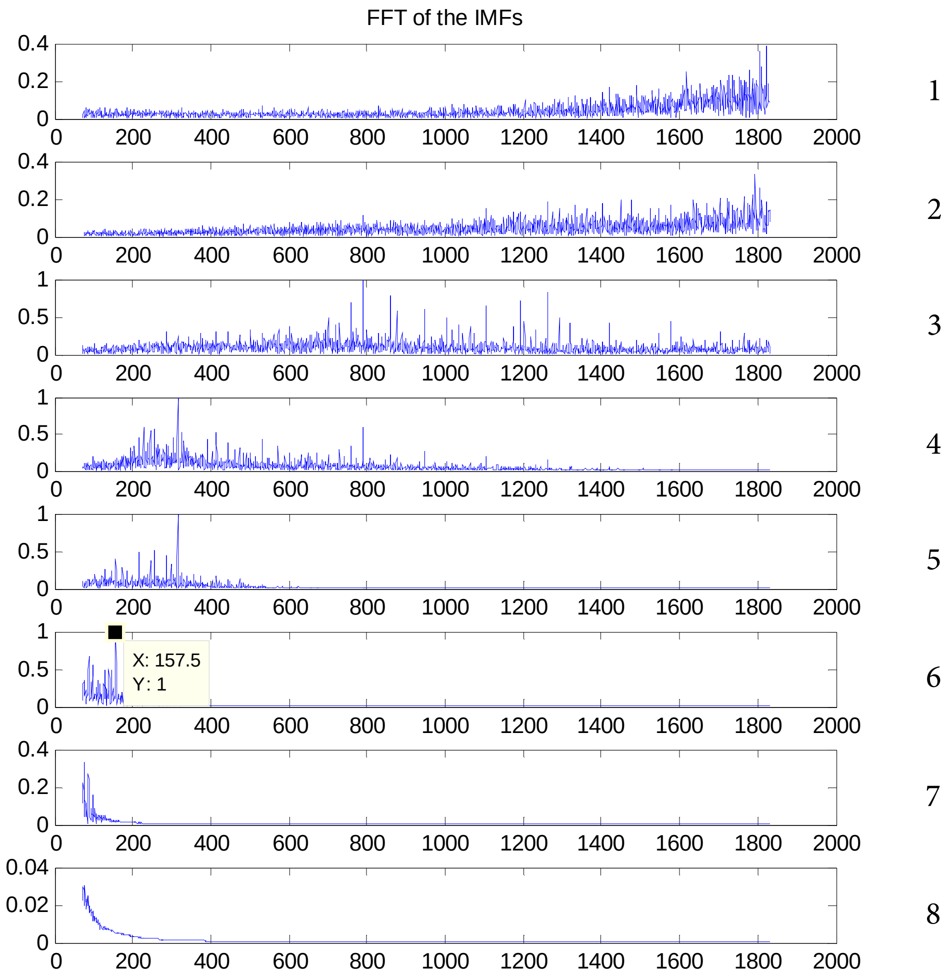


Maximum Peaks are observed at the respective Fault frequencies.

Envelope Detection proves to be a better method when compared to FFT

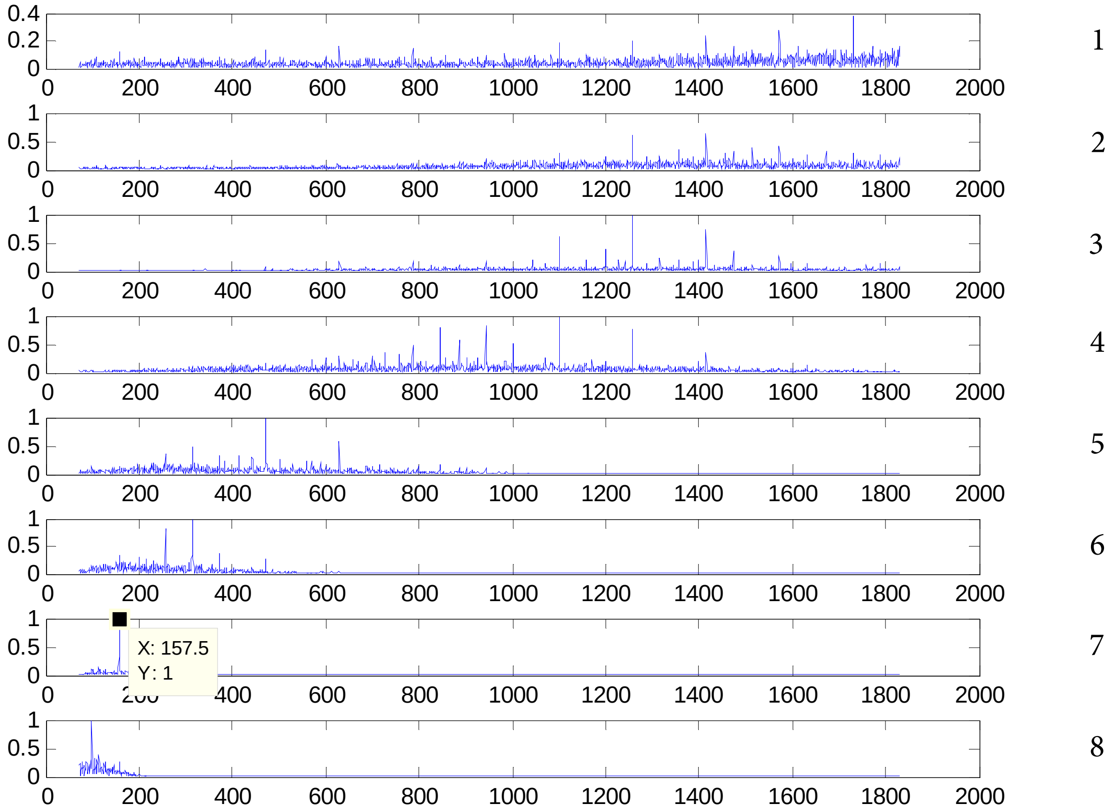
4.3 Analysis using Empirical Mode Decomposition

FFTs of IMFs for IR fault – 0.021''



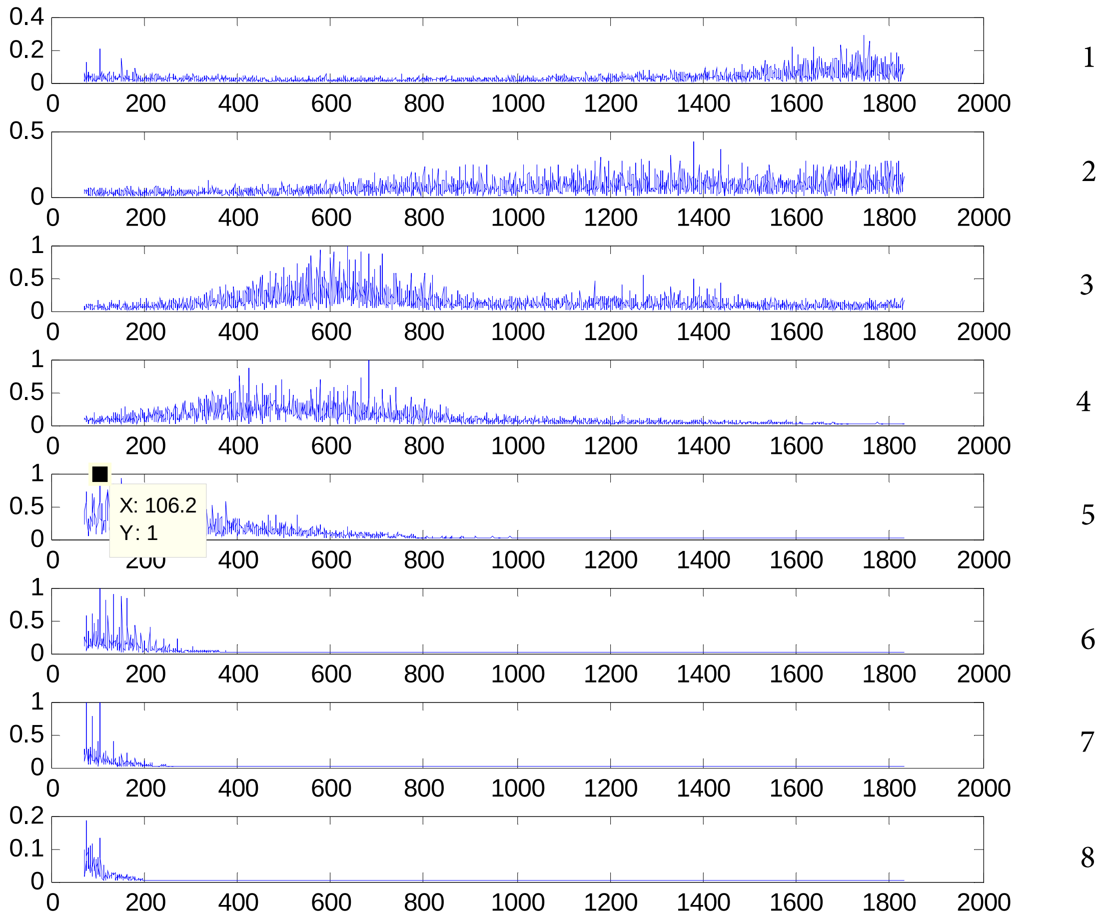
IMF 6 has a peak at the fault frequency.

FFTs of IMFs for IR fault – 0.007’’



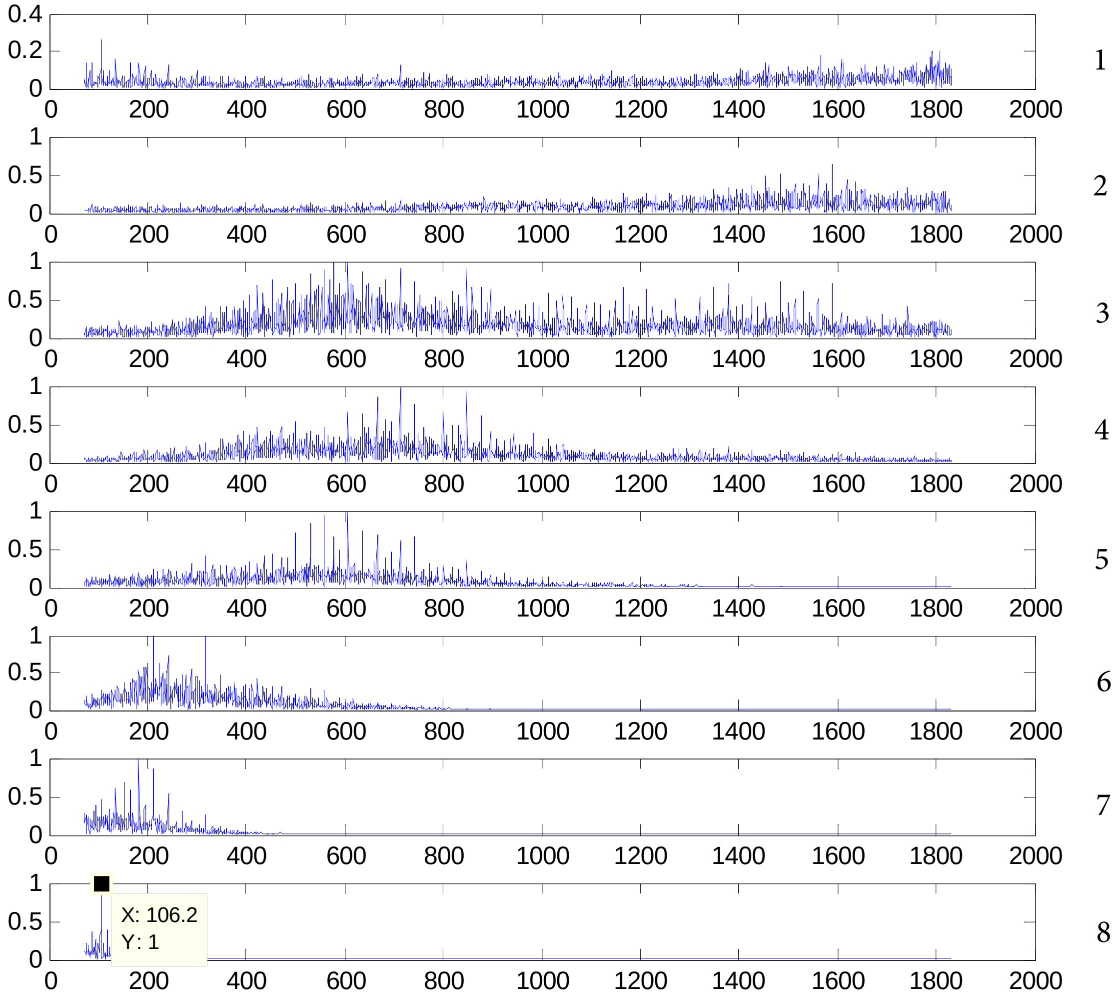
IMF 7 has a peak at the fault frequency.

FFTs of IMFs for OR fault – 0.021''



Peaks at fault frequencies are observed at IMF 5, 6, 7

FFTs of IMFs for OR fault – 0.007’’

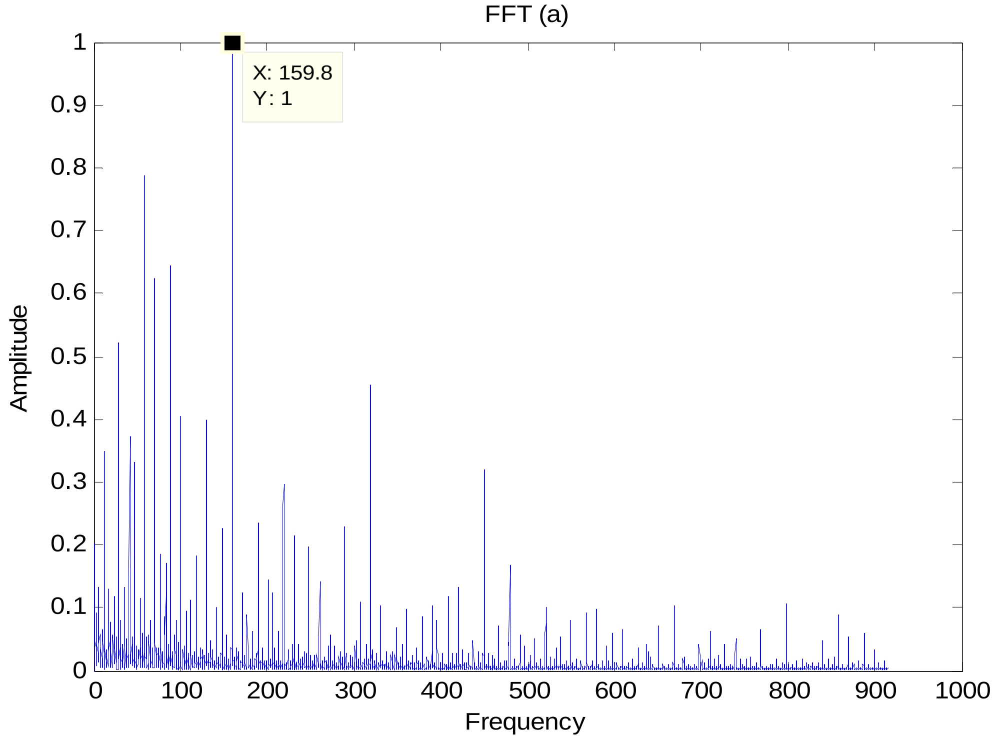


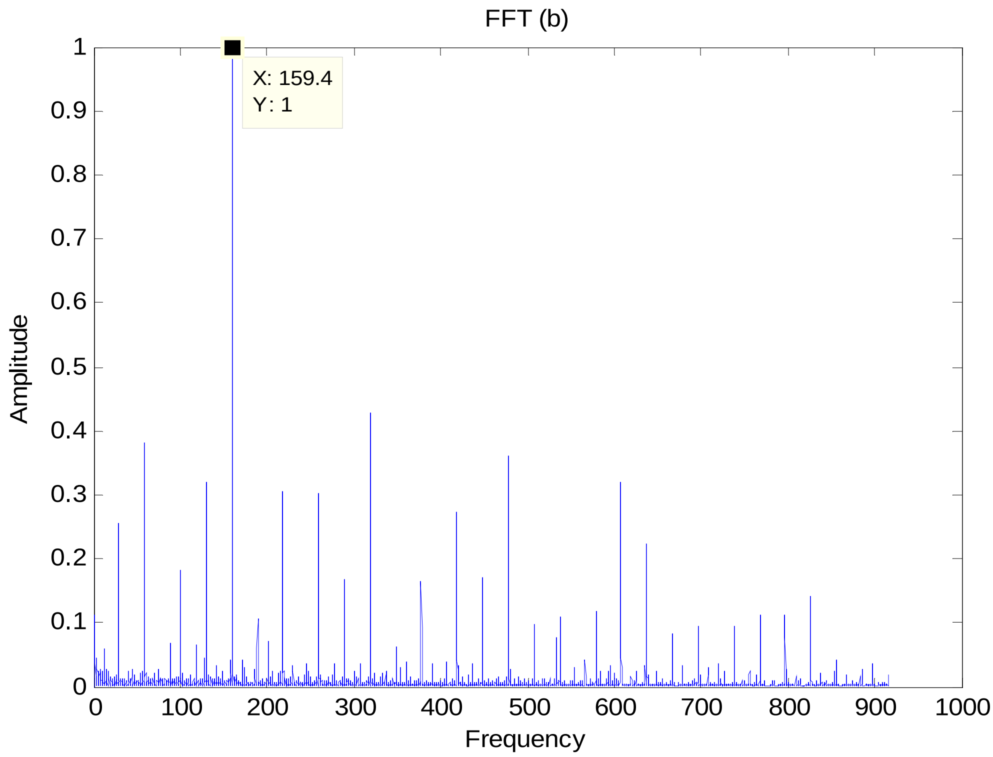
Peak at fault frequency is observed at IMF 8

The Fault Frequency have a distinctive maximum peak in some of the FFTs of their respective IMFs.

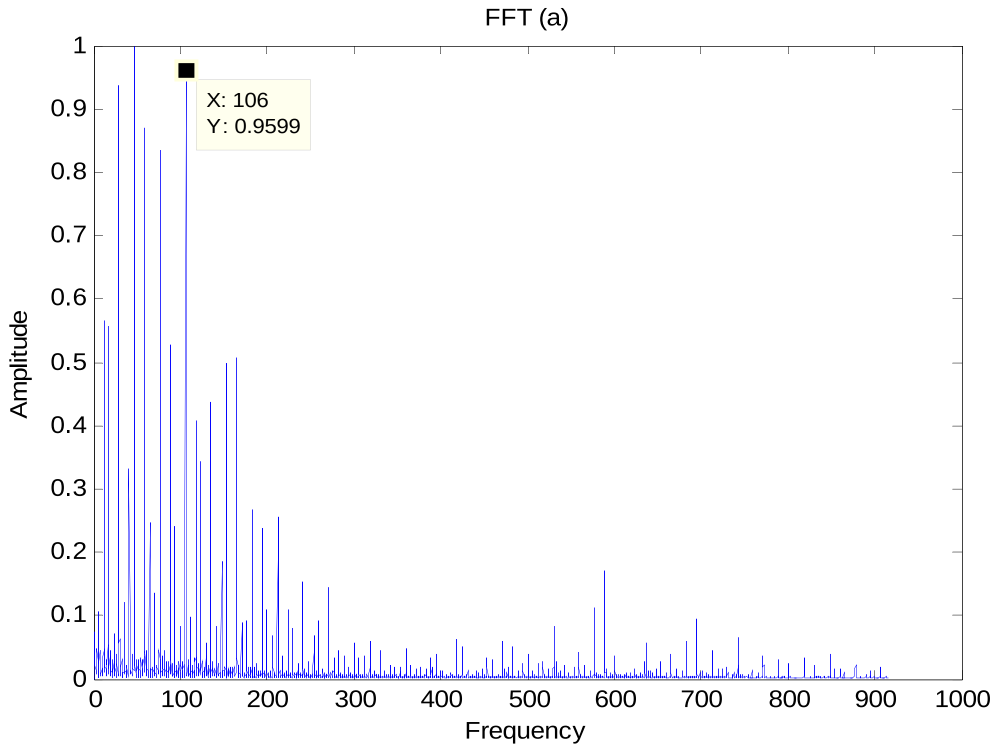
4.4 TOP-HAT FILTERING (MORPHOLOGICAL OPERATOR)

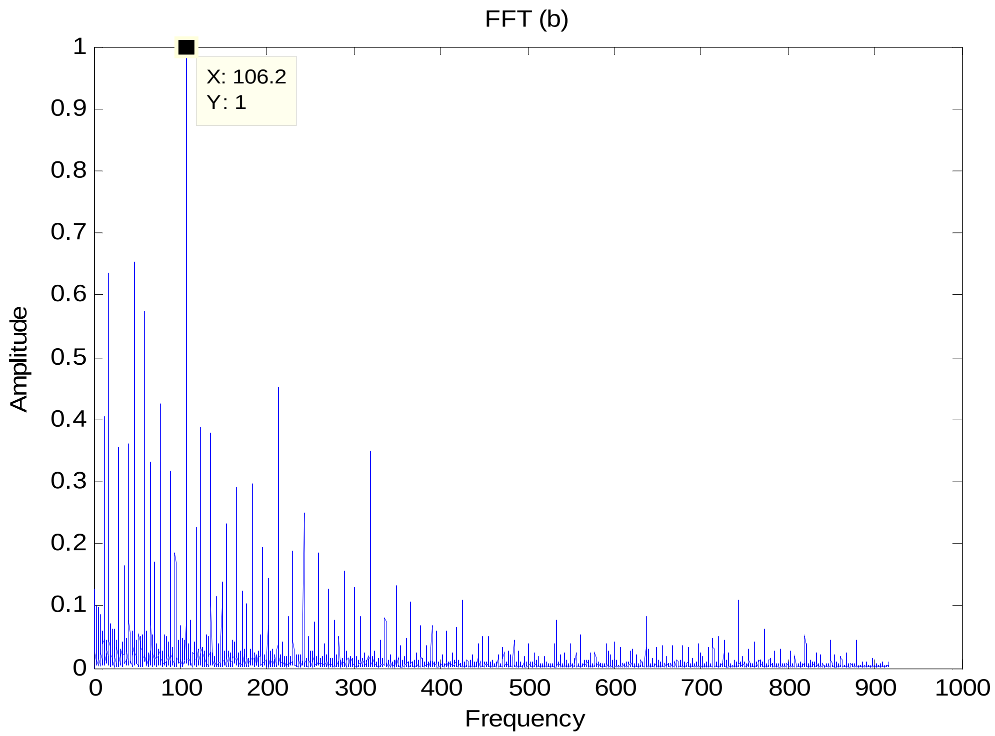
IR Fault of 0.021’’ (a) and 0.007’’ (b)





OR Faults of 0.021’’ (a) and 0.007’’ (b)





We are able to record Distinctive peaks at the respective fault frequencies.

5. CONCLUSION AND REMARKS

Fast Fourier Transform

FFT fails to detect OR faults properly. Also it fails to detect if the faults are of smaller sizes. Hence it's not very reliable.

Envelope Detection

Envelope Detection turns out to be a better method when compared to FFT as it gives peaks of relatively larger magnitude and is able to detect OR Faults.

Empirical Mode Decomposition

Distinct peaks are observable in the FFTs of the IMFs at respective fault frequencies. EMD is a promising method when it comes to processing of non-stationary and non-linear signals.

Top-Hat Filtering

Top-Hat filtering is also able to successfully detect the impulses. It is more accurate than other methods and also it's faster when compared to EMD