A Novel Approach for Bearing Fault Detection and Classification using Acoustic Emission Technique

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***Abstract*--Ball bearings are one of the most important components in the machine involving the rotary motion. Ball bearing failure can cause a significant amountof maintenance cost and serious safety problems. Hence detection of the fault at its early stage is important. In this paper, a novel approach for fault detection of ball bearing by combining time, frequency and time-frequency domains are used.Two layer multiclasssvmis used for the classification of fault into an outer race fault, inner race fault, ball fault and healthy bearing. A comparison between Envelope Wavelet Packet Transform, Wavelet Packet Transform and proposed method is carried out. The experimental observation shows that the proposed method is able to detect the faulty condition with high accuracy.**

Keywords— Envelope detection, EWPT, WPT, Spectral Subtraction, SVM

I. INTRODUCTION

Acoustic Emission (AE) monitoring is one of the emerging techniques as an alternative to Vibration monitoring. It is a noncontactive type and cost effective monitoring technique to detect, locate and distinguish faults in ball bearing. When a localized fault in the bearing comes in contact with another surface, Acoustic Emissionoccurs due to the impact. AE signals are immune to misalignment, shaft bending, faulty installation and vibrations from the other part of the system [1]. It contains huge information which can be used for condition monitoring. Condition monitoring is performed by analyzing the changes in the AE signatures in the recorded signal. Fault diagnosis helps to identify the position of the fault and maintenance can be planned accordingly. The techniques used for processing the acoustic signal for the condition monitoring of rolling element bearings can be classified as: Time, Frequency and Time-frequency domains [1].

The maximum information from the signal can be extracted using time-frequency domain. Before extraction of the information, the recorded signal must be filtered to remove the noise and obtain the signal of interest. Many techniques like Spectral subtraction [3], Shock wave filter [6], wavelet denoising etc. is used for the denoising purposes. In this paper Spectral subtraction with dual microphone is implemented. A novel approach by combining Envelope Wavelet Packet Transform (EWPT) and Wavelet Packet Transform (WPT) is used along with the Time and Frequency domain features to increase the detection accuracy.

Fault diagnosis is carried out with the model based approach. Two stage machine learning and fault classification is employed using Support Vector Machine (SVM). In the first stage,the fault is classified between outer race fault, inner race fault and others. If classified as other fault, in the second stage data is classified between nonfaulty and ball fault. This increases the resolution between the faults.

II. SPECTRAL SUBTRACTION

The very first step involved in the acoustic signal analysis is denoising of the signal. Spectral Subtraction (SS) is the effective process to extract the signal of interest [3]. The Acoustic emission is recorded with the help of acoustic pressure sensor (directional microphone). Two sensors are used in this work. The primary microphone is placed 6mm away from the bearing to record mainly the bearing noise. Secondary microphone is placed in such a way that it records mainly the ambient noise present in the environment maintaining directionality with primary microphone. The output of the two microphones is fed to the SS for denoising. The standard denoising process using SS is shown in the fig given below.

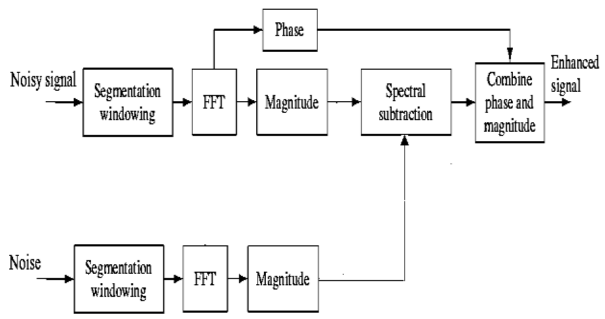


Fig1:Block diagram of spectral Subtraction

The signal from the sensors are segmented and transformed intothe frequency domain. It is assumed that the noise is uncorrelated. Hence, only the phase of the noisy signal is used in the reconstruction. The power SS is given by the equation [3]

$$\hat{X}_k^2 = Y_k^2 - \overline{N}_k^2 (1)$$

Where the $\hat{X}_k$ is the estimated signal. Y_k is the noisy signal and $\overline{N}_k$ is the time averaged noise. After this process, thedenoised signal is obtained for feature extraction.

III. FEATURE EXTRACTION

Features are the individual measurable properties of the phenomena being observed. Choosing discriminating and independent features is very important in pattern recognition algorithm for the successful classification. To detect the incipient fault in the bearing, the features used are

Time domain:

$$\text{Mean} = \overline{\text{X}} = \frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{N}} \text{X}_\text{i} \quad (2)$$

$$\text{Skewness} = \gamma = \frac{1}{\text{N}\sigma^3}\sum_{\text{i}=1}^{\text{N}} (\text{X}_\text{i} - \overline{\text{X}})^4 \quad (3)$$

$$\text{Kurtosis} = \text{K} = \frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{N}} (\text{X}_\text{i} - \overline{\text{X}})^4 \quad (4)$$

$$\text{RMS} = \sqrt{\frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{N}} \text{X}_\text{i}^2} \quad (5)$$

Frequency Domain[7]:

In the frequency domain, Envelope Detection (ED) technique is used to find the Ball pass frequency outer race (BPFO) and Ball pass frequency inner race (BPFI) With the help of Fast Fourier Transform (FFT). It involves mainly three steps as given in fig 2. First, the signal is high passed to retain only the high frequency component and then it is passed through a low passfilter to obtain the envelope. FFT is applied to the envelope which gives 1x frequency of BPFO or BPFI. This is used as the feature in training the Support Vector Machine.

Time-Frequency domain [7,8]:

The signal obtained is non-stationary, hence we cannot extract much relevantinformation using FFT. Due to this, Wavelet Packet Transform is used in this paper. Combination of EWPT and WPT is used to form a time-frequency domain feature vector. WPT is applied for both ED and the denoised signal. Particular frequency bands are chosen in which fault in all four regions can be distinguished effectively. The energy of these bands is calculated and used as features.

IV. FAULT DIAGNOSIS USING SVM[9]

A feature vector is generated using the features extracted as explained in the previous section.

$$Feature\ vector = \begin{bmatrix} A_{11} & \cdots & A_{1d} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nd} \end{bmatrix} \quad (6)$$

The extracted features are arranged in the form a matrix as shown in the equation (6). Each row represents sampled data and each column represents features extracted from it. This model is used to train the SVM for the detection of pattern and fault classification. SVM is based on the structural risk minimization principle of statistical learning theory. In their basic form SVM finds the hyperplane that separates the training data with maximum margin.

Basically SVM is a binary classifier. It can classify data between two classes only. In this work data is to be classified between four classes. Hence a multiclass SVM is implemented using one-against-one technique [10] and the result is classified to its respective classes using the maximum voting technique.

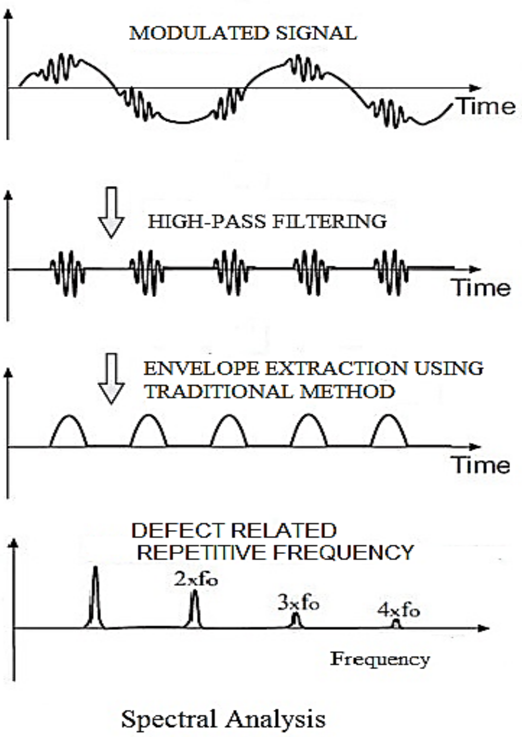


Fig 2: Envelope detection process [11]

Two layer SVM is used in this work. In the first layer data are classified between outer race fault, inner race fault and others. Ball fault and healthy bearing acoustic signatures are similar. Hence detection at its early stage is very difficult. To overcome this problem, forthe second layer, 4th level WPT decomposition is used to extract the features between healthy and ball fault. These features are used in training SVM and the fault is classified.

V. EXPERIMENTAL DATA

Four bearings with fault positions onthe outer race, inner race, ball fault and a healthy bearing is used in this analysis. Each bearing is fitted to shaft one after the other for analysis. The shaft is driven by motor through a belt drive. Acoustic signals were recorded by varying shaft speed. The fig 3 shows the complete setup of the test rig for the analysis of the faulty bearings.

- The 1st component OROS 3x, is used for the real time data analysis and recording purposes.
- 2 and 3 are Accelerometers mounted horizontally and vertically to record vibrations from the system respectively.
- 4 and 6 are secondary and primary microphones respectively. Secondary microphone is used for recording noise and primary microphone is used to record acoustic emissions produced by the bearing.
- 5th component is setup for the lubrication system. Two different oil pressures are used, $3kg/cm^2$ and $6kg/cm^2$.
- 7th component is bearing under test.

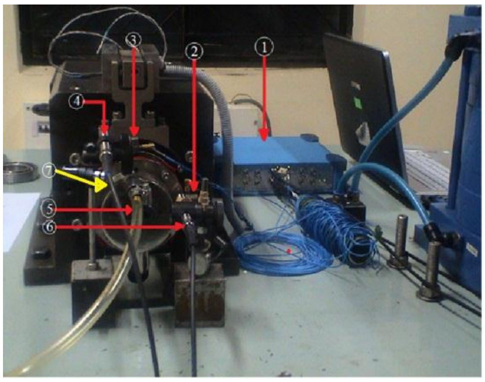
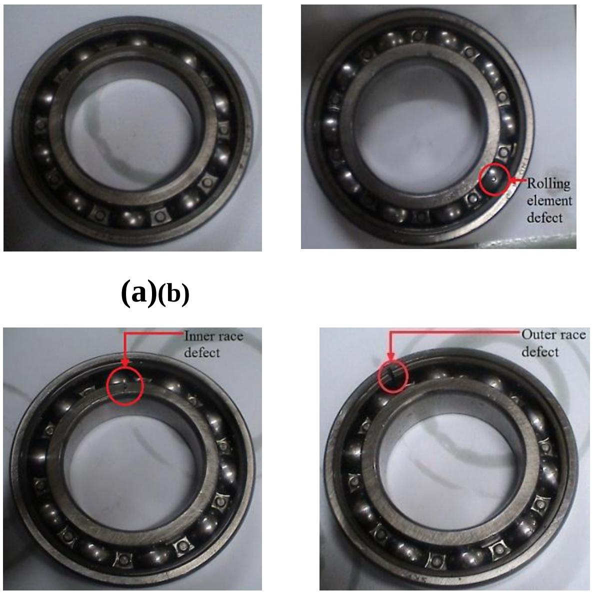


Fig 3: Testing rig (courtesy: NAL)

The bearing type used in this work is SKF 6201. Four different bearings are used for the analysis of four types of fault positions, Healthy, Outer race fault, inner race fault and rolling element fault. Each bearing is fitted separately into the rig, AE were recorded. The different fault conditions are shown below in the fig4.



(a)(b)

(c) **(d)**

Fig 4: Bearings used for testing, (a) Healthy bearing,

(b) Rolling element fault, (c) Inner race fault, (d) outer race fault

The specifications of the bearing are:

Ball diameter = 13 mm

Contact angle = 0 deg

Inner diameter = 50 mm

Outer diameter = 90 mm

No. of balls = 10

The bearing at the load end supporting the motor shaft is tested for different loads from 0kg to 40kg in steps of 10 kg. Single faultis introduced into the bearings using ElectronicDischarge Machining (EDM). Acoustic data is acquired from the acoustic pressure sensor placed 6mm away from the bearing under test. The signal is sampled at 51.2 KHz.

The acoustic signals are recorded for four different conditions of the bearing: (1) healthy, (2) outer race fault, (3) inner race fault, (4) ball fault.

VI. PROPOSED METHOD

The proposed algorithm contains three parts. The first part is signal pre-processing, second part is feature extraction and the third part is fault detection and classification.Fig 5 shows the structure of the proposed algorithm.

The raw data is acquired from the system. The data are then clipped to a length of 5seconds to maintain equal size of samples; both the noise and noisy signal are clipped. After clipping, the data is denoised using spectral subtraction as explained in section 2. Due to the spectral subtraction musical noise is induced in the output. To remove the noise, bandpass filter is used. The final processed and clean signal is taken out from the filter for further process.

The denoised signal from the pre-processing block is taken and processed in three domains. In each domain signal is processed and a suitable feature is selected, such that they describe the fault clearly. These processes are explained in section 3. Totally ten features are selected and a feature vector is formed. These feature vectors are used for fault classification and detection. In the final stage, 50% randomly selected data are used for training the SVM and remaining 50% of the data are used for testing as given in fig 5.

Since the data are to be classified into four groups, multiclass SVM is designed as stated in section 4. Two layer SVM classifiers are used to increase the accuracy and reduce the false alarm.

VII. RESULTS AND DISCUSSION

The defects simulated were to produce AE transients, as each rolling element had passed the defect, it was envisaged that the AE bursts would be detected at a rate equivalent to the position of the fault. The observations for burst values and peaks for different rpm and load conditions are analyzed. The shaft speed is fixed at 1500rpm and oil pressure is varied as 0kg/cm^2, 3kg/cm^2, and 6kg/cm^2. For each oil pressure, diagnostic parameters were calculated and analyzed.

The results obtained for the proposed algorithmin the first stage is given in table 1. EWPT and WPT techniques are used as explained in [7, 8] with single stage SVM for the same data set. The results are tabulated and analyzed. WPT and EWPT both techniques are not individually effective in the detection and classification of fault using acoustic signals. In the proposed method the drawbacks of the techniques are overcome by combining them along with the time and frequency domain features. The results are shown in table 1.

Table1: Detection and classification of fault

Fault position	WPT	EWPT	Proposed Algorithm
Others	100%	100%	100%
Outer race	84.66%	58%	86.2%
Inner race	56.8%	66%	100%

Ball fault detection is a very challenging task. The acoustic emission from the fault occurs only when it touches the outer or inner race. The table 2 compares three methods for the detection of ball fault. In each method, 50% randomly selected data are used to train and rest is used for testing. The results of each technique are tabulated and analyzed.

For the detection of the ball fault, second layer SVM is used in the proposed algorithm, where data classified as others in stage 1 is taken and processed and classified again in its respective class. This increases the accuracy of detection. EWPT and WPT are also used with single stage SVM for comparison and results are tabulated in table 2.From the table 2, it is clear that using only EWPT or WPT, detection of the presence of fault and classification to its respective class is very poor. Hence in proposed method, both the methods are combined and a two layer classification is used to achieve better results.

Table 2: comparison of Ball Fault detection

	Healthy	Outer race	Inner race	Ball fault
WPT	75.1%	16.2%	8.6%	0%
EWPT	74.5%	21.1%	0%	0%
Proposed algorithm	2.2%	0%	0%	97.7%

VIII. CONCLUSION

It has been shown that the fundamental source of AE in seeded defect tests was due to material deformation introduced with the help of EDM technique. Also acoustic emission is sensitive to the variations in the bearing. From the above inference we can conclude that acoustic data processing can be used as an alternative to well established vibration analysis. We can implement the entire system with simple microphones which are cost effective, and non-contact type data analysis is done other than laser based vibration sensor which are very costly. Acoustic technique must be implemented with great precision for better results. A new algorithm is developed and successfully implemented to achieve high detection rate and to reduce false alarm.

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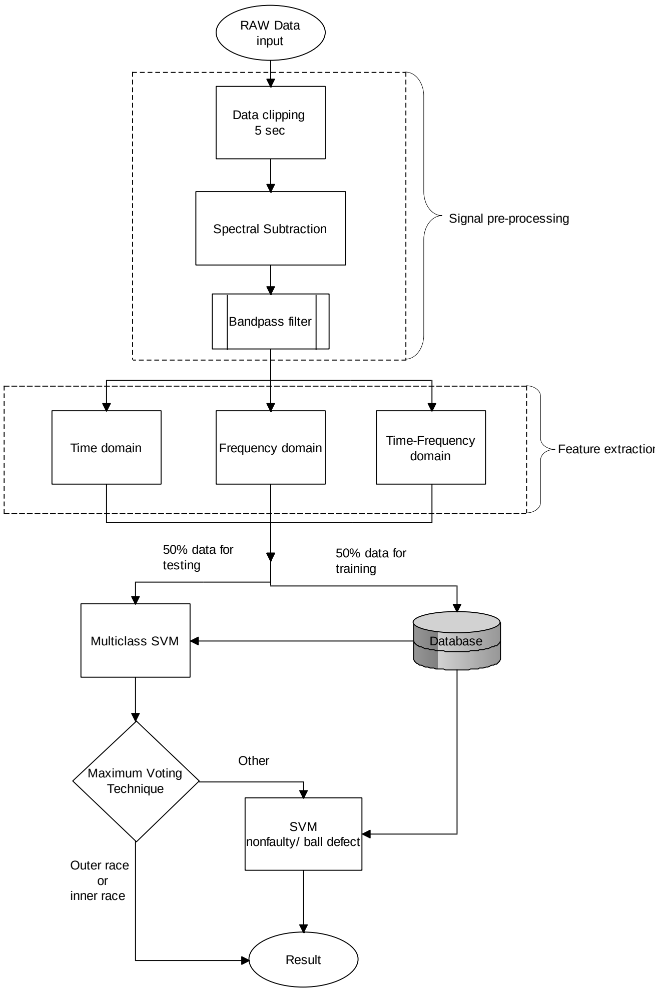

Fig 5:Flowchart for proposed method

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