A non destructive method to detect the incipient fault in rolling element bearing

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ABSTRACT

It is essential to have prior warning of incipient fault(s) in any critical equipment occurring due to vibration. Vibration monitoring is a good nondestructive technique to detect the fault of machines at an early stage. Capturing vibration signature of machines at slow speed is a difficult task due to impact of low energy, mostly absorbed by the structural path and falls much below the cut off frequency of the normally available accelerometer. To resolve the issue, a systematic procedure has been developed. It has the facility to break the signal in different level, envelope capturing and finally convert to frequency spectrum. The system has been tested under various operating condition that suits to industry to diagnose the problem of bearing. The method can predict the problem very well at its inception.

Introduction

Bearings are common element and most important to all forms of rotating machines. The failures of bearing without warning will result in catastrophic consequences in many situations like rolling stand, converter, double deck screen etc in steel industries. The most common practice in maintenance is visual inspection and change/replacement of the component at fixed time intervals. The application of health monitoring, by observing the behavioral and change of operating condition of the machine or its elements provides in service assessment and incipient condition of fault if any. This will result in lowering the production down time and help in planning the repair work at convenient time

A wide variety of techniques, using various algorithms developed for detection and diagnosis of faults in rolling element bearings, have been introduced to inspect raw vibration signals. These algorithms can be classified into time domain, frequency domain, time-frequency domain, higher order spectral analysis, neural-network and model based techniques. Time domain approaches are based on the analysis of the vibration data as a function of time. The principal advantage of this type of analysis is that no data are lost prior to inspection. However, the disadvantage is that there is often too much data for easy and clear fault diagnosis [1]. Features are extracted from the time-domain representation of vibration signals such as peak value, mean, root-mean square (RMS), kurtosis, crest factor, impulse factor, shape factor, and clearance factor.

The frequency domain refers to the display or analysis of the vibration data based on the frequency. The most basic and well-known method in this group is spectral analysis based on the Fast Fourier Transform (FFT). The power spectrum reveals how energy is distributed over frequencies and therefore is very useful in identifying periodic phenomena and determining their strength. Because a large number of forcing functions in rotating machines are proportional to a fundamental frequency such as the rotating frequency. The principal advantage of the method is that the repetitive nature of the vibration signals is clearly displaced as peaks in the frequency spectrum at the frequency where the repetition takes place. The interaction of the defect in the rolling element bearings produces pulses of very short duration, whereas the defect strikes the rotation motion of the system. These pulses excite the natural frequency of the bearing elements, resulting in the increase in the vibration energy at these high frequencies [2].

Time-frequency domain techniques use both time and frequency domain information allowing for the investigation of transient features. A number of time-frequency domain techniques have been proposed including the short time Fourier transforms, the Wigner-Ville distribution, and the wavelet transform [3]. The technique wavelet transform is the latest and it has become popular. The discrete wavelet transform offers simultaneous interpretation of the signal in both time and frequency domain which allows local, transient or intermittent components to be exposed. Such components are often obscured due to averaging inherent within spectral-only methods such as the Fourier transform. The discrete wavelet transform (DWT) employs a dyadic grid and orthonormal wavelet basis functions and exhibits zero redundancy.

This paper is arranged as follows. A description of the typical faults of the bearing is presented in section 2 while the basic concepts in wavelet analysis are explained in Section 3. The data used for monitoring and diagnosis is described in Section 4. The detailed fault diagnosis procedure based on wavelet analysis is discussed in Section 5. The last section concludes the paper.

Bearing Fault

Rolling element bearings fail because of manufacturing errors; improper assembly, loading, operation, or lubrication; or because of too harsh an environment. However, even if a bearing is perfectly made, assembled, etc. it will eventually fail due to fatigue of the bearing material.

Under normal operating conditions of balanced load and good alignment, fatigue failure of the bearing parts begins, with small fissures located below the surfaces of the raceway and rolling-elements. Another important cause of bearing failure is the bearing misalignment, which is caused by improperly forcing the bearing housing onto the shaft or in the housing. This produces a serious damage of raceways and leads to premature failure. Regardless of the failure mechanism, defective rolling-element bearing generates vibrations at the rotational speed of each component.

Each bearing element has its own characteristic frequency of defect. These frequencies can be calculated from the kinematic relations, i.e. the geometry of the bearing and its rotating speed.

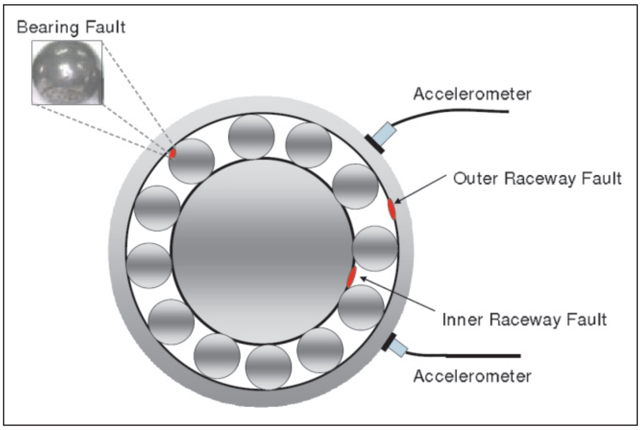


Fig. 1: General Scheme of rolling element bearing faults.

The vibration produced by a healthy, new bearing is low in level and looks like random noise. The vibration produced by the bearing changes as the fault begins to develop. Every time a rolling element encounters a discontinuity in its path a pulse of vibration results. The resulting pulses of vibration repeat periodically at a rate determined by the location of the discontinuity and by the bearing geometry. These repetition rates are known as the bearing frequencies, more specifically:

- Ball passing frequency of the outer race (BPFO) for a fault on the outer-race
- Ball passing frequency inner race (BPFI) for a fault on the inner-race
- Ball spin frequency (BSF) for a fault on the ball itself
- Rolling element defect frequency (EDF) for a fault on the ball
- The fundamental train frequency (FTF) for a fault on the cage.

The bearing frequencies can easily be calculated from the bearing geometry as follows:

$$BPFI = \frac{n_b f}{2}\left(1 + \frac{D_b}{D_p}\cos\alpha\right), \tag{1}$$

$$BPFO = \frac{n_b f}{2}\left(1 - \frac{D_b}{D_p}\cos\alpha\right), \tag{2}$$

$$BSF = \frac{f}{2}\frac{D_p}{D_b}\left(1 - \left(\frac{D_b}{D_p}\cos\alpha\right)^2\right), \tag{3}$$

$$EDF = 2BSF = f\frac{D_p}{D_b}\left(1 - \left(\frac{D_b}{D_p}\cos\alpha\right)^2\right), \tag{4}$$

$$FTF = \frac{f}{2}\left(1-\frac{D_b}{D_p}\cos\alpha\right), \tag{5}$$

where f is the rotational speed of the inner race, n_b is the number of rolling elements, D_p is the pitch circle diameter, D_b is the rolling element diameter and a is the contact angle.

Wavelet Analysis

The wavelet transform has emerged as an efficient tool to deal with non-stationary signals such as vibrational signal waveforms [4-5]. It offers simultaneous interpretation of the signal in both time and frequency domain which allows local, transient or intermittent components to be exposed. Such components are often obscured due to averaging inherent within spectral methods such as the Fourier transform. Wavelet transform can be continuous or discrete. The continuous wavelet transform reveals more details about a signal but its computational time is enormous. For most applications, however, the goal of signal processing is to represent the signal efficiently with fewer parameters and less computation time. The discrete wavelet transform (DWT) can satisfy these requirements.

The DWT employs a dyadic grid and orthonormal wavelet basis functions and exhibits zero redundancy. The DWT computes the wavelet coefficients at discrete intervals (integer power of two) of time and scales [5]. The computed DWT coefficients can be used to form a set of features that unambiguously characterize different types of signals. The dilation function of the DWT can be represented as a tree of low and high pass filters, with each step transforming the low pass filter into further lower and higher frequency components as shown in Figure 2. The original signal is successively decomposed into components of lower resolution, while the high frequency components are not analysed any further. The low-frequency components of the signal are called approximations, while the high-frequency components are called details. For example, if Fs is the sampling frequency, then the approximation of an N level DWT decomposition corresponds to the frequency band

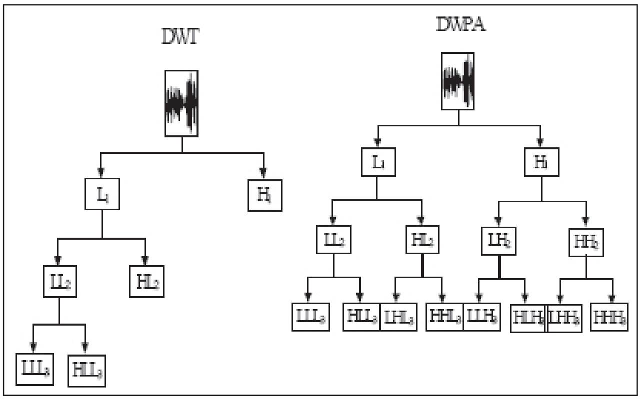


Fig. 2: Filter bank representation of the DWT and DWPA decompositions

$$\left[0, \frac{F_s}{2^{N+1}}\right]$$

whereas the detail covers the frequency range

$$\left[\frac{F_s}{2^{N-1}}; \frac{F_s}{2^{N}}\right]$$

The power and the flexibility of the DWT can be enhanced by using the discrete wavelet packet transform, (DWPT). Unlike the DWT, which only decomposes the low frequency components (approximations), DWPT utilises both the low frequency components (approximations), and the high frequency components (details) [5]. From this family of bases, a method for choosing the optimum scheme for a particular signal can be developed. This process requires a lot of a-priori information such as the choice of a mother-wavelet, the level of decomposition, and the features to be extracted. In addition, an algorithm has to be found for the selection of the best basis.

Enveloping

Envelope Analysis extracts the periodic impacts, and the modulated random noise produced within a deteriorating rolling element bearing even when the impacts and the noise relatively low in energy and "buried" within the other vibrations from the machine. It differentiates between the periodic impacting of a rolling element bearing fault and the random impacts of other phenomena. The Envelope spectrum measures the modulation of the random noise produced in the bearing. This helps to diagnose and quantify smoothened bearing defects as well as bearing mounting errors.

In rolling element bearings, when the rolling elements strike a local fault on the inner or outer race, or a fault on a rolling element strikes the inner or outer race, an impact is produced. The bearing frequencies are categorized as BPFO (ball passing frequency outer race), BPFI (ball passing frequency inner race), BFF (ball fault frequency), and FTF (fundamental train frequency).

The sidebands mingle with the frequency components of the vibration signal; it is hard to distinguish them in the spectrum at low operating speeds. Impacts in time domain generate many harmonics extending to very high frequency in frequency domain. Often some of these harmonics excite resonance in structure, bearings or sensors. Exact location of the resonance is usually not known and cannot be determined easily. However, the resonance amplifies the modulating and carrier signals. Envelope analysis when applied in this region is a useful tool for amplitude demodulation [6]. The envelope analysis function is based on the Hilbert transform method. This improved demodulation method attenuates the influences from high frequency contents and makes the envelope frequency easier to identify.

Experiment

The investigation in this paper is entirely based on the vibration data obtained from the laboratory using Machinery Fault Simulator (MFS) shown in Figure. 3, the data were collected from an accelerometer mounted on the housing of a bearing at rear end. In this set up the load can be varied by putting the dead weight and using magnetic brake of MFS. The data collection was done for the non drive-end bearing to avoid the dive noise.

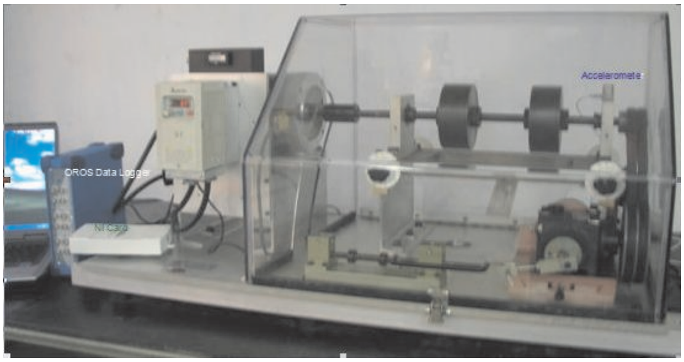


Fig. 3: Experimental Set up (Machinery Fault Simulator)

Bearings with different faults like outer race fault, inner race fault and fault at ball or rolling element were procured from bearing manufacturer. The data were gathered for four different conditions: (i) good/normal; (ii) outer race fault; (iii) inner race fault; (iv) ball fault. The data is sampled at a rate of 50 - 100kHz and the duration of each vibration signal was 5-10 seconds. All the experiments were repeated for four different load conditions and MFS was operated different speed within the limit slow speed (<500 rpm)

The experimental data were decomposed into different level using Wavelet Transformation. The level 4 and 5 i.e. d4 and d5 were used for diagnosis of incipient fault using the envelop capturing and finally enveloping the data.

Result & Discussion

The collected data were plotted (Time - Amplitude). They were raw data and mixed with surrounding noises. In some cases higher amplitudes were seen in both good and faulty bearing. Nothing could be concluded from the plot.

The data were further processed by wavelet transformation and decomposed in different levels. Mostly d4 and d5 levels were used to diagnose the existence of incipient fault if any. The amplitude of good bearing (data (i)) at a particular speed, load were used as the base data. The deviation from this was considered as abnormal.

The figure 5 was a plot (data (ii)) of wavelet coefficient. Ten bright illuminated bands were present. This was caused by ten strikes or impacts due to the passing of balls over the defect or fault. The bearing characteristic frequency i.e. BPFO was 10Hz. The presence of 10 illuminated bands in a second was the indication of fault at outer race. Such clear illuminated bands were not found in case of fault at inner race or at rolling element.

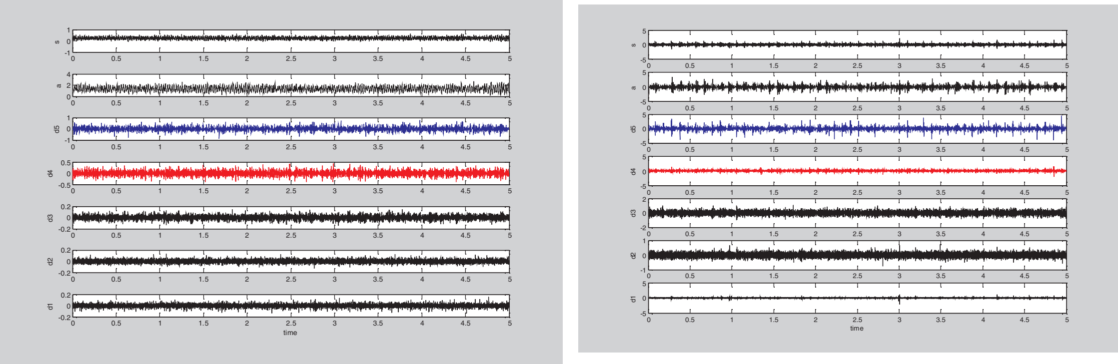
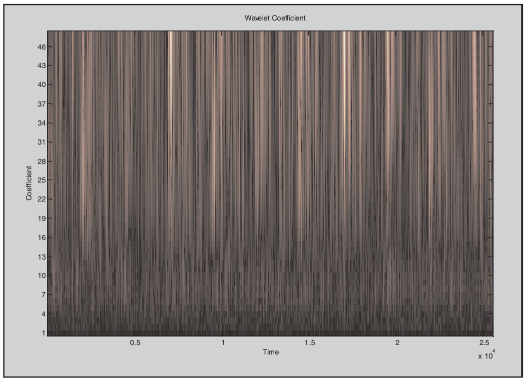


Fig. 4: Time amplitude raw data for: a) Good Bearing, b) Bearing with defect



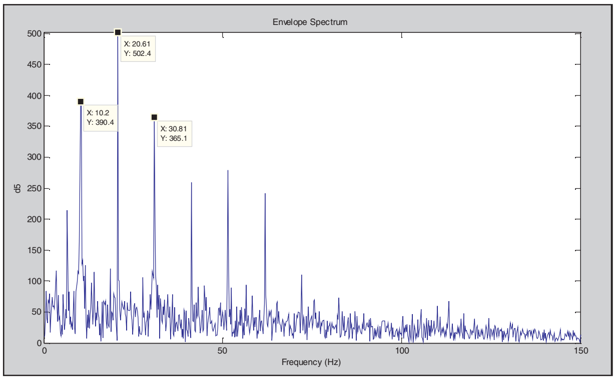


Fig. 5: Wavelet coefficient plot for bearing with Outer race defect

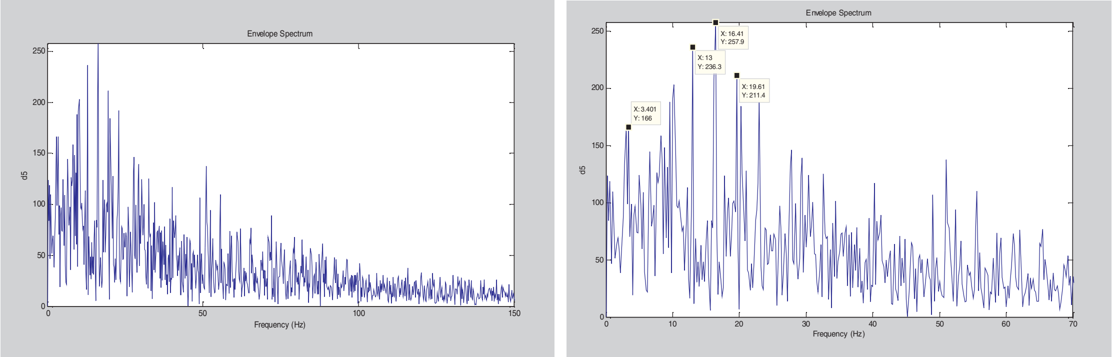
Fig. 6: Envelope spectrum of d5 for bearing with Outer race fault

The envelope spectrum (figure 6) of d5 level of wavelet transposed of data (ii) showed the appearance higher amplitude in a clear sequence. The amplitudes were present at 10, 20 and 30Hz i.e. at bearing characteristic (BPFO) frequency and at its harmonics. This was the indication of fault at outer race of the bearing.

The wavelet transposed (d5) data for inner race fault (data (iii)) was processed through envelope captured. Here lots of peaks were observed (figure 7 (a)) but clear indication of fault was absent. This plot was then zoomed at lower frequency (figure 7 (b)) area. The presence of amplitudes was noticed at 16.67 with bands (±3.4 Hz) around it. The bearing characteristic frequency for it was 16.67 Hz (BPFI). The frequency 3.4 Hz was the rotational speed for the shaft. This indicated the presence of inner race fault.

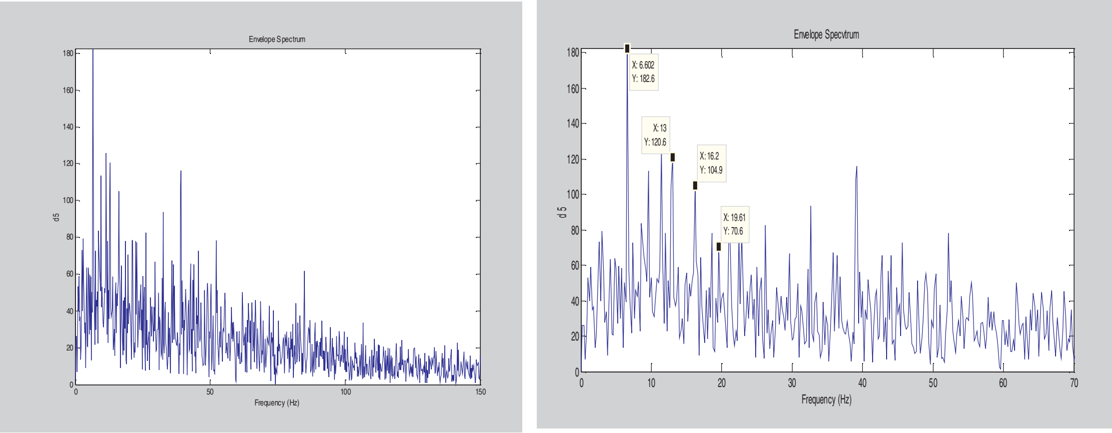
The data (iv) was decomposed and the envelope spectrum of wavelet transposed d5 was shown in figure 8.When the envelope spectrums of d5 ware zoomed in the low frequency region

(Figure. 8 (a) before zoom and (b) after zoom), The peaks observed at 16.2Hz which was close to the BPFI (16.6 Hz) and at 6.6Hz which was close to the BSF (6.3 Hz). The side bands (±3.4Hz) were also observed around the peak at 16.67 Hz. Moreover, there was also a peak at 3.2Hz corresponding to the shaft speed. It was clear symptoms of failure for rolling element



a **b**

Fig. 7: (a) Envelope Spectrum of d5 (b) Envelope spectrum Zoomed For bearing with inner race fault



a **b**

Fig. 8: (a) Envelope Spectrum of d5 (b) Envelope spectrum Zoomed

Conclusion

The wavelet decomposition of experimental data with various bearing faults show fault symptoms. These are to be analyzed to isolate the kind of fault, if any.

Based on these analyses, the following conclusions are arrived at:

a) The vibration levels of faulty bearings are considerably higher than good bearings. Therefore, certain threshold value may be set to decide if the bearing has some kind of fault or not.

b) The envelope spectrums of data collected with outer race fault clearly shows BPFO and its harmonics. If the outer race fault is not in the load zone, then it may go undetected.

c) The inner race fault symptoms are also clearly visible in the envelope spectrums. The BPFI appears as the most prominent peak and around this peak, sidebands spaced at intervals of the shaft speed are observed

d) Ball fault is the most difficult one to isolate in low speed machines. To isolate this fault, data must be collected at high sampling rate and for a longer duration. This is because the cage frequency (FTF) is very low. The symptoms of ball fault in the envelope spectrums are the prominent peaks are BPFI and BSF (ball spin frequency).

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