# BEARING FAULT DIAGNOSIS BASED ON VIBRATION SIGNALS

S. Abdusslam, F. Gu, A. Ball
University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

## ABSTRACT

*The vibration signal obtained from operating machines contains information relating to machine condition as well as noise. Further processing of the signal is necessary to elicit information particularly relevant to bearing faults. Many techniques have been employed to process the vibration signals in bearing faults detection and diagnosis. Two common techniques, time domain techniques and frequency domain techniques are used in this paper to investigate bearings condition.*

**Keywords:** Bearing, spectrum analysis, envelope analysis.

## INTRODUCTION

Bearing are used in almost all rotating machinery systems. Bearing condition monitoring has become increasingly essential to improve their reliability and avoid catastrophic failures. As machinery occupies the biggest volume of the industrial sector, therefore, special attention must be paid towards their diagnostic systems and failures [1]. Many novel bearing condition monitoring techniques have been invented in recent years to ensure the maximum performance and extend the bearing life.

The challenge lies in coming up with a highly reliable and cost efficient monitoring system which though not necessarily comprehensive but should be capable of tracking down the major causes of bearing failures and give an early indication thereby enabling effective preventive maintenance and eventually reduce costs per failure [2].

In this paper, the vibration signals of a healthy bearing and outrace and inner race bearing faults were collected and analyzed by different signal processing techniques to examine the characteristics of vibration signals and the performance of bearing faults diagnosis.

## TEST RIG FACILITIES AND VIBRATION MEASUREMENT

The test rig is demonstrated in figure 1, it comprises from a 3-phase electrical induction motor coupled with a dynamic brake (the stator of which is free to move so that torque measurements may be taken). The motor is connected to the brake by means of four shafts, which are connected by three pairs of matched flexible couplings. Two bearing housings each contain one roller and one captive ball bearing supporting these shafts.

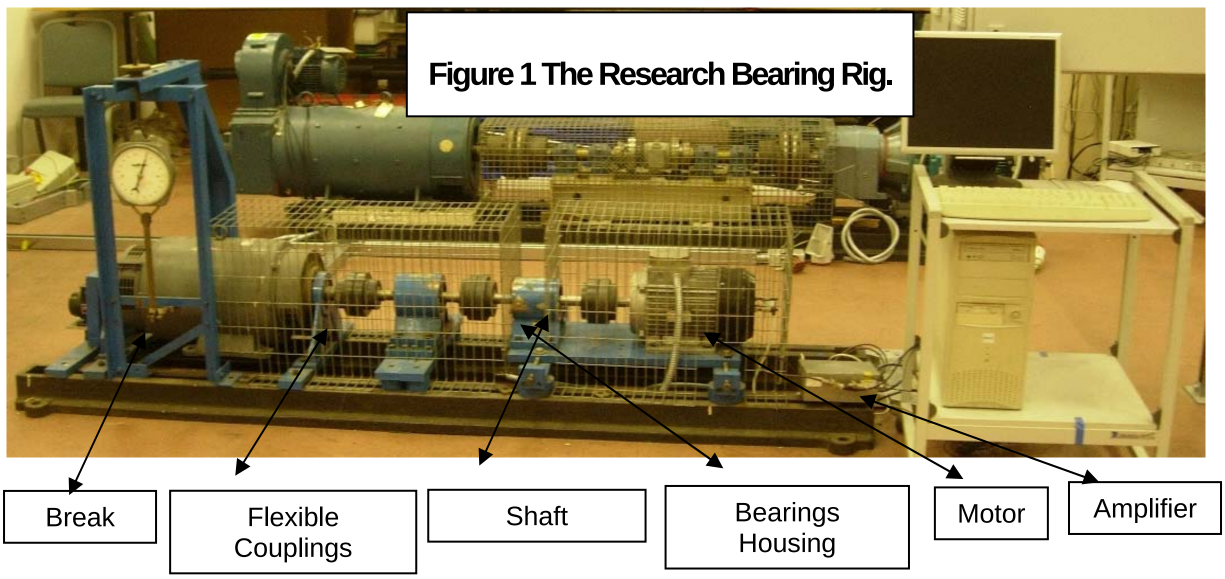


**Figure 1 The Research Bearing Rig.**

In the experiment, bearings (N406) are used in this paper and their specifications are shown in the table 1 as follows:

| Elements | Measurement |
|---|---|
| Ball Diameter | 14 mm |
| Balls' Number | 9 |
| Contact Angle | 0 |
| Pitch Diameter | 59 mm |

**Table 1** Rolling Bearing (N 406) specification

There are three basic motions used to describe the dynamic of the bearing elements in this paper, each of movement having a unique corresponding frequency [3]. The corresponding character frequencies are shown below in Table 2

Cage frequency:

$$f_c = \frac{1}{2} f_A \left[ 1 - \frac{D_b}{D_p} \cos \alpha \right] \quad \text{------------------------------------- (1)}$$

Outer race frequency:

$$f_O = \frac{N_b}{2} f_A \left[ 1 - \frac{D_b}{D_p} \cos \alpha \right] \quad \text{------------------------------------- (2)}$$

Inner race frequency:

$$f_i = N_b ( f_A - f_c ) \quad \text{------------------------------------- (3)}$$

Where:
$N_b$ number of balls, 9
$f_A$ shaft rotational frequency (Hz)
$D_b$ ball diameter (mm) 14
$D_p$ pitch circle diameter (mm) 59
$\alpha$ contact angle 0 (because there is no axial load)

| Defect position | Frequency (Hz) |
|---|---|
| Inner race | 135.1 |
| Outer race | 83.3 |
| Cage | 9.3 |

**Table 2** frequency calculations for (N 406) bearing

**Data Acquisition System (DAS)**
A data acquisition system specification (DAS) is shown in table 3.

| Parameter | Performance |
|---|---|
| No. of Channels | 8 channels |
| ADC resolution | 12 bit |
| Sampling rate (maximum) | 1 MHz |
| On-board memory | 1 Mb |
| Types of trigger | External TTL |
| Max. input voltage | ±10 V |

**Table 3** Data Acquisition System (DAS) Specification

## COMPARISON OF DIFFERENT APPROACHES TO BEARING MONITORING

A detailed comparison of the methods and techniques of bearing diagnosis are presented: FFT, time domain, frequency domain and envelope analysis. Three bearing conditions were considered, with assumptions that the bearing has no clearance, no lubrication and no slipping errors bearing in mind some other errors such as manufacturing error, speed relative errors and ball estimation error that give an accuracy about 97%, (1) normal condition, which is also used as reference; (2) small outer race fault; (3) small inner race fault. The faults conditions are very common related faults to the bearings.

## EXPERIMENTAL IMPLEMENTATION AND DATA ANALYSIS

Two channels of vibration signals were collected from the accelerometers mounted on bearing housing. Two tests were conducted for studying bearing fault detection and diagnosis. Test 1 was for two bearings corresponding to a healthy and a small outer race fault bearing respectively. Test 2 was for two bearings corresponding to a small inner race faulty bearing and the outrace fault bearing respectively. The characteristic frequencies for the faulty bearings are given in table 4.

| Defect position | Frequency (Hz) |
|---|---|
| Inner race | 135.63 |
| Outer race | 83.64 |

**Table 4** bearing characteristic frequencies

Both of the tests were under a shaft rotational speed (SRS) of 1461.7rpm or 24.36Hz under no load. Each test acquired data at a sampling rate of 62,500Hz so that frequency content can be investigated up to about 30 kHz. In addition the data length for each test record is 960,000 and three such records were obtained. This allows spectrum average to be carried out at high numbers and hence produces reliable results.

To detect and diagnosis different types of bearing faults, following key steps of data processing have been implemented:

1) Visualising the raw data waveform in the time domain;
2) Investigating the spectrum of the raw data in the frequency domain which is achieved by applying FFT to the raw data with a hanning window.
3) Investigating the envelope waveform in the time domain which is obtained by applying a band pass filter to the high frequency range, and then applying Hilbert transform to the filtered signal subsequently.
4) Investigating the envelope spectrum to check if there are bearing feature frequencies. The envelope spectrum is obtained by applying FFT to the envelope signal.

In addition, the FFT windows size was tested to be 16384 data points so that a sufficiently high frequency resolution and a high number of averages can be achieved with the data length collected.

When the envelope analysis is performed; and there are defects in the bearings, characteristic bearing fault frequencies of high amplitudes, along with their harmonics, will appear in the envelope spectra. Since the highest fault frequency of interest is 135.1 Hz, all envelope spectra plotted here are in the frequency range.

Root-Mean-Square (RMS) will work as an indicator of average amplitude level of vibration signals. As the energy within a signal is relative to the squared value of vibration amplitude, RMS can also be considered as a directory of vibration energy in this study.

## NORMAL CONDITION

When a bearing has no fault it usually has very small vibration amplitudes in the time domain. Moreover, the characteristic frequencies cannot be seen in either common spectrum or envelope spectrum. This can be illustrated by the red-dashed line in the top plot of Figure 2 and the bottom plots of Figure 3. Compared with faulty case in the same plots, the vibration from the healthy is slightly smaller and its envelope spectrum is very flat, i.e. no clear spectral lines can be seen.

## SMALL OUTER RACE FAULT BEARING

The outer race fault is simulated by scratching the outer race with a nail (seeded fault) as shown in Figure 2.

**Figure 2** Small Outer Race Fault

The waveform of the bearing in the time domain is shown by the solid-blue line in the top of the figure 3; although the figure shows the signal with the peak value and RMS as indicators, the waveform looks complicated, with successive impulses occurring at somewhat similar spacing between one another. Despite, the shaft rotational frequency and its multiples can be easily identified but the characteristic fault frequency of the outer race and its harmonics are not obvious in the spectrum. Therefore, we cannot tell much about the bearing components condition.

By applying the FFT to change the time domain into frequency domain we can see a clearer image of the signal for the raw data spectrum. From the bottom part of the figure 3 we can see where the signal is settled and where it spikes, furthermore, the amplitude can be identified.

The top part of figure 4 shows the envelope of the filtered signal in the time domain that is obtained by applying a band pass filter to the high frequency range and then applying Hilbert transform; this part shows the filtered signal amplitudes during the time.

When we apply the FFT to the envelope spectrum, we try to find out if there is any change to the characteristic frequencies of the bearing components or the employed parameters

By applying the FFT again to the filtered signal, a very clear image of the signal can be seen in the bottom part of figure 4. From the figure the outer race fault can be easily seen as high amplitude which can be identified at 0.0049 with frequency 0f 83.23 Hz which is slightly different from its feature frequency that was calculated at 83.64.

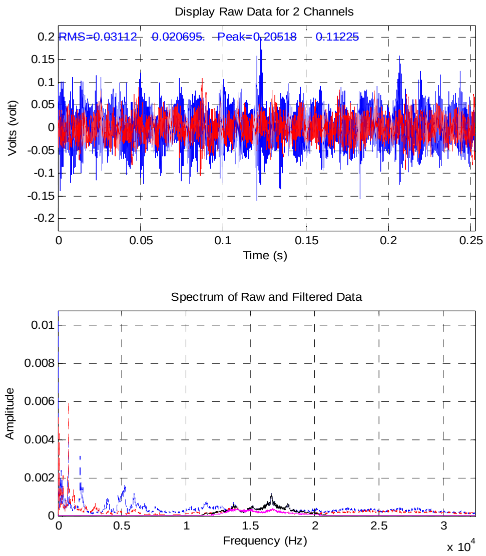


**Figure 3** Small Outer Race Fault as it is seen in the time and frequency domain

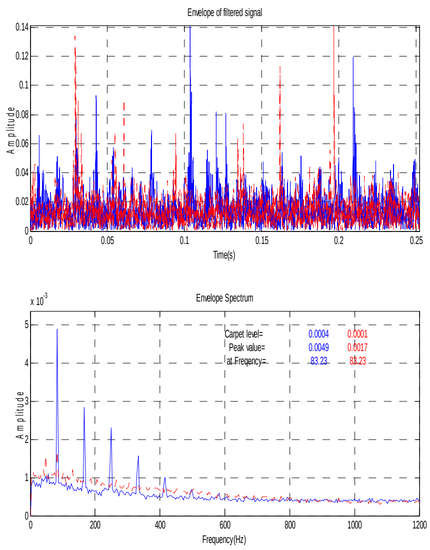


**Figure 4** Small Outer Race Fault as it is seen in the envelope and envelope spectrum

## SMALL INNER RACE FAULT BEARING

The inner race fault is simulated by a small scratch on the inner race of the bearing as shown in figure 5.

**Figure 5** Small Inner Race Fault

The same steps of discussing the faults are followed in this case. During this test the same bearing with the outer race fault is also tested.

The first impression created by the waveform in the top part of figure 6 is that the general vibration level of the signal is higher than those of the normal condition. Generally, the waveform is very complicated and overlapped with high amplitudes impulses and there seem to be no regular spacing among these impulses.

By applying the FFT to the raw data a better image can be seen as frequencies and amplitudes, however, it is still vague to identify the characteristic frequencies for the faults because the frequencies are masked by 1 x SRS and its harmonics. In addition, from the figure it is noticeable that significant increase in the amplitude of higher frequency components is obvious.

The top plot of figure 7 shows the envelope of the filtered signal in the time domain that is obtained (for the bearings) by applying a band pass filter to the high frequency range and then applying Hilbert transform; this part shows the information of signal amplitudes during the time.

By applying the FFT again to the filtered signal, we try to find out if there are any changes to the characteristic frequencies of the bearing components or the employed parameters. A very explicit image of the signal can be seen in the bottom part of figure 7. The inner characteristic frequencies are identified clearly. The fundamental inner race frequency is found to be 134.76 Hz, which has a small difference from its calculated value which was calculated at 135.63 Hz, and the outer race frequency is 83.23 Hz. Furthermore, the peak value of the inner race frequency was recorded at 0.276 V and recorded at 0.0040 V for the outer race.

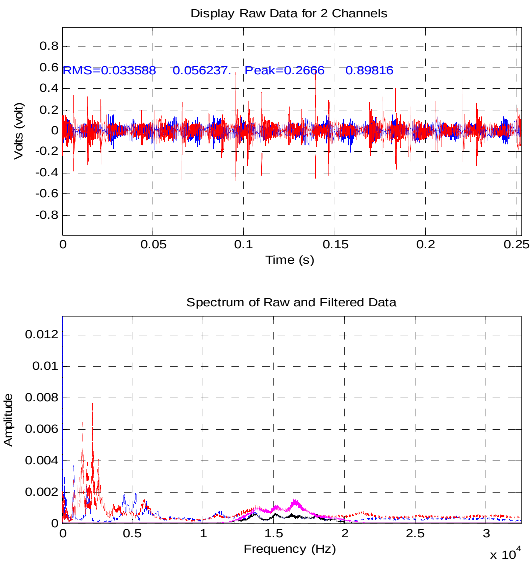


**Figure 6** Small Inner Fault (Raw Data)

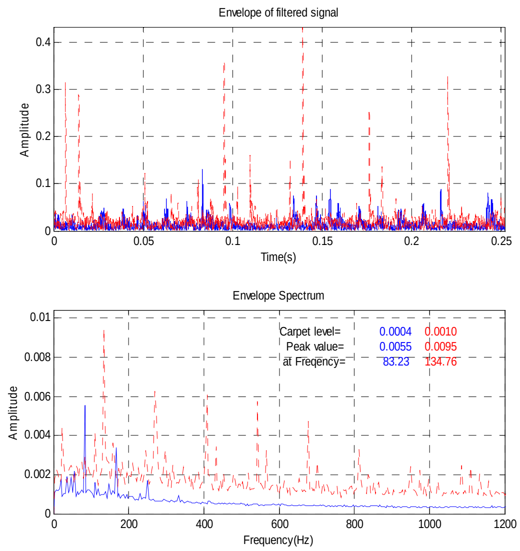


**Figure 7** Small Inner Fault (filtered Data)

## CONCLUSION

In this paper, several fault detection techniques for rolling element bearings were used. A detailed investigation of the time domain and the frequency domain methods was carried out under different bearing fault conditions. The experimental results indicate that limited information can be found from the time-domain signals. The key features of those signals comprise of a large number of sinusoidal waveforms of overlapped dissimilar frequencies. Considerable interference between vibrations signals make it difficult to figure out useful information regarding to the bearings conditions [5]. The same problem preserves in conventional spectrum analysis because the low frequency bearing feature frequencies are buried in the noise and low frequency vibrations from other sources [6]. However, envelope analysis is a more effective reliable approach to capturing the fault features as it is based on high-frequency signals where the noise and interference sources are suppressed significantly. The inner race fault exhibit itself with a harmonic spectrum at its feature frequency. So does for the outrace fault. Because the value of the feature frequency is always different for a bearing, it is possible to discriminate these two types of faults and other possible bearing faults such as those from rolling elements and carriers.
In addition, once the fault type is defined, the severity of it also assessed based on the amplitude of envelop spectrum. In particular, the maximum amplitude and carpet level of the spectrum are used as the measure of the fault severity. Finally, a decision on the status of the system is reached. In order to test the viability of the proposed diagnostic system, a series of experiments were conducted. This automated diagnostic system has a high performance with an overall reliability of 97%.

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