CONDITION MONITORING OF LOW SPEED BEARINGS: A COMPARATIVE STUDY OF THE ULTRASOUND TECHNIQUE VERSUS VIBRATION MEASUREMENTS

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Abstract: Bearing failure is often attributed to be one of the major causes of breakdown in industrial rotating machines that operate at high and low speeds. This paper presents results of a comparative experimental study on the application of the ultrasound technique for condition monitoring of low speed rolling element bearings and conventional vibration measurements with seeded faults on inner-race defects. The effectiveness of the ultrasound technique is demonstrated through signal processing techniques; use of statistical parameters derived from the time domain, and enveloped spectra in the frequency domain. The results reveal that the ultrasound technique is more effective in detecting low speed bearings failure than that of the vibration measurement.

Key Words: Condition Monitoring, Low Speed Machinery, Rolling Element Bearings, Ultrasound Technique, Vibration Measurements

1 INTRODUCTION

Condition Monitoring (CM) is the process used to determine the operational state and health of a machine for the purpose of detecting potential failures before they turn into functional failures. The CM process consists of periodical or continuous data collection, data analysis, interpretation and diagnosis. Condition Monitoring is an integral part of Predictive Maintenance (PM) which is a widely used maintenance philosophy (also known as Condition-Based Maintenance - CBM). This philosophy is based on scheduling maintenance activities only when a possible functional failure is detected. CBM enhances operational effectiveness and safety through research and development of technologies to accurately and reliably predict the remaining useful life of in-service equipment. CM optimizes equipment readiness while reducing maintenance and staffing requirements. Typical CM techniques include vibration analysis, oil analysis, wear particle analysis, ultrasonic analysis, thermographic analysis and motor current signature analysis [1, 2].

One of the more popular tools in the condition monitoring of rotating machinery is vibration analysis. By measurement and analysis of the vibration in rotating machinery, it is possible to detect typical faults such as unbalance, bent shaft, cracked shaft, misalignment, looseness, rubbing, gear faults, motor faults and impellor/blade defects. However, whilst these faults are common, they occur primarily in high speed machinery (> 600 rpm). There is limited information on faults which occur exclusively in low speed machinery, other than those initiated by rolling element bearing defects [3].

Numerous research works have been published on the detection and diagnosis of rolling element bearing defects. Tandon and Nakra [4] presented a detailed review of different vibration and acoustic methods, including vibration measurements in the time and frequency domains, sound measurements, the shock pulse method and the acoustic emission technique. Tandon and Choudhury [5] subsequently updated the reviews incorporating more recent works and advanced techniques currently being adopted in bearing defect detection. Most of the research on bearing diagnosis can be categorized in the time domain and frequency domains. The RMS, crest factor, probability density moments (skewness, kurtosis) are the most popular statistical time domain parameter for bearing defect detection [6-10]. In the frequency domain, the enveloping method, also known as demodulation or HFRT (High Frequency Resonance Technique), have been proven to be a very efficient and popular technique for detection of the characteristic frequencies of bearings [11-16]. Wavelet analysis has also been successfully applied to bearing defect detection [17-21]. In recent years, artificial neural networks and fuzzy logic have also emerged as popular tools for automated fault diagnosis [18, 22-25].

The ultrasonic technique has more recently been proposed as a powerful tool for condition monitoring of bearings in industrial applications particularly for low speeds. This technique captures and processes sound waves that manifest above the human hearing range and has been presdominantly applied in leak detection, crack detection, bearing defect detection and detecting lack of lubrication. Ultrasonic analysis is one of the less complex and less expensive CM techniques [26]. Its simplicity is directly related to the size and ease of use of handheld detectors, and the relatively straightforward presentation of measurement data on meters or digital readouts. However, a quantitative analysis of the signals from ultrasonic detector has not been conducted for condition monitoring of low speed bearings. Furthermore, traditional techniques involving vibration acceleration may not be able to detect an incipient failure due to the low impact energy generated by the relative moving components in low speed bearings.

In this study, the effectiveness of the ultrasonic technique for condition monitoring of low speed bearings is examined using on an experimental approach. An artificially induced fault in the form of a minute scratch on the bearing inner-race was utilised for this comparative study. The ultrasound signal from a normal bearing and a defective bearing are compared with vibration signals through time-domain statistical parameters and frequency-domain envelop spectrum at shaft speeds ranging from 1200 rpm to 30 rpm.

2 THE ULTRASOUND TECHNIQUE

Ultrasound is defined as sound waves that have frequency levels above 20 kHz; higher than what the unaided human ear can normally hear. Most machines emit consistent sound patterns under normal operating conditions. These sonic signatures can be defined and recognized; and changes in these signatures can be identified as components begin to wear or deteriorate. This enables technicians to identify and locate bearing deterioration, compressed air or hydraulic fluid leaks, vacuum leaks, steam trap leaks and tank leaks [26]. Airborne ultrasound operates in the lower ultrasonic spectrum of 20 kHz to 100 kHz. A compressed gas or fluid forced through a small opening creates turbulence with strong ultrasonic components on the downstream side of the opening. Also vacuum leaks produce turbulence similar to pressure leaks; however, the ultrasound is generated within the system. Poorly seated valves can also be detected.

It is worth noting that the Acoustic Emission (AE) technique also deals with signals in the high frequency range and has been increasingly used for condition monitoring of rotating machinery as well as structures. However, the AE technique differs from the ultrasonic technique in terms of the frequency range of interest and parameters for condition assessment. The AE technique generally operates in the 100 kHz to 1 MHz while the ultrasonic technique focuses on the frequency range of 20 kHz to 100 kHz. Parameters such as ring down counts, events, rising time, duration and peak amplitude are normally used in the AE technique to examine abnormality. In the ultrasonic detector, abnormality is usually detected by listening to the characteristics of sound or RMS indicator on the panel.

The heterodyne circuit is the main component in ultrasound detectors. It takes the ultrasound signal detected by the transducer, and converts it into an audible signal (< 20 kHz). This heterodyned signal can be enhanced by an audio amplifier to be heard using standard headphones, or can be processed through a converter to obtain a quantitative output in decibels (dB). The heterodyned signal can also be recorded through conventional data acquisition system.

This study uses the heterodyned structure-borne high frequency elastic waves between 20 - 100 kHz. The main advantage of ultrasound is the high signal-to-noise ratio detection ability. This advantage allows the exact localization of the energy source of the ultrasound activity, regardless of environmental interferences (i.e. noise) [27]. Although the ultrasonic technique using commercial ultrasound detectors is known to have the capability for detecting bearing defects, literature on the application of ultrasonic techniques for bearing condition monitoring using advanced signal processing techniques is generally absent. This study attempts to fill the gap where advanced signal processing techniques in the time and frequency domains are applied to signals obtained from both the ultrasonic technique and vibration measurements.

3 SIGNAL PROCESSING TECHNIQUES FOR BEARING CONDITION MONITORING

3.1 Time Domain Method

The time series signal can be used to perform fault and failure diagnosis by analysing vibration or acoustic data obtained from the equipment. Statistical methods are widely used to investigate the random characteristics of a physical system. It is important to be able to summarize the data obtained and be able to draw meaningful and useful results. The simplest method is to use overall root-mean-square (RMS) level and crest factor, i.e., the ratio of peak value to RMS. This method has been applied with limited success in the detection of localized defects [28-30]. Probability density has also been used popularly for bearing defect detection [8, 9, 29, 31, 32].

This study presents the analysis of vibration and ultrasonic signals with statistical parameters to detect the presence of defects in low speed bearings. The focus of this study lies in determining the relationship between the rotational speed of the bearing and the statistical parameters. This study presents the use of statistical parameters such as RMS, crest factor, skewness and kurtosis, to analyse an induced localized defect at low speeds.

- RMS –suited for steady-state signals
- Crest Factor – a trendable parameter which gives the ratio of the peak to RMS levels.
- Skewness – measures the relative energy above and below the mean level.

• Kurtosis –a compromise measurement between the insensitive lower moments and the over-sensitive higher moments. It is particularly useful in the detection of bearing failure.

3.2 Frequency Domain Method

The Frequency domain refers to the treatment of signals expressed as a function of frequency using the time domain signal. Whilst certain information is more easily interpreted in the time domain, the most detailed analysis of rotating machinery vibration data is often conducted in the frequency domain. Frequency-domain or spectral analysis of the vibration signal is perhaps the most widely used approach for bearing defect detection. It is often the case that signature spectral comparisons are not suitable for detecting damage to rolling element bearings. This is because the energy produced by the bearing defect is overpowered by more dominant signals from other rotating elements, nearby machinery and noise. For this reason, envelop detection is a commonly used signal processing technique for detecting incipient defects in rolling element bearings. This technique [32-34] involves a high-pass filtering operation to eliminate dominating low frequency components from the original signal. This signal is then rectified, demodulated, and a low-pass filter is finally used to eliminate the carrier high frequency. The processed signal is then displayed in the frequency spectrum showing the isolated bearing defect frequencies.

3.3 Modified Peak Ratio

In the detection of a localized bearing defect, it is essential to determine the presence and the severity of the defect. Enveloping technique or HFRT has proven to be an efficient method of displaying bearing defect frequencies by isolating other unwanted frequencies. However, for automatic diagnosis of bearing defect it is necessary to extract a symptom of failure without any human involvement. Shiroishi [32] suggested a peak ratio (PR) as an indicator to identifying the presence of bearing faults in the spectrum. PR is defined as the sum of the peak values of the defect frequency and harmonics over the average value of the spectrum and is shown in Eq. (1).

$$PR = \frac{N\sum_{j=1}^{n} P_j}{\sum_{k=1}^{N} S_k} \tag{1}$$

Where, P_j is the amplitude value of the peak located at the defect frequency harmonic, S_k is the amplitude at any frequency, N is the number of points in the spectrum, and n is the number of harmonics in the spectrum.

A *modified PR* is proposed in this study in order to make it more effective in showing the severity of the defects. The modified PR is defined in the following equation using the differences between the peak defect frequencies and the average value of the spectrum over the average of the spectrum.

$$mPR_O = 20\log_{10}\frac{\sum_{j=1}^{n}(P_j - A_s)}{A_s} \text{ (dB)} \tag{2}$$

$$mPR_I = 20\log_{10}\frac{\sum_{j=1}^{n}(P_j - A_s) + \sum_{i=1}^{l}(Ps_i - A_s)}{A_s} \text{ (dB)} \tag{3}$$

$$A_S = \frac{\sum_{k=a}^{b} S_k}{(b-a)}$$

Where, A_s is an average spectrum amplitude in the frequency band from a to b. By using a frequency band instead of whole spectrum band, *PR* can be a reliable indicator for earlier defect detection. In the case of an incipient bearing defect the amplitude of defect frequencies are often smaller than other peak frequencies.

4 EXPERIMENTS

The test rig used in this study is shown in Figure 1. The shaft is supported by two bearings and connected with an induction motor with a flange-bolt-rubber coupling. The shaft speed can be controlled by an inverter from 30 rpm to 6000 rpm. The bearings used in this test were cylindrical roller bearing (SKF, NJ2204) which has a removable inner ring. The localized defect was obtained by a minute scratch on the inner race. Previous studies have also involved seeded defects induced by using acid etching, spark erosion, scratching or mechanical indentation. Relatively small defects with a width of 1mm and average depth of 20 μm were used to assess the detection capability of incipient failures. It is well known that inner race defects are more difficult to detect than outer race defects due to the relative motion of the ring and the rolling elements. The bearing characteristic frequency for inner race fault (BPFI) is calculated to 6.713 times the shaft speed (Hz). The equipment involved in the collection of vibration and ultrasound data is shown in Fig. 1. It consists of an accelerometer (IMI 608A11), an ultrasound detector (UE Systems ultraprobe 9000), a signal conditioner (PCB 482A20), an analog filter (Krohn-Hite 3202), a DAQ Card (National Instruments 6062E) and a laptop computer with LABVIEW 7.1 (National Instruments).

Vibration and ultrasound data were collected at speeds ranging from 30 rpm to 1200 rpm. The data was analysed using statistical methods in the time domain and envelop spectra in the frequency domain. The vibration signal was sampled at 40 kHz with a cut-off frequency of 10 kHz. Ultrasound was sampled at 140 kHz with a cut-off frequency of 50 kHz. The time duration for each data set was 10 sec for the accelerometer and 4.5 sec for the ultrasound probe. The signal processing and analysis was achieved with the use of MATLAB 7.0 for feature extraction and enveloping.

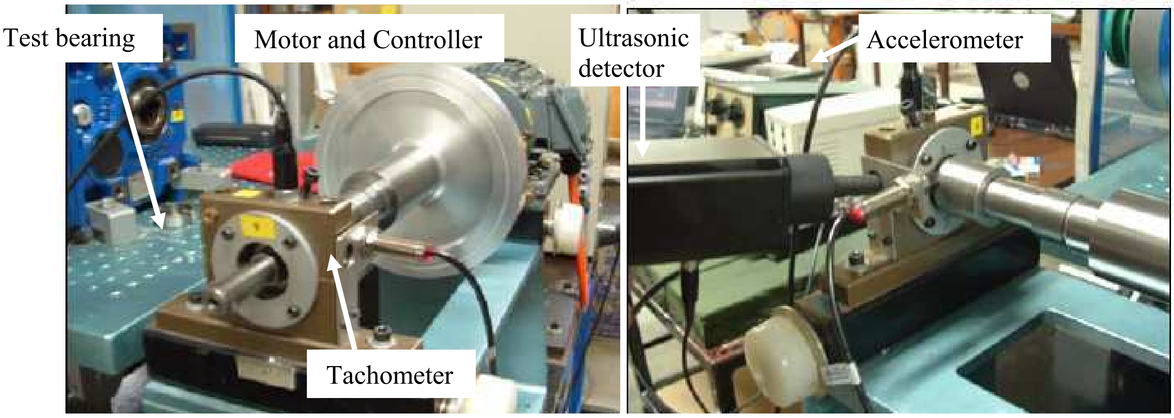


Figure 1. Experimental rig.

5 RESULTS

The signals measured in this experiment were vibration and the heterodyned ultrasound from a normal bearing and the bearing with the inner-race defect, bearing with a range of shaft speeds from 30 rpm to 1200 rpm. The objectives of this test and analysis were to gauge the effectiveness of the ultrasonic techniques by comparing it with vibration signals. The experimental tests are used to uncover the best statistical parameter for fault detection and to introduce an efficient frequency domain indicator for condition monitoring of low speed bearings.

5.1 Time wave form

Figure 2 shows the time wave forms of vibration acceleration signals from a normal and a defective bearing operating at low (150 rpm) and high speeds (1200 rpm). It was noted that at the low speed, there is no significant difference in the characteristics of signals from the normal bearing and from the defective bearing. The two signals can be easily distinguished at high speeds. This implies a potential limitation of the acceleration signal for fault detection of low speed bearing defects. Figure 3 shows ultrasound signal with a heterodyne frequency of 30 kHz under the same conditions. There are significant differences between a normal and a defective bearing in terms of magnitude and shape of the signal. Furthermore, the signals are much clearer at low speeds and display a number of impulses which are generated by the localized defects in bearings. By comparing these two figures, it can be concluded that ultrasound signals are more sensitive at detecting localized defects in bearings than acceleration signals.

5.2 Time Domain Parameters

In this paper, RMS, skewness, kurtosis and crest factor were used to compare their effectiveness for condition monitoring of low speed bearings on the basis that they are commonly used parameters for condition monitoring of bearings. For quantitative comparisons, all parameters are presented in decibel scale with reference of 1mV for each parameter. Figure 4 shows the comparisons of statistical parameters of vibration acceleration signals from a normal bearing with those from a defective bearing at different shaft speeds. RMS and skewness increased as the shaft speed decreased, while the kurtosis and crest factor decreased slightly. The relative amplitudes of parameters are shown in Figure 5. It is importantly noted that all the statistical parameters from vibration acceleration signals have smaller relative amplitudes as the shaft speed decreased, which indicates the vibration signal is not appropriate for condition monitoring of low speed bearings. The skewness and kurtosis values provided good detection at high speeds. Their detection abilities decreased sharply as speed decreased.

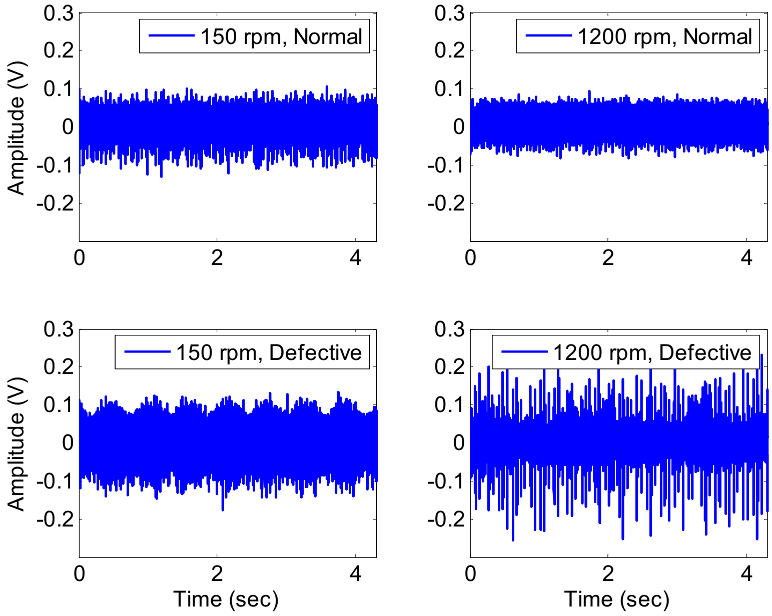


Figure 2. Time wave forms of acceleration signal from a normal and a defective bearing at 150 rpm and 1200 rpm.

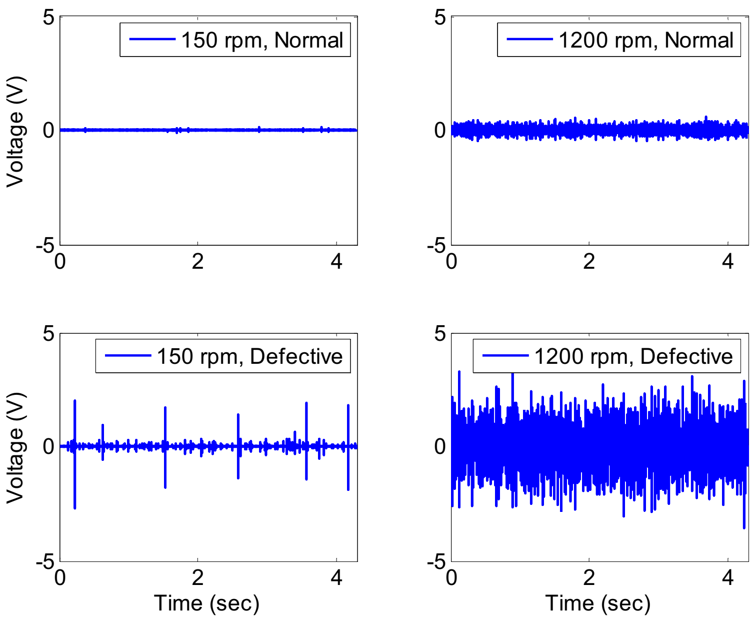


Figure 3. Time wave forms of ultrasound signals from a normal and a defective bearing at 150 rpm and 1200 rpm.

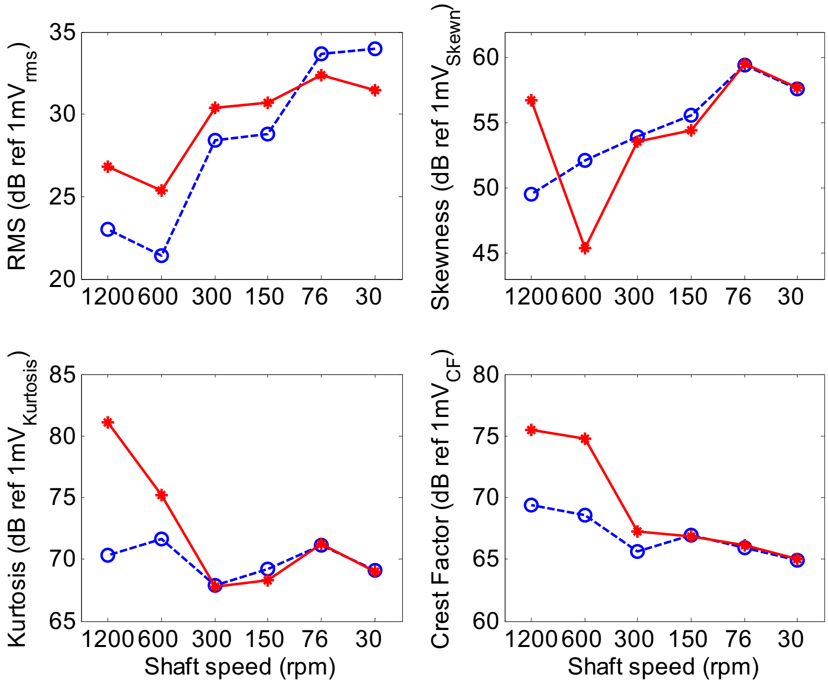


Figure 4. Comparison of statistical parameters from vibration (--o--:normal, —*—:defective).

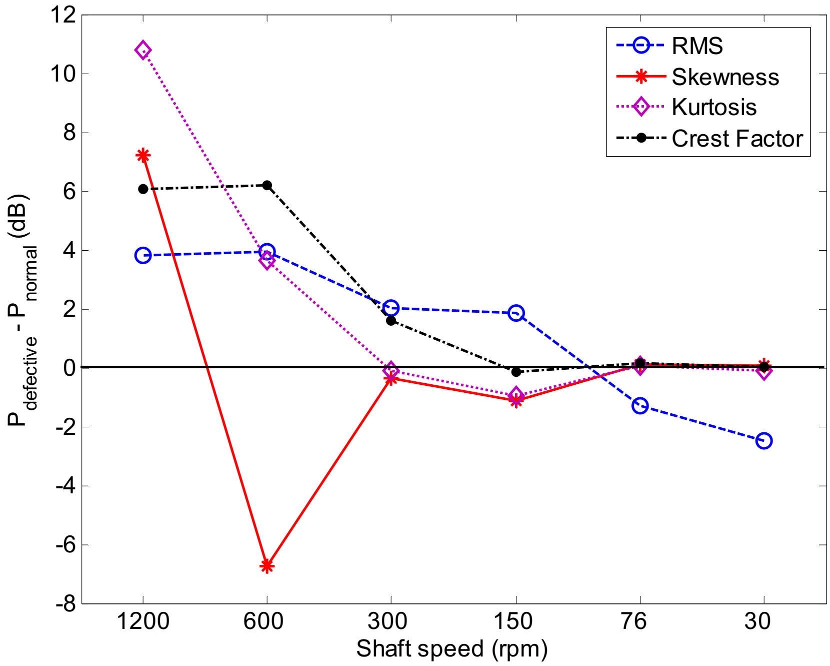


Figure 5. Relative amplitude of statistical parameters from vibration acceleration measurements.

Likewise comparisons of those parameters from ultrasound signals are presented in Figures 6 and 7. The RMS values almost linearly decreased according to a decrease in shaft speed with similar relative amplitudes at all speeds. This means that the RMS value is a good indicator for condition monitoring of bearings for the range of shaft speeds. This result reveals the reason why most ultrasound detector manufacturers use RMS as an indicator for condition monitoring. Skewness didn't show a clear trend for the range of speeds. In contrast, crest factor and kurtosis showed interesting results. Their values from a defective bearing were smaller than those from a normal bearing at high speeds. However, when shaft speeds were less than 300 rpm their relative values increased dramatically. This clearly indicates its significant potential for condition monitoring of slow speed bearings.

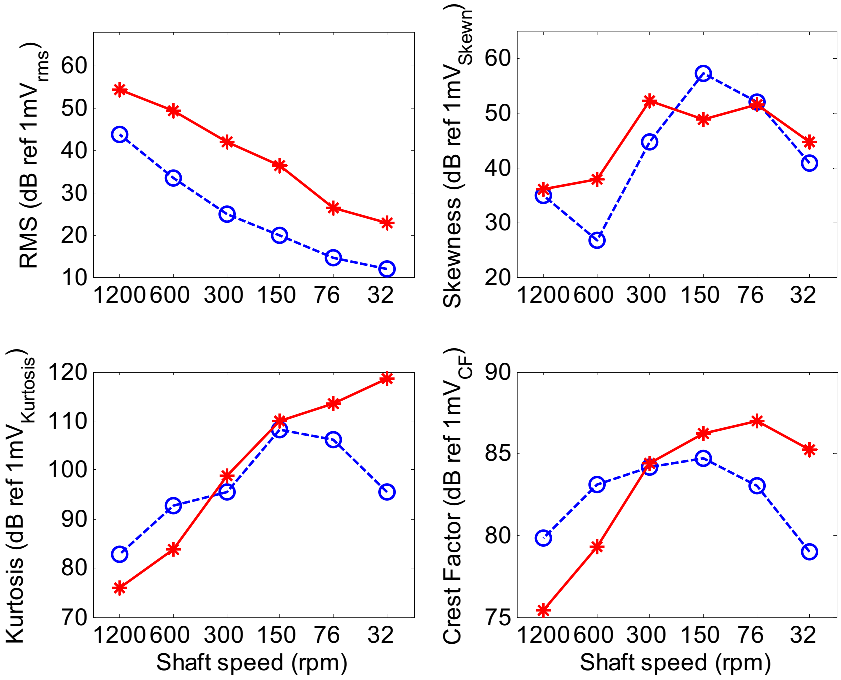


Figure 6. Comparison of statistical parameters from the ultrasound signal (--o--:normal, —*—:defective).

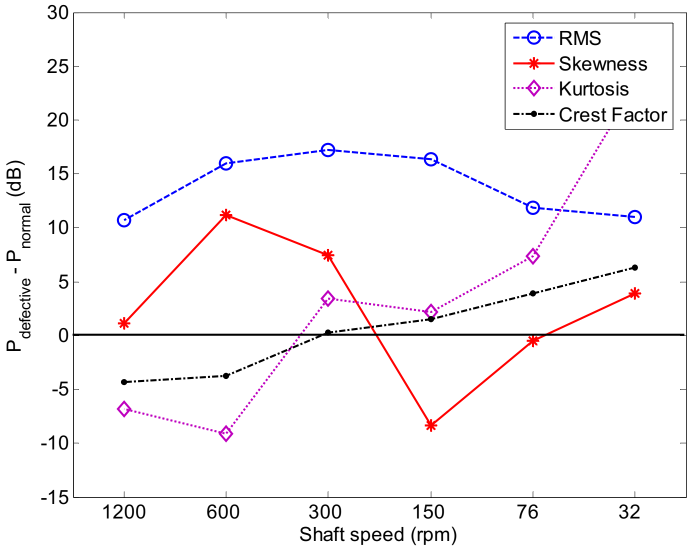
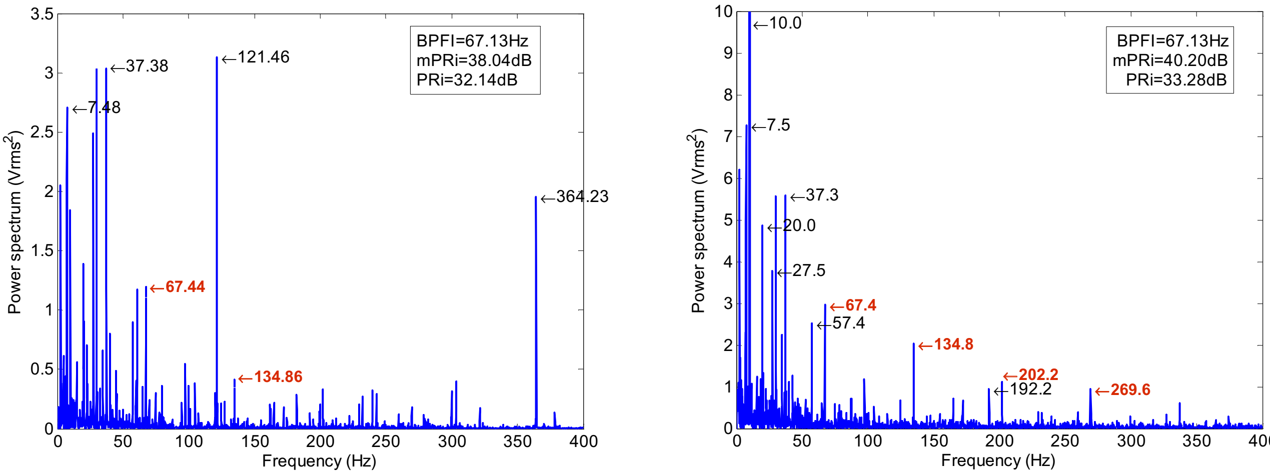


Figure 7. Comparison of differences of statistical parameters from the ultrasound signal.

It is worth noting that RMS of the ultrasound signals is a very reliable indicator at most speeds showing relatively constant amplitudes larger than 10dB. The kurtosis value of ultrasound signals is potentially the best parameter at very slow speeds (less than 50 rpm), followed by crest factor. By comparing the results from ultrasound signals in Figure 7 with those from acceleration signals in Figure 5, it is evident that the ultrasound technique is superior to vibration measurements at low speeds.

5.3 Frequency Domain Parameters

As explained in the previous section, the modified Peak Ratio is introduced in this paper to improve the reliability of identifying the presence of bearing defect characteristic frequencies in the frequency spectrum. Figure 8 shows the enveloped power spectrums of vibration acceleration signals and ultrasound signals at 600 rpm of a defective bearing. The defect frequency (BPFI=67.13 Hz) and its harmonics are clearly evident in both spectra. However, they are more significant in the ultrasound spectrum with relevant side bands of the shaft speed. It is also noted that the modified Peak Ratio for the inner-race fault frequency (*mPRi*) which is proposed in this study, has a much higher value (6-7dB) than the original Peak Ratio proposed by Shiroishi [32], implying that *mPRi* can be an effective indicator for the detection of bearing defect frequencies in frequency spectra.



(a) vibration **(b) ultrasound**

Figure 8. Enveloped power spectrum from defective bearing at 600 rpm.

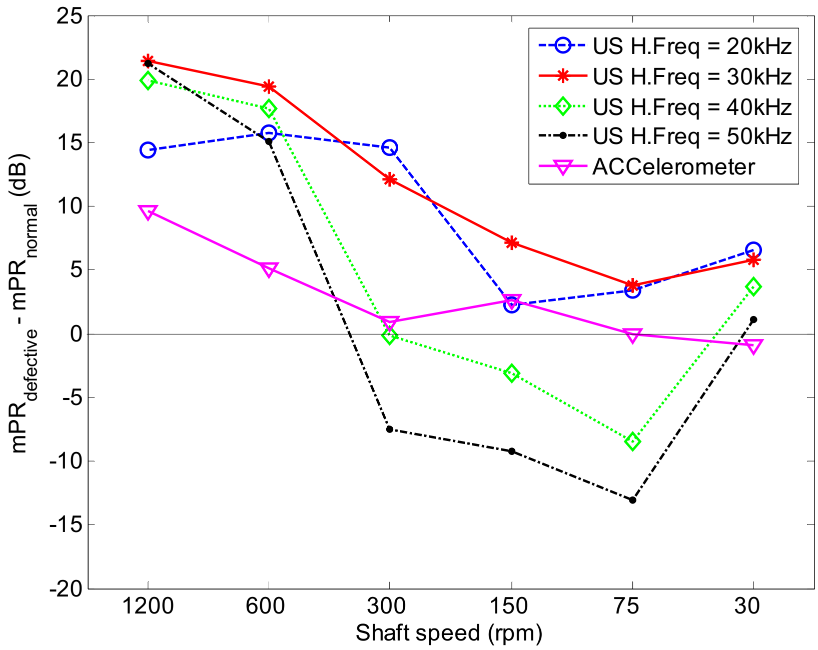


Figure 9. Relative modified Peak Ratio from ultrasound and acceleration.

Finally, the effectiveness of the *mPR* from ultrasound signals was compared with those from vibration signals and the results are shown in Fig. 9. In this study four different heterodyne frequencies in the ultrasound detector were examined for comparison. The 30 kHz heterodyne frequency gives the best result at most speeds and followed by 20 kHz. It is also clear from this study that the vibration acceleration measurements are inferior to the ultrasound technique in terms of detectability of fault in the frequency domain at all shaft speeds.

6 CONCLUSIONS

A number of experiments have been carried out to investigate the effectiveness of the ultrasonic techniques for condition monitoring of low speed bearings. A defective bearing which a simulated defect on the inner race was used in conjunction with a healthy bearing at different shaft speeds ranging from 1200 rpm to 30 rpm. The vibration signals obtained from an accelerometer were also measured and analysed for comparative purposes. The time-domain statistical parameters and frequency-domain modified Peak Ratio were calculated and compared. This study revealed that ultrasound technique is demonstrably superior to vibration acceleration measurements for detecting incipient defects in low speed bearings. The RMS of ultrasound signals provided the best parameter at almost all speeds. However, at very low speeds (less than 50 rpm), the kurtosis and crest factors performed best. In the frequency domain, a modified Peak Ratio was proposed and was proven to a better indicator than the original Peak Ratio. A setting of 30 kHz for the heterodyne frequency on the ultrasound detector gave the best result. Again, detection of fault from ultrasound signals was superior when comparisons were made in the frequency domain. The work is progressing in getting more samples from both the laboratory and the field and these results will be presented in due course.

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