A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings

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Abstract

A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings is presented in this paper. Detection of both localized and distributed categories of defect has been considered. An explanation for the vibration and noise generation in bearings is given. Vibration measurement in both time and frequency domains along with signal processing techniques such as the high-frequency resonance technique have been covered. Other acoustic measurement techniques such as sound pressure, sound intensity and acoustic emission have been reviewed. Recent trends in research on the detection of defects in bearings, such as the wavelet transform method and automated data processing, have also been included.

Keywords: Rolling element bearings; Bearing defects; Condition monitoring; Vibrations; Acoustics

1. Introduction

Rolling element bearings find widespread domestic and industrial applications. Proper functioning of these appliances depends, to a great extent, on the smooth and quiet running of the bearings. In industrial applications, these bearings are considered as critical mechanical components and a defect in such a bearing, unless detected in time, causes malfunction and may even lead to catastrophic failure of the machinery. Defects in bearings may arise during use or during the manufacturing process. Therefore detection of these defects is important for condition monitoring as well as quality inspection of bearings. Different methods are used for detection and diagnosis of bearing defects; they may be broadly classified as vibration and acoustic measurements, temperature measurements and wear debris analysis. Among these, vibration measurements are the most widely used. Several techniques have been applied to measure the vibration and acoustic responses from defective bearings; i.e., vibration measurements in time and frequency domains, the shock pulse method, sound pressure and sound intensity techniques and the acoustic emission method.

A lot of research work has been published, mostly in the last two decades, on the detection and diagnosis of bearing defects by vibration and acoustic methods. Some of these works have also been reviewed by researchers. Tandon and Nakra [1] presented a detailed review of the different vibration and acoustic methods, such as vibration measurements in time and frequency domains, sound measurements, the shock pulse method and the acoustic emission technique, for condition monitoring of rolling bearings. Some of the vibration and wear debris analysis techniques such as vibration, shock pulse, spike energy, spectrographic oil analysis, ferrography and chip detection have been reviewed by Kim and Lowe [2] with a particular reference to railway freight cars. A brief review of vibration monitoring techniques in time and frequency domains and their results on rolling element bearings have been presented by Mathew and Alfredson [3]. McFadden and Smith [4] and Kim [5,6] have also presented reviews on some specific techniques for condition monitoring of rolling bearings. Therefore, the objective of the present study is to update these reviews by incorporating recent works and the advanced techniques adopted in bearing defect detection.
2. Vibration and noise generation in bearings

Several studies [7–13] have been conducted to explain the mechanism of vibration and noise generation in bearings. Bearings act as a source of vibration and noise due to either varying compliance or the presence of defects in them. Radially loaded rolling element bearings generate vibrations even if they are geometrically perfect. This is because of the use of a finite number of rolling elements to carry the load. The number of rolling elements and their position in the load zone change with bearing rotation, giving rise to a periodical variation of the total stiffness of the bearing assembly. This variation of stiffness generates vibrations commonly known as varying compliance vibrations [7,8]. When the bearing races are assumed as continuous systems, the changing direction of the contact forces applied by the rolling elements may cause flexural or ring-mode vibration of the races even if they are geometrically perfect [9,10].

However, the presence of a defect causes a significant increase in the vibration level. Bearing defects may be categorized as ‘distributed’ or ‘local’. Distributed defects include surface roughness, waviness, misaligned races and off-size rolling elements [8–11]. The surface features are considered in terms of their wavelength compared with the Hertzian contact width of the rolling element raceway contacts. Surface features of wavelength of the order of the contact width or less are termed ‘roughness’, whereas longer-wavelength features are termed ‘waviness’ [11]. Distributed defects are caused by manufacturing error, improper installation or abrasive wear [12,13]. The variation in contact force between rolling elements and raceways due to distributed defects results in an increased vibration level. The study of vibration response due to this category of defect is, therefore, important for quality inspection as well as condition monitoring.

Localized defects include cracks, pits and spalls on the rolling surfaces. The dominant mode of failure of rolling element bearings is spalling of the races or the rolling elements, caused when a fatigue crack begins below the surface of the metal and propagates towards the surface until a piece of metal breaks away to leave a small pit or spall. Fatigue failure may be expedited by overloading or shock loading of the bearings during running and installation [13]. Electric pitting or cracks due to excessive shock loading are also among the different types of bearing damage described in the literature [13–17]. Whenever a local defect on an element interacts with its mating element, abrupt changes in the contact stresses at the interface result which generates a pulse of very short duration. This pulse produces vibration and noise which can be monitored to detect the presence of a defect in the bearing.

3. Vibration response due to localized defects

Two approaches have been adopted by researchers for creating localized defects on bearings to study their vibration response. One is to run the bearing until failure and monitor the changes in their vibration response [5,18–22]. Usually the failure is accelerated by either overloading, overspeeding or starving the bearings of lubricants [5,21,22]. The other approach is to intentionally introduce defects in the bearings by techniques such as acid etching, spark erosion, scratching or mechanical indentation, measure their vibration response and compare it with that of good bearings [23–34]. In some of these studies the size of the simulated defects has been quantified and varied [26,29–33]. The former approach of life tests is quite time-consuming. On the other hand, the testing of bearings with simulated defects is much quicker but preparation of the defective bearings requires special techniques.

Several techniques have been applied to measure and analyse the vibration response of bearings with localized defects. These techniques are not totally independent; rather, in many cases, they are complementary to one another.

3.1. Time-domain approach

The simplest approach in the time domain is to measure the overall root-mean-square (RMS) level and crest factor, i.e., the ratio of peak value to RMS value of acceleration. This method has been applied with limited success for the detection of localized defects [30,32]. Some statistical parameters such as probability density and kurtosis have been proposed for bearing defect detection [35,36]. The probability density of acceleration of a bearing in good condition has a Gaussian distribution, whereas a damaged bearing results in non-Gaussian distribution with dominant tails because of a relative increase in the number of high levels of acceleration [35]. However, Mathew and Alfredson [3] have reported obtaining a near-Gaussian distribution for some damaged bearings also. Instead of studying the probability density curves, it is often more informative to examine the statistical moments of the data, defined as

\[ M_n = \int_{-\infty}^{\infty} x^n P(x) \, dx \quad n = 1, 2, 3, \ldots, m, \]  

(1)

where \( P(x) \) is the probability density function of instantaneous amplitude \( x \). The first and second moments are well known, being the mean value and the variance, respectively. The third moment normalized with respect to the cube of standard deviation is known as the coefficient of ‘skewness’. The fourth moment, normalized with respect to the fourth power of standard deviation,
is quite useful. This is called 'kurtosis' and is given by the expression

\[ \text{kurtosis, } \beta_2 = -\frac{\int (x-\bar{x})^4 P(x) \, dx}{\sigma^4} \]  

(2)

where \( \bar{x} \) is the mean.

Dyer and Stewart [36] first proposed the use of kurtosis for bearing defect detection. For an undamaged bearing with Gaussian distribution, the kurtosis value is close to 3. A value greater than 3 is judged by itself to be an indication of impending failure and no prior history is required. However, one disadvantage is that the kurtosis value comes down to the level of an undamaged bearing (i.e., 3) when the damage is well advanced. Therefore, it has been suggested to measure kurtosis in selected frequency bands [36]. White [37] studied the effectiveness of this method under a simulated condition. Several other studies [27,28,34,36,38] have also shown the effectiveness of kurtosis in bearing defect detection but in some cases [3,5,40] the method could not detect the incipient damage effectively. Kurtosis has not become a very popular method in industry for the condition monitoring of bearings.

Local defects can also be detected in the time domain by displaying the vibration signal on an oscilloscope or plotting it on a chart recorder and observing the presence of periodic peaks due to impact of the rolling element with the defects [26,29,40,41]. Gustafsson and Tallian [40] proposed a method of defect detection based on the number of peaks crossing a preset voltage level.

Some bandpass filtering techniques have also been proposed in the time domain. The principle is based on the fact that structural resonances are excited in the high-frequency zone due to impulsive loading caused, for example, from spalling of the races or rolling elements and can be detected by a transducer whose resonant frequency is tuned to it. The shock pulse method [42], which works on this principle, uses a piezoelectric transducer having a resonant frequency based at 32 kHz (some instruments based on resonant frequency around 100 kHz have also been used). The shock pulses caused by the impacts in the bearings initiate damped oscillations in the transducer at its resonant frequency. Measurement of the maximum value of the damped transient gives an indication of the condition of rolling bearings. Low-frequency vibrations in the machine, generated by sources other than rolling bearings, are electronically filtered out. The shock pulse value generated by good bearings due to surface roughness has been found empirically to be dependent upon the bearing bore diameter and speed. This value, called the initial value, is subtracted from the shock value of the test bearing to obtain a normalized shock pulse value. The maximum normalized shock value is a measure of the bearing condition. Shock pulse meters are simple to use so that semiskilled personnel can operate them. They give a single value indicating the condition of the bearing straightforward, without the need for elaborate data interpretation as required in some other methods.

The shock pulse method has gained wide industrial acceptance and has been reported to be successful in the detection of rolling element bearing defects [3,5,34,39,43]. Some investigators [31,44,45] have reported that the method could not effectively detect defects at low speeds. However, Butler [43] has reported success of the shock pulse method in the detection of defects in low-speed spherical roller bearings in a paper production line. An on-line bearing condition monitoring technique based on the shock pulse method has been suggested by Morando [46].

3.2. Frequency-domain approach

Frequency-domain or spectral analysis of the vibration signal is perhaps the most widely used approach of bearing defect detection. The advent of modern fast Fourier transform (FFT) analysers has made the job of obtaining narrowband spectra easier and more efficient. Both low- and high-frequency ranges of the vibration spectrum are of interest in assessing the condition of the bearing.

The interaction of defects in rolling element bearings produces pulses of very short duration whenever the defect strikes or is struck owing to the rotational motion of the system. These pulses excite the natural frequencies of bearing elements and housing structures, resulting in an increase in the vibrational energy at these high frequencies. The resonant frequencies of the individual bearing elements can be calculated theoretically [1,47,48].

It is difficult to estimate how these resonances are affected on assembly into a full bearing and mounting in a housing. However, it is indicated [24] that resonances are not altered significantly. These natural frequencies are usually more than 5 kHz [1]. Therefore, monitoring the increase in the level of vibrations in the high-frequency range of the spectrum is an effective method of predicting the condition of rolling element bearings and has been used successfully by several investigators [3,21,23,24,26]. Catlin [49] has indicated that the natural frequency for which the wavelength closely matches the pulse length, is most strongly excited. Several parameters such as arithmetic mean, geometric mean and correlation have been suggested [50,51] to quantify the differences in spectra for good bearings and damaged bearings.

Each bearing element has a characteristic rotational frequency. With a defect on a particular bearing element, an increase in vibrational energy at this element's rotational frequency may occur. These characteristic
defect frequencies can be calculated from kinematic considerations; i.e., the geometry of the bearing and its rotational speed \([1,23,26,40,52,53]\). For a bearing with a stationary outer race, these frequencies are given by the following expressions:

\[
\text{cage frequency, } \omega_c = \frac{\omega_0}{2} \left(1 - \frac{d}{D} \cos \alpha\right),
\]

\[
\text{ball spinning frequency, } \omega_b = \frac{D \omega_0}{2d} \left(1 - \frac{d^2}{D^2} \cos^2 \alpha\right),
\]

\[
\text{outer race defect frequency, } \omega_{od} = Z \omega_c
\]

\[
= \frac{Z \omega_c}{2d} \left(1 - \frac{d}{D} \cos \alpha\right),
\]

\[
\text{inner race defect frequency, } \omega_{id} = Z(\omega_c - \omega_b)
\]

\[
= \frac{Z \omega_c}{2} \left(1 + \frac{d}{D} \cos \alpha\right)
\]

and

\[
\text{rolling element defect frequency, } \omega_{re} = 2 \omega_b
\]

\[
= \frac{D \omega_0}{d} \left(1 + \frac{d^2}{D^2} \cos^2 \alpha\right),
\]

where \(\omega_0\) is the shaft rotation frequency in rad/s, \(d\) is the diameter of the rolling element, \(D\) is the pitch diameter, \(Z\) is the number of rolling elements and \(\alpha\) is the contact angle.

For normal speeds, these defect frequencies lie in the low-frequency range and are usually less than 500 Hz. In practice, however, these frequencies may be slightly different from the calculated values as a consequence of skipping or skidding in the rolling element bearings \([53]\). Several researchers \([24,26,27,32,54,55]\) have reported success in bearing defect detection by identifying these rotational frequencies. It has also been observed \([24,26,27,32]\) that, in case of a defect on a moving element such as the inner race or a rolling element, the spectrum has sidebands about the components at characteristic defect frequencies. A typical spectrum \([32]\) due to an inner race defect is shown in Fig. 1. The sidebands have been attributed to the time-related changes in defect position relative to the vibration measuring position \([26]\). Tandon and Choudhury \([56]\) have derived expressions for frequencies and relative amplitudes of the various spectral lines based on the flexural vibration of races due to a localized defect on one of the bearing elements.

In some work \([23,57,58]\), it has been mentioned that it is difficult to obtain a significant peak at these frequencies in the direct spectrum obtained from a defective bearing. This is due to the fact that ‘noise’ or vibration from other sources masks the vibration signal from the bearing unless the defect is sufficiently large. Tandon and Nakra \([32]\) have also found that direct spectral analysis can detect defects of comparatively larger sizes only. Ray \([45]\) highlighted the condition under which bearing defect detection becomes difficult.

Osuagwu and Thomas \([57]\) have suggested an explanation for the absence of defect frequencies in the spectrum in terms of the average and shift effect produced by the variation of the impact period and the intermodulation effect. In this study the power cepstrum was shown to be an effective diagnostic technique. Power cepstrum is defined as the power spectrum of the logarithmic power spectrum \([35]\). Tandon \([33]\) has reported that cepstrum can detect outer race defects effectively but failed to detect inner race defects.

In order to improve the signal-to-noise ratio and make the spectral analysis more effective, some signal processing techniques have been reported. Braun and Datner \([59]\) have suggested signal decomposition into periodic components and a processing method based on averaging techniques. The adaptive noise cancelling (ANC) technique has also been proposed to improve the signal-to-noise ratio in bearing fault diagnosis \([60]\). Envelope detection or the high-frequency resonance technique (HFRT) is an important signal processing technique which helps in the identification of bearing defects by extracting characteristic defect frequencies (which may not be present in the direct spectrum) from the vibration signal of the defective bearing. A review of the technique has been presented by McFadden and Smith \([4]\). Each time a defect strikes its mating element, a pulse of short duration is generated that excites the resonances periodically at the characteristic frequency related to the defect location. The resonances are thus amplitude-modulated at the characteristic defect frequency. By demodulating one of these resonances, a signal indicative of the bearing condition can be recovered. In practice, the signal is bandpass-filtered around one of the resonant frequencies, thus eliminating most of the unwanted vibration signals from other sources. This bandpass-filtered signal is then demodulated by an envelope detector in which the signal is rectified and smoothed by an envelope detector to eliminate the carrier or bandpass-filtered resonant frequency. The spectrum of the envelope signals has been demonstrated by several investigators \([23,25,30–32,61–80]\). A single-mode vibration model has been developed by McFadden and Smith \([62–64]\) to explain the appearance of various spectral lines owing to different defect locations in the demodulated spectrum. They have suggested that the sidebands around the defect frequency are a result of the modulation of carrier frequency by loading and transmission path. This model
Fig. 1. A typical spectrum obtained from a rolling element bearing with an inner race defect.

Fig. 2. The process of extraction of demodulated spectra by HFRT.
has been extended by Su and Lin [79] to characterize the vibrations of bearings subjected to various loadings. Martin and Thorpe [80] have suggested ‘normalization’ of the envelope-detected frequency spectra of the faulty bearing with respect to the healthy bearing to give greater sensitivity to the detection of defect frequencies. The limitation of this technique is that, with advanced damage, the defect frequencies may become submerged in the rising background level of the spectrum [4, 74]. This may happen due to the reduced severity of impacts which are generated so frequently that the leading edge of the impact is buried in the decay of the previous impact [4]. However, Burgess [74] argues that this is because of the reduced difference in amplitudes of the random noise floor and the defect peak heights, which also become random as the defect progresses.

In recent years, the wavelet transform method has been suggested by some researchers [81–83] to extract very weak signals for which FFT becomes ineffective. Wavelet transform provides a variable-resolution time-frequency distribution from which periodic structural ringing due to repetitive force impulses, generated upon the passing of each rolling element over the defect, are detected. The adaptive time-frequency resolution makes it superior vis-à-vis FFT. Mori et al. [83] proposed a discrete wavelet transform theory which can detect a defect even at pre-spalling stage.

3.3. Proximity transducer technique

The literature discussed so far has mostly considered casing-mounted transducers such as accelerometers and velocity pick-up for the measurement of vibration. Some researchers have also used non-contact type displacement or proximity transducers for condition monitoring of rolling element bearings. In these studies, the transducer senses the displacement of the outer race directly as the rolling elements pass under it. Thus the extraneous vibrations of the housing structure are reduced or eliminated and the signal-to-noise ratio is improved. However, the installation of these probes is difficult as it not only involves drilling and tapping of the bearing housing but also fine adjustment of the gap between the probe and the outer race, which can change due to such conditions as vibration, dirt and thermal expansion. This monitoring technique is popularly known as REBAM (Rolling Element Bearing Activity Monitor).

Philips and associates [84–86] first reported the use of this technique. They used a fibre optic sensor to measure the elastic deformation of the outer ring. Philips [86] has also introduced the concept of ball speed ratio (BSR), which has been found to be a good parameter for bearing performance monitoring. Harker and Hansen [87] used a high-gain eddy current transducer and reported case histories for rotating machinery health monitoring using this technique. REBAM has been found to be effective in bearing defect detection in some other studies as well [34, 88]. Kim [6, 89–91] has applied this technique to a radially loaded deep groove ball bearing. He has reported an effective diagnostic method for outer and inner race damage to predict the angular location of the damaged spots. He also suggested that this technique, coupled with HFRT, will be very effective for fault detection in rolling element bearings [91].

3.4. Automated diagnostic system

The techniques discussed above need a human interpreter to analyse the results. However, the amount of data collected from modern instruments may be so vast that an automated system providing concise and reliable assessment of the machinery condition becomes necessary. This is equally true for rolling element bearings.

In 1989, Li and Wu [92] proposed a monitoring scheme based on pattern recognition. The technique employs short-time-signal processing techniques to extract useful features from bearing vibration to be used by a pattern classifier to detect and diagnose the defect. To overcome the shortcomings of this method, bispectral analysis of vibration has been applied to detect the presence of the characteristic defect frequency and its harmonics [93]. The pattern recognition technique is then applied to classify the condition of a bearing based on its bicoherence. An automatic fault diagnosis system for ball bearings, based on processing of time-domain signatures and a pattern recognition technique, has also been reported [94].

In recent times, artificial neural networks have emerged as a popular tool for signal processing and pattern classification tasks, and are suitable for condition monitoring programs. An artificial neural network can be defined as a mathematical model of the human brain and has the ability to learn to solve a problem, rather than having to be preprogrammed with a precise algorithm. Baillie and Mathew [95] proposed a model based on a neural network for fault detection in rolling element bearings. The system consists of a collection of parametric time-series models, one for each class of bearing fault to be identified, based on a back-propagation neural network. This time-domain-based model has the advantage that the diagnosis can be performed using very short data lengths and is suitable for application in slow- and variable-speed machinery. However, the main drawback is that the model cannot handle very large data without misclassifying the fault. To overcome this shortcoming, they have proposed to present the vibration data to the neural network in the frequency domain [96] and have also proposed that characteristic defect frequencies can be used for classification of faults. In separate research [97], a ‘neural bearing analyser’ model has been
developed taking only certain areas of the vibration spectrum and using a back-propagation network.

4. Vibration response due to distributed defects

As discussed earlier, distributed defects include surface irregularities like roughness, waviness or off-size rolling elements. The vibration response for these defects has been studied mostly in the frequency domain. Vibration produced by surface roughness or shorter-wavelength features has been studied by Sayles and Poon [98] and is found to be significant only when the asperities break through the lubricant film and contact the opposing surface. However, longer-wavelength features (waviness) or varying roller element diameter have a more dominant effect on the vibration level. The frequency limit in which waviness produces a significant vibration level has been assessed [11,99] and is found to be below 60 times the rotational speed.

Systematic studies of vibration produced by waviness were first made by Tallian and Gustafsson [8]. The five-degree-of-freedom motion of the outer race — considered as a body which is rigid except for the contact deformations — was analysed with a linearized dynamic model. The waviness orders of major importance have been assessed and found to have a simple numerical relationship with the number of rolling elements. Meyer et al. [9] proposed an analytical model for flexural vibration of the stationary race under axial load due to waviness on the moving race or unequal ball diameter. The amplitudes of the important frequency components have also been predicted in the model. The model was extended later by Choudhury and Tandon [10] for radially loaded rolling bearings. Vibrations produced by axially loaded angular contact ball bearings under the influence of waviness on various bearing elements have been studied by Wardle [100]. He considered an additional mass (housing) attached to the stationary outer ring. Analytical results for radial and axial vibrations have been verified experimentally [101]. A linear model has been proposed by Yliland [102] for vibration of the shaft bearing system due to form errors. Waviness orders of major importance for the vibration response of a tapered roller bearing have been investigated experimentally by Ohta and Sugimoto [103]. Sunnerso [12] has studied the vibration of a radially loaded bearing due to inner race waviness or varying roller diameter, and found the significant peaks to occur at harmonics of shaft and cage speed, respectively, with a sideband spaced at roller passage frequency in the case of inner race waviness. Similar cage harmonics have been observed by Hino [104] for circumferential ball diameter variation in the bearing of a turbopump in the main engine of a space shuttle. The effects of surface irregularities have also been investigated [105,106] to explain the spectral lines observed in the demodulated spectra of a normal tapered roller bearing.

Since many of the frequencies resulting from distributed defects coincide with those due to localized defects, it becomes difficult to identify from frequency information alone whether a peak at a particular frequency is due to a localized or a distributed defect. Therefore, it has been suggested [107,108] that, in addition to frequency information, the amplitudes of the spectral components should also be studied for defective bearings.

Some studies [109–111] have also been carried out to estimate the roughness or waviness of the races or the balls in bearings by vibration analysis. Laser Doppler vibrometry has been proposed for surface profile measurements in rolling bearings [112].

5. Acoustic emission response from defective bearings

Acoustic emission (AE) is the phenomenon of transient elastic wave generation due to a rapid release of strain energy caused by a structural alteration in a solid material under mechanical or thermal stresses. Generation and propagation of cracks, growth of twins, etc. associated with plastic deformation are among the primary sources of AE. Hence it is an important tool for condition monitoring through non-destructive testing. AE instrumentation consists of a transducer, mostly of the piezoelectric type, a preamplifier and a signal-processing unit. The transducers, which have very high natural frequency, have a resonant-type response. The bandwidth of the AE signal can also be controlled by using a suitable filter in the preamplifier. The most commonly measured AE parameters are ringdown counts, events and peak amplitude of the signal. These have been demonstrated on a typical AE signal shown in Fig. 3. Ringdown counts involve counting the number of times the amplitude exceeds a preset voltage level (threshold level) in a given time and gives a simple number characteristic of the signal. An event consists of a group of ringdown counts and signifies a transient wave. The advantage of acoustic emission monitoring over vibration monitoring is that the former can detect the growth of subsurface cracks, whereas the latter can detect defects only when they appear on the surface. It is also important to note that the energy released by neighboring components in the vibrational frequency range (up to 50 kHz), which often masks the vibrational energy released from a defective rolling element bearing, do not affect the AE signal released in the very high frequency range.

Several studies have been conducted to investigate the AE response of defective bearings. In the case of AE monitoring of local defects also, two approaches of life
tests [113–117] and simulated defects [118–120] have been adopted by researchers. In 1979, Rogers [121] suggested the application of acoustic emission as a measure of the condition of slow-speed anti-friction bearings of slewing cranes in offshore gas production platforms. Yoshioka and Fujiwara [113,114] have shown that AE parameters can detect defects before they appear in the vibration acceleration range and can also detect the possible sources of AE generation during a fatigue life test of thrust ball bearings. They also measured the propagation initiation time of cracks and the propagation time of flaking occurs by a combination of AE parameters and vibration acceleration [115]. The source locator system was also improved later by introducing two AE sensors in the system and measuring the difference of arrival times of acoustic emission signals at the sensors [116,117]. Acoustic emission signals have been shown to detect defects in the form of a fine scratch on the inner race of axially loaded angular contact ball bearings but at low speeds only [44,118]. Tandon and Nakra [119] have demonstrated the usefulness of some acoustic emission parameters, such as peak amplitude and count, for the detection of defects in radially loaded ball bearings at low and normal speeds. The distribution of events by counts and peak amplitude has also been used for quality inspection of bearings to judge whether the bearing is a new or regenerated one [122]. Tan [123] has suggested that the measurement of area under the amplitude–time curve is a preferred method for defect detection in rolling element bearings. He also applied the adaptive noise cancellation technique to filter out background AE noise emitted by other machine components [124]. The usefulness of demodulated AE signals in detecting defects in rolling element bearings has been demonstrated by some researchers [120,125–127].

6. Acoustic noise response

Measurement of acoustic noise can also be used for the detection of defects in rolling element bearings. These measurements are normally carried out in two modes: sound pressure and sound intensity. Sound pressure generated by good bearings has been studied by several researchers [128–131], but very little literature is available on sound measurements as a defect detection technique. Igarashi and Yabe [132] have shown the usefulness of sound pressure measurement for the detection of defects in axially loaded ball bearings. The role of surface irregularities in the production of noise in rolling contact has been studied with the help of sound pressure measurement [133].

Sound intensity measurement, a comparatively recent technique, has also been tried successfully for the detection of defects in rolling element bearings [5]. Sound intensity is defined as the time-averaged rate of flow of sound energy through unit area. Unlike sound pressure, it is a vector quantity and the two-microphone intensity probe has directional characteristics. Sound intensity in the frequency domain can be obtained from the imagin-
ary part of the cross-spectrum between the signals of two closely spaced microphones [134]. A special two-microphone probe is used for intensity measurements. The imaginary part of the cross-spectrum can be obtained directly using a dual-channel FFT analyser. Tandon and Nakra [135] have shown the usefulness of sound intensity measurement as a bearing diagnostic technique and have concluded that, for this purpose, it is more effective than sound pressure measurement. Spectral analysis of demodulated signals received by a sound meter has been suggested as a monitoring tool for a wide detection of rail rolling bearing defects [136].

The detectability of defects by sound measurement may be affected by sources other than bearing noise unless adequate precautions are taken to isolate the latter. A partial or full acoustic enclosure lined with sound-absorbing material is usually constructed around the test bearing for this purpose. Design of such anechoic chambers has also been discussed in the literature [133, 137].

7. Conclusions

From a review of studies on vibration and acoustic measurement techniques for the detection of defects in rolling element bearings, it is seen that the emphasis is on vibration measurement methods. Although literature is available for the detection of both localized and distributed defects, the former has drawn the attention of a greater number of researchers. Vibration in the time domain can be measured through parameters such as overall RMS level, crest factor, probability density and kurtosis. Among these, kurtosis is the most effective. The shock pulse method has also gained wide industrial acceptance.

Vibration measurement in the frequency domain has the advantage that it can detect the location of the defect. However, the direct vibration spectrum from a defective bearing may not indicate the defect at the initial stage. Some signal processing techniques are, therefore, used. The high-frequency resonance technique is the most popular of these and has been successfully applied by several researchers. For this technique, the procedure of signal processing is well established and a good explanation of the resultant demodulated spectrum is also available. The method has a disadvantage that advanced damage is difficult to detect by this method. In recent years, the wavelet transform method has been suggested to extract very weak signals for which Fourier transform becomes ineffective.

Very few studies have been carried out on acoustic noise measurements for the detection of bearing defects. Measurements of both sound pressure and sound intensity have been used for this purpose. The sound intensity technique seems to be better than sound pressure measurements for bearing diagnostics.

Acoustic emission measurements have also been used successfully for detecting defects in rolling element bearings. Some studies indicate that these measurements are better than vibration measurements and can detect a defect even before it appears on the surface. Demodulation of AE signals for bearing defect detection has also been suggested.

In recent years, attention has also been focused on the automated interpretation of data for bearing diagnostics. The pattern recognition technique and neural networks have been applied to data obtained from vibration measurements in both time and frequency domains for the detection of defects in rolling element bearings.

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