Comparison of vibration and acoustic measurement techniques for the condition monitoring of rolling element bearings

N. Tandon and B. C. Nakra

The detectability of defects in ball bearings by various vibration and acoustic measurement methods is compared. Measurements have been performed on good new bearings and bearings with simulated defects in their elements. The vibration and acoustic measurements performed are: overall vibration acceleration, envelope detected acceleration, overall sound intensity and sound pressure, shock pulse, and acoustic emission ringdown counts and peak amplitude. The results indicate that, in general, the detection of defects by acoustic emission and envelope detected acceleration is better as compared to other measurements.

Keywords: vibration measurements, acoustic measurements, rolling element bearings

Introduction

The smooth performance of rolling element bearings is vital for the proper functioning of a machine. It is important to monitor the condition of bearings in a plant to avoid sudden failures. Several techniques for the detection of defects in rolling element bearings are currently available. These include vibration and acoustic measurements like overall level, kurtosis, spectral analysis, high frequency resonance, shock pulse, sound and acoustic emission; and oil monitoring such as spectrographic oil analysis, particle counting, ferrography and chip detection. Vibration and acoustic measurements are quite effective in detecting defects in bearings. One approach to study the detection of defects by these measurements is to compare the response of new good bearings with that of bearings with simulated defects created in their elements.

A considerable amount of research on the vibration monitoring of rolling element bearings has been carried out, a brief review of which is given in the literature\textsuperscript{1-2}. Only in a few studies\textsuperscript{3-7} on vibration and acoustic monitoring of bearings, has the response of bearings with quantified and varying simulated defect size been reported. A comparison of various vibration and acoustic measurement techniques for the detection of defects in bearings should be of interest. Detailed studies comparing the usefulness of various vibration and acoustic measurement methods in a single study, especially with varying defect size, do not appear to have been reported.

In the present investigation vibration and acoustic measurements have been performed on good bearings and on bearings with defects of different sizes in their elements to evaluate the comparative usefulness of these measurements for bearing diagnostics. The vibration and acoustic measurements used are: overall vibration acceleration levels, envelope detected acceleration (high-frequency resonance technique), shock pulse, overall sound intensity and sound pressure levels, and acoustic emission ringdown counts and peak amplitude. These measurements were performed on the bearings after mounting them on a test rig developed for this purpose.

Experiment

Test rig

A simple spindle type bearing test rig, on which the test bearing can easily be mounted/dismounted at the end of the shaft, was used for the measurements. A sketch of the bearing test rig designed and constructed for the present study is shown in Fig 1. It consists of two support bearings (6) mounted on the shaft (5) which rotates inside a cylindrical casing (4). The support bearings are deep groove ball bearings, pre-lubricated and sealed at both ends. Deep groove ball bearings were selected as support bearings because they generate less vibration compared to other bearings such as spherical roller bearings. The drive to the test
rig is provided by a d.c. motor (1) through a flexible coupling (2). The control panel of the d.c. motor can provide a continuously variable speed from 100 to 1500 rev/min. Vibration isolation rubber sheets (9) were provided under the motor and between the cylinder and its supports to reduce the vibration transmission to the test bearing. The test rig was designed to withstand a maximum radial load of 150 kg (at the test bearing). A lever type radial loading arrangement as shown in Fig 2 was used. The load to the test bearing is applied through a small hollow cylinder. The transducer can be mounted at the bottom of the test bearing housing and remains inside the hollow cylinder, thus permitting measurements to be made in the zone of maximum load (Fig 2). The lower portion of the test bearing housing is flat so that the housing and thus the outer race of the test bearing are held fixed by the load.

**Test bearings**

The test bearings used in this study are normal radial clearance, deep groove ball bearings, SKF 6002. A defect simulating pit was introduced in either the raceway or the ball of these bearings by spark erosion. Defect diameters of 150, 250 and 500 μm and depths of 50, 100 and 150 μm were introduced in the bearing elements. The tolerances of the defect are −0/+30 μm on the diameter and ±10 μm on the nominal depth of the defect. Two bearings without defects and the bearings with defects as shown in Table 1 were tested. The test bearings were immersed in clean, boiling 1,1,1-trichloroethane for a few minutes and then further cleaned in the vapour phase of trichloroethane to remove the preserving oil on them. Equal amounts (approximately 0.35 g) of grease were applied to each bearing immediately after cleaning.

**Measurement conditions**

Vibration and acoustic measurements on the bearings with no defect and with the largest defect size (ie 500 μm diameter and 150 μm depth) were performed at different radial loads and speeds. Loads ranging from 20 to 100 kg and speeds from 100 to 1500 rev/min were used for the measurements. The load was varied at 1500 rev/min and the speed at 60 kg load. Measurements on all other bearings were performed at 60 kg load and 1500 rev/min. The defect diameter was varied for 150 μm depth and the depth for 500 μm diameter as shown in Table 1. The bearings with the outer race defect were mounted on the test rig in such a way that the defect was located downwards in the zone of maximum load.

In the case of the bearings with ball defects, the defect may not come in contact with any surface (either inner or outer race) for a considerable period of time. So, in the cases, especially for bigger size defects, where it was possible to find out about the occurrences of impacts from the audible noise, the measurements on ball defective bearings were performed only during the impacts of the defect with the surfaces. In other cases where this was not possible, a large averaging time was used. The vibration and acoustic measurement values of the two good bearings were quite close, so their average value has been used in the measurement results presented in this paper.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Defect location</th>
<th>Defect size (μm)</th>
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<td>Depth</td>
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<td>2</td>
<td>No defect</td>
<td></td>
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<tr>
<td>3</td>
<td>Outer race</td>
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<tr>
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<td>Outer race</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
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<td>150</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
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</table>
Vibration and acoustic measurements

Overall acceleration levels

Measuring overall levels is the simplest vibration monitoring method. Overall rms levels of the vibration acceleration signal of the bearings were measured using an accelerometer (B&K 4375) with a high natural frequency of 92 kHz and a charge amplifier (B&K 2635). The overall levels were recorded on the vibration analyser. An average value of 100 samples was recorded for each bearing.

Envelope detected acceleration

Envelope detection or the high-frequency resonance technique (HFRT) is very useful for the detection of defects in rolling element bearings. It 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 defective bearings. The impacts with the defect in the rolling element bearings excite resonances of bearing elements and its supporting structure periodically at the ball pass frequency related to the location of the defect. These resonances are amplitude-modulated at the characteristic defect frequency, and by demodulating one of these resonances a signal indicative of the bearing condition can be recovered. In practice the signal is bandpass filtered around the resonance frequency. This bandpass filtered signal is a narrowband carrier at the resonant frequency, amplitude modulated at the defect frequency. The signal is then demodulated by an envelope detector in which the signal is rectified and then smoothed to eliminate the remaining components at the carrier frequency. The spectrum of the envelope signal is then obtained to get the characteristic defect frequency of the bearing.

Envelope detection was performed with the help of the accelerometer (B&K 4375) and the vibration envelope detector (Shaker Research Corp. USA, model VED 223A) which has a built-in charge amplifier and high frequency band-pass filter. The output of the envelope detector was analysed on the fast Fourier transform (FFT) analyser (B&K 2032) and a copy of the spectrum was obtained on the graphics recorder (B&K 2313). The frequency spectrum of the bearings before applying envelope detection showed major peaks around 750 Hz, 5 kHz and 18 kHz. The HFRT applied at the peak around 18 kHz yielded the best results, so for all the bearings envelope detection was performed by bandpass filtering the 18 kHz frequency. The levels of characteristic defect frequency in the spectra of envelope detected signals of defective bearings were compared with those of the good bearings to evaluate defect detection.

Sound intensity

Sound intensity, which is a vector quantity, is obtained in the frequency domain using the following equation:

\[ I_r = \frac{\text{Im}(G_{12})}{\omega \rho \Delta r} \]

where \( I_r \) is the sound intensity in the direction \( r \), \( \text{Im}(G_{12}) \) is the imaginary part of the cross-spectrum between two closely spaced microphones' signals, \( \omega \) is the angular frequency, \( \rho \) is the density of air and \( \Delta r \) is the distance between the two microphones. Sound intensity is presented in dB levels with a reference of 10^-12 W m^-2. Sound intensity measurements can also be used for the detection of defects in rolling element bearings. The sound intensity of the bearings was measured in the radial direction at a distance of 100 mm from the test bearing housing using a two-microphone probe (B&K 3519) incorporating 12.7 mm phase-matched condenser microphones separated by a 12 mm spacer. The noise of the motor and the test rig was shielded by panels lined with foam sheets on the surfaces facing the test bearing. The overall levels of sound intensity in the frequency range from 250 Hz to 6.4 kHz were displayed on the dual-channel FFT analyser (B&K 2032).

Sound pressure

The sound pressure of the test bearings was also measured to study its relative usefulness for the detection of defects in the bearings. Sound pressure levels in dB (reference 20 \( \mu \text{Pa} \)) were measured at the same point and using the same instrumentation as for sound intensity measurements. Overall sound pressure levels in the 250 Hz to 6.4 kHz frequency range were obtained.

Shock pulse

The shock pulse method gives an indication of the condition of the rolling element bearings by measuring the magnitude of the mechanical impacts caused by damage in them. Ultrasonic shock waves are generated because of these impacts. The transducer of the shock pulse meter is a piezoelectric accelerometer tuned to a resonant frequency around 52 kHz. The shock waves caused by the impacts in the bearings initiate damped oscillations in the transducer at its resonance frequency. The maximum value of the damped resonant oscillation gives an indication of the bearing condition. Low frequency vibrations in the machine, generated by sources other than rolling element bearings, are electronically filtered out. The shock pulse value generated by a good bearing due to surface irregularities is dependent upon the bearing bore diameter and rpm/min. This value, called the 'initial value' (dB), is subtracted from the shock value of the test bearings to obtain a 'normalized shock pulse value' (dBn).

This normalized shock value is measured to indicate the bearing condition. The method is quite useful for the detection of the bearing condition and has gained wide industrial acceptance. In the present investigation the maximum normalized shock pulse values (dBn) of the test bearings were measured with the help of the shock pulse meter 43A (SPM Instrument AB). A hand-held transducer type SPM 10777 was used with the shock pulse meter. In this shock pulse meter, the initial value is automatically subtracted when the bearing bore diameter and rpm/min are set on its calculator dial, to give the normalized shock pulse value.
Acoustic emission

Acoustic emission (AE) is the spontaneously generated elastic wave produced within a material under stress. Acoustic emission transducers are designed to detect the very high frequency (greater than 100 kHz) stress waves. Plastic deformation and growth of cracks are the main sources of AE in metals. The growth of subsurface cracks can be detected by acoustic emission. Acoustic emission generated in rolling element bearings which are new and undamaged is expected to be at a low level. In the case of damaged bearings, when the rolling elements roll across a defect in races, or a defect in the rolling element strikes the races, the bearing elements are stressed and the emission is expected to increase drastically.

The AE method has been used for the detection of defects in rolling element bearings. In the present work, the 'ringdown counts' and the peak amplitude of the acoustic emission signal of the test bearings have been measured. The ringdown counts are defined as the number of times the signal rises above a preset threshold level. AE measurements were performed using a microprocessor-based measurement system (AET 5000) consisting of a transducer (AET AC175L), a preamplifier (AET 160B), a filter (AET FL12X), a central processor, a microcomputer and a printer. A threshold level of 0.75 V was selected for all the measurements. The peak amplitude of the signal is expressed in dB with 0 dB corresponding to 1 mV at the preamplifier output. AE ringdown counts in 3 s were recorded for a duration of 15 s and their average value in 3 s is used in the results presented. The AE ringdown count values for all the bearings were converted for the main amplifier gain of 8 for the load and 20 for the speed plots.

Results

Some typical results of vibration and acoustic measurements on test bearings with 500 μm diameter and 150 μm depth defects, and on those without defects at 60 kg load and 1500 rev/min speed, are given in Table 2. They give an indication about the measurement levels obtained for different techniques used in this study.

The usefulness of different vibration and acoustic measurements performed for the detection of the defects in the bearings has been compared by presenting the measurement results in the form of defect detectability, which is defined as the ratio of the value of the defective bearing to that of the good bearing. In the case of dB values, the dB increase of defective bearings has been converted to the above mentioned ratio. These defect detectability ratios are plotted for the inner race, outer race and ball defect in Figs 3 to 11. The defect detectability values of envelope detected acceleration at lower speeds and at higher loads for inner race and ball defects are not plotted because the defect frequency peaks in these cases could not be identified in the spectra.

The defect in the inner race is best detected by measuring acoustic emission ringdown counts followed by envelope acceleration and AE peak amplitude (Figs 3 to 5). The detectability of the sound

Table 2 Vibration and acoustic measurement results of bearings with no defect and with 500 μm diameter, 150 μm depth defect at 60 kg load and 1500 rev/min speed

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Measurement parameter</th>
<th>Defect location</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>No defect</td>
</tr>
<tr>
<td>1</td>
<td>Overall acceleration, m s⁻²</td>
<td>0.673</td>
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<tr>
<td>2</td>
<td>Envelope detected acceleration, m s⁻²</td>
<td>0.00163*</td>
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<tr>
<td>3</td>
<td>Overall sound intensity, dB</td>
<td>59.4</td>
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<td>4</td>
<td>Overall sound pressure, dB</td>
<td>65.3</td>
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<td>5</td>
<td>Maximum shock pulse value, dB</td>
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<td>6</td>
<td>Acoustic emission ringdown counts</td>
<td>5450</td>
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<tr>
<td>7</td>
<td>Acoustic emission peak amplitude, dB</td>
<td>60.7</td>
</tr>
</tbody>
</table>

*Value corresponding to outer race defect frequency. For inner race and ball defect frequencies no peak was observed in the spectra of good bearings, and the value of the base vibration level (0.00037 m s⁻²) was adopted for these cases.
The detectability of AE ringdown counts drops steeply with increase in load (Fig 3) because the ringdown counts of good bearings increased sharply with increase in load. The detectability of overall acceleration does not change much with increase in load. Figure 4 shows that detection of inner race defects at speeds below about 600 rev/min was not possible by shock pulse and sound pressure measurements.

Fig 3 Defect detectability of 500 µm diameter, 150 µm depth inner race defect

pressure measurements is the lowest. In the case of envelope acceleration no peak was obtained at the inner race defect frequency for the good bearings and its value has been taken as that of the base vibration

Fig 4 Defect detectability of 500 µm diameter, 150 µm depth inner race defect

Fig 5 Defect detectability of inner race defect at 60 kg load and 500 rev/min

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Acoustic emission is the only method which has shown fairly good defect detectability at lower speeds down to 100 rev/min (Fig 4). Acoustic emission has been shown to detect defects in rolling element bearings at low speeds by other investigators also. Detection of inner race defect diameters smaller than about 300 μm is difficult by measuring overall acceleration, sound pressure or shock pulses (Fig 5(a)) for the size and type of the bearings tested. Miyachi and Seki have reported that the detection of defects smaller than 500 μm in diameter was difficult by overall acceleration measurements on 30 mm bore bearings.

The detectability of defects in the outer race at higher loads is the best for envelope acceleration whereas at lower speeds it is the best for AE ringdown counts (Figs 6 and 7). The detectability of envelope acceleration and shock pulse increases with increase in load whereas that of AE ringdown count decreases with increase in load (Fig 6). Figure 7 shows that at speeds lower than about 350 rev/min the defect is not detected by the shock pulse method. The detectability of smaller size defects of 150 and 250 μm diameter is the highest for envelope acceleration and AE peak amplitude measurements and the lowest for shock pulse measurements (Fig 8). Overall acceleration measurements also give good results for the detection of defects in the outer race.

Figures 9 to 11 show that the detectability of ball defects is lower than that of the races for all the measurement methods. The ball defect is best detected by measuring AE peak amplitude as seen in these figures. AE peak amplitude measurement has shown good detection of ball defects at all loads, speeds and defect sizes. The ball defect detectability of most of the measurements does not change much with an increase in load (Fig 9). Figure 10 shows that the defect is not detected at speeds lower than about 850, 600 and 200 rev/min by measuring shock pulses, sound pressure and overall acceleration, respectively. Except for AE peak amplitude the detection of ball defects of smaller diameters is poor for all the measurements (Fig 11(a)).

The difficulty in detecting bearing defects by shock pulse measurements at low speeds has also earlier been reported in the literature and could be because of the reduced severity of impacts at low speeds. Ray has reported that an SPM 43A meter failed to register below 250 rev/min and could not indicate damage in bearings below 750 rev/min. Smith has indicated that in the presence of background vibration from gears, the SPM transducer allowed the detection of defects in bearings down to about 500 rev/min by visual inspection of the traces. However, Butler has reported success of the shock pulse method in detecting damage in a paper production line bearing at speeds as low as 2 rev/min.

Conclusions

A comparison of the vibration and acoustic measurement methods shows that the defect in the inner race
is best detected by measuring AE ringdown counts followed by envelope acceleration and AE peak amplitude. However, the detectability of AE ringdown counts drops steeply with increase in load. The detectability of defects in the outer race at higher loads is best for envelope acceleration whereas at lower speeds it is best for AE ringdown counts. The smaller size defect diameters in the outer race have been detected best by envelope acceleration and AE peak amplitude measurements. The ball defect is best detected by measuring AE peak amplitude. It is the only parameter which detected the smaller size ball defects effectively. In general, the detectability of defects at lower speeds is highest by acoustic emission and lowest by the shock pulse method.

**Fig 8** Defect detectability of outer race defect at 60 kg load and 1500 rev/min

**Fig 9** Defect detectability of 500 μm diameter, 150 μm depth ball defect

**Fig 10** Defect detectability of 500 μm diameter, 150 μm depth ball defect

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References


