Experimental investigation of cylindrical roller bearing for inner race defect under varying load

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Abstract. This paper presents an experimental investigation of inner race defect on cylindrical roller bearing under various speeds and radial load conditions. The several statistical features like RMS, crest factor, skewness, kurtosis, and frequency domain techniques like FFT, envelope spectrum have been extracted and compared it for defective and healthy bearing at various speeds and radial load to understand the performance of bearing. The experimental results indicate that increment in rotational speed and variation in radial load has a remarkable influence on various features of the signals.

1. Introduction

Roller bearings have been extensively used in various industrial machineries since the late nineteenth century. It requires constant monitoring to avoid unexpected failure. Any misalignment or faults produced in any part of bearing can cause vibration, which magnifies with the hike in load and speeds, and results in complete failure of bearing or machinery.

Some experimental research was carried out with rolling element bearings. The experimental investigation has performed by [1] for ball bearing defect with and without unbalancing mass. The effect of surface roughness damage under radial load at different positions of the outer ring of ball bearing has been studied by [2]. [3] has experimented for the fault on inner ring, outer ring, and ball considering varying speed and radial load. The experimental examination for ball bearing has been performed for dynamic motions of cage under different speeds and loads by [4]. The influence of individual and combined localized defects with variations in defect size, rotational speed, and radial load has been studied by [5]. Faulty ball bearing running at various speeds and many radial loads with several fault sizes has been analyzed by [6].

The RMS value can be consider for bearing diagnosis as an indicator of an average of overall amplitude of vibration [3]. Its value is always less than the peak value. Kurtosis is a fourth-order moment, which describes the heaviness of the tails and the peakedness of the distribution. High kurtosis value shows that high impulsive components are present in the signal [7]. Skewness measures the symmetricity of the dataset. '0' skewness indicates perfectly symmetrical data points. Skewness from -0.5 to 0.5 shows the fairly symmetrical region. Skewness from -0.5 to -1, or from 0.5 to 1 point out the moderately skewed region. Skewness below -1 or above 1 has a highly skewed region. Crest factor measures the impulsive nature of the signal. It is found by dividing the peak of the waveform by RMS. Fourier analysis transforms a signal from time-domain to frequency-domain or vice versa. A fast Fourier transform (FFT) shows frequencies present in the vibration signal. Envelope spectrum is an effective technique to detect defect frequency of bearing. However, it is not suitable for healthy bearing.

2. Experimental / Computational details
In an experimental setup, shaft is supported by two bearings. One of them is a support bearing and another is a test bearing. A 3-Φ, 3000 rpm induction motor was connected to the shaft with a flexible coupling. A 3-Φ variable frequency drive was linked with motor to control its speed. A laser tachometer was adjusted to observe the rotational speed of the shaft. The entire setup was placed on an aluminium plate having six vibration absorber pads. The artificial fault was formed on the inner race of bearing by EDM.

The bearing vibrations were acquired by piezoelectric accelerometers 352C03 with sensitivities of 10.07 mV/g; which was fitted in the vertical direction on test bearing housing. A DAQ card NI 9234 was utilized to acquire the vibration signal. Data collection was conducted through NI LabVIEW program. The sampling rate was kept to 25.6 kHz. The data was collected for a duration of 1 sec. Collected data were then loaded into MATLAB for analysis.

During the experiment, the outer race was kept motionless in bearing housing, and the inner race rotates along with the shaft. Cylindrical roller bearing NJ 305E with inner race defect and without defect were used for the experiment. Details of the bearing are registered in Table 1.

Table 1: Roller bearing specifications

| Properties               | Value | Properties               | Value |
|--------------------------|-------|--------------------------|-------|
| Number of rollers ($n_r$) | 11    | Inner race radius ($r_i$) | 17 mm |
| Diameter of roller ($d_r$) | 10 mm  | Width of defect ($W$)      | 13 mm |
| Length of roller ($l$)    | 11 mm | Depth of defect ($D$)      | 0.5 mm|
| Pitch diameter ($P_d$)    | 43.65 mm | Outer race radius ($r_o$) | 27 mm |

![Figure 1: Schematic diagram of experimental setup.](image)
The experimental tests were carried out for inner race fault of size 0.5 mm defect length and for healthy bearing. It is also tested at various speeds in the range of 300 to 3000 rpm with a speed increment of 300 rpm. The bearings were tested for 0 and 3 kg radial load.

| Frequency                        | Formula                                      |
|----------------------------------|----------------------------------------------|
| Shaft frequency                  | $\phi_s = \frac{2.\pi.n}{60}$               |
| Cage frequency                   | $\phi_c = \frac{\phi_s}{2} \times \left(1 - \frac{d_r}{P_d}\right)$ |
| Varying compliance (VC) frequency| $VC = n_r \times \phi_c$                     |
| Inner race defect (IRD) frequency| $\phi_i = n_r \times (\phi_s - \phi_c)$     |

### Table 3 Time-domain features [8]

|                |                                                             |
|----------------|-------------------------------------------------------------|
| $RMS$          | $\sqrt{\frac{1}{p} \sum_{i=1}^{p} x_i^2}$                 |
| Skewness       | $\frac{1}{p} \sum_{i=1}^{p} (x_i - \bar{x})^3 / (\text{std. dev.})^3$ |
| Kurtosis       | $\frac{1}{p} \sum_{i=1}^{p} (x_i - \bar{x})^4 / (\text{std. dev.})^4$ |
| Crest factor   | $\frac{\text{max}|x_i|}{RMS}$                              |

3. Result and Discussion

The vibration signals were acquired at various speeds for with and without load along with faulty and healthy bearing. Out of numerous vibration signals, the signals acquired for defective and healthy bearing at 900 rpm are displayed in Figure 3, and Figure 4. The periodic impacts occur at defect frequency of inner race, which can be estimated from Table 2. The shaft frequency and varying compliance frequency are also present in the system.
Figure 3: Time signal of IRD bearing

Figure 4: Time signal of Healthy bearing

Figure 5: Envelope spectrum for IRD
Figure 5 shows the envelope spectrum for bearing running at 900 rpm with inner race defect. Due to manufacturing limitations, there is always some clearance between the side flange of races and roller side face. Due to that clearance, inner race fluctuates axially with respect to outer race by some amount. This phenomenon results in the formation of periodic shaft frequency as in zone 1 and sideband frequencies around defect frequency of BPFI ± 1 x RPM and BPFI ± 2 x RPM as in zone 2, which is clarified in Figure 6.

Figure 7 shows the difference between the amplitude of defect frequency and shaft frequency at different speeds. The higher difference indicates that defect frequency has a major role, and the lower difference indicates shaft frequency has a major role in vibration signal. So, based on this, rank has been decided for the selection of optimum speed at which defect frequency is predominant. So, as per Figure 7, 2100rpm, 1500rpm & 1200rpm has been assigned Rank 1, Rank 2, and Rank 3, respectively.

Figure 6: Envelope spectrum pattern for IRD

Figure 7: Envelope spectrum amplitude difference between defect frequency and shaft frequency
Figure 8: FFT plot for (a) IRD, (b) Healthy at 900 rpm

Figure 8-a displays shaft frequency and defect frequency along with their harmonics for defective bearing. Whereas, Figure 8-b shows shaft frequency and Varying Compliance (VC) frequency along with their harmonics for healthy bearing. By carefully observing Figure 8, it seems that the defective bearing has a higher frequency amplitude compared to the healthy bearing. In Figure 8-b, with no load condition shaft frequencies $f_s$ and $3f_s$ can be observed; however, with the application of radial load, only $f_s$ is visible, which indicates that radial load reduces the effect of shaft frequency for healthy bearing.
From Figure 9 it confirms that the defective bearing has higher RMS value than healthy bearing at all speeds. With increase in speed RMS value increase for healthy and faulty bearing. At a higher speed, the no-load condition has higher RMS value compared to with load condition for defective bearing, while for healthy bearing, it is opponent.

The defective bearing has a higher kurtosis value than healthy bearing, which is witnessed from Figure 10. For healthy bearing, kurtosis is nearby 3. As shown in Figure 10, kurtosis is high at low speed and reduces continuously with increment in speed for the specified defect size, while for non-defective bearing, it increases initially and then decreases. Under the situation of 0 radial load, higher kurtosis value is observed compared to 3 kg radial load for defective bearing at all speeds.

As illustrated in Figure 11, the defective bearing has higher skewness value than the healthy bearing. With the increment in speed, skewness value decreases and approaches towards symmetricity for faulty bearing, which is described in Figure 11-a. For defective bearing up to 1500 rpm data set falls into the highly skewed region, from 1800 to 2100 rpm moderately skewed region and from 2400 to 3000 rpm fairly symmetric region. In highly skewed region, bearing without load has higher skewness value compared to with load condition. When the dataset falls into a moderately or fairly symmetrical zone, then skewness value fluctuates between no load and with load condition. Which confirms that data points in a highly skewed region will have more effect of loading than moderately or fairly symmetrical region.
Figure 11-b indicates that for healthy bearing skewness for all speeds are close to 0, which confirms that for healthy bearing perfectly symmetrical data set will get irrespective of speed.

Figure 12: Crest factor for (a) IRD, (b) Healthy

Figure 12 shows that defective bearing has a higher crest factor compared to the healthy bearing. For healthy bearing, the crest factor is around 6. From Figure 12-a it can say that for defective bearing crest factor reduces with an increase in speed, however, as per Figure 12-b for healthy bearing, it fluctuates. The no-load condition has a higher crest factor compared to with load condition for defective bearing at all speeds, while for healthy bearing crest factor varies among no-load and with load condition.

4. Conclusion

- The selection of speed based on the predominance of defect frequency can be achieved from a peak amplitude difference between defect frequency and shaft frequency.
- The loaded bearing has lower frequency amplitude compared to no-load condition for healthy bearing, while for defective bearing, it is contrariety.
- Radial load reduces the effect of shaft frequency for healthy bearing.
- Results confirm that radial load has antagonist behavior between defective and healthy bearing for RMS value at a higher speed.
- Radial load helps to reduce kurtosis value for defective bearing.
- For healthy bearing, skewness falls in the symmetrical region irrespective of speed. For defective bearing data points in a highly skewed region will have more effect of loading than other regions.
- With the increment of speed, the signal approaches towards symmetricity from the highly skewed region.
- Radial load acting on bearing results into a reduction in crest factor for defective bearing. For healthy bearing at low speeds, the radial load has a major effect on the crest factor.
- For healthy bearing kurtosis, skewness, and crest factors are around 3, 0, and 6, respectively; however, these features increase drastically with damage.
- Among all time-domain features described here, skewness has a significant influence on various loading conditions for the specified defect size.

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