Study of effects of radial load on vibration of bearing using time-Domain statistical parameters

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Abstract. Rolling element bearings are important parts of rotating machineries. Any defect in their elements causes vibration and damage. Many vibration signal analysis techniques are available for detection and diagnosis of defects in machineries. In time domain vibration analysis techniques, various statistical parameters such as RMS, crest factor, skewness, kurtosis etc. are used for defect detection in bearings. Bearing related parameters like defect type, defect size, shaft speed, radial load etc. affect the bearing vibrations. In this paper, the effects of change in bearing radial load on various time-domain statistical parameters are analyzed. New combination of indicators like Kurtosis $\times$ RMS, Kurtosis $\times$ Peak, RMS $\times$ Peak and new indicators developed by researchers TALAF and THIKAT are analyzed for change in radial load on bearing. Also the effect of outer race defect in bearing on statistical parameters is analyzed. In this paper, the bearing defect data sets with outer and inner race defects provided by Society for Machinery Failure Prevention Technology are used. The results show that these parameters can be used as condition indicators for early fault detection in bearings.

Keywords. Time domain analysis; scalar indicators; bearing defects; frequency spectrum; envelope analysis.

1. Introduction
Rolling element bearings (REBs) are used in rotating machineries to support the rotating parts and to reduce the friction. A REB consists of four main parts i.e. inner race, outer race, rolling element and cage. Any defect in these parts causes undesirable vibration. Vibration signal analysis (VSA) techniques broadly classified as time domain, frequency domain and time-frequency domain are used to analyze bearing vibrations and to detect the cause and severity of defects in bearings. In time domain analysis, statistical parameters (also known as scalar indicators) like Peak, Mean, Peak-to-peak, Root mean square (RMS), Crest factor, Skewness, Kurtosis, Impulse factor, Shape factor, Clearance factor, etc. are mostly used for analysis of vibrations. Out of these parameters, Peak, RMS, Crest factor and Kurtosis are most commonly used for analysis of bearing defects [1].

The statistical parameters compared in this paper are defined as below. Table 1 shows equations of commonly used statistical parameters for detection of bearing defects [2], [3].

1) Peak is the value of maximum amplitude of the signal.
2) RMS is the square root of mean of squares of signal. It is the measure of overall vibration level of signal.
3) Crest factor is the ratio of Peak to RMS of the signal. It indicates the spikiness/impulsive nature of signal.
4) Skewness is the measure of the asymmetrical spread of a signal about its mean value.
5) Kurtosis is the measure of peakedness of the probability density function (PDF) of a time series.

Table 1. Commonly used time domain statistical parameters

| Parameters | Formula |
|------------|---------|
| Peak       | $x_{\text{max}}$ |
| Root Mean Square (RMS) | $\sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i)^2}$ |
| Skewness (SKEW) | $\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^3$ |
| Mean ($\bar{x}$) | $\frac{1}{N} \sum_{i=1}^{N} x_i$ |
| Crest factor (CF) | $\frac{\text{Peak}}{\text{RMS}}$ |
| Kurtosis (KUR) | $\frac{\left(\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^4\right)^2}{\left(\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2\right)^2}$ |

where $x_i$ = Instantaneous amplitude of signal, $N$ = No. of samples taken within the signal

Sassi et al. [4] developed two new indicators TALAF and THIKAT using the combination of traditional statistical parameters. Table 2 shows formulae of these new indicators.

Table 2. New Indicators TALAF and THIKAT of Sassi et al

| Indicators | Formula |
|------------|---------|
| TALAF      | $\log\left[\text{KUR} + \frac{\text{RMS}}{\text{RMS}_0}\right]$ |
| THIKAT     | $\log\left[\text{KUR}^{\text{CF}} + \left(\frac{\text{RMS}}{\text{RMS}_0}\right)^{\text{PEAK}}\right]$ |

where RMS$_0$ = RMS of normal bearing
Time domain statistical parameters show the severity of the defects, but do not show the exact location of the defects. Frequency spectrum and envelop spectrum overcome this limitation and show the exact reasons of vibration [5]. In frequency spectrum analysis, the time domain signals are converted into frequency domain signals by using Fourier transform. Each bearing element has its characteristic rotational frequency. These frequencies can be calculated from kinematics of bearing as shown in table 3. Any amplitude peak found at any of these frequencies in frequency domain diagram indicates the presence of defect in that element.

**Table 3. Equations of bearing characteristics frequencies**

| Bearing characteristics frequencies          | Formula                                                                 |
|-----------------------------------------------|-------------------------------------------------------------------------|
| Outer Race Defect Frequency (ORDF)            | \( \frac{nf_r}{2} \left( 1 - \frac{D_b}{D_c} \cos \phi \right) \)   |
| Inner Race Defect Frequency (IRDF)            | \( \frac{nf_r}{2} \left( 1 + \frac{D_b}{D_c} \cos \phi \right) \)   |
| Ball Defect Frequency (BDF)                   | \( \frac{D_c}{D_b} \left( f_r^{1 - \frac{D_b}{D_c} \cos \phi} \right)^2 \) |
| Cage Rotational Frequency (CRF)               | \( \frac{f_c}{2} \left( 1 - \frac{D_b}{D_c} \cos \phi \right) \)   |

where \( n \) = no. of balls, \( f_r \) = shaft rotational speed in rps, \( D_b \) = ball diameter, \( D_c \) = Pitch/cage diameter, \( \phi \) = contact angle

Peak and RMS has same unit as amplitude, while other parameters are dimensionless [6]. When the defect size is small, it is found that peak value increases and RMS value remains unchanged. Therefore crest factor increases initially with increase in defect size. However, thereafter when the defect size increases the RMS value increases and the peak value remains unchanged. This causes decrease in crest factor with increase in defect size. This makes crest factor less sensitive to the defect size [7].

In recent years, a lot of research work is carried out by the researchers to analyze the effectiveness of statistical parameters for bearing defect detection under different conditions. Tandon et al. [8] compared the effect of bearing defect sizes on peak, RMS and crest factor. They found that values of these parameters increase with increase in defect size. They also found that Peak and RMS of outer race defect (ORD) is greater than that of inner race defect (IRD), but crest factor of ORD is smaller than that of IRD.

In year 1976, Dyer and Stewart, used Kurtosis for bearing defect detection first time. They found that the value of kurtosis is near to 3 for an undamaged (good) bearing and this value increases with the defect size. However, this value comes down to 3 when the defect size further increases. Howard [1] in his review found that for the undamaged bearing, the values of kurtosis and crest factors are approximately 3 and 3.5 respectively.

Heng and Nor [9] used crest factor, skewness and kurtosis to detect defects in REBs for both sound and vibration signals. They concluded that the bearing speed affects these statistical parameters. Tandon and Choudhury [10] in their review found that kurtosis is most effective among the statistical parameters like overall RMS level, crest factor, probability density and kurtosis. Martin and Honarvar [11] used skewness and kurtosis for bearing defect detection. Their results show that skewness and kurtosis are independent on load and speed. Kurtosis of healthy bearing is 3 and it increases with increase in defect size. Almeida et al. [12] showed that skewness is the worst parameter among RMS, Kurtosis and Skewness. Kurtosis detects only the pit fault at low speed. The results of RMS value for
acceleration signals are better than velocity signals. The detection performance of the RMS increases with the shaft speed. Patil et al. [13] studied the effect of change in defect size, speed and load on kurtosis. They found that kurtosis increases with the increase in these factors and defect size is more dominant for all types of defects. Utpat et al. [14] compared peak-to-peak value, peak value and RMS value for bearing defects detection. Their results show that peak-to-peak value gives better defect detectability for ORD, IRD and ball defect. Singh and Harsha [15] presented detection of bearing defects using empirical mode decomposition of bearing vibration signal. They found that the crest factor and kurtosis are more sensitive as compared with skewness to the ORD for the load and speed variations.

Many other researchers [2], [5], [16]–[22] also showed the applications of statistical parameters in bearing defect detection. Some researchers [4], [7], [22], introduced new indicators based on statistical parameters for bearing defect detection.

From the literature review, it is concluded that the statistical parameters can give indication of presence of defects in bearing in their early stages and hence very useful for bearing condition monitoring. These parameters depend on various factors such as defect type (inner race, outer race or rolling element defect), defect size (width and depth), shaft speed, radial load, etc. In this paper, the effect of bearing radial loads ranging from 50 to 300 lbs on various time domain statistical parameters is examined for inner and outer race defects. Also frequency spectrum and envelope spectrum analysis of necessary defective bearings are carried out. In this paper, authors used ball bearing datasets provided by Society for Machinery Failure Prevention Technology (MFPT) [23].

2. Experimental Data Analysis
In this paper, 18 ball bearing datasets provided by Society for Machinery Failure Prevention Technology (MFPT) are used for analysis. Vibration signal datasets of normal and defective bearing were obtained by using ball bearing of NICE company. Also the vibration signal data of defective bearings having ORD and IRD were collected for same size of defects. Table 4 shows the specifications of the ball bearing used by MFPT. These datasets are available on MFPT’s website in the form of MATLAB files with .mat extension. Each data file contains data of radial load (lbs), shaft speed (Hz), sampling frequency (Hz) and signal amplitude (g). For all experiments, the shaft speed 1500 rpm i.e. 25 Hz was kept constant. Table 5 shows the bearing defect characteristic frequencies for shaft speed 25 Hz. Table 6 shows the details of 18 datasets used for analysis in this paper. This table contains type of bearing defect, radial load, sampling frequency, duration of signals taken, data file codes given by MFPT and new data file codes given by authors for simplicity.

Table 4. Specifications of NICE bearing used for datasets

| Pitch/cage diameter ($D_c$) | Ball diameter ($D_b$) | No. of balls ($n$) | Contact angle ($\phi$) |
|-----------------------------|----------------------|--------------------|-----------------------|
| 1.245 inch (31.62 mm)       | 0.235 inch (5.97 mm) | 8                  | 0°                    |

Table 5. Bearing defect characteristic frequencies in Hz

| Shaft speed | ORDF | IRDF | BDF | CRF |
|-------------|------|------|-----|-----|
| 25          | 81.12| 118.88| 127.69| 10.14 |

In this paper, the time waveform, moving RMS plot, moving Kurtosis plot, frequency spectrum and envelop spectrum are obtained for each bearing data set using MATLAB R2020a software. Also the values of statistical parameters like Peak, RMS, Crest factor, Kurtosis, combined indicators like Kurtosis $\times$ RMS, Kurtosis $\times$ Peak, RMS $\times$ Peak, TALAF and THIKAT are also obtained using MATLAB codes. Frequency and envelope spectrums, band passed envelope spectrums are used for finding the reasons of defects.
Table 6. Details of datasets used for analysis in this paper

| Sr. No. | Bearing Defect | Load (lbs) | Load (N) | Sampling Freq. (Hz) | Duration (sec) | MFPT Code | New Code given |
|---------|----------------|------------|----------|---------------------|----------------|------------|----------------|
| 1       | No defect      | 270        | 1201     | 97656               | 6              | baseline_1 | Normal1 270    |
| 2       | No defect      | 270        | 1201     | 97656               | 6              | baseline_2 | Normal2 270    |
| 3       | No defect      | 270        | 1201     | 97656               | 6              | baseline_3 | Normal3 270    |
| 4       | ORD            | 270        | 1201     | 97656               | 6              | OuterRaceFault_1 | ORD1 270 |
| 5       | ORD            | 270        | 1201     | 97656               | 6              | OuterRaceFault_2 | ORD2 270 |
| 6       | ORD            | 270        | 1201     | 97656               | 6              | OuterRaceFault_3 | ORD3 270 |
| 7       | ORD            | 50         | 222      | 48828               | 3              | OuterRaceFault_vload_2 | ORD 50 |
| 8       | ORD            | 100        | 445      | 48828               | 3              | OuterRaceFault_vload_3 | ORD 100 |
| 9       | ORD            | 150        | 667      | 48828               | 3              | OuterRaceFault_vload_4 | ORD 150 |
| 10      | ORD            | 200        | 890      | 48828               | 3              | OuterRaceFault_vload_5 | ORD 200 |
| 11      | ORD            | 250        | 1112     | 48828               | 3              | OuterRaceFault_vload_6 | ORD 250 |
| 12      | ORD            | 300        | 1334     | 48828               | 3              | OuterRaceFault_vload_7 | ORD 300 |
| 13      | IRD            | 50         | 222      | 48828               | 3              | InnerRaceFault_vload_2 | IRD 50 |
| 14      | IRD            | 100        | 445      | 48828               | 3              | InnerRaceFault_vload_3 | IRD 100 |
| 15      | IRD            | 150        | 667      | 48828               | 3              | InnerRaceFault_vload_4 | IRD 150 |
| 16      | IRD            | 200        | 890      | 48828               | 3              | InnerRaceFault_vload_5 | IRD 200 |
| 17      | IRD            | 250        | 1112     | 48828               | 3              | InnerRaceFault_vload_6 | IRD 250 |
| 18      | IRD            | 300        | 1334     | 48828               | 3              | InnerRaceFault_vload_7 | IRD 300 |

3. Results and Discussion

3.1. Effect of ORD in bearing on statistical parameters:
In this section, effect of ORD in bearing on statistical parameters is analyzed. Statistical parameter values are obtained for normal and bearing with ORD running at constant speed 25 Hz and constant radial load 270 lbs. Figure 1 shows time waveform, moving RMS plot, moving kurtosis plot, frequency spectrum, zoomed frequency spectrum and envelope spectrum of one of the normal bearings coded as ‘Normal2 270’ out of three data sets loaded with 270 lbs radial load. Figure 2 shows time waveform, moving RMS plot, moving kurtosis plot, frequency spectrum, zoomed frequency spectrum and envelope spectrum of one of the bearings with ORD coded as ‘ORD2 270’ out of three data sets loaded with 270 lbs radial load. Time waveform of ‘Normal2 270’ [figure 1 (a)] shows no spikes in signals; however time waveform of ‘ORD2 270’ [figure 2 (a)] shows some spikes in signals which indicates some defects in bearing. But, from this it is difficult to identify the type of defect in the bearing. Figure 1 (b) and (c) shows moving RMS plots and moving kurtosis plots for ‘Normal2 270’ data set and figure 2 (b) and (c) shows the same for ‘ORD2 270’ data set respectively. Moving RMS plots and moving kurtosis plots shows RMS and Kurtosis values for 1 second duration spans and their mean RMS and Kurtosis values for the duration of 6 second. In both these plots, grey line is the trend line and red line is the mean line for duration of 6 seconds. RMS values of ‘Normal2 270’ and ‘ORD2 270’ do not show much difference. Kurtosis value of ‘Normal2 270’ is 3.016 which very close to 3 (kurtosis value of normal distribution) indicates the good bearing. Kurtosis value of ‘ORD2 270’ is increased to 3.5 indicate rise due to ORD. This indicates that kurtosis is sensitive to ORD as compared to RMS.
Figure 1. (a) time waveform, (b) moving RMS plot, (c) moving kurtosis plot, (d) frequency spectrum, (e) zoomed frequency spectrum and (f) envelope spectrum of ‘Normal2 270’ data set.

Figure 2. (a) time waveform, (b) moving RMS plot, (c) moving kurtosis plot, (d) frequency spectrum, (e) zoomed frequency spectrum and (f) envelope spectrum of ‘ORD2 270’ data set.
Figure 1 (d) and figure 2 (d) shows frequency spectrum for ‘Normal2 270’ and ‘ORD2 270’ data sets. Figure 1 (e) and 2 (e) shows the zoomed frequency spectrums for the same data sets. It is clearly seen from figure 1 (d) and figure 2 (d) that the vibration amplitude for ‘ORD2 270’ is higher than for ‘Normal2 270’. Zoomed frequency spectrums as shown in figure 1 (e) and figure 2 (e) shows the spikes at shaft rotating frequency 25 Hz and its harmonics. This indicates misalignment of shaft. In frequency and envelope spectrums of ‘ORD2 270’, the spikes at ORD frequency 81 Hz are not seen, it means in this case both frequency and envelope spectrums are unable to detect the ORD. Envelope spectrum obtained after bandpass filtering shows clearly the spikes at ORD frequency. Figure 3 shows bandpass filtered time domain signal, its enveloped signal and its envelope spectrum obtained after performing kurtosis band selection with fast kurtogram as explained by Saidi et al. [24]. Table 7 and 8 shows the actual values of statistical parameters and their average values respectively obtained for 3 data sets of normal bearings and 3 data sets of bearing with ORDs running under 270 radial load.

![Figure 3](image)

Table 7. Values of parameters of normal and bearing with ORD under radial load 270 lbs

| Bearing Code | PEAK | RMS | CF  | SKEW | KUR  | KR  | KP  | RP  | TALAF | THIKAT |
|--------------|------|-----|-----|------|------|-----|-----|-----|-------|--------|
| Normal1 270  | 3.709| 0.890| 4.166| 0.007| 3.014| 2.683|11.177| 3.302| 0.605  | 2.001  |
| Normal2 270  | 4.259| 0.875| 4.869|0.002 | 3.016| 2.639|12.846| 3.725| 0.603  | 2.336  |
| Normal3 270  | 4.220| 0.876| 4.816|-0.002| 3.021| 2.647|12.748| 3.697| 0.604  | 2.315  |
| ORD1 270     | 3.735| 0.721| 5.181|-0.015| 3.168| 2.283|11.830| 2.692| 0.601  | 2.595  |
| ORD2 270     | 4.349| 0.823| 5.285| 0.080| 3.501| 2.881|15.224| 3.579| 0.647  | 2.876  |
| ORD3 270     | 5.564| 0.993| 5.606|-0.010| 4.133| 4.102|22.996| 5.523| 0.721  | 3.455  |

Table 8. Average values of parameters of normal and bearing with ORD under radial load 270 lbs

| Bearing  | PEAK | RMS | CF  | SKEW | KUR  | KR  | KP  | RP  | TALAF | THIKAT |
|----------|------|-----|-----|------|------|-----|-----|-----|-------|--------|
| Normal   | 4.062| 0.880| 4.617| 0.001| 3.017| 2.656|12.257| 3.575| 0.604  | 2.217  |
| With ORD | 4.549| 0.845| 5.357| 0.018| 3.600| 3.089|16.683| 3.931| 0.656  | 2.975  |

Figure 4 shows the effect of ORD on various statistical parameters as compared with normal bearing under radial load 270 lbs. Results shown are the average values of 3 data sets of normal and defected bearing. It is observed from figure 3 that almost all parameters of defective bearings shows
higher values than that of normal bearing, which is indication of presence of defect in bearing. The peak value of defective bearing is increased, but RMS is not increased and therefore crest factor value is increased. This may be due to incipient ORD in bearing. Skewness value for normal bearing is almost near to zero and for defective bearing increased slightly. Kurtosis value of normal bearing is close to 3, a known value of normal distribution. Kurtosis value of defective bearing is raised to 3.6, which is higher than that of normal bearing. New combined indicators Kurtosis \times RMS (KR), Kurtosis \times Peak (KP) and RMS \times Peak (RP) also show rise in their values for defective bearing as compared with normal bearings. KR, KP and RP shows 16.29 %, 36.11 % and 9.98 % rise respectively.

Other two parameters TALAF and THIKAT, which are developed by Sassi et al. [4] shows 8.66 % and 34.19 % rise respectively in case of defective bearing. Among these combined parameters KP with 36.11% rise looks more sensitive to ORD. Increased parameter values can only indicate fault severity, but unable to detect type of defect.

Figure 4. Effect of ORD on various parameters under radial load 270 lbs

3.2. Effect of change in radial load on statistical parameters:
In this session, effects of change in radial load on statistical parameters are analyzed. For this analysis, both ORD and IRD are considered. Statistical parameter values are obtained for bearings with ORD and IRD at constant speed 25 Hz and radial load ranging from 50 lbs to 300 lbs. Table 9 and 10 shows the values of statistical parameters obtained for 6 data sets of bearings with ORD and 6 data sets of bearings with IRD running under radial load ranging from 50 lbs to 300 lbs.

Table 9. Values of parameters of bearings with ORD under different radial loads

| Bearing Code | PEAK  | RMS  | CF   | SKEW | KUR  | KR   | KP   | RP   | TALAF | THIKAT |
|--------------|-------|------|------|------|------|------|------|------|-------|---------|
| ORD 50       | 5.966 | 0.993| 6.007| 0.038| 5.089| 5.054| 30.359| 5.925| 0.794 | 4.244   |
| ORD 100      | 4.928 | 0.844| 5.839| -0.014| 4.399| 3.713| 21.678| 4.160| 0.729 | 3.756   |
| ORD 150      | 4.928 | 0.844| 5.839| -0.014| 4.399| 3.713| 21.678| 4.160| 0.729 | 3.756   |
| ORD 200      | 12.282| 0.986| 12.461| 0.305| 11.897| 11.726| 146.114| 12.105| 1.114 | 13.401  |
| ORD 250      | 8.588 | 0.955| 8.989| 0.121| 6.593 | 6.299| 56.620| 8.205| 0.885 | 7.362   |
| ORD 300      | 16.219| 1.504| 10.782| 0.271| 17.685| 26.604| 286.835| 24.399| 1.288 | 13.451  |
Table 10. Values of parameters of bearings with IRD under different radial loads

| Bearing Code | PEAK  | RMS  | CF  | SKEW | KUR  | KR   | KP   | RP   | TALAF | THIKAT |
|--------------|-------|------|-----|------|------|------|------|------|-------|--------|
| IRD 50       | 27.498| 1.778| 15.462| 0.621| 27.965| 49.735| 768.989| 48.904| 1.477 | 22.367 |
| IRD 100      | 22.976| 1.835| 12.520| 0.871| 30.525| 56.017| 701.341| 42.164| 1.513 | 18.588 |
| IRD 150      | 23.059| 1.740| 13.249| 1.284| 33.131| 57.662| 763.956| 40.133| 1.545 | 20.141 |
| IRD 200      | 27.382| 2.023| 13.538| 1.146| 37.283| 75.412| 1020.900| 55.385| 1.597 | 21.275 |
| IRD 250      | 27.142| 2.084| 13.022| 0.724| 37.485| 78.132| 1017.400| 56.573| 1.600 | 20.495 |
| IRD 300      | 23.128| 1.968| 11.749| 0.684| 35.300| 69.485| 816.412| 45.526| 1.574 | 18.185 |

Figure 5 shows the line graphs showing the effects of change in bearing radial load on various statistical parameters for bearing having IRD and ORD. In this figure 5, pink lines show the average parameter values of 3 normal bearings running under 270 lbs radial load and blue coloured lines show the trend lines for each defect. These lines are added in the graphs for comparison purpose. From figure 5, it is observed that values of all the parameters are higher for IRD than ORD. For bearing with ORD, values of all the parameters initially decrease upto 150 lbs and then increases with increase in radial load. Also for bearing with ORD, the overall trend lines for all the parameters are trending upward. For bearing with IRD, the values of some parameters viz. peak, crest factor, skewness and THIKAT show declining trends. The value of crest factor decreases as the value of peak decreases. From figure 5, it is observed that values of all the parameters of ORD 200 and ORD 300 are significantly high than ORD 150 and ORD 250. To identify the exact reasons of vibration, envelope spectrum analysis of these bearings is carried out. Figure 6 shows envelope spectrums of ORD 150, ORD 200, ORD 250 and ORD 300. In all these envelope spectrums, the spikes are observed at ORD frequency 81 Hz and its harmonics. However, in envelope spectrum of ORD 200 and ORD 300 (figure 6 (b) and (d)) other peaks are also observed at shaft frequency i.e. 25 Hz and it harmonics. This is an indication of misalignment of the shaft. Therefore, we can conclude that rise in all values of parameters for ORD 200 and ORD 300 is due to combined effect of ORD and misalignment.

Peak shows positive trend for ORD with slope 1.985, but seen absolutely flat for IRD with slope −0.143. It means peak value for ORD is sensitive to radial load. RMS shows similar trends for ORD and IRD for increase in load with almost equal slopes of trending lines i.e. 0.056 and 0.086 respectively. It is also observed that RMS increases linearly with the increase in radial load. Crest factor shows positive trend for ORD with slope 1.137, but negative trend for IRD with slope −0.479. Therefore, it is seen that crest factor for ORD is sensitive to radial load and is able to detect the changes in signal pattern generated due to ORD as mentioned by Jayaswal and Varma [25]. Skewness for ORD and IRD shows almost flat trends for change in load with slopes 0.548 and −0.0076 respectively. The skewness values for IRD are highly scattered. Kurtosis for ORD and IRD shows similar rising trends for increase in load with slopes 2.211 and 1.763 respectively. Kurtosis value more than its normal value which is 3 for normal distribution shows the presence of defect in both the cases.

New statistical indicators Kurtosis × RMS, Kurtosis × Peak and RMS × Peak for ORD and IRD also shows rising trends for increase in load with comparatively high positive slopes. Kurtosis × Peak looks more sensitive for change in load with positive slope values 43.228 and 41.207 for ORD and IRD respectively. TALAF and THIKAT both shows similar trends for change in load for both the defects. TALAF and THIKAT for IRD shows almost flat trends for change in load with slopes 0.0229 and −0.4016 respectively. THIKAT for ORD looks more sensitive than TALAF with positive trend line slope 1.905.

For ORD or IRD in bearings, the new indicator KP looks more sensitive to change in radial load than KR, RP, TALAF and THIKAT. The obtained values of parameters can be used for machine learning purpose to predict the defects in bearings.
Figure 5. Effects of change in radial load on various parameters
4. Conclusions
In this paper, the effect of ORD and change in radial load on various statistical parameters for bearings with ORD and IRD are analyzed. On the basis of results obtained following conclusions are made:

1) Time domain waveform and statistical parameters can identify the severity of the bearing defects; however, they cannot identify the exact location of the defect in the bearings. Frequency spectrum, envelope spectrum and band passed envelope spectrum are very useful tools to find the exact reason of defect in bearing.

2) Kurtosis for normal bearings is close to 3 and for ORD and IRD, kurtosis is more sensitive to change in load followed by RMS.

3) Values of all the parameters for IRD are much higher than ORD. Therefore, it can be concluded that these parameters can clearly distinguish the ORD and IRD in bearings.

4) For bearing with ORD, all the values of parameters increase with increase in radial load. For bearing with IRD, the values of peak, crest factor and skewness decreases with increase in radial load.

Figure 6. Envelope spectrums of (a) ORD 150, (b) ORD 200, (c) ORD 250 and (d) ORD 300
5) For ORD or IRD in bearing, the new indicator KP is more sensitive to change in radial load followed by KR, RP, TALAF and THIKAT. Therefore, KP can be used as condition indicator for condition monitoring purpose.

Although the analysis shown in this paper shows the effectiveness of statistical parameters to distinguish the defects in bearings and to analyze the effects of ORD and IRD for change in radial load, a more comprehensive analysis can be done for change in other factors such as defect width, defect depth, defect position, shaft speed, bearing clearance, etc. and analysis can be done for different ranges of these factors. The results of this analysis will help the maintenance persons to understand the effect of load on various statistical parameters and to choose the best parameter as condition indicator for condition monitoring purpose.

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