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Original Article

Analysis of Effects of Increase in Defect Size on Vibration of a Ball Bearing

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Abstract - *Bearings are an important part of any rotating or oscillating machinery that supports the rotating or oscillating parts of machinery. This work presents the use of vibration signal analysis techniques, including time-domain analysis and envelope spectrum analysis, to identify bearing defects and their severity. In this work, MATLAB codes are developed to process the vibration signals developed by the normal and defective bearings and to extract the important time-domain statistical parameters, frequency spectrums and envelope spectrums from the bearings running at different speeds. To study the effects of speed, bearing defects and their sizes on vibration responses, the vibration data uploaded by Case Western Reserve University on their website for different types of bearings are used. This work compares the vibration responses of good and defective bearings using different time-domain statistical parameters. Also, the effects of the bearing defects and increase in defect sizes on vibration signals are analyzed. The results show the behavior of statistical indicators for different shaft speeds, different types of bearing defects and increases in defect size. These indicators differentiate defective bearings from normal bearings. This study of the behavior of different time-domain statistical indicators for change in speed, defect type and defect size will be useful for the vibration analyst working in the maintenance department.*

Keywords - *Time-domain statistical indicators, Frequency spectrum, Envelope spectrum, Vibration signal analysis.*

I. Introduction

This is the age of pace. Everything is rapid and fast. But if the machine fails, everything gets stopped; hence, there is a need to diagnose the machine for defects at its early stage. If we can find out the fault in the machine at its early stage, we can avoid major damage to the machine. Therfore, it is very important to have a system that will continuously monitor the machine and give a prior indication of the defect occurring in the machine [1].

Bearing is a very common component of any machine, and defects in bearings are the common types of machine defects. Fig. 1 shows a typical SKF ball bearing.

Bearing defects are broadly divided into localized and distributed. The localized defects include cracks, indents, and spalls on the rolling element or races, occurred during installation or were caused by fatigue of rolling surfaces. The other category, i.e., distributed defects, includes surface roughness, waviness, misaligned races and off-size rolling elements. Fig. 2 shows various types of defects in rolling element bearings. These defects may result from manufacturing errors and abrasive wear.

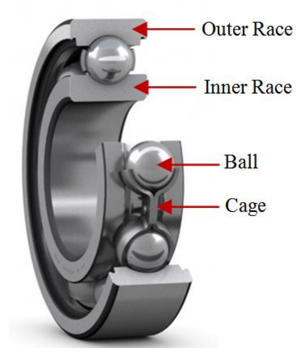


Fig. 1 Typical SKF ball bearing

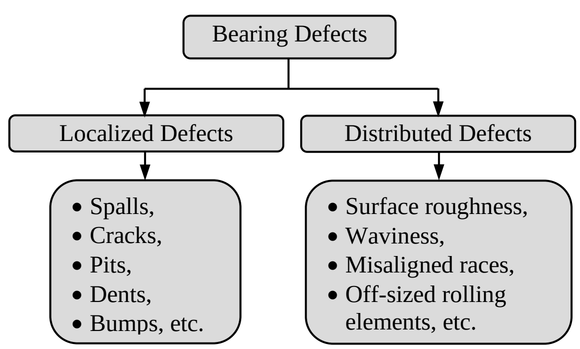


Fig. 2 Various defects in REBs

Among various condition monitoring techniques, the vibration signal analysis technique is one of the main techniques to detect the various defects in antifriction bearings due to its ease of use. The vibration signal analysis (VSA) technique is suitable for detecting various bearings defects because of its ease and fewer time requirements. VSA techniques are broadly classified as time domain, frequency domain and time-frequency domain analysis [2].

In the last few decades, many researchers demonstrated the usefulness of VSA techniques in diagnosing bearing defects.

In recent years, Tandon and Choudhary [3], Patil et al. [4], Kumar et al. [5], Jain and Bhosle [6], Patidar and Soni [7], Lin et al. [8], Gupta and Pradhan [9], Malla and Panigrahi [10], Saufi et al. [11], Rai and Upadhay [12] presented reviews on the use of VSA techniques for bearing fault diagnosis.

Recently, Shah et al. [25] studied the vibration signals of damaged surfaces of ball bearings involving localized defects on races and the waviness of races. They studied the effects of defect width, waviness order, load, speed, and lubrication on the vibration amplitude of the bearing. Jain and Bhosle [32] studied the frequency spectrums of cylindrical roller bearings due to various types of localized defects in bearings.

Tandon et al. [15], Martin and Honarvar [16], Heng and Nor [17], Tandon and Choudhury [3], Almeida et al. [18], Utpat et al. [19], Jain and Bhosle [20] analyzed the vibration signals of bearing using traditional time-domain statistical parameters for bearing defect detection.

New statistical parameters based on traditional statistical parameters are recently developed by some researchers for defect detection of bearing defects, which include ‘NM^2a’ and ‘NM^3a’ by Niu et al. [21], ‘S_α’ by Tao et al. [22], ‘TALAF’ and ‘THIKAT’ by Sassi et al. [23], ‘KUCR’ by Pradhan and Gupta [24].

This paper analyses the effects of an increase in bearing defect sizes using time-domain statistical parameters and frequency spectrums. MATLAB codes are developed to process the signals developed by the bearings.

2. Time-Domain Statistical Parameters and Bearing Defect Frequencies

VSA techniques involve time-domain and frequency-domain analysis. In time-domain analysis, signals' time vs vibration amplitude is obtained and analyzed using time-domain statistical parameters. In frequency-domain analysis, frequency spectrums are obtained from the time waveforms and used to analyse bearing defects [13].

Time-domain statistical parameters commonly used to detect defects in bearing are given in Table 1.

Table 1. Time-domain statistical parameters

Parameter	Formula
Peak	$\lvert x_{\max} \rvert$
Root mean square (RMS)	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i)^2}$
Crest factor (CF)	Peak/RMS
Kurtosis (KURT)	$\dfrac{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^4}{\left(\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2\right)^2}$
Impulse Factor (IF)	$\dfrac{\text{Peak}}{\frac{1}{N}\sum_{i=1}^{N}x_i}$
Shape Factor (SF)	$\dfrac{\text{RMS}}{\frac{1}{N}\sum_{i=1}^{N}x_i}$

where x_i = Instantaneous amplitude of the signal, N = Number of samples taken within the signal

Table 2. New time-domain statistical parameters

Parameter	Formula
TALAF	$\log\left[\text{KUR}+\frac{\text{RMS}}{\text{RMS}_0}\right]$
THIKAT	$\log\left[\text{KUR}^{\text{CF}}+\left(\frac{\text{RMS}}{\text{RMS}_0}\right)^{\text{Peak}}\right]$
KUCR	$\sqrt{\text{KUR}^2+\left[\text{CF}\times\frac{\text{RMS}}{\text{RMS}_0}\right]^2}$
ECI	$\dfrac{N\sum_{i=1}^{N}(x_i-x)^4}{\sum_{i=1}^{N}(x_i-x)^2}$
SIANA	$\log\left[\frac{\text{CF}^{\text{KUR}}}{\text{Peak}^{\text{RMS}}}\right]$
INTHAR	$\log\left[\frac{\text{CF}^{\text{KUR}}}{\text{Peak}^{\text{RMS}}}\times\text{IF}\right]$

In this work, along with the traditional time-domain statistical parameters, researchers introduced new time-domain statistical parameters to detect bearing defects that are also used for analysis. These indicators are given in Table 2.

During operation, when the balls roll over the defect, a train of impulses generate due to the balls' impact. Depending on the position of the defect, bearing geometry, and shaft speed, impulses are generated at particular frequencies. These frequencies are known as characteristic defect frequencies. Table 3 shows the equations of characteristic defect frequencies of single-row deep groove ball bearings [1].

Table 3. Equations of characteristic defect frequencies

Frequency	Equation
Outer Race Defect Frequency (ORDF)	$\frac{nf_s}{2}\left(1-\frac{D_b}{D_c}\right)$
Inner Race Defect Frequency (IRDF)	$\frac{nf_s}{2}\left(1+\frac{D_b}{D_c}\right)$
Ball Defect Frequency (BDF)	$\frac{D_c}{D_b} f_s\left[1-\left(\frac{D_b}{D_c}\right)^2\right]$
Cage Rotational Frequency (CRF)	$\frac{f_s}{2}\left(1-\frac{D_b}{D_c}\right)$

where f_s = Shaft speed in rpm, n = no. of balls, D_c = Diameter of cage, D_b = Diameter of ball,

3. Methodology Used for VSA of Bearing

In this work, the datasets uploaded by the Case Western Reserve University (CWRU) Bearing Data Center on their website [26] are used for vibration signal analysis of bearing defects. These datasets are considered standard datasets and are used by many researchers [24], [27]–[31] in their studies.

Fig. 3 shows the test rig used by CWRU for the collection of bearing vibration. This work uses 48 bearing datasets obtained from drive end-bearing vibration. These datasets are made publically by CWRU on their website. Defect diameters of 0.007 inches, 0.014 inches, 0.021 inches and 0.028 inches are made on different bearing elements of a ball bearing of number SKF 6205-2RS JEM and an NTN bearing. The defects are artificially made on bearings using EDM. Out of 48 bearing datasets, 4 datasets are obtained from normal bearings, and 44 datasets are obtained from defective bearings running at different speeds, i.e., at 1730 rpm, 1750 rpm, 1772 rpm, and 1797 rpm. Each dataset is collected for 10 seconds with a sampling frequency of 12000 Hz.

Table 4 and Table 5 show the datasets of normal bearings and defective bearings provided by CWRU with their codes.

Table 4. Datasets of normal bearings provided by CWRU with codes

Speed	Normal Bearing Dataset Codes
1797	97
1772	98
1750	99
1730	100

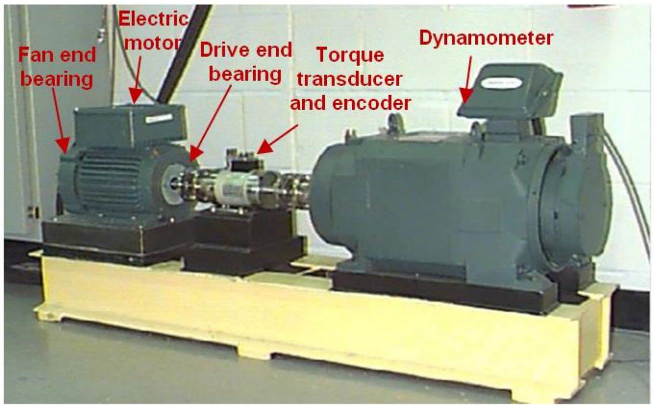


Fig. 3 Test rig used by CWRU for collection of bearing vibration signals

After downloading these datasets in the form of .mat files (MATLAB format) from the CWRU website [26], each dataset is processed using MATLAB R2020b software. A MATLAB code is developed for processing these signals, and time waveforms, frequency spectrums, envelope spectrums and different time-domain statistical parameters are obtained from the vibration signals of bearings.

4. Results and Discussion

This study presents and analyses the effects of the increase in bearing defect size on different vibration responses, i.e., on time-domain statistical parameters. Tables 6, 7 and 8 show the values of all time-domain statistical parameters for the bearings having IRD, BD and ORD of different diameters running at a shaft speed of 1797 rpm. The values of parameters for other speeds are not given in this paper due to the constraint of paper length.

The time waveforms of good (normal) and defective bearings rotating at 1797 rpm constant motor speed are shown in fig. 4 as a sample representation. Time waveforms are shown for the time duration of 0.4 sec to 0.5 sec. Time waveforms for good bearings show very small vibrations compared to defective bearings.

Fig. 5 to 16 show the changes in all the statistical indicators for different shaft speeds when defect diameters on the inner race, ball and outer race increase. Since the speed range is small, the values of parameters for different speeds are not much varying. It is observed that the curves of each indicator show deviations with the increase in defect diameter.

Table 5. Codes of the datasets of defective bearings used by CWRU

Defect Diameter and Bearings	Speed (rpm)	IRD Dataset Codes	BD Dataset Codes	ORD (In Load Zone) Dataset Codes
0.007 inch (0.178 mm) 3 SKF Bearings	1797	105	118	130
	1772	106	119	131
	1750	107	120	132
	1730	108	121	133
0.014 inch (0.356 mm) 3 SKF Bearings	1797	169	185	197
	1772	170	186	198
	1750	171	187	199
	1730	172	188	200
0.021 inch (0.533 mm) 3 SKF Bearings	1797	209	222	234
	1772	210	223	235
	1750	211	224	236
	1730	212	225	237
0.028 inch (0.711 mm) 2 NTN Bearings	1797	3001	3005	Not Available
	1772	3002	3006	Not Available
	1750	3003	3007	Not Available
	1730	3004	3008	Not Available

Table 6. Parameter values for bearings having IRD of different diameters at 1797 rpm

IRD Diameter	SPEED	CODE	Time-domain Statistical Parameters					
			PEAK	RMS	CF	KURT	IF	SF
0.007" (0.178 mm)	1797	105	1.739	0.292	5.965	5.396	8.326	1.396
0.014" (0.356 mm)	1797	169	1.934	0.198	9.778	21.957	16.569	1.695
0.021" (0.533 mm)	1797	209	3.788	0.525	7.210	7.445	10.525	1.460
0.028" (0.711 mm)	1797	3001	4.785	0.838	5.707	3.397	7.280	1.276
IRD Diameter	SPEED	CODE	Time-domain Statistical Parameters					
			TALAF	THIKAT	KUCR	ECI	SIANA	INTHAR
0.007" (0.178 mm)	1797	105	0.971	4.367	24.172	0.459	4.115	1.991
0.014" (0.356 mm)	1797	169	1.392	13.117	34.189	0.859	21.686	7.315
0.021" (0.533 mm)	1797	209	1.163	6.287	51.868	2.055	6.083	4.878
0.028" (0.711 mm)	1797	3001	1.169	5.054	64.927	2.388	1.999	2.537

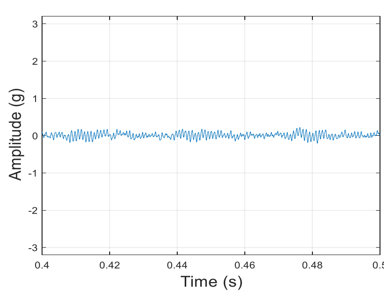
Table 7. Parameter values for bearings having BD of different diameters at 1797 rpm

BD Diameter	SPEED	CODE	Time-domain Statistical Parameters					
			PEAK	RMS	CF	KURT	IF	SF
0.007" (0.178 mm)	1797	118	0.604	0.139	4.338	2.985	5.433	1.253
0.014" (0.356 mm)	1797	185	2.278	0.153	14.918	17.769	22.680	1.520
0.021" (0.533 mm)	1797	222	1.660	0.136	12.238	8.549	16.400	1.343
0.028" (0.711 mm)	1797	3005	10.931	2.077	5.263	3.872	6.970	1.325

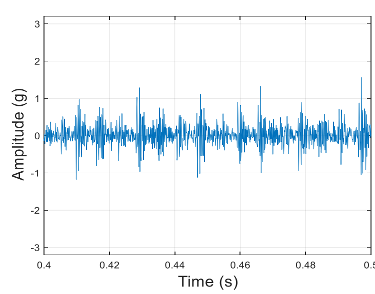
BD Diameter	SPEED	CODE	Time-domain Statistical Parameters					
			TALAF	THIKAT	KUCR	ECI	SIANA	INTHAR
0.007" (0.178 mm)	1797	118	0.688	2.065	8.709	0.058	1.932	-0.007
0.014" (0.356 mm)	1797	185	1.298	18.643	35.616	0.414	20.801	7.531
0.021" (0.533 mm)	1797	222	1.016	11.404	24.056	0.157	9.268	2.949
0.028" (0.711 mm)	1797	3005	1.505	15.843	148.166	16.703	0.635	3.366

Table 8. Parameter values for bearings having ORD of different diameters at 1797 rpm

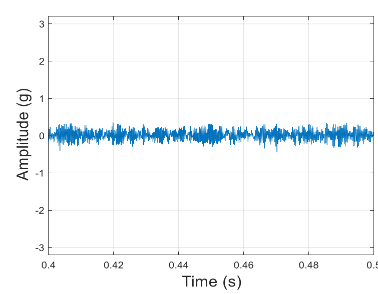
ORD Diameter	SPEED	CODE	Time-domain Statistical Parameters					
			PEAK	RMS	CF	KURT	IF	SF
0.007" (0.178 mm)	1797	130	3.630	0.670	5.423	7.649	8.948	1.650
0.014" (0.356 mm)	1797	197	0.551	0.101	5.469	3.056	6.859	1.254
0.021" (0.533 mm)	1797	234	6.653	0.583	11.408	21.006	22.600	1.979
0.028" (0.711 mm)	1797	---	NA	NA	NA	NA	NA	NA
ORD Diameter	**SPEED**	**CODE**	**Time-domain Statistical Parameters**					
			TALAF	THIKAT	KUCR	ECI	SIANA	INTHAR
0.007" (0.178 mm)	1797	130	1.223	4.812	49.783	3.429	5.241	4.743
0.014" (0.356 mm)	1797	197	0.645	2.654	8.063	0.031	2.281	-0.030
0.021" (0.533 mm)	1797	234	1.461	15.085	92.567	7.145	21.728	18.026
0.028" (0.711 mm)	1797	---	NA	NA	NA	NA	NA	NA



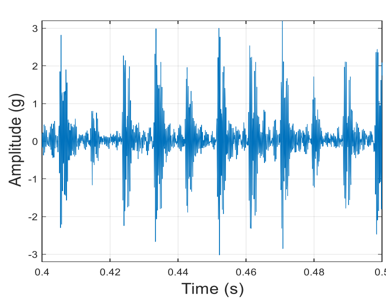
(a) good bearing



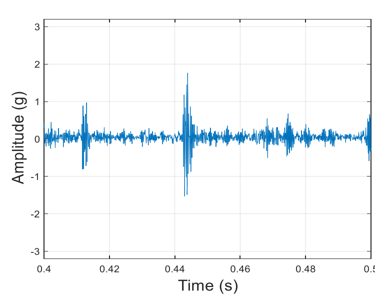
(b) IRD dia. 0.007" (0.178 mm)



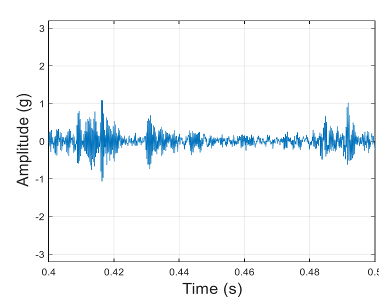
(c) BD dia. 0.007" (0.178 mm)



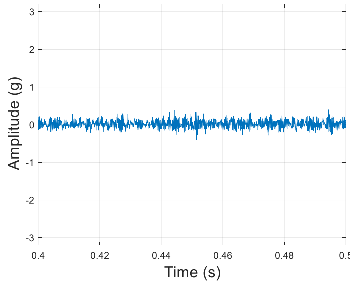
(d) ORD dia. 0.007" (0.178 mm)



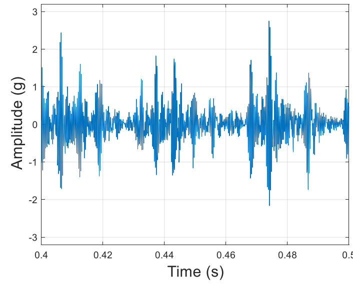
(e) IRD dia. 0.014" (0.356 mm)



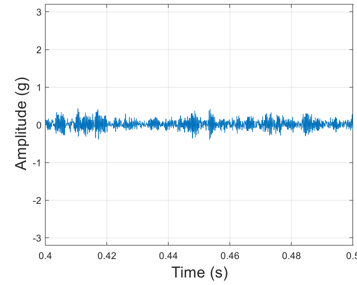
(f) BD dia. 0.014" (0.356 mm)



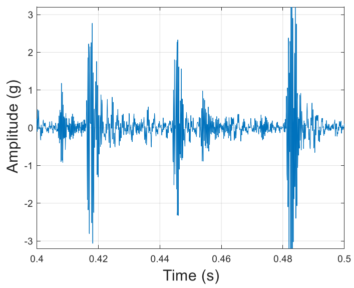
(g) ORD dia. 0.014" (0.356 mm)



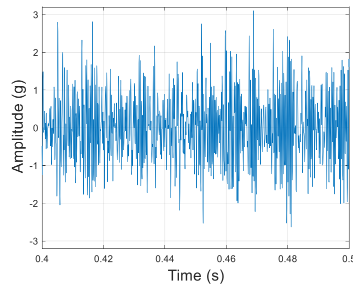
(h) IRD dia. 0.021" (0.533 mm)



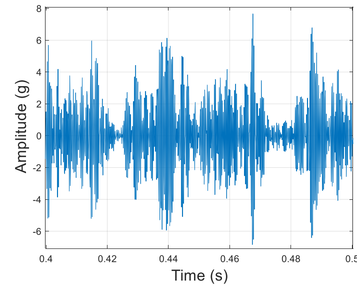
(i) BD dia. 0.021" (0.533 mm)



(j) ORD dia. 0.021" (0.533 mm)



(k) IRD dia. 0.028" (0.711 mm)



(l) BD dia. 0.028" (0.711 mm)

Fig. 4 Time waveforms of good and defective bearings running at 1797 rpm

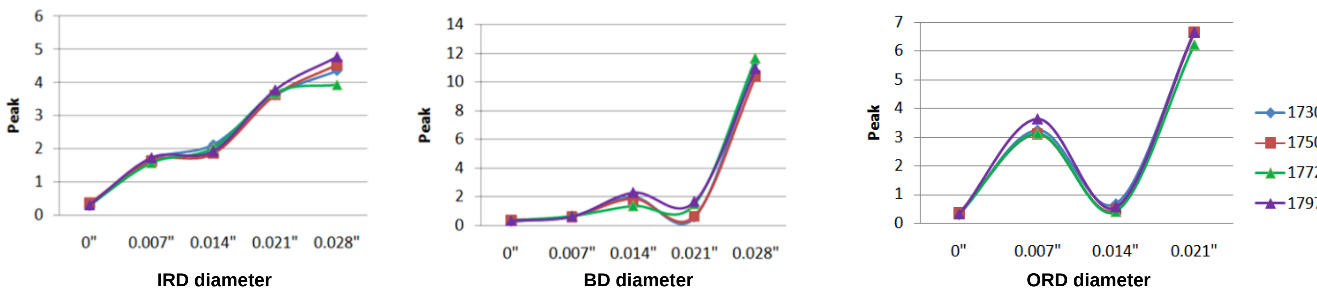


Fig. 5 Effects of increase in defect diameter of different defects on 'Peak' for different speeds

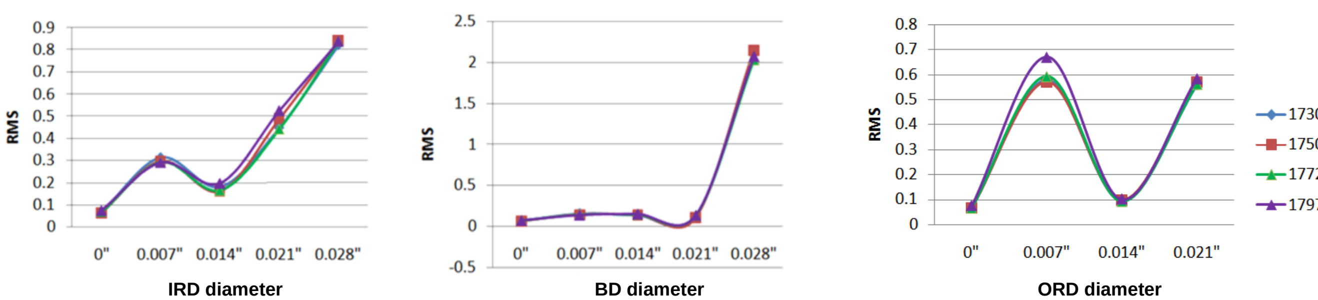


Fig. 6 Effects of increase in defect diameter of different defects on 'RMS for different speeds

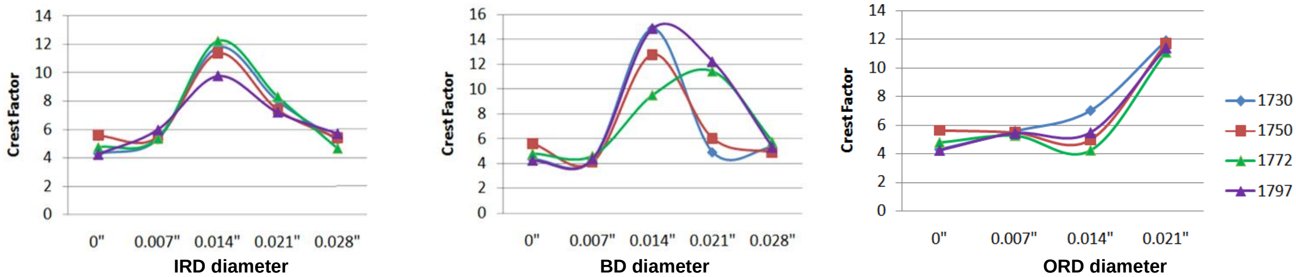


Fig. 7 Effects of increase in defect diameter of different defects on 'Crest Factor' for different speeds

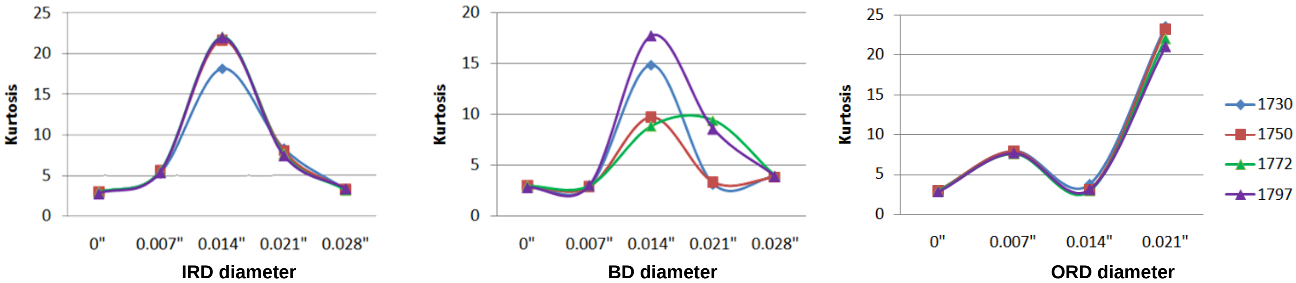


Fig. 8 Effects of increase in defect diameter of different defects on 'Kurtosis' for different speeds

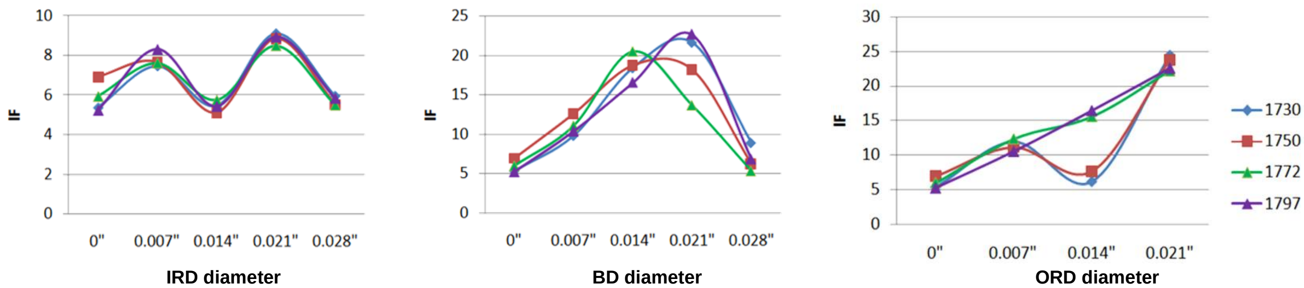


Fig. 9 Effects of increase in defect diameter of different defects on 'Impact Factor' for different speeds

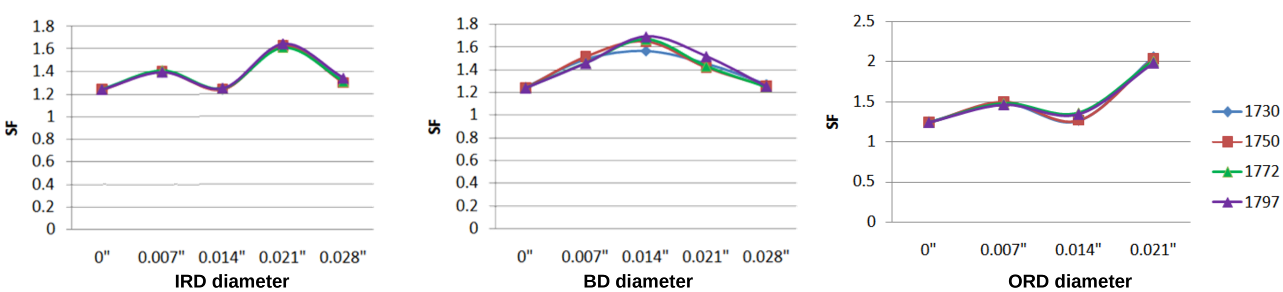


Fig. 10 Effects of increase in defect diameter of different defects on 'Shape Factor' for different speeds

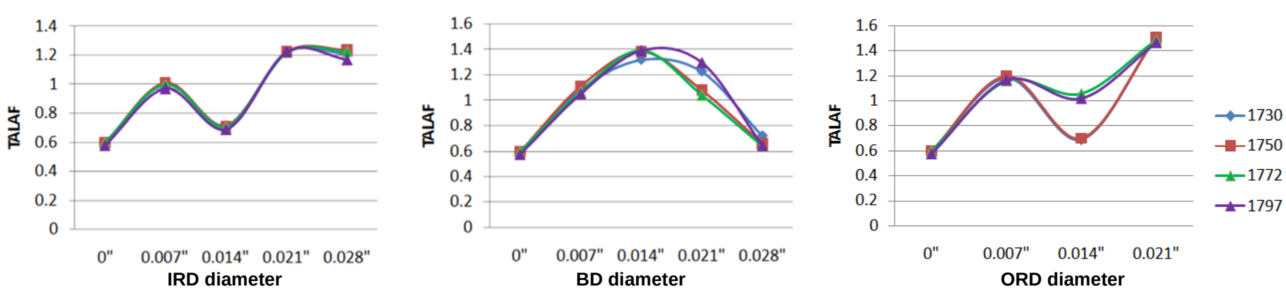


Fig. 11 Effects of increase in defect diameter of different defects on 'TALAF' for different speeds

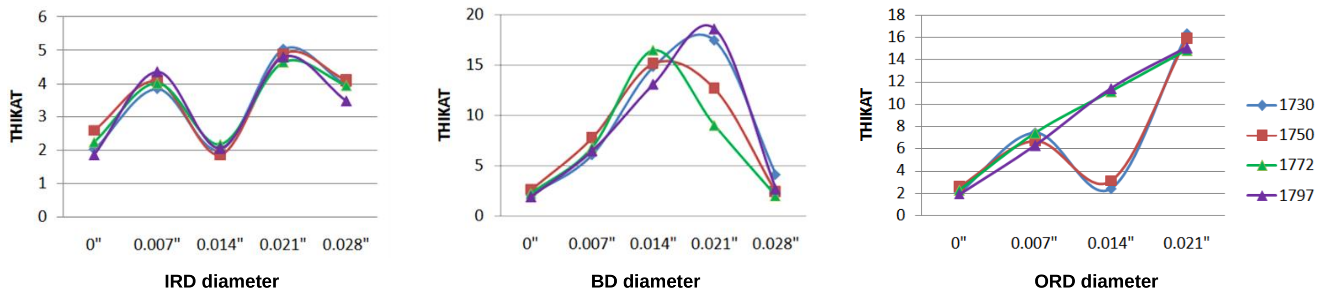


Fig. 12 Effects of increase in defect diameter of different defects on 'THIKAT' for different speeds

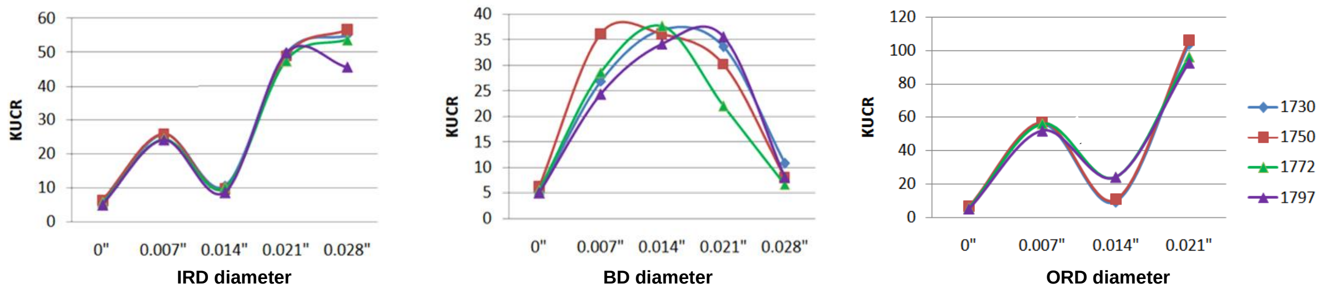


Fig. 13 Effects of increase in defect diameter of different defects on 'KUCR' for different speeds

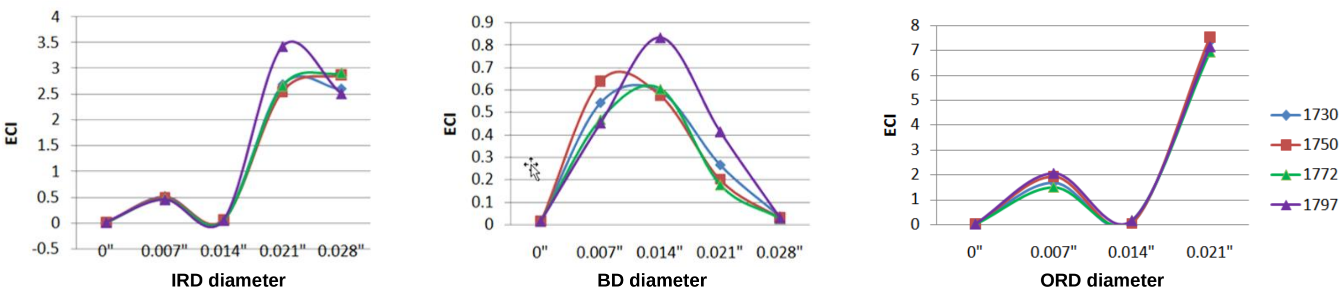


Fig. 14 Effects of increase in defect diameter of different defects on 'ECI' for different speeds

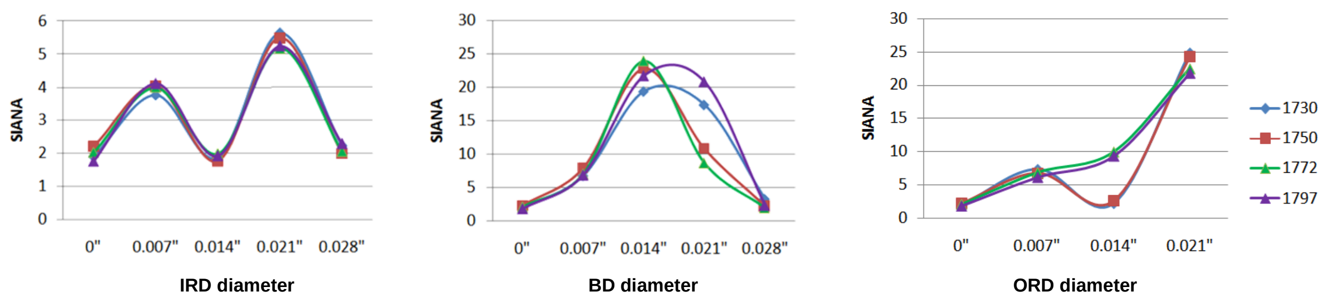


Fig. 15 Effects of increase in defect diameter of different defects on 'SIANA' for different speeds

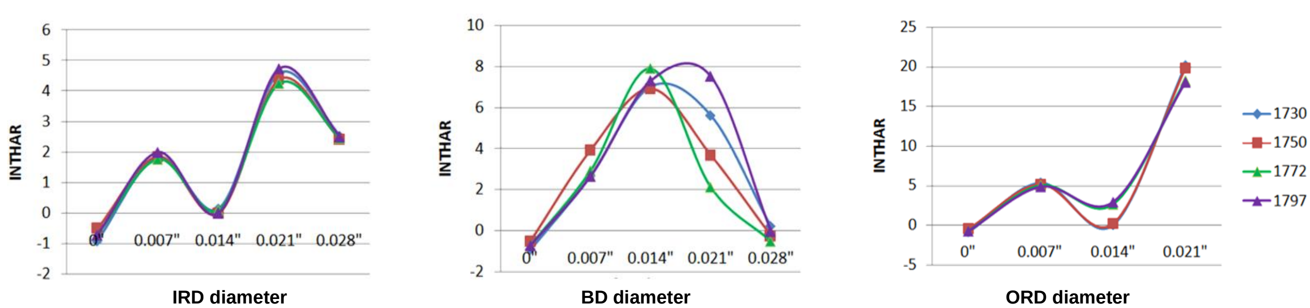
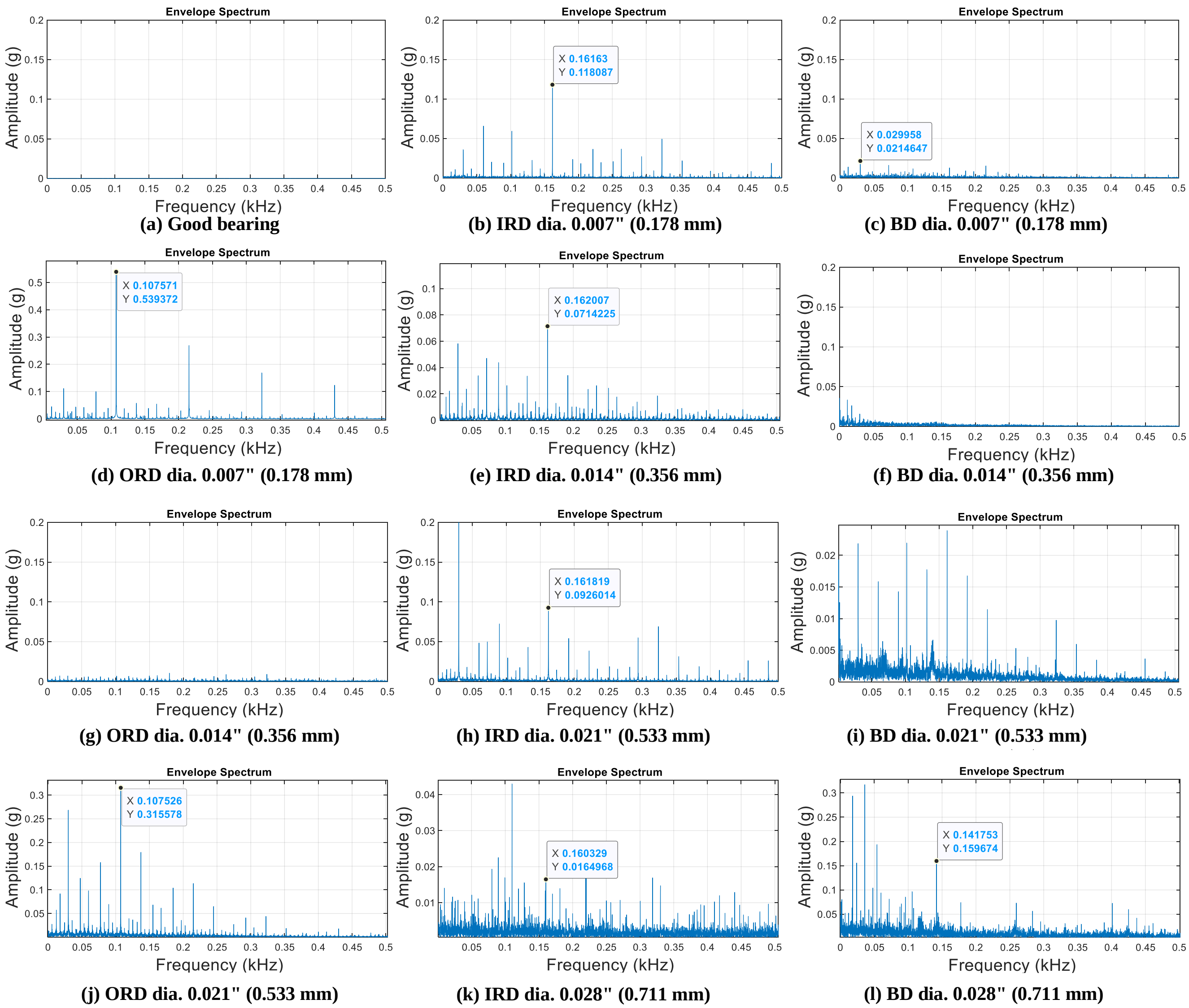


Fig. 16 Effects of increase in defect diameter of different defects on 'INTHAR' for different speeds

The envelope spectrums of normal and defective bearings rotating at 1797 rpm constant motor speed are shown in fig. 17 as a sample representation. These envelope spectrums are obtained for a whole duration of 10 seconds. For normal bearing, no peaks are found at any frequency; for defective bearing, peaks are found at their characteristic defect frequencies in most cases.



(a) Good bearing (b) IRD dia. 0.007" (0.178 mm) (c) BD dia. 0.007" (0.178 mm)

(d) ORD dia. 0.007" (0.178 mm) (e) IRD dia. 0.014" (0.356 mm) (f) BD dia. 0.014" (0.356 mm)

(g) ORD dia. 0.014" (0.356 mm) (h) IRD dia. 0.021" (0.533 mm) (i) BD dia. 0.021" (0.533 mm)

(j) ORD dia. 0.021" (0.533 mm) (k) IRD dia. 0.028" (0.711 mm) (l) BD dia. 0.028" (0.711 mm)

Fig. 17 Envelope spectrums of good and defective bearings running at 1797 rpm

5. Conclusion

In this work, a MATLAB program is developed to process the vibration signals obtained from the experimental data of good and defective bearings. The effects of defect types and increase in defect sizes are studied. Time-domain statistical parameters are used to study the effects of defect size, and envelope spectrums are used to diagnose the type of defect present in the bearing based on characteristic defect frequencies. Based on the analysis of vibration signals following conclusions can be drawn:

1. For good bearings, it is observed that for all values of speeds, the time waveforms do not show much variation and the acceleration is much below the value of 0.4 g. Frequency and envelop spectrums also do not show peaks at characteristic defect frequencies. It indicates that the bearing has no defect.
2. For good bearings, the RMS value near zero and the kurtosis near 3 were observed by many researchers earlier. The impulse factor (IF) is more sensitive to the speed, followed by KUCR and CF.

3. For defective bearings, the time waveforms show the values of overall vibration level (more than 0.4 g) higher than that for the normal bearing. For defective bearings, envelope spectrums show the peaks at the defect frequencies and their harmonics.
4. For good and defective bearings, it is observed that since the shaft speed range is low (67 rpm), there is not much variation found in the values of most of the statistical indicators.
5. It is observed that the values of all the statistical indicators are higher for the defective bearings than for the normal bearing. Indicators clearly show the variation in their values for different defect sizes. From which the defect sizes can be identified. But, this needs monitoring the trend of indicators from the beginning.
6. It is also observed that all statistical indicators vary with the increase in the defect diameter of the bearings. This variation (also called the sensitivity of the indicators) is different for all indicators, i.e., for the defect sizes, the indicators vary with more or less sensitivity.

This study of the behavior of different time-domain statistical indicators for change in speed, defect type and defect size will be useful for the vibration analyst working in the maintenance department.

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References

[1] I. Howard, *A Review of Rolling Element Bearing Vibration 'Detection, Diagnosis and Prognosis*, Defence Science and Technology Organization, Canberra, Australia, 1994. [Google Scholar] [Publisher Link]

[2] P. H. Jain, and S. P. Bhosle, "Analysis on Vibration Signal Analysis Techniques Used in Diagnosis of Faults in Rotating Machinery," *International Journal of Mechanical and Production Engineering Research and Development*, vol. 10, no. 3, pp. 3377–3396, 2020.

[3] N. Tandon, and A. Choudhury, "A Review of Vibration and Acoustic Measurement Methods for the Detection of Defects in Rolling Element Bearings," *Tribology International*, vol. 32, no. 8, pp. 469–480, 1999. [CrossRef] [Google Scholar] [Publisher Link]

[4] M. S. Patil, J. Mathew, and P. K. Rajendrakumar, "Bearing Signature Analysis as a Medium for Fault Detection: A Review," *Journal of Tribology*, vol. 130, no. 1, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[5] H. S. Kumar et al., "Wavelet Transform for Bearing Condition Monitoring and Fault Diagnosis: A Review," *International Journal of Comadem*, vol. 17, 2013. [Google Scholar] [Publisher Link]

[6] Prashant H. Jain, and Dr. Santosh P. Bhosle, "A Review on Vibration Signal Analysis Techniques Used for Detection of Rolling Element Bearing Defects," *SSRG International Journal of Mechanical Engineering*, vol. 8, no. 1, pp. 14-29, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Shyam Patidar, and Pradeep Kumar Soni "An Overview on Vibration Analysis Techniques for the Diagnosis of Rolling Element Bearing Faults," *International Journal of Engineering Trends and Technology*, vol. 4, no. 5, pp. 1804-1809, 2013. [Google Scholar] [Publisher Link]

[8] Tian Ran Lin, Kun Yu, and Jiwen Tan, *Condition Monitoring and Fault Diagnosis of Roller Element Bearing*, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] Pankaj Gupta, and M. K. Pradhan, "Fault Detection Analysis in Rolling Element Bearing: A Review," *Materials Today: Proceedings*, vol. 4, no. 2, Part A, pp. 2085–2094, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Chandrabhanu Malla, and Isham Panigrahi, "Review of Condition Monitoring of Rolling Element Bearing Using Vibration Analysis and Other Techniques," *The Journal of Vibration Engineering Technologies*, vol. 7, no. 4, pp. 407–414, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Mohd Syahril Ramadhan Saufi et al., "A Review on Signal Processing Techniques for Bearing Diagnostics," *International Journal of Mechanical Engineering and Technology*, vol. 8, no. 6, pp. 327–337, 2017. [Google Scholar] [Publisher Link]

[12] Akhand Rai, and S.H. Upadhyay "A Review on Signal Processing Techniques Utilized in the Fault Diagnosis of Rolling Element Bearings," *Tribology International*, vol. 96, pp. 289–306, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[13] Prashant H. Jain, and Dr. Santosh P. Bhosle, "Analysis of Effects of Radial Clearance and Unbalance on Vibration Responses of a Rotor-Bearing System," *International Journal of Engineering Trends and Technology*, vol. 70, no. 1, pp. 327-333, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Ganesan R et al., "Vibration-Based Condition Monitoring of a Tractor Radiator Using Machine Vision System," *International Journal of Engineering Trends and Technology*, vol. 70, no. 3, pp. 295-301, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[15] N. Tandon, "A Comparison of Some Vibration Parameters for the Condition Monitoring of Rolling Element Bearings," *Measurement*, vol. 12, no. 3, pp. 285–289, 1994. [CrossRef] [Google Scholar] [Publisher Link]

[16] H. R. Martin, and F. Honarvar, "Application of Statistical Moments to Bearing Failure Detection," *Applied Acoustics*, vol. 44, no. 1, pp. 67–77, 1995. [CrossRef] [Google Scholar] [Publisher Link]

[17] R. B. W. Heng, and M. J. M. Nor, "Statistical Analysis of Sound and Vibration Signals for Monitoring Rolling Element Bearing Condition," *Applied Acoustics*, vol. 53, no. 1, pp. 211–226, 1998. [CrossRef] [Google Scholar] [Publisher Link]

[18] Rui Gomes Teixeira de Almeida et al., "New Technique for Evaluation of Global Vibration Levels in Rolling Bearings," *Shock and Vibration*, vol. 9, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[19] Abhay Utpat et al., "Response of Various Vibration Parameters to the Condition Monitoring of Ball Bearing Used in Centrifugal Pumps," *Noise & Vibration Worldwide*, vol. 42, no. 6, pp. 34–40, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[20] Prashant H. Jain, and Santosh P. Bhosle, "Study of Effects of Radial Load on Vibration of Bearing Using Time-Domain Statistical Parameters," *IOP Conference Series: Materials Science and Engineering*, vol. 1070, pp. 012130, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Xinwen Niu, Limin Zhu, and Han Ding, "New Statistical Moments for the Detection of Defects in Rolling Element Bearings," *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 11, pp. 1268–1274, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[22] Bo Tao et al., "An Alternative Time-Domain Index for Condition Monitoring of Rolling Element Bearings—A Comparison Study," *Reliability Engineering & System Safety*, vol. 92, no. 5, pp. 660–670, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[23] S. Sassi, B. Badri, and M. Thomas, "Tracking Surface Degradation of Ball Bearings by Means of New Time Domain Scalar Indicators," *International Journal of Comadem*, vol. 11, no. 3, pp. 36–45, 2008. [Google Scholar] [Publisher Link]

[24] M. K. Pradhan, and P. Gupta, "Fault Detection Using Vibration Signal Analysis of Rolling Element Bearing in Time Domain Using an Innovative Time Scalar Indicator," *International Journal of Manufacturing Research*, vol. 12, pp. 305-317, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[25] Dipen S. Shah, V. N. Patel, and Pranav H. Darji, "Experimental Vibration Studies of Deep Groove Ball Bearings Having Damaged Surfaces," *Journal of the Institution of Engineers (India): Series C*, vol. 100, no. 6, pp. 919–935, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[26] "Download a Data File | Case School of Engineering | Case Western Reserve University," *Case School of Engineering*, 2021. [Online]. Available: Https://Engineering.Case.Edu/Bearingdatacenter/Download-Data-File

[27] Wade A. Smith, and Robert B. Randall, "Rolling Element Bearing Diagnostics Using the Case Western Reserve University Data: A Benchmark Study," *Mechanical Systems and Signal Processing*, vol. 64–65, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[28] Adel Boudiaf et al., "A Comparative Study of Various Methods of Bearing Faults Diagnosis Using the Case Western Reserve University Data," *Journal of Failure Analysis and Prevention*, vol. 16, no. 2, pp. 271–284, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[29] Yongbo Li et al., "Entropy Based Fault Classification Using the Case Western Reserve University Data: A Benchmark Study," *IEEE Transactions on Reliability*, vol. 69, no. 2, pp. 754–767, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Prashant H. Jain, and Santosh P. Bhosle "Analysis of Vibration Signals Caused By Ball Bearing Defects Using Time-Domain Statistical Indicators," *International Journal of Advanced Technology and Engineering Exploration-IJATEE*, vol. 9, no. 90, pp. 700–715, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[31] Prashant H. Jain, and Santosh P. Bhosle, "Mathematical Modeling, Simulation and Analysis of Non-Linear Vibrations of a Ball Bearing Due to Radial Clearance and Number of Balls," *Materials Today: Proceedings*, vol. 72, pp. 927-936, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[32] Prashant H. Jain, and Santosh P. Bhosle, "Frequency Spectrum Analysis of Various Defects in Rolling Element Bearings Used in Heavy Load and High Speed Machinery," *In Techno-Societal 2020, Proceedings of the 3rd International Conference on Advanced Technologies for Societal Applications*, vol. 2, pp. 649–663, 2021. [CrossRef] [Google Scholar] [Publisher Link]