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Effect of clearances in rolling element bearings on their dynamic performance, quality and operating life†

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Abstract

The performance of rolling element bearings is one of the machine quality measures in industry. The fatigue life and performance of rolling element bearings depends mainly on the dynamic characteristics of those bearings. This paper studied the effect of the internal radial clearance on the damping characteristics, natural modes of vibration, and fatigue life of rolling element bearings. Vibration modal analysis was performed on rolling bearings of the same size and type to measure their dynamic characteristics. These dynamic characteristics include the natural frequency of the first mode of vibration, damping, and amplitude of frequency response function at resonance. The internal radial clearances of these bearings were measured. A statistical analysis was performed to study the correlation between the internal radial clearance and the dynamic characteristics of rolling bearings. It was found that the damping ratio of the bearing assembly increased by reducing the internal radial clearance of the bearing. Similarly, rolling bearings that have large internal clearances showed short predicted fatigue life. It is concluded that the dynamic characteristics, and consequently the dynamic performance, of rolling bearings are significantly affected by the internal radial clearance.

Keywords: Modal analysis; Internal radial clearance; Bearing life; Dynamic load rating; Dynamic characteristics

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1. Introduction

The performance of various machinery systems depends mainly on the dynamic characteristics of the rotating components (e.g., rolling element bearings), because most of those systems are subjected to dynamic cyclic loads while providing a relative rotational motion. The selection of rolling bearings is one of the challenges in many applications, especially certain critical applications in the aerospace industry that require high performance [1-3]. According to the literature, rolling bearings of the same type and size do not exhibit the same performance under similar operating conditions. Manufacturing and assembly errors, which are the main source of error in rolling bearings, have a strong influence on the fatigue life of rolling bearings [4-9]. The internal radial clearance affects the load distribution, and consequently the fatigue life of rolling bearings. Zero radial clearance bearings generally have the highest fatigue life. The fatigue life of rolling bearings decreases by increasing the internal radial clearance [10-13]. The performance and life of rolling element bearings are affected by damping and stiffness of bearing assembly [13]. Although the bearing manufacturers provide a formula to calculate the fatigue life of rolling bearings, predicting the actual fatigue life of those bearings is still one of the main challenges in bearing research [14-17]. The Lundberg-Palmgren life theory provides the same fatigue life index for bearings of the same size and type. However, the dynamic response of rolling bearings is affected by any variations in lubrication, clearances, and any other assembly error [16-24]. Experimental modal analysis has been recently used for determining the dynamic characteristics of complex structures and for predicting the fatigue life of single components and assembly structures [9, 25-34]. Previous research stated that these dynamic characteristics act as the deoxyribonucleic acid (DNA) characteristics of rolling element bearings, and represent a quality tool for predicting the performance and operating life of those bearings [9, 15, 27, 35]. Since the internal radial clearance has a strong influence on the fatigue life of rolling bearings [20], it is potentially expected that the internal clearance affects the dynamic characteristics of rolling bearings. It has been reported that the estimated bearing life can be enhanced by reducing the internal clearance. This estimated bearing life considers the rolling element size and static load (Stribeck factor) parameters only [20]. Also, the bearing life and dynamic load rating are affected by any variations in the dynamic character-

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istics [9, 15, 27]. The present work studied the correlation between the internal radial clearance and dynamic characteristics of rolling element bearings, as well as their influence on fatigue life.

2. Experimental procedures

Experimental modal analysis and internal clearance measurements were conducted on ten rolling element bearings from the same manufacturer (i.e., NSK Ltd.) and of the same type and size (i.e., bearings with the same bearing code 6006zz). Table 1 shows the specifications of the deep groove ball bearing 6006zz as provided by the bearing manufacturer.

An impact hammer was used to apply impulses on the tested bearing in the radial direction and the corresponding impulse signal was measured with a force transducer. The bearing response was measured by using a piezoelectric uniaxial accelerometer mounted by wax on the outer ring of the bearing as shown in Fig. 1. Both impulse and response signals were analyzed by a front-end data acquisition unit. The signals were recorded in PULSE labshop© software to obtain the frequency response function (FRF) of each bearing. Arithmetic average of four impulses was calculated for each bearing to ensure test repeatability. The experimental modal analysis could be used to determine both flexible and rigid body modes of vibration. The developed setup, shown in Fig. 1, counted only the flexible body modes of vibration. Using elastic cords allowed the cancelation of the rigid body modes of vibration during the analysis. The setup was calibrated, and the weight of the accelerometer was less than 10 % of the weight of the bearing. Anti-aliasing filter and least squares curve fitter were used to avoid aliasing and truncations of signals. The FRF and coherence function of each bearing were recorded. Transient and exponential windowing functions were selected for excitation and response signals, respectively. During the selection of bearing modes, only vibration modes with high coherence values (higher than 0.99) were considered for analysis. The fixation points of the setup were kept the same during the testing of all bearings to avoid any discrepancies.

The second test in this study was measuring the radial clearance of each bearing. The test setup used for measuring the radial clearance of each individual bearing separately is shown in Fig. 2. Each bearing was mounted on a mandrel that was fixed between two lathe centers. These centers were located on slideways that allow guided movements in the axial direction. A dial indicator with a scale value of 1 μm was located on the outer ring of the bearing in the radial (i.e., vertical) direction. Two clamps were mounted in the axial direction to secure the position of the centers on the slideways. The test setup was calibrated, and the parallelism error of the carriage movement and the coaxiality error of the mandrel rotation were minimized. Four radial displacement readings were taken and averaged from four different positions on the outer ring of the bearing, by rotating the bearing around the mandrel. Two measurements (R_1 and R_2) were taken: With and without applying force on the radial direction as shown in Fig. 3. Each displacement reading was repeated three times to ensure the repeatability of the dial indicator readings. The radial clearance (C_r) was calculated for each individual bearing. The perpendicularity between the dial indicator axis and the bearing axis was initially checked to ensure accurate measurements.

Table 1. Specifications of bearing 6006zz provided by manufacturer.

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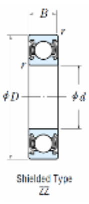
<tr><td rowspan="2">Dimensions (mm)</td><td colspan="5">d</td><td colspan="5">D</td><td colspan="5">B</td><td colspan="5">r</td><td rowspan="8">
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<tr><td colspan="5">30</td><td colspan="5">55</td><td colspan="5">13</td><td colspan="5">1</td></tr>
<tr><td>Mass (kg)</td><td colspan="20">0.116</td></tr>
<tr><td>Dynamic load rating, C_D (N)</td><td colspan="20">13200</td></tr>
<tr><td>Static load rating, C_o (N)</td><td colspan="20">8300</td></tr>
<tr><td rowspan="2">Clearances (μm)</td><td colspan="4">C2</td><td colspan="4">CN</td><td colspan="4">C3</td><td colspan="4">C4</td><td colspan="4">C5</td></tr>
<tr><td colspan="4">1-11</td><td colspan="4">5-20</td><td colspan="4">13-28</td><td colspan="4">23-41</td><td colspan="4">30-53</td></tr>
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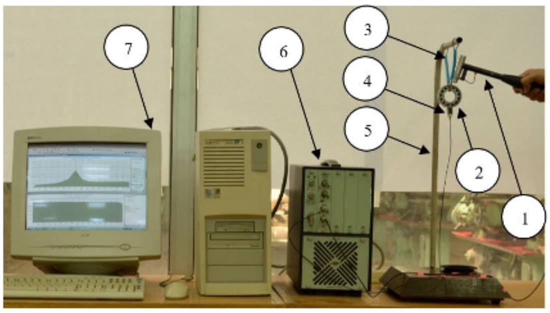
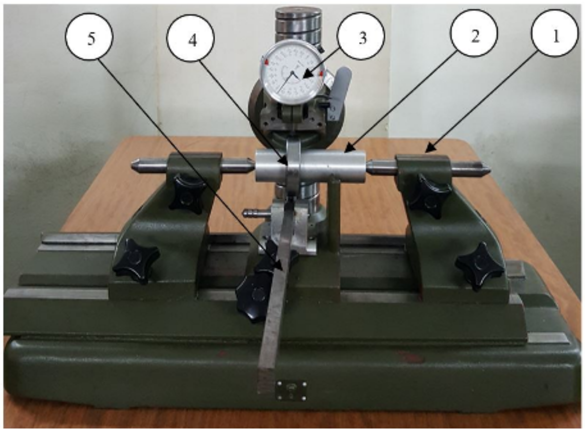


(1) Impact hammer, (2) Bearing under test, (3) Elastic cord, (4) Accelerometer, (5) Rigid support, (6) Front-end acquisition unit, (7) Processing unit

Fig. 1. The experimental modal analysis test setup.



(1) Lathe center, (2) Test mandrel, (3) Dial indicator, (4) Bearing under test, (5) Loading lever for applying force

Fig. 2. The radial clearance measurement setup.

3. Experimental results and discussion

Figs. 4 and 5 show both the impulse force and acceleration

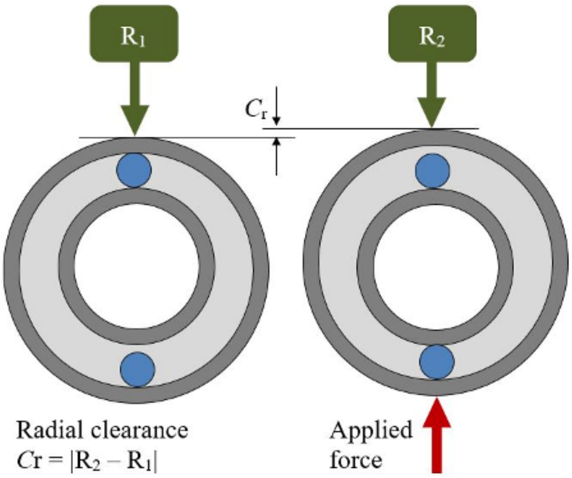
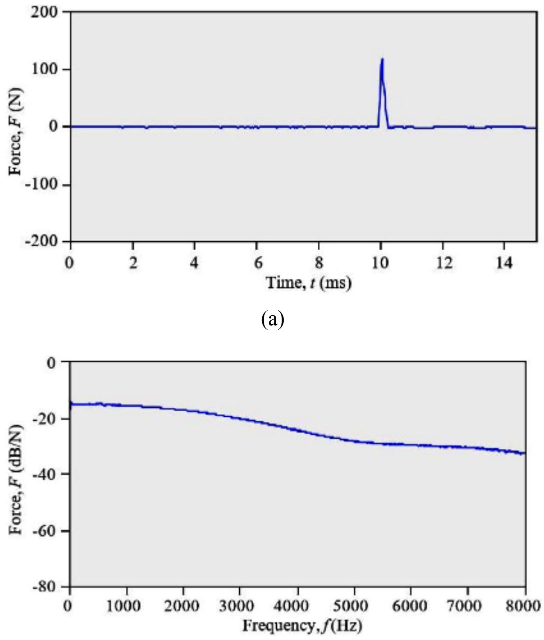


Fig. 3. Radial clearance measurement.

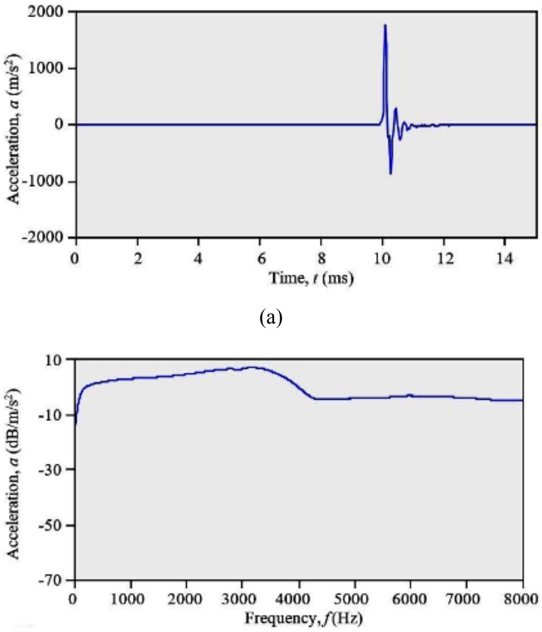


(a)

(b)

Fig. 4. Force signal in (a) time; (b) frequency domains.

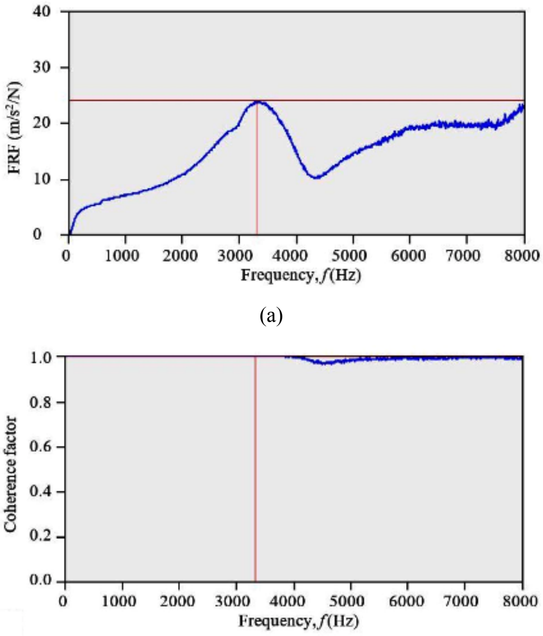
response signals in time and frequency domains. Using fast Fourier transformation (FFT), the signals were implied to determine the FRF shown in Fig. 6(a). Auto and cross correlations of signals were used to determine the corresponding coherence function shown in Fig. 6(b). The frequency range was set between 0 to 8 kHz to determine the first mode of vibration for each rolling bearing. The first natural frequency (f_n), damping ratio (ξ), FRF amplitude (H), and corresponding coherence value at the first resonant mode of vibration were recorded for each bearing. Table 2 lists the measured radial clearance values for the ten bearings tested. The radial clearances of these bearings varied between 13 μm to 33 μm, which are within the specified range of radial clearances provided by the bearing manufacturer (see Table 1).



(a)

(b)

Fig. 5. Vibration response signal in (a) time; (b) frequency domains.



(a)

(b)

Fig. 6. (a) Frequency response function (FRF); (b) coherence function in frequency domain.

Fig. 7 shows the relationship between the damping ratio and radial clearance of rolling bearings. The damping ratio of rolling bearings drastically decreased with the increase of the radial clearance. This could be attributed to the size of the lubricant film between rolling elements and races of inner and outer rings. The overall damping of rolling bearings depends on the material damping of rolling elements and bearing rings,

Table 2. Radial clearance values of the tested bearings.

Bearing no.	1	2	3	4	5
Radial clearance, C_r (μm)	33	29.8	32.7	31.8	28.16
Bearing no.	6	7	8	9	10
Radial clearance, C_r (μm)	15.88	24.75	13.6	18.38	13

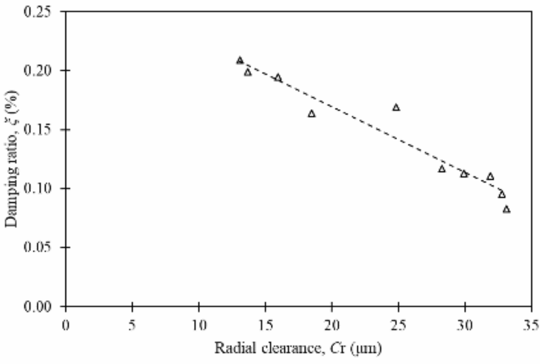


Fig. 7. Relationship between the radial clearance and damping ratio of the bearings tested.

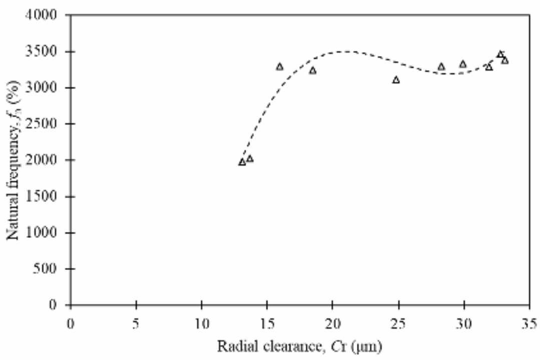


Fig. 8. Relationship between the radial clearance and natural frequency of the bearings tested.

as well as the damping of the lubricant film [20]. The damping of the lubricant film depends on the radial clearance of the bearing. The inverse correlation between the damping ratio and radial clearance could be attributed to the size of the oil film. The size of the oil film increases by increasing the radial clearance, which allows higher vibration under dynamic loading condition (lower system damping). The relationship between the natural frequency and radial clearance of rolling bearings is shown in Fig. 8. As observed, the natural frequency of rolling bearings increased by increasing the radial clearance. This could be attributed to the dynamic stiffness of the bearing. The natural frequency of machinery elements depends on mass and stiffness of those elements. Since the mass of the bearing does not change when increasing the radial clearance, then the increase in the natural frequency could be attributed to an increase in the dynamic stiffness of the bearing.

A modified equation is reported in the Ref. [9] for calculating the dynamic load rating (C_D) of each individual bearing based on the dynamic characteristics of the first mode of vibration for this bearing ($\xi/f_n.H$). This equation was used to calculate the dynamic load rating of each individual bearing tested in this study. By substituting the calculated dynamic load rating in Lundberg-Palmgren model, the absolute fatigue life of each individual bearing was determined as listed in Table 3. This modified equation predicts the fatigue life of each individual bearing based on the results of the modal analysis. An experimental modal analysis was performed at room temperature and atmospheric pressure while the bearing under test was hanging free. These boundary conditions should be applied in order to use the model developed in Ref. [9] for evaluating the fatigue life of each individual bearing nondestructively.

Table 3. Calculated fatigue life of the bearings under test.

Bearing no.	1	2	3	4	5
Life, L_{10} (10^6 revolutions)	1817	2122	1977	2220	2472
Bearing no.	6	7	8	9	10
Life, L_{10} (10^6 revolutions)	4963	8428	15389	3892	15928

Table 4. Correlation matrix between the radial clearance and dynamic characteristics.

Dynamic property	Radial clearance			
	Pearson correlation		Spearman correlation	
	r	p-value	ρ	p-value
Damping ratio	-0.706	0.023	-0.903	0.000
Natural frequency	0.751	0.012	0.827	0.003
FRF amplitude	0.845	0.002	0.879	0.001
Calculated bearing life	-0.803	0.005	-0.952	0.000

Pearson and Spearman correlation tests were performed between the radial clearance and dynamic characteristics (i.e., damping ratio, natural frequency, FRF amplitude, and calculated bearing life) of rolling bearings. Table 4 shows the correlation matrix between the radial clearance and each dynamic characteristic, where r represents the Pearson correlation coefficient and ρ represents the Spearman correlation coefficient. It was observed that the correlation between the radial clearance and the dynamic characteristics were significant. The p-value of all factors was less than the significance level (α = 0.05) and the correlation coefficients were approaching ±1 (+1 means positive correlation, 0 means no correlation, and -1 means negative correlation). The correlations between the radial clearance and the dynamic characteristics are considered statistically significant. The damping ratio and bearing life were inversely (negatively) correlated with radial clearance, but the natural frequency and FRF amplitude were directly (positively) correlated with radial clearance.

Fig. 9 illustrates the influence of the internal radial clearance on rolling element bearing life. The calculated bearing life decreased when the internal radial clearance increased. It

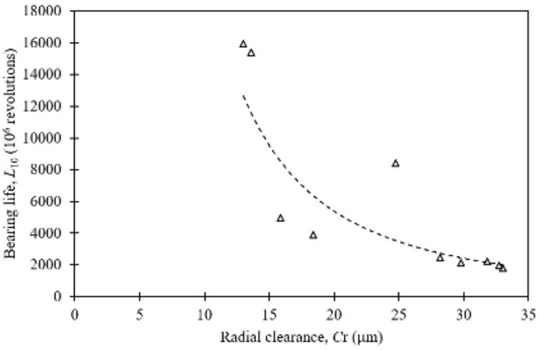


Fig. 9. Relationship between the radial clearance and calculated bearing life.

is reported in the Refs. [12, 20, 23, 24] that the internal radial clearance has a strong influence on the load distribution and bearing life in which bearing life decreases when the radial clearance increases. The main reason is that the load is not evenly distributed on all rolling elements when having a large internal radial clearance. In comparison with the damping results shown in Fig. 7, the calculated bearing life showed a quite similar trend with the internal radial clearance.

4. Conclusions

Individual ball bearings of the same type and size showed various internal radial clearances and dynamic characteristics. This may be potentially attributed to variations in the inherent dynamic characteristics of these identical rolling bearings. This paper examined the relationship between the dynamic characteristics and internal radial clearance of rolling bearings from the same manufacturer with the same bearing code. An inverse correlation between the damping ratio and internal radial clearance was found. The experimental results showed that the bearing with the largest radial clearance had the lowest damping ratio, highest natural frequency, and shortest bearing life. The developed procedure could be used to modify the calculated bearing life provided by the bearing manufacturer based on the internal radial clearance measurements. Validating these findings for other types of rolling element bearings is considered for future work.

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References

[1] B. Dykas, Factors influencing the performance of foil gas thrust bearings for oil-free turbomachinery applications, *Ph.D. Thesis*, Department of Mechanical and Aerospace Engineering, Case Western Reserve University (2006).

[2] S. A. Yadav, Dynamic performance of offset-preloaded two pad foil bearings, *M.Sc. Thesis*, College of Engineering, University of Texas at Arlington (2013).

[3] C. Zhang, J.-G. Yang, S. Liu, Q.-S. Gao and Y. Yang, Influence of varnish on bearing performance and vibration of rotating machinery, *International Journal of Rotating Machinery,* 2017 (2017) 10.

[4] T. A. Harris and M. N. Kotzalas, *Rolling Bearing Analysis*, 5th Ed., CRC Press (2006).

[5] J. R. Weiss, Rolling element bearing metrology, *M.Sc. Thesis*, Mechanical Engineering, Pennsylvania State University (2005).

[6] T. Yoshioka, S. Simizu and H. Shimoda, A new form of rolling contact damage in grease-lubricated, deep-groove ball bearings, *Tribology Transactions,* 53 (1) (2009) 154-160.

[7] M. Behzad and A. Bastami, A new method for detection of rolling bearing faults based on the local curve roughness approach, *Polish Maritime Research,* 18 (2) (2011) 44.

[8] R. K. Holman and P. K. Liaw, Methodologies for predicting fatigue life, *JOM,* 49 (7) (1997) 46.

[9] M. Yakout, A. Elkhatib and M. G. A. Nassef, Rolling element bearings absolute life prediction using modal analysis, *J. of Mechanical Science and Technology,* 32 (1) (2018) 91-99.

[10] S. H. Upadhyay, S. P. Harsha and S. C. Jain, Analysis of nonlinear phenomena in high speed ball bearings due to radial clearance and unbalanced rotor effects, *J. of Vibration and Control,* 16 (1) (2010) 65-88.

[11] K. Radil, S. Howard and B. Dykas, The role of radial clearance on the performance of foil air bearings, *Tribology Transactions,* 45 (4) (2002) 485-490.

[12] R. Tomović, Investigation of the effect of rolling bearing construction on internal load distribution and the number of active rolling elements, *Advanced Materials Research,* 633 (2013) 103-116.

[13] M. Sarangi, B. C. Majumdar and A. S. Sekhar, Stiffness and damping characteristics of lubricated ball bearings considering the surface roughness effect. Part 1: Theoretical formulation, *Proceedings of the Institution of Mechanical Engineers, Part J: J. of Engineering Tribology,* 218 (6) (2004) 529-538.

[14] A. Palmgren, The service life of ball bearings (Die Lebensdauer von Kugellagern), *Zeitschrift des Verctires Deutscher Ingeniuere,* 68 (14) (1924) 339-341.

[15] M. Yakout and A. Elkhatib, Rolling bearing reliability prediction - A review, *Proceedings of the 20th International Congress on Sound and Vibration (ICSV20)*, Bangkok, Thailand, 4 (2013) 3288-3296.

[16] E. V. Zaretsky, Rolling bearing life prediction, theory, and application, *Recent Developments in Wear Prevention, Friction, and Lubrication,* 37 (166) (2010) 45-136.

[17] E. V. Zaretsky, J. Poplawski and C. R. Miller, Rolling bearing life prediction - Past, present, and future, *NASA Technical Memorandum,* 210529 (2000).

[18] J. I. McCool, Load ratings and fatigue life prediction for

ball and roller bearings, *J. of Lubrication Technology,* 92 (1) (1970) 16-20.

[19] S. Spottswood and H. F. Wolfe, Comparing fatigue life estimates using experimental and spectral density based probability distributions, *J. of Aircraft,* 39 (3) (2002) 493-498.

[20] F. B. Oswald, E. V. Zaretsky and J. V. Poplawski, Effect of internal clearance on load distribution and life of radially loaded ball and roller bearings, *Tribology Transactions,* 55 (2) (2012) 245-265.

[21] R. M. Barnsby, *Life Ratings for Modern Rolling Bearings: A Design Guide for the Application of International Standard ISO 281/2,* ASME International (2003).

[22] E. V. Zaretsky, J. V. Poplawski and L. E. Root, Relation between Hertz stress-life exponent, ball-race conformity, and ball bearing life, *Tribology Transactions,* 51 (2) (2008) 150-159.

[23] F. B. Oswald, E. V. Zaretsky and J. V. Poplawski, Interference-fit life factors for roller bearings, *Tribology Transactions,* 52 (4) (2009) 415-426.

[24] F. B. Oswald, E. V. Zaretsky and J. V. Poplawski, Interference-fit life factors for ball bearings, *Tribology Transactions,* 54 (1) (2010) 1-20.

[25] É. L. Oliveira, N. M. M. Maia, A. G. Marto, R. G. A. da Silva, F. J. Afonso and A. Suleman, Modal characterization of composite flat plate models using piezoelectric transducers, *Mechanical Systems and Signal Processing,* 79 (2016) 16-29.

[26] F. Cakir, H. Uysal and V. Acar, Experimental modal analysis of masonry arches strengthened with graphene nanoplatelets reinforced prepreg composites, *Measurement,* 90 (2016) 233-241.

[27] M. Yakout, Life prediction of rolling element bearings using vibration modal analysis, *M.Sc. Thesis*, Production Engineering Department, Alexandria University (2013).

[28] M. Nassef, A. Elkhatib and M. Hamed, Correlating the vibration modal analysis parameters to the material impact toughness for austempered ductile iron, *Materials Performance and Characterization,* 4 (1) (2015) 61-72.

[29] H. S. Park and B. K. Oh, Damage detection of building structures under ambient excitation through the analysis of the relationship between the modal participation ratio and story stiffness, *Journal of Sound and Vibration,* 418 (2018) 122-143.

[30] G. Mansour, K. Tsongas and D. Tzetzis, Modal testing of nanocomposite materials through an optimization algorithm, *Measurement,* 91 (2016) 31-38.

[31] A. N. Damir, A. Elkhatib and G. Nassef, Prediction of fatigue life using modal analysis for grey and ductile cast iron, *International J. of Fatigue,* 29 (3) (2007) 499-507.

[32] E. S. Elsayed, A. Elkhatib and M. Yakout, Vibration modal analysis of rolling element bearing, *Proceedings of the 4th International Conference on Integrity, Reliability and Failure,* Funchal, Portugal (2013).

[33] R. Ebrahimi, H. R. Mirdamadi and S. Ziaei-Rad, Operational modal analysis and fatigue life estimation of a chisel plow arm under soil-induced random excitations, *Measurement,* 116 (2018) 451-457.

[34] H. El-Labban, M. Abdelaziz, M. Yakout and A. Elkhatib, Prediction of mechanical properties of nano-composites using vibration modal analysis: Application to aluminum piston alloys, *Materials Performance and Characterization,* 2 (1) (2013) 454-467.

[35] A. Elkhatib, *Rolling Element Bearing Acceptance and Life Testing (BAT)*, UK (2002).

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