Numerical Studies on Vibration Characteristics on Ball Bearing Operated under Hexagonal Boron Nitride (hBN) Nanoparticles

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ABSTRACT

This paper presents a simulation approach on the vibration responses of a bearing system operated under different volume of concentration of hexagonal boron nitride (hBN) nanoparticles mixed with diesel engine oil. The characteristic frequency between new bearing, 0.5 mm outer defected bearing and 0.5 mm inner defected bearing are distinguished by using a 3D finite element model of bearing system. This model is numerically solved using ANSYS WORKBENCH 16.0 solver. The vibration amplitude of ball bearing is also investigated for all conditions of ball bearing by varying the hBN nanoparticles concentration. The simulation results show that the lowest value of vibration amplitudes of the bearing system is obtained by 0.2 vol% of volume concentration of hBN nanoparticles. In conclusion, this study proved that the addition of hBN nanoparticles in diesel engine oil can function effectively in reducing the vibration responses on the bearing system.

Keywords: *Finite element analysis, vibration characteristic, ball bearing, hexagonal boron nitride*

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Introduction

Ball bearing can play an important role in addressing the issue of noise and vibration generators due to the imperfection of geometrical bearing components, rotation of the lubricated contacts, stiffness in the bearings and parametric excitations. The performance of machine is also limited by the frequency of bearing failure compared to the other components[1]. Over the time, bearing failure will lead to mechanical system breakdown because of the misalignment, defect on bearing elements, unsuitable lubricants, and unbalanced force. Eventually, these problems will become a reason for undesirable vibration. This phenomenon can be examined from the early stages of bearing defects. The defects that occur on bearing element such as inner race, outer race and ball spin can be detected by their own vibration frequency characteristic[2],[3] and [4]. Monitoring and analysing the vibration signal of the bearing defects give researchers the fastest way to distinguish the existence of faults and the worseness of the system condition.

New additives in the lubricants has become one of the important research because the additive presence in the lubricants can helps to reduce wear and friction between the contacting surfaces of the bearing system. The past research used the copper nanoparticles as an additive to prevent severe anti-wear, load-carrying and friction reduction performances added in diesel engine oil. As published by Asrul et al. (2013), they found that 0.2% of Cu nanoparticle additives can effectively improve the lubricating properties of the engine oil[5] and the higher the concentration of Cu, a protective film with lower elastic modulus and hardness is formed on the particle surface. These findings were followed by other nanoparticles like zirconia/silica ($ZrO3/SiO2$) composite nanoparticles additive, titanium oxide ($TiO2$) and also silver nanoparticles.Filip et al. (2016) reported that $TiO2$ nanoparticles show better anti-wear and friction reducing property as an additives in engine oil and other industrial lubricants[6]. All these nanoparticles were observed as efficient in improving tribological properties.As an environment friendly solid lubricant, hexagonal boron nitride was widely used as lubricant additive for high temperature lubrication. Other than that, it can also use as electrical insulators, standard parts materials, heat radiation material, aeronautics and space application. In previous study, it was found that hBN nanoparticles can act as promising additives in reducing the wear and friction. Abdullah et al. (2015) investigated the best concentration of hBN nanoparticles mixed diesel engine oilwas 0.5 vol% with lowest wear scar diameter compared to the base oil[7]. As followed by Qingming et al. (2015) revealed that 0.1 wt% of hBN nanoparticles could exhibit excellent tribological performance [8]. In extension to this, the performance of nanoparticles on reducing the vibration on ball bearing was conducted experimentally by Prakash et al. (2013) whereby in their paper, it is stated that 0.2 wt% of CuO nanoparticles mixed engine oil can reduce the vibration on ball bearing[9].

There are several methods used to determine the vibration analysis in operating machine with new and deteriorating bearings in the machines such as finite element analysis and vibration monitoring condition. Numerical techniques to analyze the vibration responses have become very popular in recent years. Many researchers are using the commercial software ABAQUS in order to obtain the vibration responses for the bearings. Purwo et al. (2008) conducted a numerical approach using ABAQUS on the vibration analysis of defected ball bearing using the signal parameter such as RMS and peak to peak value[10]. Similar to their findings, Weiming et al. (2015) investigated the vibration responses of the ball bearings with the different sizes of defects on the outer races using the explicit dynamic analysis in ABAQUS [11]. Liu et al. (2013) investigated the effects of defects shape, radial load and shaft speed by employing the method of explicit dynamic finite element analysis. However, there are few studies on investigation of the vibration characteristic on ball bearing using the numerical approach and there are no significant studies have showed the performance of hBN nanoparticles additives through the bearing frequencies.

In this paper, the vibration characteristic on ball operated under hexagonal boron nitride nanoparticles mixed diesel engine oil is obtained through the numerical approach by using Modal and Harmonic Response analysis in ANSYS WORKBENCH 16.0.

Methodology

Nano-Lubricant Preparation

Hexagonal boron nitride (hBN) in a form of white powder as shown in Figure 1 is mixed with the conventional diesel oil SAE 15W40 to produce a nanoparticles lubricant.Table 1 showed the properties of the hexagonal boron nitride powder provided by manufacturer.

The following procedures are the steps to prepare the nanoparticles. Firstly, the hBN powder is weighted by using electronic weight balancing to get the acquired mass in gram (g). This mass is equivalent with the total volume of diesel engine oil used in this project which is 650 ml where it is the total volume of the lubricant for the bearing partially submerged during the experiment. The volume concentration of nanoparticles is arbitrarily varying from 0.0 vol%, 0.2 vol%, 0.5 vol% and 1.0 vol% of hBN. The volume of 650 ml engine diesel oil added to this concentration by using the density formula as follows:

$$\rho = \frac{m}{v} \tag{1}$$

where:

ρ = density of hBN powder

m = the mass of hBN powder
v = volume of hBN at different concentration.

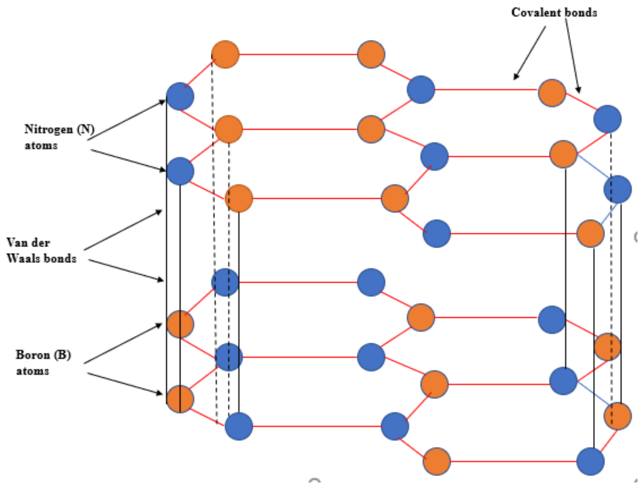


Figure 1: hBN nanoparticles structure.

Table 1: Properties of hBN powder.

Properties	**Details**
Appearance	White
Crystal sturucture	Hexagonal
Density	2.2 g/cc
Coefficient of friction (COF)	< 0.3
Thermal conductivity	30-130 W/mK

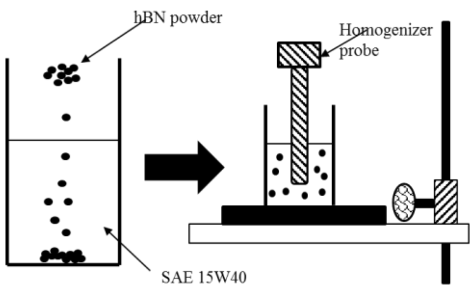


Figure 2: Ultrasonic homogeniser.

The mixture of solid particles in diesel engine oil is homogenized for 20 minutes using an ultrasonic homogenizer (Sartorius Labsonic P) with 50% amplitude and 0.5 active time interval as shown in Figure 2.

Tribological testing

In this analysis friction force, (F_f) is used to represent the friction that happens between the nanoparticles and contact surface of the bearing element. The F_f can be obtained by conducting the tribological testing to determine the coefficient of friction (COF) of lubricant oil by using a four-ball tester (TR 20). Experimental procedures are followed the standard test of ASTM D4172. In this standard, the speed, load, time, and temperature used are 1200 rpm, 392.4 N, 3600 secs and 75 ºC, respectively. There are three carbon-chrome steel balls with 12.7 mm diameter were clamped together and covered with 10 ml of lubricant. The fourth steel ball referred as top ball was held in collet inside a spindle and it rotates as the AC motor is running. The top ball is rotated in contact with the three fixed balls which is immersed in the sample lubricant as shown in Figure 3.

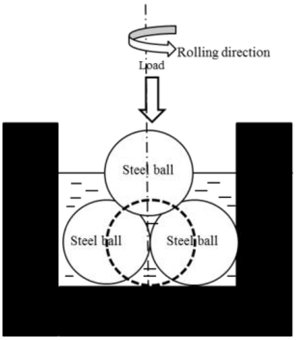


Figure 3: Four- ball tester.

The COF was recorded using a data terminal processing system. Detailed mechanical properties of the balls are shown in Table 2.

Table 2: Mechanical properties of ball bearing.

Properties	**Ball bearing (Carbon-chromium steel)**
Hardness (*H*), HRC	61
Density (*p*), g/cm^3	7.79
Surface roughness R_a, µm	0.022

The COF value is acquired for hBN mixed lubricant with 0.0 vol%, 0.2 vol%, 0.5 vol% and 1.0 vol% of concentration of hBN as tabulated in Table 3.

Table 3: COF values of the nano-lubricant.

Vol% of concentration of hBN	**COF values**
0.0	1.00
0.2	0.09
0.5	0.07
1.0	1.20

Model Development

In this study, the bearing system consist of single row deep groove ball bearing and shaft are developed using Computer Aided Three-dimensional Interactive Application (CATIA) which is powered by the Dassault System management. Table 4 showed the dimensions of the bearing and shaft used in CATIA development. Figure 4 illustrated the graphic user interface (GUI) of CATIA with full model of the bearing system.

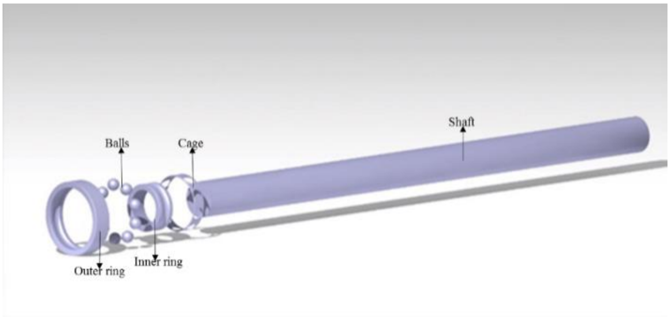


Figure 4: CATIA assemble of bearing system.

Table 4: Dimensions of bearing system.

Feature name	**Dimension (mm)**
Outer diameter, OD	62.0
Inner diameter, ID	30.0
Ball diameter, D	8.0
Pitch diameter, PD	35.6
Breadth, B	16.0
Ball number, N	9
Shaft diameter, OS	30.0
Length shaft, LS	500

Numerical Procedure

The finite element analysis is a numerical method which is traditionally a branch from Solid Mechanics. Nowadays, this technique iswidely used for multiphysic problems such as vibration, solid mechanics, fluid flow, thermal analysis and structure analysis to find their approximate solutions. The main advantage of this technique is it have a comprehensive set of resultsto generate the physical response of the system at any location.

In this study, finite element analysis using ANSYS WORKBENCH 16.0 is used to analyze the vibration amplitude of ball bearing operated under hexagonal boron nitride (hBN) nanoparticles mixed with diesel engine oil. In ANSYS WORKBENCH 16.0, there are two different analysis used to perform the vibration analysis which are Modal and Harmonic Response analysis.The model is imported into the workbench in form of the Initial Graphics Exchange Specification (IGES) file from the CATIA V5 software. The material and element properties of the model is tabulated in Table 5. The material used in this study is chrome steel which commonly used for bearing manufacturing.

Table 5: Properties of bearing system

Property name		**Details**
Material	Name	Chrome steel
	Density, ρ	7 800 kg/m^3
	Young's Modulus, E	206 GPa
	Poisson's ratio, υ	0.33

In order to simplify the modelling and simulation, the bearing and shaft are the only part to be analyzed. All components (outer ring, inner ring, balls and cage) of the bearings system are modelled as rigid body. Proper boundary condition is applied on the surface of the outer ring to replace bearing housing. In meshing part, outer and balls element are using Tetrahedron (Solid 168) free meshing and the rest are using free mapped meshing Hexahedron (Solid 164). Each bearing element, edge sizing with number of division of 100 and bias factor of 5 is applied on the model. The behavior of meshing is hard type and the total number of nodes is 126378 with number of elements is 56947. For simulation purpose, there are three bearing conditions taken into consideration which are new bearing, 0.5 mm outer defected bearing and 0.5 mm inner defected bearing as shown in Figure 5.

The actual speed of motor is 1440 rpm which equivalent to 25 Hz, therefore the moment of 5 Nm is to represent the input torque from the motor. The moment is applied on the shaft as the motor rotates the shaft. In addition, to exhibit the existences of hBN nanoparticles mixed lubricant, the frictional force, F_f is applied by calculating the frictional force by using the following equations:

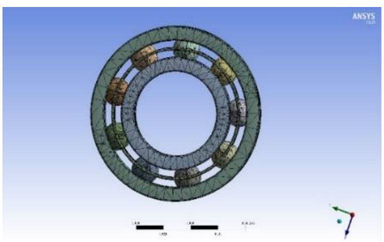
$$F_f = \mu N \tag{2}$$

where:

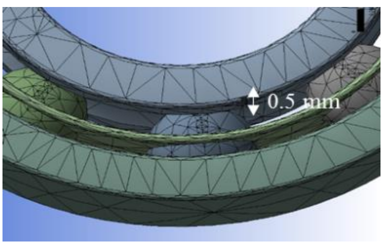
μ= coefficient of friction (COF)

N= normal load

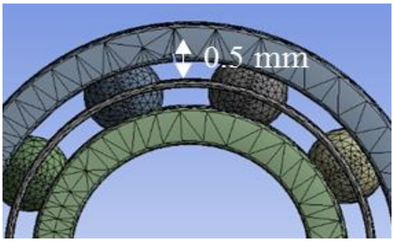
The values of the F_f is tabulated in Table 6 and it is applied on the surface of inner ring to represent the movement of the nanoparticles rotating inside the bearing.



(a) New bearing



(b) 0.5 mm inner defected bearing



(c) 0.5 mm outer defected bearing

Figure 5: Meshed model of bearing system.

Table 6: Frictional force values.

Vol% of concentration of hBN	COF values	F_f values (N)
0.0	1.00	2.00
0.2	0.09	1.80
0.5	0.07	1.40
1.0	1.20	2.40

Bearing Frequencies Calculation

The physical defects can occur on bearing elements such as inner race, outer race, ball and cage. The defects will cause a high amplitude of vibration.

Each element has variant characteristic frequencies such as fundamental frequency, ball spin outer frequency (BPFO) and ball spin inner frequency (BPFI) which can be calculated by using the formula as follows:

$$BPFO = \frac{N_b}{2} f_s \left(1 - \frac{B_d}{P_d} \cos\phi \right) \tag{3}$$

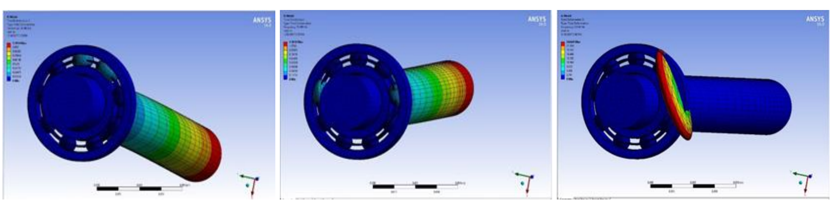
$$BPFI = \frac{N_b}{2} f_s \left(1 + \frac{B_d}{P_d} \cos\phi \right) \tag{4}$$

whereN_b is the number of balls, f_s is the shaft speed in rpm, P_d is the pitch diameter in mm, B_d is the ball diameter in mmand $\phi$is thecontact angle.

For bearing model in this paper, the calculated value for new bearing is 25 Hz, f_{BPFO} is 87 Hz andf_{BPFI} is 130 Hz.

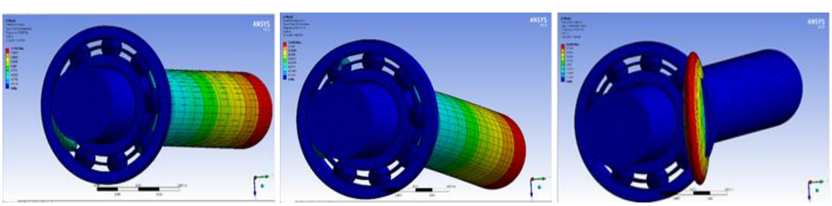
Results and Discussion

The mode shapes and natural frequencies of the bearing system are obtained from the Modal analysis. Figure 6 summarised the first three mode shapes for all types of bearing conditions before the frequency response is analyse through the Harmonic Response analysis.



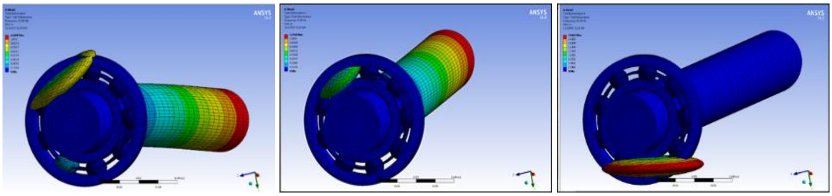
1st mode | 2nd mode | 3rd mode

(a)1st, 2nd and 3rd mode shapes for new bearing



1st mode | 2nd mode | 3rd mode

(b)1st, 2nd and 3rd mode shapes for outer defected bearing

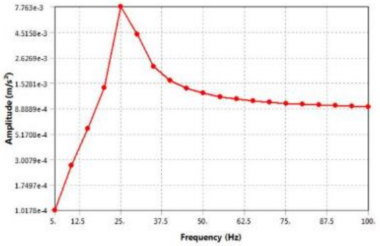


1st mode   2nd mode   3rd mode

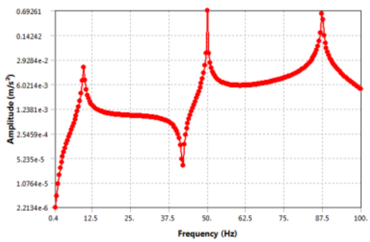
(c)1st, 2nd and 3rd mode shapes for inner defected bearing

Figure 6: Mode shapes for all conditions of bearing

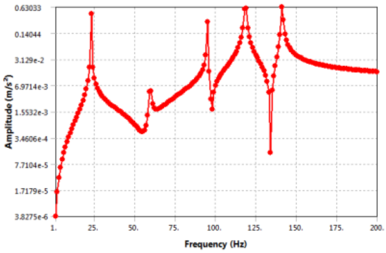
From the Figure 6, in new bearing case 1st mode shape shows that there is a deflection occur at the end of the shaft and this is due to the rotational speed from the motor applied on the shaft. In outer defected bearing case, the mode shapes show deflection occur on the 2nd mode whereas in inner defected bearing, the deformation happens at the balls only as the defect occur in the inner race of the bearing.The frequency domain graphs from the ANSYS WORKBENCH 16.0 for all bearing conditions are shown in Figure 7.



(a) New bearing



(b) Outer defected bearing



(c) Inner defected bearing

Figure 7: Frequency domain graphs

Figure 7 indicate the vibration response for new bearing, outer defected bearing and inner defected bearing, respectively. From the theoretical formula, the defect frequencies can be detected by the significant peaks that appeared on the frequency graph. Figure 7(a) shows the significant peaks of fundamental frequency of the bearing system at 1X significant peak. Particularly for BPOF, the non-synchronous peak is detected at 3X as shown in Figure 7(b) and Figure 7(c) shows that BPFI is appeared at 5X non-synchronous peak. From the simulation findings, it is found that the finite element analysis was able to predict results qualitatively and quantitavely similar to the theoretical calculations is tabulated in Table 7.

Table 7: Bearing frequencies

Types of bearing	**Peaks**	**Frequency (Hz)**
New bearing	1X	25.0
Outer defected bearing	3X	89.7
Inner defected bearing	5X	130.5

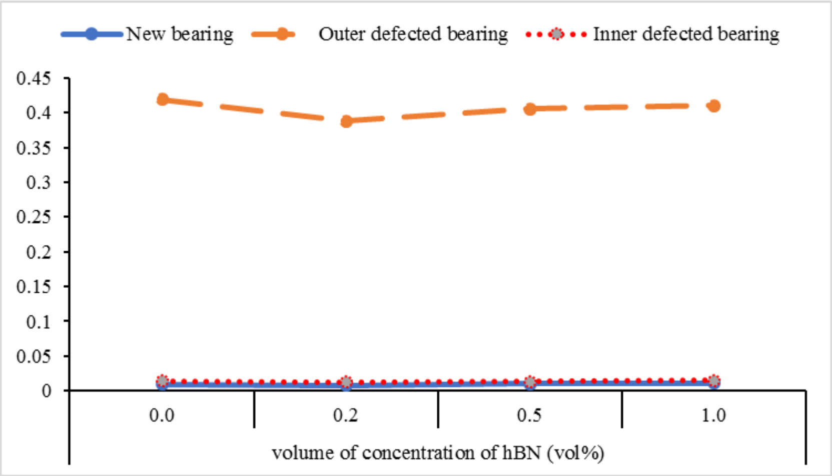


Figure 8: Vibration amplitude responses

It is also found that the significant peak on new bearing and non-synchronous peaks appeared on the inner and outer defected bearings shows good predictive agreement with the experimental results published by Apandi et al. [12]. In addition, the outer and inner defected bearing results shown that the stronger impact wave with the more non-synchronous peak compared to the new bearing. The vibration amplitude is also change because of the defect size where it shows the stronger amplitude.

The significant peaks for new bearing also appeared on the obvious characteristic frequency as calculated at 25 Hz. This is happened due to the variable elastic compliance of the ball bearing. As the position of ball continuously change over time, the stiffness of the bearings varies. Comparing the frequency for defected bearings, the amplitude is smaller. The vibration amplitude for the new and defected bearings is also taken to see the performance of hBN nanoparticles in reducing vibration. The data from the simulation is illustrated in Figure 8.

From Figure 8, it is found that 0.2 vol% of concentration of hBN gives the lowest value of vibration amplitude for new and defected bearing. This is because the reducing in vibration amplitudes are due to the spherical shape of nanoparticles of hBN.A rolling motion effect created from this spherical shape can reduced the wear and also the vibration of the bearing systems. The absorbed nanoparticles may result in rolling effect between rubbing surfaces and the situation will change from sliding to rolling. Therefore, the vibration is reduced. This is supported by Prakash et al., 2013 [9] in his previous research which also stated that 0.2 vol% of CuO nanoparticles is the good concentration in reducing vibration compared to the other concentrations.

For the simulation purpose, we obtain the value of COF for each concentration of nano-lubricant are from the four ball tester, and the results have showed that the COF for 0.5 vol.% and 1.0 vol.% are higher than 0.2 vol%, this is because the more hBN nanoparticle was mixed with lubricant, the potential for agglomeration process occurs is high. Agglomeration is the a bunch of particles stack together and it will reduce the performance of the particles. Thus, for the 0.5 and 1.0 vol.%, the nanoparticles agglomerates as the volume of concentration was increase. That is why the amplitudes obtained for the 0.5 and 1.0 vol.% are higher than 0.2 vol.% of hBN nanoparticles.It also found that the vibration amplitude for outer defected bearing is higher than the inner defected bearing. This is because the outer race defect is remained at the load zone at the maximum position meanwhile inner race defect moves in and out of the load zone. The strong vibration amplitude occurs in the load zone while the weaker vibration amplitude is produce as the defect is outside the load zone.

Conclusion

This paper propose a numerical approach on identifying the performances of hexagonal boron nitride nanoparticles mixed lubricant in reducing the vibration amplitude for new and defected bearing. A 3D finite element bearing model is developed through CATIA V5 and solved numerically within the ANSYS WORKBENCH 16.0. The vibration response is monitored through the acceleration on top of the outer surface which is located near the defects is occured. By analysing the simulated vibration signals, the characteristic frequency of new bearing, inner and outer defected bearings are distinguished. The vibration amplitude of the bearings also are obtained.

The numerical simulation also examines the different value of friction force applied on the bearings sytem as it is represents the existance of the nano-lubricants on the bearings. It is found that the 0.2 vol% of hBN concentration effectively reduce the vibration amplitude compared to the conventional diesel engine oil for all types of bearing condition is due to the manometer size of nanoparticles which make it easily to enter the surface of defected area.

This numerical approach can be used as one of the method in vibration condition monitoring to detect the early deteriotation on bearing due to the characteristic frequency obtained from the frequency spectrum. This is because frequency domain analysis is the most popular method as well as the time domain analysis. The 3D finite element bearing model presented in this paper will be used in our future work to investigate the vibration response of the bearing on different sizes of the defects and the performances of the nano-lubricants in order to reducing the vibration.

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