EXPERIMENTAL STUDIES ON THE NOISE CHARACTERISTICS OF BALL BEARING UNDER HEXAGONAL BORON NITRIDE (hBN) NANOPARTICLE ADDITIVES IN ENGINE OIL

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Report

Projek Sarjana Muda II

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DECLARATION

I declare that this project report entitled “EXPERIMENTAL STUDIES ON THE NOISE CHARACTERISTICS OF BALL BEARING UNDER HEXAGONAL BORON NITRIDE (hBN) NANOPARTICLE ADDITIVES IN ENGINE OIL” is the result of my own work except as cited in the references

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Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Plant & Maintenance).

Signature :. ....

Name of Supervisor : DR. RAINAH BINTI ISMAIL

Date : ....

DEDICATION

To my beloved family

ABSTRACT

The use of rolling element bearings is significant in most of the mechanical applications. Thus, the reliability and efficiency of the mechanical machines depends critically on the health of the rolling bearings. Vibration and noise generated by bearings are one of the big concerns in industry since they limit the performance of machines. Noise characteristics are to be determined for ball bearings lubricated with hexagonal Boron Nitride (hBN) nanoparticles additives in engine oil for different concentrations of concentrations of hBN namely 0.1%, 0.2%, 0.3%, 0.4%, 0.5%. A test rig consists of a motor that drive the system, coupling, rotor to support imposed loads and a bearing which its performance is to be validated. The overall performance has shown a reduction in noise level. Samples of hBN nano-lubricant with different % volume of hBN concentrations were prepared using ultrasonic homogenizing technique. Three conditions of ball bearing were investigated which are healthy bearing, inner defected bearing and outer defected bearing. Sound Level Meter was used to record the noise level for 10 minutes for each concentration and load condition and the average of the equivalent sound level for that period was calculated. The measurement of noise level has shown that the imposed load and concentration of hBN nanoparticles in the lubricant have a significant contribution to the noise level of the bearing. The noise level increases slightly with the increasing of unbalance imposed load while noise level decrease with addition of volume concentration of hBN nanoparticles.

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I would like to thank my course mates for giving me their support, patience and encouragement. Finally, I would like to thank my family for their support.

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hBN	Hexagonal Boron Nitride
SLM	Sound Level Meter
dB	Decibel
Leq	Equivalent Sound Level

CHAPTER 1

INTRODUCTION

1.1 Background

Bearing is a part of machine components that is designed to reduce the friction between the moving parts or to support moving loads. There are thousands of sizes, shapes, and kinds of rolling bearings such as ball bearings, roller bearings, needle bearings, and tapered roller bearings which are the major kinds. However, bearings can be classified into two main types, the antifriction type such as roller bearings and ball bearings which work on the principle of rolling friction. The second main type is the plain or sliding type, such as the journal bearing and the thrust bearing which work according to the principle of sliding friction. More studies and researches are being carried out in order to improve the bearing performance and reduce the noise and vibrations that it produces. One of the methods suggested is by adding hexagonal boron nitride (hBN) nanoparticles to the bearing lubricants. **Figure 1.1** shows a schematic diagram of a straight roller bearing.

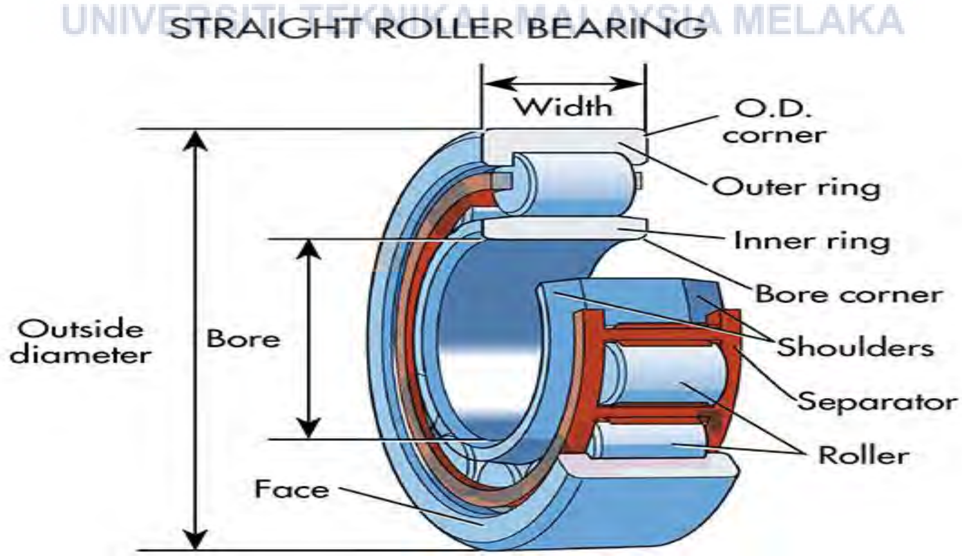


Figure 1.1: Schematic diagram of a straight roller bearing (Gonzales, 2015).

Basically, the main function of bearings is to reduce mechanical friction. Friction reduction enables machinery to run more efficiently and smoothly. Other advantages of bearing are extending the machinery life and, less frictional wear, and avoiding mechanical breakdown. Usually, Ball bearings are found in light precision machinery where high speeds are to be maintained, friction being is to be reduced by the rolling action of the hard steel balls. Bearings are usually lubricated with grease or oil in order to lower the frictional value. However, the friction is still relatively high which produce noise. Using the nanoparticles as additives and mixing them with the lubricants with certain concentrations would reduce the noise resulting from the bearings. The oil is continuously dragged in between the surfaces such that the bearing and the outer ring are separated from each other.

Hexagonal Boron Nitride (hBN) is a chemical combination of boron and nitrogen. Boron nitride exists in various forms, one of them is the hexagonal form that has the same structure as the graphite which is the most stable and soft and the most widely used. It’s thermal and chemical stability properties make it useful at elevated temperature equipment. The low coefficient of friction makes it a good lubricant additive. Lubricants tribological properties can be enhanced in terms of wear and friction by addition of nanoparticles to the lubricants. Nanoparticles of hBN can significantly reduce the anti-wear and anti-friction properties for the base oil. Currently, many types of nanoparticles exist which are being used in industry such as hBN, CuO, Al_2O_3, TiO_2 etc.

Noise in bearings can be due to variety of sound sources that are unwanted by the customer. A source of noise in bearings is mainly due to the structural vibration and sound. There are several types of noise in bearings such as, race noise, click noise, squeal noise and cage noise and rolling passage vibration. Race noise is the basic sound in rolling bearings which is smooth and continuous sound and it gets louder with faster speed. The click noise is more apparent at large bearings under radial loads and it occurs at low speeds. Squeal noise is the metallic noise that sounds like a metal sliding on other metal and usually with grease lubrication. For the cage noise, it is either suggestive of the cage colliding with rolling elements or bearing rings or low frequency noise. The rolling element passage vibration is another factor of noise especially when operating under radial load, and it is mainly influenced by the radial clearance.

Other than the structural vibration and sound are the noise related to bearing manufacturing, improper handling, and contamination noise (Momono *et* al. , 1999).

1.2 Problem Statement

In the modern industrial applications, vibration and noise generated by bearings is one the big concerns in industry since they limit the performance of machines. The addition of small amount of nanoparticles powder into the diesel engine oil as an additive contribute to the enhancement of bearings performance in terms of low friction and low vibration measurements. The different volume of concentration of nanoparticles gives different measurement of coefficient of friction and vibration level. However, there are no researches that studied about the performance of hBN in term of noise reduction. Thus, the characterization of noise level will be investigated to determine the behavior of noise for new and defected bearings operated under hBN nanoparticles mixed lubricant.

1.3 Objectives

The objectives of this project are:

1. To determine the noise characteristics of sound level and its behavior in time domain for ball bearings lubricated with hBN nanoparticle additives in engine oil through experimental means.
2. To determine the performance of hBN nanoparticles mixed lubricants in terms of noise reduction for different volume of concentrations of hBN namely 0.1%, 0.2%, 0.3%, 0.4%, 0.5%.

1.4 Scope of Project

The scopes of this project are to:

1. Prepare the samples of hBN nano-lubricant with different % volume of hBN concentrations using ultrasonic homogenizing technique.
2. Modify the existing test rig in order to make it compatible with our experiment requirements by replacing the motor and rotor.
3. Conduct experimental work in order to obtain the noise characteristics for ball bearing under various lubricant conditions by using sound meter level equipment.
4. Analyze the noise characteristics of the ball bearing under various lubricants conditions and study the performance by using Excel and MATLAB software.

1.5 Study outline

First, chapter 2 presents a critical review of the literature of Ball bearing, diesel engine oil, hBN nanoparticles as lubricant additives and Sound Level Meter. Second, chapter 3 illustrates about the methodology used to carry out the experimental measurements. It provides a detailed explanation starting from the SolidWorks design, development and fabrication, the preparation of lubricant samples by mixing conventional oil with hBN nanoparticles additives, experimental apparatus and ending with experimental procedures. After that, chapter 4 which provides the results of the experimental measurements that has been carried out to investigate the effects of the addition of hBN nanoparticles in terms of the noise produced by the ball bearing being investigated. It also provides comparison and analysis for the obtained experimental data. Finally, chapter 5 concludes this study and provides suggestions for potential future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nanotechnology is considered as the 21st century's most revolutionary technology on which a molecular and atomic scale matter is manipulated. Many fields such as ushers and science of materials is brought into new era by nanotechnology. Lubricants tribological properties were among those fields in which a large number of investigations were carried out by addition of different nanoparticles to the lubricants. Addition of nanoparticles to lubricants was reported by many papers as an effective factor to reduce noise, friction and wear(Pisal *et* al. , 2014). Among the additives investigated was hexagonal boron nitride (hBN). However, the existed studies have not yet extensively explored the effectiveness of hBN nanoparticles additives in diesel engine oil. Current studies on the optimized hBN mixed with engine showed that friction was reduced and resistance against wear was increased. The reduction in friction would be attributed to the formation of boron oxide due to tribo-chemical reactions which results in a significant reduction in the rate of wear. Reduction in friction and rate of wear depends on nanoparticles characteristics such as concentration, shape and size which mostly range from 2 to 120 nm.(Abdullah *et* al. , 2015). The reduction in friction will result in a decrease on the level of noise produced by the operating machines which can be measured and analyzed to determine the performance improvement.

2.2 Bearings

For almost all rotating machinery, bearings are considered of paramount importance and are the machine elements most commonly used in industrial applications. If bearing failure occurred, it would cause machinery breakdown leading to significant losses. Therefore, it is essential to detect the bearing failure at early stages to prevent system breakdown (Xu *et* al. , 2016). Mechanical bearings are components used to reduce friction between two or more parts to allow their movement and enhance the performance. There are a wide variety of bearings as shown in **Figure 2.1** which are used and designed for specific functions and loads such as (1) ball bearings, (2) roller bearings, (3) tapered bearings, magnetic and fluid bearings as well. Some of the bearing types are:

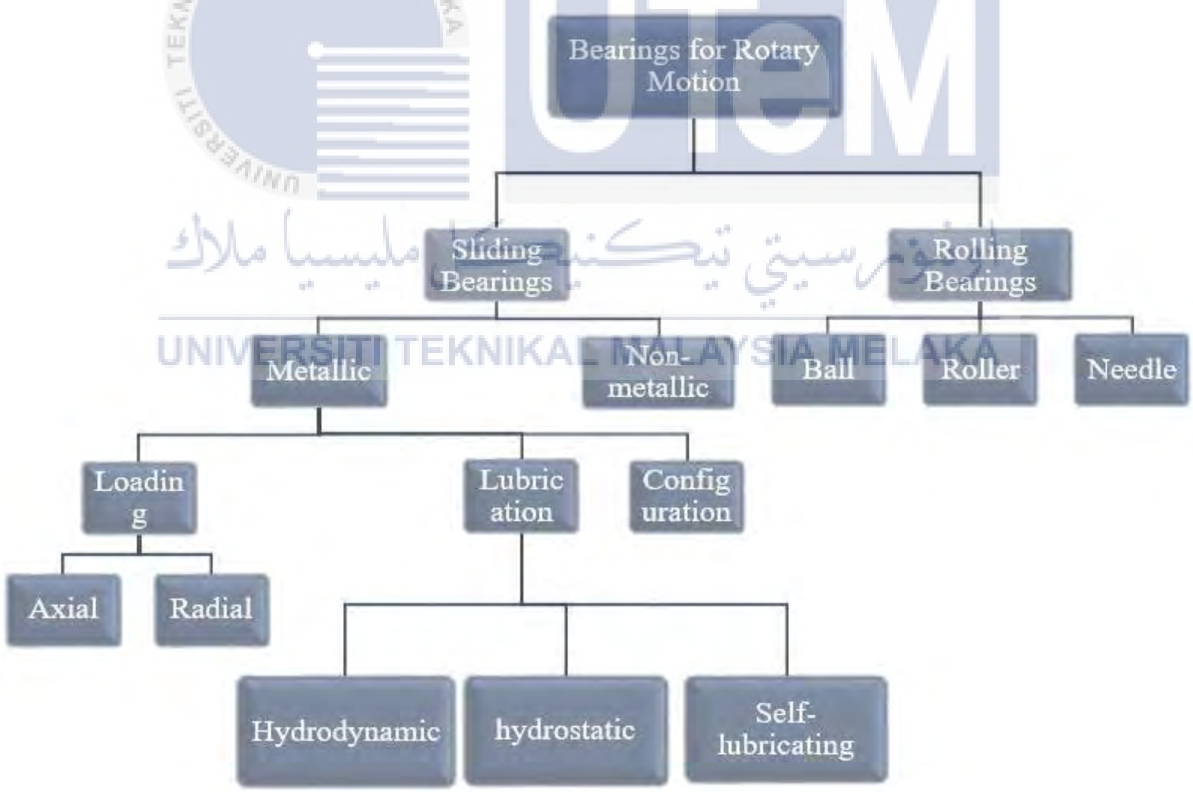


Figure 2.1 Classification of bearings.

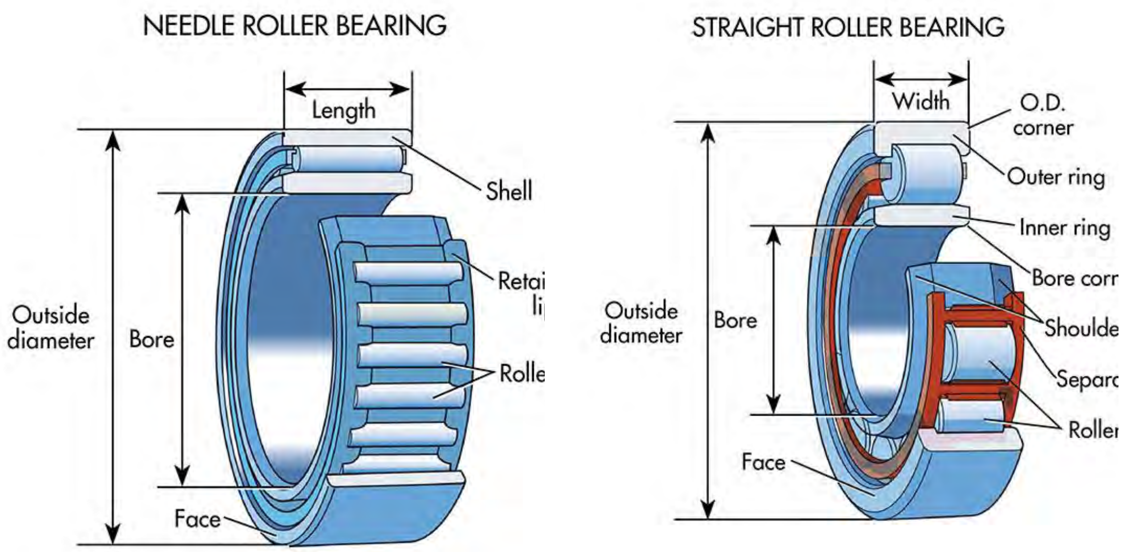
2.2.1 Ball Bearings

Ball bearing are also called as anti-friction bearings which are the most common and used type of bearings exist in numerous applications in daily life. Ball bearings are made in small spheres to reduce the friction between axles and shafts in mechanical applications and usually used where the loads are relatively small otherwise balls will deform which ruing the bearing. The load is to be transmitted from the ball bearings outer surface to the inner surface through the ball which helps in smooth motion. **Figure 2.2** shows ball bearings type.

Figure 2.2: ball bearings (Hyatt, 2009).

2.2.2 Roller Bearings

Cylinders are used instead of spheres as in **Figure 2.3 (a)** in which the inner and outer race contact is line not a point like in ball bearings. Therefore, the contact area is larger which allows for greater loads. There are a variety of applications for roller bearings such as conveyer belts. Needle bearing is a special roller bearing. Needle bearings can be used where space is an issue. It can also bear higher radial loads. Figure **2.3 (a) and (b)** shows roller bearing types.



(a) Needle Roller Bearing **(b)** Straight Roller Bearing

Figure 2. 3: Roller bearings (Gonzales, 2015).

2.2.3 Tapered Roller

Bearing which use conical rollers as shown in **Figure 2.4**. They can support both axial and radial loads and able to bear higher loads due to the larger contact batch. The geometry of those bearings distributes the speed equally along the contact patch which reduces friction and wear.

Figure 2.4: Tapered roller bearings.(Hyatt, 2009).

2.3 Diesel Engine Oil

Lubrication is of paramount importance for all vital parts of internal combustion engine to be lubricated in order to provide safe and undisturbed performance.as technology of engines goes for further development, lubricants needs to be improved as well to get greater power from the engine and withstand higher wear, load, working temperature and last longer. Mineral engine oils were used at first, but to fulfill higher requirements, synthetic engine oils are implemented and globally gain the major market share. For an engine to function properly, some basic requirements need to be fulfilled: reducing friction, minimizing wear, assisting in cooling, and controlling depositions. The wear rate arises to the highest when starting the engine since the oil still not reached all critical parts of engine immediately. While the engine is operating, oil should not lose all of its viscosity, a proper thickness should be kept to provide adequate protection against wear for the engine(Ljubas *et* al. , 2010).

SAE 15W40 diesel engine oil is a heavy duty engine oil which is premium multigrade and synthetic diesel oil. It provides high performance for the diesel engines with higher ability to control deposits and wear. It is one of the purest in base oils with HT purity process of 99.9% purity. Purity has main role in maximizing oil's effectiveness and that can be achieved by controlling chemistry and additives to the system. Unburned fuel would mix in engine oil if not leaves the engine which is due to the uncompleted burn of fuel either in Otto of Diesel engines. This would cause partial or total dissolution for the fuel in engine oil which can result in contamination of the oil. As a result, viscosity, flash and fire point are essential to be analyzed.

2.4 Hexagonal Boron Nitride (Hbn) Nanoparticles

Hexagonal boron nitride (hBN) powder exists in white color with a lamellar crystalline structure that is similar to graphite which is black in color. The lattice parameters such as density and Mohs hardness of hBN are close to those of graphite, even though when it comes to lubrication effects, they have different effects (Pawlak *et* al. , 2009). hBN is distinguished with several unique engineering properties and uses such as improving the resistance to thermal shock by adding hBN to silicon nitride. This improvement is regarded to the micro cracks existed in between the basal planes in hBN. Another use of hBN is between layers of silicon filaments as a weak interface. The physical and mechanical properties vary with the concentration of hBN(Trice & Halloran, 1999). Beside the good thermal stability and the high rate of thermal conductivity hBN is an environmental friendly solid lubricant.

Based on a comparison made, line roughness and friction coefficient of the wear surface showed an optimal concentration for hBN nanoparticles of 0.1 %. Different tests have indicated that a small amount of hBN nanoparticles mixed with lubricant oil would improve the tribological performance including x-ray energy dispersive spectroscopic and atomic force microscopic analysis. However, the good influence of hBN as a lubricant additive has been rarely reported. Nanoparticles of BN could reduce significantly the anti-wear and anti-friction properties for the base oil (Wan *et* al. , 2015).

Today, with the advancement in nano-technology, studies on nanoparticles effects on tribological structure, reducing friction and anti-wear has rapidly increased. Several advantages have been reported by previous studies on the advantages of using nanoparticles as an oil advantages. Improving the friction coefficient by 14.4%, decreasing the wear rate by 65%, and enhancing the performance of lubricating oil can be achieved by the addition on hBN nanoparticles additives (Çelik et al., 2013). The chemical and physical properties of hBN that were used in this project are shown in Table 2.

Table 2.1: The chemical and physical properties of hBN.

[a]Properties	hBN nanoparticles
Appearance	White powder
Chemical formula	BN
Crystal structure	Hexagonal
Melting point, $^{\circ}C$	3,000 dissociates
Average diameter particle size, nm	70
Density, kgm^{-3}	2.3
Hardness, HRC	40
Maximum use temperature in air, $^{\circ}C$	1,000
Thermal conductivity, $Wm^{-1}K^{-1}$	27
Thermal expansion coefficient @25-1000°C	$1 \times 10^{-6}/^{\circ}C$ (parallel to press dir.)
Note: a. from manufacturer	

2.5 Studies on Nanoparticles Additives to Lubricants and Their Effects

The vibration suppression characteristics of ball bearing supplied with nano-copper oxide (CuO) mixed lubricant have been studied by (Prakash *et* al., 2013) . During the their study of vibration suppression characteristics of ball bearing , a test rig consists of an operating DC motor, a ball bearing and the loading arrangement. Chemical methods were used to prepare the CuO nanoparticles. The base lubricants mixed with the CuO nanoparticles were added to the ball bearings to partially immerse the bearings and the radial vibration was measured. The experiment was repeated for CuO concentrations of 0.2%,0.5% and 1%. The results of the vibration test showed that the 0.2 % CuO nanoparticle mixture with base lubricant has effectively reduced the vibration level especially for the defected bearing comparing to the other concentrations.

(Patel *et* al., 2014) aimed to investigate the vibration manners of healthy and defected deep groove ball bearings operating under dynamic radial loads. The experiment used a test rig of a rotating shaft supported by tow deep groove ball bearings. The ball bearings were lubricated and subjected to a dynamic radial load with varying frequency by an electromechanical shaker. Artificial circular defects with different sizes were made. An accelerometer was used to capture vibration signals. Presence of local defects enhances the overall vibration. Vibration peaks are gets more visible with the increase in defect size especially with local defects on outer race comparing to those of inner race defects.

Furthermore, investigation of the vibration behavior of roller bearings as a function of lubricant viscosity have been done by (Serrato *et* al. 2007). Rolling bearings of NU205 were tested using mineral oil as lubricant of three different viscosity grades ISO 10 (V1), ISO 32 (V2) and ISO 68 (V3). The tested bearing was oil bath lubricated and vertically loaded. A piezoelectric accelerometer was used to measure the bearing radial vibration. The measured signals were amplified and acquisitioned and finally analyzed. Vibration level is smaller as oil viscosity degree becomes higher, in contrast to the effect of temperature on oil viscosity.

Besides the vibration behavior of roller bearings, (Jayaram *et* al., 1978) have studied the operating speed and imposed load effects on the noise level of ball bearings at varying speeds and loads using different lubricants. A test machine was designed in such that, a DC motor with smooth and stepless speed control at range of 550-4500 rev per min, is used to drive a stiff shaft by a variable speed. A self-aligning ball bearing type was used to support the rotating shaft. Using a condenser microphone and a sound level meter, noise was pick-up and noise level was measured. In order to prevent oil mist forming, a noise cone was placed instead of usual microphone. The experiment results showed a proportional relation between the operating speed and the noise level. The lubricant contributes significantly as well. As noise level increase with lower viscosity lubricant. The imposed load has insignificant effect on the noise levels.

Moreover, noise characteristic of polymer ball bearings at different viscosity grades through experimental work has been done by (Dinç *et* al., 2013). The authors have used the test rig technique. Whereas, the testing design includes an AC motor to rotate the shaft coupling of the test rig, the tested bearing with hanged weight, and a microphone to measure the sound pressure level. An acoustic chamber was used to provide acoustic insulation for the microphone from the environmental noise factors. At a 75 cm far from the bearings, the sound pressure level was measured. In the experiment, polypropylene cages as well as polypropylene inner and outer rings were used. The results indicated that the lubricant at different oil viscosity doesn't have a significant change on noise level of polymer ball bearings, at least for those can be recognized by human senses. On the other side, an increase on running speeds is translated to increase in sound pressure. While an average of 10 dB at 200 rpm and 25 dB at 900 rpm is the difference in the sound pressure between dry and lubricated running conditions.

(Laad *et* al., 2016) experimentally investigated the nanoparticles of titanium oxide (TiO_2) as additives in multi-grade engine oil it terms of tribological behaviour. Lubricating oil of varying concentrations of nanoparticles were tested under variable load. Pin-on-disc tribotester was used to perform the friction and wear experiments. The results of tests shew that the mixture of TiO_2 nanoparticles with engine oil provided a significant reduction in the friction and rate of wear and improved the lubricating properties of the engine oil. Good stability and solubility of TiO_2 nanoparticles in lubricant was confirmed by dispersion analysis. The mechanism of anti-wear can be regarding the deposition of TiO_2 nanoparticles on worm surfaces which decrease the shearing resistance and as a result improve the tribological properties.

The unique characteristics on hBN nanoparticles make it an attractive performance-enhancing alternative to inorganic solid lubricants due to its lamellar structure. That incited (Çelik et al, 2013) to investigate hBN particles effects on the friction and wear properties of AISI 4140 steel material when the hBN particles are used as an oil additive. Varied volume of hBN was used raged from 0 to 10% by volume. Wear tests were conducted using ball-on-disc geometry. Scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS) were utilized to analyse the worn surfaces of substrates. While ball-on disc geometry was used for wear tests. The experiments showed that the nano hexagonal boron nitride particles that were used as an oil additive affected the friction and wear behaviour. A 14.4% improvement in the friction coefficient and a 65% decrease in the wear rate were achieved through the use of the nano hBN as an oil additive.

2.6 Sound Level Meter (SLM)

Sound level meter is a device used to measure the level of sound which travels via air (acoustic) by determining the pressure level of sound. By means of microphone that is usually hand-held, sound level input is received as a respond to the changes caused by sound waves to air pressure. Sound pressure that is in pascal (Pa) is converted to electrical signals in volts (V). The microphone is able to distinguish voltage values as sound pressure is applied in constant value which is known as sensitivity of microphone. After that, the sound is evaluated accurately by the instrument as the sensitivity is known for the particular microphone. Finally, the electrical signals are converted back to a sound pressure and displayed in decibels (dB).

The common use for sound level meters is studying noise pollution to quantify the various kinds of noise, mostly for industrial and environmental purposes. The function and performance of sound level meter international standards are specified by IEC 61672-1:2013. According to the current standards, there three kinds of instruments for sound measuring which are integrating and integrating-averaging sound level meters besides the conventional sound level meter. Root-mean –square (RMS) circuit is used to covert the AC signal of the microphone to DC. Therefore, an integration time constant is referred to as a time-weighting. The international standards have three time weightings which are ‘S’ (1 s) which is called slow, the second is ‘F’ (125ms) refers to Fast which is usually used for measuring all the sound in your environment, which may vary widely over time, and ‘I’ (35 ms) refers to Impulse weighting is no longer used due to the unsatisfactory results but still included as an informative annex (Narang *et* al. , 2008).

The RMS circuit output is in linear voltage then it is passed in a logarithmic circuit and the output is given in decibels (dB) which is equal to 20 times of the base 10 logarithm for ratio of root-mean-square of a given sound pressure to a reference sound pressure. The international reference pressure is set to 20 micro Pascals of airborne sound. The decibels is a dimensionless ratio. Noise measurements are offered with A, C and Z frequency weighting. A-weighting is the weighting which human is physically able to recognize while C weightings represents the sound that is more sensitive at lower frequencies. One of the most widely used measurement is Leq which is a sound pressure level that is equivalent to the average of sound energy during a specific time (periodKomorn, *et* al., 1979).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains the methodology used in this project to measure noise characteristics of ball bearings lubricated with hBN nanoparticle additives in engine oil. This project started with literature review for previous studies that has been conducted in the same field in order get the information and guidance. Next step was the development of the test rig which started by SolidWorks sketches. The drawings were made for the test rig, ball bearings with illustration for the artificial defects. After the drawings, modification on an existed test rig were done. The fabrication included welding, cutting and drilling. The modified test rig consists of a motor driving a shaft connected to a bearing through coupling was used.

Once the test rig was ready to be used, the mixture lubricant of hBN nanoparticles with engine oil of shell brand were prepared. Five samples are prepared with five concentrations of hBN which are 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% beside the conventional base engine oil. First, calculations were made to determine the exact quantity of oil and hBN nanoparticles powder before they are mixed together. Second, Ultrasonic homogenizer were used to make sure that hBN nanoparticles are completely dispersed. After the engine oil samples were prepared, ball bearings were submersed with the lubricant mixture of base oil and hBN nanoparticles and run for specific period which is for this study 10 minutes for each concentration and load case. While running the test rig, sound level meter was used to measure the noise produced by the ball bearing. The sound level meter is fixed in a hole at the top of isolating box made of acrylic box and a thick layer acoustic soundproof foam. The data obtained from the sound level meter is then analyzed to find out the effectiveness of hBN nanoparticles in reducing noise and the optimum concentration of hBN in engine oil. Finally, report was written presenting the study and its achievements.

3.2 Flow Chart

The methodology of this study is summarized in the flow chart as shown in **Figure3.1.**

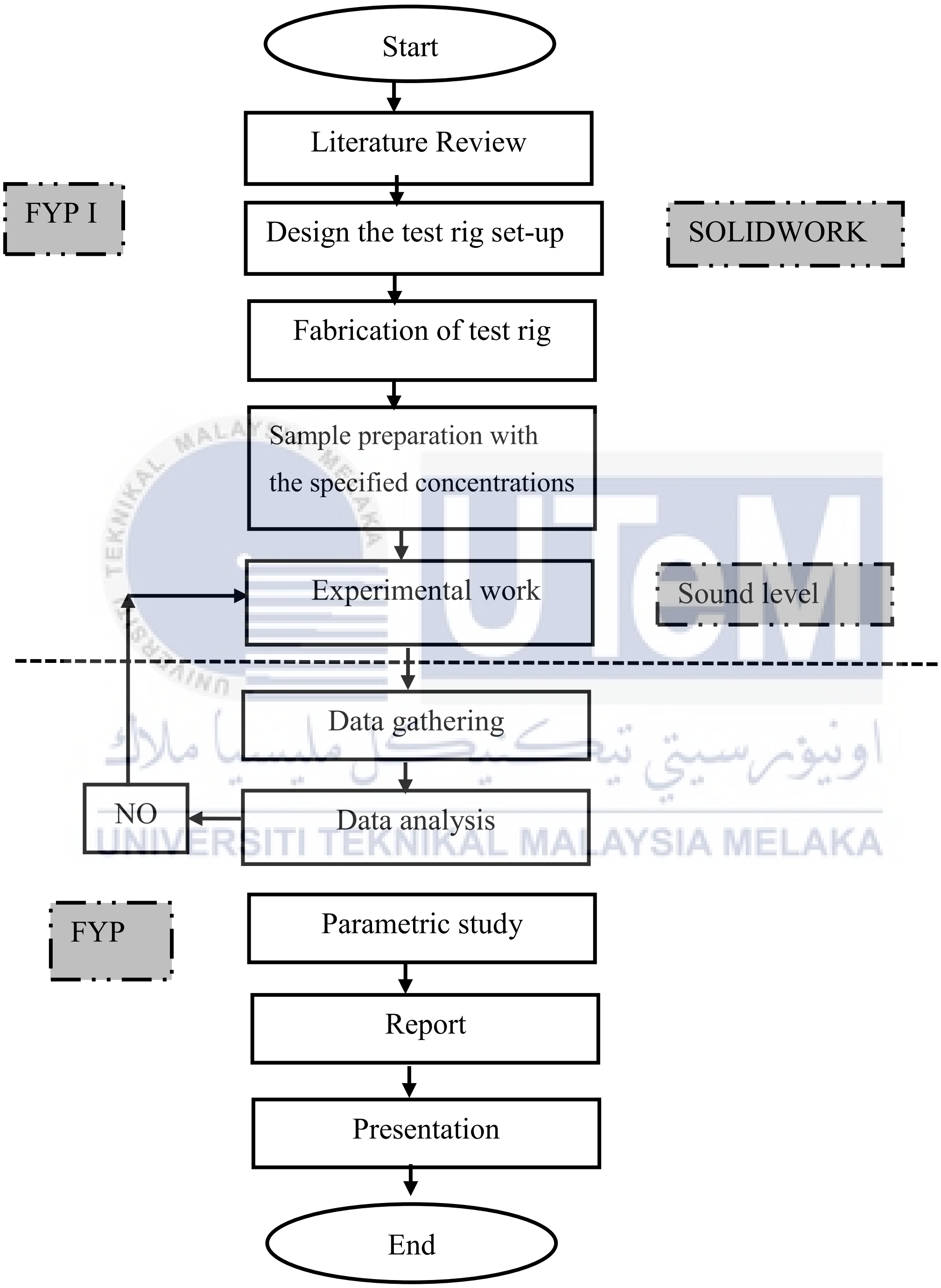


Figure 3.1: Flow chart of the general methodology (General Flow chart of FYP Methodology).

3.3 Development and Fabrication

After the objectives of this project were set, the second step was to determine what is the best mean that will is make it possible to achieve them. Based on literature reviews of previous similar projects, the test rig was proposed and then approved by the supervisor. The first step was to sketch the test rig and for this purpose SolidWorks was used in this project. Then, the test rig was fabricated. Finally, the experimental work started to fulfill the objective of this project.

3.3.1 Development Using SolidWorks

It is of paramount to use technical drawings in engineering applications to fully define the dimensions and items involved in the engineering construction or application. In this project, SolidWorks was implemented to provide a clear idea about the test rig I'm going to use to facilitate my job towards achieving the objectives set earlier. A schematic diagram was sketched using SolidWorks before the fabrication of the test rig started. **Figure 3.2** shows the schematic diagram for the proposed test rig to be used to study noise characteristics. This sketch enabled us to visualize the components that are needed to be involved in the fabrication of the test rig. Based on the drawings, it was possible to define the fabricating processes.

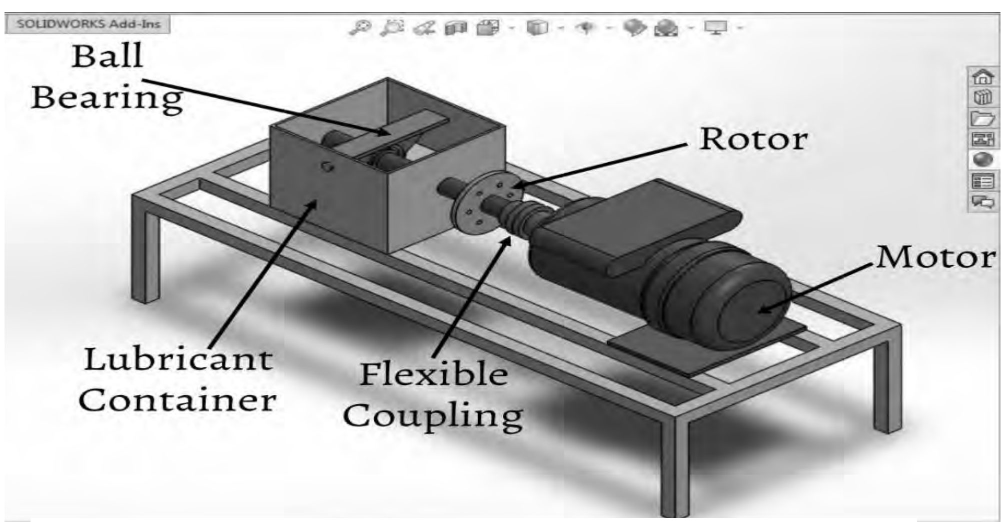
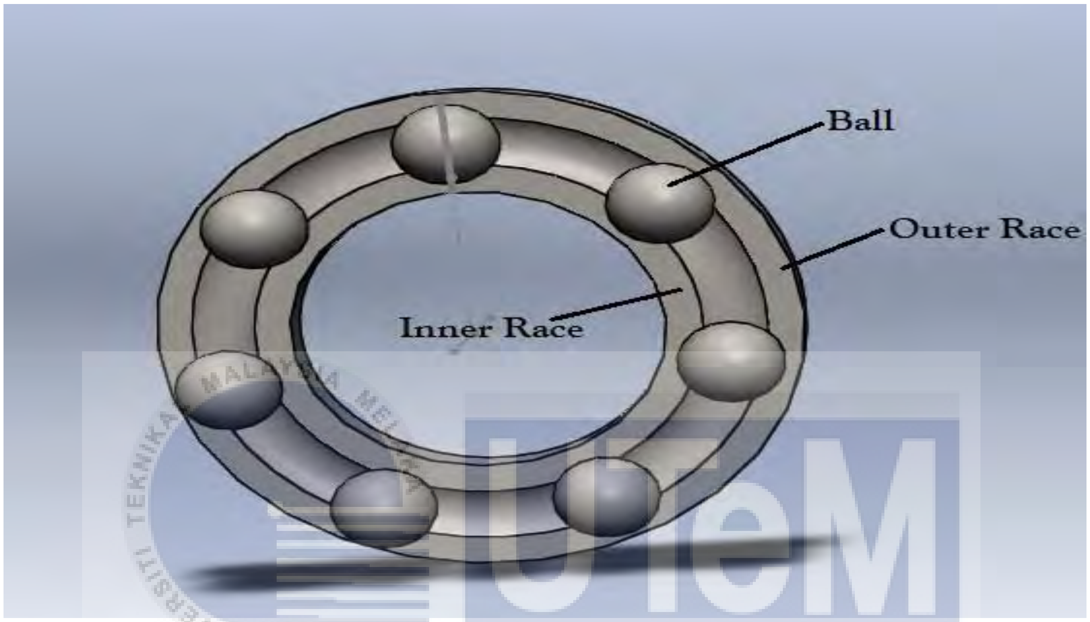
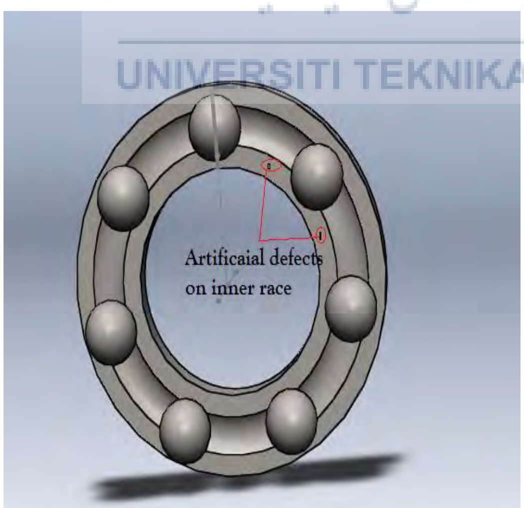


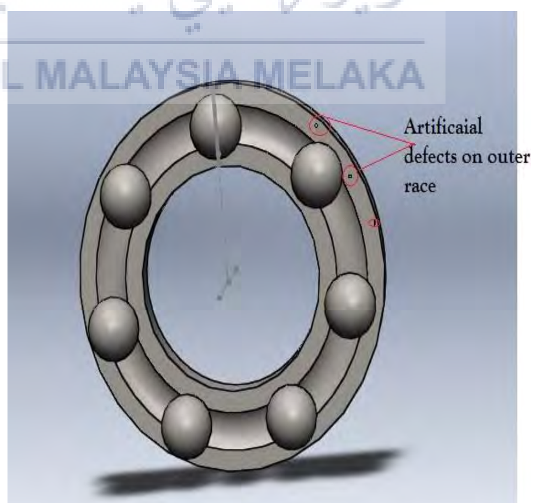
Figure 3.2: Design of test rig using SolidWorks

Ball bearing is the main scope of this project in which the noise resulted from the ball bearings is to be studied. In this study, three types of bearings are to be investigated which are healthy bearing, inner defected bearing, and outer defected bearing as shown in **Figures 3.3**. (a) and (b) and c respectively. SolidWorks was used to sketch the three types of bearings. The artificial defects are fabricated manually with dimension equal to 0.5 mm.



(a) Healthy Bearing





(b) Inner defected bearing

(c) Outer defected Bearing

Figure 3.3: Types of Bearing used during this study.

3.3.2 Fabrication of Test Rig

The test rig was previously fabricated to perform similar experiment but it had to be modified to fit this experiment. The test rig was modified and enhanced at lab with the help and guidance of technicians. Starting with cutting the hard metal that the base of test rig is made from using CNC machine and hand grinder. Some parts of the test rig were repositioned by welding. The driving motor was replaced with motor of higher speed and was attached by welding as shown in **Figure 3.4**. Other fabrication process was drilling to fit screws that fix the motor to the base. Drilling was done to the rotor as well, to make able to hold different loads that the lubricant can be tested at several loads.

Figure 3.4: Welding process during the test rig fabrication.

3.3.3 Fabrication of an Insulating Box

In order to insulate the measurements of the bearing sound level from being interrupted by the external noise sources such as the motor, rotor and environment, an insulating box was fabricated. The box was made of acrylic sheets which is considered as a good insulation medium, light weight and easy to handle. To ensure a good insulation, the box made of acrylic sheets was stuffed with a thick layer of acoustic soundproof foam sponge with a thickness of 5 cms which was compressed inside the box as a second insulating layer as shown in **Figure 3.4**. A hole was made at the top of the box to enable the microphone of the Sound Level Meter to be inserted inside the box while not allowing the noise to penetrate in. This box has limited a great deal of the disturbance caused by the external noise sources other than the bearing. However, the disturbance noise cannot be totally controlled.

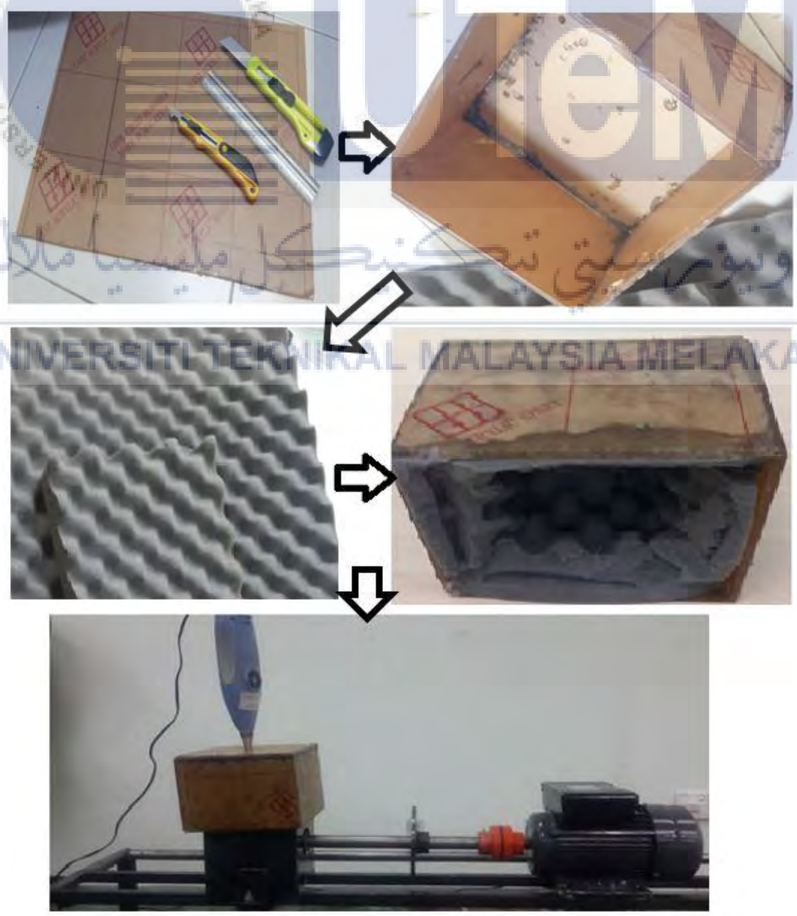


Figure 3.5: Fabrication of insulating box.

3.4 Sample Preparation

The first step to conduct this project was preparing the engine oil samples by dispersing hBN nanoparticles powder in conventional diesel engine oil (SAE 15W40). For this study, five concentrations of hBN nanoparticles additives are used which are 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%. The amount of oil required to submerge the ball bearings is estimated to be 500 mL. After the addition of hBN powder to the base oil, ultrasonic probe homogenizer is used to ensure that hBN nanoparticles are completely dispersed in the lubricant.

3.4.1 Calculation of hBN Mass Required for Each Concentration

By knowing the density of hBN nanoparticles and the volume of the lubricant sample, we can determine the mass of the amount of hBN nanoparticle powder required to be added to the base oil. Then digital analytical balance is used to weight the calculated amount of hBN nanoparticles as shown in **Figure 3.5.**

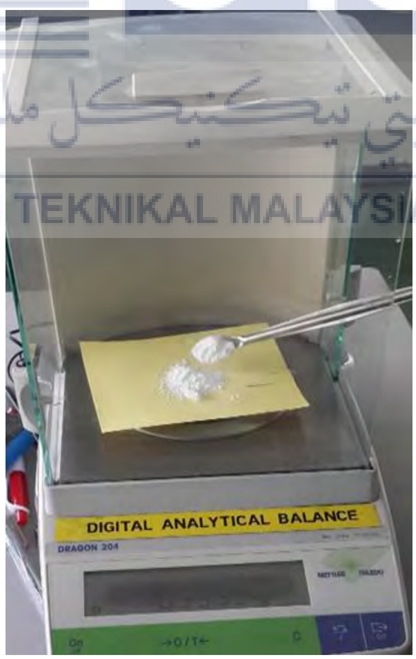


Figure 3.6: Weighting of hBN powder using digital analytical balance.

Equation 3.1 is used calculate the mass.

$$\boldsymbol{m = \rho v} \quad \textbf{(3.1)}$$

Where m is mass, $\boldsymbol{\rho}$ is density**,** and **v** is volume**.** Using Equation (3.1), calculations were done to determine the required mass of hBN nanoparticles for every concentration. Based on the hBN nanoparticles properties, density is determined.

(The density of hBN)$\rho = 2.3\ g/cm^2$

(Volume of lubricant used)$v = 500ml$

3.4.1.1 Concentration of 0.1 %

Volume of 0.1 % into 500 mL of lubricant

V= 0.1 % x 500 = 0.5 mL

$m = \rho v$

m = 2.3 x0.5= 1.15 g

Therefore 1.15 g of hBN nanoparticles is added to the 500mL of the lubricant as shown in **Figure 3.5** but before that an equivalent volume for the 1.15 g is subtracted from the lubricant before the addition of the 1.15 g of hBN to the oil as in Figure 3.5 which is equal to:

v = m / ρ

v = 1.15/ 2.3 = 0.5 mL

Hence, 0.5 mL is to be subtracted from the 500 mL base oil before the addition of hBN powder as shown in **Figure 3.6**.

Figure 3.7: Subtracting of oil

The same calculation is made to determine the amount of hBN nanoparticle powder to be added to the base lubricant which is SAE 15W40 diesel engine oil for the other four concentrations. **Figure 3.7** shows base oil and hBN before being mixed.

Figure 3.8: The determined amount of hBN before being mixed.

3.4.2 Ultrasonic Homogenizing

In order to ensure even distribution of hBN nanoparticles in the lubricant, ultrasonic homogenizer of model LABSONIC P made by Sartorius was used. The process of homogenization improves the stability and uniformity of the mixture by reducing nanoparticles into small particles. The probe of ultrasonic homogenizer emits ultrasonic sound waves and applies sound low heat vibrations to the mixture which effectively disperse the hBN particles that is used in powder form. The mixture was homogenized for a period of 15 minutes. **Figure 3.8** shows the ultrasonic homogenizer used to homogenize hBN nanoparticles in this project.

Figure 3.9 The Ultrasonic Homogenizer model LABSONIC P made by Sartorius.

The mixture of engine oil (SAE 15W40) with hBN nanoparticles was kept in a glass jar. The glass jar is inserted into the homogenizer and fixed in a position that the probe is in contact and penetrate as much as possible of the mixture. However, the probe should be in contact or so close to the glass, otherwise the glass will be broken due to the strong waves generated by the probe. Due to the heat generated during the homogenizing process, the glass jar is placed inside a water container to ensure even distribution of heat thought the whole mixture. After fixing the position of the glass jar inside as in as shown in **Figure 3.9** the machine is calibrated. Cycle was set to 0.5 and amplitude is set to 60 % then machine is switched on. The lubricant mixture is left to be homogenized for 15 minutes.

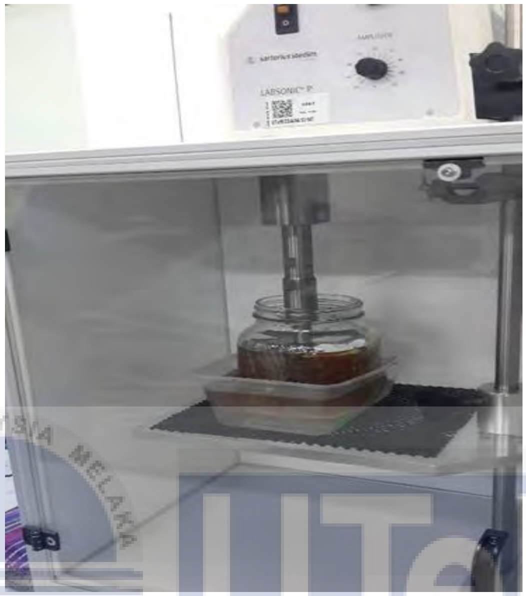


Figure 3.10: Fitting the position of the lubricant mixture inside the ultrasonic homogenizer.

After homogenizing process is done, it can be realized that all the hBN powder is completely dispersed into the mixture and the color of the lubricant is changed from honey color before homogenizing to a color close to white as shown in **Figure 3.10 (a)** and **(b)** Respectively.

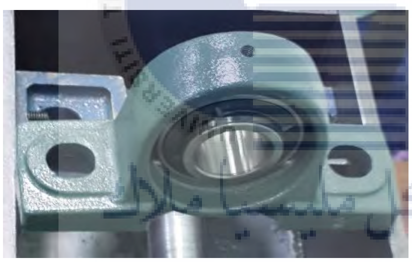
(a) : Before homogenization **(b) :** After homogenization

Figure 3.6: The lubricant mixture

3.5 Apparatus of Experiment

In this research, the apparatus used are listed down as in **Table 3.1** with the description of their specifications and function respectively. These apparatuses are set based on the experiment requirements.

Table 3.1: List of the apparatus used during this experiment.

Apparatus	Description
1. Sound Level Meter 	• Model: NA-28 • Brand: RION • Used to measure the level of sound which travels via air (acoustic) by determining the pressure level of sound.
2. Ball Bearing 	• Three types of SKF ball bearings were used: • Healthy Bearing • Inner defected bearing • Outer defected bearing • Measurements were take separately for each type of bearing
3. AC Motor 	• Model: YL-905-4 • RPM: 1450 r/min • Frequency: 50Hz • Volt: 240 V
4. Personal Computer 	• Brand: Acer • 64-bits, 16 GB RAM, Windows 7 OS. • Used to Matlab software to analyze the data obtained from Sound Level Meter

3.6 Experimental Procedures

After the fabrication is done, the apparatus need to be set up properly to ensure precise measurements. Firstly, the measurement is taken without unbalance load. First of all, the test rig is set up the apparatus as the **Figure 3.11**. Then the mixture of oil and nanoparticles is poured in the lubricant container. After that, Make sure the screws of coupling, rotor, bearing , motor and insulating box are all tighten. Then, fit the Sound level Meter inside the insulating box hole and keep a distance from the ball bearing. Next, calibrate the Sound Level Meter to measure the noise level of A weighting sound level and F frequency weighting and time for 10 minutes. Then the motor is to be run. After that, we need to make sure that no other sources of noise would disturb the measurement. Sound level Meter is to be started to record the data of noise produced by the ball bearing. Then, we need to import data from Sound Level Meter. Finally, comes the turn of analysis using MATLAP and Excel software to calculate the mean sound level and sketch the graphs. Then, for unbalanced loads 1, 2, and 3, screw the load to the rotor and sure it is tightened and repeat the same steps for the rest of the experiments.

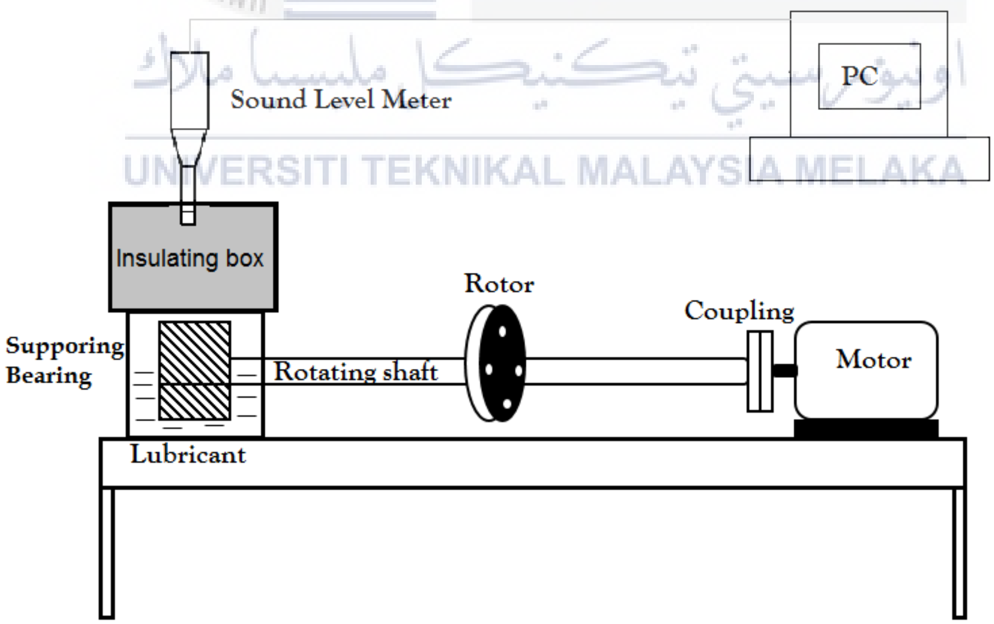


Figure 3.7 Schematic diagram for the experimental apparatus.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the data and results obtained from the experimental measurements performed to obtain the noise levels produced by ball bearing. Three conditions of ball bearing were investigated which are healthy bearing, inner defected bearing and outer defected bearing. The ball bearing was lubricated with hBN nanoparticle additives added to the engine oil. For this project, five volume concentrations were investigated which are 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5% and were compared with the base oil that does not contain any portion (0.0 %) of hBN nanoparticles. The measurements for each volume concentration were carried out under four load conditions. First, the shaft rotates without addition of unbalance load (load 0). Second, one unbalance load (load 1) is added to the rotor of the rotating shaft. Third, two loads (load 2) are added to the rotor and three loads (load 3) for the forth condition. Sound Level Meter was used to record the noise level for 10 minutes for each concentration and load condition and the average of the equivalent sound level (Leq) for that period is calculated.

4.2 Noise Behaviour Data

During experimental work, the motor was operated for **10** minutes for every concentration and load. Initially, the base oil without any addition of hBN nanoparticles was run for 10 minutes and SLM recorded the noise level produced by the healthy ball bearing and the obtained data is considered as base line to be compared with the noise level produced by the same healthy ball bearing after the addition of the hBN nanoparticles to lubricant at different concentrations. Gradually, unbalanced loads were added to rotor and operated for the same period. There are three unbalanced masses, each load is equal to 60 g, so the unbalance loads are 60 g, 120g and 180 g named as load 1, load 2, and load 3 respectively in addition to the balanced condition without any addition of unbalanced load (load 0). The same procedures were performed for the inner defected ball bearing and the outer defected ball bearing. **Table 4.1, Table 4.2** and **Table 4.3** shows the average of the equivalent sound level in dB at the different loads and concentrations measured by SLM for healthy bearing , inner defected bearing and outer defected bearing respectively.

Table 4.1: The equivalent sound level in dB at different loads and concentrations for Healthy bearing.

Concentration	Sound level at load 0 (balance) (dB)	Sound level at load 1 (dB)	Sound level at load 2 (dB)	Sound level at load 3 (dB)
0.00%	91.48	92.35	93.68	93.88
0.10%	90.29	90.73	91.12	90.45
0.20%	89.77	89.72	89.94	90.84
0.30%	89.86	91.04	91.69	92.11
0.40%	90.51	91.15	92.06	92.34
0.50%	91.58	91.19	92.55	92.99

Table 4.2: The equivalent sound level in dB at different loads and concentrations for inner defected bearing

Concentration	Sound level at load0(balance) (dB)	Sound level at load1 (dB)	Sound level at load 2 (dB)	Sound level at load 3 (dB)
0.00%	91.68	91.74	92.8	94.81
0.10%	91.11	91.59	92.16	93.4
0.20%	89.15	89.88	91.58	92.04
0.30%	90.3	90.8	92.03	92.33
0.40%	89.82	91.58	92.25	92.21
0.50%	90.35	91.83	92.33	92.95

Table 4.3: The equivalent sound level in dB at different loads and concentrations for outer defected bearing.

Concentration	Sound level at load0(balance) (dB)	Sound level at load1 (dB)	Sound level at load 2 (dB)	Sound level at load 3 (dB)
0.00%	91.51	92.85	93.5	94.7
0.10%	91.02	91.54	92.15	93.01
0.20%	89.93	89.62	91.28	90.61
0.30%	90.36	90.76	92	91.87
0.40%	91.8	92.11	92.25	92.88
0.50%	91.85	92.27	92.33	93.46

4.3 RESULTS & DISCUSSIONS

Based on the data on **Table 4.1, Table 4.2** and **Table 4.3**, and the bar graphs in **Figure 4.1**, **Figure 4.2**, and **Figure 4.3** that represents the data obtained, it is apparent that noise level increases with the addition of unbalance loads comparing with balanced condition such as for base oil noise level increase from 91.48 dB for balance condition to 93.88 for load 3 in healthy ball bearing and similarly for the other concentrations. Small reduction in the noise level can be inferred for the concentrations that contain hBN nanoparticles comparing with the base oil. The level of noise produced by the ball bearing is the highest at the condition of base oil, then it is reduced with the addition of hBN nanoparticles at variant rates. According to the **Figure 4.1, Figure 4.2** and **Figure 4.3,** noise reduction among the five concentrations of hBN nanoparticles is the most for 0.2 %.

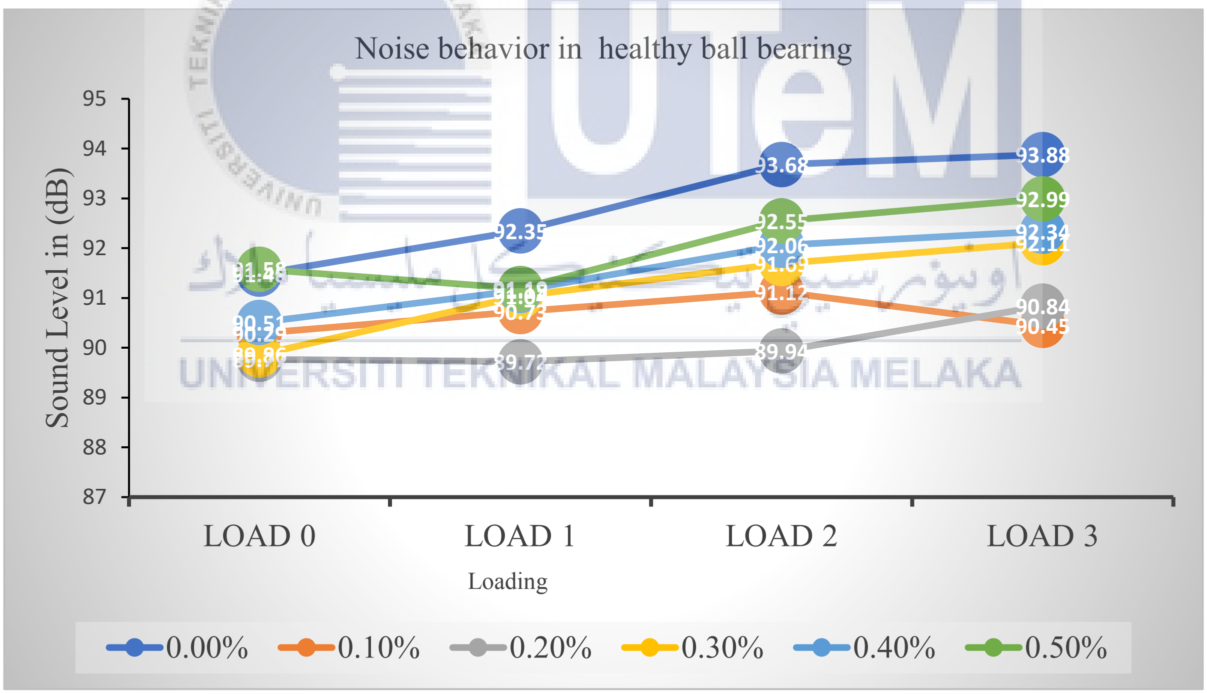


Figure 4.1: The noise behavior in a healthy ball bearing with the average sound level in dB at different loads and hBN concentrations in engine lubricant.

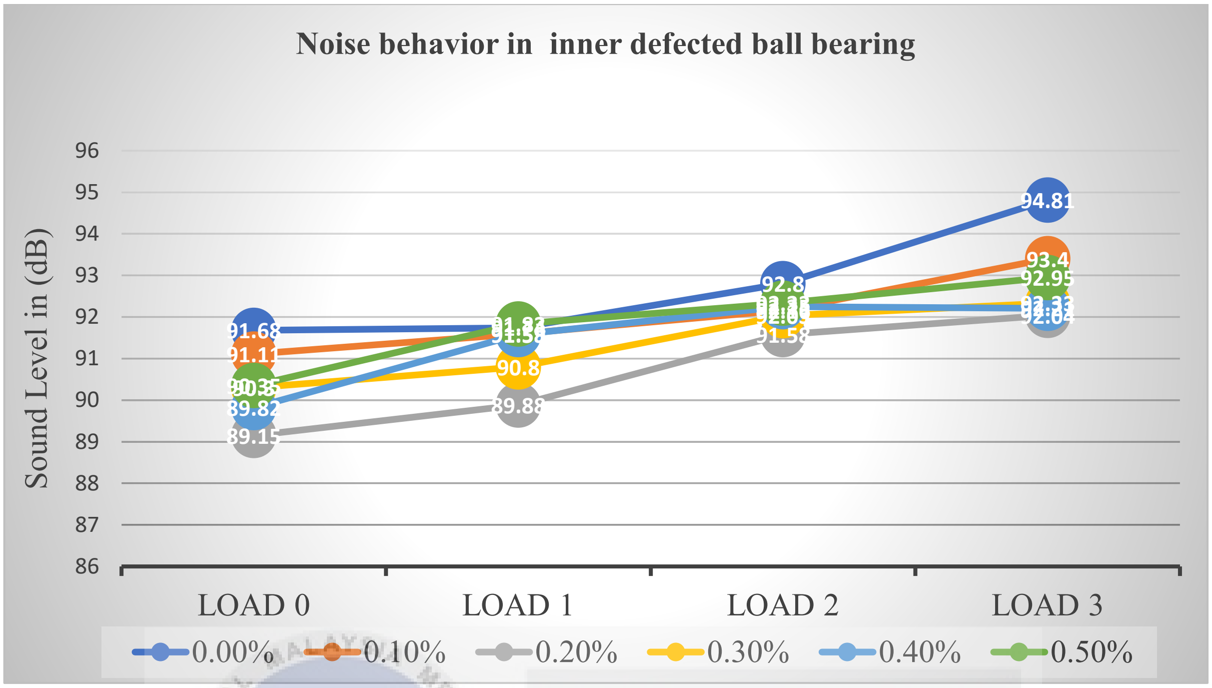


Figure 4.2: The noise behaviour in inner defected ball bearing with the average of sound level in dB at different loads and hBN concentrations in engine lubricant.

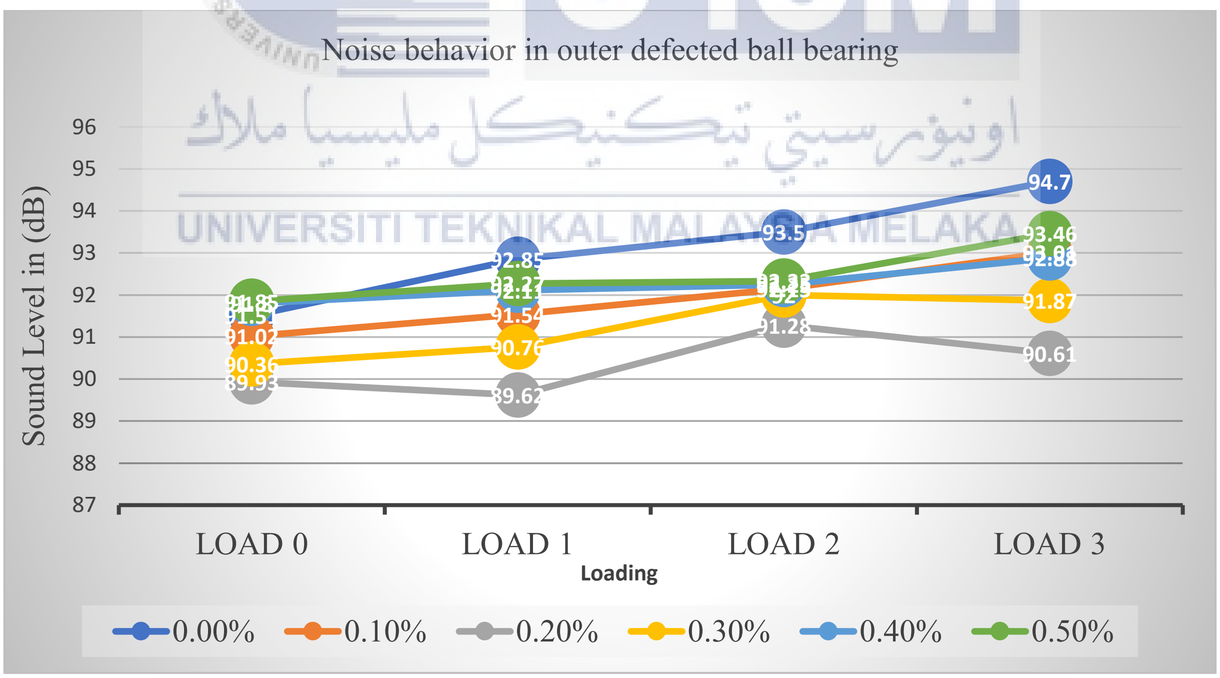


Figure 4.3: The noise behaviour in outer defected ball bearing with the average of sound level in dB at different loads and hBN concentrations in engine lubricant.

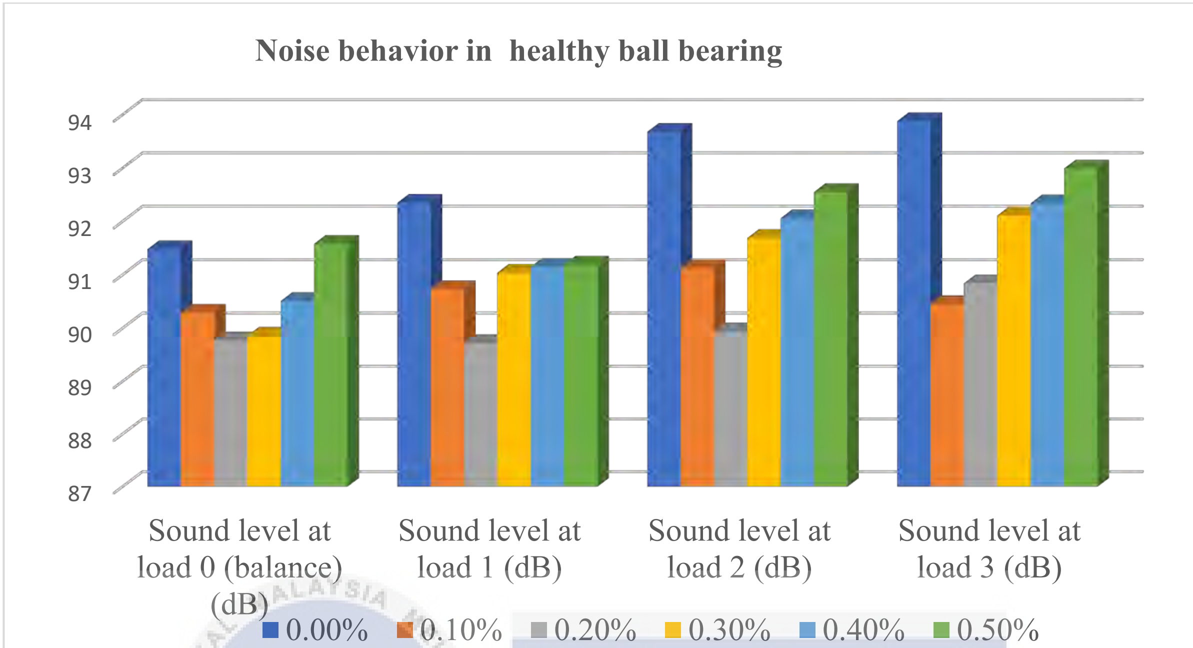


Figure 4.4 The noise behavior in a healthy ball bearing with the average sound level in dB at different loads and hBN concentrations in engine lubricant.

Figure 4.4 shows the behaviour of noise of a ball bearing in healthy condition without any defects. The noise level varies from 89 dB to almost 94 dB depending on the loading and the hBN nanoparticles concentration on the lubricant. It is apparent that addition of hBN nanoparticles to the lubricant reduce the noise level at small rates. The different concentrations of the hBN nanoparticles vary in the amount of reduction in the noise level. The graph shows that the highest level of noise is for the 0.00 % concentration which is for the conventional oil without any addition of hBN nanoparticles. For example, we can see that noise level for conventional oil has decreased from 91.48 dB to 90.29 dB for 0.1 % concentration at balanced load. The reduction increased for 0.20 % concentration of hBN nanoparticles to 89.77 dB at the same loading but then decreased slightly for 0.30 % concentration to 89.86. A similar behaviour can be realized for the other loading conditions. However, there are some deviations that are caused by the external disturbances.

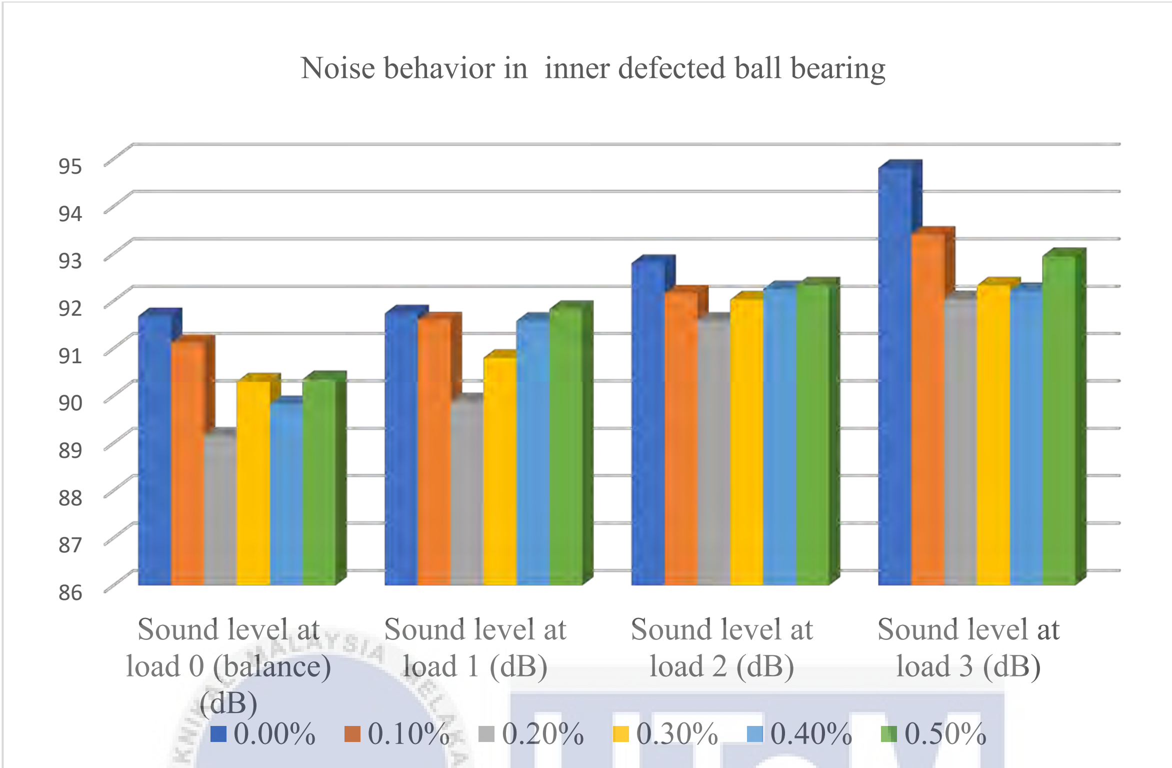


Figure 4.5: The noise behaviour in inner defected ball bearing with the average of sound level in dB at different loads and hBN concentrations in engine lubricant.

Figure 4.5 shows the effect of the addition of hBN nanoparticles additives to the lubricant on the noise characteristics comparing to the conventional oil in inner defected bearing. The chart reveals a rise in the noise level with the addition of unbalance. As shown in **Figure 4.5,** there is a slight reduction in the noise level as with the addition of hBN nanoparticles for 0.1% and 0.2 % comparing with 0.0% which is the conventional oil without addition of hBN nanoparticles. However, the reduction is less significant with the hBN concentration more than 0.2 % and the noise rise up as the concentration increase. Based on the chart, we can conclude that the optimum concentration for the inner defected bearing is 0.2% of hBN which matches with the results obtained for the healthy bearing.

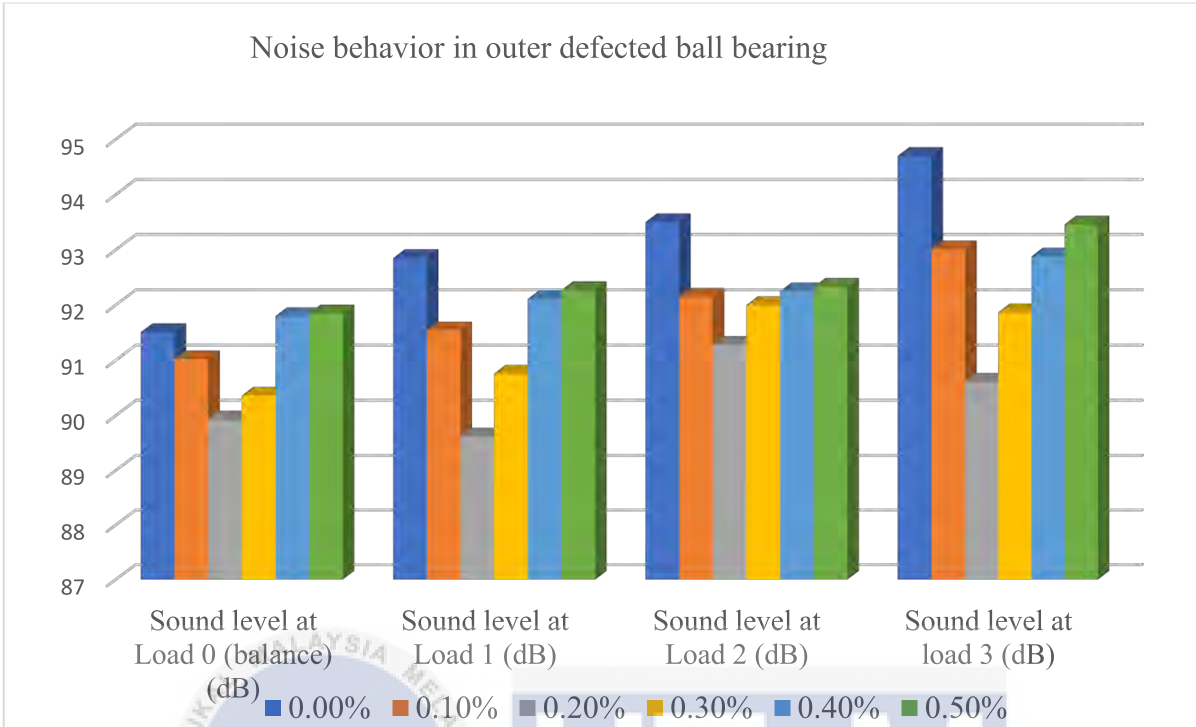


Figure 4.6: The noise behaviour in outer defected ball bearing with the average of sound level in dB at different loads and hBN concentrations in engine lubricant.

Figure 4.6 shows the noise characteristics of outer defected ball bearing under hBN nanoparticles for six hBN volume concentrations and four load conditions. The bar chart reveals clearly that noise level increase with addition of unbalance loads. Based on the graph, the highest level of noise reached is for the concentration of 0.0% which is for the conventional oil without any addition of hBN nanoparticles and it is considered as the base line to be compared with the noise level after the addition of hBN nanoparticles. The bar chart shows a slight reduction of noise level with the addition of hBN nanoparticles. The reduction is most for the 0.2% volume concentration which is considered as the optimum concentration for outer defected bearing. We also can see that for the outer defected bearing the noise level is a bit greater than those for healthy and inner defected bearing.

Table 4.4: The reduction in equivalent sound level between 0.0% and 0.2% of hBN nanoparticles volume concentration.

Item	Eequivalent sound level of ball bearing for base oil 0.0% hBN volume concentration after subtracting the room noise Leq= $leq_{measured} - 45$ (dB)	The average reduction in equivalent sound level **(R. Leq)** between 0.0% and 0.2% of hBN nanoparticles volume concentration in (dB) = $Leq_{0.0\%}$- $Leq_{0.2\%}$	Average rate of reduction in noise level =**(R.Leq.av/Leq_m)*100**
Healthy new bearing	48.14	2.80	5.80%
Inner defected bearing	47.8475	2.78	5.70%
Outer defected bearing	47.7575	2.095	4.30%

Table 4.4 shows the reduction in equivalent sound level between 0.0% and 0.2% of hBN nanoparticles volume concentration. It can be realized that noise reduction is more for the healthy new bearing and inner defected bearing than for outer defected bearing. Based on experimental measurements, the sound level on the testing room before operating the test rig is approximately 45 dB. The average rate of noise reduction noise level produced by the four load conditions was determined as shown in **Table 4.4**. The noise reduction achieved by mixing hBN nanoparticles additives to conventional diesel oil is 5.8% for healthy new ball bearing, 5.7 % for inner defected bearing and 4.3% for outer defected ball bearing.

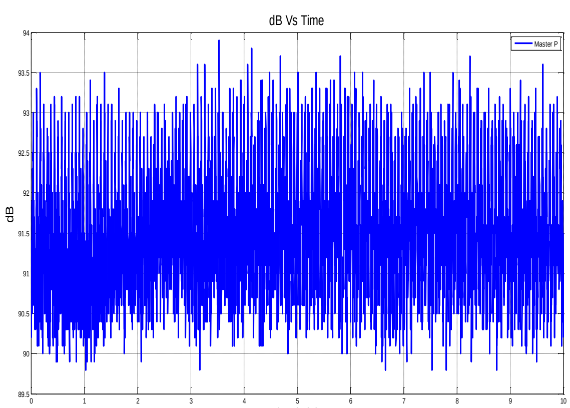
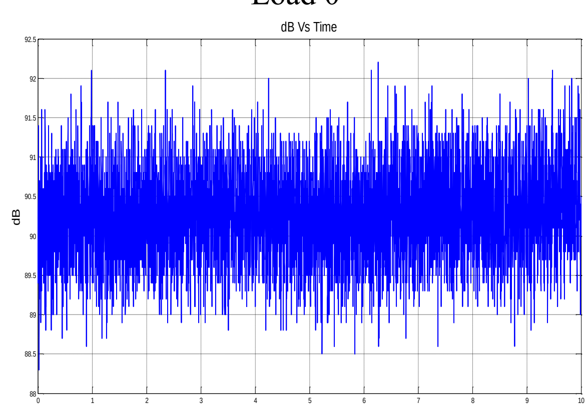
4.4 Noise Behaviour in Time Domain

MATLAB was used to sketch the graphs that shows the behaviour of noise for every load at 0.0 % base oil and oil mixed with 0.2% volume concentration of hBN nanoparticles. SLM was set to record the sound level every 100 ms which means about 6000 values for sound level were recorded during the 10 minutes for each load and concentration. The graphs for sound level in dB against time in minutes were sketched using MatLab **Code 1**. **Table 4.6** shows a comparison concentrations 0.0% and 0.2% concentrations of hBN nanoparticles for sound level in dB against time for the four loading conditions. The graphs show that the range of noise is much wider and scattered in the conventional oil without addition of hBN nanoparticles comparing with the graphs obtained for the lubricant mixed with hBN nanoparticles.

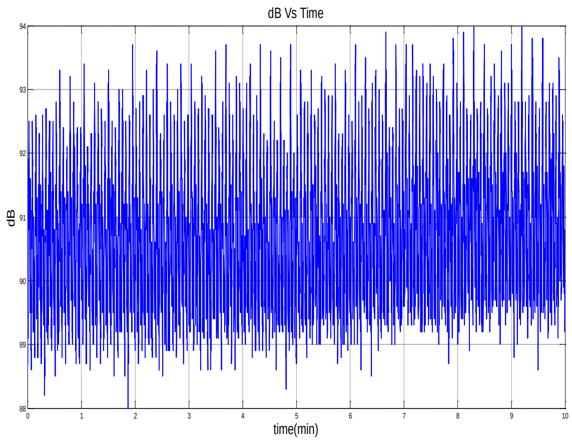
```
{ x=[ time values in minute];
y=[ sound level in values in dB ];
figure(1)
plot(x,y)
grid on }
```

Code 1

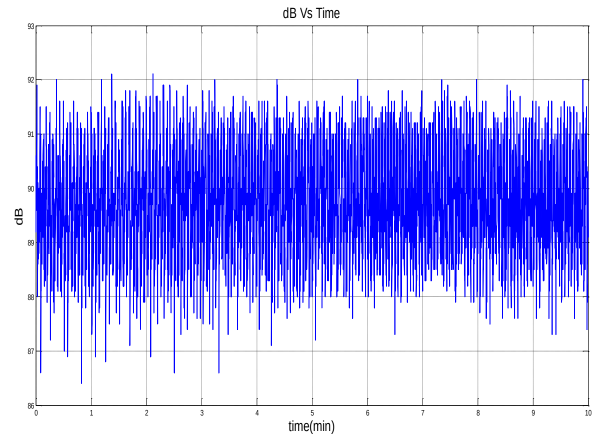
Table 4.5: Comparison for sound level in dB against time for the four loading conditions.

0.0% concentration	**0.2 % conentration**
Load 0 	Load 0 

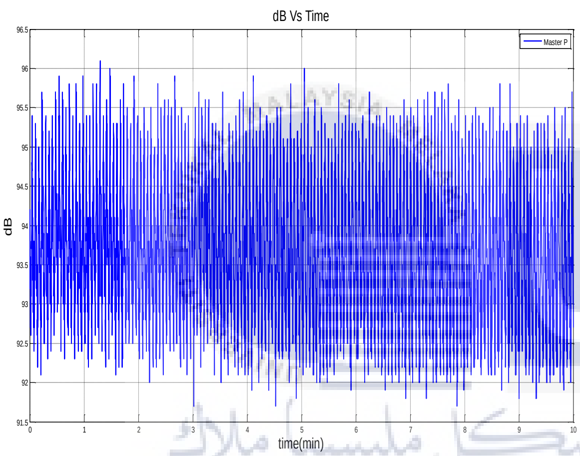
Load 1



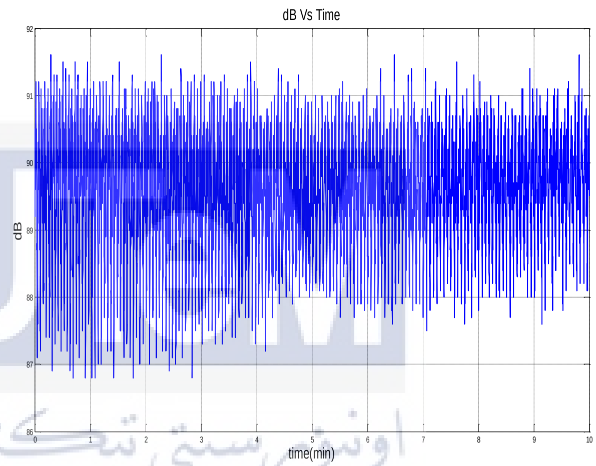
Load 1



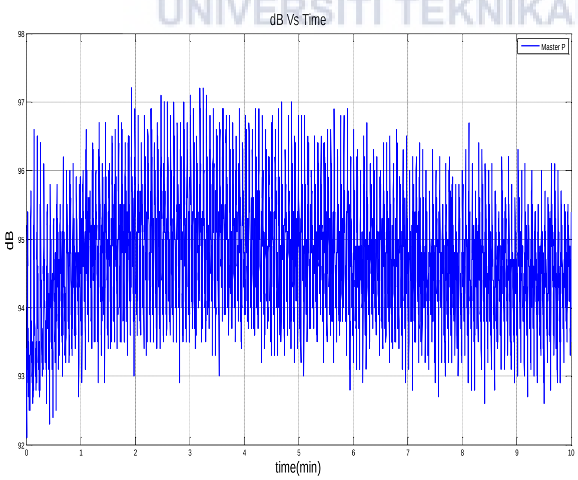
Load 2



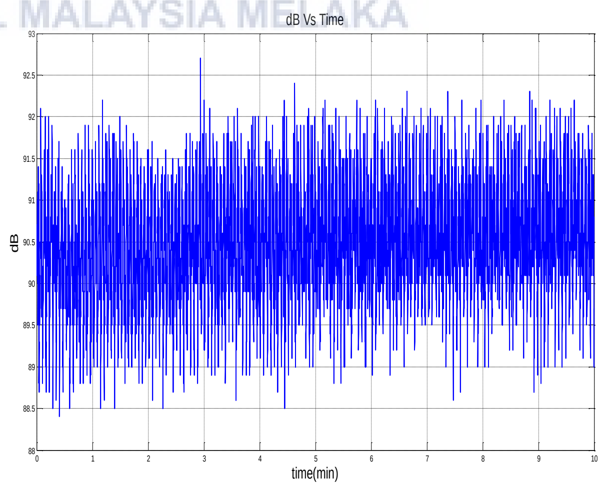
Load 2



Load 3



Load 3



4.5 Vibration Analysis

The experimental results of vibration analysis showed a reduction in the acceleration of the bearings being lubricated with hBN nanoparticles added to the base oil which reveals an improvement in the lubricant performance. As shown in **Figure 4.7**, the highest rate of reduction is for 0.2% of hBN nanoparticles volume concentration. The vibration decrease with the addition of 0.2 % concentration but then increase gradually for 0.5% and 1% concentrations. This can be illustrated as that when adding 0.2 % concentrations of hBN nanoparticles, the lubricant performance is enhanced and the friction between the bearing components is reduced but with the addition of higher concentration, agglomeration occurred which stick the lubricant particles together and again increase the friction. The figure also reveals that vibration is the highest for outer defected bearing, less for the inner defected bearing and the least for healthy new bearing.

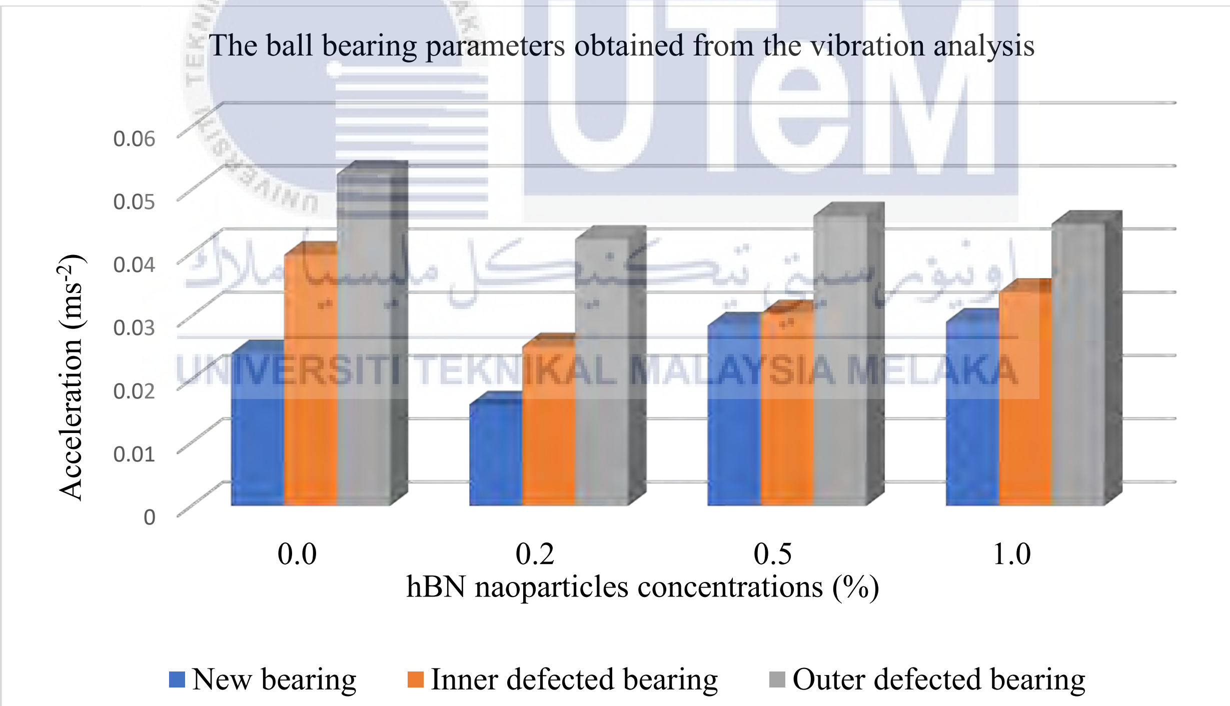


Figure 4.7: The ball bearing parameters obtained from the vibration analysis.

4.6 The Mechanism in Which Nanoparticles Additives Enhance Lubricants Performance

The results achieved by this study are supported by previous studies which have reached to similar conclusions such as (Ilman et al., 2014) who stated that hBN nanoparticles additive presence in the diesel engine oil lowered the friction coefficient which suggests that hBN nanoparticles had an effect on ball bearing. The nanoparticles presence changed the sliding friction to a rolling friction between the frictional pairs, which reduce the contact area. Another property for the hBN nanoparticles that was realized is providing a good anti-wear effect a reduction in the material's wear rate by 58%, which is considered as a good quantitative agreement with coefficient of friction. Furthermore, a smoother worn surface was obtained with hBN nanoparticles additive

The particle size and shape have effects on the tribological performance where smaller particles in nanometer-size are more spherical which allow the particles to coalesce more easily in the asperity valleys, creating a smoother transfer layer that is less abrasive, where the particles align themselves parallel to the relative motion and slide over one another with relative ease providing lubrication and effectively reducing friction. This demonstrates the effects of particle size and shape on the tribological performance where smaller more spherical particles have a greater affinity for minimizing wear. Particles with size larger than Nano still lower wear when compared to a lubricant mixture with no particle additives, but not to the same degree as smaller particles because the larger particle size and plate shaped geometry tends to behave detrimentally by acting as a third-body abrasive particle that can damage the softer disk surface by plastic deformation. (Reeves et al., 2017)

The friction low coefficient can be attributed to the viscosity effect at low temperature and the rolling effect at high temperature. The sphere-like nanoparticles may result in rolling effect between the rubbing surfaces, and the situation of friction is changed from sliding to rolling. Therefore, the friction coefficient can be reduced. For the anti-wear test, when CuO was added to the SF oil and the Base oil, the worn scar depths were decreased by 16.7 and 78.8%, respectively, as compared to the oils without nanoparticles. The anti-wear mechanism is attributed to the deposition of CuO nanoparticles on the worn surface, which may decrease the shearing stress, thus improving the tribological properties (Wu et al., 2007).

4.7 Summary

Noise characteristics of ball bearing were experimentally investigated to find out the effect of hexagonal baron nitride (hBN) nanoparticle additives in engine oil in terms of noise characteristics at different loading conditions and constant speed. The measurement of noise level has shown that the imposed load and concentration of hBN nanoparticles in the lubricant have a significant contribution to the noise level of the bearing. The noise level increases slightly with the increasing of unbalance imposed load while noise level decrease with addition of volume concentration of hBN nanoparticles. During the experimental work, three types of bearing were investigated which are healthy new bearing which does not have any defects beside inner and outer defected bearings in which artificial defects were fabricated on the inner and outer races of the bearing. The measurements were first performed for the conventional oil without any addition of hBN nanoparticles which then considered as base line to be compared with the noise level of the bearings after the addition of hBN nanoparticles. The hBN volume concentrations that were investigated are 0.0 %, 0.1 %, 0.2 % , 0.3%, 0.4% and 0.5% as shown on **Table 4.1**, **Table 4.2 and Table 4.3** and the graphs obtained from them. According to the results obtained using the Sound Level Meter, it can be realized that noise reduction is the highest at 0.2% concentration at least for the experimental work conditions. Therefore, it can be concluded that 0.2% is the optimum volume concentration that can enhance the bearing performance in terms of noise level. The reduction in noise for 0.2% in comparison with 0.0% conventional oil was is 5.8% for healthy new ball bearing, 5.7 % for inner defected bearing and 4.3% for outer defected ball bearing.

The vibration analysis results that has been done by other study for the same bearings and lubricants correspond with those results obtained for the noise characteristics which both proves that 0.2 % of hBN nanoparticles is the optimum volume concentration to enhance the lubricants performance. This vibration analysis and other studies mentioned in the literature review which has come to similar results, emphasis that our study was performed properly. However, there are some fluctuations which can be regarded to supported loads, operating speed instability, the temperature of lubricant and test rig components and the surrounding environmental disturbance at the lap in which the measurements are carried out. Those external parameters contribute randomly in the increment of noise level at some conditions and decrement on others. Therefore, some modifications on the test rig design were made based on the advice of the panel examiners in order to limit those influences. One of those modifications is the fabrication of an isolating box made from acrylic plate and internal layer of acoustic soundproof foam in order reduce the noise produced by the motor which affect the measurement for the ball bearing noise level. The insulating box was fixed on the ball bearing container and a hole was made to fit the SLM sensor which gave more accurate measurements.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

Nowadays, bearings became a main component in most of the rotating machineries. However, bearings are exposed to be worn which limit the performance of machines and cause unwanted noise due to the metal to metal friction. The addition of small amount of nanoparticles powder into the diesel engine oil as an additive can reduce the friction in bearings and enhance their performance. Therefore, this study was carried out to study the noise characteristics of ball bearings lubricated with hBN nanoparticle additives in engine oil. The ball bearing performance was investigated at different volume concentrations of (0.1%, 0.2%, 0.3%, 0.4%, 0.5%) of hBN nanoparticles additives and compared with performance of the conventional oil that does not contain any concentration of hBN nanoparticles under the same conditions. The test rig was fabricated to achieve the study objective. The samples of the five concentrations of the diesel engine oil mixed with hBN nanoparticles were prepared using ultrasonic homogenizer to ensure that hBN nanoparticles were completely and evenly dispersed in the mixture. Sound Level Meter (SLM) was used to record the noise produced by the ball bearing. Noise measurements were carried out for the five concentrations beside the base oil. For each lubricant concentration, four conditions of loading were used. The noise measurements were recorded for 10 minutes for base oil and the same was done for the other concentrations of hBN nanoparticles. Excel and MATLAB were used to obtain the results and draw the graphs from the data recorded by the SLM.

The results showed a reduction in the noise level of the ball bearings lubricated with mixture of hBN nanoparticles and base oil comparing with the noise level of the same ball bearings lubricated with the conventional oil. Based on the data obtained, it is apparent that noise level increases with the addition of unbalance loads. The experimental measurements revealed that 0.2% volume concentration of hBN nanoparticles is the optimum concentration among the other five concentrations with 5.8% reduction in noise for healthy new ball bearing, 5.7 % for inner defected bearing and 4.3% for outer defected ball bearing. This effect could be due to the rolling of the sphere like nanoparticles between the rubbing surfaces, thus reducing friction which in return reduce the noise produced by the ball bearing. With an increasing concentration of nanoparticles the level of noise increased but not more than noise level of oil without hBN nanoparticles, this effect can be justified due to the agglomeration of hBN nanoparticles

For the same objectives, vibration analysis has been done by other study for same bearings, lubricants and using the same test rig. The results of this study have corresponded with those results obtained for the noise characteristics which both proves that 0.2 % of hBN nanoparticles is the optimum volume concentration to enhance the lubricants performance. This vibration analysis and other studies mentioned in the literature review which has come to equivalent results, emphasis that our study was performed properly. The performance of hBN nanoparticles can be clearly observed when heavy system operated under 0.2% volume of hBN concentration mixed with diesel engine oil. Therefore, we can conclude that the noise characteristics oh hBN nanoparticles agree very well with vibration characteristics in which it showed that 0.2 % volume of concentration function effectively as an additive.

5.2 Recommendation

For the future work, it is recommended to benefit from this study and provide better experimental conditions since the role of nanoparticles in enhancing the performance of the machines in case verified, would make a revolution in industry. Some of the recommendations to be applied for future work are to:

- Provide an anechoic chamber that can absorb sound reflections and isolate the bearings being investigated from external environmental disturbances. That will provide measurements that are more precise and accurate.
- Utilize different nanoparticles additives such as Aluminum Oxide (AL2O3) and Copper(II) oxide (CuO).
- Carry out the experimental work for varied brands of diesel oil and a viscosity grades.

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