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A comparative study between two lubrication nano-additives (Bi_2O_3 & TiO_2) based on vibration response analysis

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HIGHLIGHTS

- This research is a new study for the use of nano additives to improve the properties of oil free of any additives.
- The purpose of this study is reducing vibrations in the journal bearings as a result of changing loads and speeds.
- The effect of different dynamic loads and the concentrations of nanoparticles were tested through monitoring the vibration response on the journal bearing of the rotor-bearing system.

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ABSTRACT

The purpose of this paper is to present a vibration monitoring analysis of a hydrodynamic journal bearing working with nano-additives lubricants. The vibration response is generated on bearings at various rotational speeds and dynamic load conditions. These bearings were tested experimentally by adding two types of nano additives; Bismuth (3) oxide (Bi_2O_3), which is considered a green, nontoxic metal, as well as a new additive, and nano Titanium dioxide (TiO_2), which is moderately toxic, with SN150 base oil. The performance of additives was studied on the base oil. The comparisons between the two nano-additives Bi_2O_3 with (1, 2, and 4 wt.%) and TiO_2 with (1 and 1.25 wt.%) were studied experimentally with the SN150 base oil. And the obtained results manifested that at different concentrations of Bi_2O_3 and TiO_2 in the SN150 base oil for each rotational speed and dynamic load, there was a reduction in the vibration system response, where Bi_2O_3 has a good performance at a wide range of rotational speed and dynamic load. At the same time, TiO_2 performs better at higher rotational speed and dynamic load.

1. Introduction

Journal bearings provide a relative rotational or linear movement between two components. It consists of two moving surfaces separated by a thin lubricant film for hydrodynamic lubrication. A thin film of lubricant separates the load-bearing surfaces in the hydrodynamic journal bearing, preventing metal contact and providing the pressure required to separate the surfaces from the load on the bearing. The additives of nanoparticles increase the capacity of the hydrodynamic journal bearings by raising the viscosity of the fluid, which affects the dynamic characteristics. Journal-bearing elements are the most accurately made devices. This is because they could absorb the vibration that occurs in the rotating system.

The effect of blending (0.075%, 0.1%, and 0.15%) volume fractions of TiO_2 nanoparticles with SAE30 base oil on the bearing performance was investigated by Singh et al. [1]. Although the properties of the 0.1% TiO_2 additive volume fraction disfavored its application in journal bearings, the volume fraction of 0.15% of TiO_2 produced more favorable results in comparison to the rest, where the hydrodynamic journal bearing efficiency improved, and it performed better under higher loading conditions.

Bou-Saïd et al. [2] indicated that the effectiveness of nano-additives in lubricating oil is their ability to increase the lubricant's viscosity, which enhances the minimum thickness of the oil film and improves the carrying capacity.

Mohammad Y. A. Jamalabadi [3] investigated the effects of adding CuO, TiO_2, Ag, and Cu in a base oil SAE 20W50 with volume fractions of (0, 0.01, 0.02, 0.03, and 0.04) on the dynamic response of the short and long plain journal bearings. The

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tests showed that increasing the nano-particles volume fraction led to an increase in all mass elements, damping elements, stiffness elements, and critical velocity. Reynold's Equation, Energy Equation, and Heat Conduction Equation were mathematically used by Abass et al. [4] to study the effect of adding TiO_2 nanoparticles in a base oil at various concentrations (0.1%, 0.5%, 1%, 1.5%, and 2%), where the stiffness coefficient (Kxx, Kxy, and Kyy) increased at a higher concentration of 1.5% TiO_2. At the same time, the (Kyx) decreased, the equivalent stiffness coefficient critical mass increased at 0.5% TiO_2, and the damping coefficient (Cxx, Cyy, Cxy=Cyx) increased at 0.5% and 1% TiO_2, according to the study. Kornaev et al. [5] utilized a low viscosity mineral oil with a 0.05% addition of the mass of fullerene black, fullerene, molybdenum disulfide, and fluoropolymer. Fullerene black and fluoropolymer outperformed the others by lowering the coefficient of friction, vibration level, and load-carrying capability.

Binu et al. [6] theoretically studied the effect of TiO_2 with a size of 777 nm and concentrations of (0.001, 0.005, 0.01, and 0.02) in engine oil by using a linear perturbation method modified Reynolds equation, and modified Krieger-Dougherty model. The results depicted that the stiffness and damping coefficients increased, and the steady working zone increased owing to the (TiO_2) volume fraction at higher eccentricities through a heavy burden and high-speed processes.

The effect of TiO_2 in lubricating oil was theoretically studied by Abass et al. [7] using the Reynolds equation, Dufrane wear model, and modified Krieger-Dougherty viscosity model for short journal bearing (L/D<1). It was revealed that raising the TiO_2 concentration in base oil improved the damping coefficient.

Jian-Qiang Huet al. [8] stated that when adding bismuth dialkyl dithiocarbamate (BiDDC) nano-particles to mineral oil SN150 with concentrations of (0, 1, 3, and 4 wt%), the anti-wear capacity and the load-carrying capacities increased .

Fatima Leonor Guzman Borda et al. [9] used a Tribometer with a pin-on-disk, four-ball configuration, and copper nano-particles (0.3% and 3.0%wt) that were applied to the mineral and synthetic ester-based oils. Unfortunately, both concentrations were ineffective as antifriction and anti-wear agents in the synthetic polar oil. Still, they reduced the friction and improved the anti-wear in the mineral oil, particularly at 0.3% wt.

Nano additions had previously been studied for their effect on the tribological properties of lubricating oils. Still, there have been few practical studies on their impact on the dynamic performance of rotating systems.

Therefore, this paper aims to investigate the practical implications of including TiO_2 and Bi_2O_3 nanoparticles in low viscosity mineral base oil (SN150), as well as to compare the two additives in terms of minimizing the vibrations created on the hydrodynamic journal bearings. To achieve this, a test rig has been manufactured to conduct the required experimental work depending on a suitable vibration measuring system and then acquire the signals for processing and analysis.

2. Methodology

Most oil-lubricated journal bearing failures are caused by lubrication system problems or bearing attrition, which will increase the shaft vibration. Vibration analysis can therefore be used to monitor the state of hydrodynamic journal bearings. However, the in-field monitoring of the journal-bearing issues relies substantially on the interpretation of mechanical data, such as acceleration or displacement [10]. According to that, the dependent method in this work is based on employing an acceleration board mounted on the bearing housing to measure the bearing vibration. A MATLAB - Simulink application drives the data acquisition device (Arduino Mega 2560 R3), which acquires analog signals and converts them to a digital form, which is then recorded and processed by a PC to achieve a Root Mean Square (RMS). For the various shaft rotational speeds, the test was conducted with a balanced and unbalanced mass of 10 g placed on the flywheel disk radius of (24 mm, 48 mm, 72 mm, and 96 mm) from the center of the shaft. The numerous steps of the experimental approach are depicted in Figure 1, which are repeated for each nano additive type and concentration.

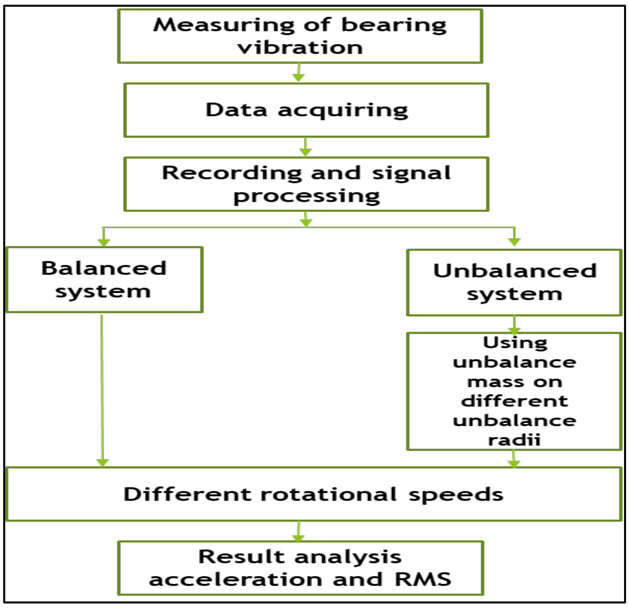


Figure 1: The flowchart of the experiment methodology

3. Used Materials

Bismuth (3) oxide (Bi_2O_3) nanoparticles of particle size (20-30 nm) in various weight percentages of (0.5, 1, 1.5, 2, 4, 6, and 8 wt.%), and Titanium dioxide (TiO_2) nanoparticles of particle size (30-50 nm) with the weight percentages of (0.1, 0.25, 0.5, 0.75, 1, 1.25, and 2 wt.%) were employed in the experiment. The properties of these two materials are listed in Table 1. They were blended with the mineral base oil SN150, which has the properties listed in Table 2. Using UP200Ht ultrasonic processing equipment, as in Figure 2, to get the best dispersion of the nanoparticles in the oil, each sample was blended for 30 minutes [11].

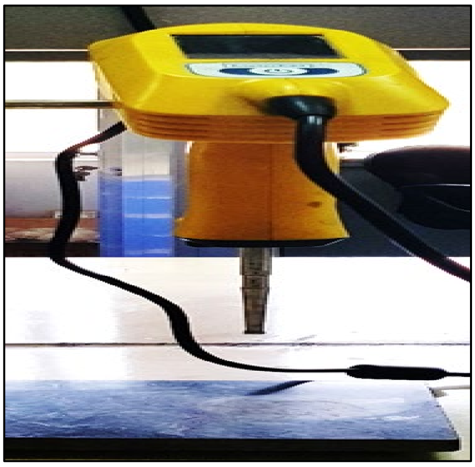


Figure 2: UP200Ht ultrasonic processor

Table 1: Bismuth (3) oxide and Titanium dioxide nanoparticles properties **[12]**

Molecular Formula	Bi_2O_3	TiO_2
molar mass	465.96 g/mol	g/mol 79.866
Appearance	yellow crystals	White solid
Density	8.64 g/cm^3	3.78 g/cm^3 (rutile), 4.23 g/cm^3 (anatase)
Melting point	825°C	1,843°C
Boiling point	1890°C	2,972°C
Solubility in water	Insoluble	Insoluble

Table 2: SN150 oil properties

Base oils	SN150
Viscosity at 40°C	15.34 C.s.t
Viscosity at 100°C	3.46 C.s.t.
Viscosity Index (V.I)	100
COC Flash	196°C
Pour point	-6°C
Color	0.5
H_2O % Vol.	Nil

The lubrication mechanisms of nanoparticles can be summarized as the rolling effect, mending effect, polishing effect, and protective film formation by which the nanoparticles reduce friction and wear [13], as shown in Figure 3. In Rolling (or ball bearing) mechanism, the nanoparticles act like ball bearings and roll between the two surfaces, Figure (3-a). In the mending mechanism, the nanoparticles get deposited on the rubbing surfaces, Figure (3-b) and fill the grooves on the surface. In the polishing mechanism, the nanoparticles make the surface smooth by polishing the rubbing surface, Figure (3-c). Finally, in the protective film mechanism, the nanoparticles form a lubricious layer on the friction surface and thus prevent direct metal contact between the friction surfaces, Figure (3-d).

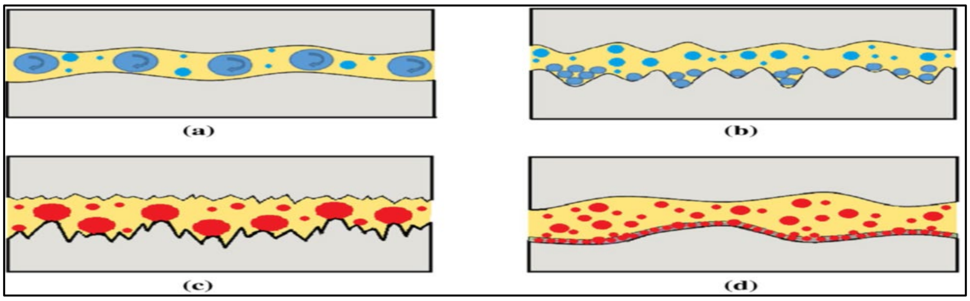


Figure 3: Lubrication Mechanism of Nanoparticles (a) rolling mechanism; (b) mending mechanism; (c) polishing mechanism; (d) protective film [13]

TiO_2 nanoparticles reduce wear and friction by direct and indirect mechanisms. In the direct effect (also called primary effect), the nanoparticles act as a ball bearing between the surfaces and form a protective layer over the surface. In an indirect effect (also called a secondary effect), nanoparticles compensate for the loss of the material by depositing on the surface, as explained by Binu et al. [14].

As for bismuth (3) oxide, it is new nanoparticles (as referred to in the introduction) that were not used in previous research. However, Bi nanoparticles are a low-melting-point soft metal. They fix the holes and scratches generated by friction in the frictional process, producing a glossy and flat metallic surface that permits self-repair and decreases friction and wear [15].

4. Vibration Test

Figure 4 displays the test rig designed and manufactured to assess the effect of nano-additives on the vibration response. The test rig consists of a rotating hollow shaft with diameters of 25 mm and 20 mm. The hydrodynamic journal bearings were adjusted to suit the experiments by varying the types of additives. A three-phase AC motor Y3-71M2-2 (0.75 HP) drove the shaft and flywheel via a V-belt pulley arrangement. To control the speed of the single-phase motor, a Variable Frequency Driver (VFD) inverter from VEIKONG (1.5 KW, 220 volts) was used. A flywheel was mounted on the shaft to simulate the dynamic load on the bearing system.

Additionally, unbalanced mass pieces were mounted on the side of the flywheel at different radii to achieve varied dynamic forces on the bearings. The acceleration board sensor (GY-61 ADXL335 3-axis) was mounted on the test bearing housing and connected to an Arduino Mega 2560 R3. The output signal was read by Matlab Simulink software, which recorded and presented the collected data. Finally, the trials were carried out, as shown in Table 3.

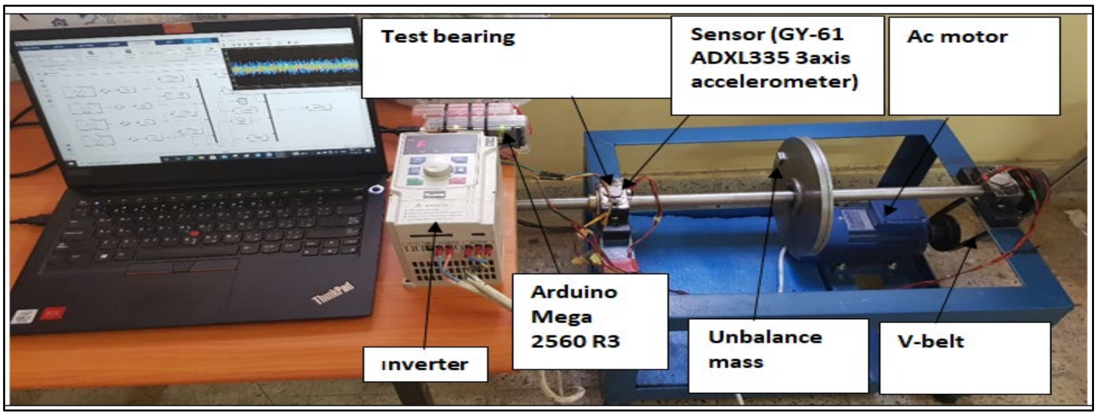


Figure 4: Test rig and experimental setup

Table 3: Experiments parameters

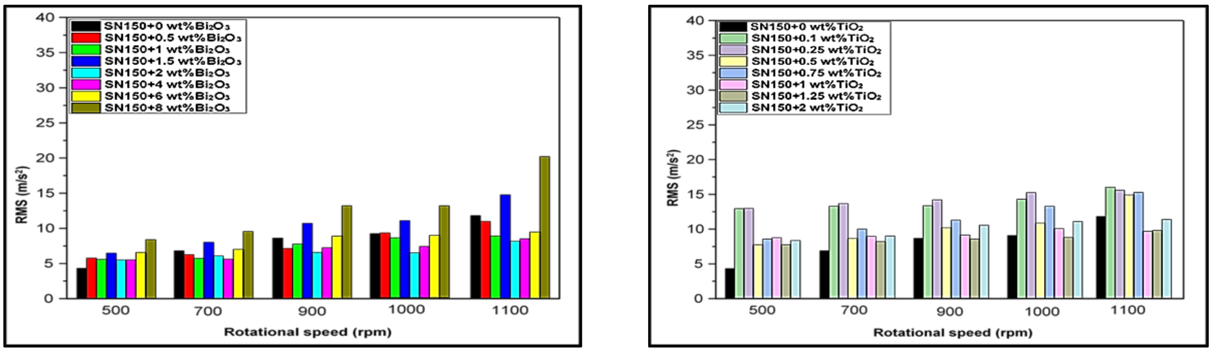
Load state	Unbalance mass (g)	Unbalance radii (mm)	Rotational speed (rpm)	Lubricant oil	Additives (Bi_2O_3) wt.%	Additives (TiO_2) wt.%
Balanced	-	-			0.5	0.1
system			500		1	0.25
			700		1.5	0.5
Unbalanced		24	900	SN150	2	0.75
system	10	48	1000		4	1
		72	1100		6	1.25
		96			8	2

5. Results and Discussion

5.1 Comparison of the Influence of Rotational Speed and Dynamic Loads on the Nano Additives Concentrations

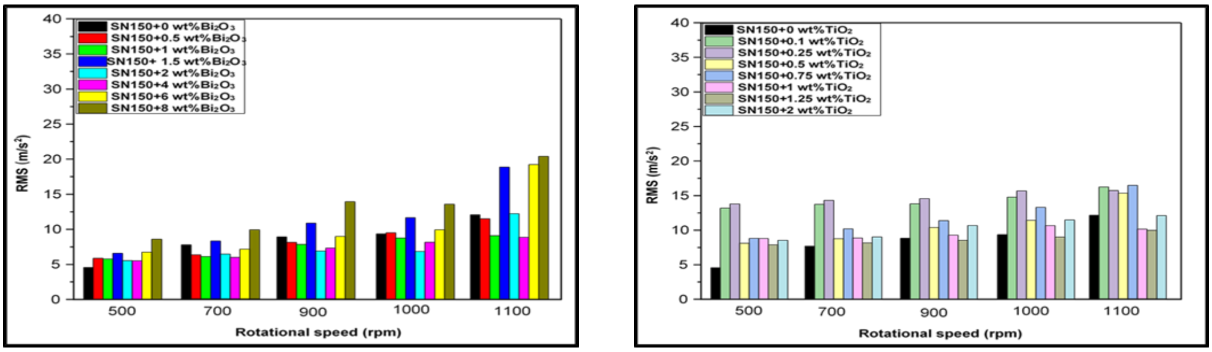
The variation of the vibration response Root Mean Square feature (RMS) was monitored and analyzed in this section for the test bearing with different nano-additive (Bi_2O_3) and (TiO_2) concentrations blended with the base oil (SN150) at various rotational speeds under different dynamic loads, as listed in the following cases:

Figures (5 to 9) illustrate the change in the vibration response feature in the test bearing represented by the Root Mean Square (RMS) value with the rotational speeds. It is noticeable that the value of RMS increases gradually with the increase of the rotational speed. However, this increase varies when adding different concentrations of Bi_2O_3 and TiO_2 to the base oil SN150. Figures 5-a, 6-a, 7-a, 8-a, and 9-a show the effect of blending Bi_2O_3 with the oil. The RMS value decreases in both the balanced and unbalanced cases at speeds (700 to 1100 rpm) and concentrations (1, 2, and 4 wt.%). The percentage of reduction in the value of the Root Mean Square (RMS) ranges from (17% to 61%) compared with pure oil. Figures (5-b, 6-b, 7-b, 8-b, and 9-b) indicate that when TiO_2 is blended with oil, the RMS value drops at concentrations of (1 and 1.25 wt.%). The percentage of decrease in the value of the Root Mean Square (RMS) ranges from (1% to 61%) compared with the pure oil at rotational speeds (900 to 1100 rpm). It can also be observed that the oil SN150 was effective at a lower speed (500 rpm), but as the speed increased, the addition of nano additives, such as Bi_2O_3 or TiO_2, to the base oil SN150 showed more effect.



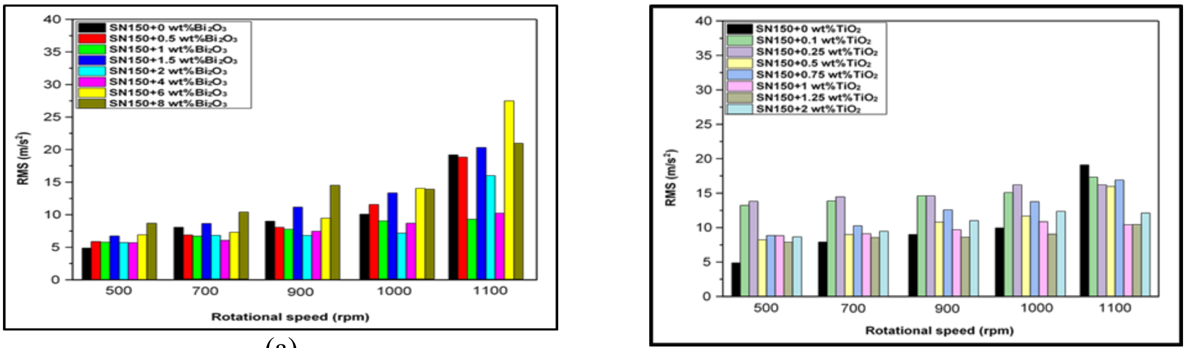
(a) (b)

Figure 5: Variation of RMS with different rotational speeds and concentrations of nano-additives at a balanced system: (a) $SN150+Bi_2O_3$ and (b) $SN150+TiO_2$



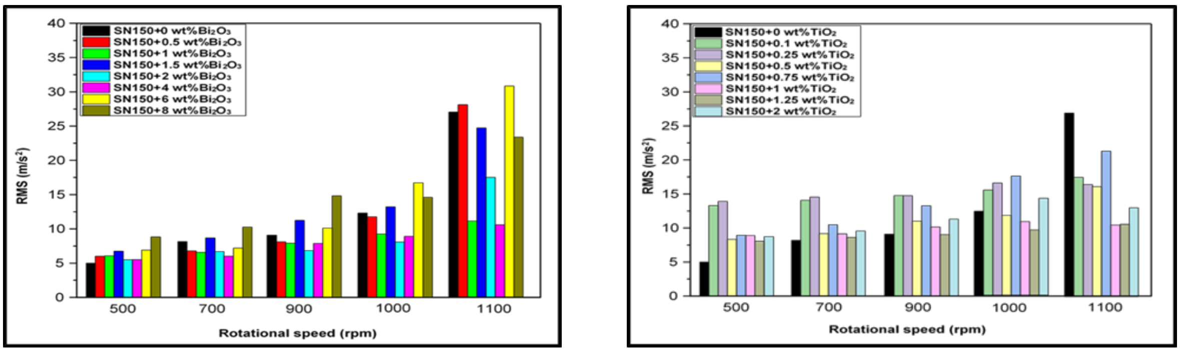
(a) (b)

Figure 6: Variation of RMS with different rotational speeds and concentrations of nano additives at an unbalanced system (r_u=24 mm): (a) $SN150+Bi_2O_3$ and (b) $SN150+TiO_2$



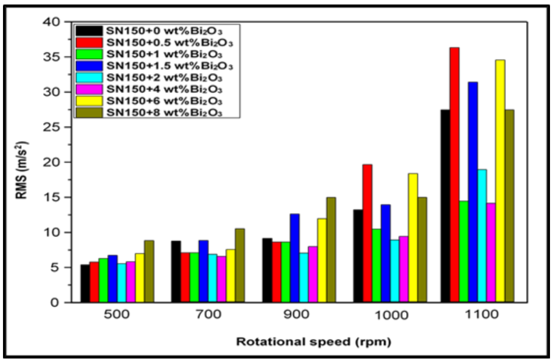
(a) (b)

Figure 7: Variation of RMS with different rotational speeds and concentrations of nano additives at an unbalanced system (r_u=48 mm): (a) $SN150+Bi_2O_3$ and (b) $SN150+TiO_2$

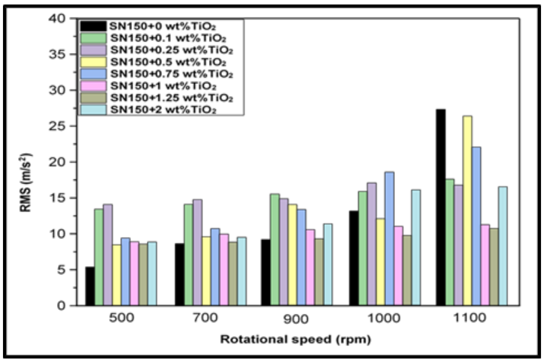


(a) (b)

Figure 8: Variation of RMS with different rotational speeds and concentrations of nano additives at an unbalanced system (r_u=72 mm): (a) $SN150+Bi_2O_3$ and (b) $SN150+TiO_2$



(a)

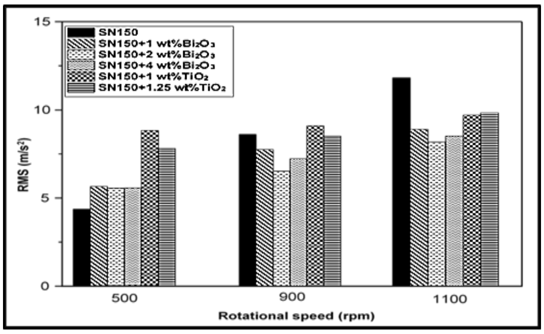


(b)

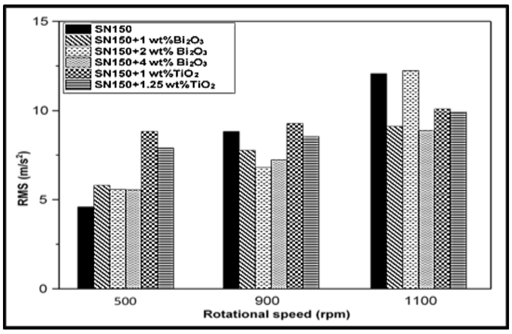
Figure 9: Variation of RMS with different rotational speeds and concentrations of nano additives at an unbalanced system (r_u=96 mm): (a) SN150+Bi_2O_3 and (b) SN150+TiO_2

It was also determined which of the two types of nanoparticles was the best to add to the oil SN150 within the optimal concentrations for each rotational speed and dynamic load in the following Figures (10-a to 10-e).

As it was noticeable that the system was balanced, Bi_2O_3 was better as the rotational speed was increased, as shown in Figure (10-a). By adding an unbalance mass of 10 g at r_u (24 and 48) mm, the effect of Bi_2O_3 remained the best, as shown in Figures (10-b) and (10-c). But when the dynamic load was increased, i.e., by applying an unbalanced mass of 10 g at r_u (72 and 96) mm, TiO_2 performed better than Bi_2O_3, as shown in Figures (10-d) and (10-e).



(a)



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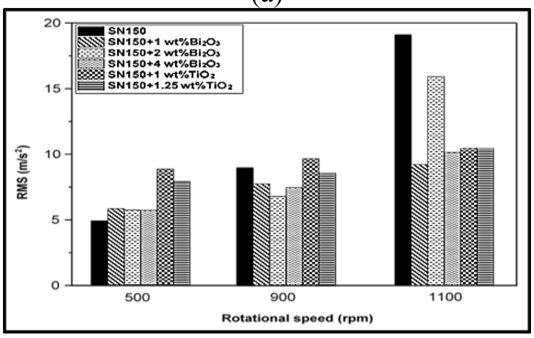
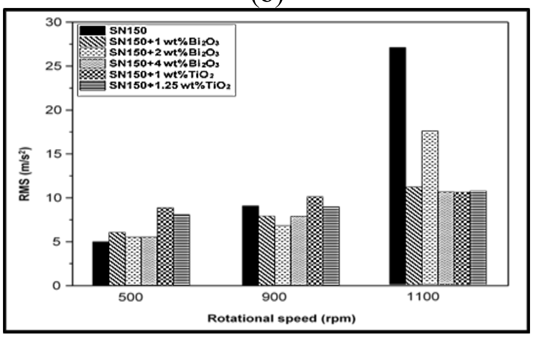
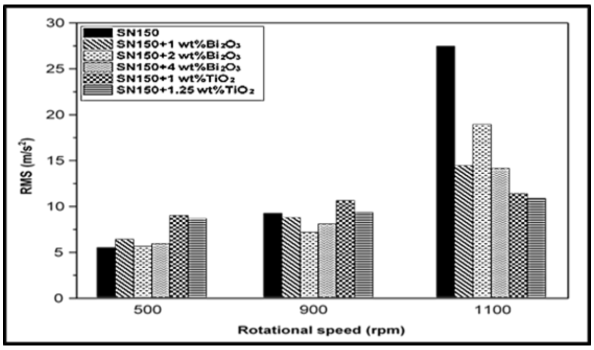


(c)



(d)



(e)

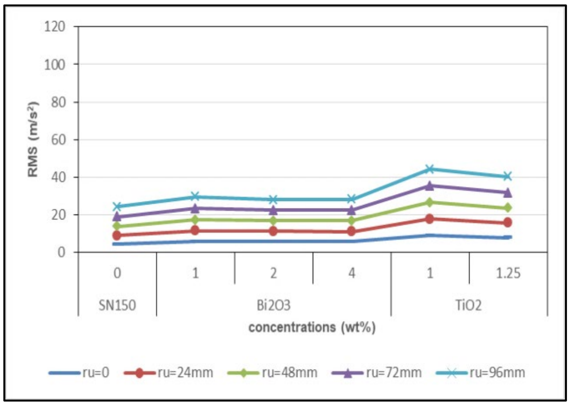
Figure 10: Optimum concentrations of Bi_2O_3 and TiO_2 blended with SN150 at various rotational speeds and dynamic loads of: (a) balanced system, (b) unbalanced system (r_u=24 mm), (c) unbalanced system (r_u=48 mm), (d) unbalanced system (r_u=72 mm), and (e) unbalanced system (r_u=96 mm)

From the previous results, it can be concluded that the use of pure SN150 oil in lubricating the journal bearing was good just for low rotational speed. However, at higher rotor speed, there will be a need to use nano additives with SN150 oil to reduce the RMS value and, consequently, reduce the vibration response of the system.

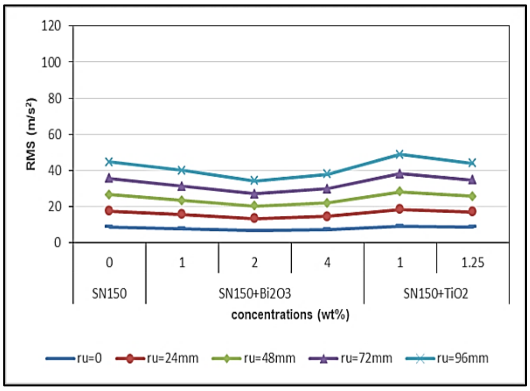
5.2 Comparison of the Influence of Nano Additives Types at Different Rotational Speeds and Dynamic Loads

The following results reveal how the type of nano additives that should be blended with SN150 oil minimizes the vibration response effect of different rotational speeds and dynamic loads.

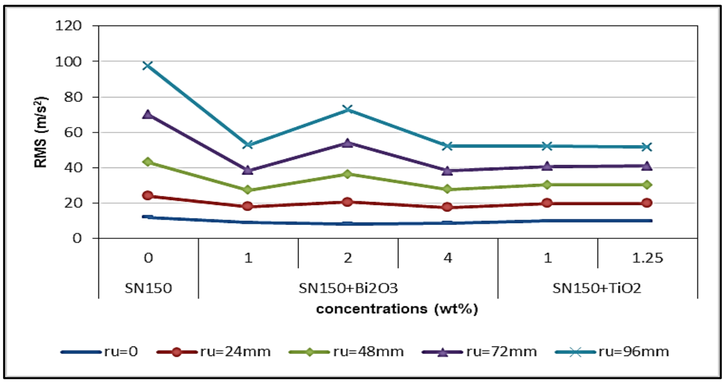
Figure (11-a) manifests that the RMS is still almost constant at 500 rpm when adding less than 4% Bi_2O_3. However, as the speed was increased to 900 rpm, the addition of nano-additives became apparent, particularly when adding Bi_2O_3 with SN150 at all load conditions, as shown in Figure (11-b). When the system was balanced and unbalanced at r_u (24 and 48) mm, the addition of Bi_2O_3 was the best at the whole range of speeds; however, when the system was unbalanced at r_u (72 and 96) mm, the TiO_2 was the preferable choice for the higher speed, Figure (11-c).



(a) 500 rpm



(b) 900 rpm



(c) 1100 rpm

Figure 11: Variation of RMS value under various dynamic loads: (a) 500 rpm, (b) 900 rpm, and (c) 1100 rpm

The type of nano-additives mixed with the base oil affects the vibration response of the system when changing the rotational speed and the dynamic loads applied to the system, as low speeds and low dynamic loads are unaffected by the nano-additives.

The above results are consistent with those of Akbulut et al. [16]. They concluded that nanoparticle concentration in a base oil significantly affects the tribological properties of lubrication systems, with a perfect concentration resulting in the lowest vibration response.

Both Bi_2O_3 and TiO_2 nano-additives have a good effect on the base oil, and the addition of Bi_2O_3 to the oil SN150 leads to an increase in the load-carrying capacity and reduces the wear, as this agrees with [8,17]. However, as indicated in [1], TiO_2 operates better at high rotational speeds and load conditions because the nanoparticles act as a ball bearing between the surfaces and form a protective layer over the surface.

6. Conclusion

In this work, the effects of two nano-additives blending with the base oil SN150 were investigated experimentally, namely Bi_2O_3 with (1, 2, and 4 wt.%) and TiO_2 with (1 and 1.25 wt.%). The experimental work has been carried out by a test rig manufactured using vibration measuring equipment. Then, from the obtained results, the following can be concluded:

1) The optimum concentrations of Bi_2O_3 blended with SN150 oil were (1, 2, and 4 wt.%), where Bi_2O_3 had a good effect on reducing the vibration response at the normal operation condition (balanced system) and the unbalanced system of lower load condition at r_u (24 and 48) mm for a wide range of rotational speeds.
2) The optimum concentrations of TiO_2 blended with SN150 oil were (1 and 1.25 wt. %), where TiO_2 minimized the vibration response only at the high load condition at r_u (72 and 96) mm and the high rotational speed (1100 rpm).
3) Every load condition has its preferable weight percentage of nano additives according to the various forces generated on the bearing.
4) The SN150 oil without nano additives is better for low rotational speed, while it is necessary to add nano additives at high rotational speeds.
5) The reduction in vibration amplitude at several concentrations and increases with others returns to the effect of nano-additives on the oil viscosity and then affects the damping ratio. Because of that, for a specific damping ratio, the amplitude ratio increased with increasing frequency ratio until it reached near the resonance case. After that, the amplitude ratio decreased with the increasing frequency ratio. Also, for a specific excitation frequency, the amplitude will be decreased when the damping ratio is increased.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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