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Design and Testing of a Measurement Device for High-Speed Bearing Evaluation

Michal Duhancik [1,*], Tibor Krenicky [2] and Tomas Coranic [2]

1 Department of Industrial Engineering and Informatics, Faculty of Manufacturing Technologies with a Seat in Presov, Technical University of Kosice, Bayerova 1, 080 01 Presov, Slovakia
2 Department of Design and Monitoring of Technical Systems, Faculty of Manufacturing Technologies with a Seat in Presov, Technical University of Kosice, Bayerova 1, 080 01 Presov, Slovakia; tibor.krenicky@tuke.sk (T.K.); tomas.coranic@tuke.sk (T.C.)
* Correspondence: michal.duhancik@tuke.sk; Tel.: +421-55-602-6315

Abstract: The submitted article focuses on the proposal of a testing device for researching alternative methods of lubricating technical systems, specifically high-speed rolling bearings using lubricants containing nanoparticles. The aim of this research is to verify the functionality of the proposed technical device, whose main task is to ensure the measurement of the functional and operational characteristics of high-speed rolling bearings. The proposed technical device allows us to carry out a series of measurements, primarily for the purpose of selecting specific bearings and secondarily for the purpose of conducting technical diagnostic measurements. The results of these measurements are significant in the selection of suitable nano-particle additives for the lubrication of the tested bearings. The tests was carried out using speeds reaching 110,000 rpm. Methods of monitoring vibrational and acoustic diagnostics were chosen for the analysis of the operational processes of loaded technical systems.

Keywords: technical diagnostics; high-speed rotation; bearings; nanoparticles; lubrication

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1. Introduction

Nanotechnologies enable the manipulation and modeling of substances at the atomic level, allowing the creation of materials with unique structures and improved properties. These materials are subsequently used either independently or in combination with other substances, forming nanocomposites or nanofluids—colloidal liquid or gaseous solutions of nanoparticles. They have found relatively wide-ranging applications in various sectors, including the automotive industry (tires with increased road adhesion and reduced rolling resistance, water-repellent and scratch-resistant car paints, thin-film coatings on windows repelling water and dirt, and motor oils with enhanced lubricating properties), as well as in other areas such as cosmetics (toothpaste, sunscreens with UV filters), the food industry (anticoagulants in food powders), textile manufacturing (fabrics resistant to odors and hydrophobic textile materials), and construction.

Currently, nanotechnology is an intriguing field in lubrication. A significant number of researchers have been exploring the idea of using nanoparticles as anti-friction additives to combat wear. Some potential advantages of using nanoparticles as lubricant additives are cited by Spikes [1]. These include low interaction with other additives, the ability to form a film on various types of surfaces, increased resistance, inertness to other additives, high non-volatility, and resistance to high temperatures. Metallic nanoparticles exhibit excellent chemical and physical properties [2]. Numerous studies have explored the use of various types of metallic nanoparticle additives such as Cu, Fe, Co, Ag, Pd, Ni, or Au as lubricants. The incorporation of these additives into lubricating oils significantly reduces friction and enhances wear resistance [3]. Padgurskas et al. [4] conducted tribological tests with Fe, Cu, and Co nanoparticles added to mineral oil, resulting in a significant reduction in friction and wear, with the best results achieved with Cu nanoparticles. Qiu et al. [5] evaluated the tribological behavior of Ni nanoparticles as additives in lubricating oils and concluded that Ni nanoparticles improve lubricants' frictional properties and extend their lifespan. Maliar and colleagues [6] studied the lubrication, friction, and wear of rapeseed and mineral oils with and without the presence of surface-active iron particles. These authors noted that adding 0.1% by weight of Fe nanoparticles to rapeseed oil reduced the coefficient of friction and wear.

Nanoparticles composed of metal oxides can be made from various materials, including zirconium oxide, titanium oxide, zinc oxide, copper oxide, cerium oxide, aluminum oxide, and iron oxide. Hernández Battez and co-authors [7] discussed the tribological behavior of CuO, ZrO_2, and ZnO nanoparticles as anti-wear additives in polyalphaolefin (PAO6). They concluded that all nanoparticle dispersions can reduce the friction coefficient and enhance the wear resistance properties of the base oil (PAO6). Patil et al. [8] published a review on the tribological properties of several metal oxide nanoparticles, such as CuO, TiO_2, and CeO_2, as anti-friction properties and anti-wear additives. Wu and colleagues [9] examined the tribological behavior of two different lubricants, motor oil and base oil, with added CuO, TiO_2, and nanodiamond nanoparticles. The results obtained by these authors demonstrated that all nanoadditives exhibited excellent friction reduction and wear reduction, particularly with CuO. Ingole et al. [10] investigated the effects of titanium oxide nanoparticles on the tribological behavior of mineral oil. An increase in the friction coefficient was observed in comparison to the base oil for all compositions that used commercially available TiO_2 nanoparticles.

The use of nanoparticles as additives in lubricants can enhance the performance of lubricants in various applications, such as the automotive industry, aerospace industry, and heavy machinery industry. Nanoparticles can help to increase wear resistance, reduce friction, and improve lubricity. A current trend in the industrial processing of oil and lubricant manufacturing is the shift towards the development and utilization of alternative fuels from renewable sources and the creation of environmentally friendly and easily degradable lubricants and additives [11,12].

Organic and organometallic compounds, such as zinc dialkyl (diaryl) dithiophosphate (ZDDP), tricresyl phosphate (TCP), trixylyl phosphate (TXP), and dilauryl phosphate, are used due to their excellent properties as extreme-pressure/anti-wear (EP/AW) additives in motor and industrial oils. Typically, these compounds incorporate one or more polar groups into their molecular structure, with heteroatoms such as sulfur, phosphorus, or chlorine. However, due to environmental considerations, the use of these effective additives is becoming increasingly restricted, mainly due to the presence of the aforementioned heteroatoms. Attention in the development of new additives for lubricants is currently focused on the development and utilization of new environmentally friendly compounds. A promising and novel area in the development of EP/AW additives involves the use of inorganic nanoparticles. With the discovery of the unique properties of fullerenes and nanotubes, scientists' interest in researching nanoparticles and nanocomposite materials has rapidly increased. Nanoparticles and nanotechnologies find applications in almost all scientific fields, including tribology and tribochemistry [13].

While research on the use of nanoparticles has experienced significant growth in recent years, the use of nanoparticles in industrial lubricants has been practiced for over 50 years [14]. Surface-modified $CaCO_3$ nanoparticles are used as detergent additives in oils and are a common component of what is known as an additive package. In oils, they primarily serve a detergent function and are carriers of what's called alkaline reserve.

Research on nanoparticles in tribology is mainly focused on testing their high-pressure and anti-wear properties. More than 50 different types of inorganic compounds and elements have been experimentally tested so far [15], and some of them have proven to be excellent EP/AW additives in these experiments. The results of some studies [16,17] have even demonstrated better EP/AW properties for inorganic nanoparticles than the standard ZDDP-based additives used today. However, the disadvantage of most inorganic substances can be their insolubility and inability to form a stable dispersion in the base oil. Therefore, it is usually necessary to modify the nanoparticles' surfaces before use. Surface modifications of nanoparticles are achieved using suitable coatings or the addition of appropriate dispersing agents.

Several diagnostic methods can be employed to assess the impact of nanoparticle additives on the functional and operational characteristics of rolling bearings. Vibration measurement is a common method for diagnosing rotating machinery and is also the primary method for bearing diagnostics [18]. Vibrations are typically measured in the range of 1 Hz to 25 kHz. Frequencies lower than 1 Hz or higher than 25 kHz are also used for diagnostics. For measuring vibrations higher than 1 kHz, piezoelectric accelerometers are the most suitable. They typically have a sensing frequency range from approximately 1 Hz to 10 kHz. Velocity sensors and position sensors are also used for vibration measurement. Position sensors are based on eddy current sensing and are primarily used for lower-frequency vibrations [19].

Vibrations in bearings can have several causes. They can be induced by external forces, such as the centrifugal force caused by an unbalanced rotating shaft. Bearing vibrations can also be caused by inherent vibrations, which are determined by the bearing's geometry and material properties, defined in terms of stiffness and damping. Elastic deformations of components also contribute to the generation of vibrations. The most common cause of vibrations is related to the kinematic motion of individual parts and imperfect dimensions. Vibrations can also be caused by damage to individual bearing components.

In addition to direct measurements, there are diagnostic methods for analyzing the used lubricant. Tribodiagnostics is a non-invasive method of technical diagnostics that uses the lubricant as a medium to gather information about changes in frictional interfaces. The result of these measurements provides information about the condition of foreign substances in the lubricant. With tribodiagnostics, the aging of the oil during operation was monitored and we assessed how changes in the intensity and degree of oil degradation affect its functional properties and, consequently, its ability to ensure trouble-free operation [20].

2. Materials and Methods

Several existing studies point to the positive impact of using nanoparticles on high-speed bearings in terms of their performance. Significant results have been obtained by various researchers at different times. Gundarneeya in 2015 discovered that adding nanoparticles to the lubricating oil leads to increased viscosity, improved friction coefficient, and better pressure distribution, subsequently increasing the load-bearing capacity of sliding bearings. These findings demonstrate the potential for a significant improvement in bearing performance when using nanoparticulate lubricants [21].

Lijewski, in 2014, focused on the development of nanocomposites for self-lubricating bearings and achieved success by using solid lubricating nanoparticles to reduce friction. His work opened the path to utilizing modern materials and technologies to create self-maintaining bearings that reduce friction [22].

Zhang in 2015 proposed a revolutionary approach to creating nano-bearings through physical adsorption by confining the oil to a solid surface. This innovative method demonstrated a significant load-bearing capacity in thin lubricating film layers, offering new possibilities for effective solutions in high-speed and low-friction applications [23].

Tuzun in 1995 engaged in simulations of various graphite bearing models and explored their frictional properties. His work emphasized the potential of molecular bearings in nanodevices and their ability to carry loads, which is crucial in microscopic technology [24].

Overall, these studies provide evidence that the incorporation of nanoparticles into high-speed bearings can significantly enhance lubrication efficiency, reduce friction, and improve the properties of these bearings.

To gain deeper and relevant insights into the impact of nanoparticle additives on the physical properties of rolling bearings, an experiment on a specific type of bearing—TX72-

06 D36—was conducted (Figure 1). We pressed two pieces of non-dismantlable bearings onto the shaft and these bearings are known for their ability to operate at high speeds, which is significant in various industries. One of the industries where these bearings are found is the textile industry, specifically in rotor spinning machines [25].

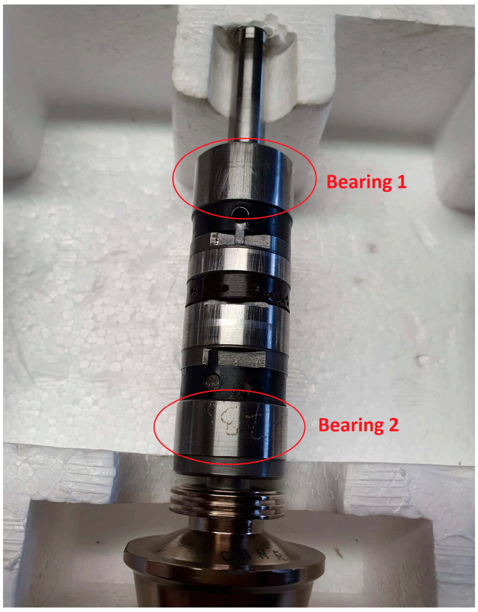

Figure 1. Tested high-speed bearing TX72-06.

Rolling bearings are a crucial component in textile machines, and their development is closely linked to finding the best ways to store and utilize the most critical components in textile machines. Their use, however, is not limited to just textile machines, as they find applications in instrument technology where the properties offered by these bearings are required. As seen in Figure 2, special double-row ball bearings designed for textile machinery are engineered and dimensioned to withstand the high rotational frequencies commonly found in the textile industry. They are known for their high dimensional precision and reliable operation. These characteristics ensure their significant utility of using rolling bearings in these applications.

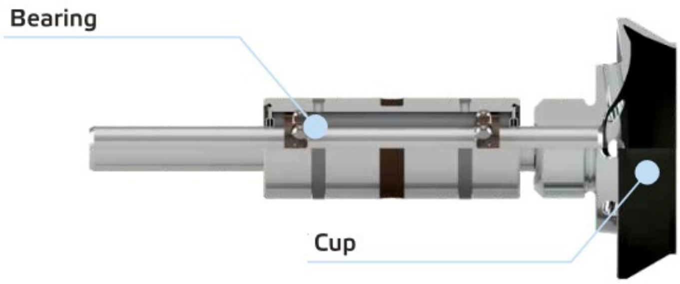

Figure 2. Model of the tested bearing.

Performing experiments on these specific bearings can provide crucial insights into how nano-particle additives affect their performance and longevity. These findings can have significant implications for improving the efficiency and reliability of rolling bearings in industrial applications, where high speeds and precision are critical for achieving optimal results. Understanding how nano-particle additives influence the performance of such bearings can lead to advancements in their design and maintenance, potentially extending their lifespan and reducing maintenance costs, all of which are essential in industries relying on high-speed and high-precision machinery.

Measurement Stand

To ensure optimal and precise working conditions for complex testing, a special measurement stand was designed and constructed. This stand became a key tool in this research because it allowed us to conduct detailed tests aimed at understanding the impact of nanoparticle additives on the physical properties of rolling bearings. The main goal was to gain thorough insights into these properties and their changes through the use of nanoparticle additives [26].

The measurement stand was designed with careful consideration of the requirements of research and was inspired by equipment used in the textile industry (Figure 3). This means that the inspiration came from existing technologies and was adapted to the requirements of the described experiment. This solution was suitable because the textile industry is an area where rolling bearings are widely used and exposed to various operational conditions.

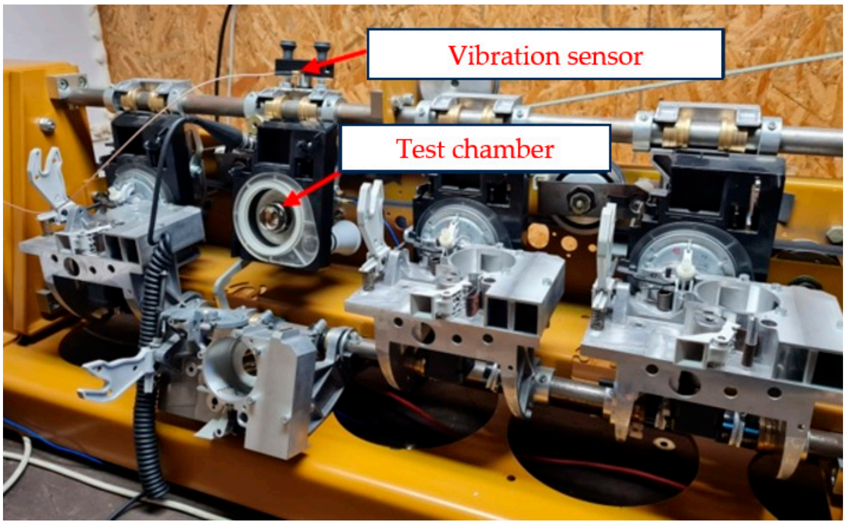

Figure 3. Measurement stand for testing textile bearings.

The created measurement stand consists of four separate chambers, which are used to heat rolling bearings to their operating temperature. This is crucial because temperature significantly influences the behavior and physical properties of bearings. One of these chambers is used to measure the monitored parameters.

The control of the rotational speed of the tested bearing is provided by an electric motor. In the case of the created design, an asynchronous electric motor controlled by a frequency converter was selected [27]. To achieve the desired rotational speed, scalar control with feedback based on speed sensing was chosen. As is well known, this type of closed-loop control (Figure 4) is a reliable solution for starting asynchronous rotating machines and maintaining their speed [28].

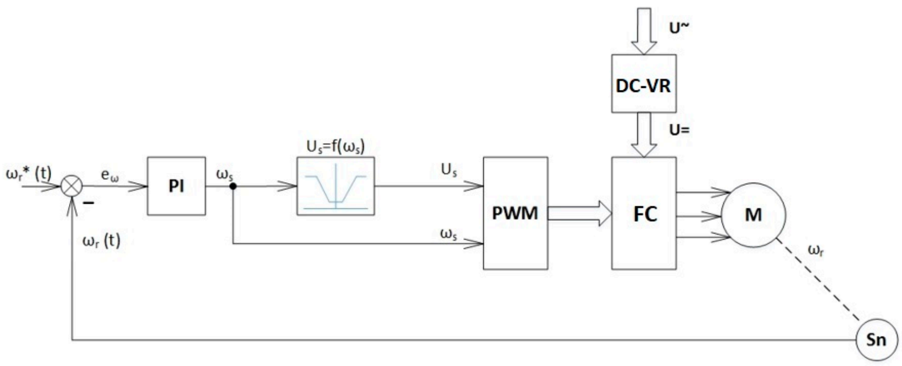

Figure 4. Block diagram of scalar control of an asynchronous motor.

The identification of the actual rotational speeds of the bearings was carried out using an optical probe (Figure 5) by sensing the speeds of the rotating mechanism coupled to the shaft of the measured bearing. This choice allowed us to set the speeds of the tested bearings precisely and variably, which was essential for the research. By adjusting the speeds, various operating conditions could be simulated and the impact of nano-particle additives at different speeds on the operational characteristics of the rolling bearings could be verified.

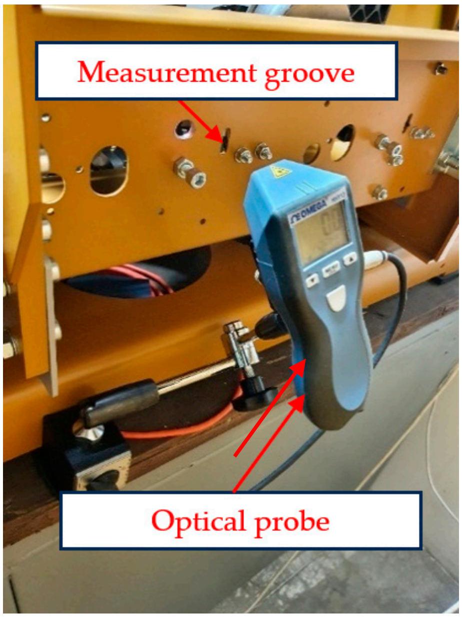

Figure 5. Placement of the rotation measurement probe.

The following equipment for data collection was used:

- A vibration sensor (Figure 6—left) with a range up to 10 kHz labeled as MTN/2200S. It is a universal constant current accelerometer with a side input and an isolated AC output, made from durable stainless steel for long-term vibration analysis in harsh environments. A vibration sensor (Figure 7—right) with a range up to 60 kHz was labeled as 352A60.

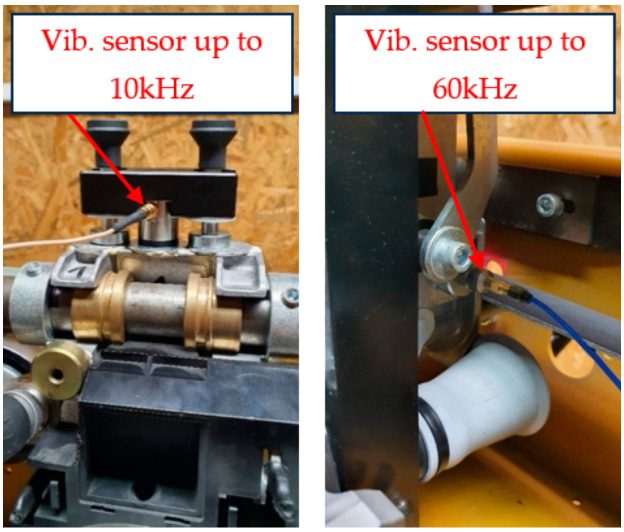

Figure 6. Placement of the vibration sensor for up to 10 kHz on the test stand (**left**); placement of the vibration sensor for up to 60 kHz (**right**).

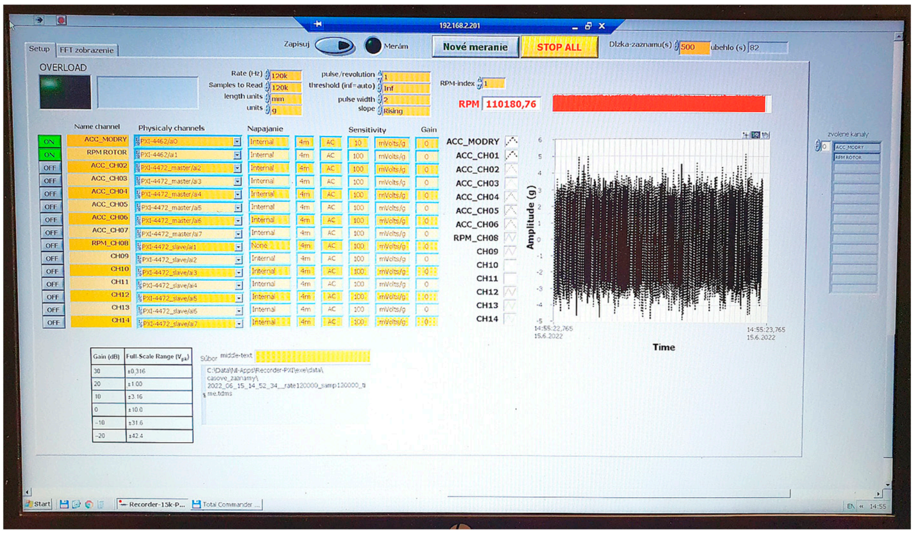

Figure 7. Software front panel developed in NI LabVIEW 2021–Settings and analysis screen.

- A portable data collector/FFT analyzer called Microlog GX, designed for monitoring or analyzing vibrations with recording capability. It allows for easy condition monitoring of equipment in industries such as paper, energy, petrochemical, and others. It includes vibration signals and process variables in a range from 10 cycles per minute (0.16 Hz) to 2,400,000 cycles per minute (40 kHz).
- Specialized software for collecting and analyzing dynamic data on the LabView platform (Figure 7).

3. Results

Measuring the dynamic response of the bearing-system environment through vibrations with frequencies up to 60 kHz is a significant tool in the field of diagnostics and monitoring the condition of rolling bearings and related systems. These vibrations serve to provide information about various issues such as bearing wear, inadequate lubrication, misalignment, and imbalance. Analyzing the frequency spectrum of these vibrations allows for the identification of characteristic components for different types of faults and problems.

Measuring dynamic responses has become an integral part of predictive maintenance, serving as an early warning system for potential faults and issues and thereby contributing to increased safety and minimized downtime in industrial processes. Additionally, it has a significant impact on quality control in manufacturing and the validation of new designs.

The main goal was to conduct preliminary measurements to test the constructed stand and verify the measurability of the dynamic operational characteristics of selected bearings. In this specific case of a measurement, the overall dynamic response of the bearing-system was monitored using vibrations up to 60 kHz. This measurement was performed while increasing the speed of the tested roller bearings, with the speeds ranging from 70,000 to 110,000 rpm. The collected data were then recorded and processed for further analysis.

When selecting roller bearings for vibration measurements, it is essential to consider several factors, such as the rotational speed of the bearings, the load on the bearings, and the vibration frequency. Textile bearings tend to exhibit a significant range of vibration values, which poses a challenge when choosing suitable samples for testing. To ensure precise and comparable measurements, a "sorting" measurement method was applied to 25 different bearings while gradually increasing the speed (Figure 8).

The selection of suitable bearings for experiment was carefully considered, taking vibration alarms into account. For textile bearings, two alarms were set:

1. Alarm 1—Warning, marked in yellow,
2. Alarm 2—Danger, marked in red.

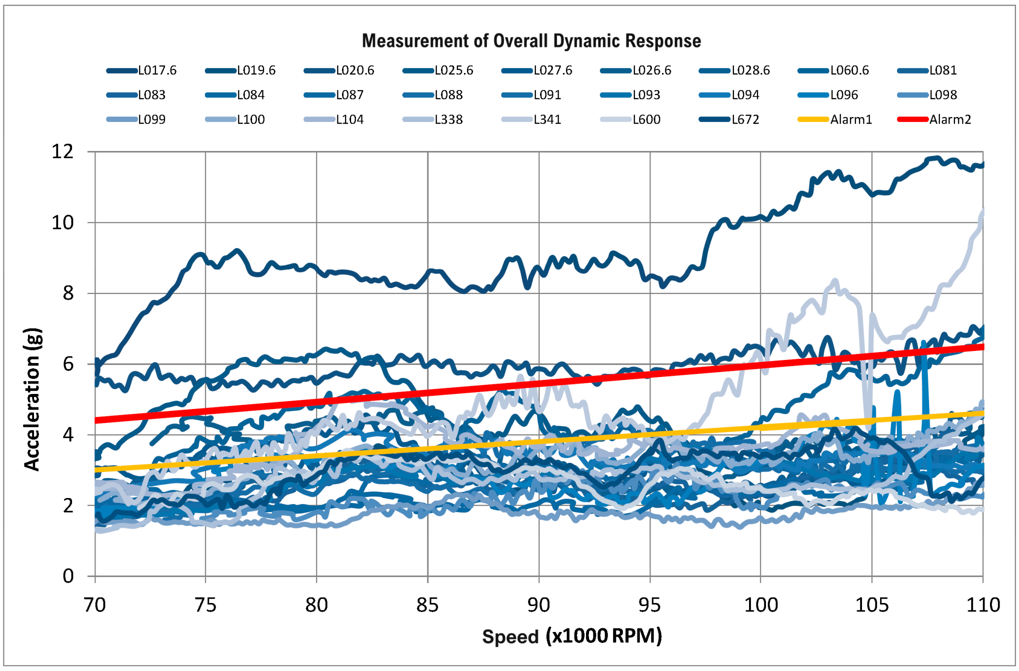

Figure 8. Comparison of vibrations of all bearings during bearing sorting.

Differential measurement was conducted on 25 bearings of the same type and dimensions. In order to select suitable bearings for nanoadditive tests, vibration characteristic measurements were performed for all available bearings. Based on these measured data, 16 bearings with lower vibration values were chosen and are shown in Table 1.

Table 1. Classification breakdown of the tested bearings.

ID	Bearing Number	Condition	Group
1	L017.6	A2	x
2	L019.6	A1	A
3	L020.6	A2	x
4	L025.6	A2	x
5	L026.6	A1	A
6	L027.6	A1	A
7	L028.6	A1	A
8	L060.6	A2	x
9	L081	OK	A
10	L083	OK	A
11	L084	OK	A
12	L087	OK	A
13	L088	OK	B
14	L091	A1	B
15	L093	OK	B
16	L094	A1	B
17	L096	A2	x
18	L098	OK	B
19	L099	OK	B
20	L100	A1	B
21	L104	A2	x
22	L338	A1	B
23	L341	A2	x
24	L600	A1	x
25	L672	A1	x

Then, these selected bearings were divided into two groups:

- Group A: It included 8 bearings that were intended for testing with the original lubricant.
- Group B: It included 8 bearings that were intended for testing with lubricant containing nanoadditives.

This thorough process of selecting suitable bearings and categorizing them into these groups was a fundamental element of this paper's research methodology and contributed to the accuracy and validity of the tests and subsequent results.

3.1. Measuring Dynamic Response

The next step within the experiment was to conduct a comprehensive measurement of the dynamic response to the bearings included in Group A (Figure 9) and Group B (Figure 10). This step was carried out with a wider range of speeds, specifically speeds ranging from 40,000 rpm to 110,000 rpm. The objective was to obtain more comprehensive and detailed data regarding the dynamic operational characteristics of these bearings over a wider range of speeds.

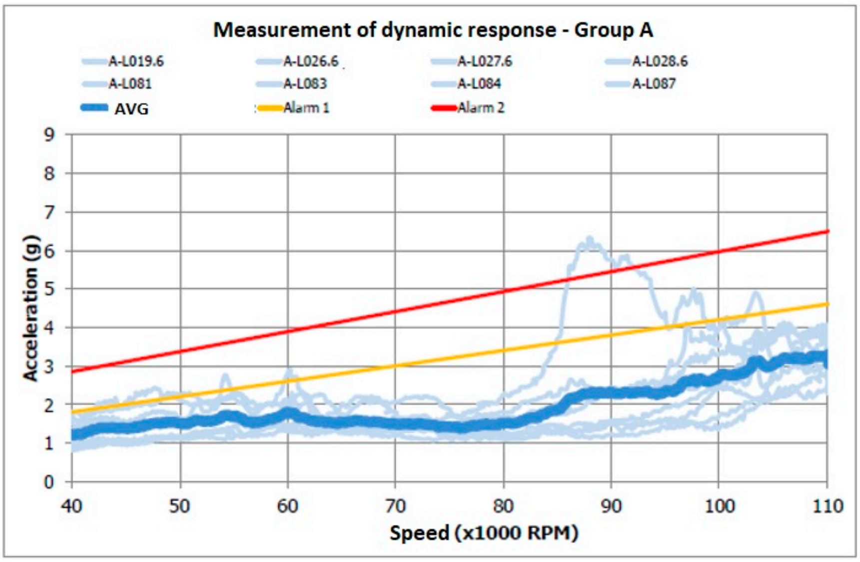

Figure 9. Graphical representation of the dynamic response of bearings in Group A.

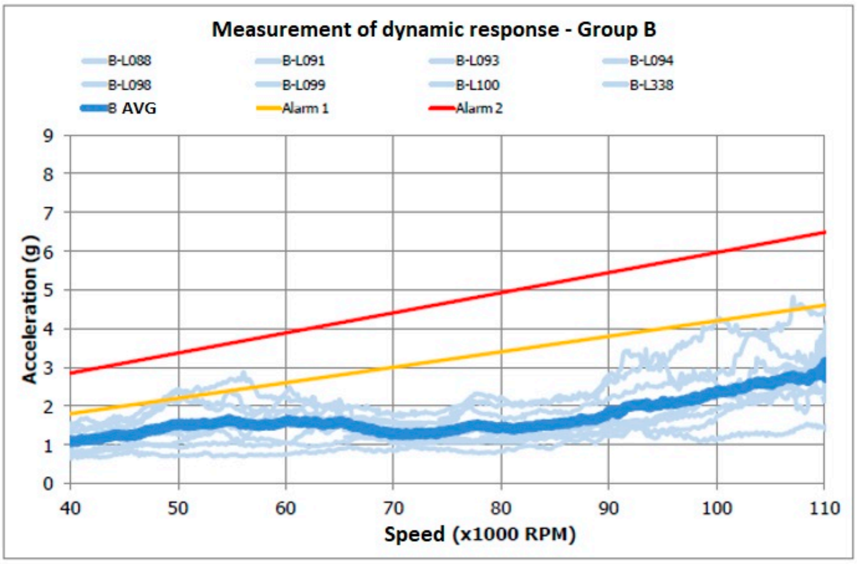

Figure 10. Graphical representation of the dynamic response of bearings in Group B.

From the obtained measurements, we averaged values of dynamic responses for each group of bearings. These average values were recorded during the ramp-up process, which reached a maximum speed of 110,000 rpm, and were represented in graphical dependencies. The dynamic responses were marked on these graphical dependencies with a thick blue line, allowing for a clear observation of the development of these characteristics as the speed increased.

As can be seen from the collected data, the used bearings exhibit almost identical characteristics. This ensures the possibility of comparing the impact of re-lubrication on these bearings. The obtained characteristics resulting from this measurement have significant applications for future analysis and the comparison of the effects of different lubricants on the tested bearings. These data serve as reference information for analyzing the impact of re-lubrication on bearings with various lubricants and providing detailed information about the dynamic properties of the bearings depending on their rotational speeds.

3.2. Measurement of High-Frequency Vibrations

Measurement of high-frequency vibrations is the process of obtaining quantitative data on vibrations that have high frequencies. Measuring high-frequency vibrations is important for diagnosing faults, monitoring conditions, and preventing failures in these systems.

Measurement of high-frequency vibrations is one of the subsequent stages of the overall measurement and is carried out at 110,000 RPM. These are the maximum speeds at which the measurement is conducted. This value is not common in the use of bearings, but it allows us to test the bearings under increased load. At steady high speeds (110,000 RPM of the rotor), further measurements were carried out to evaluate additional parameters.

Were measured:

- A total of 5 different high-frequency parameters commonly used for assessing the condition of textile bearings. From these, the overall average parameter AVG5 (g) was calculated.
- Acoustic emissions (AE).

Each bearing was measured at stable speeds twice: once when reaching the desired speed of 110,000 RPM, and then after another continuous 5 min of operation to assess any changes in the operational parameters of the bearings under extended load.

During the measurement of high-frequency vibrations, values were recorded and documented, subsequently processed, and included in Tables 2 and 3. These tables contain detailed data on the dynamic responses of the bearings to high-frequency vibrations under the same settings and conditions. Based on this measured data, the average values of these dynamic responses were calculated, which serve as the basis for further analysis and comparisons.

Table 2. High-frequency vibrations—parameter AVG5 (g)—Group A.

Bearing	L019.6	L026.6	L027.6	L028.6	L081	L083	L084	L087	Avg.
AVG5 110 k rpm (0 min)	3.68	2.08	1.98	3.87	2.61	2.79	1.44	1.97	2.55
110 k rpm (5 min)	3.82	3.51	2.24	4.28	1.69	2.82	1.78	2.39	2.82

Table 3. High-frequency vibrations—parameter AVG5 (g)—Group B.

Bearing	L088	L091	L093	L094	L098	L099	L100	L338	Avg.
AVG5 110 k rpm (0 min)	1.74	2.95	3.01	2.54	1.87	1.69	2.51	2.61	2.37
110 k rpm (5 min)	2.26	2.12	3.15	3.16	2.36	2.17	1.55	3.28	2.51

The graphical representation of these measured values and average characteristics was performed in the form of a bar chart shown in Figure 11 for group A and in Figure 12 for group B. This chart clearly illustrates the mutual comparison and displays the differences in dynamic responses between different bearings. These visually presented data serve as an important tool for obtaining a better understanding of the impact of various lubricants on the dynamic characteristics of bearings.

$$\overline{AVGS_{A11}} = \frac{\sum_{i=1}^{n} AVGS_{A11i}}{n} = \frac{3.68 + 2.08 + 1.98 + 3.87 + 2.61 + 2.79 + 1.44 + 1.97}{8} = 2.55 \quad (1)$$

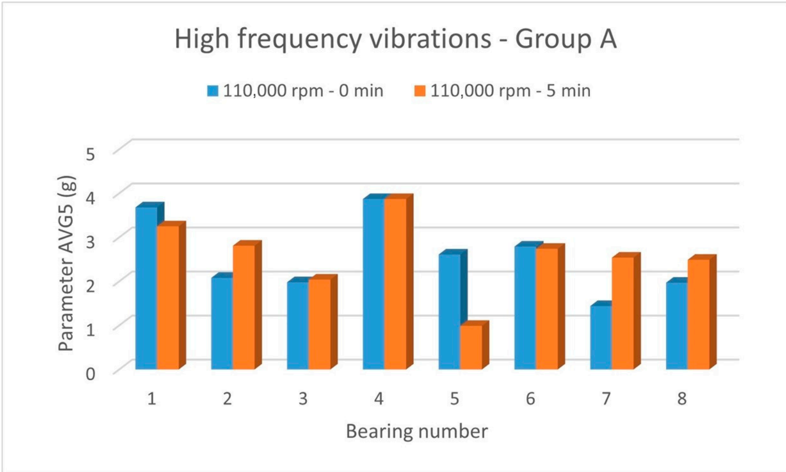

Figure 11. Graphical representation of high-frequency vibrations of bearings at 110,000 rpm and after 5 min at 110,000 rpm—Group A.

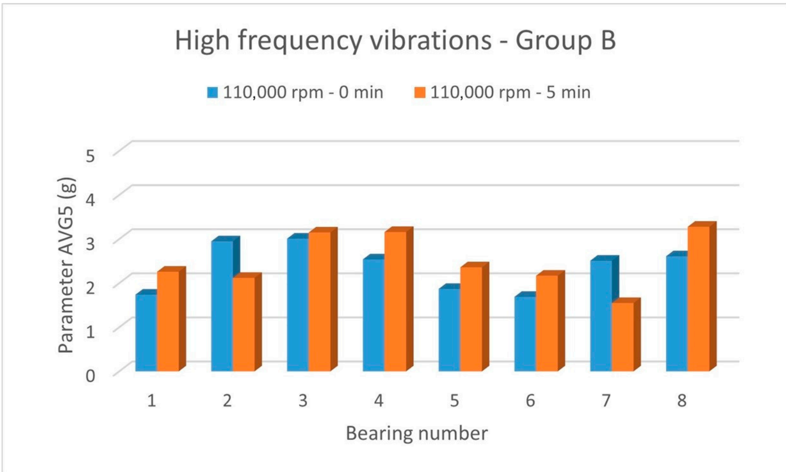

Figure 12. Graphical representation of high-frequency vibrations of bearings at 110,000 rpm and after 5 min at 110,000 rpm—Group B.

These measured values and their graphical representations play key roles in the analysis of the impact of relubrication with the original lubricant and the lubricant with the addition of nanoparticle additives. These data allow us to quantitatively compare the effects of these changes in terms pf the impact of lubricant configuration on dynamic responses and contribute to broader research results analysis.

Similarly, the impact of relubrication upon reaching 110,000 rpm (Figure 13) and after 5 min of operation at 110,000 rpm (Figure 14) were analyzed using FFP (fast Fourier transform) spectra. Frequency analysis (FFP) is an important tool in the diagnosis and condition monitoring of bearings. This analysis focuses on processing the vibrations generated by the bearings and allows for the identification of various problems and faults that may occur in the bearings. It is possible to detect the impact of relubrication on suppressing these negative anomalies in the tested bearings extracted from the analyzed data.

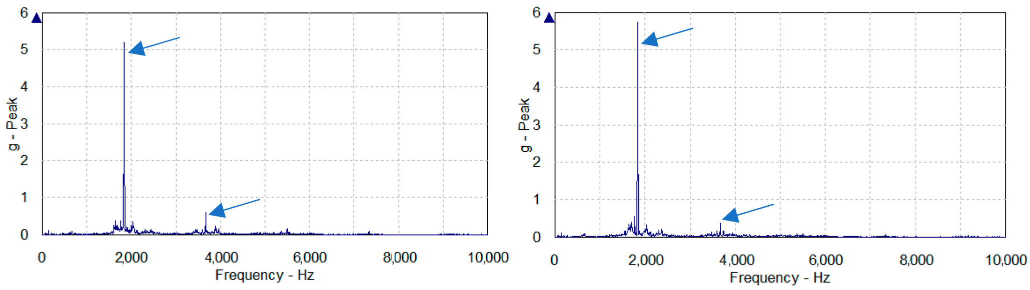

Figure 13. Bearing L027.6, high-frequency vibrations—FFT spectrum of Group A before relubrication upon reaching 110,000 RPM (**left**), after 5 min of operation at 110,000 RPM (**right**).

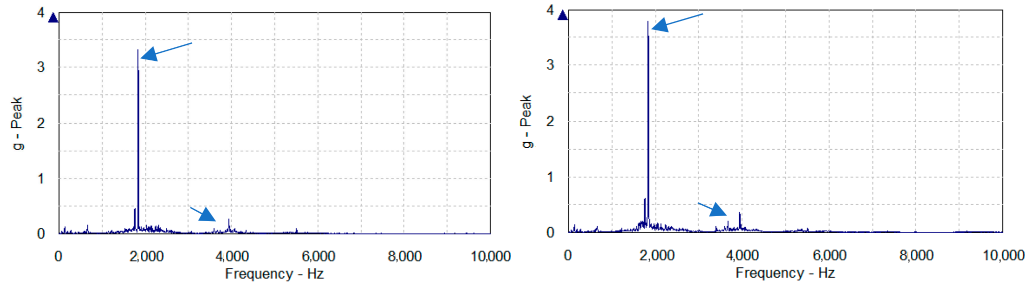

Figure 14. Bearing L093, high-frequency vibrations—FFT spectrum of Group B before relubrication: upon reaching 110,000 RPM (**left**); after 5 min of operation at 110,000 RPM (**right**).

The measured frequency characteristics clearly show that the most dominant peak for the tested bearing L027.6 in both cases is 1.83 kHz, which corresponds to a shaft rota-tional speed of 110,000 RPM. A distinct second harmonic is indicated by the arrow at about 3.67 kHz with a relatively small amplitude. Thus, its presence was not a reason for further diagnostics of its cause. After applying the lubricant, it is possible to monitor whether there have been any changes in these frequency characteristics or if new harmonics have emerged that might impact the bearing's performance.

3.3. Measurement of Acoustic Emission

Measurement of acoustic emission is a technique used to capture, analyze, and interpret sounds generated by objects or systems. This method is based on the idea that materials, structures, or devices emit sounds as a result of internal processes or interaction with the environment. Measurement of acoustic emission is often used for diagnosing, monitoring, and assessing the condition of materials, structures, and mechanical devices.

To investigate the acoustic emission of rolling bearings, measurements under the same conditions were conducted and at the same time intervals as the measurements of high-frequency vibrations. Two tables of values were created, one for reaching 110,000 rpm (Table 4) and the other for 5 min of operation at 110,000 rpm (Table 5).

Table 4. AE—Group A.

	L019.6	L026.6	L027.6	L028.6	L081	L083	L084	L087	Avg.
110 k rpm (0 min)	104.5	107.2	107.9	100.9	103.9	105.5	101.2	100.8	103.99
110 k rpm (5 min)	104.8	104.6	105.9	102.1	105.2	106.9	100.3	102.1	103.99

Table 5. AE—Group B.

	L088	L091	L093	L094	L098	L099	L100	L338	Avg.
110 k rpm (0 min)	102.8	102.4	109.7	110.1	109.7	103.9	111.6	105.9	103.99
110 k rpm (5 min)	101.4	102.9	110.1	109.2	108.2	103.9	110.8	106.2	106.21

Based on the measured values, graphical representations were created (Figures 15 and 16) for a better illustration of changes in the acoustic emission of the tested bearings in both time intervals. These data are crucial for assessing the overall impact of re-lubrication with nano-particle-based lubricants on acoustic emission and its potential effects on the operational characteristics of rolling bearings. With this data, it is possible to evaluate whether re-lubrication with nano-particle-based lubricants is suitable and effective in achieving the desired results in the field of rolling bearing acoustic emission.

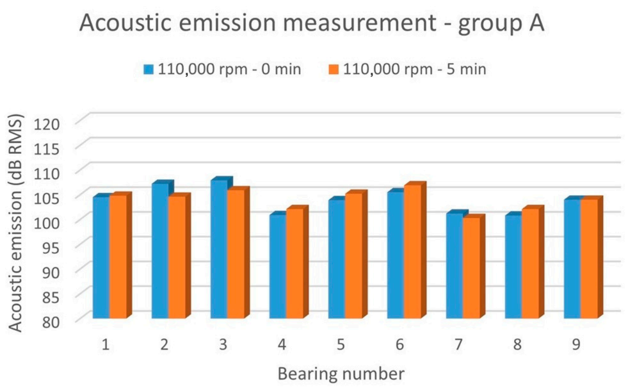

Figure 15. Graphical representation of acoustic emissions of bearings at 110,000 rpm and after 5 min at 110,000 rpm—Group A.

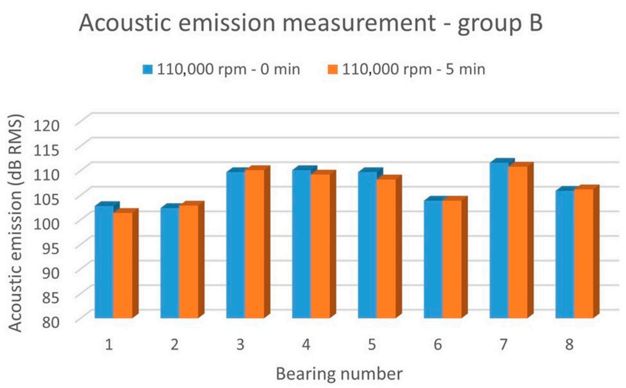

Figure 16. Graphical representation of acoustic emissions of bearings at 110,000 rpm and after 5 min at 110,000 rpm—Group B.

On the selected bearings from Group A and B, specifically bearing L027.6 and L093, the FFT method was used (Figures 17 and 18) to analyze the frequency spectrum of acoustic emission. The goal is to determine and compare the impact of adding nano-particle-based additives to the lubricant on this spectrum. Once again, the test is conducted for both cases, that is, for reaching the desired speed of 110,000 RPM and after 5 min of operation at the same speed.

Fourier analysis was conducted on selected bearings from Group A and Group B to provide a more comprehensive evaluation of the impact of nano-particle additives compared to lubrication with the original lubricant.

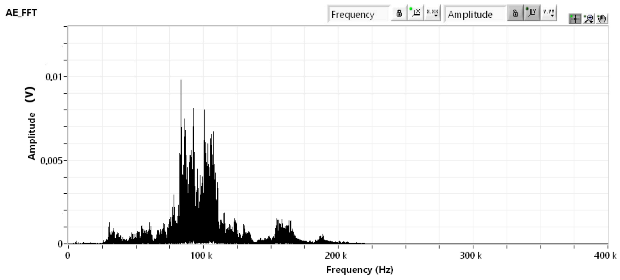

Figure 17. Bearing L027.6, acoustic emissions—FFT spectrum of Group A before relubrication: upon reaching 110,000 RPM (**left**); after 5 min of operation at 110,000 RPM (**right**).

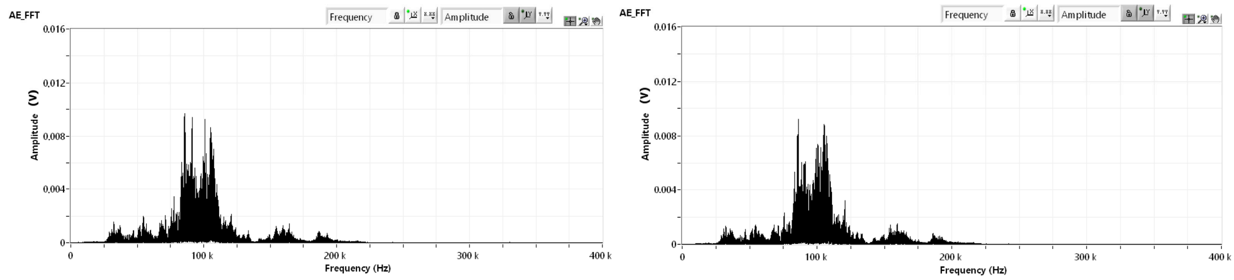

Figure 18. Bearing L093, acoustic emissions—FFT spectrum of Group B before relubrication: upon reaching 110,000 RPM (**left**); after 5 min of operation at 110,000 RPM (**right**).

The determination of the frequency spectra of selected bearings can provide crucial information about the impact of lubrication with modified lubricant. A decrease in significant amplitudes in the resonance frequency ranges can be expected. This should be verified by applying the lubricant and conducting repeated tests on the selected bearings.

4. Conclusions

The presented contribution is a fundamental segment of a research project, focused on the design and implementation of a measuring and testing device to assess the impact of nanoparticles on the functional properties of rolling bearings at high speeds.

The objective of the measurements is to empirically evaluate the influence of nano additives on the operational parameters of bearings. The research analyzes how nanoparticles affect bearing operation, utilizing technical measurements, and assessing changes in vibrations in two groups of bearings:

Group A: 8 bearings tested with the original lubricant.

Group B: 8 bearings tested with lubricant containing nano additives.

Groups are formed based on initial measurements of dynamic responses, identifying bearings with significant anomalies. Tests gradually increase from 70,000 RPM to 110,000 RPM. Selected bearings undergo load tests and measurements of operational properties.

Dynamic response measurements within the speed range from 40,000 RPM to 110,000 RPM enable the detection of characteristic changes due to lubrication with original and modified lubricants containing nanoparticles. High-frequency characteristic measurements at 110,000 RPM and, after 5 min of continuous operation, allow us to compare lubrication effects on bearings' vibrations under stable conditions and after 5 min of operation. FFT analysis provides an additional indicator in high-frequency vibration analysis.

As a concluding diagnostic method, acoustic emission measurement, a common approach in diagnosing the operational behavior of rolling bearings, is implemented. Evaluations are conducted at 110,000 RPM and after five minutes of continuous operation.

The subsequent phase involves identifying and preparing suitable nanoparticles for the lubricant in Group B, considering their size, shape, and chemical properties for optimal application in this specific research context.

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