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Assessment of the Impact of 3D Printed Water-lubricated Cutless Bearings Material on Vibration Parameters

Jędrzej Blaut*

Abstract. The main purpose of the research was to determine the possibilities and experimentally verify the benefits of using thermoplastic materials in a cutless plain bearing. The tested bearings were subjected to equal loads and rotational speeds, using water as the lubricant. Analysis showed that they achieved the best vibration damping at lower speeds, between 600 and 1100 RPM. Comparative studies of bearings made of different materials, such as available on the market bearings made of rubber, bearings printed with a 3D printer from PETG, PLA, ABS or Tribo filament materials, revealed differences in their vibration damping ability and operational stability. Conclusions from the study suggest that higher vibration acceleration may increase the radius of the trajectory, which may affect the function and performance of the bearings. The importance of the operational stability of water-lubricated plain bearings cannot be assessed solely on the basis of the RMS of vibration acceleration or trajectory radius. Both of these parameters are crucial from the user's point of view, especially in the context of various applications such as electric boats.

Keywords: stability of journal bearing, water-lubrificated plain bearings, cutless bearing, bearings with multiple axial grooves, 3D printing, electric boat, cutlass bearing material decision-making

Mathematics Subject Classification: 93E99

JEL Classification: D81, D24, L16

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1. INTRODUCTION

The advancement of electromobility in Europe is pivotal for the future of the marine craft industry, and the use of new thermoplastic materials is introducing innovations

*AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Poland, Krakow, e-mail: blaut@agh.edu.pl

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that have the potential to revolutionize these systems. This trend has the potential to encourage a shift from traditional propulsion solutions towards cleaner and more technologically advanced systems in marine vessels. The current transition plays an important role in reducing the negative impact on marine ecosystems and increasing the energy efficiency of these vessels.

Electric boats have significantly lower noise levels compared to units powered by conventional internal combustion engines. Therefore, it becomes important to use quiet stern bearings to reduce the noise generated by the rotating propeller, which has often been downplayed in boats with internal combustion engines. In addition, these specialized silent bearings enhance reliability by minimizing wear and tear and the risk of mechanical failure in the propulsion structure of electric boats.

Innovative thermoplastic materials and advancements in 3D printing technology offer new possibilities for the development of bearings (Valino et al., 2019). The transition of technology from hobbyist applications to industrial use enables the production of advanced components, including bearings, which can be optimized for performance, durability, and noise reduction. The use of 3D printing in the marine industry allows for rapid prototyping and the production of custom, high-quality parts from advanced materials, which is critical to improving the efficiency, cost savings and energy performance of marine propulsion systems. This synergy between new thermoplastic materials and advanced manufacturing methods such as 3D printing plays an important role in creating more efficient and environmentally friendly solutions for the future of electromobility in the marine sector.

2. WATER-LUBRICATED CUTLESS TYPE PLAIN BEARING APPLICATION IN MARITIME TRANSPORT

Cutless bearings are a type of plain bearings used in watercrafts, especially in the propulsion systems of marine transportation means such as boats, yachts, ships or other vessels.

Cutless bearings are installed in locations with the rotation of the propeller shaft, such as within thrusters, aft of the hull, or in propeller supports. They provide support and reduce friction as the shaft rotates, allowing the vessel to move smoothly. Typical stern bearings are made of bronze or other metal alloys that are resistant to abrasion and corrosion. Modern versions of bearings can also incorporate advanced synthetic materials that are more resistant to abrasion and provide longer machine operation life.

One of the most widely favored materials used in the manufacturing of cutless bearings is nitrile rubber. A study conducted by Cabrera and other authors in 2005 contributed to the understanding of how pressures are distributed in cutless bearings. It was found that in the area of minimum lubricating film thickness, three staves, or three contact points, carried the main part of the load (Cabrera et al., 2005). The research conducted by Wang et al. in 2014 was based on theoretical analyses related to the characteristics of plain bearings. This research work focused mainly on theoretical approaches using mathematical models and numerical simulations to understand the behavior of bearings under different operating conditions, and presented experimental results from a test stand (Wang et al., 2014). The research conducted by Zhou and team focused on the experimental study of water film pressure in water-lubricated rubber bearings with multiple grooves (WLRBMG). As part of the research, a special test rig was designed to measure various parameters of WLRBMGs to further analyze the properties of this type of bearing (Zhou et al., 2017).

Currently, there exists a necessity to integrate theoretical findings with experimental data to enhance the performance characteristics of water-lubricated plain bearings (Blaut & Breńkacz, 2020). The research includes analysis of vibration and the effect of improper shaft alignment on the bearings. In addition, research is being conducted to develop a theoretical model based on experimental data, with the aim of designing cutless bearings efficiently (Smith, 2020). This research work aims not only to better understand the dynamics of bearing operation under water lubrication conditions, but also to develop more precise design methods that take into account the various factors that affect bearing performance and durability.

Research work is also being carried out on polymers for sliding bearings. Research on PEEK material showed an interesting effect of lapping of the polymer material in that the coefficient of friction in the lapped bearing was almost independent of the load (Żochowski et al., 2023). A separate research topic is the study of the wear of polymer bearings lubricated by contaminated water, which is characteristic of vessels (Litwin et al., 2023). There is also a need to analyze the possibility of replacing traditional petroleum-based lubricants by water. This has beneficial effects on the environment, lubricants are an environmental hazard in case of spills and their elimination reduces the need for petroleum. Replacing traditional lubricants with water results in lower friction losses in bearings due to the lower viscosity of water, which reduces energy dissipation in machinery (Wasilczuk et al., 2023).

Figure 1 shows a cutless water bearing, characterized by noise reduction, environmental protection by eliminating oil spills into the seas, and minimized friction, which extends their life. However, their sensitivity to leakage requires regular maintenance and monitoring, which is a limitation. Performance can be affected by environmental conditions, such as water temperature and the presence of contaminants.

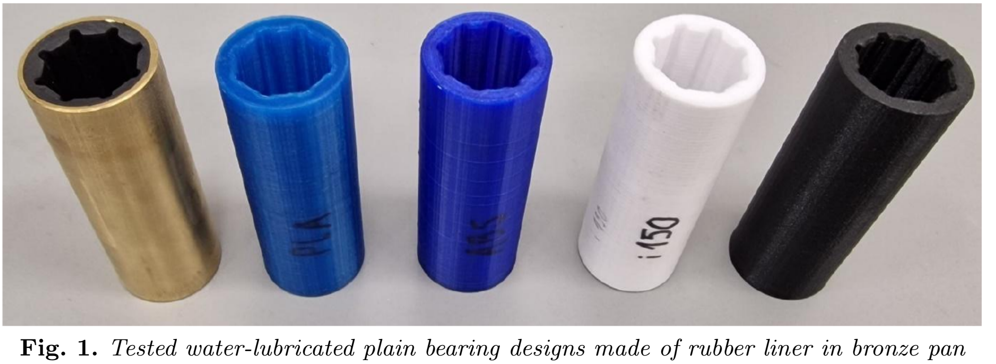

Fig. 1. *Tested water-lubricated plain bearing designs made of rubber liner in bronze pan (commercial solution), PLA, ABS, Tribo filament, PETG*

3. PREPARATION OF CUTLESS TYPE PLAIN BEARINGS FOR TESTING

Experimental studies have focused on the shape and configuration of the flexible liners used in cutless bearings, particularly related to the number of grooves used. Researchers such as Pai and Pai in 2008 conducted experiments to understand how different numbers of grooves affect bearing behavior and performance under water lubrication conditions (Pai & Pai, 2008).

Studies have also been conducted on the effect of scratches on the performance of water-lubricated rubber-lined plain bearings are well known. Experiments showed a significant effect of scratches on the critical load and critical speed of these bearings. According to the results of these experiments (a scratched shaft has a longer motion orbit and a lower equilibrium point compared to a shaft without scratches (Liang et al., 2023).

Fused Deposition Modeling (FDM) 3D printing technology involves the layering of a material, usually a thermoplastic, in a computer-controlled manner, which allows the construction of three-dimensional objects. In the context of the study, four thermoplastic materials were selected to enable 3D printing:

ABS (acrylonitrile butadiene styrene) is a thermoplastic polymer that is distinguished by its mechanical strength and resistance to damage. ABS has good compressive and tensile strength, making it ideal for printing parts with increased strength requirements, such as mechanical parts, utility components or functional prototypes.

PETG (polyethylene terephthalate glycol) is a thermoplastic polymer with high transparency, chemical and mechanical resistance. PETG is relatively easy to print, and its characteristics of strength, flexibility and durability make it popular for packaging, electronic components, and prototypes with higher strength requirements.

PLA (polylactic acid) is a biodegradable polymer of organic origin, most commonly used in 3D printing due to its ease of printing and environmental sustainability. PLA is odorless, emits no harmful substances, and has good strength and plasticity. It is commonly used to print prototype models, decorative elements, and objects that do not require high mechanical resistance.

Tribo filament is an advanced thermoplastic polymer that exhibits unique properties such as high chemical, thermal and mechanical resistance. Tribo filament is used in applications where exceptional properties are required, such as production of industrial parts, machine components, or in applications where high chemical resistance is needed.

Each of these thermoplastic materials has its own unique characteristics and applications, so it was decided to test them for use in cutless bearings. The geometry of the bearings made is based on an outer diameter of 30 mm and an inner diameter of 20.2 mm, and a diameter-to-length ratio of 1:4 which coincides with the general guidelines of flex-lined plain bearings. The bearings, made of thermoplastic materials, were compared with a commercial cutless plain bearing made of bronze pan with rubber lining.

4. TEST STAND DESCRIPTION

The test stand, located in the Machine Diagnostics and Monitoring Systems Laboratory, was used to test sliding bearings. This test fixture was specially adapted to carry out tests at different speeds and loads. Enables the conduction of tests for the diagnostic assessment of plain bearings and the evaluation of their technical condition (Fig. 2).

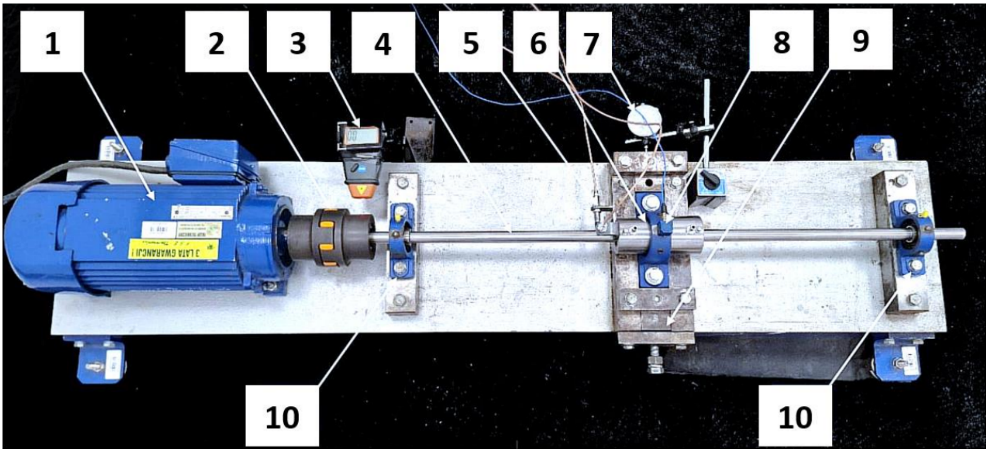

Fig. 2. *Test stand parts: 1 – motor, 2 – clutch, 3 – tachometer, 4 – shaft, 5 – eddy current sensors x, y, 6 – test bearing assembly, 7 – shaft deflection dial sensor, 8 – triaxial accelerometer, 9 – loading system, 10 – rolling bearings*

The bearing is positioned within a housing located at the center of the shaft, between two support bearings. The system is loaded laterally by tightening a screw, moving the test bearing assembly. Based on the deflection distance (center of deflection of the beam), the force acting on the test bearing is determined. The basic elements of this measuring station are:

- a drive system moving the shaft in a rotating motion, consisting of a motor and a clutch,
- two roller bearings supporting the ends of the shaft,
- a tachometer measuring the speed of the shaft,
- a set of test plain bearing with mounted eddy current distance sensors MDS10PO and piezoelectric accelerometer 3-axis PCB-356B08,
- a system loading the test bearing set with a lateral force, equipped with a shaft deflection sensor with a timer.

5. PERFORMANCE TESTS ON PLAIN BEARINGS

Each of the plain bearings tested was subjected to identical tests, under equal conditions of overhung loads and rotational speeds. Lubricating water was supplied through nozzles, completely filling the bearing shell along with the bearing. Lateral loading of the bearing with a force of 40 N, 80 N and 120 N corresponded to shaft deflections of 0.5 mm, 1 mm and 1.5 mm, respectively. The rotational speeds were determined based on typical operating conditions of recreational boats, where speeds do not exceed 3,000 RPM, and the range of typical speeds is between 600 and 1,800 RPM.

Table 1. *RMS values of acceleration and radius of rotational trajectory for 0 N, 40 N, 80 N, and 120 N excitations for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

Rubber	0 N		40 N		80 N		120 N	
RPM	RMS	Radius	RMS	Radius	RMS	Radius	RMS	Radius
600.0	0.02	0.15	0.07	0.06	0.01	0.07	0.08	0.08
1000.0	0.06	0.15	0.08	0.10	0.07	0.10	0.18	0.012
1200.00	0.18	0.28	0.08	0.15	0.25	0.10	0.16	0.11
1500.00	0.08	0.25	0.17	0.15	0.17	0.15	0.09	0.07
1800.00	0.02	0.18	0.09	0.13	1.14	0.18	0.20	0.11
ABS	0 N		40 N		80 N		120 N	
RPM	RMS	Radius	RMS	Radius	RMS	Radius	RMS	Radius
600.00	0.08	0.15	0.13	0.09	0.08	0.06	0.09	0.08
1000.00	0.28	0.15	0.55	0.09	0.20	0.07	0.20	0.07
1200.00	0.29	0.13	0.32	0.13	0.30	0.06	0.17	0.11
1500.00	0.10	0.16	0.31	0.09	0.36	0.11	0.66	0.11
1800.00	0.75	0.13	0.71	0.13	0.60	0.12	0.39	0.14
PETG	0 N		40 N		80 N		120 N	
RPM	RMS	Radius	RMS	Radius	RMS	Radius	RMS	Radius
600.00	0.07	0.09	0.04	0.04	0.12	0.07	0.03	0.04
1000.00	0.07	0.07	0.13	0.07	0.03	0.06	0.18	0.04
1200.00	0.06	0.07	0.07	0.07	0.25	0.10	0.11	0.05
1500.00	0.16	0.05	0.27	0.06	0.23	0.06	0.31	0.04
1800.00	0.09	0.06	0.16	0.05	0.32	0.05	0.34	0.05
PLA	0 N		40 N		80 N		120 N	
RPM	RMS	Radius	RMS	Radius	RMS	Radius	RMS	Radius
600.00	0.05	0.11	0.06	0.06	0.06	0.05	0.05	0.05
1000.00	0.13	0.10	0.19	0.06	0.02	0.06	0.17	0.04
1200.00	0.22	0.07	0.10	0.07	0.05	0.06	0.12	0.05
1500.00	0.18	0.11	0.08	0.07	0.16	0.06	0.04	0.07
1800.00	0.31	0.10	0.19	0.08	0.37	0.09	0.53	0.05
Tribo filament	0 N		40 N		80 N		120 N	
RPM	RMS	Radius	RMS	Radius	RMS	Radius	RMS	Radius
600.00	0.07	0.07	0.11	0.06	0.02	0.06	0.08	0.06
1000.00	0.22	0.06	0.20	0.05	0.10	0.04	0.11	0.06
1200.00	0.31	0.07	0.61	0.07	0.27	0.07	0.18	0.06
1500.00	0.46	0.09	0.70	0.07	0.34	0.09	0.62	0.07
1800.00	0.61	0.11	0.25	0.07	0.39	0.10	0.28	0.08

The RMS values of vibration acceleration on the bearing housing, shown in Table 1 and illustrated in Figures 3–10. Measuring the RMS values of vibration acceleration is a key tool for monitoring the operational stability and performance of water-lubricated plain bearings, and is also used to diagnose problems and prevent possible failures. A high RMS level of vibration acceleration can signal various types of failure, such as material wear, friction, loosening or structural damage. By analyzing vibration acceleration, it is possible to assess lubrication efficiency. Excessive vibration levels can indicate insufficient lubrication or problems with its even distribution inside the bearing.

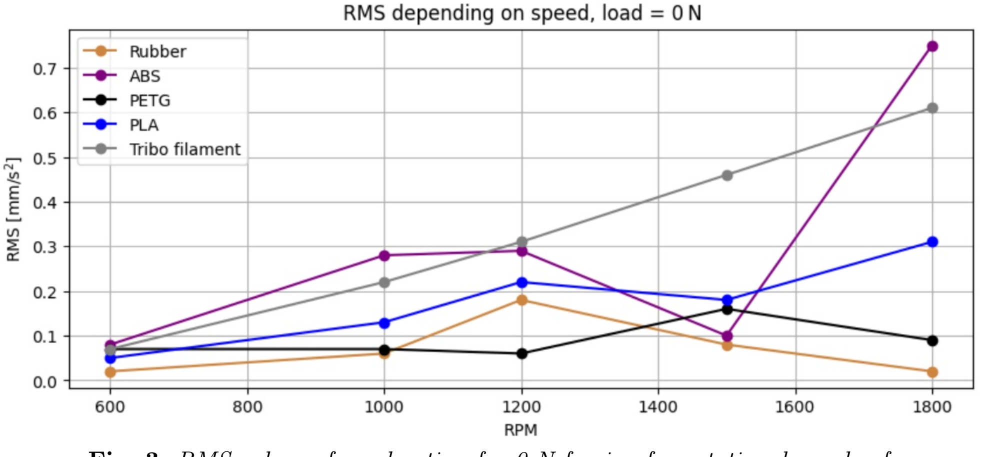

Fig. 3. *RMS values of acceleration for 0 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

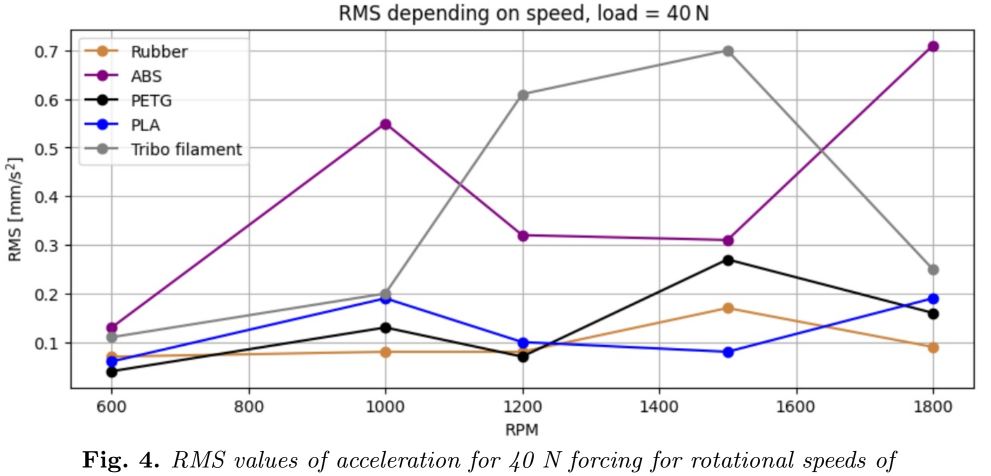

Fig. 4. *RMS values of acceleration for 40 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

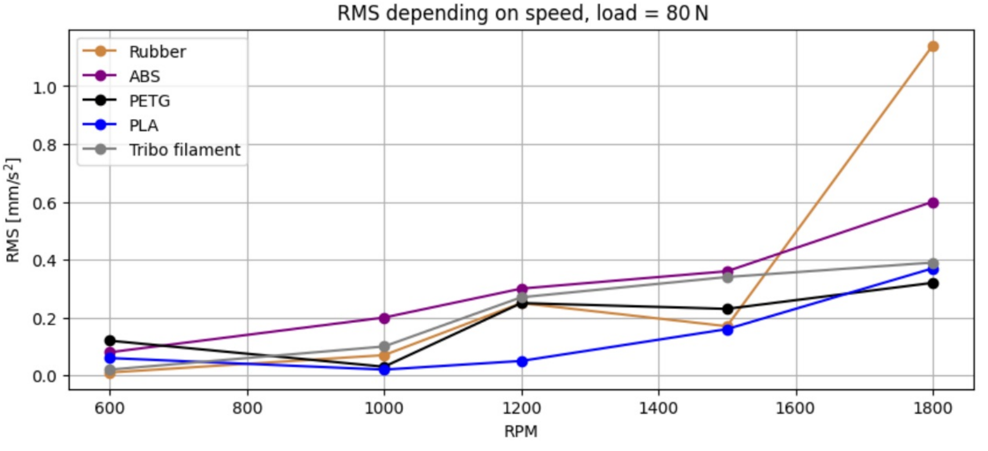

Fig. 5. *RMS values of acceleration for 80 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

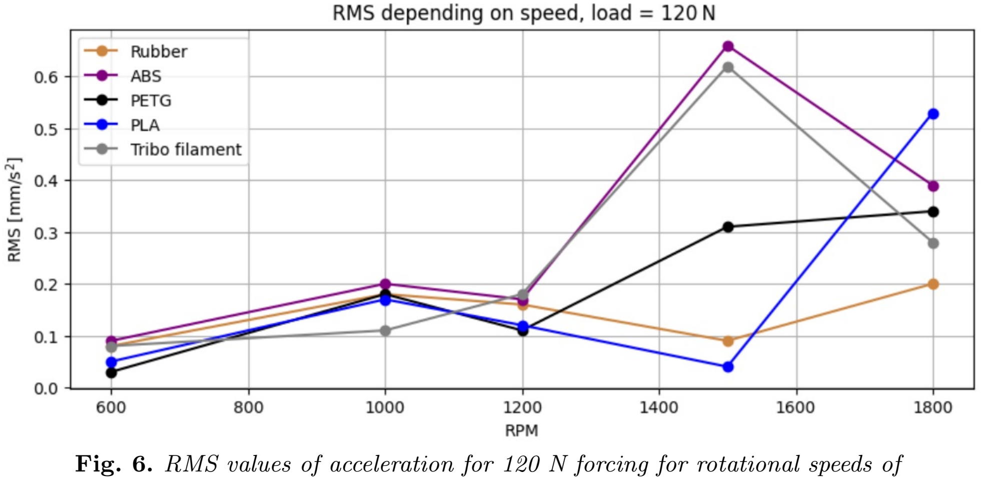

Fig. 6. *RMS values of acceleration for 120 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

Measuring the radius of the trajectory allows the evaluation of a sliding bearing. Changes in this value can indicate problems with achieving proper balance or symmetry in the movement of the shaft. The trajectory radius should remain within the bearing clearance, as its deviation may signify impending wear on the bearing. It can be assumed that the smaller the radius is, the more stable the bearing operates, but in the case of elastohydrodynamic bearings, the acceptable value of the radius is higher. The value of the trajectory radius can change with the load of the bearing. An increase in the radius is associated with overuse or improper operating conditions, which can lead to faster wear of the bearing. The radius of trajectory determines the performance characteristics of the bearing, especially in terms of friction, material wear and stability of shaft motion. Distinct changes in the radius can affect the smoothness of operation and performance of the bearing. Abnormal or unstable values of the trajectory radius can suggest bearing problems such as clearances, excessive wear, friction or mounting errors.

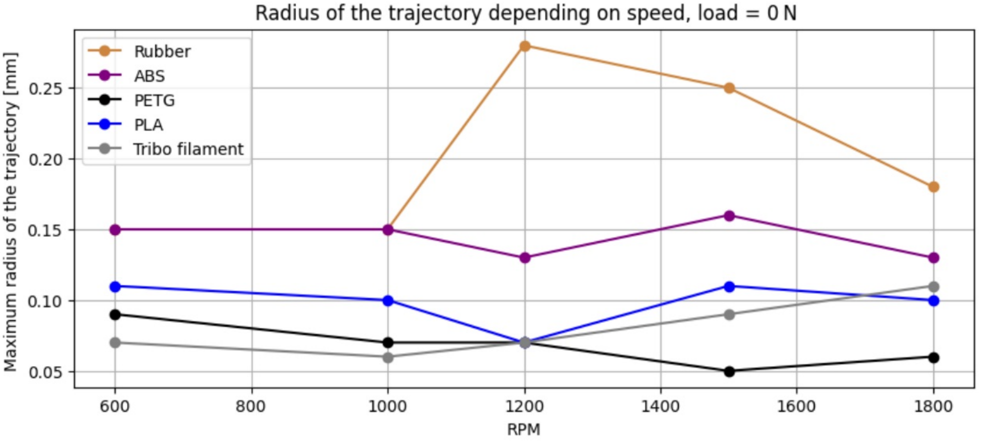

Fig. 7. *Radius of the rotational trajectory for 0 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

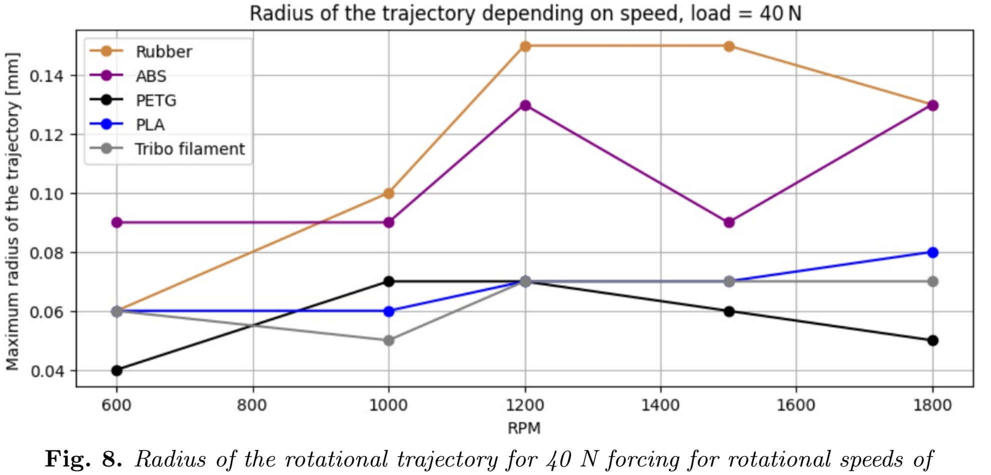

Fig. 8. *Radius of the rotational trajectory for 40 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

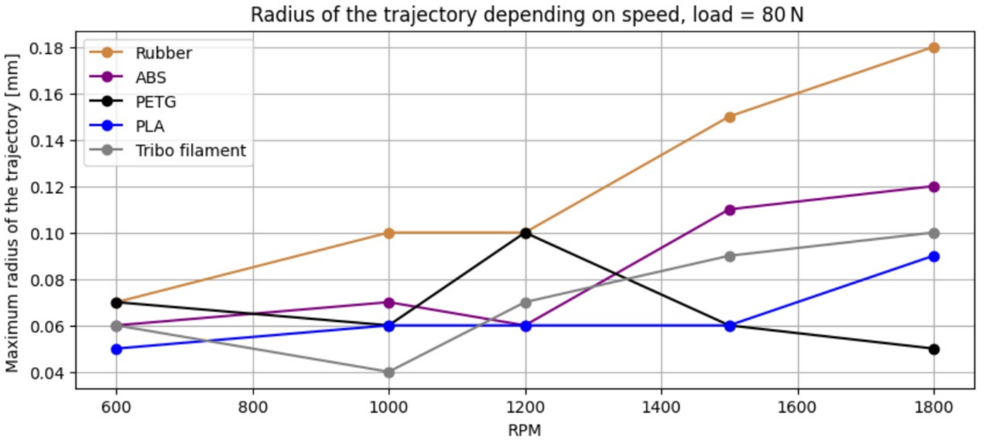

Fig. 9. *Radius of the rotational trajectory for 80 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

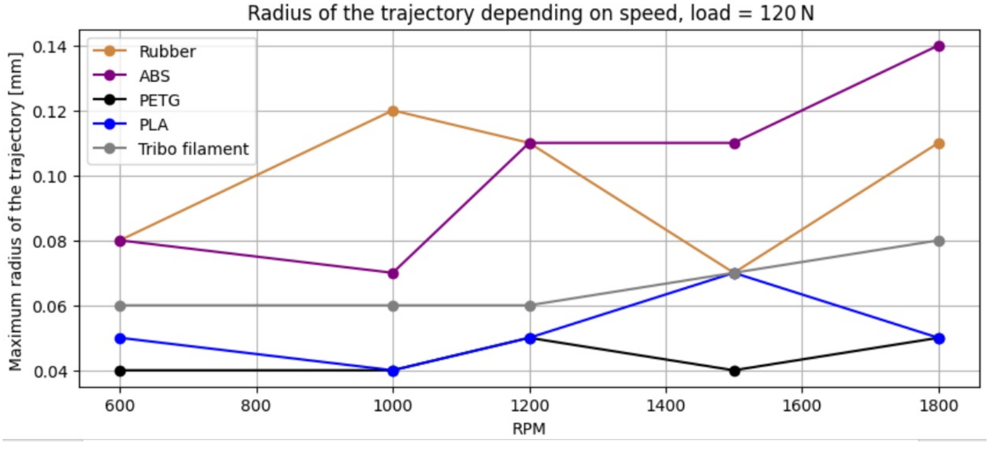

Fig. 10. *Radius of the rotational trajectory for 120 N forcing for rotational speeds of 600 RPM, 1000 RPM, 1200 RPM, 1500 RPM, and 1800 RPM for the tested bearings*

The primary task of a water-lubricated plain bearing is to keep a lubricating wedge that helps reduce frictional forces, water-lubricated bearings have a thinner lubricating wedge compared to conventional bearings lubricated with conventional oils. Another task of the bearing is cooling, water-lubricated bearings have better heat dissipation performance compared to conventional oil-lubricated bearings. Using water as a lubricant instead of oil or mineral grease reduces the negative impact on the environment by eliminating the risk of water and soil pollution. Using water as a lubricant can be simpler and more user-friendly, especially for maintenance and grease replenishment, especially where water is the operating environment. The plain bearings tested showed the best stability of operation at low speeds, according to an analysis of the relationship between speed and average values of machine vibration. In most cases, regardless of the load and type of material, the smallest values of average vibration occurred at rotational speeds of 600 RPM and 1000 RPM. In contrast, increased vibration was often recorded at speeds of 1500 RPM and 1800 RPM.

These results have important implications for the actual application of water-lubricated plain bearings. In practice, this type of bearing most often finds its application in the low-speed area, oscillating between 600 RPM and 1100 RPM. This value indicates optimum operating conditions that are conducive to minimizing vibration and ensuring efficient bearing operation in a water-lubricated environment.

The RMS analysis of acceleration shows that bearings available on the market-made of nitrile rubber has the best vibration damping among the tested bearings within the limits of low loads and speeds. Nevertheless, the radius of the rotational trajectory in the case of bearings made from thermoplastics is consistently smaller, which favors the solutions crafted from thermoplastics. This is because the Young's modulus for rubber is noticeably lower than for thermoplastics at around 0.01 to 0.1 GPa. This means that rubber is more flexible and less rigid than thermoplastics.

The PETG filament bearing has presented promising test results among thermoplastics. The low RMS acceleration values and the smaller radius of the shaft journal trajectory in the bearing than the commercial solution suggest that it is a promising research material worthy of further experimental testing.

The PLA-filament bearing had the best vibration damping properties for higher loads and speeds as can be seen in the RMS plots of vibration velocity for loads of 80 N and 120 N. However, despite these indisputable advantages, the material was not considered for further research due to its biodegradability. Under conditions of temperature 50–60°C and humidity – PLA decomposes in 45–60 days. However, it can be considered for prototype units such as underwater ROVs where missions are relatively short.

Low values of the radius of vibration trajectory are characterized by bearings made of ABS and tribo filament. However, compared to other thermoplastics, the RMS of vibration velocity on the housing is high. Typically, tribo filament has better vibration damping capability. The advantage of tribo filament is that it has a long dry life if the lubricating wedge is lost.

6. CONCLUSIONS

The tested bearings were tested under identical conditions of lateral loads and speeds. Water served as the lubricant, fed through the ferrules, filling the pan completely with the bearing. Analysis showed that the plain bearings tested performed best at lower speeds, typically 600–1100 RPM. This suggests that these bearings achieve the best performance and minimize vibration in this speed range. Studies have shown that bearings made of different materials (such as rubber, PETG, PLA, ABS, Tribo filament) show differences in their vibration damping properties and operational stability. Larger vibration velocities may partly affect the larger radius of the trajectory, which may be related to the function or performance of the bearing. The research conducted, showed on the significant differences of the thermoplastics used on the stability and performance of vibrations transmitted to the pan of water-lubricated plain bearings. The study showed that the stability of plain bearing performance cannot be evaluated only by the RMS of vibration acceleration on the bearing housing or by the trajectory radius. Both of these parameters are important from the user's point of view. For example, for an electric watercraft, a large high RMS vibration acceleration on the housing will indicate vibrations transmitted to the vessel while a large radius will indicate oscillations of the propeller motion which will reduce the efficiency of the ship.

The radius of rotational trajectory of the commercial bearing is in any case larger than the radius of trajectory of bearings made of thermoplastics, which speaks in favor of solutions made of thermoplastics. In most cases, the RMS acceleration values of the commercial bearing are comparable to the design made of PLA and PETG. ABS and tribo-filament bearings fare worse.

In the research work, easily available thermoplastic materials were selected, allowing the shaping of geometry using additive technology; the selected materials should have repeatable operating parameters of the sliding bearing. Further research should examine the performance parameters of bearings made using the additive method from thermoplastics reinforced with glass or carbon fiber, metal powders or crushed wood.

Continuing the analysis and research is essential to enhance our understanding of the mechanisms and optimize the performance of these bearings across various application conditions.

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