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RESEARCH ON HYDRODYNAMIC PEEK JOURNAL BEARINGS LUBRICATED WITH WATER AND OIL

BADANIA HYDRODYNAMICZNYCH ŁOŻYSK POPRZECZNYCH Z MATERIAŁU PEEK SMAROWANYCH WODĄ ORAZ OLEJEM

Key words: journal bearing, PEEK bearing, water lubrication.

Abstract: The main purpose of the research was to determine the possibilities and experimentally test the benefits of replacing conventional oil lubrication with ecological water lubrication. Tests were carried out on a test rig for hydrodynamic radial bearings under conditions representative of the expected applications for the bearing in water turbines. Bearings made from the polymer material PEEK (polyether ether ketone) were tested under static loads. The tests were carried out for two types of lubrication: pure water and oil, with a viscosity of ISO VG 46. A comparison of friction coefficients and load-carrying capacity for both lubricants was made. During the tests, an interesting phenomenon of polymer material running in was observed for relatively high pressures when lubricated with a very low-viscosity lubricating medium, i.e., water (pressures in the bearing over 2 MPa).

Słowa kluczowe: łożyska poprzeczne, łożyska PEEK, smarowanie wodą.

Streszczenie: Głównym celem badań było określenie możliwości i doświadczalne sprawdzenie korzyści płynących z zastąpienia konwencjonalnego smarowania olejowego ekologicznym smarowaniem wodnym. Przeprowadzono testy na stanowisku badawczym do hydrodynamicznych łożysk poprzecznych w warunkach odpowiadających oczekiwanym zastosowaniom łożyska w turbinach wodnych – prędkość ślizgania około 3 m/s i średnie naciski przekraczające 2 MPa. Łożyska wykonane z materiału polimerowego PEEK (Polieteroeteroketon) były badane w warunkach obciążeń statycznych. Testy zostały przeprowadzone dla dwóch rodzajów smarowania: czystą wodą oraz olejem o lepkości ISO VG 46. Dokonano porównania współczynników tarcia oraz obciążalności dla różnych mediów smarujących. Podczas badań zaobserwowano bardzo wyraźnie przejście od tarcia płynnego to tarcia mieszanego przy naciskach średnich około 0,65 MPa oraz interesujący efekt docierania się materiału polimerowego dla stosunkowo wysokich nacisków przy smarowaniu wodą (naciski w łożysku ponad 2 MPa) polegający na tym, że współczynnik tarcia w dotartym łożysku był niemal niezależny od obciążenia.

INTRODUCTION

Hydrodynamic bearings are now facing new environmental challenges, so it is the moment for their development based on new research results. An obvious development direction is the use of water lubricated bearings in applications where the lubricant leakage can directly affect the environment, for example, in the case of ship propulsions or hydroelectric power plants, where

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any lubricant leakage is easily deployed into the surrounding water. Water lubrication of sliding bearings has quite a long history, starting from 1854, when a British engineer and inventor, Sir John Penn, was the author of the first documented and successful application of a water lubricated bearing, being a substitute for a metallic grease lubricated bearing **[L. 1]**. After a series of tests on a specially built test stand, he selected ironwood (Lignum Vitae) as the best material to meet specific operating conditions **[L. 2]**. Another historical milestone was the application of rubber for a water lubricated bearing in a gold mine in the 1920s by Charles F. Sherwood, followed by US Patent No 1376043 **[L. 3]**. Later, apart from rubber and ironwood, other materials, including polymers and special metal alloys or metal-based composites, were adopted for water lubricated bearings. Applications and research were described in various papers **[L. 4–7]**. Water lubricated bearings are of principal interest for ship propulsions, for which numerous bearing materials and bearing designs were studied **[L. 8–10]**. On the other hand, bearings in which Poly-Ether-Ether-Ketone (PEEK) modified with Poly Tetra Fluor Ethylene (PTFE) and graphite was successfully introduced to oil lubricated bearings as a substitute to tin-based bearing alloys **[L. 11–16]**, were not extensively studied in the conditions of water lubrication.

The main goal of this research was to establish how the journal bearings made from PEEK composite perform under water lubrication compared to more conventional oil lubrication. Such information will give clues on the possible direction in which such tribosystems should be developed to possibly replace oil-to-water lubrication. In order to achieve this goal, short series of tests on the test rig were performed following some additional inspections of the test bearings. Since, as a desired situation, water lubricated bearings should be introduced as retrofits to the machines designed initially with oil or grease lubricated bearings, specific loads should not be lower than these of the oil lubricated bearings. This is not the case in water lubricated stern tube bearings in ship propulsions, where the specific loads are much lower than 1 MPa **[L. 17]**.

TEST BEARINGS AND TEST STAND

A complete bearing consists of a PEEK shell mounted into a stainless-steel housing. The bearing was working in unison with a stainless-steel sleeve mounted directly on the test rig main shaft. The parameters of the bearings and the shaft are presented in **Table 1**.

Laboratory tests were carried out with the use of the PG-2 test rig shown in **Fig. 1**. The test rig is used for testing journal sliding bearings. The test stand is computer controlled with an internal feedback loop for input parameters adjustment and has a digital data acquisition system offering high repeatability of test conditions and immunity to interference. The radial force and the rotational speed can be changed according to pre-programmed functions. Bearings can be tested with oil or water lubrication. The test stand is equipped with a unique, precise friction force sensor. The tested bearing is fixed in a rigid housing supported on a spherical hydrostatic bearing. The rotational speed is controlled by a vector-type frequency inverter, which allows testing fully loaded bearings in start-up and stop conditions. The main specifications of the test rig are shown in **Table 2**.

Table 1. Bearings and shaft parameters
Tabela1. Parametry badanych łożysk oraz wałów

Parameter	Value
Bearing	
Inner diameter	95.08 +/-0.010 mm
Outer diameter	124 mm
PEEK shell thickness	7.5 mm
Bearing axial length	80 mm
Roughness	Ra 1.25
Circumferential length	160°
Radial clearance (relative)	0.00084 +/-0.002
Shaft	
Outer diameter	95.00 +/- 0.007 mm
Roughness	Ra 0.63
Material	AISI 304L
Length	150 mm

Table 2. PG-2 Test rig parameters
Tabela 2. Parametry stanowiska pomiarowego PG-2

Parameter	Value
Radial Load	0-60 kN
Rotational speed	0-3000 rpm
Bearing diameter	30-110 mm
Bearing width	10-150 mm

The test rig can measure the following quantities: friction force/torque, radial force, hydrodynamic pressure distribution, rotational speed, the temperature of sliding elements and lubricant, etc.

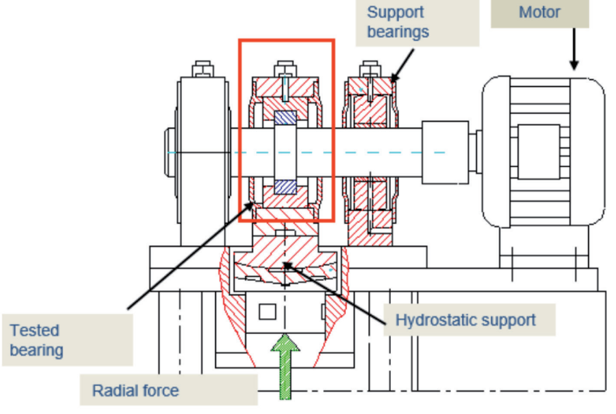

Fig. 1. Test stand schematic view
Rys. 1. Schemat stanowiska pomiarowego

TESTS PERFORMED

A variety of tests were performed – 38 in total. The tests described in this paper are listed in **Table 3**. The main focus was to carry out the tests with a nominal intended sliding speed (approximately 3 m/s, which is 600 rpm for 95 mm diameter) without destroying the bearing (due to a really high cost of PEEK material, the number of test bearings was limited). For water lubrication, which was the main concern, the tests with lower and higher sliding speeds (1 m/s and 5 m/s) were performed further to investigate the behaviour of the bearing during the tests.

There were two types of lubrication used:
- Lubrication with clear water without any additives,
- Lubrication with ISO VG 46 mineral oil (as a lubricant conventionally used in such bearings, for reference).

Table 3. Test parameters
Tabela 3. Parametry testów

No	No of repetitions	Bearing No	Rot. speed [rpm]	Specific load [MPa]	Lubricant
1	2	1	600	0.2 / 0.35 / 0.5	water
2	6	1	1000	0.2 / 0.35 / 0.5	water
3	6	1	0-600-0	0.2	water
4	4	1	0-600-0	0.35	water
5	2	1	200	1.1-2.6 /+0.15	water
6	5	1	600	1.1-2.6 /+0.15	water
7	4	2	0-600-0	0.2	oil
8	4	2	0-600-0	0.5	oil
9	2	2	0-600-0	1.1	oil
11	3	2	600	1.1-2.6/+0.15	oil
12	2	2	1000	0.2 / 0.35 / 0.5	oil

For these types of lubrication, three main types of tests were performed:
- With constant rotational speed and increasing load in steps,
- With a constant load and rotational speed changing continuously from 0 rpm to 600 rpm and then back to 0 rpm to check how the bearing operates during start-stop when the bearing works under limited and mixed lubrication.

RESULTS

Comparison of the PEEK bearing operating with oil and water lubrication is shown in **Fig. 2** and **Fig. 3**. The changes in the friction coefficient in the sliding bearing are usually illustrated with the use of the Stribeck curve as a function of a dimensionless Hersey number. The minimum friction coefficient is observed at the transition from full film to mixed lubrication. Contrary to the classical graphs, in **Fig. 2** and **Fig. 3**, the friction coefficient changes are shown as a function of a specific load. Due to this, one can expect the transition to occur at increasing values of the specific load, i.e., towards the right in the graphs. Both bearings did not reach the minimum friction coefficient at low specific load and high speed (**Fig. 2**), so they were operating in the regime of full film lubrication (hydrodynamic lubrication). The friction coefficient in the bearing with water lubrication was approximately ten times lower than in the same bearing with oil lubrication. Such a low value of the specific load is not practically used in oil lubricated bearings, while it is quite normal in water lubricated bearings, e.g., in naval applications.

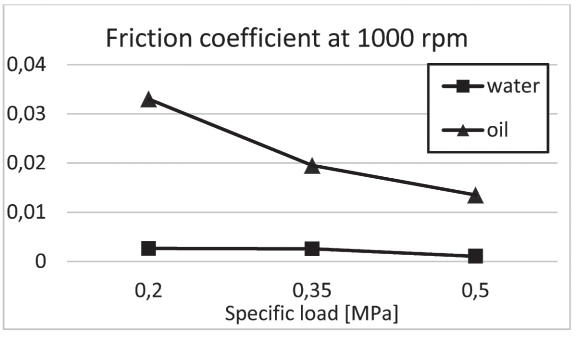

Fig. 2. Comparison of the friction coefficients in water and oil for low specific load operation and 1000 rpm rotational speed
Rys. 2. Porównanie współczynników tarcia przy smarowaniu wodą oraz olejem dla niskich nacisków oraz prędkości obrotowej 1000 obr./min.

In **Fig. 3**, friction coefficients in both types of lubrication are compared over a broader range of specific loads. The results were obtained in the tests carried out at the rotational speed of 600 rpm. In the water-lubricated bearing, one can see the minimum value of the friction coefficient occurring at the specific load of 0.65 MPa showing the transition from fluid film to mixed friction, and then, above 0.65 MPa, a gradual increase of friction coefficient. In the bearing lubricated with ISO VG-46 oil, with the increase of a specific load, the friction coefficient decreases gradually from 0.03 by a factor of 8 down to 0.004. This is because the oil-lubricated bearing did not reach the transition point, despite a much higher specific load, and it operates in the regime of full film lubrication over the whole range of specific loads used in the tests.

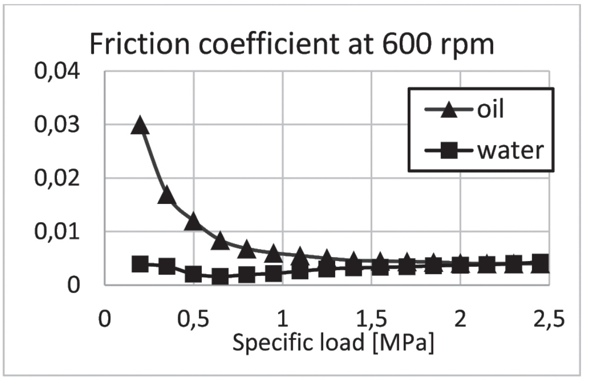

Fig. 3. Comparison of the friction coefficients in water and oil for a wide range of specific loads
Rys. 3. Porównanie współczynników tarcia przy smarowaniu wodą oraz olejem dla szerokiego zakresu nacisków występujących w łożysku

It is worth noting that during short runs, the bearing lubricated with water and operating in a mixed lubrication regime was running in and gradually improved its performance. The process of running in is illustrated in the subsequent figures. The graphs show the results of the test at 600 rpm, carried out with stepwise increasing specific load, from 1.1 MPa to 2.6 MPa with the increments of 0.15 MPa – test parameters as a function of time are shown in **Fig. 4**. In **Fig. 5** two trials with identical stepwise increasing loads and constant rotational speed are compared. In the left side

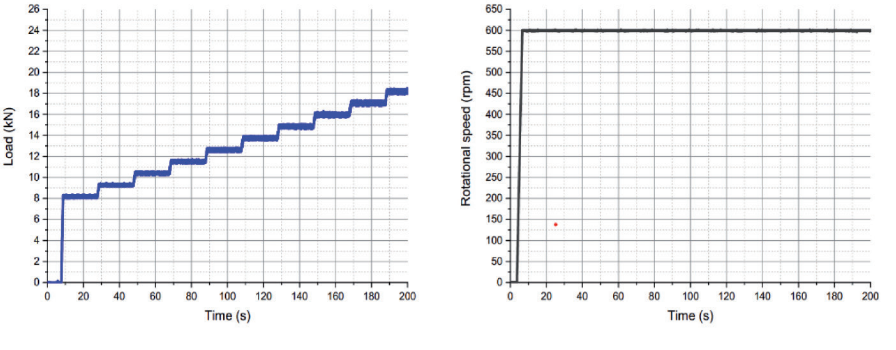

Fig. 4. Load and rotational speed vs time in trials 1–5 in water lubrication
Rys. 4. Obciążenie oraz prędkość obrotowa w funkcji czasu dla prób 1–5 przy smarowaniu wodą

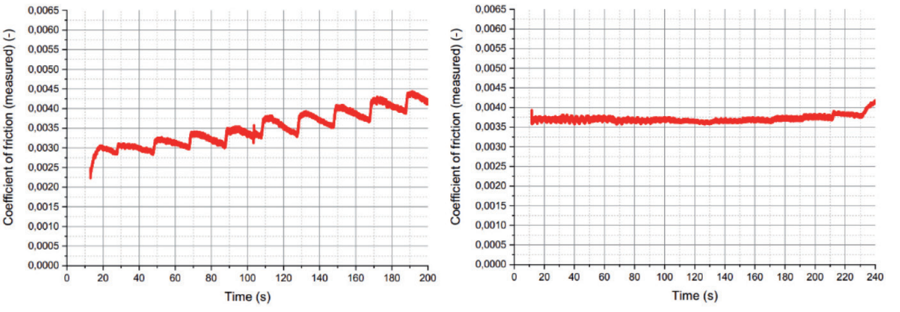

Fig. 5. Friction coefficient for the first trial, right side: friction coefficient at the fifth trial with the same working conditions
Rys. 5. Współczynnik tarcia dla pierwszej próby, z prawej strony współczynnik tarcia dla piątej próby w tych samych warunkach testu

graph, it is clearly seen that during the first trial, the bearing is still in the process of running-in and the coefficient of friction changes at each load step, with an increase at the beginning after the change of load and then a gradual decrease until the next load step. The course of the friction coefficient is entirely different during the fifth trial carried out in the same bearing (right side graph). The friction coefficient becomes almost constant over the whole range of loads.

The visual inspection and profilometry confirmed the running-in process ongoing during the tests. In **Fig. 6**, one can see the traces of contact, which caused the smoothing of the PEEK surface. The running-in process is combined with the profile of the surface after machining – seen as a series of matt and glossy stripes. One can also observe the extent of contact between the bearing and the shaft – on both sides of the glossy area, the polymer surface is uniformly matt. These matt areas were not in direct contact with the shaft.

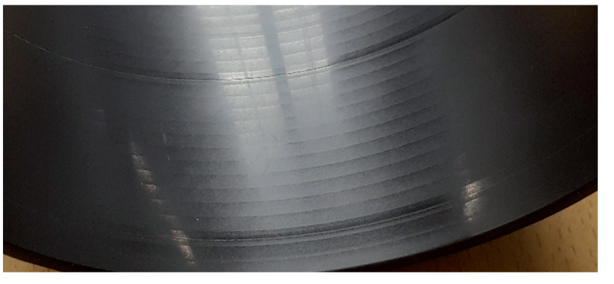

Fig. 6. Bearing surface after a series of tests in water lubrication
Rys. 6. Powierzchnia łożyska po przeprowadzeniu serii testów przy smarowaniu wodą

The results of profilometry (**Fig. 7**) also show the effect of running-in, in the upper graph, showing the initial roughness profile, one can see a symmetrical distribution of peeks and pits, while in the lower graph, showing the profile after the fifth trial, the peeks are worn out, and only the pits remained on the profile.

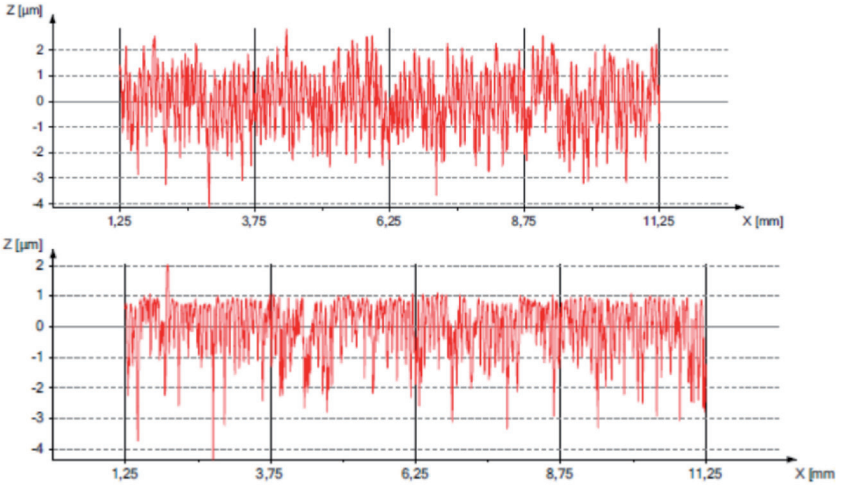

Fig. 7. Distribution of surface roughness at the beginning of tests at the upper graph, after the fifth trial at the lower graph
Rys. 7. Chropowatość powierzchni badanych łożysk, u góry przed przystąpieniem do testów, u dołu: po przeprowadzeniu 5 próby

DISCUSSION AND CONCLUSIONS

Remarks from the rig tests and inspections were summarised below:

- PEEK Pocket bearing operated properly in the operating conditions defined for the tests, i.e., up to approximately 2.5 MPa for oil lubrication, as well as for water lubrication.
- The tests at the start-stop regime also showed the ability of the bearing to withstand such operational conditions with no problems, both in oil and in water.
- In the test in oil in the whole test program, the bearing operated in an entire film lubrication regime.
- During the tests in water, a transition to mixed friction could be observed. At the rotational speed of 600 rpm, it occurred at the specific load of 0.65 MPa. Despite this regime of operation, considered unacceptable for conventional bearing material, the PEEK bearing was operating very well.
- In water lubrication, the transition to mixed friction was not causing any substantial increase in friction coefficient up to 2.5 MPa and was smaller than 0.005, which is an extremely low value. The material demonstrated the tendency to run in – the manufacturing irregularities were gradually smoothing, which influenced the stabilisation of the friction coefficient value.
- The most visible advantage of the PEEK bearing was the ability to operate properly in water lubrication in mixed friction regime. The advantage of friction losses over a bearing lubricated with oil would be visible at high speed and low loads, while at high loads and low speed, both bearings demonstrated similar losses.

In summary, PEEK bearings performed well above expectation, and further research into water-lubricated bearings of such type is considered highly recommended.

REFERENCES

1. Hartree R.: John Penn and Son of Greenwich 1799–1911, makers of the Xantho engine. 14th National Engineering Heritage Conference, Cravley 2007.
2. Lignum-Vitae Self Lubricated Bearings. www.lignum-vitae.com
3. Sherwood Ch.F.: Shaft bearing, US Patent No 1376043 (1921).
4. Orndorff R.: Water lubricated rubber bearings, history and new developments, Nav Eng J. (1985), pp. 39–52.
5. Litwin W.: Water lubricated marine stern tube bearings – attempt at estimating hydrodynamic capacity, ASME/STLE International Joint Tribology Conference. 2010.
6. Dong C.L., Yuan C.Q., Bai X.Q., Yang Y., Yan X.P.: Study on wear behaviours for NBR/stainless steel under sand water-lubricated conditions, Wear. 332–333 (2015), pp. 1012–1020.
7. Barszczewska A.: Experimental Research on Insufficient Water Lubrication of Marine Stern Tube Journal Bearing with Elastic Polymer Bush, POLISH MARITIME RESEARCH 27 (2020), pp. 91–102.
8. Olszewski A., Żochowski T., Gołębiewski G.: Analysis of the load-carrying capacity of a hydrodynamic water-lubricated bearing in a hydroelectric power plant., Tribologia, (2018), pp. 103–110.
9. Litwin W., Olszewski A.: Assessment of possible application of water-lubricated sintered brass slide bearing for marine propeller shaft. (2012) POLISH MARITIME RESEARCH 19, pp. 54–61.
10. DNVGL-CP-0081. Synthetic bearing bushing materials, 2016.
11. Schubert A., Brescianini T.: Application of a PEEK coated thrust bearing on the occasion of a refurbishment of a large hydro power plant with concurrent load increase. 10th EDF/Pprime (LMS) Poitiers Workshope, Futuroscope 2011.
12. Zhou J.: Temperature Monitoring of PEEK Bearings, STLE Conference, Las Vegas 2016.
13. Wodtke M.: Hydrodynamic thrust bearing with PEEK sliding layer (in Polish), Gdańsk University of Technology, 2017.

14. Peter J.: Blau On the nature of running in. Tribology International (2005), pp. 1007–1012.
15. Akagaki T., Yamato K., Masahiko K.: Effects of surface roughness of PEEK materials on the friction and wear behaviors in oil lubrication. Proc. of the International Tribology Conference, Hiroshima, Japan 2011.
16. Sander D.E., Allmaier H., Priebsch H.H., Witt M.: A. Skiadas, Simulation of journal bearing friction in severe mixed lubrication – Validation and effect of surface smoothing due to running-in., Tribology International (2016), pp. 173–183.
17. Litwin, W. Study of the research and design problems of marine propulsion main shaft bearings lubricated with water (in Polish) Gdańsk University of Technology (2013), pp. 1–139.