Artur OLSZEWSKI*, **Tomasz ŻOCHOWSKI****, **Grzegorz GOŁĘBIEWSKI*****

ANALYSIS OF THE LOAD-CARRYING CAPACITY OF A HYDRODYNAMIC WATER-LUBRICATED BEARING IN A HYDROELECTRIC POWER PLANT

ANALIZA NOŚNOŚCI HYDRODYNAMICZNEGO ŁOŻYSKA SMAROWANEGO WODĄ ELEKTROWNI WODNEJ

Key words: hydrodynamic bearing, water lubrication, computer simulation, modernization, guaiacum wood, historic object.

Abstract The paper presents an analysis of the load-carrying capacity of a historic hydrodynamic water-lubricated radial bearing of an unconventional segment design installed in the Braniewo Hydroelectric Power Plant. The aim of the calculations was to determine whether the bearing operates in the conditions of hydrodynamic or mixed lubrication, as well as to establish the optimal geometry of the axial grooves allowing for the highest load-carrying capacity. Computer simulations were performed using proprietary ARTbear software developed at Machine Design and Vehicles Department of Gdańsk University of Technology. The calculation results led to the creation of the technical documentation of the bearing's modernization serving to increase its lifespan and reliability.

Słowa kluczowe: łożysko hydrodynamiczne, smarowanie wodą, symulacja komputerowa, modernizacja, drewno gwajakowe, zabytek.

Streszczenie W artykule przedstawiono analizę nośności zabytkowego hydrodynamicznego łożyska poprzecznego smarowanego wodą o nietypowej konstrukcji segmentowej zainstalowanego w elektrowni wodnej Braniewo. Celem obliczeń było określenie, czy łożysko pracuje w warunkach tarcia płynnego czy mieszanego oraz wyznaczenie optymalnej geometrii szczeliny smarowej umożliwiającej uzyskanie maksymalnej nośności. Symulacje komputerowe wykonano, wykorzystując autorski program komputerowy ARTbear opracowany w Katedrze Konstrukcji Maszyn i Pojazdów Politechniki Gdańskiej. Wykonane obliczenia posłużyły do opracowania dokumentacji modernizacji łożyska zwiększającej jego trwałość i niezawodność.

INTRODUCTION

Hydroelectric power plants frequently utilize water-lubricated bearings because of their many undeniable advantages, i.e. they are environmentally friendly, can be lubricated with the surrounding water, do not require complicated oil-lubrication systems, etc. [**L. 21**] Water-lubricated bearings present considerable variety regarding their design [**L. 2, 3, 5, 8, 10, 14, 16, 23, 24**] and bearing material. The first documented implementation of water-lubricated bearings was performed in 1854 by Sir John Penn on the Great Eastern steamboat [**L. 21**] where natural guaiacum wood was utilized as the bearing material. This material (also known as lignum vitae) is distinguished by its unmatched tribological properties as well as resistance to water and living organisms [**L. 9**]. In the 1960's, together with the development of the chemical industry, new bearing materials were introduced in the form of polymers, composites, and ceramics [**L. 1, 4, 6, 7, 11, 12, 13, 15, 17, 18, 20, 22**]. However, the natural guaiacum wood is still being used to this day and is considered by many to surpass the man-made synthetic materials [**L. 9**].

* Gdańsk University of Technology, Faculty of Mechanical Engineering, Machine Design and Vehicles Department, e-mail: artur.olszewski@pg.edu.pl.
** Gdańsk University of Technology, Faculty of Mechanical Engineering, Machine Design and Vehicles Department, e-mail: t.j.zochowski@gmail.com.
*** ENERGA Wytwarzanie S.A., e-mail: grzegorz.golebiewski@energa.pl.

SUBJECT OF STUDY

The study concerns a historic hydrodynamic radial bearing installed in the Braniewo Hydroelectric Power Plant, manufactured in 1930 according to the design of Schichau Elbing shipyard. The power plant utilizes a vertical shaft with an unconventional arrangement of two Francis turbines located one under the other (**Fig. 1**). The turbine shaft is upheld by two radial bearings, with the bottom one being water-lubricated and immersed directly in the river, and top one placed above the water level. The turbine shaft is connected with a flange to a generator shaft, which is supported by an axial bearing carrying the loads resulting from the weight of the shaft and the generator, as well as the water pressure acting on the turbines.

The bearing subjected to the analysis presents a very interesting and uncommon design (**Fig. 2**). It consists of a cast-iron, split housing inside of which three bearing segment compartments are located 120° apart from each other. The side surfaces in each compartment are parallel and the back surface is angled 5° to the vertical, converging towards the top. Thanks to this arrangement, continuous adjustment of the bearing clearance is possible.

Fig. 1. Disassembled Braniewo HEP Plant turbine shaft with original double Francis turbine arrangement placed one under another. Bottom (subject of analysis – on left) and top (on right) bearing locations marked. In plant shaft operates vertically

Rys. 1. Widok ogólny zdemontowanego wału turbiny EW Braniewo z oryginalnym układem dwóch wirników Francisa umieszczonych jeden pod drugim. Zaznaczono położenie łożyska dolnego (z lewej) będącego przedmiotem analiz oraz górnego (z prawej). W elektrowni wał pracuje w pozycji pionowej

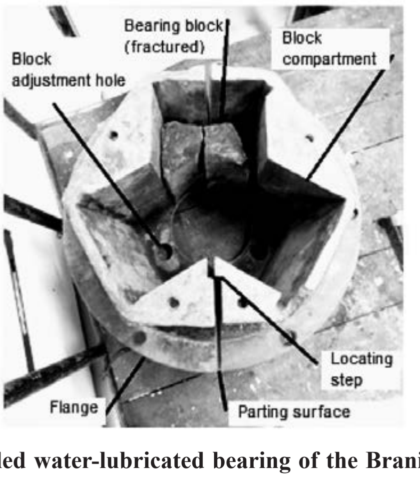

Fig. 2. Disassembled water-lubricated bearing of the Braniewo HEP Plant (on left). Three wooden block compartments and adjusting bolt holes visible. On right computer model of bearing housing

Rys. 2. Widok ogólny zdemontowanego łożyska smarownego wodą EW Braniewo (z lewej). Widoczne trzy kieszenie pod drewniane segmenty łożyskowe oraz otwory pod śruby regulacyjne. Z prawej komputerowy model korpusu łożyska

This adjustment is accomplished with three vertical bolts, whose shanks exit the housing through holes designed for this purpose. The lowering or raising of the segments with the bolts causes them to slide on the converging back surfaces, respectively increasing or decreasing the radial clearance (**Fig. 2**).

Because the shaft operates in a vertical position, the load on the radial bearings results mainly from its imbalance and the asymmetric distribution of the hydrodynamic forces acting on the rotors (it does not result from its weight, as is the case with horizontal shafts).

ANALYSIS OF LOAD-CARRYING CAPACITY

Computer software

The calculations were performed by ARTbear computer software, which has been developed over many years at the Machine Design and Vehicles Department [**L. 21**]. It employs an adiabatic model of the hydrodynamic film and allows for the determination of all important parameters of a hydrodynamic bearing, such as pressure and film thickness distribution, lubricant expenditure, stiffness and damping coefficients, journal position, etc. The software enables the simulation of cylindrical and multi-surface bearings of complex axial groove geometry with an accommodation of the influence of the shaft's angular misalignment and bearing shell imperfections.

Analysed cases

The main purpose of the calculations was to establish whether fully hydrodynamic lubrication without contact between the journal and the bearing shell is possible in normal operating conditions, as well as to find the bearing geometry providing maximum load capacity. This information was necessary to determine the optimal bearing material suitable for the particular application.

The paper presents the results of an analysis of two bearings of different geometries and clearances. The first is a cylindrical bearing consisting of three symmetrically-placed segments with angular spans of 100°. The second bearing also has three segments, but with a certain preload value, corresponding to a geometry resulting from turning a cylindrical diameter and decreasing the clearance by adjusting the segments with the adjusting bolts (the geometry changes from a cylindrical bearing to a three-segmented preloaded bearing). The differences between both bearings' geometries are presented in **Table 1** and on **Fig. 3**.

Table 1. Calculation parameters
Tabela 1. Parametry łożysk przyjęte do obliczeń

	Bearing No. 1 (cylindrical)	Bearing No. 2 (preload)
Journal Ø	180 mm	180 mm
L (shell length)	250 mm	250 mm
Rotational speed	108 RPM	108 RPM
Water viscosity	0.0018 Ns/m^2	0.0018 Ns/m^2
Number of bearing surfaces	3 – cylindrical bearing	3 – multi-surface bearing
Preload	0	0.5
Axial gap angle span	10°	10°
Relative clearance	0.001 and 0.002	0.001 and 0.002
Absolute clearance (diametric)	0.18 and 0.36 mm	0.09 and 0.18 mm

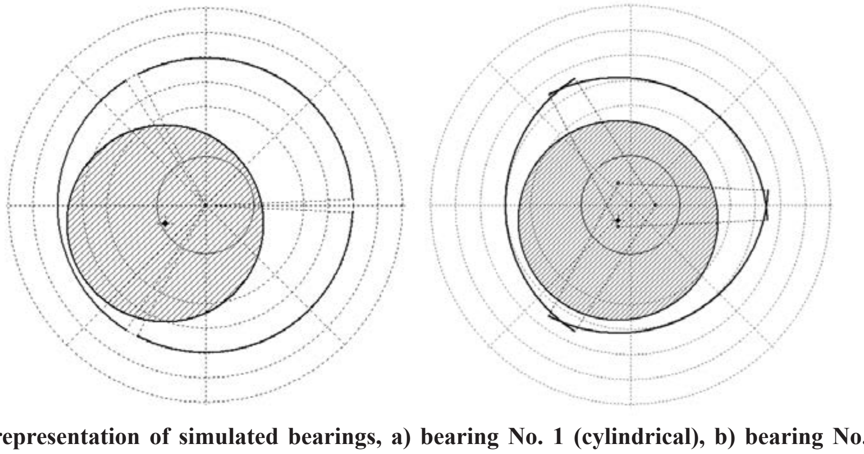

Fig. 3. Schematic representation of simulated bearings, a) bearing No. 1 (cylindrical), b) bearing No. 2 (three-surface preloaded)
Rys. 3. Schematyczne przedstawienia geometrii symulowanych łożysk, a) łożysko nr 1 (cylindryczne), b) łożysko nr 2 (trójpowierzchniowe wstępnie obciążone)

Another of the major aims of the calculations was to determine which of the analysed geometries is optimal with regard to the achievable load-carrying capacity. The influence of load direction was also simulated. The calculations were performed for both the direction towards the middle of a segment and towards an axial groove (between the segments). Because the exact magnitude of the radial force acting on the bearing is unknown, a wide range of load magnitudes was considered. The journal eccentricity was taken in the range of 0.5 to 0.95. The calculation parameters are presented in detail in **Table 1**.

Calculation results for bearing No. 1 (cylindrical)

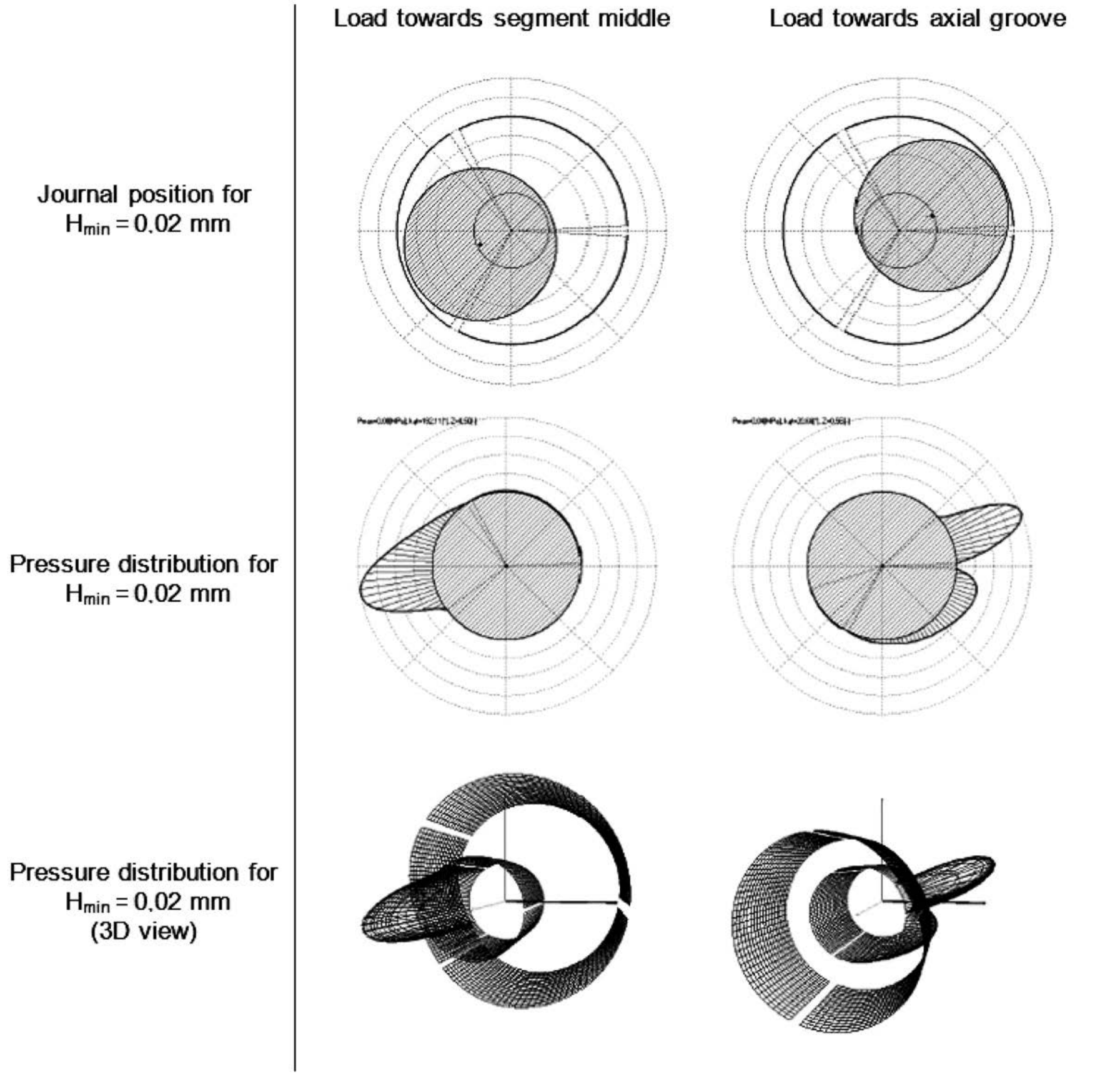

Fig. 4. Selected calculation results for bearing No. 1 (cylindrical) with 0,001 clearance
Rys. 4. Wybrane rezultaty obliczeń łożyska nr 1 (cylindrycznego) z luzem 0,001

Calculation results for bearing No. 2 (three-surface preloaded)

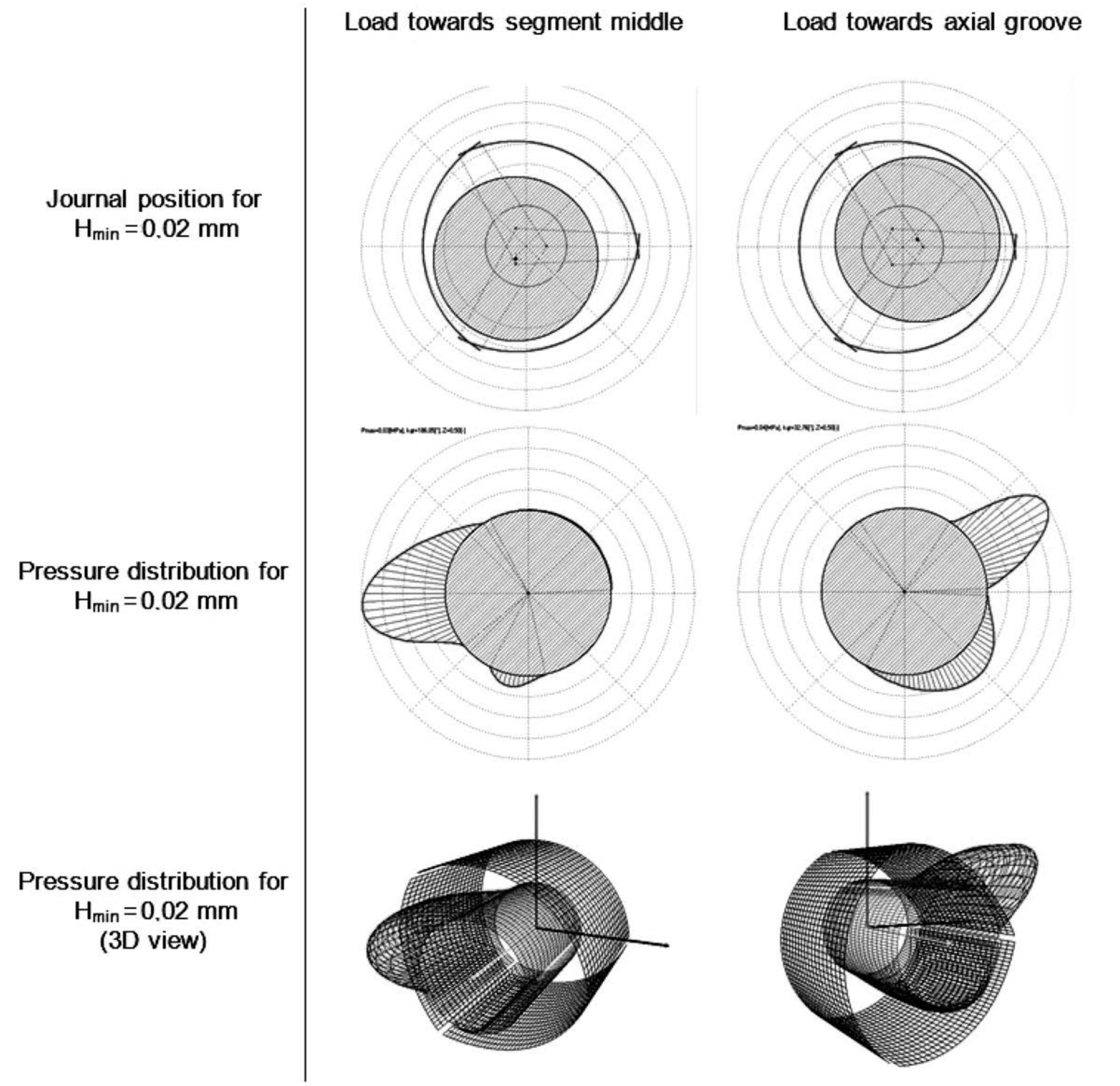

Fig. 5. Selected calculation results for bearing No. 2 (three-surface preloaded) with 0.001 clearance
Rys. 5. Wybrane rezultaty obliczeń łożyska nr 2 (trójpowierzchniowego wstępnie obciążonego) z luzem 0,001

Comparison of obtained results

After performing the computer simulations, graphs for the comparison of the load-carrying capacities were created (**Figs. 6, 7**). On the following graphs, these capacities as well as the minimum water film thicknesses for bearings No. 1 (no preload) and No. 2 (three-surface preloaded) are presented as a function of journal eccentricity. The characteristics were plotted for two assumed values of relative clearances – 0.001 and 0.002. The estimated radial load acting on the analysed bearings is 1 kN.

Figure 6 depicts a comparison of the load-carrying capacities of four variants as a function of journal eccentricity, where the load is directed towards the axial groove. It is obvious that the highest capacity is achieved by bearing No. 2 (three-surface preloaded) with its relative clearance of 0.001. The lowest capacity is achieved by bearing No. 1 (cylindrical) with a clearance of 0.002. For example, for the eccentricity value of 0.87, the most favourable variant is demonstrated to possess the load-carrying capacity of 2 kN, while the least favourable only 0.27 kN.

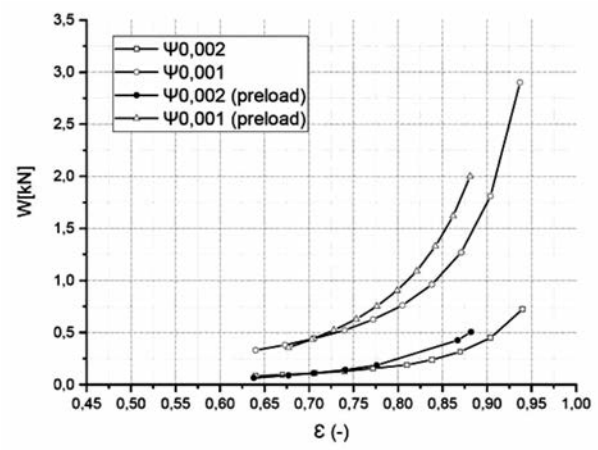

Fig. 6. Comparison of load-carrying capacity of bearing No. 1 (cylindrical) and No. 2 (three-surface preloaded) for two variants of relative clearance value – 0.001 and 0.002. Load directed towards axial groove (between segments)

Rys. 6. Porównanie nośności łożyska nr 1 (cylindrycznego) oraz łożyska nr 2 (trójpowierzchniowego wstępnie obciążonego) dla dwóch wariantów wartości luzu względnego – 0,001 i 0,002. Wektor obciążenia działa w kierunku kieszeni (pomiędzy segmentami)

Figure 7 depicts a comparison of the load-carrying capacities of four variants as a function of journal eccentricity, where the load is directed towards the middle of a segment. In this case as well, the highest capacity is achieved by bearing No. 2 (three-surface preloaded) with its relative clearance of 0.001. The lowest capacity is achieved by bearing No. 1 (cylindrical) with a clearance of 0.002. However, there is no substantial

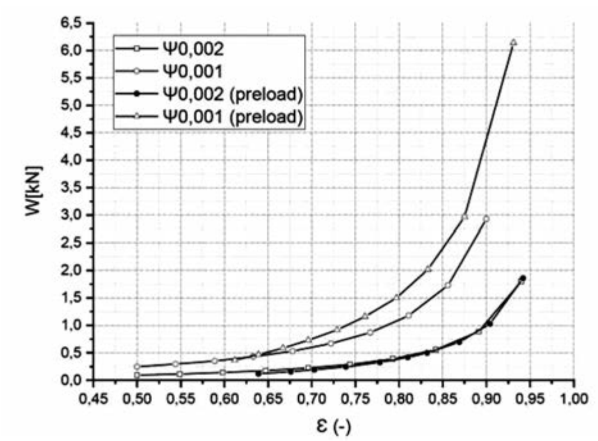

Fig. 7. Comparison of load-carrying capacity of bearing No. 1 (cylindrical) and No. 2 (three-surface preloaded) for two variants of relative clearance value – 0.001 and 0.002. Load directed towards middle of segment

Rys. 7. Porównanie nośności łożyska nr 1 (cylindrycznego) oraz łożyska nr 2 (trójpowierzchniowego wstępnie obciążonego) dla dwóch wariantów wartości luzu względnego – 0,001 i 0,002. Wektor obciążenia działa w kierunku środka segmentu

difference between bearings No. 1 and No. 2 for the clearance value of 0.002. For the journal eccentricity value of 0.87, bearing No. 2 with a clearance of 0.001 achieves a load-carrying capacity of approx. 3 kN. The capacity of both bearings with a clearance of 0.002 does not exceed 0.75 kN.

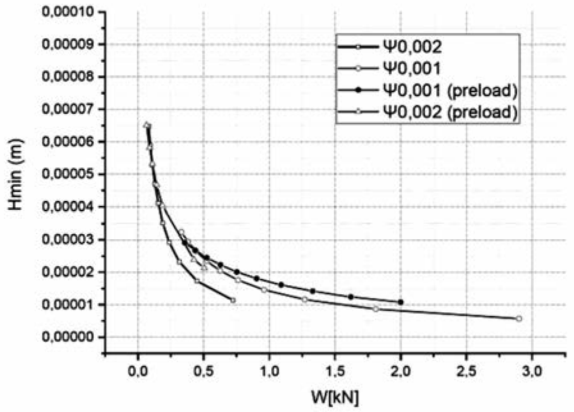

Fig. 8. Comparison of minimum water film thickness of bearing No. 1 (cylindrical) and No. 2 (three-surface preloaded) as function of acting load for two variants of relative clearance value – 0.001 and 0.002. Load directed towards axial groove (between segments)

Rys. 8. Porównanie wartości minimalnej grubości filmu wodnego nośności łożyska nr 1 (cylindrycznego) oraz łożyska nr 2 (trójpowierzchniowego wstępnie obciążonego) dla dwóch wariantów wartości luzu względnego – 0,001 i 0,002. Wektor obciążenia działa w kierunku kieszeni smarowej (pomiędzy segmentami)

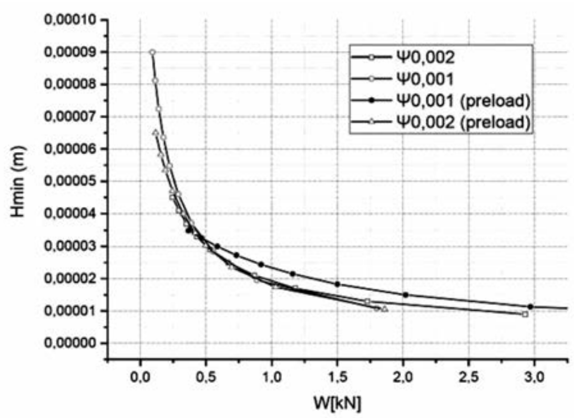

Fig. 9. Comparison of minimum water film thickness of bearing No. 1 (cylindrical) and No. 2 (three-surface preloaded) as function of acting load for two variants of relative clearance value – 0.001 and 0.002. Load directed towards middle of segment

Rys. 9. Porównanie wartości minimalnej grubości filmu wodnego nośności łożyska nr 1 (cylindrycznego) oraz łożyska nr 2 (trójpowierzchniowego wstępnie obciążonego) dla dwóch wariantów wartości luzu względnego – 0,001 i 0,002. Wektor obciążenia działa w kierunku środka segmentu

Figures 8 and **9** depict a comparison of the minimum water film thicknesses of four variants as a function of the acting load. For an assumed minimum water film thickness of 0.02 mm, the load-carrying capacity for each variant differs significantly, spanning 0.375 to 0.75 kN in the case of the load directed towards an axial groove and 0.75 to 1.4 in the case of the load directed towards the middle of a segment.

CONCLUSIONS OF PERFORMED CALCULATIONS

The performed calculations allow for the following conclusions:

1. The analysis demonstrated that, for the estimated 1 kN radial load, both bearing variants are capable of theoretical operation under hydrodynamic lubrication conditions. For the estimated 1 kN load, the minimum film thickness amounts to 0.015–0.025 mm, depending on the bearing geometry and load direction.
2. The calculation results point to a relatively low hydrodynamic load-carrying capacity of the bearings, which is mainly caused by the low rotation speed of the journal and its small diameter
3. The calculations did not consider any imperfections of the journal shape and the bearing shells, the angular misalignment of the journal, surface roughness, and other factors which, in real-life conditions, will lower the load-carrying capacity of a bearing compared to the obtained theoretical results. Consequently, the utilized bearing material must be able to operate in the condition of mixed lubrication without significant wear.
4. The two analysed bearing types (cylindrical and three-surface preloaded) were examined with relative clearance variants of 0.001 and 0.002 demonstrate significantly varying load-carrying capacities.
5. As could be expected, the relative clearance of 0.001 increases the load-carrying capacity by about four times compared to the relative clearance of 0.002. A reduction of clearance under 0.001 is difficult to achieve in practice due to manufacturing errors, thermal expansion of components, etc.
6. For an assumed minimum water film thickness of 0.02 mm, the highest capacity is achieved by the preloaded bearing with a relative clearance of 0.001; therefore, in this case, the three-surface preloaded bearing was recommended for modernization.
7. Predictably, the load-carrying capacity of the bearings also depends on load direction. When the load is directed towards the middle of a segment, the capacity is approximately twice lower. Concurrently, the lowest sensitivity to a change in load direction is demonstrated by a three-surface preloaded bearing with a clearance value of 0.001.

SUMMARY

Based on the performed calculations, the bearing's installation conditions, and a cost analysis, it was decided that the modernization of the Braniewo Hydroelectric Power Plant should utilize natural guaiacum wood as the bearing material, by virtue of it being able to operate in the conditions of lubrication with water directly from the watercourse. This solution will guarantee a bearing lifespan of many years.

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