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EXPERIMENTAL RESEARCH ON GAS FOIL BEARINGS WITH POLYMER COATING AT AN ELEVATED TEMPERATURE

BADANIA GAZOWYCH ŁOŻYSK FOLIOWYCH Z POWŁOKĄ POLIMEROWĄ W PODWYŻSZONEJ TEMPERATURZE

Key words:

foil bearings, gas bearings, high-speed bearings, micro-turbines

Słowa kluczowe:

łożyska foliowe, łożyska gazowe, łożyska wysokoobrotowe, mikroturbiny

Abstract

As demand for high-performance fluid-flow machines (including micro-turbines) increases across the globe, new non-conventional bearing systems are needed. In the last years, specialized technical solutions involving the use of gas foil bearings have been progressively introduced. The application of carefully selected, thin foils as key parts of foil bearings ensures stable operation of the rotor, which is supported by such bearings, even at very high rotational speeds. The article discusses the tests performed on the foil bearings incorporating a friction relieving polymer coating. The research was conducted on an

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advanced test rig allowing the experiments to be run at high speeds and elevated temperatures, which is in conditions that are typical for micro-turbine operation. The measurements of bearing components' temperature and vibration levels were carried out at various rotational speeds. The tested bearings were also assessed from the point of view of wear and durability. Conducted research demonstrated that the carefully selected materials that were used to manufacture foil bearings' key components have successfully contributed to achieving reliable operation within a wide range of rotational speeds, providing very good dynamic properties for the rotor.

INTRODUCTION

Following the development of high-speed fluid-flow machinery (including micro-turbines), scientists and engineers are increasingly trying to implement new, often unconventional solutions for bearing systems. Foremost among these are bearing systems based on gas foil bearings. The use of appropriately selected thin foils ensures stable operation of the rotor supported on such bearings, even at very high rotational speeds in combination with elevated temperatures **[L. 1–4]**.

In many countries and research and industry centres, studies are being conducted on foil bearings. These studies focus on both the practical approach for preparing new bearing systems and their theoretical modelling **[L. 1, 2, 5]**. In general, significant attention is placed on the optimization of bearing design and tribological issues, including the selection of suitable constructional and functional materials. Foil bearings' sliding layers may be made of carefully selected metals, metal-ceramic composites, and plastics **[L. 4, 6, 7]**. On the basis of a literature review and the authors' past experiences, it can be concluded that, in the case of bearings operating at low temperatures, the best results in terms of surface durability and resistance to motion are achieved by using soft sliding coatings for top foils that come into contact with a hard and wear-resistant journal **[L. 7, 8]**. When bearings are exposed to high temperatures (above 200°C), metal-ceramic composites are commonly used **[L. 4**, **6]**.

A foil bearing is a mechanical system, the modelling of which is extremely difficult. A model of such a bearing has to take into account several physical phenomena, such as non-linear deformations of thin foils having a complex geometry, friction and wear processes on the contact surfaces, heat exchange, thermal deformations, flow-related phenomena taking place within the lubricating gap, and fluid-structure interactions **[L. 9–11]**. Therefore, in this case, computational models are of limited reliability and are usually used only at the initial design stage, in order to analyse the phenomena that are difficult to measure on real objects. In practice, this generally means that each manufactured foil bearing goes through a series of tests prior to its application in a target machine. This is done on specially designed test rigs, allowing the simulation of real operating conditions **[L. 4, 7, 12]**.

The aim of the experimental research that is described in this paper is to verify that all components of the new foil bearing have been properly assembled and are operating satisfactorily. The bearing has a protective coating (made of carefully selected plastics) that is intended specifically to reduce friction and protect its parts from wear. The thermal and vibration characteristics of the bearing operating at both room and elevated temperatures were presented and then compared with each other very thoroughly. During the tests conducted, the technical condition of the bearing and the wear level of the sliding coating were assessed.

DESCRIPTION OF THE TEST RIG AND THE BEARING TESTED

The experimental studies were carried out in the Machine Vibrodiagnostics Laboratory at the Institute of Fluid-Flow Machinery, Polish Academy of Sciences in Gdańsk. The test rig used makes it possible to perform experimental research on rotors supported by foil bearings, and it is equipped with a drive motor with a maximum rotational speed of 24,000 rpm. Elevated ambient temperatures are obtained by means of a "heat gun" (consisting of an instantaneous air heater and a fan) and the infrared radiators. All components of the test rig are fixed to a massive steel plate. The whole structure rests on a rigid steel frame. **Figure 1** illustrates the test rig that is configured so that the research discussed herein was made possible.

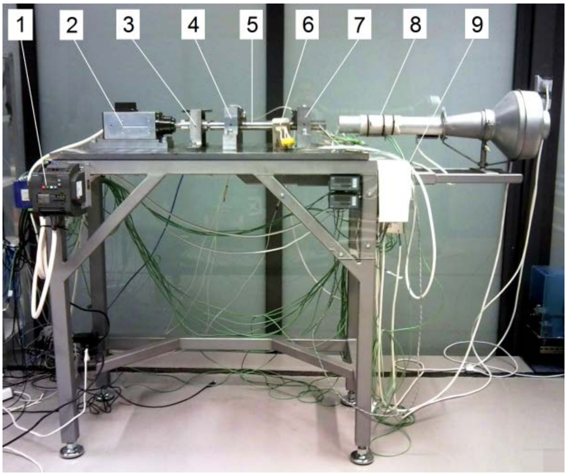

Fig. 1. Test rig for testing rotors supported by foil bearings (1 – speed controller, 2 – electro-spindle, 3 – coupling guard, 4 – bearing support no. 1, 5 – shaft, 6 – infrared radiator, 7 – bearing support no. 2, 8 – heat gun, 9 – temperature controller)

Rys. 1. Stanowisko do badania wirników z łożyskami foliowymi (1 – regulator napędu, 2 – elektrowrzeciono, 3 – osłona sprzęgła, 4 – podpora łożyska nr 1, 5 – wał, 6 – promienniki podczerwieni, 7 – podpora łożyska nr 2, 8 – działo cieplne, 9 – regulator temperatury)

The test rig is equipped with a measuring system consisting of a 36-channel data acquisition and signal conditioning system LMS SCADAS Mobile and a set of sensors such as thermocouples, accelerometers, eddy current sensors, and tachometers. For the purpose of monitoring temperature changes of Bearing Number 2, data collection was conducted using 12 measurement points. The thermocouples' measuring junctions were in contact with the top foil on the bushing side. The method for bringing the thermocouples into the bearing is presented in **Fig. 2a**. **Figure 2b** illustrates the method of the measurement of the relative displacement of the shaft near the bearing. The arrangement of temperature measuring points inside the bearing is shown in **Fig. 3b**.

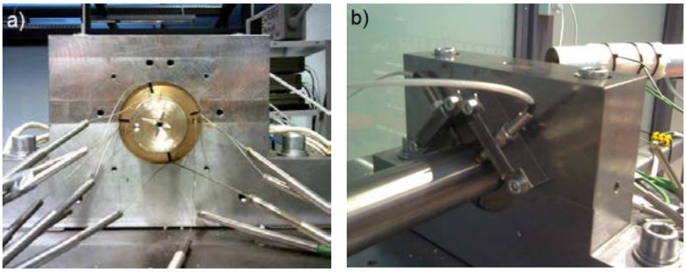

Fig. 2. Method of affixing of the measurement sensors in the test rig: a – thermocouples, b – eddy current sensors

Rys. 2. Sposób mocowania czujników pomiarowych na stanowisku badawczym: a – termopary, b – czujniki wiroprądowe

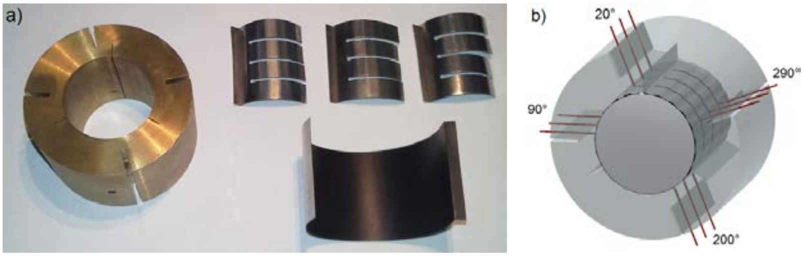

Fig. 3. Parts of the tested foil bearing before its assembly (a) and location of the temperature measurement points (b)

Rys. 3. Części badanego łożyska foliowego przed złożeniem (a) oraz rozmieszczenie punktów pomiaru temperatury (b)

The bearing tested included one top foil and three bump foils. It was developed in cooperation with the research team from the Institute of Turbomachinery, Lodz University of Technology, within the framework of the project no. POIG.01.01.02-00-016/08 **[L. 13]**. The journal diameter was 34 mm and the bushing width was 40 mm. The sheets forming the foils with thicknesses of 0.1 mm were made of chromium-nickel alloy (sold under the brand name Inconel). The top foil is covered on one side with a thin fluoropolymer layer that reduces friction and wear during the run-up and run-down processes. The bearing journal is made of steel and has a plasma-sprayed surface layer of chromium oxide. The bump foil was formed by means of cold working. All components of the bearing, just prior to its assembly, are shown in **Fig. 3a**. **Figure 3b** presents the arrangement of temperature measurement points.

TEMPERATURE DISTRIBUTION IN THE FOIL BEARING

In order to assess the effect of the ambient temperature on the foil bearing operation, the experimental studies were conducted at both room and elevated temperatures. Temperature measurement of the elements of a foil bearing is a very good way to check the proper functioning of this bearing. When a bearing node malfunctions, the top foil temperature increases rapidly, particularly where it is the most heavily loaded. This is because the demanding operating conditions (e.g., high load, too low rotational speed or a skewed bearing) do not allow the lubricating wedge to form. During such an operation, there is a direct interaction between the journal and the top foil. The bearing elements are not only exposed to the heaviest wear but also have to cope with a rapid increase in temperature. A similar situation occurs in the case of run-up and run-down processes; however, low speeds and short durations do not cause damage to the bearing.

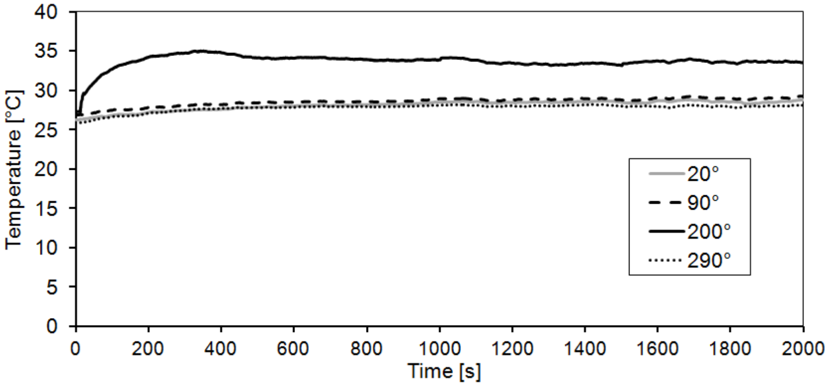

Fig. 4. Top foil temperature vs. time (foil bearing operating at room temperature)
Rys. 4. Zmiany temperatury folii ślizgowej w łożysku foliowym pracującym w temperaturze otoczenia

The measurement results concerning the temperature inside the bearing operating at room temperature (approx. 25°C) and elevated temperatures (approx. 100°C) are presented in **Figures 4** and **5**, respectively. During this research, the rotational speed of the rotor was gradually increased until it reached 24,000 rpm, after which the speed was kept constant until thermal equilibrium of the bearing node was reached. The heating of the bearing elements took well over 50 minutes, and it was carried out while the rotor was in motion. The temperature values shown in **Fig. 5** are presented from the time when the temperature reached 100°C in the coldest place inside the bearing.

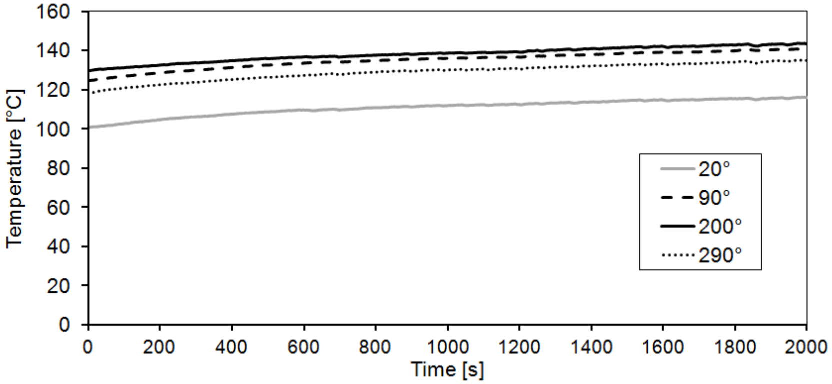

Fig. 5. Top foil temperature vs. time (foil bearing operating at elevated ambient temperature)

Rys. 5. Zmiany temperatury folii ślizgowej w łożysku foliowym pracującym w podwyższonej temperaturze

Figures 4 and **5** present the only measurement results for the thermocouples placed in the bearing's centre, since the temperature differences recorded for the neighbouring thermocouples were around 1°C **[L. 14]**. During the operation at room temperature (**Fig. 4**), the highest increase in temperature took place in the lower part of the bearing (at an angular position equal to 200°), namely from 10°C to 35°C. At other measuring points, the temperature increases were significantly lower (e.g., the temperature recorded in the upper part of the bearing was only 29°C). The increases in temperature observed during tests carried out at an ambient temperature of 100°C were significant and even higher than the ones found at room temperature operation. The temperatures in the lower and upper parts of the bearing stabilised at around 144°C and 116°C, respectively. The temperatures in the side parts of the bearing reached up to 140°C. It is apparent that the temperature rise did not exceed 50°C when tested at a constant rotational speed of 24,000 rpm. According to the authors of this paper, this was mainly due to a thermal expansion of the journal (causing the reduction in the radial clearance of the bearing), a change of material characteristics and a worsening of the cooling conditions of the bearing. The hot air flowing from the heat gun towards the bearing had a temperature around 160°C. Despite a constant exchange of air between the inside and outside spaces, the conditions conducive to cooling the bearing are no longer present, unlike during the operation at room temperature. Since the longer operation of the system did not cause a further increase in temperature of the top foil, the conclusion can be made that the bearing analysed was capable of operating under the tested conditions.

VIBRATION OF THE ROTOR SUPPORTED BY FOIL BEARINGS

During the temperature measurements in the foil bearing, the displacements of a rotating shaft with respect to the bearing supports were also measured. The objective of these measurements was to identify possible dynamical problems connected with the temperature rise in the space located in the immediate vicinity of the bearing. The measurement was made for both bearings, close to their supports (**Fig. 2b**). Furthermore, in order to check the system's vibrations at different temperatures and for the whole range of rotational speeds, the measurements were conducted during the run-up of the rotor to a speed of 24,000 rpm at a constant acceleration.

The measurement results obtained for both room and elevated operation temperatures are presented in **Fig. 6** and **Fig. 7**, respectively. In these graphs, the resonance area can be clearly identified, which occurred around a rotational speed of 8,000 rpm. The analysis of the results shows that the change in ambient temperature of the system resulted in a change of the resonance speed. When the bearing operated at room temperature (approx. 25°C), the highest vibration amplitudes were observed at a rotational speed of around 8,400 rpm. After the ambient temperature was increased to 100°C, the highest vibration amplitudes were recorded at approximately 7,800 rpm. The decrease in the speed value can be explained by a higher compliance of the bearing's foils when operating at an elevated temperature. In this context, attention must also be given to the increase in the maximum vibration amplitude levels in both bearings. Looking at **Figures 6** and **7**, it can be observed that the maximum peak-to-peak vibration amplitude, relating to a horizontal direction, changes from 0.18 to 0.28 mm for Bearing Number 1 and from 0.09 to 0.13 mm for Bearing Number 2 (at the heat gun). Similar differences can be observed regarding the vibration amplitudes in a vertical direction recorded in Bearing Number 1. However, the maximum vibration level in Bearing Number 2 measured in a vertical direction was only minimally dependent on the ambient temperature level.

At lower and higher rotational speeds outside the resonance range, the rotor supported by foil bearings was characterized by a stable operation, and the maximum vibration level did not exceed a few dozen micrometres. There was no increase in vibration level or signs of unstable operation noted – even at the maximum speed (24,000 rpm). Thus, it can be concluded that a very stable operation of the rotor-bearing system can be achieved on the condition that the current rotational speed remains outside the resonance area of the rotor, and this condition is independent of ambient temperature. In the case of a real machine having a similar rotor-bearing system, it is apparent that only the speeds above the resonance speed (i.e. from approximately 12,000 rpm) could be taken into consideration for determining the operating speed range. A stable gaseous lubricating film was not formed in any of the bearings operating below a rotational speed of 8,000 rpm. A continuous and reliable operation, in this speed range, would therefore be impossible.

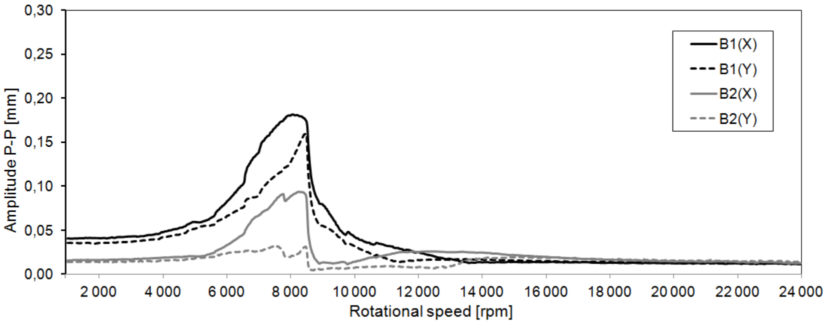

Fig. 6. Peak-to-peak shaft vibration amplitude vs. rotational speed (foil bearings operating at room temperature)

Rys. 6. Przebiegi amplitud drgań względnych czopów łożysk foliowych w zależności od prędkości obrotowej w temperaturze otoczenia

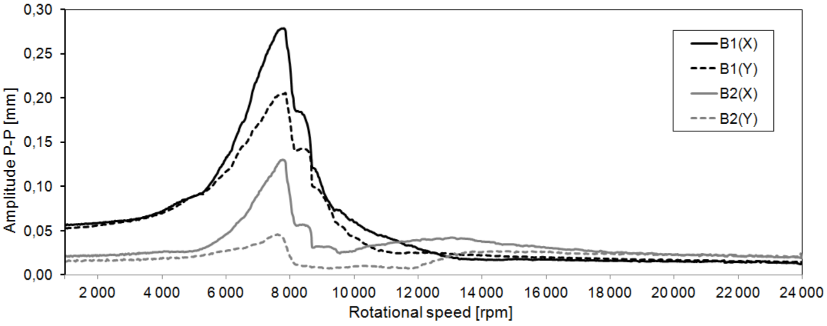

Fig. 7. Peak-to-peak shaft vibration amplitude vs. rotational speed (foil bearings operating at elevated ambient temperature)

Rys. 7. Przebiegi amplitud drgań względnych czopów łożysk foliowych w zależności od prędkości obrotowej w podwyższonej temperaturze

ASSESSMENT OF THE FOIL BEARING WEAR

During the experimental research carried out for this paper, the rotor and the bearing were separated from the bearing support at the end of every measuring series in order to assess the wear of bearing components. Previous studies have shown that, under some operating conditions, damage to the sliding layer can occur in a short period of time **[L. 7]**. In the overwhelming majority of cases, the reasons behind this phenomenon are the following: an impact of measuring devices on the bearing operation, an improper selection of materials, excessive load, or an incorrect support of the bearing sleeve. In the light of past experience, any factors influencing accelerated bearing wear are eliminated and not treated extensively herein. The sliding layer's condition after the tests carried out at elevated ambient temperatures can be seen in **Fig. 8**.

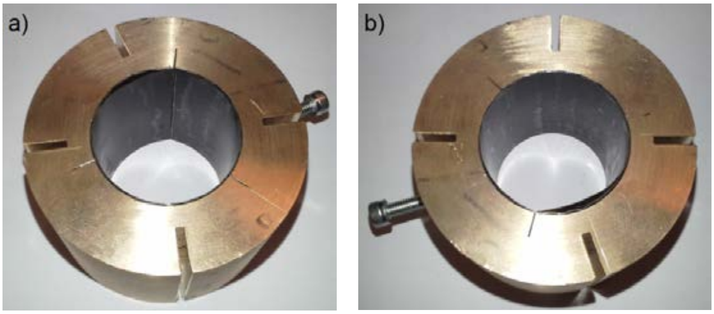

Fig. 8. Photographs presenting an external surface of the top foil mounted in a tested bearing: a – upper part, b – lower part

Rys. 8. Zdjęcia przedstawiające stan powłoki ślizgowej w badanym łożysku: a – widoczna górna część folii ślizgowej, b – widoczna dolna część folii ślizgowej

The visual examination of the condition of the top foil's surface being in contact with the journal did not show any damage. At several places distributed across the foil, a smoothing of its surface was observed, but there was no place in which the protective coating was worn out. Although small signs of wear in the sliding layer have been noted, they should be treated as a result of breaking in the bearing. After testing, the foil bearing was in a very good technical condition that allows its subsequent exploitation without any operating restrictions.

SUMMARY AND CONCLUSIONS

The article presents the results of research on gas foil bearings operating at two ambient temperatures (25°C and 100°C). The experimental investigation was conducted using a specialised test rig equipped with a high-speed rotor supported by the pair of foil bearings. The rotor was set in motion by means of an electro-spindle. As a result of the study, thermal and dynamic characteristics of the system were obtained for a wide range of rotational speeds.

The results of this study showed that the temperature of the top foil increased in a gradual manner until thermal equilibrium of the bearing node was reached, and this process was independent of the ambient temperature. The highest temperatures were recorded in the lower part of the bearing, which was in line with expectations. This part of the bearing is subjected to the static load caused by the shaft mass, narrowing the lubrication gap. This is an area where the lubricating air is compressed and the layer of air has intensive contact with the top foil and the journal. Moreover, considerable amounts of heat are also produced. The rise in temperature of the top foil was higher at an increased ambient temperature than at room temperature, due to both the change in the lubricating gap's geometry and the deterioration of conditions conducive to cooling the bearing (a flow of hot air was directed at the bearing).

The change of bearings' operating temperatures entailed the alteration of dynamic characteristics of the rotating system. In line with an increase in temperatures, the resonance speed of the system decreased. The vibration amplitudes of the bearing journals also rose, but this mainly concerned the resonance area. At the rotational speeds both above and below the resonance speed, the rotor-foil bearing system operated stably and the vibration amplitudes remained at very low levels with no noteworthy fluctuations to report. The very good condition of the polymer coating on the top foil is also a strong indication of the proper operation of the foil bearing. The coating does not have any signs of visible damage, despite the demanding operating conditions of high rotational speeds and elevated temperatures.

Information on research funding

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Streszczenie

W artykule omówiono badania eksperymentalne łożysk foliowych ze specjalną powłoką polimerową zmniejszającą tarcie. Powłoką polimerową została pokryta jedna strona foli ślizgowej, która współpracuje z czopem. Badania zostały wykonane na specjalistycznym stanowisku badawczym umożliwiającym prowadzenie eksperymentów przy wysokich prędkościach w podwyższonej temperaturze, a więc w warunkach typowych dla mikroturbin. Podczas badań prowadzono pomiar temperatury elementów łożyska oraz drgań czopa przy różnych prędkościach obrotowych. Badane łożyska foliowe były również oceniane pod kątem zużycia i trwałości. Przeprowadzone badania wykazały, że przy odpowiednio dobranych materiałach łożyska foliowe mogą pracować przy minimalnym zużyciu, zapewniając bardzo dobre właściwości dynamiczne wirnika w szerokim zakresie prędkości obrotowych.