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EXPERIMENTAL INVESTIGATION OF A FOIL BEARING STRUCTURE WITH A POLYMER COATING UNDER STATIC LOADS

BADANIA EKSPERYMENTALNE STRUKTURALNEJ WARSTWY NOŚNEJ ŁOŻYSKA FOLIOWEGO Z POWŁOKĄ POLIMEROWĄ W ZAKRESIE OBCIĄŻEŃ STATYCZNYCH

Key words: foil bearings, high-speed bearings, static load, structural stiffness.

Abstract Gas foil bearings can operate at very high temperatures and rotational speeds. The operation under such conditions requires developing an appropriate bearing design, including the use of advanced material solutions. This article presents one of the basic stages of work on a new foil bearing, namely, experimental research on the structural supporting layer of such a bearing regarding its static loads. Tests of the bearing were carried out on a test rig specially prepared for this purpose. Changing the magnitude and direction of the load was possible. The elasto-damping elements of the bearing were made of thin metal foils. In addition, a layer of carefully selected polymer was applied onto one side of the top foil in order to protect the surface and reduce friction. Characteristics of the structure of the foil bearing were determined at various load variants after taking a series of measurements upon it. The conducted research has yielded much information about static characteristics of the structural supporting layer of a new foil bearing in which the top foil's surface is covered with a layer of polymer. These results can be used, among other things, to optimise the bearing design and to verify numerical models.

Słowa kluczowe: łożyska foliowe, łożyska wysokoobrotowe, obciążenie statyczne, sztywność strukturalna.

Streszczenie Gazowe łożyska foliowe mogą być stosowane przy bardzo wysokich prędkościach obrotowych oraz w wysokich temperaturach. Praca w takich warunkach wymaga jednak odpowiedniej konstrukcji łożyska oraz zaawansowanych rozwiązań materiałowych. W niniejszym artykule przedstawiono jeden z podstawowych etapów prac nad nowymi łożyskami foliowymi, polegający na badaniach eksperymentalnych strukturalnej warstwy nośnej takich łożysk w zakresie obciążeń statycznych. Badania wykonano na specjalnie do tego celu przygotowanym stanowisku laboratoryjnym, umożliwiającym zmianę wartości i kierunku działania obciążenia. Elementy sprężysto-tłumiące badanego łożyska zostały wykonane z cienkich metalowych folii. Dodatkowo, folia ślizgowa została z jednej strony pokryta wyselekcjonowanym materiałem polimerowym, który zmniejszał tarcie i pełnił funkcję ochronną. Badania obejmowały kilka serii pomiarowych, w których wyznaczono charakterystyki badanego układu przy różnych wariantach obciążenia. Dzięki przeprowadzonym badaniom pozyskano charakterystyki statyczne strukturalnej warstwy nośnej nowego łożyska foliowego z powłoką wykonaną z materiału polimerowego, które można wykorzystać m.in. do optymalizacji konstrukcji oraz weryfikacji modeli łożyska.

INTRODUCTION

Unlike commonly used types of bearings, gas foil bearings can withstand extremely harsh operating conditions. They can operate at rotational speeds exceeding 100,000 rpm as well as at temperatures above 500°C [**L. 1**]. Although foil bearings have been developed for some decades, new material solutions, as well as advances in design and production methods, allow obtaining better and better classes of performance [**L. 2, 3**]. In bearings of this type, appropriately formed compliant elements are placed between the journal and

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the sleeve in order to improve elastic-damping properties [**L. 4**]. In both radial and thrust bearings, these elements usually have the form of thin metal foils, suitably shaped and fitted to other bearing parts [**L. 5**]. During operation of the rotating system, foils deform under static and dynamic loads, which is accompanied by energy dissipation. An adequate selection of the shape of foils, as well as constructional and functional materials, allows modifying both the properties of the bearing [**L. 6**] and the entire rotating system [**L. 7**]. Sometimes, only minor modifications to the foil bearings are enough to significantly improve the dynamic performance of a high-speed rotor. Paper [**L. 8**] describes very unusual foil bearings. It was explained how their properties can be actively regulated in order to adjust the support characteristics to the current regime of the rotating system. The dynamic performance of foil bearings can also be made better by increasing the preload by mounting additional foils [**L. 9**] or altering the number and size of elements that support the top foil [**L. 10**].

During run-up and coast-down of the rotor supported by foil bearings, the top foil comes into direct contact with the journal due to the low rotational speed. A poorly selected friction couple may result in premature wear of the bearing. Depending on the regime, top foils are coated with various types of metals, metal-ceramic composites, or plastics [**L. 11**]. As far as low-temperature regimes are concerned, the highest durability and the lowest resistance to motion are achieved by using soft anti-friction coatings made of plastics [**L. 12**]. Foil bearings with appropriately prepared top foils can operate for long hours at ambient temperatures greatly above 100°C [**L. 13**]. At higher ambient temperatures, metal-ceramic composites are preferred, which have high durability and are characterized by a low coefficient of friction [**L. 14**]. Bearings whose top foils are coated with such materials can even be used in gas microturbines, where they are able to operate in the immediate vicinity of a combustion chamber and exposed to off-gas [**L. 3**].

Before applying newly designed foil bearings in a particular machine, one has to conduct a series of experimental tests in order to check their functioning under various operating conditions. This is due to the fact that even the most sophisticated numerical models of foil bearings are not able to predict their actual characteristics at various operational loads and do not allow one to estimate how long their service life can be. From a mechanical point of view, a foil bearing is a very complex system, so numerical models can imitate its way of operation only in some operational ranges [**L. 15**]. Obtaining accurate results of numerical simulations of foil bearings is extremely difficult, because deformations of their elastic components are highly not reproducible [**L. 16**]. Even though simulation methods are more and more often used at the initial stages of the development of foil bearings, the final check of their properties is still carried out using experimental methods.

The following part of the article describes experimental research aimed at determining the characteristics of the foil bearing's structure subjected to static loads. The research was necessary to assess the static stiffness of the structural part of a newly designed foil bearing as well as to verify numerical models that had been developed earlier [**L. 6**]. Since the top foil of the tested bearing has the coating made of a polymer, the presented results are a novelty in the literature.

CHARACTERISTICS OF THE TEST RIG AND OF THE RESEARCH OBJECT

The research on the structural part of the foil bearing was carried out using a test rig (**Fig. 1**) specifically adapted for this purpose. In an earlier period, the test rig served for testing the dynamic performance of rotors supported by foil bearings. Interestingly, it is equipped with very rigid bearing supports that can be fixed at various points on the steel massive plate. In order to determine the characteristics of only the structural part of the bearing, the rotor was dismantled and replaced with a rigidly supported, smooth shaft with a diameter of 34 mm. The tested bearing was situated in the middle of the shaft, between the supports. The bearing sleeve was inserted into an additional sleeve, which made it possible to install a force sensor and a steel rope that served for loading the bearing (**Fig. 2**). A precise laser displacement sensor was fixed at the opposite side of the sleeves. The tests were carried out at four different bearing sleeve's positions in relation to the load direction. The bearing was rotated by an angle of 90° before each measurement series. Loading the bearing was carried out using a set of steel weights. Each measurement series involved the gradual increase of the load acting on the bearing's structure and then its decrease until all weights were removed. The sleeve displacement in the direction consistent with the

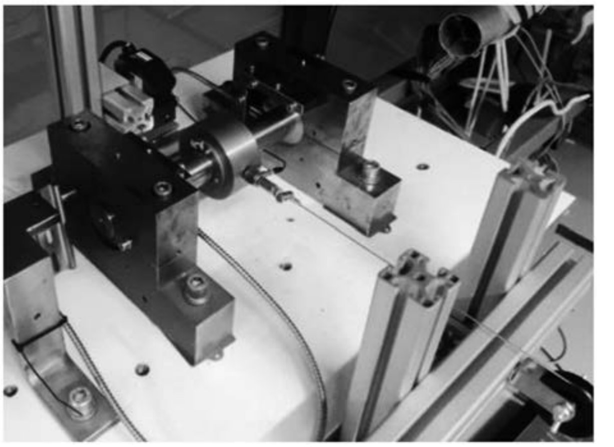

Fig. 1. Test rig used for testing the foil bearing subjected to static loads

Rys. 1. Stanowisko badawcze przygotowane do badań łożyska foliowego przy obciążeniu statycznym direction of the acting force was registered. In order to provide increased reliability of measurements, three measurement series were conducted for each angular position of the bearing.

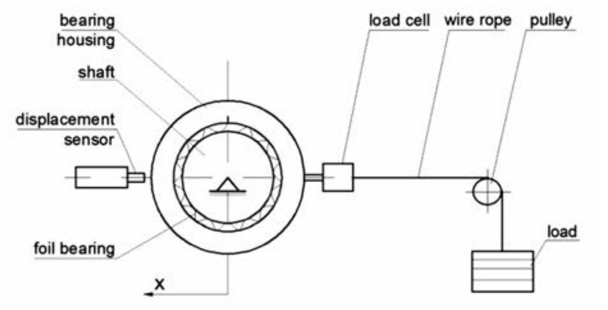

Fig. 2. Schematic diagram of the test rig
Rys. 2. Schemat stanowiska badawczego

The tests discussed herein were made for a newly designed and manufactured foil bearing whose nominal diameter is 34 mm and length is 40 mm. This bearing has one top foil with one side covered with a layer of polymer, which is about 25 μm thick. The top foil is supported by three bump foils distributed evenly around the entire circumference of the sleeve. The bump foils are divided equally into four sections (in the axial direction). All foils are made of a nickel-chromium-molybdenum alloy and have a thickness of 0.1 mm. The geometry of the bump foil before assembling in the sleeve is presented in **Fig. 3**. The bearing sleeve and its external guards are made of bronze. In the developed foil bearing, one thermocouple had been mounted in such a way that it was possible to measure the temperature of the top foil at the point where the load was the highest. **Figure 4** presents all components of the tested bearing prior to its assembly and the fully assembled bearing.

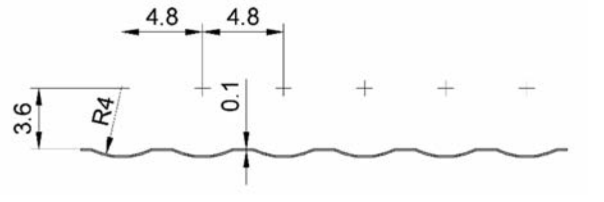

Fig. 3. The bump foil geometry (dimensions in mm)
Rys. 3. Geometria folii podpierającej (wymiary podano w mm)

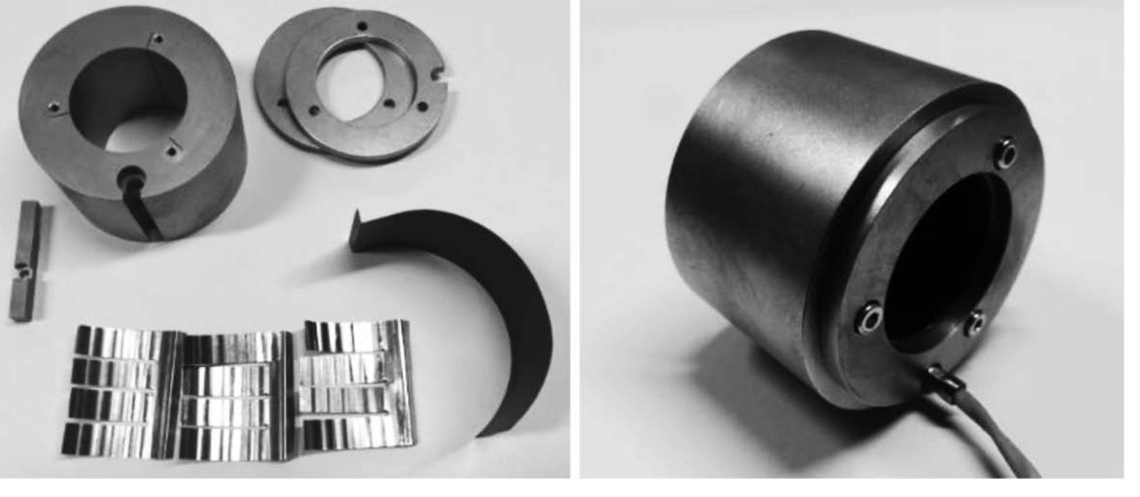

Fig. 4. The tested foil bearing before and after the assembly
Rys. 4. Badane łożysko foliowe przed i po złożeniu

RESULTS OF THE EXPERIMENTAL RESEARCH

In each measurement series, the foil bearing sleeve was loaded in several steps until the maximum load (approx. 70 N) was achieved. The displacement of the sleeve was recorded. Based on the load curve, it was possible to assess the static stiffness of the bearing. The measurement of the journal displacements during its unloading was an equally important stage of the research. Load and unload curves are needed for the preparation of the "hysteresis loop," which demonstrates energy losses due to energy dissipation in the bearing. The losses are primarily caused by the friction between the mating elements of the bearing, including friction between the top foil and the bump foils as well as between the bump foils and the sleeve.

The results of experimental research, in the form of load and unload curves (at various angular positions of the sleeve in relation to the direction of the force that acted on it), are presented in **Figs. 5–8**. All of these curves were plotted on the basis of measurements made during the subsequent steps of the loading and unloading phases. The angular position of the sleeve was changed (from the position denoted by 0° to the position denoted by 270°) in order to determine characteristics of the bearing in various directions. The first angular position (denoted by 0°) corresponds to the initial position of the sleeve, namely, the mounting location of the top foil (the "lock") was situated at the top of the bearing (**Fig. 2**). Moreover, it is the orientation similar to that in which bearings are mounted in machines whose shafts are loaded with the gravitational force. In subsequent measurement series, the next position of the bearing sleeve was obtained by quarter-turning. When the sleeve rotates, so does the lock. The subsequent positions of the top foil's lock were the following: 90° – it was close to the displacement sensor, 180° – it was at the bottom of the bearing, 270° – it was near the place for wire rope fixing.

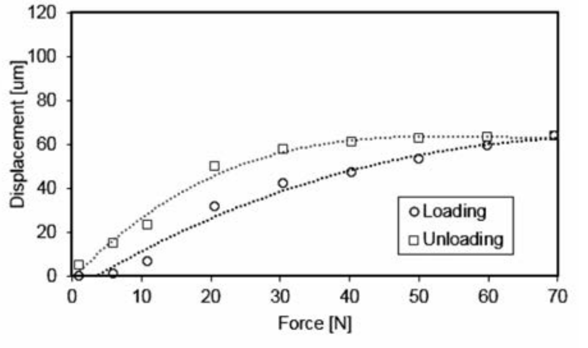

Fig. 5. Displacement of the foil bearing sleeve vs. static load at the sleeve's angular position denoted by 0°

Rys. 5. Przebieg przemieszczeń panwi łożyska foliowego w zależności od obciążenia statycznego przy położeniu panwi oznaczonym jako 0°

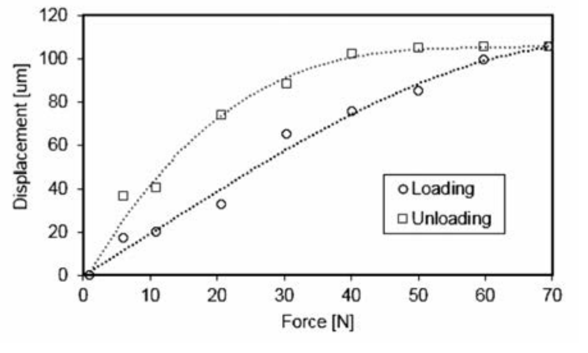

Fig. 6. Displacement of the foil bearing sleeve vs. static load at the sleeve's angular position denoted by 90°

Rys. 6. Przebieg przemieszczeń panwi łożyska foliowego w zależności od obciążenia statycznego przy położeniu panwi oznaczonym jako 90°

The obtained characteristics show that the direction of the load had a great impact on the measurement results in such a way that both the magnitude of the displacements and the shape of curves changed at a constant load. In all of the analysed cases in the investigated load range, none of the load/unload curves was linear. The tested system has the progressive characteristics, which means that its stiffness increases as the load increases. This is a beneficial feature of the rotating system, because its bearings can prevent excessive displacements of the rotor when large external loads are acting. In each analysed case, the load and unload curves differ significantly in terms of their shape. This showed that the system is very capable of dissipating energy. This is an advantage for these bearings, due to the stable operation of the rotor and a lower vibration level in connection therewith.

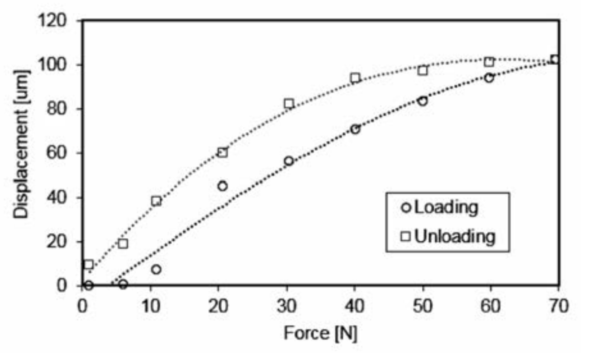

Fig. 7. Displacement of the foil bearing sleeve vs. static load at the sleeve's angular position denoted by 180°

Rys. 7. Przebieg przemieszczeń panwi łożyska foliowego w zależności od obciążenia statycznego przy położeniu panwi oznaczonym jako 180°

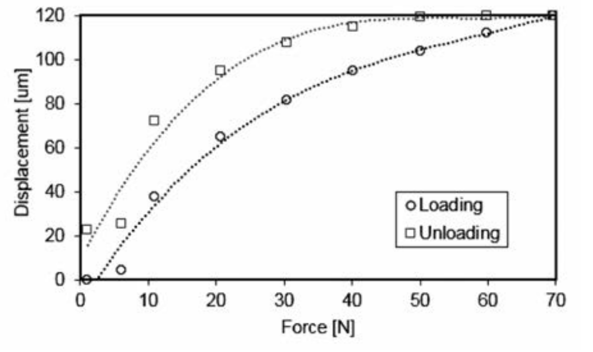

Fig. 8. Displacement of the foil bearing sleeve vs. static load at the sleeve's angular position denoted by 270°

Rys. 8. Przebieg przemieszczeń panwi łożyska foliowego w zależności od obciążenia statycznego przy położeniu panwi oznaczonym jako 270°

After having compared with each other the results obtained for different directions of the acting load, it has become clear that the smallest displacement was registered at the sleeve's position denoted by 0° and was approx. 60 μm at the maximum load (**Fig. 5**). The maximum registered displacement was around 120 μm and occurred at the position denoted by 270° (**Fig. 8**). For the sleeve's positions denoted by 90°

and 180° (**Figs. 6** and **7**), the maximum displacement reached 100 µm. It can, therefore, be concluded that the bearing's structure is characterised by varying stiffness in the radial direction. The stiffness mainly depends on the position of the locks for fixing the top foil and the bump foils as well as on the distance of the place on which the load acts from the fixing points and from the unattached ends of the foils. Subsequent tests carried out for the same position of the bearing sleeve have not produced reproducible experimental results. In some cases, differences in the displacements for the same loads reached 50% and decreased as the load increased. Such large differences in successive tests result from the way the foils mate within a small lubrication gap that is bordered by the journal and the sleeve. Some researchers also experienced such differences [**L. 16, 17**]. When the load was low, the bearing stiffness depended a lot on the current deformation of the flexible foils as well as on the pace the load accrued and other factors.

CONCLUSIONS

This article has presented research on the structural supporting layer of a foil bearing subjected to static loads. The tested bearing has a nominal diameter of 34 mm and its top foil has one side coated with a polymer. The research results showed that the curve representing the bearing's load versus the displacement of the sleeve is not linear. The investigated bearing has progressive characteristics, because the displacement of the component on which the load acted decreased as the magnitude of the load increased. Furthermore, it was observed that the direction of the load has a great impact on the measurement results. The reason for this is the nonlinear geometry of the foil bearing along the internal circumference of the sleeve, where the fixing places of the foils are situated at certain distances from each other. Obtained results are also a proof that energy is dissipated during the displacement of the journal and the sleeve in relation to each other (the unload curve does not coincide with the load curve). Due to the conducted research, real characteristics of the structural supporting layer of a new prototypical foil bearing subjected to a static load were obtained, which allow estimating the stiffness of the bearing structure in various directions.

The studies presented herein are an initial stage of assessing the properties of the newly constructed foil bearing. Their results, along with the results of the tests carried out under dynamic loads (which are presented in a publication prepared in parallel), constitute a complete set of characteristics of the foil bearing's structure. They could be used, among other things, to assess the stiffness and damping properties of the structural part of the foil bearing. This information can then be used to optimize its construction and verify numerical models. Future research on foil bearings, apart from refining the modelling methods, will concern the further development of experimental techniques to estimate their characteristics. These activities will be accompanied by constant improvements to the construction of foil bearings. Present and future works are intended to spread the practice of applying foil bearings in high-speed turbomachines.

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