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OPERATIONAL PROBLEMS OF HIGH-SPEED FOIL BEARINGS TESTED UNDER LABORATORY CONDITIONS

Key words: foil bearings, gas bearings, high-speed bearings, bearing wear.

Abstract: The article discusses several issues related to the operation of gas foil bearings. Such bearings can withstand operation under very difficult conditions, such as very high rotational speeds or elevated temperature. At high rotational speeds, they provide low vibration levels. However, at low speeds, their operation causes some problems that are rarely discussed in the literature. The long-term operation of a foil bearing at low speed can result in a rapid wear of bearing components and their damage. The article gives special attention to issues such as wear of mating surfaces, material selection, the considerable journal displacements occurring at changes in speed, load and temperature, high starting torque, and initial clamp load after assembly. The discussed problems are illustrated by means of practical examples. Gaining a thorough understanding of these problems is a key factor when determining application areas of foil bearings, taking into consideration their essential operational properties. This paper sums up experiences the authors gathered so far, especially the ones related to testing and manufacturing gas foil bearings as well as attempts of applying such bearings to various types of fluid-flow machinery.

Problemy eksploatacyjne wysokoobrotowych łożysk foliowych badanych w warunkach laboratoryjnych

Słowa kluczowe: łożyska foliowe, łożyska gazowe, łożyska wysokoobrotowe, zużycie łożysk.

Streszczenie: W niniejszym artykule omówiono zagadnienia związane z eksploatacją gazowych łożysk foliowych. Łożyska tego typu mogą pracować przy bardzo wysokich prędkościach obrotowych, zapewniając niski poziom drgań wirnika. Podczas ich eksploatacji występują jednak pewne problemy, które nasilają się przy niskich prędkościach obrotowych. Może to powodować przyspieszone zużycie elementów łożyska prowadzące do ich uszkodzenia. W artykule zwrócono szczególną uwagę na: zużycie współpracujących powierzchni i dobór materiałów, przemieszczenia czopa występujące przy zmianach prędkości, temperatury i obciążenia oraz duży moment rozruchowy i zacisk wstępny. Omawiane problemy zostały poparte kilkoma przykładami. Znajomość tych zagadnień ułatwia określenie potencjalnych obszarów zastosowań łożysk foliowych oraz uwzględnienie ich rzeczywistych właściwości eksploatacyjnych. Artykuł stanowi podsumowanie dotychczasowych doświadczeń autorów związanych z rozwojem metod badania i wytwarzania gazowych łożysk foliowych oraz próbą ich zastosowania w różnego typu maszynach przepływowych.

Introduction

The development of high-speed fluid-flow machinery is accompanied by an increased demand for innovative bearing systems. One such option is foil bearings that enable stable operation of high-speed rotors at elevated temperatures [1–4]. Even under such conditions, there is no need for an external lubrication system. Very good dynamic properties of foil bearings are achieved by the use of special elastic-damping elements (made mostly of thin metal foils with appropriately modified surfaces). Their advantages are the reason why such bearings are widely applied to gas/vapour microturbines, compressors, and expanders [1, 2, 4]. However, foil bearings also exhibit some drawbacks that render them unsuitable for certain types of high-speed fluid-flow machines. Teams of engineers and scientists from all over the world are constantly working to eliminate these drawbacks and subsequent generations of foil bearings are getting better and better in terms of their load capacity [1, 5].

Actions aiming at the development of the above-mentioned bearing systems focus primarily on optimising the structure of bearing components as well as selecting materials that have suitable tribological and mechanical properties. Sliding layers of the journal and of the foils can be made of different materials, including plastics and metal-ceramic composites [6]. The type of material chosen for a given bearing system invariably depends on operating conditions. When it comes to operation at low temperatures, slide layers are made of soft plastics, but journals of hard materials that are resistant to abrasion [3, 6–8]

In order to speed up the process of designing foil bearings, new numerical models are often developed. Because of the fact that foil bearings are very complex mechanical systems, their modelling raises problems. A model of such a bearing should take into account, inter alia, nonlinear deformations of the thin foil of a complex geometry, friction processes, contact between the sliding surfaces, heat transfer, thermal deformations, flow phenomena in the variable geometry lubricating gap, and fluid–structure interactions [9, 10]. More or less advanced foil bearing numerical models are currently used at an early stage in the bearing system design. This means that each new bearing has to have undergone tests enabling the assessment of its tribological and dynamic properties under conditions similar to real operating conditions. It is done with the use of specially designed test rigs [11].

In this article, we discuss problems that we encountered during work on new foil bearings. Information provided here may be helpful for other researchers who want to develop and implement bearing systems equipped with such bearings.

1. Research on the temperature distribution in foil bearings

The research on the temperature distribution was conducted using a bearing that has one top foil and three bump foils. Figure 1 shows a photo of this bearing taken before it was assembled. The journal diameter and the bearing width are 34 mm and 40 mm, respectively. The top foil and bump foils are made of thin (0.1 mm in thickness) sheet metals, which are alloys sold under the trade name of Inconel. The top foil is coated with a polymer with carefully selected tribological properties. The steel bearing journal is coated with a molybdenum layer, protecting it against rapid wear. The bush, on which were mounted the foils and thermocouples (used to monitor temperature rises), is made of bronze. We used 12 thermocouples placed in the notches and holes, which were prepared specifically for this purpose.

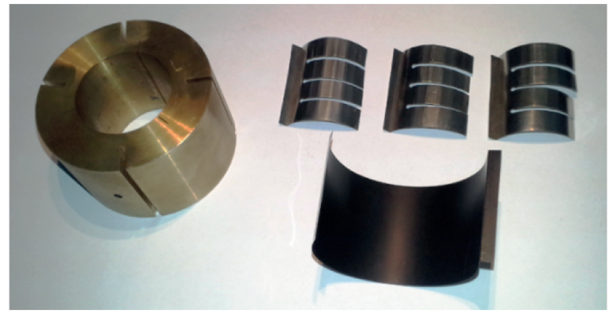

Fig. 1. Bearing components (the bush and the foils) prepared for assembly

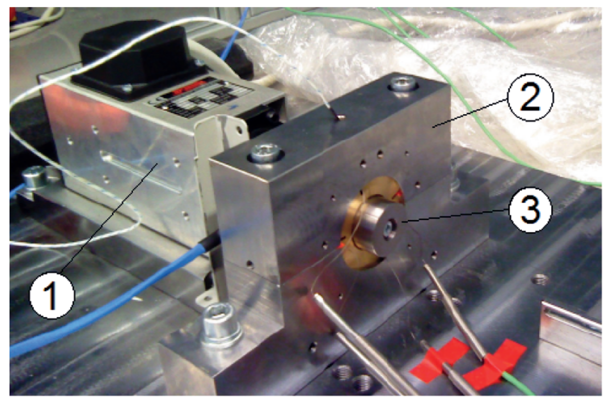

Fig. 2. Test rig (1 – electro-spindle, 2 – bearing support, 3 – journal)

The research on the temperature distribution may be carried out at speeds up to 24000 rpm, using the test rig demonstrated in Fig. 2. The experiment presented herein consisted in gradually increasing the rotational speed up to 15000 rpm (it lasted 55 seconds) and then maintaining that speed until a thermal equilibrium of the bearing node was achieved. The placement of all thermocouples in the bush, as well as the top foil temperatures measured by them at the central cross-section of the bearing, is presented respectively in Fig. 3a and 3b.

The highest temperature (59°C) was registered at the bottom part of the bearing, i.e. at the angular position denoted by ‘200°’ in Fig. 3a. The lowest rise in temperature can be observed at the top part of the bearing (angular position – 90°), where the top foil achieved a temperature of 25°C. At two other angular positions, denoted by ‘90°’ and ‘290°’, the measured temperatures achieved values of 52°C and 31°C, respectively. It can, therefore, be concluded that, during the first 55 seconds of the measurement, the increase in the temperature of the bearing as a whole was in the range of 5°C to 39°C. The occurrence of the highest rise in temperature at the bottom part of the bearing stems from the way it was loaded. It goes without saying that the bearing was subjected to the highest loads at its bottom part and, at the same time, this was the part where the lubricating film had the lowest thickness. The temperature measurement

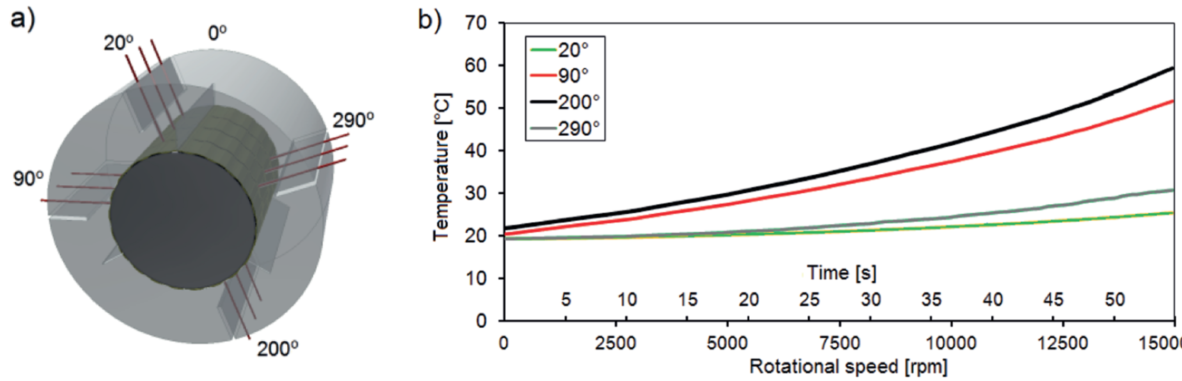

Fig. 3. The location of points for the measurement of temperature (a) and the obtained temperatures presented as functions of the rotational speed (b)

results obtained for two other cross-sections of the bearing are similar to the ones registered for the central cross-section, and the highest differences are approx. 2°C.

The expected temperature stabilisation of the bearing–after it operated at a constant rotational speed for some time–did not materialise. In fact, a continuing increase in the top foil temperature was observed. After some time (roughly 300 seconds passed), the foil achieved a temperature of 130°C. Under these conditions, the temperature distribution measurement was also conducted by means of a thermal imaging camera. The exemplary results of this measurement are presented in Fig. 4a. The journal temperature near the bearing rose to about 100°C. The temperature registered in the central part of the shaft was even higher, i.e. around 200°C. Since this temperature is close to the heat resistance of the sliding layer, it was suspected that it might have been damaged. That is why the research in question discontinued and the bearing was subjected to a visual inspection. It was found that there was considerable damage to the sliding layer in some places (Fig. 4b). The damage was caused by the gradual abrasion of the sliding layer by the rotating journal. An elevated temperature fostered the accelerated abrasion, because it resulted in a deterioration of material properties. Since the journal came into direct contact with the top foil, a continuation of the experiment would have the effect of increasing the temperature even more and would damage the bearing permanently. A misalignment of the journal and bush caused the excessive bearing load and, consequently, the damage to the foil. Such operating conditions were not favourable for forming a stable gaseous lubricating film.

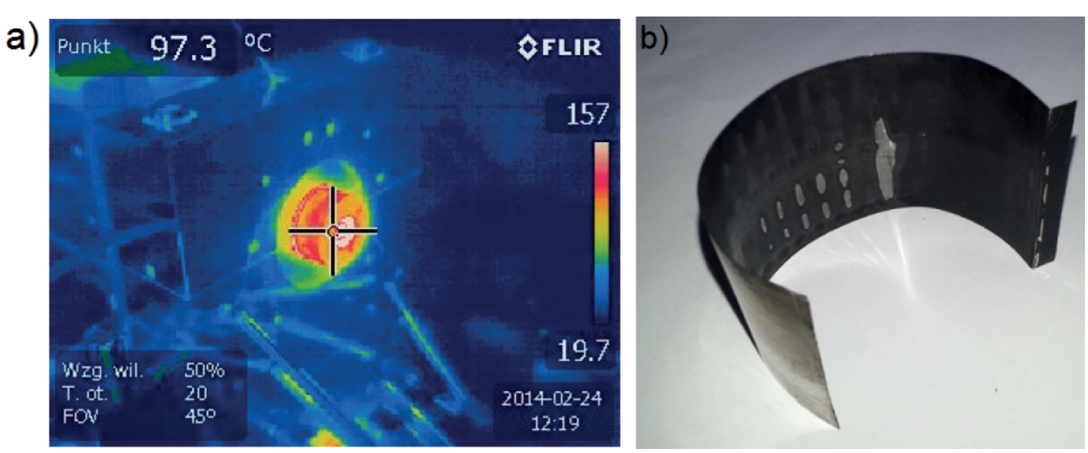

Fig. 4. Temperature distribution measured using a thermal imaging camera (a) and the top foil with the visible signs of abrasion (b)

The study shows that the operation of the foil bearing under an excessive load has led to a very rapid wear of the sliding layer. In this case, a reduction of the bearing load could be achieved by a very precise alignment of the bush and the electro-spindle shaft. A similar effect can be achieved by using the "floating bush" which self adjusts its position to current operating conditions. In addition, it has to be noted that, despite quite a high flexibility of the foil set, exceeding the permitted limit for the displacement may lead to an accelerated wear of the sliding layer. Therefore, an opportunity to precisely align the rotor should be provided already at the design stage of new machines with such bearings.

An important factor here is also a careful selection of materials for structural components and sliding coatings. In the case under consideration, the sliding layer of the top foil is made of a soft polymer, in contrast to the hard journal. Notwithstanding the fact that this combination of materials successfully passed tests under lower loads, the sliding layer has been damaged during the experiment at hand. This was caused by the following factors: excessive load of the bearing, inappropriate operating conditions for the creation of a gaseous lubricating film, and poor heat transfer from the top foil [12]. The bearing operation under such conditions caused a sharp increase in temperature to the level at which the sliding layer lost its properties ensuring a proper functioning of the bearing. That is why the wear of this layer occurred in such a short time.

2. Vibrations of the rotor with foil bearings at elevated temperature

A set of foils applied to foil bearings may improve the dynamic properties of the rotor supported by such bearings, making them a better alternative than ordinary gas bearings. In ordinary gas bearings (in which the journal and bush are rigid), a gaseous lubricating film is the only one vibration damping element, creating a thin and rigid load-bearing layer at high relative speeds. The vibration damping capability of such bearings is very limited. By introducing an additional flexible and vibration damping element between the journal and the bush, one can improve the dynamic properties of such a bearing. Desired properties of the foil set are obtained by selecting its geometry and suitable materials.

Compared to ordinary gas bearings, the flexible support of a shaft (using foil bearings) has disadvantages as well, such as higher vibration levels in certain speed ranges and a lower critical speed of the rotor. These disadvantages may sometimes cause serious operational problems. This is of particular importance in some types of fluid-flow machinery, for instance, in microturbines, where the aim is to minimise blade gaps in order to improve the flow efficiency. Similar problems may occur in bearing systems for high-speed rotors of electric generators in which there are very small gaps between the rotor and stator. In such cases, making a decision to use foil bearings must be thoroughly thought out, because abrasions of the rotating elements or even a permanent damage to the machine can come about when operating under extremely difficult conditions.

This section of the article presents an experimental study aimed at assessing the effect of temperature on the vibration level of the rotor supported by two foil bearings. The rotor was driven by an electro-spindle attached to it through a coupling (Fig. 5). The shaft diameter is 34 mm, and its length is 435 mm. The bearings are 245 mm apart. Elevated temperatures were achieved by blowing hot air (using a "heat gun") and also by IR emitters that are mounted near the bearing (see Fig. 5). In order to investigate the vibration levels at different speeds, measurements were carried out during a slow run-up of the rotor up to a speed of 24000 rpm.

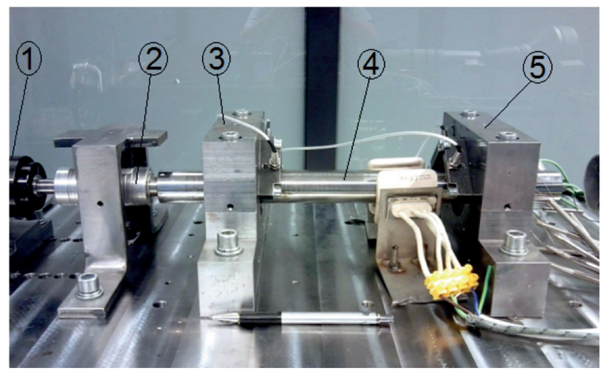

Fig. 5. Test rig (1 – electro-spindle, 2 – coupling, 3 – bearing support No. 1, 4 – shaft, 5 – bearing support No. 2)

The vibration measurement results for the bearing situated at the free end of the shaft are shown in Fig. 6. At a speed of approximately 8000 rpm, the resonance can be observed. It can also be noted that the change in the ambient temperature from 25°C to 100°C caused a decrease of the resonant speed – from 8400 rpm to 7800 rpm. Temperature changes affected the vibration level as well. At a temperature of 25°C, the maximum vibration amplitude in the horizontal direction was 0.1 mm (at the resonant speed); whereas, at a temperature of 100°C, it achieved a value of 0.13 mm. Changes in the vibration level were also observed in the vertical direction.

If the speed is out of the resonance range, the operation of the rotor supported by foil bearings is very stable. Even at speeds that are well above the resonant speed, the vibration level did not exceed a value of 50 μm. It can, therefore, be concluded that the rotor operation out of the resonance range can be regarded as stable, irrespective of the ambient temperature. Due to a high vibration level at low speeds (when a gaseous lubricating film is not fully formed yet), it might happen that rotating elements of the machine come into contact with the casing. Therefore, both start-up and shut-down of the rotor have to be done very quickly to prevent it from operation at a resonant speed for too long. However, it would be better to design foil bearings with different characteristics so that vibrations in a particular speed range are at a low level.

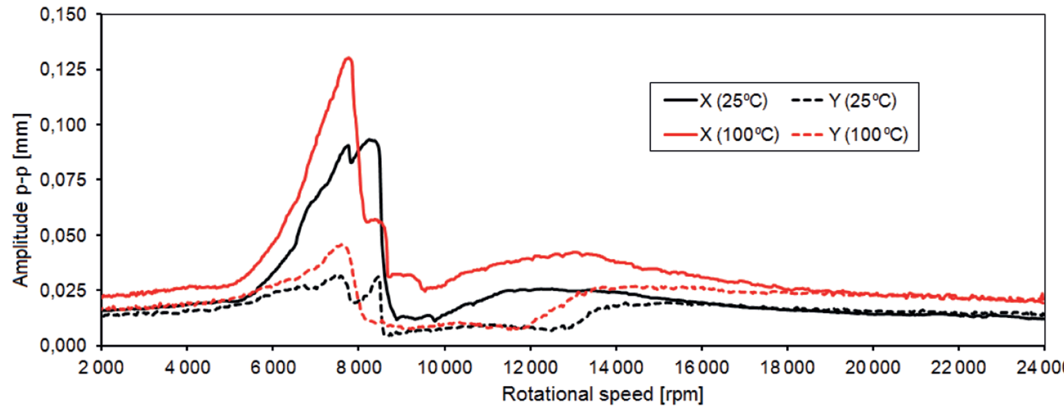

Fig. 6. Peak-to-peak vibration displacement amplitudes of the journal (Bearing No. 2) vs. rotational speed

3. Pre-clamp of foil bearing components

A very important aspect regarding the functioning of a foil bearing is the proper selection of the pre-clamp of its components. It can be obtained by choosing the geometry of the top foil and of the bump foil in such a way that the inner diameter of the top foil (being still under no load) is smaller than the diameter of the journal before inserting the journal into the bush. Such a clamp is needed in order to ensure proper conditions for the interaction of the journal with the set of foils at high speeds. Here, it is of particular importance to limit the amount of clamping force to the necessary minimum so that the frictional resistance at low speeds is not too high. However, clamping force that is too low allows the journal to move freely within the bush, leading to excessive vibration. The pre-clamp also has an impact on the conditions of forming a gaseous lubricating film [8].

During tests conducted at the IMP PAN laboratory, it was noted that the pre-clamp is one of the most important factors affecting both the thermal characteristics of foil bearings and the dynamics of the rotor supported by them. This was particularly evident during the investigation of new foil bearings, where, with a properly selected pre-clamp, the wearing-in process was very fast with only a temporary rise in temperature [6]. Similar observations were made during vibration measurements. With a properly selected bearing geometry, the speed range needed to produce a gaseous load-bearing layer was very narrow, thereby reducing vibration and wear.

Conclusions

The article discusses selected issues related to the use of gas foil bearings in modern fluid-flow machinery. Compared to conventional gas bearings, such bearings have many advantages, some of which are as follows: They enable the stable operation of rotors at high rotational speeds and do not need an external lubrication system. Any use of foil bearings must be preceded by a detailed analysis of the machine they are to be applied to, and the machine itself has to be adapted to such a bearing system. The following drawbacks of this type of bearings should be considered when choosing such a bearing system: low load capacity, low resistance to overloading, high vibration level in some speed ranges, high impact of temperature on bearing characteristics, the need for high precision of manufacturing and assembling processes to achieve an adequate pre-clamp. In this article, these drawbacks are presented using several examples. Maladjustment of foil bearings to a specific machine or an incorrect operation usually results in an accelerated wear of the sliding layer and the need to repair or replace the bearing(s).

It should also be stressed that the presented examples do not cover all the operational problems associated with the use of foil bearings. In this context, it is also pertinent to mention that, during the construction of foil bearings, one has to develop a proper technology for manufacturing and assembling foils and a complete bearing system also requires thrust bearings to be designed and constructed (similar problems may be encountered as well). The examples included in the article aim to give some idea of the real scale of problems that have to be faced when designing machines equipped with foil bearings.

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