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FOIL MICRO-BEARING TESTS

***Wojciech Miąskowski*[1], *Krzysztof Nalepa*[2], *Grzegorz Żywica*[3]**

[1] Chair of Mechanics and Machine Design
[2] Chair of Power Engineering
University of Warmia and Mazury in Olsztyn
[3] Institute of Fluid-Flow Machinery Polish Academy of Sciences in Gdańsk
Rotor Dynamics and Slide Bearing Department

K e y w o r d s: foil bearing, high-speed machines bearings, bearing systems testing.

A b s t r a c t

Selected methods of testing applied in the research centres dealing with foil bearings technology are overviewed in this paper. Tests analyzing foil bearings require special test rigs and a testing methodology that simulates the bearings' actual working conditions. Test rigs should allow factors, that influence on a bearing's exact operating environment. For this reason, most tests investigate selected key parameters Tribological tests under extreme bearing operating temperatures and with the effect of lubricants make a separate group of tests. Another tests group is focused on the optimal bearing stiffness determination through the choice of adequate structural solutions and manufacturing technologies. Foil bearing test methods presented in this paper do not exhaust the study domain, in which new constructions may be tested. They only overview basic test methods used for the foil bearing systems.

BADANIE ŁOŻYSK FOLIOWYCH

***Wojciech Miąskowski*[1], *Krzysztof Nalepa*[2], *Grzegorz Żywica*[3]**

[1] Katedra Mechaniki i Podstaw Konstrukcji Maszyn
[2] Katedra Elektrotechniki i Energetyki
Uniwersytet Warmińsko-Mazurski w Olsztynie
[3] Instytut Maszyn Przepływowych Polskiej Akademii Nauk w Gdańsku
Zakład Dynamiki Wirników i Łożysk Ślizgowych

S ł o w a k l u c z o w e: łożysko foliowe, łożyskowanie maszyn szybkoobrotowych, badania systemów łożyskowania.

A b s t r a k t

W artykule przedstawiono wybrane metody badań stosowane w ośrodkach badawczych zajmujących się technologią łożysk foliowych. Badania eksperymentalne łożysk foliowych wymagają opracowania specjalnych stanowisk badawczych i tworzenia metod badań, które pozwoliłyby na odtworzenie warunków, w jakich będą pracować badane łożyska. Stanowiska badawcze powinny uwzględniać czynniki, które mają wpływ na warunki pracy łożyska. Badania są prowadzone w kilku głównych kierunkach. Jedną gałąź stanowią badania tribologiczne w ekstremalnej temperaturze, w jakiej będą pracować łożyska, a także z użyciem mediów smarnych. Inna gałąź badań jest skierowana na zapewnienie optymalnej sztywności łożysk przez odpowiednią konstrukcję i dobór technologii wykonania elementów konstrukcyjnych. Przedstawione w artykule metody badań łożysk foliowych nie wyczerpują zakresu badań, jakim mogą być poddawane nowo opracowywane konstrukcje. Stanowią jedynie przegląd podstawowych metod badań stosowanych w systemach łożysk foliowych.

Introduction

The contemporary demand for energy requires solutions that rely on the latest technological advancements. New concepts are increasingly often evaluated based on criteria such as environmental protection, cost effectiveness and comprehensiveness of application. As a result, power equipment undergoes constant minimization, while ensuring the right operating parameters, in particular the power output. The reduction in the size of elements responsible for energy processing increases the speed of moving parts. Their operating speed is controlled by bearings supporting the working elements. In principle, the theoretical premises for conventional bearing solutions also apply to micro-turbines and other devices of the type. Yet new impediments are encountered at high rotational speeds. The main problem is the choice of structural materials which are resistant to high temperatures and guarantee the required structural precision. This, in turn, necessitates the development of new bearing designs.

A wide variety of micro-bearings are described in scientific publications, and their usefulness has to be analyzed in view of numerous criteria. Based on the available sources, the following key criteria for the selection of micro-bearings are applied (Żywica 2007):

– allowable rotational speed,
– load capacity,
– allowable operating temperature,
– working life and reliability, ease of repair,
– bearing precision and stiffness,
– vibration damping,
– resistance to external factors.

In view of the rapid advancement of the micro-bearing technology, in particular magnetic and foil bearings, the published sources describe various experiments, numerical analyses and analytical calculations that aim to optimize the structure of micro-bearings. This study overviews selected micro-bearing tests which evaluate the key properties of the analyzed foil bearings.

Measuring the vibration of rotors equipped with foil bearings

Operating vibration is one of the key working parameters of every rotor-bearing system. Tests measuring the vibration level of rotor journals are performed for every type of bearings, in particular journal bearings. In view of the specific structure of foil bearings, their geometry varies subject to working conditions. For this reasons, tests measuring the vibration of rotors equipped with foil bearings are of special significance.

Since foil bearings operate at very high speeds and temperatures, they have to be analyzed in test rigs consisting of a real object equipped with the tested bearings (XIONG et al. 1996, HOU et al. 2004). Figure 1 presents a photograph of a turboexpander applied in a test rig. Figure 2 shows the structural diagram of two bearing variants applied in the turboexpander rotor with bearing diameter of 12 mm, weight of 90 g and rotational speed of approximately 230 000 rpm.

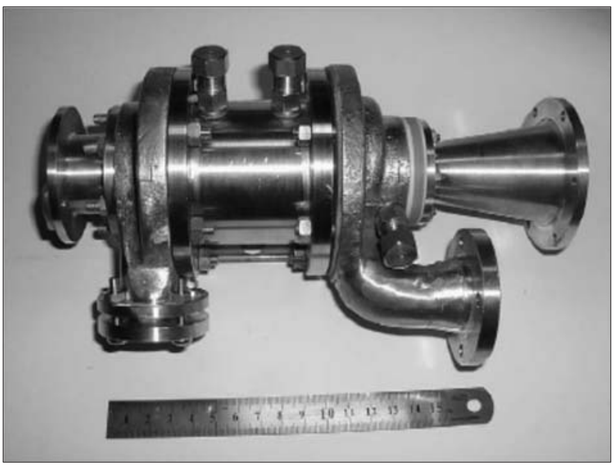

Fig. 1. Turboexpander applied in the study

Source: HOU et al. (2004).

The bearing's rotational speed was measured with the use of fiber optic probes. Rotor vibrations were measured in two mutually perpendicular directions with probes inserted in the stationary part of the device. Tests were carried out for two bearing types in several variants:

– spiral bearings where foil is supported with the following number of copper wires: $n = 15, 17, 19, 21, 23$

– multileaf bearings with the following number of foil elements: $n = 6, 7$

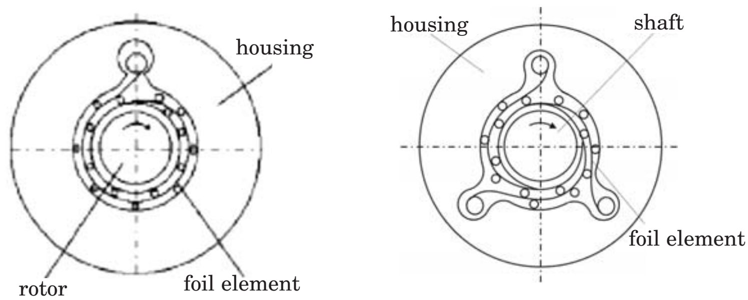

Fig. 2. Structural diagram of the tested bearings. On the left – a spiral foil bearing (Hou et al. 2004); on the right – a multileaf bearing
Source: On the basis of Xiong et al. (1997).

Figures 3 and 4 present selected experimental results.

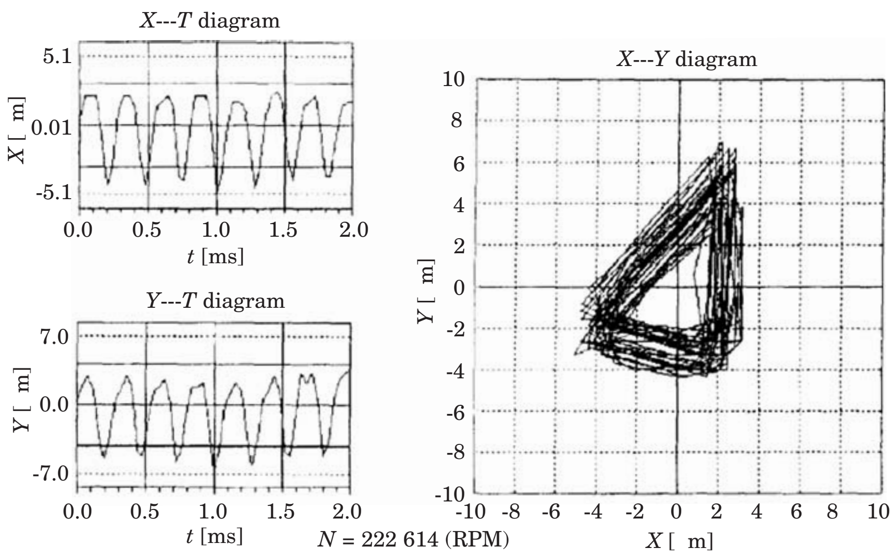

Fig. 3. The results of vibration measurements in a rotor equipped with a spiral foil bearing where the foil element is supported by 15 copper wires with a diameter of 0.2 mm.
Rotational speed: 222 614 rpm
Source: Hou et al. (2004).

Bearings with a more complex structure (multileaf and bump foil bearings) were subjected to similar tests. The author of the study measured rotor shaft displacement in two directions as well as working temperatures (DellaCorte 2004). Owing to the high operating temperature of foil bearings, optical displacement probes were applied (devices based on the resistance of the structural material lose their properties at temperatures higher than 400°C,

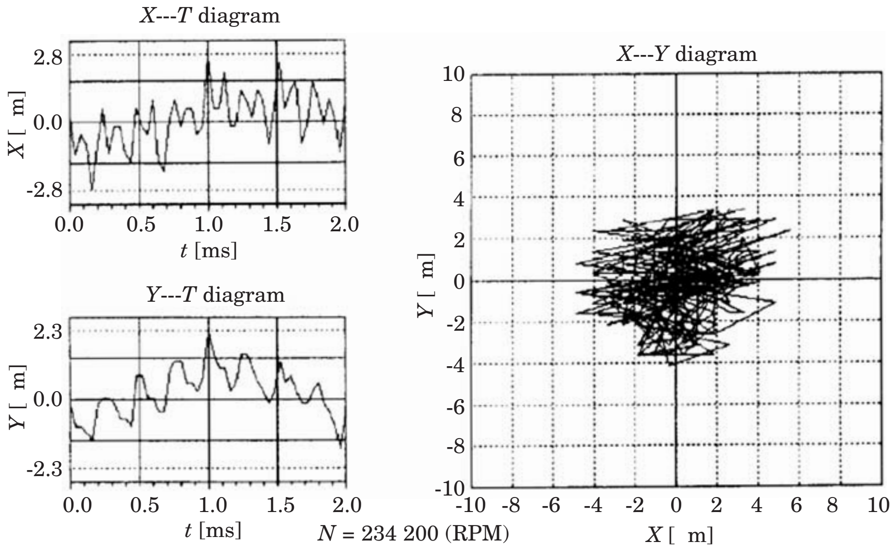

Fig. 4. The results of vibration measurements in a rotor equipped with a multileaf foil bearing with 6 foil elements. Rotational speed: 234 200 rpm

Source: Hou et al. (2004).

and the correlation between temperature and resistance cannot be determined).

The sensor comprises a fiber optic unit with two functions. Some fibers emit light with a set frequency. The emitted light beam is reflected from the moving rotor shaft. Subject to the shaft's location, reflected light is channeled to a different fiber which intercepts the reflected beam. Based on the results of specific calculations, the probe determines the location of the rotor surface in the measured direction.

The rotor surface has to be adequately prepared for the optical measurement of rotor displacement. Having tested various chemical compounds, a platinum-based surface was chosen due to its ability to withstand operating temperatures higher than 600°C. This measurement method was selected due to the following factors:

– the light reflecting properties of the tested materials changed with temperature and rotational speed (e.g. silver becomes softened and the shaft coating layer changes its thickness with speed),

– the coating layer has to demonstrate stable and high light reflecting parameters. At high temperatures, many compounds become coated with an oxide layer or change their color.

Temperature was measured with temperature sensors placed on the "rear" side of the foil element. The detailed distribution of sensors was not described

Testing foil bearing stiffness

The stiffness of every bearing type is one of its main operating parameters. Model test rig with the rotor weight of around 5 kg, its diameter of 35 mm and total length of 594 mm is presented in YONG-BO et al. 2004. The turbine was installed at the end of the rotor. The rotor was equipped with two bearings on both ends in the axial direction.

Two mutually perpendicular displacement sensors were installed in the midspan of the rotor. A rotational speed sensor was also used.

The rotor has a diameter of 60 mm, and it is supported by two ball bearings. The tested bearing is placed in the midspan of the rotor. The bearing has the inside diameter of 61.45 mm, the length of 60 mm and the weight of 5.3 kg. Displacement was measured with the use of 4 displacement sensors placed in mutually perpendicular directions on both sides of the tested bearing. Each ball bearing was equipped with two accelerometers measuring acceleration in mutually perpendicular directions.

The test was carried out for two foil bearing structural variants (foil bearings with Cu coated viscoelastic foil and bump foil).

The effect of double bump foil on the properties of foil bearings (TAE HO KIM, 2007)

The properties of a foil bearing, in particular the bearing's overload resistance, can be improved through the use of a double bump foil element where one foil layer is characterized by higher stiffness. Under normal operating conditions, the bearing relies on the properties of the inside foil layer. During overload, the rotating journal comes into direct physical contact with bump foil. The foil layer is deformed, yet it does not damage the bearing because the external foil layer absorbs some of the overload energy. The discussed tests involved a numerical analysis of the Reynold's equation. The structural diagram of the bearing and the model bearing with a double bump foil layer are presented in Figure 5.

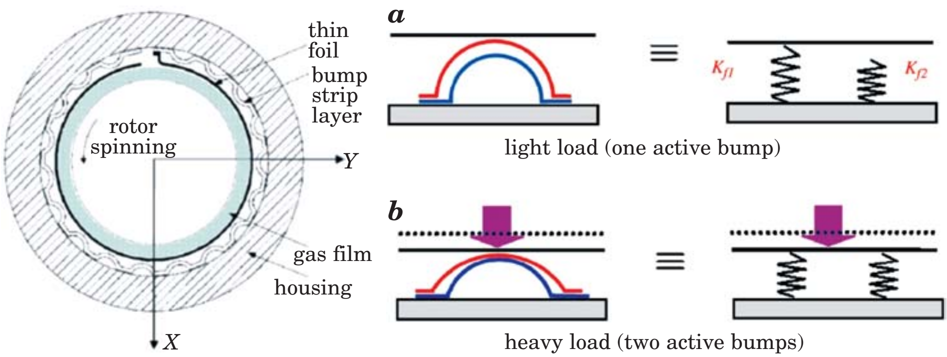

Fig. 5. A schematic diagram of a bump foil bearing and a model bearing with a double bump foil layer
Source: KIM, SAN ANDRES (2007).

The results of simulation tests are presented in Figures 6–8.

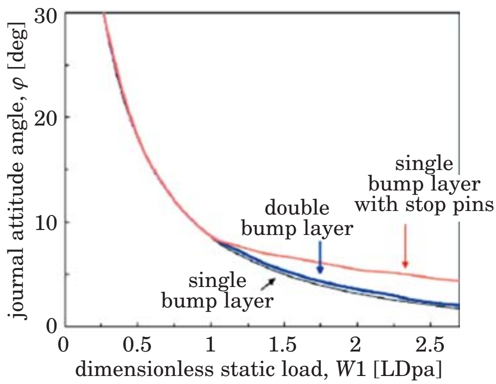

Fig. 6. Measurement of relative eccentricity subject to static load in three bearing variants
Source: KIM, SAN ANDRES (2007).

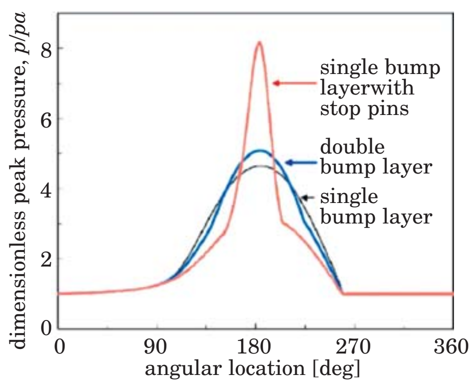

Fig. 7. The effect of bearing overload on three types of foil elements
Source: KIM, SAN ANDRES (2007).

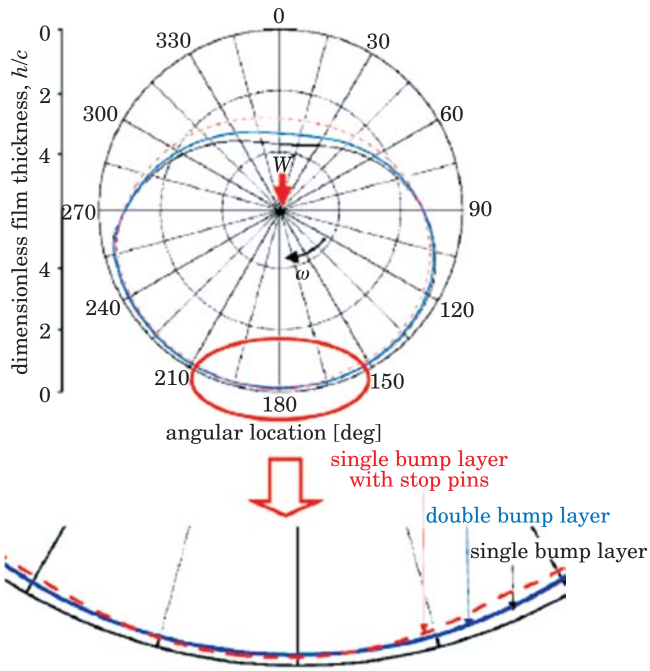

Fig. 8. Thickness distribution of lubricating film in three bearing variants
Source: KIM, SAN ANDRES (2007).

Testing micro-bearing surface wear caused by high temperature and friction

The properties of structural materials applied in bearings' working elements are investigated separately owing to foil bearings' very high rotational speed, small size and high operating temperature. The choice of materials which retain their elastic properties in a wide range of temperatures and which are resistant to friction wear during the start-up, rundown and overload of machines equipped with foil bearings is a very important consideration. A model test rig for analyzing the tribological wear of materials applied in the production of bearing foil is presented in MITI commercial materials (MiTi® Tribometers for Friction, Wear and Lubrication Testing).

The device supports tests within the speed range of up to 10 000 rpm and working temperatures of up to 900°C. The operating radius of the torque measuring rod is 3.18 to 79.4 mm. The load applied to the tested element ranges from 100 to 500 g.

The effect of high temperatures on bearing operation is analyzed in a test rig shown in MITI commercial materials. The test rig investigating normal bearing operation is placed in the proximity of the heat source. This solution supports the evaluation of changes in the bearing's operating parameters and its fitness for use in an environment simulated by the device.

Conclusions

Tests analyzing foil bearings require special test rigs and a testing methodology that simulates the bearings' actual working conditions. A bearing's exact operating environment is very difficult to recreate, and such tests are performed by very few research centers around the world. For this reason, most tests investigate selected key parameters. Tribological tests have to account for extreme operating temperatures as well as the effect of lubricants which are often highly chemically active substances. Tests aiming to determine the optimal bearing stiffness through the choice of adequate structural solutions and manufacturing technologies should be preceded by simulations which significantly reduce experimental costs.

In recent years, a research team pooling the resources of the University of Warmia and Mazury in Olsztyn, the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk and other research centers was created to further research into the development of foil bearings, the appropriate testing methodology and the use of foil bearings in power microturbines.

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