TECHNICAL SCIENCES
Abbrev.: Techn. Sc., No 12, Y 2009

DOI 10.2478/v10022-009-0020-9

MODELING FOIL BEARINGS

***Wojciech Miąskowski*[1], *Paweł Pietkiewicz*[1], *Grzegorz Żywica*[2]**

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

Key words: foil bearing, modelling foil bearings.

Abstract

This paper presents selected numerical models of foil bearings developed in a few research centres around the world. The development of reliable foil bearing numerical models still poses many problems. Such difficulties are encountered mainly due to foil bearings' complex structure. In addition to elements found in conventional journal and sleeve bearings, elastic-plastic elements as a foil complex occur. Foil bearing models have to account for the structural base, the fluid lubricating film as well as the interactions between the two factors. A reliable foil bearing models would significantly contribute to bearing design At present, such bearing modeling process requires time-consuming and costly experiments.

MODELOWANIE ŁOŻYSK FOLIOWYCH

***Wojciech Miąskowski*[1], *Paweł Pietkiewicz*[1], *Grzegorz Żywica*[2]**

Katedra Mechaniki i Podstaw Konstrukcji Maszyn
Uniwersytet Warmińsko-Mazurski w Olsztynie
Instytut Maszyn Przepływowych Polskiej Akademii Nauk w Gdańsku
Zakład Dynamiki Wirników i Łożysk Ślizgowych

Słowa kluczowe: łożysko foliowe, modelowanie łożysk foliowych.

Abstrakt

W artykule przedstawiono wybrane modele numeryczne łożysk foliowych opracowane w kilku ośrodkach badawczych na świecie. Opracowanie wiarygodnych modeli numerycznych takich łożysk wciąż sprawia wiele trudności. Wynika to przede wszystkim ze złożonej budowy łożysk foliowych, gdyż oprócz elementów znanych z klasycznych łożysk ślizgowych, występują elementy sprężysto-podatne w postaci zespołu folii. Modelując łożyska foliowe, oprócz strukturalnej oraz przepływowej warstwy nośnej, należy również uwzględnić ich wzajemne oddziaływanie. Wiarygodne modele łożysk foliowych znacznie ułatwiłyby proces projektowania. Obecnie opracowywane konstrukcje takich łożysk wymagają bowiem przeprowadzania bardzo czasochłonnych i kosztownych badań eksperymentalnych.

Introduction

Foil bearings applied in high-speed machines are complex structures as regards the applied materials and structural characteristics. In functional terms, they are similar to hydrodynamic bearings where the dynamically formed lubricant with adequate dynamic pressure is responsible for the bearing's load capacity. There are, however, several differences between foil bearings and bearings with a stiff sleeve. The sleeve elements of a foil bearing are subjected to complex load which deforms the foil layer. This type of bearings cannot be adequately described with the use of the classic theory of modeling hydrodynamic and aerodynamic bearings. New modeling methods have to be developed to design the required solutions in foil bearings.

This paper presents selected approaches to modeling the operating parameters of foil journal bearings and foil thrust bearings. The discussed models highlight the main trends in research studies investigating foil bearings.

Modeling the effect of bearing structure on the load capacity of foil bearings

Foil bearings have been applied for many years, yet the development of reliable numerical models still poses many problems. Such difficulties are encountered mainly due to foil bearings' complex structure. In addition to elements found in conventional journal and sleeve bearings, foil bearings feature a foil complex (bump foil and top foil layers). Owing to this solution, rotors equipped with foil bearings are characterized by a much higher stability reserve than conventional journal bearings. Excess energy is dispersed through foil deformation and friction between the co-acting foil elements, and the shape of the lubricating gap adapts to the operating environment. The structure of a typical foil bearing is presented in Figure 1. The foil complex

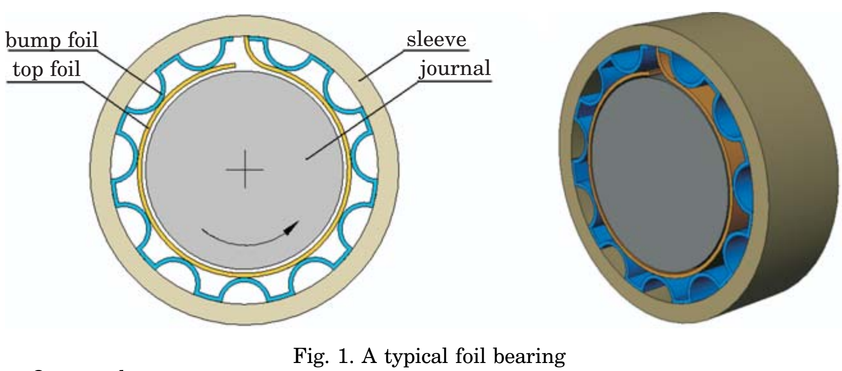

Fig. 1. A typical foil bearing

Source: Own work.

forms the bearing's structural base which, together with the fluid lubricating film, determines the dynamic properties of bearing systems.

Foil bearing models have to account for the structural base, the fluid lubricating film as well as the interactions between the two factors. During machine start-up and shut-down, the journal and the top foil layer come into direct contact. This creates additional problems as fluid friction requires a different modeling approach than that applicable to stable rotor operation. It should also be noted that the properties of materials used in the production of bearing elements are largely dependent on temperature. In typical applications, the working temperature of foil bearings can change within a very wide range (several hundred °C). In view of the above, the modeling of foil bearing operation requires complex fluid-structural numerical analyses that account for thermal phenomena. Owing to the complexity of the discussed problem, the discrepancies in the published numerical calculations and experimental results can reach up to 500% (AGRAWAL 1997).

The problem of developing foil bearing models is investigated by various research teams around the world. A reliable operating model would significantly contribute to bearing design. At present, the modeling process requires time-consuming and costly experiments. The use of reliable models could significantly simply this procedure.

The most popular methods in foil bearing modeling rely on the Reynold's equation to describe the lubricating fluid film base (LEZ et al. 2007, SUDHEER KUMAR REDDY 1997, KIM, SAN ANDRES 2007). Algorithms of the finite difference method or the finite volume method are usually applied in the numerical model. The interactions between the foil complex and the sleeve surface are usually simulated with the finite element method (LEZ et al. 2007, SUDHEER KUMAR REDDY 1997, BRAUN 1997). Some authors propose to replace bump foil with a single stiffness-damping element (RUBIO, SAN ANDRES 2006). The entire foil bearing is modeled by coupling the fluid film model and the structural model. Some references suggest he use of analytical formulas (HESHMAT et al.1983, KU, HESHMAT 1992, WELOWIT, ANNO 1975, LEE et al. 2006). According to the authors of this study, such formulas are developed based on highly simplified theoretical models and their usefulness is debatable.

Research studies into foil bearings are carried out by the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) in Gdańsk in collaboration with the research team of the University of Warmia and Mazury in Olsztyn. The main objective of those efforts is to design a foil bearing suitable for use in micro-turbines operating in the ORC cycle. A special bearing structure is required to match the operating parameters of such machines. In this case, the key advantages delivered by foil bearings are: high rotational speeds, operability in a wide range of temperatures, excellent vibration damping, long working life, easy maintenance and compatibility with a variety of lubricants.

To facilitate the design process, the research team of IMP PAN in Gdańsk developed a numerical model supporting the preliminary selection of bearings. The proposed method combines customized solutions with commercially-available software. MESWIR-series applications developed by IMP PAN was used to describe non-linear phenomena in the lubricating gap and the dynamic characteristics of the rotor. Foil complex deformations were analyzed with the application of the MES – ABAQUS package. A complete model of a foil bearing integrated with the rotor model was developed by combining the strengths of both software applications (KICIŃSKI, ŻYWICA 2008). The model was partially validated in an experiment which confirmed its suitability for predicting the properties of bearing-rotor systems (KICIŃSKI et al. 2008).

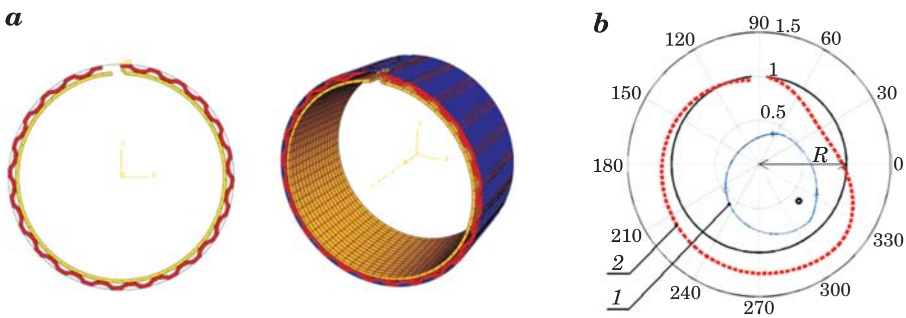

Fig. 2. MES model of a foil bearing's structural base (*a*) and selected calculation results (*b*) (*1* – trajectory of journal vibration, *2* – shape of deformed foil complex)
Source: Own work.

The bearing model and the results of calculations determining the deformation of the foil complex and the trajectory of journal vibrations are presented in Figure 2. The calculations were performed for the rotor-foil bearing system with dimensions corresponding to a 3 kW micro-turbine. The rotor diameter was 10 mm and the rotor length – 140 mm. The lubricating fluid was isobutane, a low-boiling medium. The calculations were performed for a speed range of 10 000 – 100 000 rpm (Fig. 3). The obtained results validated the system's stability in the majority of the tested speed ranges. The models developed by IMP PAN support the analysis of practically every rotor-foil bearing system, and the achieved results facilitate the design of new structures and the optimization of the existing designs.

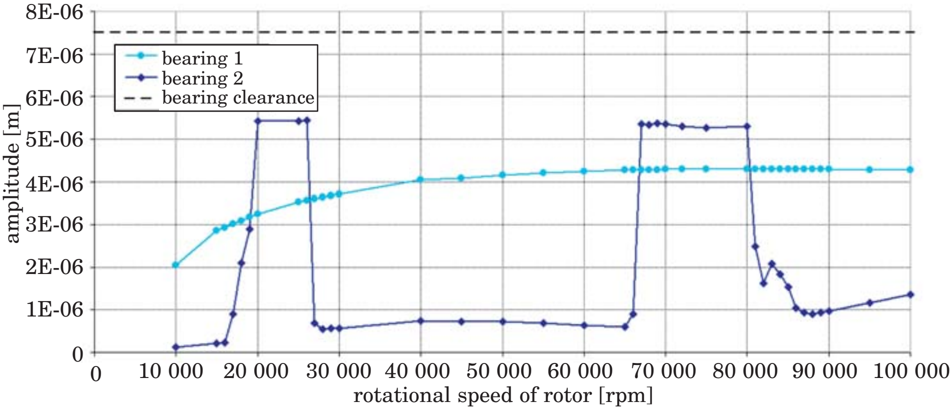

Fig. 3. Amplitude of relative journal-sleeve vibrations in the speed range of 10 000 – 100 000 rpm
Source: Own work.

Modeling the wear of structural elements during foil bearing operation

Since foil bearing elements come into direct physical contact during operation, models supporting the analyses of surface friction in the bearing's structural base during start-up, rundown and overload need to be developed. A numerical analysis of the above was carried out by Bruckner in a study of thrust bearings. The thrust bearing with eight bearing pads of a foil complex uniformly placed around the bearing perimeter is a subject of his study (BRUCKNER 2004). The tested bearing's diagram is show in Figure 4 and its basic technical data are presented in Table 1.

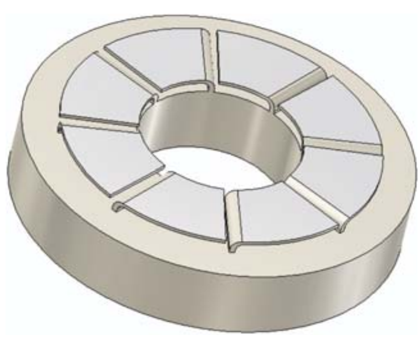

Fig 4. Structural diagram of a foil thrust bearing with eight bearing pads of foils
Source: Own work.

Table 1

Technical data of a foil thrust bearing

Radius inner	23 mm
Radius outer	45 mm
Azimuthal extent of one foil set	43 deg
Characteristic speed	40 000 rpm
Midspan speed	148 m/s
Lubricant	Air at see level conditions
Top foil material	Inconnel X-750
Top foil thickness	0.13 mm

Source: Own work.

The objective of the study was to simulate and validate the results of foil wear during the operation of a foil thrust bearing. Visible wear of the mating surfaces begun with the midspan of all foils sets even during low load tests. The top foil layer was divided into two regions (outboard and inboard) when the numerical model of a foil thrust bearing developing. According to model, different inclination angle of the outboard region and the bearing disc plane were assumed. The calculations also took temperature changes and the thickness distribution of lubricating film on mating surfaces into account. The pressure distributions on the top foil surface was determined inter alia on the basis of such models development. A comparison of simulation and experimental results confirms the model's usability to predict areas, where one may deal with the substantial friction wear. Despite the bump foil substitution with the stiffness coefficients, determined in the numerical calculations, such way model development allowed the reliable results of the biggest wear of the top foil regions occurrence prediction, to be attained.

Conclusions

This paper presents selected models of foil bearings. One should notice, that the present state of art and available software supporting engineering calculations do not allow entire representation of all phenomena, that occur in such type bearings. Despite those difficulties, discussed, simplified models allowed analysis and particular properties prediction of the foil bearings, according to current needs of the research teams. At the present knowledge and computer techniques state, the numerical models development, which describe the most important properties with regard to the present research conduction, is the reasonable attempt to the complex systems modelling, as the foil bearings are. Models' development requires an intensive team-work of scientists, who deal with the modelling as well as with the experiments. The suitable technical abilities, which mean a high-efficiency computer working station with the adequate software and dedicated test stands, are also essential.

Research on subjects, discussed in this paper, are conducted by the recently established research team of the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk and the University of Warmia and Mazury in Olsztyn. Besides the formulation of a simulation model, which considerably simplify and speed up the design process, the final foil bearing construction solution, anticipated for the application in the low power micro-turbines, become the result of this cooperation. The task requires a number of the research work, such as the adequate structural materials for the bearing elements selection, development of their manufacturing process and the specialized test stands construction (necessary for close to the reality conditions tests), to be conducted. Research findings will support the validation of the existing, as well as simplify the new numerical models of the foil bearings development. All those issues will be a subject of the further publications.

Accepted for print 03.07.2009

References

AGRAWAL G.L. 1997. *Foil Air/Gas Bearing Technology – An Overview*. International Gas Turbine & Aero engine Congress & Exhibition, Orlando (USA) June 1997.

BRAUN M., CHOY F., DZODZO M., HSU J. 1997. *Two-dimensional dynamic simulation of continuous foil bearing*. Tribology International, 29(1): p. 61–68.

BRUCKNER R.J. 2004. *Simulation and Modeling of the Hydrodynamic, Thermal, and Structural Behavior of Foil Thrust Bearings*. Department of Mechanical and Aerospace Engineering, Case Western Reserve University.

HESHMAT H., WALOWIT J., PINKUS O. 1983. *Analysis of Gas-Lubricated Foil Journal Bearings*. ASME Journal of Lubricate Technology. 105: 647–655.

KICIŃSKI J., ŻYWICA G. 2008. *Metody łożyskowania wysokoobrotowych wirników mikroturbin stosowanych w układach kogeneracyjnych*. Archiwum Energetyki, XXXVIII (2): 137–145.

KICIŃSKI J., ŻYWICA G., BANASZEK S. 2008. *Modelling the Elastic Strains of Foil Bearing Bush*. 7th EDF & LMS Poitiers Workshop: "Operational Limits of Bearings: Improving of Performance through Modelling and Experimentation" – FUTUROSCOPE, Poitiers (France) 2 October 2008.

KICIŃSKI J., ŻYWICA G., RZĄDKOWSKI R., DREWCZYŃSKI M. 2008. *Modelowanie strukturalnej warstwynośnej łozyska foliowego*. Acta Mechanica et Automatica, 2(1): 45–50.

KIM T.H., SAN ANDRES L. 2007. *Analysis of Advanced Gas Foil Bearings with Piecewise Linear Elastic Supports*. Tribology International, 40: 1239–1245.

KU R., HESHMAT H. 1992. *Compliant Foil Bearing Structural Stiffness Analysis:* Part I – *Theoretical Model Including Strip and Variable Bump Foil Geometry*. ASME Journal of Tribology, 114: 394–400.

LEE Y.B., PARK D.J., KIM CH. 2006. *Numerical Analysis for Bump Foil Journal Bearing Considering Top Foil Effect and Experimental Investigation*. 7th Conference on Rotor Dynamics IFToMM, Austria, paper ID-229.

LEZ S., ARGHIR M., FRENE J. 2007. *Static and Dynamic Characterization of a Bump-Type Foil Bearing Structure*. ASME Journal of Tribology, 129: 75–83.

MIĄSKOWSKI W., NALEPA K., PIETKIEWICZ P. 2008. *Charakterystyka prac prowadzonych w światowych ośrodkach naukowych i przemysłowych zajmujących się mikrołożyskami*. IMP PAN, Arch. 24/2008, Gdańsk.

MIĄSKOWSKI W., NALEPA K., PIETKIEWICZ P. 2008. *Opracowanie koncepcji układu pomiarowego dla stanowiska badawczego dynamiki wirników. Przegląd aparatury pomiarowej*. IMP PAN, Arch. 169/08, Gdańsk.

RUBIO D., SAN ANDRES L. 2006. Bump-Type Foil Bearing Structural Stiffness: Experiments and Predictions. ASME Journal of Engineering for Gas Turbines and Power, 128: 653–660.

SUDHEER KUMAR REDDY D., SWARNAMANI S., PROBHU B. 1997. *Analysis of Aerodynamic Multileaf Foil Bearings*. Wear, 209: 115–122.

WELOWIT J., ANNO J. 1975. *Modern Development in Lubrication Mechanics*. Applied Science Publisher, London.

ŻYWICA G. 2008. *Kształtowanie własności strukturalnej warstwy nośnej łożyska foliowego*. XXXV Sympozjum DIAGNOSTYKA MASZYN, Węgierska Górka, 3–8 marca.