THE STATIC PERFORMANCE ANALYSIS OF THE FOIL BEARING STRUCTURE

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Abstract: Foil bearings are a variety of slide bearings, in which an extra compliant foil set is applied between journal and bush, in order to improve the selected static and dynamic properties. Bearings of this type are investigated by engineers and researchers from all over the world since many years – both from simulation as well as experimental point of view. Due to the complexity of construction, the reliable simulation models are still being searched for. This paper discusses the most important stages of elaboration of the structural supporting layer of the foil bearing as well as results of verification tests. The main goal of the conducted study was assessment of reliability of the elaborated numerical model, in order to ensure that in future it could play a role of a reliable research tool, which could be used for elaboration of the numerical model of the entire foil bearing.

1. INTRODUCTION

Constant development characterizes field of bearing systems. In recent years the most dynamic development can be observed especially in the field of small-dimension, high-rotational bearing systems for rotors of machines such as: micro-turbines, turbo-compressors or turbo-expanders. One of the relatively new approaches is the foil bearing technology (Agrawal, 1997; Rubio and San Anders, 2006; Heshmat et al., 1983; Ku and Heshmat, 1992). Bearings of this type, thanks to the application of the compliant foil set (Fig. 1), exhibit a number of advantages compared to the classic bearing methods. First of all, the geometry of the lubricating gap in the bearing alters with the actual working conditions of the system. Thanks to the high ability to damp vibrations, foil bearings exhibit anti-vibration properties. It is especially important in case of high rotational speeds, when high dynamic loads occur and the system operates on the stability limit. Additionally, a gas foil bearings may operate under very high temperatures, even up to 700ºC, which makes them irreplaceable in some applications.

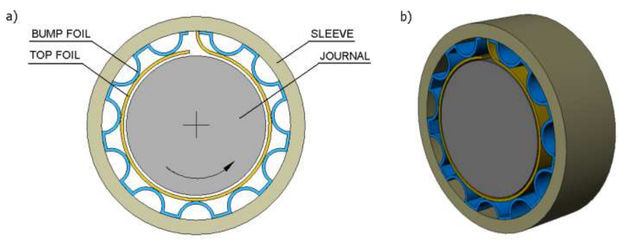

Fig. 1. Basic parts of a foil bearing

The characteristic property of foil bearings is a small versatility of specific construction solutions. As a result, each foil bearing has to be designed and constructed for a particular machine, considering the following parameters: static and dynamic load, range of operational speeds, temperature of operation, type of a lubricating medium etc. Due to this reason, new methods enabling the correct design of foil bearings, which do not require the time-consuming and costly experiments, are still under investigation. Numerical models may become very useful in this range, since they enable the determination of properties of new construction solutions, prior to their realization. The basic difficulty while modelling and performing simulation analysis is connected with the reliability of the results that are obtained. This applies particularly in case of complex mechanical systems, such as foil bearings. The following needs to be considered when such bearings are modelled: nonlinear deformation of a compliant foil set, flow of the medium in a deformed lubricating gap as well as contact and heat phenomena. Although those aspects are thoroughly described in literature (Rubio and San Anders, 2006; Ku and Heshmat, 1992; Braun et al., 1996; Salehi and heshmat, 2000; Lee et al., 2004; Kiciński et al., 2008; San Anders and Kim, 2008, 2009; Kim and park, 2009), the credible and tested solutions are still missing. This paper also focuses on the topic of modelling and analysis of foil bearings.

The research aimed at development of the simulation model of foil bearings are conducted also in the IFFM PASci. in Gdansk since couple of years. So far, investigation focused mainly on the analysis of the properties of a foil set fragment, rolled on a flat surface (Kiciński et al., 2008; Żywica, 2008). Currently conducted research works concentrate on the analysis of the properties of the whole foil set without any geometrical simplifications and are aimed to elaborate the complete model of the foil bearing, including both the structural as well as flow supporting layer. In this paper the following stages of research works dealing with the foil bearing model development, such as elaboration of the FEM model of the structural supporting layer of the foil bearing and validation tests, are discussed.

2. NUMERICAL MODEL OF THE FOIL BEARING STRUCTURE

2.1. Model geometry

The complex geometry of the model of the structural supporting layer of the foil bearing was elaborated by means of the Autodesk Inventor 2011 software. Thanks to the wide range of software capabilities in terms of modelling, a parametric model was developed, which enables a quick alteration of selected geometric parameters of the bearing. Due to the low computational efficiency, which is characteristic for 3D models, the investigation under consideration was based on the simplified, 2D geometry of the foil bearing. Such a model fully reproduced the geometry of the investigated bearing in the plane perpendicular to the rotation axis, however the changes in shape along the width of the bearing were not considered. By means of such a model it was thus possible to imitate the structural supporting layer of the foil bearing of 1st and 2nd generation.

Basic dimensions of the investigated bearing were selected basing on the literature data (Rubio and San Anders, 2006), which approach enables the comparison of the simulation results with results of experiments obtained by other researchers. The selected dimensions and parameters of the foil bearing are presented in Tab. 1.

Tab. 1. Nominal dimensions, parameters and material specifications of the foil bearing

No	Dimension/Parameter	Value
1	Inner diameter	38.17 mm
2	Bearing length	38.10 mm
3	Nominal journal diameter	38.10 mm
4	Nominal radial clearance	0.035 mm
5	Number of bumps	25
6	Bump pitch	4.57 mm
7	Bump length	4.06 mm
8	Bump height	0.38 mm
9	Bump and top foil thickness	0.1 mm
10	Poisson's ratio	0.29
11	Young's modulus	$2.1 \cdot 10^{11}$ Pa

Bump foil of the real bearing, based on which the model was created, consisted of five foil sectors of the same type, distributed evenly around the circumference of the bush. The total number of bump foil convexities amounted to 25 around the whole circumference. Additionally, every sector of the bump foil in the real bearing consisted of four narrow metal plates of the same type, distributed evenly along the bearing width. The division of the bump foil sectors into four smaller foils was not imitated in the model due to its 2D character. Due to the fact that journal and bush of the foil bearing are elements characterized with significantly higher stiffness than top and bump foil, both journal and bush were treated as rigid bodies during the investigation.

2.2. Numerical model and boundary conditions

Numerical model was elaborated in ABAQUS CAE software, version 6.10. Simulation was planned in a manner enabling imitation of the conditions of the experiment conducted by the American researchers, during the analysis (Rubio and San Anders, 2006). During the simulation, the journal of the bearing under investigation was loaded with a static force with maximum value of 224 N. The value of the force was increasing in a linear manner with time of analysis, and it reached its maximum after 1 second. One end of the top foil and one end of the bump foil were fixed to the bush surface. Displacements of free fragments of foil were limited by the surfaces of journal and bush, between which a contact was modelled, with a friction coefficient equal to 0.1. The journal of the bearing could be displaced only in a vertical direction (according to the force direction) in the surface perpendicular to the axis of the journal. The described system is presented in the Fig. 2.

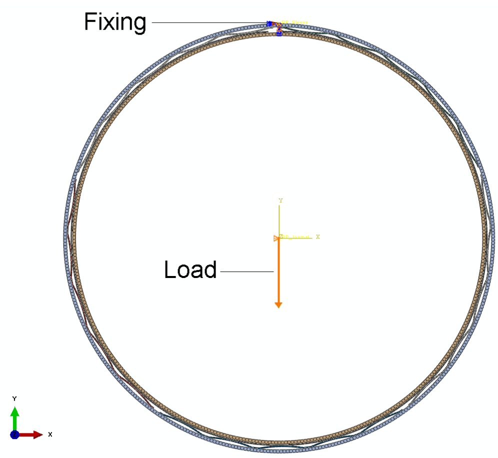

Fig. 2. FEM model with fixing and load

Fig. 2 depicts also discretisation of the model. Model consisted of 9778 degrees of freedom by total. 2D finite elements marked as CPE4RH were used. These were a four-nod elements with linear shape functions and reduced integration. Elements of this type are dedicated for analysis of deformations. Deformations of journal and bush were not considered during the investigation, since they were treated as rigid elements. Properties of construction materials used during calculations are given in Tab. 1.

Selection of particular finite elements as well as applied means of discretisation of the bearing were preceded by thorough investigation. Based on that, the optimum parameters of the FEM mesh were chosen for the study presented in this paper, enabling the achievement of exact results within the shortest possible time of analysis.

3. VERIFICATION TESTS

As a verification of the numerical model, the results of the computational analysis were compared with the results of the experiments. The procedure of verification was divided into two stages. In the first stage of verification the stiffness characteristics of the system, obtained for static load, were compared. The team conducting experimental study noticed, that the size of the nominal clearance has a strong influence on the stiffness of the foil bearing (Rubio and San Anders, 2006). Because of that the simulation study, similarly to the experiment, was conducted for bearings with three different sizes of the nominal clearance. The variable size of the clearance was obtained by alteration of the journal diameter, which was equal to the following values: 38,07, 38,10, 38,13 mm. Thanks to this changes, the nominal radial clearance with values equal to 0,05, 0,035, 0,02 mm was obtained. One needs to notice though, that the value of the nominal radial clearance in the foil bearing stems mainly from the design assumptions. The dimensions of the real bearing, due to the difficulties in its actual construction, differ slightly from the design assumptions. This results mainly from the limitations of the technology of production of top and bump foil, which does not allow for preparation of these elements with the assumed precision of 5 µm. Foils used for construction of the structural supporting layer are elastic elements, and their assembling is most often achieved with a certain initial tension. Due to all this, the achievement of the dimensional accuracy over the entire circumference and length of the bearing is practically unrealizable. Therefore, the given value of the nominal clearance for foil bearing shall be treated as an approximate value.

The below figures (Fig. 3-5) exhibit the comparison of the results of computer-aided simulations with results of the experiments presented in paper (Rubio and San Anders, 2006). The characteristic feature of the system under investigation was a small initial stiffness, which was a result of the incidence of clearance. When clearance was eliminated, the system under investigation was increasing its stiffness, and its characteristic in the investigated range of loads was close to the linear one. The above comments are related to the three bearings with journals of different diameter. In case of the bearing with journal of the biggest diameter, no clear area with incidence of clearance was noticed in the results of the experiment, what certifies the formerly described difficulties with achievement of the dimensional accuracy of top and bump foils.

The compatibility of results from simulations and experiments was compared for each of the investigated bearings separately. The highest compatibility of results was obtained for the system with the lowest clearance. In the range of load above 50 N one could observe overlap of simulation and experimental characteristics. Certain incompatibilities occurring for lower loads can be explained by some inaccuracy in realization of the foil set, which was the cause of the loss of clearance in a real bearing. In case of two other bearings, with journal diameter of 38,07 and 38,10 mm, the compatibility of the characteristics was lower. In these two cases, model represented the results of the measurements with low load in a satisfactory manner, with respect to the elimination of the radial clearance, which this time revealed itself also at the testing rig. At higher values of load, the differences between results of displacements determined by calculations and experiments reached ca. 20%. It should be however noticed, that in each of the cases under consideration, the curves determined by simulations and experiments, after elimination of the clearance in the bearing, exhibited a close value of the inclination angle.

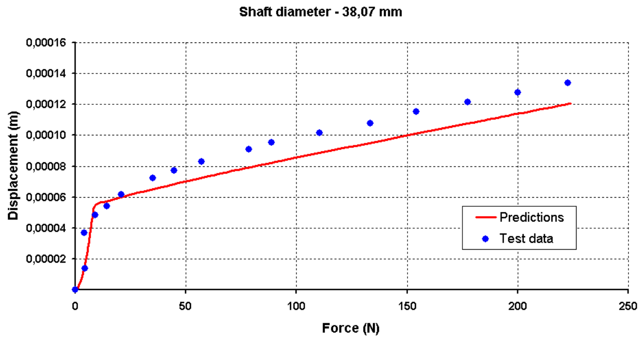

Fig. 3. Foil bearing structure deflection versus static load (nominal clearance 0,05 mm)

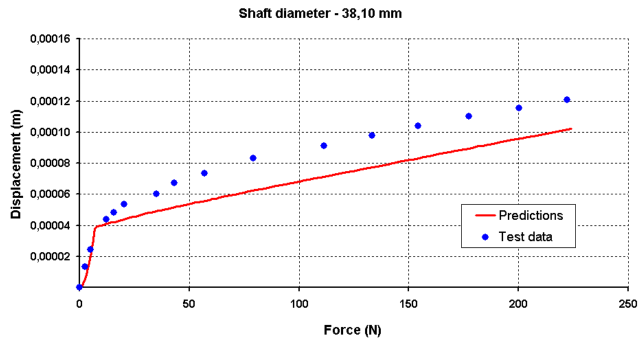

Fig. 4. Foil bearing structure deflection versus static load (nominal clearance 0,035 mm)

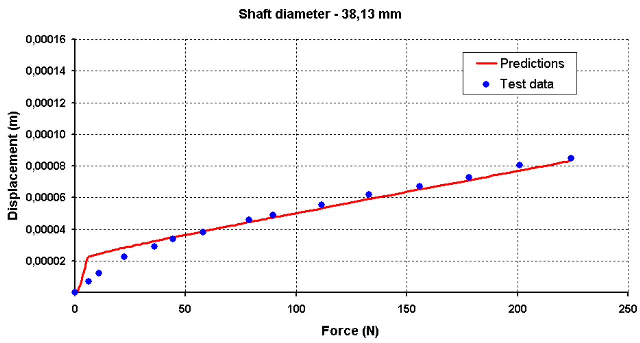

Fig. 5. Foil bearing structure deflection versus static load (nominal clearance 0,02 mm)

In the second stage of verification, in order to better identify the model of structural supporting layer of the foil bearing, investigation enabling the assessment of the model in terms of energy dissipation during the loading and unloading processes was conducted. In the model under investigation the dissipation of energy occurred as a result of the sliding friction between cooperating elements of the bearing. For the purpose of the comparison of the model characteristics with results of the research published in already mentioned article (Rubio and San Anders, 2006), only procedure of the loading of the system was modified in a previously developed model. During the first second of the analysis the system was loaded linearly with a force of maximal value of 224N, and in the second of analysis this force was decreasing linearly to 0. Comparison of the obtained characteristics is shown in figure 6. The investigation under consideration was realized only for the bearing of journal diameter equal to 38,10 mm.

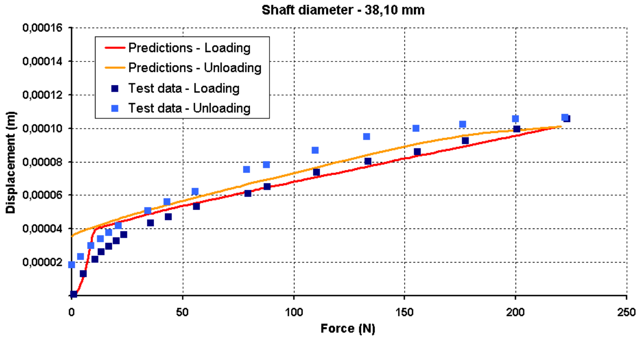

Fig. 6. Foil bearing structure deflection versus static loading and unloading

The characteristics shown in Fig. 6 confirms the high compatibility of the developed model. A very high consistency of characteristics during the process of the system loading was obtained. Slightly worse matching of characteristics was obtained during the unloading of the system. The results of simulations showed, that during the decreasing load, the values of journal displacement corresponding to the same values of the force were higher than in case of the loading process. It was consistent with the results of the experiments and was connected with the friction phenomenon occurring during the journal displacements inside the bearing. As a result of the dissipation of part o the energy supplied to the system so-called hysteresis loop was created. The surface area of the hysteresis loop obtained as a result of experiments was slightly higher than the one obtained as a result of calculations, which can be explained by the fact that some simplifications of the model were assumed, such as: omission of the internal friction or two-dimensional character. Due to the fact, that the mechanical system under investigation was very complex, and apart from deformation of elements with complex geometry, the contact phenomena occurred as well - it can be stated that the obtained results are satisfactory.

4. SUMMARY AND CONCLUSIONS

This paper discusses the results of verification tests of the numerical model of the structural supporting layer of the foil bearing. The developed model was verified in two stages in terms of the static loads. The results of the investigation confirmed the validity of assumptions made while developing the model. Because the developed model can be treated as reliable, it can be used as a very useful research tool and will be applied for investigation of the influences of selected parameters on the static characteristics of the foil bearing structure. Soon the model under consideration will be also tested in terms of dynamic loads, which will be the topic of the following publications.

Finally, the comprehensively tested FEM model of the foil bearing structure, after connection with a flow model developed in parallel, will be applied for development of the simulation model of the whole foil bearing.

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The research work was supported by scientific project No POIG.01.03.01-00-027/08 "Application intelligent materials and structures to develop and implement the concept of the innovative bearing system for power micro-turbine rotors"