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CFD Analysis of A Starved Four-Pad Tilting-Pad Journal Bearing with An Elastic Support of Pads

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Abstract. Tilting-pad journal bearings are widely used in technics. Oil starvation operation regime is not common for hydrodynamic bearings. However, correctly designed low-flow journal bearing have to operate efficiently and consistently on high rotor speeds. An elastic support of bearing pads is a set of elastic pins made of steel. Elastic support allows pads to self-align and achieve an optimal operational mode. The article presents the thermohydrodynamic performance of an axial journal bearing. The study deals with 60 mm diameter four-pad tilting-pad journal bearing, submitted to a static load varying from 1000 to 30000 N with a rotating speed varying from 1000 to 10000 rpm. The investigation focuses on numerical studying the characteristics of low-flow tilting-pad journal bearings under oil starvation conditions. Dependencies of the bearing performance on the load, rotational speed of the shaft, and the size of the radial clearance are presented.

1. Introduction

Tilting-pad journal bearings (TPJB) are widely used in high-speed rotating machines due to their high dynamic stability, damping characteristics, ability to operate at high rotational speeds, and long service life [1]. TPJB can be classified by the type of mounting: bearings with pads mounted on hinges; rolling-pad bearings with an elastic support of pads. The lower surface of the smaller radius of rolling pads leans on the internal surface of the housing. An example of such a bearing is H. Hashimoto's rolling-pad journal bearing with six pads [2]. These bearings are more rigid, compared to bearings with hinged pads. Hydrodynamic bearings with elastic pads increase the load bearing capacity by up to 30%, compared to conventional thrust bearings with tilting (pivoted) pads [3]. However, there is a tendency to improve the efficiency of gas turbine engines. Therefore, designing low-flow tilting-pad journal bearings for gas turbine engines with high rotational speeds is relevant.

The boring of bearing pads into the shaft radius with a close radial clearance of the bearing speeds up the onset of fluid friction. Forced load of all pads can prevent "pad fluttering" that is typical for tilting-pad journal bearings [4]. Such a bearing can operate without forced supply of oil to the oil grooves ("oil starvation" mode). These features significantly reduce the engine weight and oil flow, thus increasing the efficiency of the engine overall.

Elastic support of bearing pads is used to even out the load among pads (thrust bearings), and for force closure of the running clearance (journal bearings). The main requirements to the elastic support of pads are maintenance of set stiffness properties and high damping properties. Elastic support of bearing pads can be realized with elastic pins (Figure 1), "squirrel cage", Belleville washers, elastic plates or elastic porous materials like the metal analogue of rubber (Metal analogue of Rubber, designed by the Samara University).

TPJBs with an elastic support of pads can utilize such lubricant properties as continuity and wettability to maintain their lifting properties and improve their flow characteristics [5].

In order to utilize these properties (under "oil starvation"), it is necessary to make it so that the running clearance in passive pads that are opposite to the carrying ones is not closed completely, while the elastic support is capable of both closing and opening the running clearance. A bearing with elastic pins and Metal analogue of Rubber is capable of this, unlike "squirrel cage" supports, Belleville washers, elastic plates, and the "Allison" ring. A combined support with two elastic pins, maximally spread across the length of the pad, compensates for this flaw to a certain extent. The advantage of such a support is the technological simplicity of the boring of pads into the shaft radius with subsequent closure of the clearance into the shaft diameter by boring on technological fixing pins. Furthermore, the presence of elastic pins in the support solves the problem of circumferential fixation of pads in constructions with a support, for instance, in "Allison" rings.

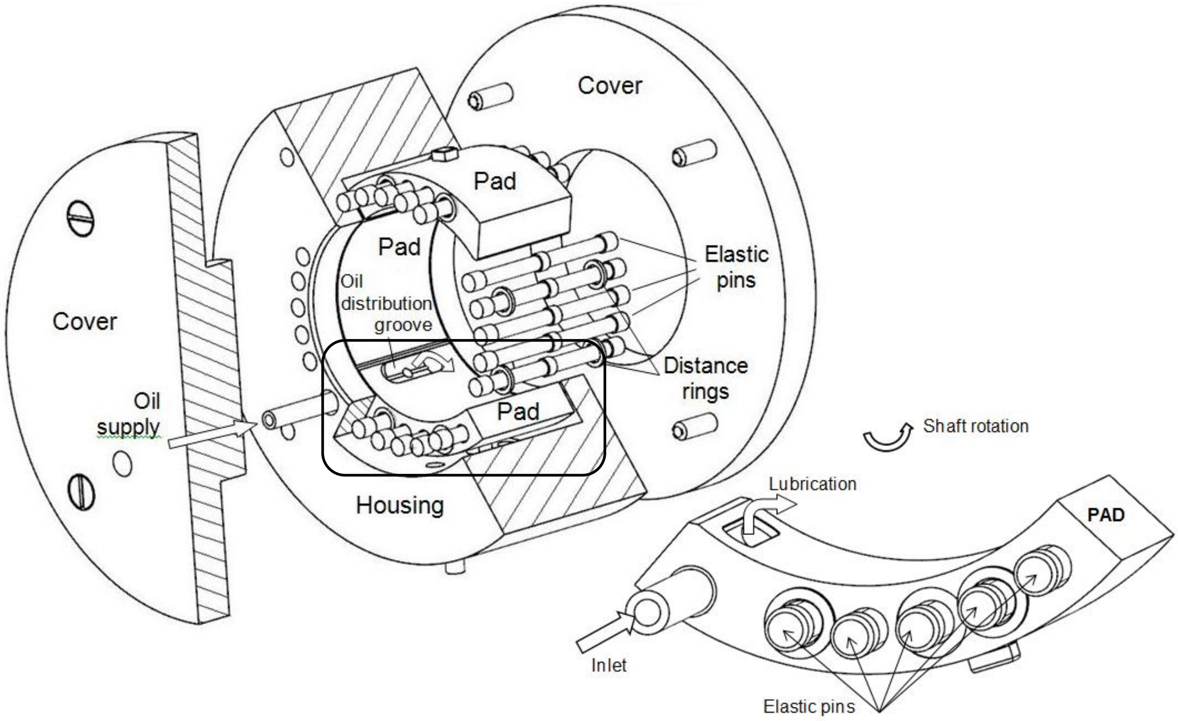


Figure 1. Tilting-pad journal bearing with elastic support of pads (elastic pins configuration)

The bearing operates in the hydrodynamic lubrication mode. The lubricant is supplied to the running clearance through an oil groove, after which it is set in motion by the surface of the rotating shaft.

At present, an adequate technique of design of the bearing under consideration that would take into account the peculiarities of its design and utilize modern tools of computer-aided engineering is lacking. Furthermore, the experimental development of studied bearings is also complicated due to the numerous factors that affect their characteristics. Thus, the design of reliable computational techniques is a crucial component when creating and developing the theory of design of the bearings under consideration. The purpose of this research is to study numerically the characteristics of low-flow tilting-pad journal bearings under oil starvation conditions.

2. Literature survey

Many studies of tilting-pad journal bearings are experimental.

The conventional (analytical) design method of journal bearings is based on Reynold's equations and continuity [6]. Nowadays, these models are modified to include components that take into account the effect of roughness, heat effect, cavitation, turbulence, multiphase nature of lubricant flow, use of non-Newtonian fluids, etc. [7]. Thermoelastohydrodynamic models are used to study the characteristics of tilting-pad journal bearings [8].

The literature survey showed that the development of mathematical models of TPJB must be confirmed by the results of numerous experiments.

Thus, empirical and semi-empirical models are only applicable to a certain structure of the bearing and even to a certain range of their standard size [9, 10, 11]. Furthermore, most existing techniques of thermoelastohydrodynamic analysis are unsuitable for starved bearings. V.A. Voskresensky offered a purely analytical method of designing tilting-pad journal and thrust bearings [9]. This method was adapted to the conditions of oil starvation in the part of heat balance problems and estimation of oil flow through the bearing and is currently used to design roughly the low-flow journal bearings at such Russian companies as "Kuznetsov" and "Salyut", as well as at the Samara University.

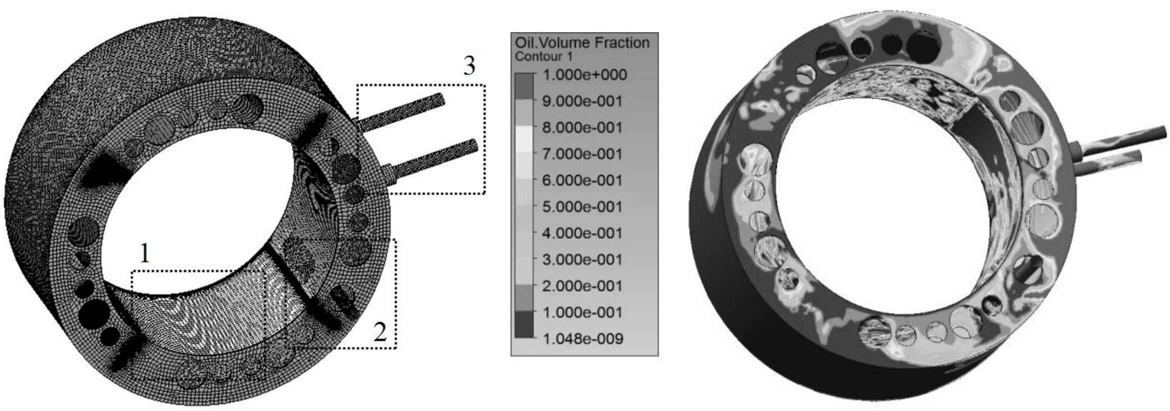
The analysis of pressure distribution in the clearance of bearings with an axial boring of pads and boring of pads into the shaft radius showed the following. The type of dependencies matched the theoretical ones for tilting-pad journal bearings [9]. The nature of pressure distribution with the boring of pads into the shaft radius is smoother ("filled" distribution); with axial boring, the distribution is "peaked" and the maximum pressure is almost twice as high as with boring into the shaft radius. Identical results for conventional bearings were obtained in studies [12]. A smoother distribution of pressure in the lubricant film is indicative of an extended service life of such bearings [6, 9].

The above methods have obvious restrictions when it comes to bearings with new geometry (inaccurate description of flow recirculation, mixing, mass balance, etc.). These restrictions can be eliminated by means of computational fluid dynamics (CFD) [13]. CFD provides for accurate calculations [14].

3. CFD solution of a two-phase problem

The multiphase nature of the working fluid significantly affects the accuracy and physics of processes in the designed model of the bearing. A finite element model of internal cavities of the bearing was generated in ICEM CFD for the CFD analysis (Figure 2, A). Here 1 is a mapped grid of the running clearance; 2 – mapped grid of the inlet; 3 – mapped grid of the discharge area.

The feature of the finite element model is the mapped grid of finite elements in the running clearance and inlets – lubricant discharge and face clearances of pads.



A **B**

Figure 2. Bearing model

The modelling of a two-phase operating environment (oil + air) was performed with the Ansys CFX package for gas-hydrodynamic analysis with regard to surface tension, adhesion, and modelling of a free boundary between the phases. A surface tension coefficient with the continuum surface force option and the initial liquid phase was set to model the free boundary between the liquid and gaseous phase.

4. Results

A series of computations in accordance with the modified method showed the dependencies of the characteristics of bearings on the clearance size and the rotational speed of the shaft. The maximal oil temperature in the bearing rises with the reduction of the running clearance and with the increase of the rotational speed of the shaft (Figure 3, A). The load factor reduced with an increase in the rotational speed of the running clearance and a reduction of the clearance (Figure 3, B). The lubricant flow through the bearing increased linearly with the increase of the clearance and the rotational speed (Figure 3, C).

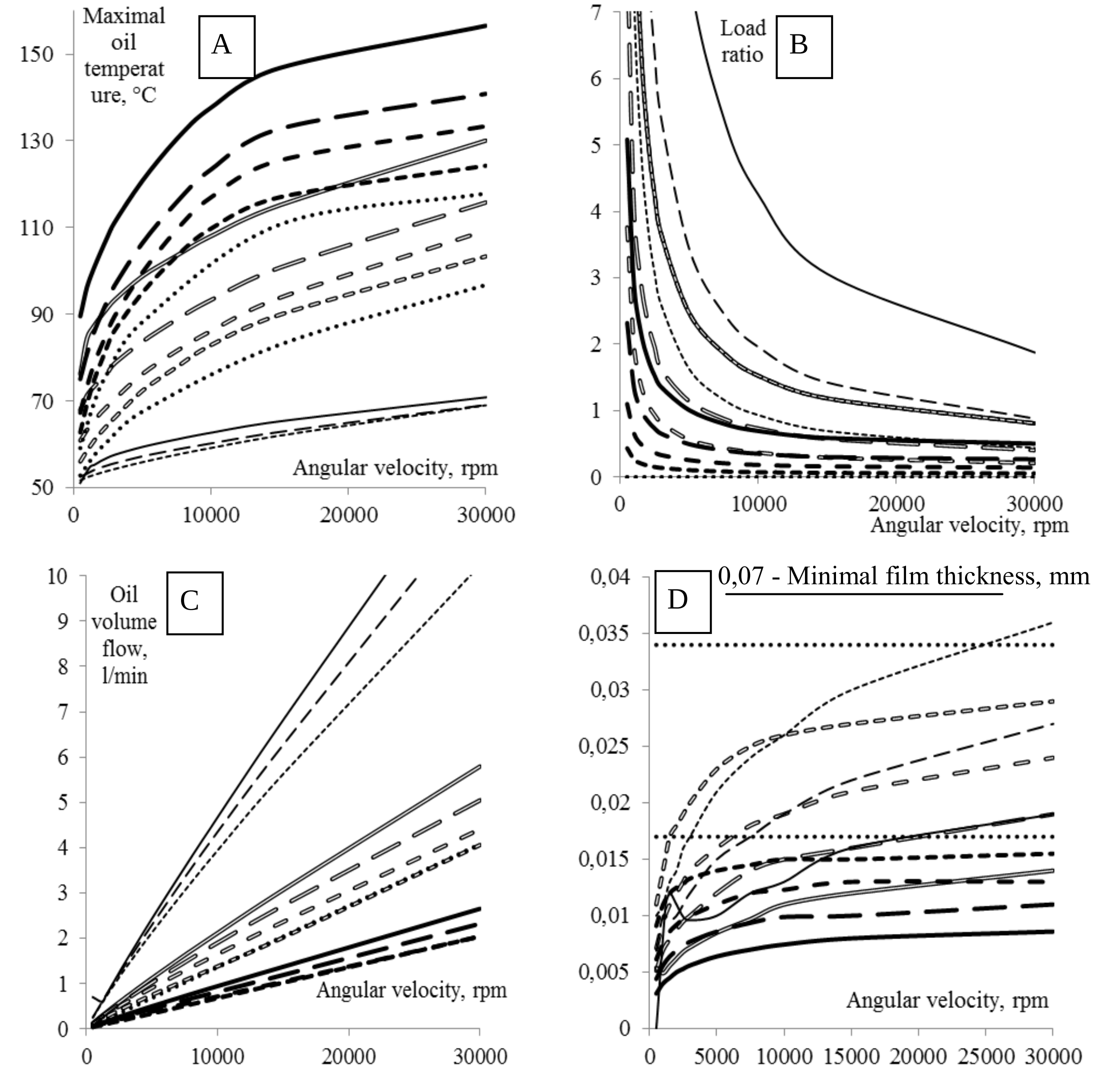


Figure 3. Dependencies on the rotational speed: A - of the maximal oil temperature; B -of the load factor on the rotational speed; C - of the maximal oil temperature; D - of the minimal clearance thickness on the rotational speed

The minimal thickness of the clearance increases with an increase in the rotational speed of the rotor (shaft floating) and with the reduction of the running clearance (Figure 3, D). The dependency chart has an asymptote (for unloaded bearings). The hydrodynamic design of a two-phase model of a TPJB showed the distribution of model phases and the flow parameters: total and for each modelled phase.

The main problem of rotary bearings is that they consume too much oil in order to maintain reliability and their bearing capacity (heat sink, reduction of friction). High oil consumption is the main reason behind the low efficiency and environmental unfriendliness of high-speed machinery.

Journal bearings are commonly used in Russia in ground gas-pumping plants. Tests with the industrial compressor station that first used the prototype of a low-flow TPJB showed good results. After the oil flow was dropped from the design 12 l/min (oil bath) to 0.2 l/min (oil starvation), the bearing operated for more than an hour according to the plan of the test. When the unit was disassembled, it was found that the bearing was in ideal state. At that, the lower carrying pad had a surface polished to a mirror finish – a result of functional bedding in the rotating shaft during the spin-up and stop of the rotor.

Foreign experience. Scientists laid an extensive theoretical and experimental foundation for the development of techniques of designing TPJB. The hydrodynamic theory of lubrication that scientists use in most theoretical studies has proven to be efficient in solving problems that are related to the description of the operation of journal bearings. The elaboration of the hydrodynamic theory of lubrication – M. Fillon's, M. Khonsari's [12, 15] and other researchers' thermohydrodynamic and thermoelastohydrodynamic theories for journal bearings, are interesting and helpful. The results of experimental studies of various TPJB [16], including the results that prove the workability of tilting-pad journal bearings with an elastic-pivot pad [17], as well as the outstanding results of D. Childs [18,19] and results of computer simulation [20] show the following trends in the study of TPJB:

1) engineering study of different TPJB designs, including elastic-pivot pad and elastic-pad TPJBs;
2) development of advanced technological computational methods, including CAE;
3) start of experimental studies of oil starvation in journal bearings.

In order to increase the service life of future high-speed bearings, it is necessary to refer again to the hydrodynamic theory of lubrication, which, in turn, requires high oil flow, but can guarantee high bearing capacity. In a hydrodynamic mode, the flow can be reduced by using new bearing designs and new unconventional materials. At present, unconventional materials with a low coefficient of friction are being developed. At that, these materials lack a specific area of application, including TPJB.

In Russia, several scientific schools have worked successfully for decades in the area of hydrodynamics of journal bearings. However, their main inventions concern tilting-pad journal bearings (operating in an oil bath). Thus, the experimental studies of low-flow TPJB should be substantiated theoretically. Uniting the studies of low-flow TPJB into a single complex – a simultaneous solution of the hydrodynamic problem, the thermal problem, and the problem of the wear of the friction pair surface – provides for a comprehensive solution of the outlined problem.

In future, the developed technique of designing starved TPJB with an elastic support of pads can help cut the time required to design and tune the bearing and cut the production costs of experimental models. Thus, low-flow TPJB with an elastic support of pads can solve the problem of cutting lubricant consumption in high-speed machinery.

5. Discussion

Obtained dependencies of the characteristics of bearings on the size of the clearance and the rotational speed of the shaft are in line with the TPJB characteristics that were obtained by other authors [9, 14]. At that, the diagrams of dependencies of the minimal clearance thickness on the rotational speed for different dimensions of the radial clearance of the bearing show a hopped peak at a load of 10000 N and 5000 N and a clearance Δ_1 = 25 μm. This peak is caused by "shaft floating". High loads, small radial clearance, and low rotational speed fail to generate force that is sufficient to support the shaft on the hydrodynamic wedge. By default, V.A. Voskresensky's method [9] uses tabulated results of hydrodynamic computations, which results in a limited applicability of this method. However, hydrodynamic computations, the results of which are presented in tables, are performed in boundary conditions that correspond to an oil bath – unlimited oil supply to pads and zero excess pressure across the pads, while low-flow journal bearings requires computations at numerically specific lubricant flow through the bearings and their pads.

The graphic presentation of a non-stationary design of a two-phase bearing model with oil spillage during the shaft spin-up in the bearing (Figure 2, B) shows that the lubricant spreads in the form of an elongated stain. The lubricant is sucked from the oil groove into the running clearance of the bearing. The rough surface of the shaft bearing helps small parts of the lubricant to attach to it and moistens the impact of rubbing surfaces. A similar flow pattern of a two-phase liquid in the face clearance was obtained by Lebeck in his experimental study of face seals [21]. He found liquid traces, elongated in the direction of shaft rotation, at the breakage of the lubricant layer in the gaseous phase. This proves the reliability of results that were obtained during the present research. The herein presented thermal design technique for radial journal bearings could also be used to design face bearings and seals [22].

The CFD method is applicable to all journal bearings, including smooth bearings that work on oil that requires multiphase hydrodynamic analysis: water journal bearings; bearings that work at high rotational speeds and (or) on low-viscous lubricants; low-flow bearings. The CFD method can serve as the basis for linked unilateral and bilateral CAE analysis of smooth and tilting-pad journal bearings and for direct optimization. A comprehensive technique of designing TPJB is lacking at present. Herein, a comprehensive technique implies a design technique that takes into account the peculiarities of the TPJB structure and actual load, and utilizes to the extent possible the modern computational means (CFD). Thus, developing reliable computational techniques is a crucial element when creating and developing the theory of design of new TPJB structures.

The present paper is based on the existing concept of hydrodynamic lubrication. However, the case under consideration lies at the very edge of the applicability of this concept (small clearances).

Computations with this technique for bearings with conventional clearance sizes yielded similar results, which prove its validity. Open literature lacks computational results with small clearances; however, examples of positive tests of bearings under these conditions prove the quality of the developed technique. Further researches will involve specialized experimental studies of low-flow small-clearance bearings. The herein considered issues of designing low-flow journal bearings with a ceramic friction pair with a low coefficient of friction enable making bearings with improved and efficient performance characteristics. This will enable compressor and pump designers to create turbomachines with advanced parameters.

6. Conclusion

The scientific novelty of this research consists in the discovered regularities of lubricant flow in small clearance of TPJBs, as well as in the regularities of their main characteristics.

Researchers of journal bearings may also be interested in the herein developed two-phase CAE model of a low-flow journal bearing with a small radial clearance (20 µm), which takes into account the effect of lubricant adhesion, surface roughness, inertia, and the presence of a free boundary between the liquid and gaseous phase. The analysis of results showed that the lubricant spreads in the two-phase low-flow bearing in the form of a stain. The rough surface of the shaft bearing helps small parts of the lubricant to attach to it and moistens the impact of rubbing surfaces. Thus, it was shown, that even with small clearances under oil starvation, the lubrication of the surfaces of the bearing is performed, besides the velocity head of the lubricant, by a continuous layer of fluid particles. Adhesion and microscopic roughness facilitates the presence and preservation of these particles.

The shortcoming of the designed bearing model is that it does not consider the effect of pad deformation on the form of the clearance and the characteristics of the bearing.

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