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Low-Flow Tilting-Pad Hydrodynamic Bearings with an Elastic Support of Pads. Mechanism and Theoretical Approaches

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Abstract: The research investigates the peculiarities of the numerical study of low-flow tilting-pad journal bearings. The low-flow nature of these bearings comes from their operation under oil starvation with a close radial clearance. The study describes the structural features, the mechanism and the design of low-flow journal bearings. The features of these bearings are their resistance to self-oscillation, high performance, efficiency and load bearing capacity. The efficiency of mounting groups in modern turbomachines including journal bearings, largely depends on their design technology. The purpose of this research is to study numerically the characteristics of low-flow tilting-pad bearings under oil starvation. The known technique for determining the characteristics of tilting-pad bearings was chosen as the prototype. This technique was modified for the conditions of oil starvation. The modified technique was used to carry out a series of computations and to determine the dependencies of the performance of the bearing on the load, rotational speed of the shaft and the size of the radial clearance. Obtained dependencies matched the usual characteristics of tilting-pad journal bearings. A 2-phase model of a low-flow tilting-pad journal bearing was designed with regard to the effect of lubricant adhesion, surface roughness, inertia and the presence of a free boundary between the liquid and gaseous phase.

Key words: Bearing performance, dynamic viscosity, gas turbine engine, load ratio, volume flow, tilting-pad

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 (Chadaadaev and Novikov, 2009).

Their main advantage is that each pad can rotate independently to create its own pressure profile. 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 (Mikami *et al*., 1988). 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 (Mikami *et al*., 1988).

However, there is a tendency to improve the efficiency and environmental friendliness of gas turbine engines. Therefore, designing low-flow journal bearings for gas turbine engines with high rotational speeds is relevant (Chadaadaev and Novikov, 2009).

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 (Parovay and Falaleev, 2013). 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 (suspension bearings). The main requirements to the elastic support of pads are as follows:

- Maintenance of set stiffness properties
- Maintenance of high damping properties (for the detuning and improvement of the vibrational state of the gas turbine engine)
- Maintenance of the self-aligning of pads in a position that is optimal for each mode
- Maintenance of the service life of the bearing
- Provision of heat sink
- Workability of the construction
- Lack of shared contact surfaces between the pad and the mounting to rule out jamming during self-alignment of pads
- High contact wear resistance of contact surfaces of elastic elements

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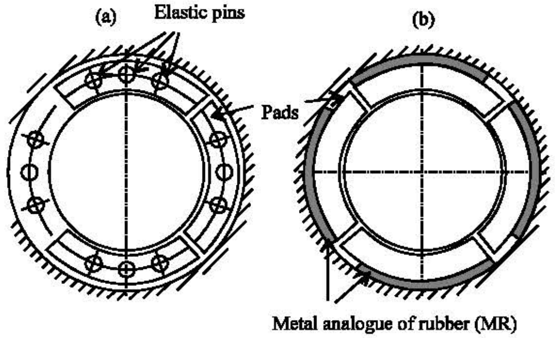

Fig. 1: Tilting-pad journal bearing with elastic suspension of pads; a) With pads on elastic pins and b) With an elastic suspension of pads made out of metal analogue of rubber

Elastic suspension of bearing pads can be realized with elastic pins (Fig. 1a), "squirrel cage", Belleville washers, elastic plates or elastic porous materials like the metal analogue of rubber (Metal analogue of rubber, designed by the Samara State Aerospace University) (Fig. 1b).

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

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 suspension 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" suspensions, Belleville washers, elastic plates and the "Allison" ring. A combined suspension 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 suspension 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 suspension solves the problem of circumferential fixation of pads in constructions with a suspension for instance in "Allison" rings.

The design of the operating bearing pad on elastic pins is presented in Fig. 2. 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.

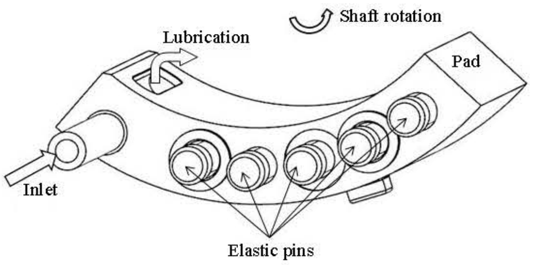

Fig. 2: Design of an operating bearing pad

The lubricant is supplied through the canal in the flange of the bearing mounting. Then the lubricant enters the oil groove through the inlet in the pad, it is then spread across the running clearance.

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 conventional (analytical) design method of journal bearings is based on Reynold's equations and continuity (Bruce, 2012). Mathematical models of lubricant flow in journal bearings are based on the Navier-Stokes equation. Now a days, 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. (Dimond *et al*., 2011). For example, Fillon (1996)'s thermohydrodynamic model of journal bearings consists of Reynold's equation, equation of energy in the film and the equation of heat transfer between the pad and the shaft, all equations are solved simultaneously (Boncompain *et al*., 1986). The hydrodynamic model takes into account the cavitation in the film, the lubricant recirculation and the released flow at the inlet. In addition, the thermoelastic deformations are also calculated in order to define the film thickness. Khonsari *et al*. (1996)'s thermohydrodynamic model of journal bearings takes into account the rheological properties of lubricants under high pressure (piezo-viscous fluids).

The results of Khonsari *et al*. (1996)'s experimental studies could be used to generate empirical rate equations which are useful in modelling elastohydrodynamic traction in journal bearings (Bair *et al*., 1988).

Thermoelastohydrodynamic models are used to study the characteristics of tilting-pad journal bearings (Fillon *et al.*, 1992). 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 (Chernavsky, 1963). Furthermore, most existing techniques of thermoelastohydrodynamic analysis are unsuitable for starved bearings (He *et al.*, 2015).

Voskresensky *et al.* (1983) offered a purely analytical method of designing tilting-pad support bearings. 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 support bearings at such Russian companies as “Kuznetsov” and “Salyut” as well as at the Samara State Aerospace University (Samara, Russia). At present, thrust bearings are designed in accordance method by Chernavsky (1963)’s. Adapting this method to the conditions of oil starvation is difficult due to its empirical nature. Therefore, the reliability of design of starved thrust bearings is doubtful.

The analysis of pressure distribution in the clearance of bearings with an axial boring of pads (conventional structure) and boring of pads into the shaft radius showed the following. The type of dependencies matched the theoretical ones for tilting-pad journal bearings (Voskresensky *et al.*, 1983). 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. A smoother distribution of pressure in the lubricant film is indicative of an extended service life of such bearings (Bruce, 2012; Voskresensky *et al.*, 1983). This was proven during experimental studies of bearings with boring of pads into the shaft radius.

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) (Huebner, 1974). CFD provides for accurate calculations. The results of measurements and calculations for bearings with similar structures provide material for further studies (Tschoepe and Childs, 2014).

The purpose of this research is to study numerically the characteristics of low-flow tilting-pad bearings under oil starvation. Therefore, it is necessary to accomplish the following objectives:

- To develop an analytical technique of determining the operating characteristics of tilting-pad journal bearings
- To substantiate the reliability of the developed technique
- To carry out a CFD analysis of the lubricant flow in the bearing with a two-phase model of the bearing
- To determine the prospects for future studies

The contribution of the research to world science is as follows: the developed analytical technique enables determining tentatively the operating characteristics of journal bearings that operate under oil starvation without expensive experiments at the early stages of design. The study initiates the study of low-flow TPJB in marginal conditions of lubrication at small running clearances. The developed technique of designing low-flow TPJB should be considered from the joint perspective of tribology, application of new materials and hydrodynamic theory of lubrication. The technique regards oil starvation as the operating mode of the bearing which has advantages over the conventional lubrication mode (oil bath).

MATERIALS AND METHODS

Analytical solution: Voskresensky’s method (Bair *et al.*, 1998) for bearings operating in an oil bath was used to determine primarily the characteristics of tilting-pad bearings.

The initial data used to determine the characteristics of bearings include the load of the bearing W; the number of pads k; the pad form coefficient; the Diameter of the shaft D_{shaft} and the bearing $D_{bearing}$ (used to find the size of the radial clearance in the bearing δ), the width of the pad, the rotational speed of the rotor ω, the type of oil and the oil temperature in the lubrication system.

The thermal design and calculation of the total discharge characteristics is performed for conditions of oil starvation. The existing method was modified accordingly.

For the energy balance equation, it is assumed at first that the oil that enters the clearance contains an amount of cold oil which is mixed with oil that was heated under the previous pad, equal to the side leakages:

$$Q_{inletk}\times t_{inletk}=\left[Q_{inletk}-\left(Q_{inletk-1}-Q_{Tk-1}\right)\right]\times t_0+\left(Q_{inletk-1}-Q_{Tk-1}\right)\left(t_{inletk\text{-}1}+\Delta t_{k\text{-}1}\right) \quad (1)$$

Where:

t_0 = The temperature of oil between pads

t_{inletk} = The temperature of oil at the inlet of pad k

$t_{inletk\text{-}1}$ = The temperature of oil at the inlet of the previous pad

$\Delta t_{k\text{-}1}$ = Oil overheating at the previous pad

Q_{inletk} = The oil flow at the inlet of pad k
Q_{tk} = The face oil flow of pad k
$Q_{inletk-1}$ = The oil flow at the inlet of the previous pad

The heat balance equation for any pad if $Q_{inlet\,k}>(Q_{inlet\,k-1}-Q_{Tk-1})$ is:

$$Q_{inletk}\times t_{BXk}=\left[Q_{inletk}-\left(Q_{inletk-1}-Q_{Tk-1}\right)\right]\times t_0+\left(Q_{inletk-1}-Q_{Tk-1}\right)\left(t_{inletk-1}+\Delta t_{k-1}\right) \tag{2}$$

and if, $Q_{inlet\,k}\leq(Q_{inlet\,k-1}-Q_{Tk-1})$, then:

$$t_{inletk}=t_{inletk-1}+\Delta t_{k-1} \tag{3}$$

with dimensionless coefficients and with $q_{inlet\,k}>(q_{inlet\,k-1}-A\times q_{Tk-1})$:

$$t_{inletk}=t_0+\frac{q_{inletk-1}-Aq_{Tk-1}}{q_{inletk}}\cdot\left(t_{inletk-1}-t_0+\Delta t_{k-1}\right) \tag{4}$$

and with $q_{inlet\,k}\leq(q_{inlet\,k-1}-A\times q_{Tk-1})$:

$$t_{inletk}=t_{inletk-1}+\Delta t_{k-1} \tag{5}$$

The dimensionless coefficient of flow at the inlet of the lubricant layer q_{inlet} and the dimensionless coefficient of face flow q_T are found, assuming that the lubricant flow through the lubricant layer is a function of the geometry of the pad:

$$Q_{inlet}=R\times l\times\omega\times\Delta q_{inlet} \tag{6}$$

$$Q_T=A\times R\times l\times\omega\times\Delta q_T \tag{7}$$

Where:
$A=(R/l)^2$ = The Reynold's equation coefficient
R = The shaft Radius
l = The axial dimension of the bearing
ω = The angular rotational speed

As $a\times t_{inletk}+b\times t_{inletk-1}$ with $q_{inlet\,k}>(q_{inlet\,k-1}-A\times q_{Tk-1})$:

$$t_{inletk}+\left(-\frac{q_{inletk-1}-Aq_{Tk-1}}{q_{inletk}}\right)t_{inletk-1}=t_0-\left(-\frac{q_{inletk-1}-Aq_{Tk-1}}{q_{inletk}}\right)\left(-t_0+\Delta t_{k-1}\right) \tag{8}$$

and if $q_{inlet\,k}\leq(q_{inlet\,k-1}-A\times q_{Tk-1})$:

$$t_{inletk}+(-1)\,t_{inletk-1}=\Delta t_{k-1} \tag{9}$$

The mean oil overheating in the lubricant layer of pad k:

$$\Delta t_k=\frac{N_k}{c\times\rho\times\left(Q_{inletk}-\frac{Q_{Tk}}{2}\right)}=\frac{\xi_k\times\omega\times\mu_m}{c\times\rho\times\psi^2\times\left(q_{inletk}-\frac{A\times q_{Tk}}{2}\right)} \tag{10}$$

Where:
N_k = Loss of power due to friction in pad k
c = The heat capacity of the lubricant
ρ = The density of the lubricant
ζ_k = The coefficient of power loss due to friction in pad k
μ_m = The mean dynamic viscosity of the lubricant
Ψ = The relative clearance of the bearing

The method assumes that the oil that flows from out of the exit edge of the pad enters the inlet of the next pad without any losses. Therefore, the volume oil flow through the bearing consists of face losses Q_T and losses of oil overflow Q_{over} which form before the pads whose discharge characteristics Q_{inletk} are less that the volume oil flow that is supplied to the inlets of said pads from the previous pad $Q_{inletk-1}-Q_{Tk-1}$.

In systematized form with dimensionless coefficients that are used in the computational algorithm, this is written as follows:

$$Q_1=0.25\psi ld^2\omega q_{total}=0.25\psi ld^2\omega\left(A\times\Sigma q_{Tk}+\Sigma q_{overk}\right) \tag{11}$$

where if:

$$q_{inletk}<\left(q_{inletk-1}-A\times q_{Tk-1}\right)\rightarrow q_{overk}=q_{inletk-1}-A\times q_{Tk-1}-q_{inletk} \tag{12}$$

and if:

$$q_{inletk}\geq\left(q_{inletk-1}-A\times q_{?\,k-1}\right)\rightarrow q_{overk}=0$$

Solution of a two-phase problem in ANSYS CFX: 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 (Fig. 3). The feature of the finite element model is the ordered grid of finite elements in the running clearance and inlets-lubricant discharge and face clearances of pads.

The following recommendations should be taken into consideration when designing a hydrodynamic finite element model of a low-flow bearing with $H_{min}<100$ μm.

The need to overlay the ordered grid on the clearance, the form of the finite element that is determined

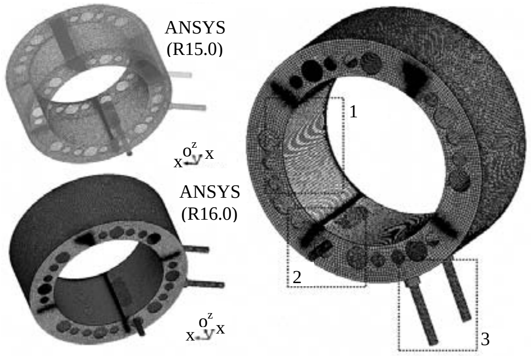

Fig. 3: Finite element model (ICEM CFD): 1) Ordered grid of the running clearance; 2) Ordered grid of the inlet and 3) Ordered grid of the discharge area

by the demands of hydrodynamics is the form of a cuboid (hexahedron). Furthermore, maintaining the aspect ratio of 1-20, …, 100 is necessary to guarantee satisfactory results of computing, a sufficient number of finite elements across the width of the clearance (at least 8), grid refinement (the presence of a near-wall layer), overall fineness of the grid.

The fineness of the grid provides for adequate computational studies of the operating characteristics of bearings:

- Design of CFD Models of bearings
- Determination of characteristics of bearings in stationary and non-stationary positions

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.

RESULTS AND DISCUSSION

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 (Fig. 4).

The load factor reduced with an increase in the rotational speed of the running clearance and a reduction of the clearance (Fig. 5). The lubricant flow through the bearing increased linearly with the increase of the clearance and the rotational speed (Fig. 6).

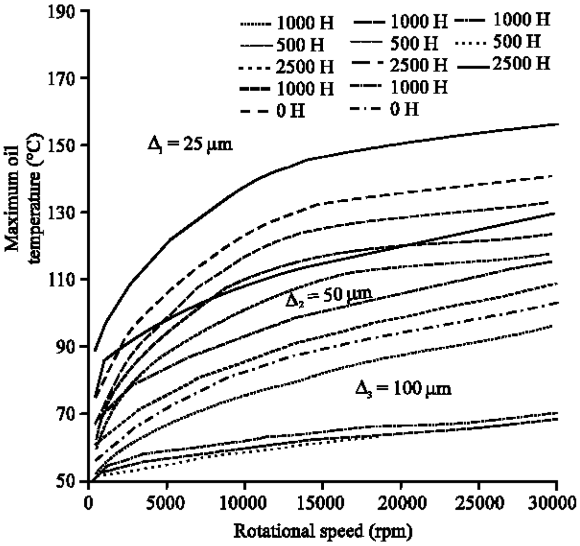

Fig. 4: Dependency of the maximal oil temperature on the rotational speed for various dimensions of the radial clearance of the bearing and load intensity

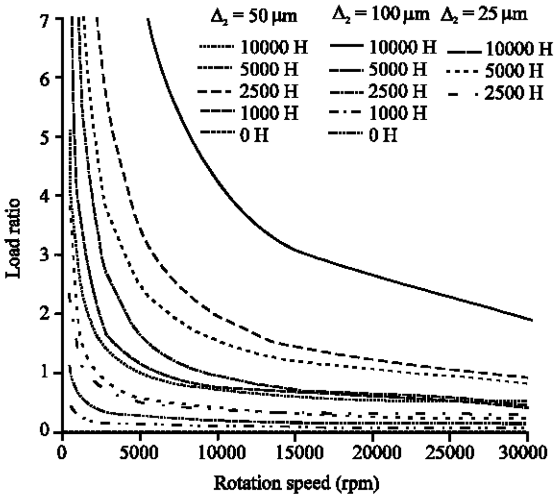

Fig. 5: Dependency of the load factor on the rotational speed for various dimensions of the radial clearance of the bearing and load intensity

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 (Fig. 7). The dependency chart has an asymptote (for unloaded bearings).

The results of the CFD analysis of the bearing are presented in Fig. 8. The hydrodynamic design of a

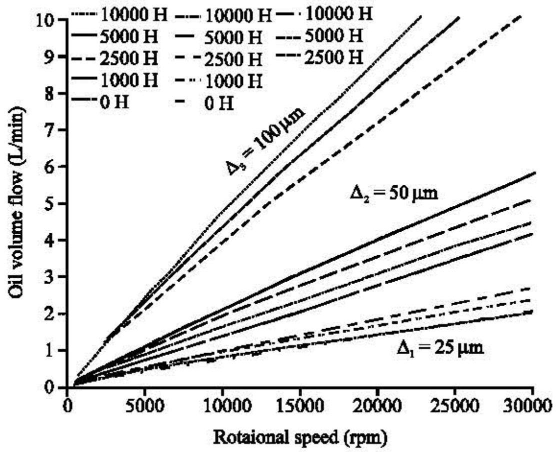

Fig. 6: Dependency of the maximal oil temperature on the rotational speed for various dimensions of the radial clearance of the bearing and load intensity

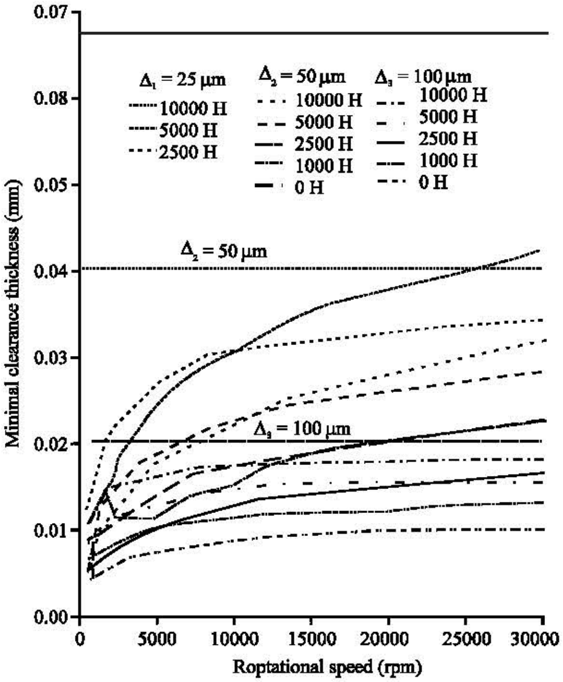

Fig. 7: Dependency of the minimal clearance thickness on the rotational speed for various dimensions of the radial clearance of the bearing

two-phase model of a tilting-pad bearing showed the distribution of model phases and the flow parameters: total and for each modelled phase.

The main problem of rotary table 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.

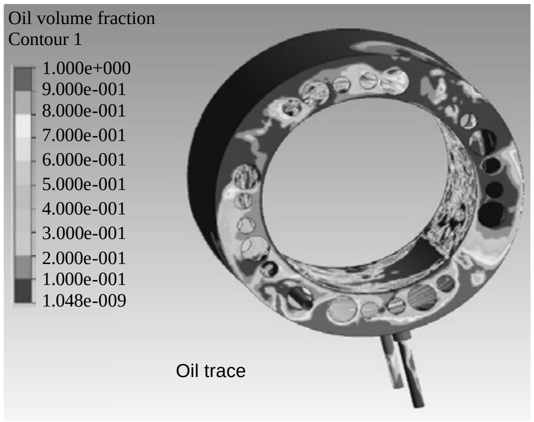

Fig. 8: Distribution of the oil fraction in the bearing in ANSYS CFX

Journal bearings are commonly used in Russia in ground gas-pumping facilities, based on aircraft gas turbine engines in particular by "Salyut" Moscow machine-building manufacturing enterprise federal state unitary enterprise and "Kuznetsov" JSC. 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 m/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. The side and upper pads retained a matte surface in the same state as that after the final mechanical treatment without any signs of contact with the rotating shaft.

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, Khonsari *et al*. (1996) thermohydrodynamic and thermoelastohydrodynamic theories for journal bearings are interesting and helpful. The results of experimental studies of various TPJB (Andres *et al*., 2015), including the results that prove the workability of tilting-pad journal bearings with an elastic-pivot pad (Zhang *et al*., 2015) as well as the outstanding results of

Childs and results of computer simulation (Suh and Palazzolo, 2015) show the following trends in the study of TPJB.

Engineering study of different TPJB designs, including elastic-pivot pad TPJB, rocker-pivot TPJB, elastic-pad TPJB which showed their workability and good statistical and dynamic operating characteristics.

Development of advanced technological computational methods including CAE for the design of bearings with new structures. 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 and low wear of friction pairs are being developed. At that, these materials lack a specific area of application including TPJB.

In Russia, several scientific schools have researched 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 suspension 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 suspension of pads can solve the problem of cutting lubricant consumption in high-speed machinery.

Obtained dependencies of the characteristics of bearings on the size of the clearance and the rotational speed of the shaft is in line with the TPJB characteristics that were obtained by other researchers (Bruce, 2012; Voskresensky *et al*., 1983). 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 and 5000 N and a clearance $\Delta_1 = 25$ 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, Voskresensky *et al*. (1983)'s method 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 (Fig. 8) 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 (Lebeck, 1991). 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 described approach to designing hydrodynamic devices also proved efficient for computing liquid flow in small face clearances (smaller than 1 μm) (Falaleev, 2015).

The herein presented thermal design technique for radial journal bearings could also be used to design face bearings and seals (Balyakin and Falaleev, 2015). The CFD method is applicable to all journal bearings, including smooth bearings that research on oil that requires multiphase hydrodynamic analysis:

- Water journal bearings
- Bearings that research 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 (ANSYS CFX ANSYS structural) and for direct optimization in ANSYS workbench.

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 (Parovay and Parovay, 2013).

The present study 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). With conventional materials and small clearances, the bearings were unfit for service which is why these cases were not computed previously. Nowadays, it is possible to create working constructions of bearings that operate with small clearances under oil starvation by using materials with high thermal conductivity, low coefficient of friction and wear rate.

Computations with this technique for bearings with conventional clearance sizes yielded similar results which proves 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.

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 that were obtained with the model 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.

The design techniques that were developed during the research were used to design and optimize the structure and characteristics of new journal bearings which could potentially replace rolling bearings in aircraft gas turbine engines.

Solving the heat problem is necessary to simulate the operation of the bearing in conditions most closely resembling real ones. This will specify the constructive parameters of the bearing. Other plans involve experimental bench tests of bearing prototypes. Obtained experimental results will allow verifying the accuracy of developed mathematical models, approaches and techniques and correct the design techniques if needed. Further studies will investigate the dynamics of the rotor with bearings under consideration and determine the changes in the parameters of the bearings which maintain the stable operation of bearing pads. The determination of stiffness and damping characteristics of bearings under consideration with regard to their flow-flow nature and small clearance is also of interest.

The herein discussed approach to estimating the tribological properties of friction pairs with a low lubricant flow is useful when designing and computing not only journal bearings but also contact seals, gears, etc.

CONCLUSION

The modified technique was used to carry out a series of computations and to determine the dependencies of the performance of the bearing on the load, rotational speed of the shaft and the size of the radial clearance. Obtained dependencies matched the usual characteristics of tilting-pad journal bearings. A2-phase model of a low-flow tilting-pad journal bearing was designed with regard to the effect of lubricant adhesion, surface roughness, inertia and the presence of a free boundary between the liquid and gaseous phase.

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REFERENCES

Andres, L.S., Y. Tao and Y. Li, 2015. Tilting pad journal bearings: On bridging the hot gap between experimental results and model predictions. J. Eng. Gas Turbines Power, 137: 1-11.

Bair, S., M. Khonsari and W.O. Winer, 1998. High-pressure rheology of lubricants and limitations of the Reynolds equation. Tribol. Intl., 31: 573-586.

Balyakin, V.B. and S.V. Falaleev, 2015. Study of temperature state of mechanical gas dynamic sealing. J. Frict. Wear, 36: 213-217.

Boncompain, R., M. Fillon and J. Frene, 1986. Analysis of thermal effects in hydrodynamic bearings. J. Tribol., 108: 219-224.

Bruce, R.W., 2012. Handbook of Lubrication and Tribology: Theory and Design. 2nd Edn., CRC Press, Boca Raton, Florida, ISBN-13:978-1-4200-6909-9,.

Chaadaev, K.N. and D.K. Novikov, 2009. Dynamics of a rigid rotor in the NK-14ST-10 engine free power turbine with sliding bearings. Russ. Aeronautics, 52: 426-431.

Chernavsky, S.A., 1963. Journal Bearings. Mashinostroenie Publishers, Moscow, Russia, Pages: 344.

Dimond, T., A. Younan and P. Allaire, 2011. A review of tilting pad bearing theory. Intl. J. Rotating Mach., 2011: 1-23.

Falaleev, S.V., 2015. Techniques for calculating the hydrodynamic characteristics of mechanical face seals with gaps of complex forms. J. Frict. Wear, 36: 177-183.

Fillon, M., 1996. On the generalization of tliermohydrodynamic analyses for journal bearings. J. Tribol., 118: 571-579.

Fillon, M., J.C. Bligoud and J. Frene, 1992. Experimental study of tilting-pad journal bearings-comparison with theoretical thermoelastohydrodynamic results. J. Tribol., 114: 579-587.

He, M., H. Cloud, J. Byrne and J. Vazquez, 2015. Fundamentals of fluid film journal bearing operation and modeling. Proceedings of the 44th Symposium on Turbomachinery, September 14-17, 2015, Texas A&M Engineering Experiment Station, Texas, USA., pp: 155-176.

Huebner, K.H., 1974. A three-dimensional thermohydrodynamic analysis of sector thrust bearings. ASLE. Trans., 17: 62-73.

Khonsari, M.M., J.Y. Jang and M. Fillon, 1996. On the generalization of thermohydrodynamic analyses for journal bearings. J. Tribol., 118: 571-579.

Lebeck, A.O., 1991. Principles and Design of Mechanical Face Seals. John Wiley & Sons, New York, USA., Pages: 765.

Mikami, M., M. Kumagai, S. Uno and H. Hashimoto, 1988. Static and dynamic characteristics of rolling-pad journal bearings in super-laminar flow regime. J. Tribol., 110: 73-79.

Parovay, E. and S. Falaleev, 2015. Designing of low-flow rate sliding bearings for turbo machinery rotors. Biosci. Biotechnol. Res. Asia, 12: 731-736.

Parovay, E.F. and F.V. Parovay, 2013. Hydrodynamic bearing with an elastic suspension of liners made of MAR. Aerosp. Equip. Technol., 8: 201-205.

Suh, J. and A. Palazzolo, 2015. Three-dimensional dynamic model of TEHD tilting-pad journal bearing-Part II: Parametric studies. J. Tribol., 137: 1-15.

Tschoepe, D.P. and D.W. Childs, 2014. Measurements versus predictions for the static and dynamic characteristics of a four-pad, rocker-pivot, tilting-pad journal bearing. J. Eng. Gas Turbines Power, 136: 1-11.

Voskresensky, V.A., V.I. Djakov and A.Z. Zile, 1983. Computing and Design of Liquid Friction Bearings. Mashinostroenie Publishers, Moscow, Russia, Pages: 232.

Zhang, F., W. Ouyang, H. Hong, Y. Guan and X. Yuan *et al*., 2015. Experimental study on pad temperature and film thickness of tilting-pad journal bearings with an elastic-pivot pad. Tribol. Intl., 88: 228-235.