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Steady state characteristics of a tilting pad journal bearing with controllable lubrication: Comparison between theoretical and experimental results

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ABSTRACT

This paper is aimed at presenting results regarding the static and thermal behavior of a tilting-pad journal bearing operating under controllable regime. The bearing is rendered controllable by injecting high pressure oil into the clearance using holes drilled across the bearing pads in the radial direction. The modification of the injection pressure enables to modify the bearing static and dynamic properties according to the operational needs. The results presented are obtained using a theoretical model, which considers all the effects that determine the bearing behavior (controllable elastothermohydrodynamic lubrication regime), as well as using a test rig designed and built to this effect. The comparison between experimental and theoretical results provides solid ground to determine the accuracy of the available model for the the prediction of the steady-state behavior of the tilting-pad bearing with controllable lubrication. Among the parameters considered for the study are: oil film temperature field, resulting forces over rotor and pads, and rotor equilibrium position. The results obtained show good agreement between theory and experiment, as long as the assumptions on which the model is based are respected. Also, it is shown that some improvements are possible when it comes to model the steady-state behavior of the controllable bearing with the injection system turned off.

1. Introduction

Tilting-pad journal bearings are widely used within the industry, due to their superior stability characteristics when compared to other oil film bearing designs. Their successful application for industrial purposes is a direct result of the current level of knowledge regarding their static and dynamic properties. Such knowledge is the result of many publications available within the literature, which deal both with the theoretical modeling of these mechanical elements, as well as with experimental investigations of the tilting-pad bearings operational characteristics.

The state of the art regarding the modeling of tilting-pad bearings establishes the need for including several effects within the model formulation. Namely, one has to consider the oil film pressure build-up or hydrodynamic effect, the thermal effects related to temperature build up within the oil film and the bearing pads, and the flexibility effects associated with the elastic deformations of the pads and pivots due to the loads exerted over them. Hence, an elastothermohydrodynamic (ETHD) lubrication regime must be established within the model in order to represent accurately the static and dynamic properties of the tilting-pad bearing. Such conclusion is the direct result of the work of several authors regarding bearing modeling, such as Ettles [1,2], Brockwell and Dmochowski [3], Fillon et al. [4,5], Kim and Palazzolo [6,7], among others.

The continuous development of more sophisticated models for the tilting-pad bearing is a direct result of the critical review of the results of such models by comparison with experimental results available in the literature. Such sets of results deal mainly with the static and thermal properties of these bearings, as well as with the obtention of bearing dynamic coefficients by experimental means. Regarding steady state static and thermal properties of tilting-pad bearings, the experimental results obtained by Brockwell and Kleinbub [8], Taniguchi et al. [9], Fillon et al. [4,5,10] are good examples. Concerning the experimental identification of dynamic coefficients for the tilting-pad bearing, one should refer to the results published by Brockwell [11], Dmochowski [12], Wygant et al. [13], Ha and Yang [14], Childs [15], among others.

The versatility of the tilting-pad journal bearing design can be further expanded by modifying its basic configuration, with the aim of transforming it into a “smart” machine element. Such modifications involve the inclusion of additional elements or variables within the original design, which can be controlled directly during the bearing operation, resulting in the adjustment of the static and dynamic properties of the bearing according to the operational demands. With this objective in mind, Santos [16]

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introduced the concept of an active lubrication system for the tilting-pad bearing, which considers the injection of high pressure oil directly into the bearing clearance, through holes drilled across the pad in the radial direction. The injection pressure can be modified during the bearing operation using a servovalve, enabling to alter the pressure field within the oil film. Hence, the bearing equilibrium position can be altered, resulting in a modification of the system behaviour depending on the requirements at hand.

Since the introduction of this technology, there has been a constant effort dealing with the improvement of the model for the actively lubricated tilting-pad bearing. Firstly, Santos and Russo [17] presented in a thorough way the Modified Reynolds Equation for Active Lubrication, which enables to calculate the oil film pressure field considering the effect of the radial oil injection. A rigid-pad, isothermal modeling assumption was established for the analysis performed in such work. Then, Santos and Nicoletti [18,19] introduced an energy equation for the calculation of the oil film temperature field, including the effect of the oil injection. Such model assumed an adiabatic regime for the oil film temperature calculation, thus neither heat transfer towards the pad or shaft, nor resulting thermal growth of those elements was considered. The rigid-pad assumption was kept at that time. Hence, the bearing model achieved a controllable thermohydrodynamic regime. Later on, Haugaard and Santos [20,21] developed a finite element model for the fluid and solid domain of the active bearing, which enabled to include the pad flexibility effects using a pseudo modal reduction scheme. No thermal effects were included at that point, hence such model considered a controllable elastohydrodynamic regime. Hertzian local deformations in the surface of the pad are not considered for the analysis. Cerda and Santos [22] coupled the previously exposed models, by expanding the finite element model developed by Haugaard and Santos [20,21] in order to include oil film temperature build up and thermal growth for the pads and journal. Also, the pivot flexibility was included in such work, taking advantage of the pseudo modal reduction scheme already implemented within the model. Regarding thermal effects, such model included the heat transfer process between the oil film and the pad surface using a highly simplified approach, by assuming an infinite heat transfer coefficient between oil film and pad surface. Hence, the oil film temperature was calculated using the energy equation as stated in [18,19], with no explicit heat transfer terms, which is decoupled from the pad heat conduction model. Later on, the oil film temperature is imposed as a Dirichlet boundary condition in the pad surface when solving the Fourier law for heat conduction in the pads. This simplified approach for modeling the thermal effects was modified in [23]. Here, the oil film energy equation and Fourier law implementation were modified to include explicitly heat flux terms to model the heat transfer process between oil film and pad surface, by assuming a parabolic oil temperature distribution in the radial direction, as originally proposed by Knight and Barrett [24].

Thus, the state of the art regarding the modeling of a tilting-pad bearing with controllable lubrication considers a controllable elastothermohydrodynamic (ETHD) lubrication regime. The model has been validated [22,23] on its standard configuration (no injection holes) against experimental results available in the literature, regarding static, thermal and dynamic properties of tilting-pad journal bearings operating within laminar regime. By performing such validation, it is now possible to state that the available model is capable to capture all the relevant effects taking place within the tilting-pad bearing, which entails an accurate prediction of its static and dynamic properties. However, the validation of the modeling approach used for including the effect of the oil injection that renders the bearing “active” remains pending until now.

The benefits of employing the actively lubricated tilting-pad bearing in an industrial application have been demonstrated by several studies. The potential of the active lubrication system for reducing the bearing oil film average temperature, as well as for extending the stable operational range of an industrial compressor and reducing its unbalance response when crossing critical speeds has been shown using the available ETHD model [25,22]. The feasibility of modifying the tilting-pad bearing dynamic coefficients using the active lubrication system was proven experimentally in [26]. In this work, a comparison against theoretical results using the model available at the time (controllable hydrodynamic lubrication regime) was presented, which yielded better results for the prediction of the stiffness coefficients than for the damping coefficients. On the other hand, the experimental results shown in [27,28] depict the feasibility of modifying the frequency response function as well as to reduce the vibrations amplitude of a rotor test rig using the actively lubricated bearing as the actuator of a control loop.

In order to apply this technology in a real industrial application, it is mandatory to be able to predict accurately the static and dynamic behavior of the rotating machine where the actively lubricated bearing is being installed. For doing so, it is necessary to achieve a high level of confidence in the results delivered by the available theoretical model for the bearing, considering its static and thermal behavior, as well as its dynamic properties. Such confidence can only be achieved by validating the existing model using experimental data. The first step in this direction is to determine the accuracy of the model regarding the prediction of equilibrium position of the system under steady state conditions, which will depend on the quality of the available models for the hydrodynamic, thermal and flexibility effects. The tilting-pad journal bearing, in both its standard and controllable configuration, exhibits non-linear behaviour, hence the linearization of the oil film forces for rotor design purposes via dynamic coefficients will produce good results only if the steady state equilibrium position is determined accurately.

The main original contribution of this paper is to present a comparison between experimental and theoretical results, regarding the steady state properties of the tilting-pad journal bearing with controllable lubrication. Among the parameters to be studied are the journal equilibrium position, oil film temperature field and resulting forces over pads and rotor. As a result of this study, the validation of the available ETHD model for tilting-pad journal bearings with controllable lubrication will be achieved, in terms of the steady state behavior of such system.

2. Tilting-pad journal bearing with controllable lubrication: mathematical modeling

In this section, the mathematical model for the modeling of the tilting-pad journal bearing with controllable lubrication is presented briefly. The reader is advised to refer to the cited publications [16–21] in order to get a more complete presentation of the model.

2.1. Oil film pressure build-up: Modified Reynolds Equation for controllable lubrication

The oil film pressure build up for the tilting-pad journal bearing has been traditionally described by means of the Reynolds Equation, based on the assumption of laminar flow and negligible effects of the fluid inertia and radial viscous shear forces. Such basic model was extended in [16,17], including some terms to model the effect of the oil injection into the bearing clearance using n_0 orifices. Hence, the Modified Reynolds