Tribology International 103 (2016) 449–464

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

An efficient quasi-3D rotordynamic and fluid dynamic model of Tilting Pad Journal Bearing

R. Conti [a], A. Frilli [a], E. Galardi [a], E. Meli [a,*], D. Nocciolini [a], L. Pugi [a], A. Rindi [a], S. Rossin [b]

[a] MDM Lab-Department of Industrial Engineering-University of Florence, Via di Santa Marta n°3, Italy
[b] General Electric Nuovo Pignone, Via Felice Matteucci, Italy

ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form
8 July 2016
Accepted 27 July 2016
Available online 2 August 2016

Keywords:
Tilting Pad Journal Bearing
Thin film lubrication
Hydrodynamic lubrication
Mineral oils

ABSTRACT

Over the last few decades the use of Tilting Pad Journal Bearings (TPJBs) has spread due to their better performances in the most demanding operating conditions (i.e. in the presence of high loads and speeds). This research paper describes the development and experimental validation of a new quasi-3D TPJB model, able to analyze both the fluid dynamics (also including the supply plant) and rotor dynamics of the system and their complex interactions. The developed model is characterized by a high numerical efficiency, thus allowing for complex simulation tasks, and strongly modular, with the possibility to easily represent different layouts of TPJBs. The proposed model has been developed and experimentally validated in collaboration with *Nuovo Pignone General Electric S.p.a.* considering a complete plant test rig which includes rotor, bearings and lubrication circuit. Finally, an innovative heuristic law is proposed in order to predict the TPJB fluid dynamical characteristics taking into account the coupled effects neglected by classical simplified models.

1. Introduction

Nowadays Tilting Pad Journal Bearings (TPJB, Fig. 1) are widely used for the support of rotating machinery in the full range of available sizes and powers, thus representing the coupling element between the different components of a plant (i.e. lubricant supply plant, supporting structures, rotors).

Compressors, turbines and pumps benefit from the presence of TPJBs because their performances largely overtake those of fixed geometry journal bearings [1,2]. Compared to classical journal bearings, TPJBs fit better for high speed applications [3] and for heavily loaded rotors thanks to the possibility to adjust their supporting action to the rotor motion, thus ensuring optimal stability [4–6] both in transient [7,8] and steady state conditions [9]. The behavior of the rotor–bearing–plant system depends on the complex interactions between the fluid dynamical (including the effects of the lubricant supply plant) and rotor dynamical phenomena involved in the process: an accurate modelling of both the aspects is mandatory for the correct design and operation of the entire plant. On the other hand, the system complexity itself (a plant can include several different bearings) requires a TPJB model as computationally efficient as possible; therefore a compromise between the accuracy and the numerical efficiency of a TPJB model is necessary to fulfill industrial requirements.

The classical literature TPJBs models are often based on the lumped parameters approach [10–12]: from the rotor dynamical point of view TPJB are usually represented in terms of stiffness and damping matrices, whose forces are applied in the rotor node corresponding to the bearing center. While a procedure for the calculation of dynamic coefficients for journal bearings was already available [13], the first to develop a calculation method for Tilting Pad Journal Bearings was Lund [14]. Starting from that pioneering work, many researchers have investigated how to improve the lumped parameters dynamical representation of TPJBs: Tschoepe and Childs [15] and Brockwell et al. [16] experimentally validated the dynamic coefficients prediction taking into account pivot contact flexibility and different pad geometries; Wilkes and Childs [4] and Rodriguez and Childs [17] analyzed the influence of frequency and model degrees of freedom on the calculation of coefficients and on stability; Lihua et al. [18] investigated the calculation of dynamical coefficients in gas lubricated bearings and Cha et al. [19] analyzed the influence of pad compliance on the bearing dynamic characteristics. Similarly, from the hydraulic point of view the behavior of TPJBs within the lubrication auxiliary plant is typically treated as that of a lumped parameters orifice [13,20]. The numerical efficiency of these simplified models is very high and their use is widely diffused in many applications,

* Corresponding author.
E-mail addresses: roberto.conti@unifi.it (R. Conti), amedeo.frilli@unifi.it (A. Frilli), emanuele.galardi@unifi.it (E. Galardi), enrico.meli@unifi.it (E. Meli), daniele.nocciolini@unifi.it (D. Nocciolini), luca.pugi@unifi.it (L. Pugi), andrea.rindi@unifi.it (A. Rindi), stefano.rossin@ge.com (S. Rossin).

http://dx.doi.org/10.1016/j.triboint.2016.07.024
0301-679X/

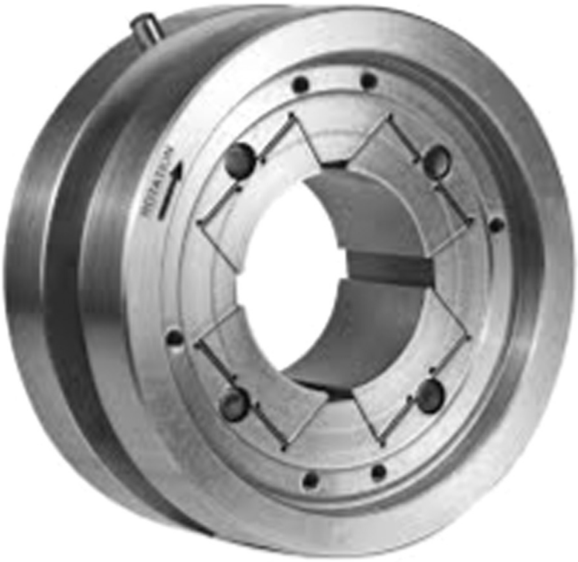

Fig. 1. Tilting Pad Journal Bearing.

especially in classical harmonic analysis in the rotordynamic field [21], where the spring–damper representation allows also for an easy assembly of the FEM problem. However, even if the coefficients calculations include different aspects, those models cannot correctly represent the three dimensional phenomena which are involved in the bearing operation, especially in nonlinear transient analyses in the time domain, where it is essential to take into account the couplings between different physical phenomena. In fact, a complete unconcern on the interactions between the fluid dynamical and rotordynamical aspects of the bearings could be extremely dangerous in modern rotating systems; furthermore, those couplings are fundamental in order to perform an analysis of the complete plant, including a number of bearings and rotors, their baseplates and the auxiliary system.

Several three dimensional (3D) TPJB models can be found in the literature, most of them developed using Computational Fluid Dynamics (CFD) [22]. A first step concerns the analysis of the three dimensional motion of the rotor [8], especially in transient analyses [7,23] in order to be able to represent the system behavior not only in steady state conditions but also in transient phases. Furthermore, since the thermal and elastic effects play an important role, especially in the most extreme operating conditions [24], many authors performed 3D coupled analysis considering the interactions of a number of physical phenomena: Fillon et al. [25] investigated the influence of pad thermal deformations; Brugier and Pascal [26] analyzed elastic deformations; Chang et al. [27], Kuznetsov et al. [28], Kim et al. [29] developed advanced thermoelastohydrodynamic model. The accuracy of those 3D models is very high and they can represent the interactions between the physical phenomena present in the whole system (analyzing simultaneously the phenomena). Such models are often necessary but their complexity (both for development and calculation) and numerical inefficiency are important limits to their common use.

Nowadays many researcher have also started to investigate new fields of analysis: Haugaard et al. [30], Varela et al. [31] and Glavatskih and Höglund [32] have analyzed the possibility to develop actively lubricated bearings; Simmons et al. [33] have analyzed the use of innovative pad surface covering; Hargreaves and Fillon [34] have analyzed the onset of pads instability phenomena; Bouard et al. [35] have analyzed the influence of turbulent transition within the oil films and Brito et al. [36] have studied the influence of the lubricant supply.

Finally, since all those models need accurate validation in order to provide reliable results [37], many experimental studies can be found in the literature concerning the behavior of Tilting Pad Journal Bearings in different operating conditions and considering various physical phenomena [38–40].

From the analysis of existent TPJBs models, it is evident that an innovative model, while analyzing simultaneously the involved physical phenomena, should reach a compromise between accuracy and numerical efficiency to provide reliable results employing reduced computational and temporal resources, especially for systems containing a large number of bearings and for long transient analyses.

This research paper focuses on the development of an innovative quasi-3D TPJB model which allows the coupled analysis of fluid dynamical (including the supply plant) and rotordynamical phenomena involved in the bearing dynamics, considering the interactions between the rotor, the bearing and the lubricant supply plant, which plays an important role in influencing the system performance [31,32,36]. Classical simplified models represents these aspects separately but their interactions cannot be neglected if accurate results are required for the design (or control) of the plant. One of the most important features of the proposed model is the high computational efficiency: the model is in fact suitable to perform long nonlinear simulations in the time domain both in transient and steady state conditions regarding the dynamic behavior of the whole plant, even in the presence of many different bearings. Through those nonlinear analyses it is possible to understand how the rotor behavior is influenced by bearings and plant and the model numerical efficiency is an essential feature. The proposed model is also highly modular, allowing for the analysis of TPJBs with different pads and supply plant configurations.

Consequently, the new model aims at partially replacing, especially for the analysis of plants including a large number of bearings, the existent classical lumped parameters models, allowing the use of a single model for the complete analysis of the plant behavior. The developed model presents an accuracy near to that of 3D CFD models, achieving a good compromise between accuracy and numerical efficiency.

The model architecture proposed in this research paper consider all the relative motions between the rotor and the bearing (i. e. the pads): the rotor fraction inside the bearing is part of a FEM model of the complete rotor and has 6 degrees of freedom (DOFs), while each pad is a constrained rigid body with 2 rotational DOFs.

The proposed model is composed through the coupling of n basic modules, each including an oil film fluid dynamic analysis, a pad dynamics analysis and a lubricant supply analysis: this repetition of a single basic pad module allows us to easily modify the configuration and layout of the bearing, thus readily representing different TPJBs. The whole supply plant–bearing–rotor model has been developed in the *COMSOL Multiphysics®* environment.

A definitive TPJB model should also include other important physical phenomena related to the bearing behavior like the pad flexibility [41], which is strongly linked to the lubricant elasticity (elastohydrodynamic lubrication [19,29,40]), and the heat exchange between solid elements and lubricant [42]. At this initial phase of the research activity the authors only focused on the modelling of the rotordynamical and fluid dynamical effects due to the oil films and to the lubricant supply plant. However the modelling approach proposed in this paper is suitable to easily include the previously mentioned effects.

The entire model has been developed and validated in collaboration with *Nuovo Pignone General Electric S.p.a.* which provided the required technical and physical data [43]. The data refer to a lubrication testing system built at the GE testing center located in Massa-Carrara (Italy): the experimental test rig considered for the comparison with the developed TPJB-rotor model consists of a