Tribology International 120 (2018) 115–126

Contents lists available at ScienceDirect

Tribology International

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

Component level study of an actively lubricated LEG Tilting Pad Bearing: Theory and experiment

Alejandro Cerda Varela [a,*], Ilmar Ferreira Santos [b]

[a] Escuela de Ingeniería Mecánica, Pontificia Universidad Católica de Valparaíso, Los Carrera, 01567 Quilpué, Chile
[b] Department of Mechanical Engineering, Technical University of Denmark, 2800 Kgs, Lyngby, Denmark

ARTICLE INFO

Keywords:
Experiment
Modelling
Tilting pad bearing
Active

ABSTRACT

This article constitutes the second step in a research effort aiming at evaluating the feasibility of introducing active characteristics into standard leading edge groove (LEG) tilting pad journal bearings. The strategy proposed is to control the LEG inlet flow using a servovalve. This work portrays the first experimental study for the“proof of concept” of this configuration, as well as a comparison with theoretical results. A simplified setup, featuring a rigid rotor supported by a single pad arrangement is the subject of study. The obtained results prove the viability of the proposed active bearing design, validate the available simulation tool and exemplify on a conceptual level the operational benefits from introducing this technology into standard LEG Tilting Pad Bearings.

1. Introduction

The requirements arising from the so called 4th industrial revolution call for an expansion of the usual manner in which rotating machinery is designed and operated. Following these new trends, it is desirable that machines feature a higher degree of adaptability to new operational conditions, by introducing “smart” characteristics into their design. As such, the conception of new mechatronic machine elements is an alternative to comply with these requirements.

Bearings are key components to determine the steady state and dynamic characteristics of the rotating machinery [1,2]. Consequently, by introducing “smart” characteristics into their design, it is feasible to transfer those properties to the whole machine. For high speed and load applications, tilting pad journal bearings are the support elements of choice, due to their improved stability behavior, compared to other oil film bearing designs [3]. Hence, the improvement of their characteristics by means of the introduction of active characteristics would entail an expansion of the operational limits for turbomachinery as a whole.

Within this scope, a number of investigations have been carried out over the years, considering several strategies for achieving an active tilting pad journal bearing design. The introduction of piezoelectric actuators affecting the tilting pad radial position and resulting bearing clearance was introduced in Ref. [4]. Linear and rotational actuators acting directly over the tilting pads were studied in Refs. [5–7]. The usage of electromagnetic actuators installed within the tilting pads was explored by Ref. [8].

The usage of hydraulic actuation for achieving active properties in tilting pad journal bearings was introduced by Santos in Ref. [9]. Two methods were proposed, being the so called active lubrication concept [10] the one that has received more attention and development in terms of follow-up publications. It proposed the usage of servovalve controlled pressurized oil injection into the bearing clearance, by means of nozzles located on the tilting pad surface, in order to generate controllable forces over the supported rotor. Latest developments in this research effort consider theoretical and experimental investigations. A multiphysics theoretical model for this bearing design has been refined over the years [11–13], including a ETHD tilting pad bearing model coupled with the effect of the radial oil injection and dynamics of the hydraulic supply system. The theoretical model has been applied to synthetize model-based controllers to alter the dynamics of a flexible rotor setup in Ref. [14]. The feasibility of using this active bearing as an excitation source for carrying out operational modal analysis testing in rotating machinery was experimentally studied in Ref. [15].

Recently, the application of the active lubrication concept in tilting pad journal bearings featuring the leading edge groove lubrication system has been theoretically studied in Ref. [16]. Under such configuration, the injection nozzles located in the tilting pad surface are replaced by the leading edge groove, as the method to provide controllable pressurized oil supply to the bearing clearance. The leading edge groove has already been studied in terms of its benefits considering reduced oil

* Corresponding author.
E-mail addresses: alejandro.cerda@pucv.cl (A.C. Varela), ifs@mek.dtu.dk (I.F. Santos).

https://doi.org/10.1016/j.triboint.2017.12.024
Received 1 November 2017; Received in revised form 13 December 2017; Accepted 16 December 2017
Available online 20 December 2017

consumption and reduced bearing losses, when compared to other lubrication methods [17–20].

The results obtained from the mathematical model for the proposed active bearing design validated the initial concept. However, the presented results were only of theoretical nature, being their experimental validation the following step to continue the development of this idea. This is the main motivation for the present publication.

This work inherits the knowledge developed in previous investigations related to tilting pad journal bearings under active lubrication regime. In particular, the test rig and experimental methodologies synthetized previously in Refs. [13,21–23] constitute the foundation on which this work is developed. As such, the main original contributions of this article are twofold. Firstly, it provides the first set of experimental results concerning the application of the active lubrication concept to a LEG Tilting Pad Bearing arrangement. The experimental data thoroughly describes the steady state and dynamic properties of this novel active bearing design. Secondly, a comparison with theoretical results is provided, obtained by means of the theoretical model presented in Ref. [16]. Consequently, this article results enable to validate this simulation tool, and to determine its limitations and range of applicability.

The experimental data reported here was obtained in a simplified setup (single pad arrangement, supporting a rigid rotor with vertical degree of freedom), when compared to the real geometry and application of a tilting pad bearing arrangement. Furthermore, the range of applied loads and journal rotational speeds are within the "low" range, when considering industrial applications. In this respect, in Ref. [16] the mathematical model in passive configuration (no active LEG included) was already validated against experimental results reported in Ref. [24], obtained under operational conditions resembling an industrial application of a passive tilting pad bearing. Therefore, the scope of this study is to prove experimentally the feasibility of transforming the LEG Tilting Pad Bearing into a mechatronic machine element, and to verify the simulation tool available for such system. Considering these objectives, the simplified test rig setup is sufficient and convenient for a "proof of concept" test campaign, as it reduces the amount of variables that can introduce errors in the experimental results. Based on the results presented here, one can determine the viability of testing the proposed active bearing design in a more complex test facility, resembling in a closer manner an industrial application.

2. Experimental setup

2.1. Test facilities

The experimental results reported in this article were obtained at the Laboratory of Mechatronic Machine Elements at the Technical University of Denmark (DTU). The experiments were conducted using the test facilities depicted in Fig. 1. A list of the parameters that describe the setup are provided in Table 1. It consists of a rigid rotor supported in the vertical direction by a tilting pad bearing arrangement. The rotor is attached to a tilting arm by means of roller bearings. The arm constrains the rotor to move solely in the vertical direction. The rotor horizontal movement is restricted by the arm, which is pivoted in one end by a rigid shaft and preloaded angular contact bearings. The driving torque for the rotor is supplied by an electric motor and a belt transmission.

The tilting pad setup used for the test plan is shown in Fig. 2. A single pad, featuring the leading edge groove lubrication system and a rocker pivot design, provides vertical support for the rigid rotor mounted on the tilting arm. The oil supply for the leading edge groove (LEG) is provided by a hydraulic hose connected to a high pressure pump and high response servovalve (see Table 1 for details). The bearing chamber is open, and the oil evacuation takes place due to gravity. The servovalve enables to regulate the oil flow towards the LEG using a electrical signal generated in a control unit, introducing active characteristics to the tilting pad arrangement.

The test rig is instrumented to characterize the behavior of the rotor, tilting pad bearing and associated hydraulic supply system. The rotor vertical movement is sensed by means of displacement probes, measuring at the free end and at the midspan of the tilting arm. Different load cells arrangements can characterize excitation forces and oil film forces over

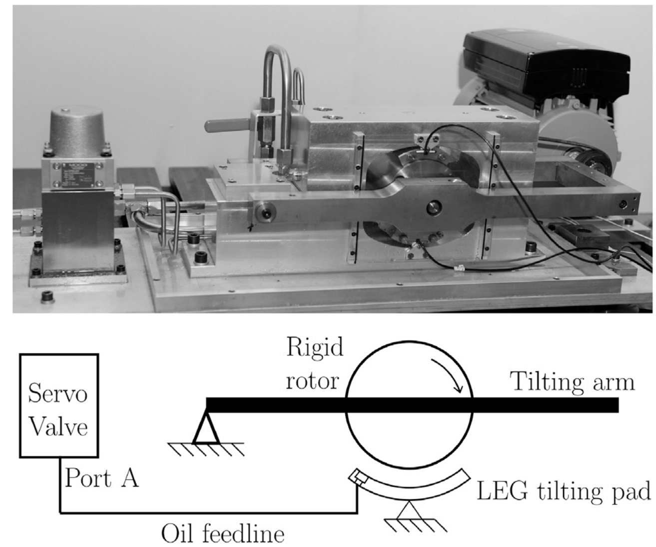

Fig. 1. Component level testing of the Actively Lubricated LEG Tilting Pad Bearing: picture and schematics depicting the main components of the experimental setup. Only the bottom tilting pad was retained for the experimental study reported in this article.

Table 1
Test rig parameters.

Parameter	Value
Pad inner radius	49.920 *mm*
Journal radius	49.692 *mm*
Bearing axial direction length	60 *mm*
LEG axial length	50 *mm*
LEG angular position (measured from pad edge)	5 *degrees*
LEG circumferential direction width	10 *mm*
LEG depth	12 *mm*
Number of pads	1
Pad arc	70 *degrees*
Offset	0.5
Load Angle	On pad
Pad thickness	16 *mm*
Oil type	ISO VG22
Pad material	Brass
Pivot insert material	Steel
Pivot design	Rocker
Oil Supply Pump Maximum Pressure	250 *bar*
Oil Supply Pump Maximum Flow	2.5 L per minute
Servovalve cut-off frequency ω_V	150 *Hz*
Servovalve leakage flow q_V^*	Variable
Servovalve flow pressure coeff. K_{pq}	1e-12 $m^3/(sPa)$
Servovalve flow voltage coeff. R_V	Variable
Servovalve damping ratio ξ_V	0.95

Table 2
Test cases for the steady state characterization section.

Case#	Pad Load	LEG Supply Flow q_V
1	1000 *N*	1.0 *LPM*
2	1000 *N*	2.0 *LPM*
3	1000 *N*	2.5 *LPM*
4	2500 *N*	1.0 *LPM*
5	2500 *N*	2.0 *LPM*
6	2500 *N*	2.5 *LPM*
7	5000 *N*	1.0 *LPM*
8	5000 *N*	2.0 *LPM*
9	5000 *N*	2.5 *LPM*