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Investigation on an experimental approach to evaluate a wear model for hydrodynamic cylindrical bearings

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ABSTRACT

This work aims to investigate and identify the wear parameters in cylindrical hydrodynamic bearings, an inherent problem due to repeated use of rotating machinery, accentuated in starts/stops or during the crossover of resonance. Thereby, a mathematical model to represent the wear in terms of its main parameters is used, namely, the maximum depth, the angular span and the angular position. The pressure distribution and the hydrodynamic forces generated by the oil film are numerically obtained, properly adapted for discontinuous oil film. The rotor model is represented by finite element method and the bearings are approximated by dynamic coefficients of stiffness and damping. The evaluation and identification of the wear parameters is taken from the unbalanced frequency response of the rotor-bearing system in directional coordinates.

1. Introduction

The dynamic analysis of rotating machines involves many parameters and, therefore, this analysis should not only take into account the dynamic behavior of the rotor, but also the interaction with other components of the same system, such as journal bearings. Several types of journal bearings can be used according to the system characteristics. Basically, they are classified into two major groups: fixed profile bearings and tilt pad bearings. According to Lüneburg et al. [1], “Both bearing types have very specific advantages and disadvantages regarding to the application area. The tilt pad bearings can be the preferred choice if the main focus of the application lies on stability concerning to bearing self-excitation. Fixed profile bearings generally provide higher stiffness and damping factors than tilt pad bearings and have even more improvement capabilities with regard to high speed–high load applications, being the chosen for a wide range of applications”.

Hydrodynamic bearings, specially fixed profile bearings, are subject to a great variety of failures, since they are the principal responsible to transmit efforts between the rotor and the foundation structure. Consequently, a critical issue in rotor dynamics is the evaluation of the bearings conditions, which directly affects the dynamic behavior and stability of the rotating system. One of the most common failure associated with these bearings is the wear of the bearing material. From practical observations in real plants, this is not a problem only associated with stability, but with the load capacity, excessive vibration and, most importantly, the need for starting and stopping the machine, which certainly trigger failures of this nature in lubricated bearings of different types: cylindrical plain, elliptical and tilting-pad bearings. Therefore, the wear identification in rotors mounted on bearings configures a topic of great interest in rotor dynamic investigations.

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One of the first studies related to the emergence and development of wear in hydrodynamic bearings during numerous start/stop cycles of rotating machines dates back to the experiments performed by Mokhtar et al. [2]. The wear was easily noticeable, and changes in diametrical clearance, surface finishing and roundness of the bearing were measured after different operation cycles. The analysis of the wear location in the bearings pointed to the cause by sliding motion during the start cycles, being the contribution of the stop process not much significant to the wear development.

In the following decade, the first models appeared in order to represent the wear effects in cylindrical hydrodynamic bearings. In 1983, Dufrane et al. [3] proposed two models to the wear with non-circular geometry. The first model was based on the concept that the shaft makes a 'print' in the bearing and the second model, on the assumption of an abrasive wear with an arc larger than the bearing diameter. The authors investigated the wear of bearings in steam turbines, making measurements to estimate the extension and the nature of the wear. An analysis of the effect of geometric changes due to wear on bearing lubrication at low speeds showed that a limited amount of wear could enhance lubrication. The analysis predicted that there was an optimum amount of wear, beyond which the altered geometry would accelerate the wear process. Some years later, Hashimoto et al. [4] used the model proposed by Dufrane et al. [3] to theoretically and experimentally investigated the effects of geometric changes due to wear in both laminar and turbulent hydrodynamic lubrication regimes.

In the early nineties, Vaidyanathan and Keith [5] numerically analyzed the characteristics of noncircular bearings, considering the effects of turbulence and cavitation. Later, Suzuki and Tanaka [6] and Kumar and Mishra [7] analyzed the stability of worn bearings. In [6], the authors concluded that the wear decreases the stability of the bearing when submitted to a light load. Kumar and Mishra [7], instead, examined the wear effects on bearings in the stability of a rigid shaft supported by two hydrodynamic bearings in turbulent regime and with the non-circular wear model.

In the context of most recent works, Fillon and Bouyer [8] studied the performance of worn plain journal bearings taking into account the local thermal effects. The authors concluded that the wear could lead to an increase in thermohydrodynamic performance. The wear led to a significant drop in maximum temperature and also decreases the average operating temperature. Moreover, the presence of wear minimized the pressure peak and the dissipated power was also decreased. Continuing the studies, Bouyer et al. [9] investigated the behavior of two lobes bearings subjected to numerous start/stop cycles of the rotating system. At the same year, Wu et al. [10] conducted an experimental study on the friction conditions in hydrodynamic bearings with a system called by the authors as "On-Line Visual Ferrograph". It was observed that the predominant wear mechanisms were the 'micro-plowing' and 'micro-cutting' induced by the initial roughness of the surfaces in the start of the rotor. Finally, Nikolakopoulos et al. [11] presented an analytical model in order to find the relation between the friction force, the misalignment angles and the wear depth. They concluded that the friction coefficient was increased, in general, with the increase of the wear depth as well as misalignment and Sommerfeld number.

Regarding the wear identification in cylindrical hydrodynamic bearings, Papadopoulos et al. [12] presented a theoretical clearance identification method by means of measurements of the rotor response at a given point (usually the rotor midpoint). The authors used the least square technique with the objective function being the difference between the measured and calculated values at the predefined point. The stability of a rotating system with worn clearances was also examined, indicating stable or unstable operation of the system. Gertzos et al. [13] developed a practical methodology to identify the wear depth in cylindrical hydrodynamic bearings. The graphical wear depth detection method was based on measurements of basic bearing characteristics, at certain operation conditions, in order to obtain a real time (online) wear identification. Machado and Cavalca [14] presented a numerical approach to identify the bearing wear parameters using the unbalance response of the system. The technique was only tested with numerical data, showing promising results. Recently, Chasalevris et al. [15] presented an experimental investigation on the emergence of additional harmonic components in the transient response of a continuous rotor mounted on worn cylindrical hydrodynamic bearings. The authors observed that the harmonics were more sensitive to wear especially in the frequency of 1/2X and during the crossover through the resonance.

Finally, Machado and Cavalca [16] presented a numerical model, based on the model proposed by [3], to represent the wear in cylindrical hydrodynamic bearings. The authors validated the wear model with the experimental results given by Hashimoto et al. [4] and performed an analysis of the model sensitivity to different geometric and operational bearings parameters by verifying the influence of wear model in the oil film thickness, the locus curve, the pressure distribution and the dynamic coefficients of stiffness and damping. They also concluded that the wear significantly influences the dynamic frequency response of the rotating system, especially when using directional coordinates.

As previously shown, the identification of the wear conditions in cylindrical hydrodynamic bearings is of recent interest both in academic and industrial fields. Therefore, predictive analysis and wear detection are still open research topics. In this context, this paper deals with the estimation of wear characteristic parameters in cylindrical lubricated bearings, from the dynamic response of the rotor-bearings system in the frequency domain. The wear parameters evaluation is conducted through a search method to minimize an objective function, which compares the numerical model with the experimental response obtained from a test rig.

The pressure distribution, and consequently, the hydrodynamic forces generated in the oil film, are evaluated and properly adapted for situations where the oil film is discontinuous (Machado and Cavalca [17]). The wear model was previously presented in [16]. A test rig was assembled in order to evaluate the behavior of the rotating system when the hydrodynamic bearings present different wear patterns. The frequency response of the rotor-bearings system in directional coordinates is used in the objective function due to its sensitiveness to the anisotropy influence, which tends to increase the backward component in presence of wear (Machado and Cavalca [16]). The search technique was presented in [14], however here, it is