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Directional frequency response applied to wear identification in hydrodynamic bearings

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ABSTRACT

This work analyzes the influence of the wear in hydrodynamic bearings in the directional frequency response of a rotating system. Previous works presented a numerical approach to identify the bearing wear parameters using the unbalance response of the system in different rotational speeds. In continuity, this paper analyzes the directional frequency response function (*dFRF*) to identify the wear model, prompting a feasible application of the method, taken into account that it is not possible to operate the rotor near the critical speeds. The results show that the *dFRF* matrix is sensitive to the wear parameters and more suitable for bearing wear identification, based on the cross-coupled terms of the *dFRF* matrix, which present a higher sensitivity to the bearing wear.

1. Introduction

The development of fault detection and identification technologies to be applied in rotating machines has significant impact in industry and, recently, it has received special attention in academy. The idea is to replace expensive scheduled based maintenance by a more efficient, less costly alternative of condition-based maintenance. In this context, one of the most useful tool for early faults diagnosis in rotating machines is vibration analysis. By measurements and analysis of the vibration characteristics of rotating machines, it is possible to detect typical faults such as unbalance, misalignment, shaft bow, shaft crack, bearing and gear faults, among others. Since several of these failures degrade relatively slowly, special attention must be given to fault diagnosis at early stages. Therefore, vibration analysis can provide useful information from data monitoring of rotating machines, being an appealing field for many researchers.

In the context of vibration analysis, the modal analysis can be a very useful tool for detection and diagnosis of faults in rotating systems. The classical modal analysis applied to rotor dynamics, in some cases, is not sufficient to clearly identify the vibration modes present in this type of machine due to the existence of asymmetries in the stiffness and damping matrices, usually generated by the gyroscopic effect and the inherent anisotropy of the bearings and the foundation structure. Therefore, adaptations of the classical methods of modal analysis were needed for this specific application.

In 1982, Nordmann [1] introduced a method that combines experimental and analytical data to identify the modal parameters (eigenvalues and natural modes) in order to study the dynamic behavior of rotating machines and how the change in these parameters influence the dynamics of the system. In 1991, Lee [2] presented the complex modal analysis for rotating machines used to distinguish forward and backward modes shapes, and compared it with the classical modal analysis. With the use of complex notation, not only the forward and backward modes were easily distinguished, but were also separated in the frequency domain, facilitating the identification of the modal parameters, and enabling the analysis of the degree of anisotropy of the system. Later, Kessler [3] identified the natural and operational modes of a rotating system using complex coordinates. Cavalca and Okabe [4] also used the *dFRF* in the study of the foundation effect on the rotor behavior inside the concept of mixed coordinates (directional to the rotor and modal coordinates to the foundation).

Failures associated with hydrodynamic bearings are among the most common causes of forced shutdowns in rotating systems. Consequently, the evaluation and the monitoring of the bearings conditions are critical issues in rotor dynamics. In this context, the wear of the bearing material affects the bearing clearance, which results in changes in the dynamic characteristics of the bearing and, consequently, of the rotating system.

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Duckworth and Forrester [5] and Mokhtar et al. [6] experimentally conducted the first studies related to the wear in hydrodynamic bearings. Dufrane et al. [7] propose two geometrical model for the bearing worn region, one based on the concept that the shaft makes a 'print' in the bearing and other based on the assumption of an abrasive wear. Hashimoto et al. [8] investigated theoretically and experimentally the effects of geometric changes due to wear, validating the second model proposed by Ref. [7]. Regarding the most recent works, Fillon and Bouyer [9] studied the performance of worn plain journal bearings, taking into account the local thermal effects. Later, Bouyer et al. [10] presented and discussed some experimental data about the influence of wear on the behavior of a journal lobed bearing subjected to numerous starts and stops.

Considerable research has been carried out for the development of various techniques for bearing fault detection and diagnosis. These techniques can be mainly classified into two categories: time domain and frequency domain techniques.

In the context of time domain techniques, Wu et al. [11] experimentally monitored the friction conditions in the hydrodynamic bearings with a system called "on-line visual ferrograph". The conclusion was that the predominant wear mechanisms were the 'micro-plowing' and 'micro-cutting' induced by the initial roughness of the surfaces in the startup of the rotor. Gertzos et al. [12] developed a practical methodology to identify the wear depth in hydrodynamic bearings. The method was based on measurements of the basic bearing characteristics and thereby to obtain a real time (online) wear identification. A graphical detection was used to identify the wear depth associated with the measurements of the dynamic characteristics. Okac et al. [13] developed a new scheme based on wavelet packet decomposition and hidden Markov modeling (*HMM*) for tracking the severity of bearing faults, such as wear. Chasalevris et al. [14] presented an investigation on the emergence of additional harmonic components in the transient response of a continuous rotor mounted on worn hydrodynamic bearings. The harmonics were more sensitive to wear especially on the frequency of 1/2X and during the crossover through resonance. The 3/2X and 5/2X components were also detected due to the presence of the wear.

Regarding the frequency domain techniques, Papadopoulos et al. [15] presented a theoretical identification method for the wear in hydrodynamic bearings by means of measurements of the rotor response at a given point (usually the rotor midpoint). Least square technique was used to the identification, and the objective function was the difference between the measured and simulated values at the predefined point. Machado and Cavalca [16] presented a numerical approach to identify the bearing wear parameters using the unbalance response of the system. The analysis took into account the frequency response of the rotor-bearing system in directional coordinates. A searching method to minimize an objective function compared the numerical simulated response with the experimental response, considering the rising of the backward component due to the increasing of bearing anisotropy degree.

Recently, some other works have been published with numerical and experimental results related to wear on journal bearings. Among these, we can mention the work of Phalle et al. [17], where the authors analyzed the influence of wear on the performance of the 2-lobe multirecess hybrid journal bearing system compensated with membrane restrictor. And the work of Muzakkir et al. [18] with an experimental investigation on effectiveness of axial and circumferential grooves in minimizing wear of journal bearing operating in mixed lubrication regime.

Facing the whole scenario, this paper gives continuity to analyze the influence of the wear in hydrodynamic bearings in the directional frequency response of a rotation system. For this purpose, the wear model presented by Machado and Cavalca [19] is used. However, this work applies this concept to the directional frequency response function (*dFRF*), using a magnetic actuator to externally excite the rotor. The measurements can be taken in the bearings position, prompting a feasible application of the method. Moreover, this paper deals with the identification of the wear characteristic parameters. The identification procedure is tested using a simulated experimental response obtained by a noise formulation applied in the numerical response.

Therefore, the objective and also the main novelty of the paper can be summarized as: through the method presented in this paper, the wear detection can be performed using the same tests used for the commissioning of rotors for stability analysis, i.e., standard tests already used in experimental rotordynamics. In addition, most of the wear identification methods available in literature are based on direct measurements of the bearings characteristics, such as pressure distribution, locus of the shaft, Sommerfeld number, etc. The advantage of the method proposed here is to use vibration measurements to access the information necessary to fault parameters identification, directly on the rotor, a more accessible procedure for application in real systems. As the identification is done through direct measurements of rotor vibration, there is no need to stop and disassemble the system, as required in most of the methods proposed in the literature.

2. Methodology

The evaluation of the hydrodynamic forces generated in the oil film uses the approach developed by Machado and Cavalca [20], for situations where the oil film is discontinuous. The modeling of the rotor-bearings system considers the rotor represented by finite element method and the bearings dynamic coefficients are approximated by a spring-damper concept. Then, Lee's complex modal analysis [2] is applied to the conversion of the measured *FRF* (frequency response function) to the *dFRF*. Finally, a searching technique to find the wear parameters from the experimental response is presented.

2.1. Hydrodynamic bearings formulation and wear model

The hydrodynamic lubrication theory is governed by the Reynolds equation, whose solution gives the pressure distribution and, consequently, the hydrodynamic supporting forces in the lubricant film. The hydrodynamic forces can be linearized to calculate the equivalent stiffness and damping coefficients of the bearing, which compose the stiffness and damping matrices of the complete system.

The wear effect is included in the bearing modeling as a geometric discontinuity in the radial clearance of the bearing and, consequently, in the oil film. The procedure for the numerical solution of the Reynolds equation, for the specific case of a discontinuous oil film thickness, was adapted from Arghir et al. [21] and expanded to two dimensions in Machado and Cavalca [20]. The approach uses a discretization of the fluid film into a finite volumes mesh. To calculate the bearing dynamic coefficients, the nonlinear hydrodynamic forces, obtained by the integration of the pressure distribution, are expanded into a first order Taylor series:

$$
\begin{aligned}
F_y &= K_{yy}\Delta\bar{y} + K_{yz}\Delta\bar{z} + B_{yy}\Delta\dot{\bar{y}} + B_{yz}\Delta\dot{\bar{z}} \\
F_z &= W + K_{zy}\Delta\bar{y} + K_{zz}\Delta\bar{z} + B_{zy}\Delta\dot{\bar{y}} + B_{zz}\Delta\dot{\bar{z}}
\end{aligned} \tag{1}
$$

where W is the bearing load, K_s are the stiffness coefficients, B_s are the damping coefficients and $\Delta\bar{y}$, $\Delta\bar{z}$, $\Delta\dot{\bar{y}}$ and $\Delta\dot{\bar{z}}$ are the small perturbations in the shaft displacements and velocities around its equilibrium position. The coefficients are the partial derivatives evaluated at the equilibrium position and the resulting