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Experimental detection of additional harmonics due to wear in journal bearings using excitation from a magnetic bearing

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ABSTRACT

An experimental rotor bearing system with an elastic rotor mounted in worn journal bearings is designed and investigated. The system is operated at run-up and run-down conditions and the response is analyzed with emphasis on passage through the first critical speed. Wear introduces additional sub- and super-harmonics in the response signal compared to the intact system. Time histories are analyzed in the time–frequency domain and bispectrum analysis is also performed in order to extract information on the influence of wear depth to these additional harmonics. Wear in one journal bearing is artificially produced and two cases of wear depth are investigated, one of 20% of bearing radial clearance and one of 40%.

1. Introduction

Wear in journal bearings is considered as a defect developed after long-term operation of rotor bearing systems. Hydrodynamic journal bearings, supporting rotating shafts for a long period of time, are the cause of significant wear in the bearing surface. The detection of the new operating radial clearances is of great importance since the defect leads to a decrease of the bearing load carrying capacity and alters the dynamic behaviour of the rotor bearing system. Wear as a defect and its influence on the dynamic characteristics of the system is an object that has been investigated mostly during the last three decades and for its detection there are also contributing researches in the literature. State of the art concerning behaviour of worn bearings and methods to detect or even identify presence and extent of wear in journal bearings is presented herein.

The onset and development of wear in plain hydrodynamic journal bearings under repeated stop/start cycles have been studied experimentally by Mokhtar et al. [1]. Wear was easily discernable, but localized changes in diametric clearance, surface finish and roundness of the bearing bore were measured after varying numbers of operating cycles had been completed. A study of wear location within the bearings showed that it was caused entirely by the sliding motion occurring during start-up and that no significant contribution to the wear process was a result of shutdown. This group also observed that, once an initial rapid wear phase was completed, the surface finish of the hardened steel shaft was reproduced in regions of the bearing surface subjected to continuing wear.

Dufrane et al. [2] investigated a worn journal bearing and established a model that describes wear geometry. This worn model was not of circular type. Two models of wear geometry were established to be used in further analysis of the effect of wear on hydrodynamic lubrication. These wear models are not of circular type. The first of the proposed models is based on the concept of imprinting in the bearing and the second one is based on a hypothetical abrasive wear model with the worn arc at a radius larger than the journal.

Dynamic characteristics of the fluid film in journal bearings of various types, including worn bearings, where evaluated by Vaidyanathan and Keith [3]. Wear effects in journal bearing performance for turbulence and laminar regimes were examined theoretically by Hasimoto et al. [4]. A study on the effect of non-circular wear pattern on the stability of a rigid shaft was performed from Kumar and Mishra [5], using two journal bearings with turbulent flow, while thermodynamic analysis of worn fluid film bearings was performed by Fillon and Bouyer [6] concluding that a benefit of wear is the lower temperature of operation.

Measurement of wear in journal bearings was discussed by Ligterink and de Gee [7] through a distinction between stationary and non stationary contact conditions using the Holm/Archard's wear law [8] that defines the influence of the bearing load to the wear rate.

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Nomenclature

$\delta_n(\theta)$	additional fluid film thickness
δ_0	relative wear depth
ε	eccentricity ratio
θ	circumferential coordinate
θ_s	starting angle of the wear zone
θ_f	ending angle of the wear zone
μ	Lubr.dyn.viscocity
ρ	material density
φ_0	attitude angle
x	axial coordinate
Ω	rotating speed
Ω_{EX}	frequency of excitation
C_r	bearing radial clearance
d_0	wear depth
$h(\theta)$	fluid film thickness
E	Young's modulus
L	shaft span
L_d	disc width
m_j	journal mass
m_d	disc mass
m_m	AMB journal mass
R	shaft radius
R_b	bearing radius
R_d	disc radius
S	Sommerfeld number
W	load of the journal bearing

Põdra and Andersson [9] used the finite element (FE) software ANSYS for an approach of the wear simulation proposing a simulation scheme that combines the linear Archard's wear law and the Euler integration scheme.

A study on the performance of a worn hybrid journal bearing was presented by Awasthi et al. [10]. The Reynolds equation was solved numerically using a suitable iterative technique and they concluded that wear affects bearing performance considerably; although influence of the wear defect on journal bearing performance can be less if a suitable configuration for the bearing is selected.

A theoretical identification of the bearing radial clearances using response measurements was presented by Papadopoulos et al. [11]. Response measurements have to be taken at different speeds and with different wear effects. Nikolakopoulos et al. [12] developed a theory about the relationship of friction force, misalignment angles and wear depth in a journal bearing. Furthermore, visual ferrograph system was used by Wu et al. [13] for experimental monitoring of wear condition in a journal bearing.

Torque measurement of a journal can be achieved through several methods and it is important for the precise study of the influence of wear in the friction related parameters of the bearing. Del Din and Kassfeldt [14] used a crowbar with strain gauges to obtain friction torque measurements and to study wear parameters under mixed lubrication conditions in a journal.

Using a static torque sensor, the torque applied to a bearing can be measured and thus it is possible to calculate friction loss in a journal bearing as a function of the parameters of operation such as load, eccentricity, attitude angle and velocity. The method was applied for wear depth identification by Brito et al. [15].

Very recently, Gertzos et al. [16] achieved wear identification via measurements of dynamic bearing characteristics. CFD analysis was performed to solve the Navier–Stokes equations and to produce diagrams of bearing characteristics such as relative eccentricity, attitude angle, lubricant side flow and friction coefficient vs. Sommerfeld number for various wear depths, to be used them for online wear identification. A graphical detection method was developed in order to identify wear depth in association with the measured dynamic characteristics.

A recent work by Chasalevris et al. [17] presents an investigation of the additional harmonic components developing in the transient response of a continuous rotor mounted on worn bearings. It was noticed that those harmonics are more sensitive to wear especially in the frequency of 1/2 of synchronous and during passing through resonance. Components of 3/2 and 5/2 of synchronous were also developed because of the wear existence and in the wear extent of 20% of radial clearance. Chasalevris et al. [18] investigated the development of the additional harmonics due to wear in aligned and misaligned wear pattern observing that the sensitivity of additional harmonic development is higher when wear is aligned to the rotor pattern. Chasalevris et al. [19] applied a transient electromagnetic excitation in a rotor bearing system under steady state operation and the additional components were developed when bearings were considered to be worn. Using external excitation, the system can be inspected for wear in its journal bearings through decomposition of its response signals in time and frequency domain.

The main innovation in this work is that it is based on components that are additional to the response and are due to the presence of wear while previous works are based on measurements of the operational characteristic of the bearing, or other indicators regarding the lubrication or the substances of the lubricant. Additionally, the incorporation of an AMB excitation gives in the current work a further objective. However, the incorporation of an exciter in a real system is not always possible, or beneficial due to other reasons but the upcoming types of hybrid bearings that incorporate simultaneously hydrodynamic lubrication and magnetic support, gives to the current issue a point in worth seeing the contribution of magnetic exciters to the detection of faults in the main machine elements e.g. bearing wear or rotor crack.

Coexistence of journal bearings with active magnetic bearings (AMBs) in rotor bearing systems provides the possibility for exciting the system as to provoke sub-resonances due defects such as wear in the plain journal bearings. In this work, the response of an experimental system consisting of a simple elastic rotor mounted in two fluid-film bearings, with one of them being worn, is investigated under conditions of start up and under the AMB transient excitation. The artificially produced wear pattern is assumed to be aligned with respect to the bearing longitudinal axis. The central idea of this study is to apply an external excitation force of variable frequency, while the system is at normal operation at steady constant rotational speed. This enables generation of additional harmonics and correlates them to the wear pattern without the need to disturb system nominal operational conditions. Additional harmonic components in the system response are observed during normal start up with the onset of the frequency components at $1/2\Omega$, $3/2\Omega$ $5/2\Omega$ etc. During the passage through the first critical speed the sub-harmonic component at $1/2\Omega$ proves the most sensitive to a change in wear depth and this observation stands both for simulation and experimental results. This correlation can also observed at an additional external excitation at a sweep frequency Ω_{EX}.

The experimentally obtained time histories of the response under the combined excitation of unbalance force at steady frequency and external force from AMB at linearly variable