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Active magnetic bearing-supported rotor with misaligned cageless backup bearings: A dropdown event simulation model

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ABSTRACT

Active magnetic bearings (AMB) offer considerable benefits compared to regular mechanical bearings. On the other hand, they require backup bearings to avoid damage resulting from a failure in the component itself, or in the power or control system. During a rotor-bearing contact event – when the magnetic field has disappeared and the rotor drops on the backup bearings – the structure of the backup bearings has an impact on the dynamic actions of the rotor. In this paper, the dynamics of an active magnetic bearing-supported rotor during contact with backup bearings is studied with a simulation model. Modeling of the backup bearings is done using a comprehensive cageless ball bearing model. The elasticity of the rotor is described using the finite element method (FEM) and the degrees of freedom (DOF) of the system are reduced using component mode synthesis. Verification of the misaligned cageless backup bearings model is done by comparing the simulation results against the measurement results. The verified model with misaligned cageless backup bearings is found to correspond to the features of a real system.

1. Introduction

Active magnetic bearings (AMB) possess several advantages when compared to conventional bearings. AMBs have no parts that could wear out mechanically and are therefore suitable for large diameters and high speeds. In addition, the AMB stiffness can be adjusted, which is beneficial when the critical speed of the rotor bearing system needs to be exceeded. One additional important advantage is that an AMB system does not suffer from the effects of bearing currents, which can be damaging for the rolling element and sleeve bearings.

Mechanical backup bearings are an integral part of an AMB system. The backup bearings are in use when the AMB is out of operation, and they may be needed when the AMB is in operation and under overload conditions. The primary purpose of the backup bearings is to ensure safe coast-down of the rotor after an emergency drop-down. In practice, this means that contact is avoided between the rotating rotor and the stator of the electric machine or AMBs.

In recent years, a considerable amount of literature has been published on contact situations. The most frequently examined characteristics of rolling element backup bearings are stiffness, and damping and friction coefficients between the

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rotor and bearing. The influence of these coefficients is widely recognized, as reviewed by Ishii and Kirk [1], Schmied and Pradetto [2], Zeng [3] and Cole et al. [4]. These studies examined the dynamic behavior of a cageless rolling element bearing after rotor impact and stated that the inner race of the bearing should be allowed to accelerate as rapidly as possible in order to minimize the energy dissipation in the bearing and, consequently, minimize the likelihood of a friction induced whirling motion of the rotor. A detailed bearing model that includes a flexible inner race of a cageless bearing is presented in Cole et al. [4]. However, their work studies only the dynamics of the bearing model and the effect of the flexible rotor is ignored. Hawkins et al. [5,6] studied rotor drops to backup bearings. The backup bearings were a duplex pair of face/face mounted angular contact ball bearings. Helfert [7,8] studied the acceleration behavior of cageless ball bearings by high-speed video recordings of the contact between the rotor and the backup bearings.

Kärkkäinen et al. [9,10] studied the misalignment of backup bearings in the contact situation using a simulation model and measurements. Further development of a simulation model of misaligned backup bearings was presented in [11] and a configuration verified in which one backup bearing is cageless and one with a cage. El-Shafei et al. [12] and Ahmed and El-Shafei [13] studied the effect of misalignment when using plain journal bearings and their work indicates that misalignment is an important research problem, providing justification for this study.

Rotor contact with backup bearings while operating in the proximity of critical speeds is studied in references [14–16]. Schlotter and Keogh [14] proposed a methodology for control of the rotor after contact between the rotor and backup bearings at critical speed, which can occur if the magnetic bearing damping is not large enough. Keogh [15] and Sugai et al. [16] studied short duration contact during abnormal operation conditions. An active backup bearing is suggested as a solution for abnormal operating conditions, an approach which was studied also by Sahinkaya et al. [17] and Cade et al. [18]. Specifically, Sahinkaya et al. and Cade et al. studied vibrations control as a strategy to prevent rotor contact with the backup bearings.

Zhu et al. [19] examined a double-level backup bearing, where two bearings are on top of each other at both ends of the rotor, as an enhancement of the AMB backup system. The rigid rotor and contact between the rotor and inner race were taken into account in their work. In addition, a bearing force model and thermal model were included in the study. Condition monitoring of the backup bearings is examined in references [20–22]. Lee and Palazzolo [20] studied lifecycle extension of backup bearings by side-loads, drop speed, support stiffness and damping, as well as by reducing bearing friction. Ginzinger et al. [21] studied a model-based approach for a condition monitoring system for backup bearings. The system proposed checking the backup bearing condition after each impact. Tsai et al. [22] studied fault patterns in monitoring of a rotor system and proposed an algorithm for detecting defects at the earliest possible occasion. Ji et al. [23] studied rotor contact with backup bearings using a predictive tool for abnormal situations. Papers by Inayat-Hussain [24,25] and El-Shafei and Dimitri [26] examined load sharing between the magnetic and backup bearings. In their approach, the active magnetic bearings are used only as controlling actuators and the backup bearings have continuous contact. Ishida and Inoue [27] studied how an AMB system might stay alive when one or two of the four electromagnets are not functioning.

Unlike a ball bearing with a cage, the balls of a cageless ball bearing are located next to each other at the bottom of the bearing during normal operation of the AMB. For this reason, at the moment of the drop-down, the impact force of the rotor is distributed to a greater number of rolling elements and as a result, the life expectation of the cageless rolling element bearing is more promising than that of a regular ball bearing with a cage. Furthermore, in a bearing with a cage, it is possible that the cage can be damaged in the contact situation. In real systems, unlike most models, the alignment of bearings is non-ideal, due to earlier drop-downs and tolerances in the manufacturing and assembly. The objective of this paper is to introduce a simulation approach for dynamic analysis of a drop-down event. The introduced model can be used to shed light on the dynamic behavior of an AMB supported rotor system when the rotor drops due to failure of all electrical backup systems. The electrical systems include those of the AMB, the generator mode of the frequency converter, the uninterruptible power supply (UPS) and the batteries.

In this study, the model consists of a flexible rotor, a regular ball bearing with cage, and a cageless ball bearing. The backup bearings are described using a ball bearing model that includes damping and stiffness properties, the inertia of the rolling elements, and friction between the races and the rolling elements. In the cageless bearing model, each ball is described using two degrees of freedom. The drop-down is simulated so that both backup bearings are misaligned and cageless. The model of the rotor system is modeled using a finite element approach with unbalances of the flexible rotor. The friction coefficient between the rotor and inner ring is not a variable as in the real case. The stiffness and damping properties of the support are included in the model.

2. Model of the backup bearing system

This section presents the models of the rotor and ball bearings with and without a cage, and provides a description of the contact. The model of the rotor is constructed using the finite element approach.

2.1. Flexible rotor model

Modeling of the rotor is done using beam finite elements. The beam elements are constructed based on Timoshenko beam theory, which takes into account shear deformation. In this study, the rotor analysis concentrates on the lateral vibration and therefore the axial and torsion degrees of freedom are not incorporated in the beam element analysis.