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Experimental validation of a rotor delevitation model with quantified severity indicators

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ABSTRACT

This paper presents the experimental validation of BBSim: a non-linear model for simulation of rotor delevitation in an active magnetic bearing system with backup bearings (BBs). The rotor delevitation model's purposes are to understand the dynamics involved during delevitation and to quantify the severity of the delevitation event. The subsequent challenge consists of validating both the delevitation dynamics and the impact of the rotor on the backup bearing as a quantitative measure of delevitation severity. Severity indicators are derived from the relationship between the rotor's impact and the average lateral rotor speed after delevitation. Model validation employs both the defined severity indicators and the rotor delevitation orbit characteristics as basis for comparing experimental and simulated results. The severity indicator validation confirms the rotor lateral kinetic energy during delevitation as a satisfactory predictor of the BB impact forces. Furthermore, calibration of the simulation model together with the subsequent validation process affirms the model's validity.

1. Introduction

This paper presents a detailed explanation of the experimental validation of a previously published model, called BBSim, which was used to simulate rotor delevitation in an active magnetic bearing system [1]. Model validation refers to the process of establishing whether a model of a particular process or system is an accurate representation of the actual process or system from the perspective of the intended use of the model [2,3]. The high cost of full-scale experimental validation of models necessitates alternative approaches to model validation [4]. Quantitative model validation is an active research field with a drive towards affordability and reliability [5].

When validating a prospective model of a process, both the model structure and the model parameterization need to be validated. Certified reduced basis model validation based on a frequentist uncertainty framework can be used [6]. This approach introduces a spectral representation of the misfit and a certified reduced basis model, achieving improved computational performance, without loss of rigor relative to full discretization.

Three key issues regarding validation commonly agreed upon among researchers include: (i) quantifying the accuracy of the computational model in terms of comparisons with experimentally measured responses, (ii) extrapolation of the model to conditions of intended use and (iii) establishing its accuracy for the conditions of intended use [7].

The intended use of the rotor delevitation model is to understand the dynamics involved during delevitation and to quantify the severity of the delevitation event. Typical industrial applications of active magnetic bearings (AMBs) are not equipped with force measurement sensors. As such, this paper presents methods to quantify the severity of a rotor delevitation event based on only position data. Since any AMB system already includes position sensors, these methods of quantification can be applied to any existing AMB system. The severity indicators also play a role in quantitatively validating a non-linear model of rotor delevitation (BBSim) as described in previously published work [1].

The severity of the rotor delevitation event (RDE) is regarded as directly related to the impact of the rotor on the backup bearing as well as the number of impacts. Validation of the delevitation model should, therefore, include a comparison of the simulated rotor impact severity with measured rotor impact severity.

Sun et al. [8] reported on the details of a comprehensive ball bearing model for backup bearing (BB) applications. The results of this publication reveal that the friction coefficient, support damping and side loads are critical parameters in the simulation of BBs and the prevention of backward whirl.

Kärkkäinen et al. [9] presented the transient simulation of a rotor

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Nomenclature

AMB	active magnetic bearing
BB	backup bearing
BBSim	backup bearing simulation model used in this paper
RDE	rotor delevitation event
I	impulse N s
F	contact force, N
m	mass of the rotor, kg
m_b	mass of the inner-race, balls and cage, kg
m_{mt}	mass of the outer-race and mount, kg
t_k	duration of sampling window, s
t_d	total delevitation time, s
i_d	index number when t_d is reached
Δv	change in velocity, m·s^{-1}
$\overline{v}$	average velocity, m·s^{-1}
$V_{val\,k}$	non-dimensionalised velocity of geometric centre of rotor during window number k
$D_{val\,k}$	non-dimensionalised lateral distance travelled by the geometric centre of rotor during window number k
V_{vala}	average non-dimensionalised velocity of geometric centre of rotor during entire rotor delevitation event
D_{vala}	total non-dimensionalised lateral distance travelled by the geometric centre of rotor during entire rotor delevitation event
$x_{(i)}$	horizontal position of geometric centre of rotor within backup bearing clearance at index number i, m
$y_{(i)}$	vertical position of geometric centre of rotor within backup bearing clearance at index number i, m
R_{airgap}	radius of backup bearing clearance, m

delevitation onto BBs, but the authors only validated the free-free modes of the flexible rotor.

Multi-body mechanics developed for classic ball bearing applications were utilised by Anders et al. [10]. Their model was validated by comparing the rotor delevitation behaviour with recorded data from experimental rotor delevitation events. The internal bearing mechanics produced by the simulation model correlated with physical evidence discovered on the bearings after the rotor delevitation events.

Collins et al. [11] developed a transient rotor delevitation dynamic simulation model using numerical tools and combined the rotor dynamics with the sleeve backup bearing characteristics. The model includes compliance system stiffness effects as well as friction and contact models between rotor and backup bearings. Simulation and experimentally measured orbital plots of the rotor were compared as a means of model validation together with physical dye penetrant inspection of the landing sleeves on the rotor.

Denk et al. [12] present a comparison between simulated results and experimental results for a delevitation event of a 9-ton rotor in rolling-element backup bearings. The experimental and simulated results compare well and the validation of this model is presented in [13] by Siegl et al. Validation is achieved by subjectively comparing the resulting experimental rotor orbits and displacement against rotational speed graphs with the simulated results.

Kang and Palazzolo [14] present a coupled two-dimensional finite element model for simulation of the elastic deformation and heat transfer of a sleeve bearing used as a backup bearing. Validation of the two-dimensional heat transfer model is achieved by comparing the results with those of a three-dimensional model. The rotor delevitation events predicted by the model are compared with experimental results found in literature by examining rotor orbit plots. The authors also investigate the effect of the friction factor on the rotor behaviour and compare experimental results for various materials used in the sleeve-type backup bearings with simulated results.

Orth et al. [15] also compared the simulated and experimental rotor orbits as a means of validating a model of a magnetically suspended elastic rotor during contact with rolling-element backup bearings. Three phases of rotor motion are compared; the first phase is the rotor delevitation due to its weight, then the one of first impact, and lastly where the rotor performs an oscillating motion along the inner ring of the backup bearing. Orth et al. regarded a small difference in the height of rotor rebound after first impact between simulated and experimental results as indicative of modelling accuracy. The height of the rebound was established to be highly dependent on the flexibility and damping properties of the rotor as well as the corresponding properties of the backup bearing. According to Orth et al., this representative exchange of energy during rotor impact was thus indicative of model validation.

The approach followed in this paper share similarities with the work of Orth et al. [15]. This work, however, follows a two-pronged validation approach. Firstly, quantified indicators of rotor delevitation severity are defined and validated as a measure of BB impact. The quantified severity indicators use the rotor's lateral position as available information. Secondly, the validation of the delevitation model is addressed. The approach followed in this paper employs both the mentioned severity indicators and the rotor delevitation orbit characteristics as basis for comparing experimental and simulated results.

Even though the focus of this paper is the experimental validation of the non-linear model called BBSim, a brief overview of the model is provided first in Section 2. The rest of this paper continues with Section 3.1 wherein quantification of the rotor delevitation severity is discussed, followed by severity indicator validation in Section 3.2. Section 4 is devoted to the validation of the simulation model and the rotor orbital plots, with Section 5 concluding the paper.

2. Overview of BBSim

This section provides a brief overview of the non-linear model called BBSim. The main purpose of BBSim was to better understand the dynamics involved during a rotor delevitation event in an AMB system with backup bearings. For a full explanation of the model development process behind BBSim, the reader is referred to work by Janse van Rensburg et al. [1].

The model consists of different submodels: a flexible rotor model, two radial BB models and two radial AMB models. These submodels are coupled to represent the complex interaction between the various components during an RDE in both the translational and rotational direction. The flexible rotor model is based on the work by Bucher [16]. Each backup bearing is a rolling-element bearing consisting of an outer-race fitted to the stator, an inner-race on which the rotor lands during delevitation and the balls and cage between the two races. The elements of the BBSim model are illustrated in the diagram of Fig. 1 with half of the system duplicated around the axis of symmetry.

The BB is modelled as a set of three inline mass-spring-damper systems. From the rotor in the direction of the stator, the first system represents the airgap and contact stiffness and damping. The second system represents the mass of the inner-race, balls and cage (m_b) with bearing stiffness and damping. The final system represents the mass of the outer-race and mount (m_{mt}) with stiffness and damping of the mount. The AMB is modelled as a spring-damper system between the rotor and the stator acting in parallel to the BB model.

The aim of BBSim is to accurately predict the real-world forces experienced by the BBs. The submodels are solved for delevitation events with mostly friction models governing the coupling between the translational and rotational directions. The integrated BBSim model also aims to accurately simulate rotor orbital behaviour during delevitation both in terms of rotor translational and rotational position, and the actual forces experienced by the BB components.