Mechanical Systems and Signal Processing 66-67 (2016) 665–678

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A rotor unbalance response based approach to the identification of the closed-loop stiffness and damping coefficients of active magnetic bearings

Jin Zhou [a], Long Di [b], Changli Cheng [a], Yuanping Xu [a], Zongli Lin [b,*]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China
[b] Charles L. Brown Department of Electrical and Computer Engineering, and Rotating Machinery and Controls Laboratory (ROMAC), University of Virginia, P.O. Box 400473, Charlottesville, VA 22904, USA

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form
1 June 2015
Accepted 11 June 2015
Available online 3 July 2015

Keywords:
Active magnetic bearings
Rotor dynamics
Stiffness coefficient
Damping coefficient
Parameter identification

ABSTRACT

The stiffness and damping coefficients of active magnetic bearings (AMBs) have direct influence on the dynamic response of a rotor bearing system, including the bending critical speeds, modes of vibrations and stability. Rotor unbalance response is informative in the identification of these bearing support parameters. In this paper, we propose a method for identifying closed-loop AMB stiffness and damping coefficients based on the rotor unbalance response. We will use a flexible rotor-AMB test rig to help describe the proposed method as well as to validate the identification results. First, based on a rigid body model of the rotor, a formula is derived that computes the nominal values of the bearing stiffness and damping coefficients at a given rotating speed from the experimentally measured rotor unbalance response at the given speed. Then, based on a finite element model of the rotor, an error response surface is constructed for each parameter to estimate the identification errors induced by the rotor flexibility. The final identified values of the stiffness and damping coefficients equal the sums of the nominal values initially computed from the unbalance response and the identification errors determined by the error response surfaces. The proposed identification method is carried out on the rotor-AMB test rig. In order to validate the identification results, the identified values of the closed-loop AMB stiffness and damping coefficients are combined with the finite element model of the rotor to form a full model of the rotor-AMB test rig, from which the model unbalance responses at various rotating speeds are determined through simulation and compared with the experimental measurements. The close agreements between the simulation results and the measurements validate the proposed identification method.

1. Introduction

Active magnetic bearings (AMBs) have been increasingly used in centrifugal gas compressors and other high-speed rotating machinery applications [1]. AMBs do not need lubrication and their non-contact working environment significantly reduces the friction, which makes the rotor bearing system more efficient. Since the stiffness and damping coefficients of a rotor-AMB system have substantial effects on the bending critical speeds, modes of vibrations and system stability, research

---

[*] Corresponding author. Tel.: +1 434 924 6342.
E-mail addresses: nuaazhoujin@gmail.com (J. Zhou), ld4vv@virginia.edu (L. Di), 970053197@qq.com (C. Cheng), xuyuanping1075@yeah.net (Y. Xu), zl5y@virginia.edu (Z. Lin).

http://dx.doi.org/10.1016/j.ymssp.2015.06.008
0888-3270/© 2015 Elsevier Ltd. All rights reserved.

on identifying those support parameters has been well recognized to be important and many identification methods can be found in the literature.

On the theoretical analysis of stiffness and damping, Humphris et al. [2] derived the equivalent stiffness and damping coefficients from the AMB system transfer function, Yu [3] and Hu et al. [4] analyzed the static and dynamic characteristics of the AMB, and Wang and Jiang [5] proposed a method to estimate the bearing stiffness by using the control current ratio. These studies were all based on a simplified model, and the support parameters of magnetic bearings are identified through theoretical analysis, which, in the absence of experimental verification, often leads to inaccurate results. In addition, it is difficult to identify support parameters based on theoretical analysis for some magnetic bearing systems that involve complex control strategies. In contrast to the theoretical analysis approach, which entails simplified rotor-AMB model, the experimental identification approach is an easier but more effective way to identify AMB stiffness and damping coefficients.

On the experimental approach to the identification of AMB stiffness and damping coefficients, Budig and Werner [6] confirmed that the AMB stiffness and damping coefficients are closely related to the controller frequency response, with the controller bandwidth having the strongest impact. Yang et al. [7] used the AMB as an exciter for the stiffness identification. Since the excitation force is obtained through the electrical current conversion, magnetic flux leakage causes the actual force to be inconsistent with the theoretical value. Wu [8] and Wang and Gao [9] used the external load method to identify the static stiffness, but they did not consider the dynamic characteristics of magnetic bearings. Zhou and Lin [10] used the hammer impact method to estimate the stiffness and damping of a single degree of freedom (SDOF) AMB system, and then verified the results through the sine sweep frequency response. According to the amplitude–frequency characteristic curve, the estimated system stiffness is close to the value obtained by the hammer impact method, but the study was only limited to an SDOF system. Shen and Yu [11] used the multiple frequency excitation approach, in combination with the least squares method, to identify the AMB support parameters, but a rigid rotor motion equation was used as the rotor model. A drawback for these existing experimental identification approaches is that they mostly do not consider rotor flexibility, which leads to inconsistent results at different rotating speeds.

In this paper, we present a rotor unbalance response based approach to identifying the closed-loop AMB stiffness and damping coefficients, which are the AMB's complex impedance as a function of the forcing frequency. This identification process for a given speed consists of two steps, and is presented on a flexible rotor-AMB test rig. In the first step, based on a rigid body model of the rotor, a formula is derived that computes the nominal values of the closed-loop bearing stiffness and damping coefficients at a given rotating speed from the experimentally measured rotor unbalance response. The derivation of such a formula is made possible by the simplicity of the rigid body model of the rotor. In the second step, based on a finite element model (FEM model) of the rotor, an error response surface is constructed for each parameter to estimate the identification errors induced by the rotor flexibility. The final identified closed-loop AMB stiffness and damping coefficients equal the sums of the nominal values initially computed from the experimental unbalance response and the identification errors determined by the error response surfaces. We will also present the experimental validation of the identification results. The identified stiffness and damping coefficients are combined with the finite element model of the rotor to form a full model of the rotor-AMB test rig, from which the model unbalance responses at various rotating speeds are determined through simulation and compared with the experimental measurements.

In comparison with the many existing works, in this paper, a flexible rotor-AMB test rig is studied and the effect of the rotor flexibility is emphasized. Although the unbalance response based stiffness and damping identification method has been widely used on rolling element bearings and sliding bearings, few works have been reported on its application to magnetic bearings. By identifying the closed-loop support parameters, we can predict the critical speed, mode shape and amplitude of synchronous vibrations without the closed-loop transfer function. Since the unbalance force is the simplest form of external excitation, this method does not require additional mechanical devices and online measurements can be made [12–14], it is ideal for the closed-loop AMB support parameter identification. Furthermore, the proposed identification approach does not require any knowledge of the control strategy and thus is widely applicable. With a flexible rotor, even when the controller is known and has the simple structure of a PID controller, extracting the closed-loop AMB support parameters from the closed-loop transfer function is not an easy task.

This paper proceeds as follows. In Section 2, a flexible rotor-AMB test rig that is introduced and, based on the test rig, the proposed approach to the closed-loop AMB stiffness and damping identification is described. Section 3 presents identification results on the test rig. Section 4 presents the experimental validation of the identification results from Section 3. Section 5 draws a conclusion to the paper.

2. A rotor unbalance response based approach to AMB identification

This section contains three subsections. Section 2.1 describes the flexible rotor-AMB experimental test rig that we are to use to present our AMB identification method on in the next two subsections. The identification results will also be validated on this test rig in Section 4. Section 2.2 assumes a rigid body model of the rotor and derives a formula to calculate the nominal values of the AMB stiffness and damping coefficients from the measured unbalance response. Section 2.3 adopts a finite element model of the rotor to construct error response surfaces for rectifying the identification errors induced by the rigid rotor modeling of the flexible rotor.