Mechanism and Machine Theory 98 (2016) 48–63

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

An efficient rotor suspension with active magnetic bearings having viscoelastic control law

H.K. Roy [a], A.S. Das [b,1], J.K. Dutt [a,*]

[a] Department of Mechanical Engineering, IIT Delhi, Hauz Khas, New Delhi 110016, India
[b] Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, West Bengal, India

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 17 September 2015
Accepted 25 November 2015
Available online xxxx

Keywords:
Active magnetic bearings
Novel control law of AMB
Viscoelastic control laws of AMB
An efficient AMB control law
Control law based on viscoelastic characteristics

ABSTRACT

Research on active magnetic bearings (AMBs) has received good attention as such bearings not only provide electromagnetic forces over an air-gap to levitate or bear a rotor-shaft system, but at the same time, such bearings may also be used for providing active suspension forces to obtain the desired position of a rotor inside the bearing as well as the desired dynamic behaviour of rotor-shaft systems. The proportional, integral, derivative (PID) control law, as well as a few nonlinear control laws can be found in the literature, of which the former is very common. This paper attempts to study, theoretically and experimentally, the influence of a simple proportional and high-frequency band limited derivative control law (PD_{hfbl}), proposed in this work as the viscoelastic control law to generate viscoelastic semisolid-like behaviour of the AMB, on the dynamic behaviour of a rigid rotor-shaft system. It is observed that within the same limits of control current, the (PD_{hfbl}) control law is much more efficient than the PID in positioning the rotor within closer tolerances and reducing the rotor response amplitude due to unbalance.

1. Introduction

Electromagnetic suspension of rotors has obtained special attention from contemporary researchers primarily due to two reasons. The first one is that such a suspension system is capable of applying the force borne by the suspension system over an air gap, and thus eliminates contact with the rotating surface so there is no friction as in the case of rolling element bearings, no viscous drag as in the case of the hydrodynamic bearings and consequently there is no wear and tear or need for maintenance, etc. The second reason is that by suitable design of the suspension model (which is easier to implement in the case of electromagnetic systems than in the case of classic mechanical bearing systems), the desired dynamic behaviour of the rotor-shaft system may be achieved. This is convenient for the purpose of vibration control of the rotor-shaft system. The book by Schweitzer and Maslen [1] is a very good reference for designing active magnetic bearings (AMBs), where the bearings are primarily designed to give an elastic damped or 2-element model, in which the suspension is characterized by a Voigt model. Corresponding to that, the controller is a proportional-derivative or a PD controller. Many researchers reported attempts to actively control rotor vibration using AMBs or electromagnetic actuator according to Abduljabbar et al. [2]. Electromagnetic actuators follow the same as the AMB but does not support the static load, which is borne by conventional bearings. Schweitzer [3] proposed an active damper to stabilize a rotor system; Schweitzer and Lange [4] also presented a design methodology of an AMB based on linearized force current characteristics and Schweitzer and Ulbrich [5] reported vibration control of a vertical centrifuge using AMB. Bleuler et al. [6] reported the effectiveness of a decentralized state feedback control scheme for a rigid rotor supported on AMB by using pole-placement

* Corresponding author. Tel.: +91 11 26596334/919968284097.
E-mail addresses: hemanta.kol47@gmail.com (H.K. Roy), anindya990052003@yahoo.com (A.S. Das), jkrdutt@yahoo.co.in, jkdutt@mech.iitd.ac.in (J.K. Dutt).
[1] Tel.: 91 3324572657/91 9051998485.

http://dx.doi.org/10.1016/j.mechmachtheory.2015.11.012

technique. An active vibration control strategy of a single mass rotor supported on flexible supports at the ends was proposed by Allaire et al. [7], simultaneously using proportional control law, to increase the critical speed and derivative control law, and to reduce the amplitude of vibration. They showed that the increase in critical speed and reduction of vibration amplitude depend upon the proportional control ratio and derivative control ratio, respectively.

Burrows et al. [8] presented an efficient least-squares method to minimize the vibration of general rotor-bearing systems (modelled by lumped parameters estimated in the frequency domain) by applying external control force from a magnetic bearing actuator; later, Burrows et al. [9] used a technique to control the vibration of a flexible rotor-shaft supported on conventional oil-film bearings by employing partial pole placement technique together with an open loop control strategy based on least-squares method. Burrows et al. [10,11] showed that vibration signal sensed from a limited number of carefully selected measurement sites is adequate for generating control force through a single magnetic actuator. Chen et al. [12] investigated the role of a velocity observer in achieving damping and that of an acceleration observer in achieving rotating force control experimentally for a relatively rigid rotor supported at one end on a rigid ball bearing and at the other end on an AMB. Salm et al. [13] demonstrated an active control strategy, composed of non-expansive direct output feedback with collocated sensors and actuators for a flexible rotor suspended on two magnetic bearings and showed that the technique could guarantee stability. Cross-coupled bearing stiffness is understood to improve the stability of the rotors. The design of a controller for flexible rotor-magnetic bearing system was proposed by Cole et al. [14] to simultaneously mitigate the rotor response due to direct unbalance excitation as well as the base input. Use of H_∞ optimization technique and suitably selected weighting function helped to determine the state-space controller in achieving optimal control. Later, Cole et al. [15] developed a method for controlling the lateral vibration of a flexible rotor-magnetic bearing system under multi-frequency excitation using a generalized algorithm for real-time computation of the amplitude and phase of vibration components at individual frequencies. The possibility of nonlinear control of rotors supported on AMBs has been reported by Markert and Hoffman [16] as well as by Hsua and Chen [17].

Matsushita et al. [18] proposed and implemented a cross-coupled stiffness effect in an AMB by introducing 'cross talks' between channels corresponding to two transverse co-ordinate directions of the decentralized controller layout for controlling the whirl motion of a rotor, stabilizing self-excited vibration in forward whirling and avoiding low-frequency backward instability. Recently, Das et al. [19] showed the application of a suitably placed electromagnetic actuator to reduce unbalanced response and increase the stability limit speed of a rotor-shaft system by using a proportional-derivative (PD) control law applied to the air gap between the actuator pole-face and the rotor surface to decide the control current in the actuator coils and through that the force applied on the rotor-section. All the above research work show that AMBs or broadly electromagnetic force-based suspension and actuator systems generate active forces, which may be utilized with the help of a proper control objective to change the system dynamic behaviour according to the desired one. In brief, such electromagnetic forces work as compensators, and add suitable restoring force as well as dissipative forces to the system to control system dynamics.

Damping applied to rotor supports was understood to provide stationary dissipative force on rotors and thus helps the rotor-shaft systems stabilize and reduce rotor response long back. Lund [20], Gunter and Trumpler [21], Gunter [22], Kirk and Gunter [23], among many others, proved these about four decades ago with the help of an elastic damped support or Voigt model, which is essentially a 2-element viscoelastic solid model. The book by Bland [24] is a very good reference on viscoelastic solid models and taking ideas of such models, Dutt [25], Dutt and Nakra [26], Dutt and Toi [27] later showed through dynamic simulation that support models having more than 2 elements, like the 4-element viscoelastic model, have the propensity to provide better energy dissipation ability and through that higher stability and lower response of rotor-shaft system. Panda and Dutt [28,29] reported a theoretical study on the optimum values of support parameters for obtaining minimum stability limit speed and maximum stability limit speed at a spin speed. However encouraging the results might be, one problem exists with the use of viscoelastic support material and that is such support materials present different material properties with temperature, suffer from the problems of ageing and degradation in the presence of oil and oxygen, and thus are not very reliable. Due to these reasons, the concept of putting viscoelastic supports may not be viable from a realistic point of view; however, the formulations render immense help to a designer to get an idea about the influence of efficient support model and their properties on the dynamic behaviour of rotor-shaft systems. This paper proposes the generation of viscoelastic solid-like behaviour with the help of AMBs by modifying the control law applied to the movement of the rotor-section to decide the control current in the coils. Both numerical and experimental investigations are presented in this paper. In this paper, the control law to obtain a 3-element viscoelastic solid-like behaviour (same as the Zenner model in [24]) of the AMB, and named as the PD_{hfbl} control law, has been used for the purpose of system dynamic modification. The PD_{hfbl} control law is found to improve the levitation accuracy during non-spinning condition of the rotor-shaft, and reduce the unbalanced response of a rigid rotor very much in comparison with the PID control law normally used in any AMB and thus proposes that a viscoelastic solid like the AMB model holds a very strong promise for research in AMB technology.

2. The active magnetic bearing (AMB)

2.1. The concept of an AMB

The book by Schweitzer et al. [1] is a very good reference to know the basics of AMBs. Following the same, the simplest possible schematic diagram of an active magnetic bearing is sketched in Fig. 1. This is, in principle, a methodology to control the current in the coil and apply a resulting controlled electromagnetic force over an air-gap on a ferromagnetic rotor-shaft to levitate it against gravity and other time-varying forces due to the spin of the rotor. The coil current and the resulting electromagnetic force