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MIMO Repetitive Control of an Active Magnetic Bearing Spindle

Sandeep Rai * **Grant Cavalier** † **James Simonelli** ‡ **Tsu-Chin Tsao** §

* *Mechanical and Aerospace Engineering Department, University of California, Los Angeles, USA (e-mail: sandyrai00@ucla.edu).*
† *Mechanical and Aerospace Engineering Department, University of California, Los Angeles, USA (e-mail: gcavalier58@gmail.com).*
‡ *Mechanical and Aerospace Engineering Department, University of California, Los Angeles, USA (e-mail: jsimonelli@ucla.edu).*
§ *Mechanical and Aerospace Engineering Department, University of California, Los Angeles, USA (e-mail: ttsao@ucla.edu)*

Abstract: We present the identification and control of an open loop unstable MIMO Active Magnetic Bearing Spindle (AMBS) for machining applications. A 20th order model is obtained from reducing a higher order model identified by the ARX method. For verification purposes, the model is compared to the system's frequency responses obtained by the frequency sweep method. The model is used to design a linear quadratic optimal controller, where the weighting gains are tuned by simulation and experiment. A plug-in repetitive controller for asymptotic regulation and tracking of signals synchronous to the spindle rotation is designed by formulating the control design as a model matching filter design problem. The model matching's optimal solutions for the non-minimum phase MIMO stabilized system are obtained respectively for H_∞ and H_2 norm minimizations. Simulation and experimental results are presented to compare the proposed MIMO repetitive control design methods and demonstrate the control performance.

Keywords: active magnetic bearing, high speed machining, multivariable control, repetitive control, system identification, implementation

1. INTRODUCTION

Active magnetic bearings are used in many applications such as molecular pumps, compressors, magnetic levitating vehicles, and flywheels (Bleuler et al. (2009)), to name a few. An active magnetic bearing spindle (AMBS) has also been of interest for its use in high speed machining (HSM) because of its potential benefits of mitigating wears, thermal-mechanical effects, and creating high bandwidth and dynamic stiffness for precision machining Chen and Knospe (2007). However, AMBS is a challenging mechatronic system, as it presents unstable, nonlinear, and coupled-axis MIMO open-loop dynamics that require careful modeling, identification, and control to enable the realization of the potential benefits. This paper presents the methods and results of real-time control instrumentation, system identification, and digital control we conducted on a commercial grade AMBS for future applications in high-speed machining and machining of irregularly-shaped surfaces.

Control approaches to AMB mainly address establishing stability or compensating unbalanced spindle motion. Compensation can take the form of either minimizing unbalance force transmitted to the housing or minimizing rotor runout Zhou and Shi (2001). Because precision is valued above vibration suppression in the HSM application, we will focus exclusively on runout minimization for the purposes of this paper. Fujita et al. (1993) and Balini et al. (2011) use a H_∞ loop shaping approach to design a robust levitating controller. In most control design considerations, the magnetic bearing can be decoupled, so SISO techniques can be used (Noshadi et al. (2015), Kang and Tsao (2016)). In Pipeleers et al. (2009), a SISO repetitive controller based on the decoupled plant model for an active air bearing system was developed for disturbance rejection. In Nonami and Ito (1996), a μ synthesis approach was used to design a controller for a flexible shaft on a magnetic bearing system similar to the one considered in this paper.

Our test set-up exhibits significant coupling, so SISO techniques will not work. We propose high-gain feedback control— specifically a MIMO Repetitive Control. Repetitive control is based on the internal model principle of Francis and Wonham (1976) that states that to achieve zero tracking error, a model of the reference/disturbance must be contained in the controller. Repetitive control places an internal model at a fundamental frequency and its harmonics. Traditional repetitive control methods (Tomizuka et al. (1989), Cuiyan et al. (2004)) are SISO formulations, therefore it is not clear how to easily extend these methods to the multivariable setting. In Kim et al. (2004), μ-synthesis is used to design a repetitive controller and can be extended to the multivariable setting, but it is highly sensitive to the weighting parameters. In Longman (2010), an FIR interpolation method is discussed;

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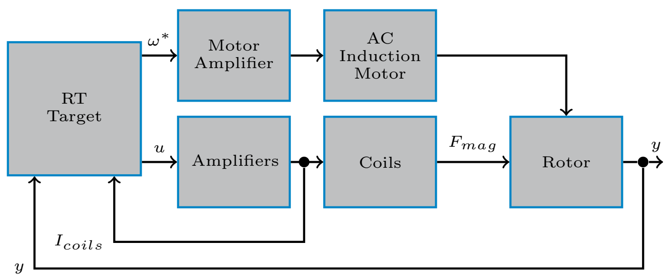

Fig. 1. Experimental Setup

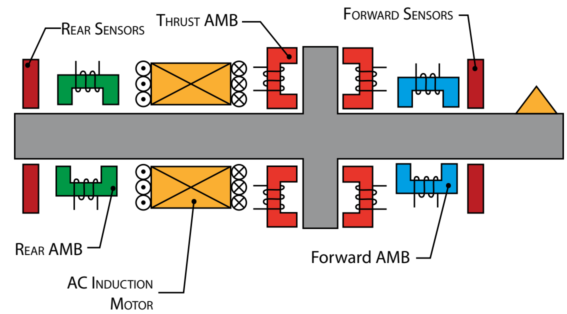

Fig. 2. Schematic of AMBS System

this method extends naturally to the MIMO setting, but cannot claim optimality and may result in long FIR filters. In this paper, two simple MIMO repetitive controllers are formulated by solving H_∞ or H_2 model matching problem.

For conventional HSM applications, the spindle runout motion must be eliminated to create desirable axis-symmetric surfaces. This requires control that rejects the spindle runout motion, which is synchronous to the spindle rotation. Another special machining application that creates irregularly shaped surfaces, termed non-circular or axis-asymmetric machining, requires precise tracking of specified spindle orbital motion. A specific example motivating our investigation here is boring of non-circular holes for wrist pin holes in internal combustion engine pistons.

Current production engine piston's pin bore profiles have elliptical cross sections and tapered diameters to increase the fatigue limit of the pin bore under cyclic combustion loads (Whitacre and Trainer (1986)). To create this non-circular bore shapes, various fast tool servos have been developed to either rapidly move the cutting tip mounted on the rotating boring bar (Cselle (2003), Zhai et al. (2008)), or to move the non-rotating piston (Liang (2013)). AMBS has the potential of performing this task if spindle orbital motion can be controlled precisely to generate tool tip motion for creating the specified non-circular bore. This presents a tracking control problem of a periodic signal whose fundamental frequency is an integer multiple of the spindle speed.

This paper addresses the AMBS control problem with consideration of the HSM application. Specifically, we present the following methods and results:

(1) A high order ARX system identification of a coupled 4x4 MIMO AMBS, model reduction, and comparison to the empirical frequency response data
(2) A stabilizing LQGi controller, tuned for broad bandwidth
(3) MIMO Repetitive controller asymptotic regulation and tracking of periodic signals based on model matching of non-minimum phase systems

The remainder of this paper is organized as follows: Section 2 describes the AMBS control system instrumentation, system identification, and the stabilizing LQGi tuning; Section 3 presents the MIMO repetitive control design; Section 4 presents the experimental results followed by conclusions in Section 5.

2. SYSTEM IDENTIFICATION & STABILIZING CONTROL

The experimental system shown in Figure 1 consists of an SKF AMBS instrumented with an induction motor drive, electromagnet power amplifiers, and a digital control system. The system has two radial AMBs and one axial AMB (Figure 2). The radial AMB system considered in this paper is four-input, four-output. National Instruments analog and digital conversion cards were used to interface the five analog gap sensors and ten electromagnetic coil power amplifiers to the digital computer. The system identification, data acquisition, and real-time digital control were realized by LabVIEW Real Time target installed on the computer, sampling at 10 kHz. The axes of the sensors are not co-located with those of the actuators, which introduces strong off-diagonal coupling. The electromagentic force is nonlinear with respect to the coil current and the air gap. Bias currents are applied to the opposing coils to render a linear approximation within ±100 microns from the AMBS centerline. In this paper, linear control is considered for spindle motion within the linear range. Since the system is open loop unstable a stabilizing controller was created and used to perform a closed-loop system identification of the open-loop plant.

2.1 High Order Multivariable ARX Identification

A time-domain identification using Pseudo-Random Burst Sequence (PRBS) input data and Autoregressive Exogenous Input (ARX) modeling (Equation 1) was performed to identify the open-loop plant model. The A and B ARX coefficient matrices are both 4x4 while both $y(t)$ and $u(t)$ are 4x1 vectors. Given experimental input and output data, equation 1 can be cast as a ordinary least squares problem.

$$y(t) + \sum_{k=1}^{N} A_k y(t-k) = \sum_{k=0}^{N} B_k u(t-k) \tag{1}$$

In this application, a high order (≈ 120) ARX model was used to solve the least squares problem, which was then put into observer form (Equation 2). This translates the input-output form into a high order state space system, which is suitable for a balanced model reduction. Figure 3, shows the Hankel Singular Values of the high order ARX model from which a 20th order model was chosen. Interestingly, a high order model followed by a model reduction was seen to give a much better fit than simply solving for a low order