Control Engineering Practice 46 (2016) 166–175

Contents lists available at ScienceDirect

Control Engineering Practice

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

Unbalance compensation for AMB systems with input delay: An output regulation approach ☆

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ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form
3 November 2015
Accepted 5 November 2015

Keywords:
Time delay
Output regulation
Unbalance compensation
Magnetic bearing
Vibration control

ABSTRACT

Unbalance compensation is an important technique for reducing rotor vibration in high speed rotating machines caused by residual rotor unbalance. As rotating machines in remote applications aim for higher speeds to gain efficiency and to reduce footprint, there is a need to extend the unbalance compensation techniques to active magnetic bearing (AMB) systems with delays in the control loop. This paper investigates the unbalance compensation problem for AMB systems with input delays. An unbalance compensation method is developed based on a solution to the output regulator problem for systems with input delay. The proposed unbalance compensation method is verified through simulation, and experimentally validated on an AMB test rig.

1. Introduction

Active magnetic bearings (AMBs) are electromagnetic actuators for rotating machines. AMBs have seen steady growth in popularity over the past decades, starting from small turbomolecular pumps to larger compressors in the megawatt range. Using the magnetic forces generated by electric coils acting on the conductive material in the shaft, the AMBs levitate the rotor within the clearance of the bearing to allow machines to operate without any mechanical contact between the static and the rotating components. As a result, the rotating machine operates more efficiently and at higher speeds with negligible frictional losses, and for longer periods of time without servicing (Schweitzer & Maslen, 2009). These capabilities are highly desirable for compressors, especially those in applications such as subsea oil and gas development, where the compressors are in harsh remote environments not easily accessible for frequent diagnosis and maintenance. Remote applications such as the subsea energy development have become technically and economically feasible with the availability of the AMB technology.

A technical challenge that needs to be addressed in the control of AMB systems in remotely operated compressors has to do with the communication delay introduced by the cabling system. Because the electronics driving the AMB actuators are sensitive to their environment, manufacturers many times choose to install the AMB control electronics at the control site, separated from the AMB actuators that are integrated to the remote machine. Long cables are then needed to connect the electronics to the actuators, which may add significant transmission delays in the control loop. Such delay may rapidly degrade the performance and stability of AMB systems, leading to undesired machine downtime, or even catastrophic machine failures. Therefore, the presence of input delays in the control of AMB systems needs to be explicitly addressed in the design of the rotor levitation controller.

The control of dynamic systems with time delay has been an active area of research. The predictor feedback control method is a popular approach among engineers and researchers for the control of systems with input delays. In this control method, a future state prediction is utilized in the computation of the control signal to cancel out the influence of the input delay. In other words, the delay system is transformed into an equivalent delay-free system by utilizing the state prediction in the control calculation. The majority of predictor feedback methods for linear systems are based on the Artstein model reduction technique (Artstein, 1982) and the finite spectrum assignment technique (Manitius & Olbrot, 1979). Many variations of the predictor feedback control method have been developed in the literature over the years (see, for example, Bresch-Pietri & Krstic, 2010; Krstic, 2010; Sharma, Bhasin, Wang, & Dixon, 2011). A finite dimensional predictor, which is obtained by truncating the equation of traditional predictors, was

☆This work was supported in part by the National Science Foundation under Grants CMMI-1129752 and CMMI-1462171.

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http://dx.doi.org/10.1016/j.conengprac.2015.11.002
0967-0661/

developed in Lin and Fang (2007) for linear systems with all poles in the closed left-half plane. The truncated predictor relies on the low gain feedback design (Lin, 1988) to ensure the stability of the closed-loop system. This finite dimensional predictor was later expanded in Zhou, Lin, and Duan (2012) to systems with time-varying delays, and in Yoon and Lin (2013) and Yoon, Anantachaisilp, and Lin (2013) to exponentially unstable systems.

High speed rotating machines are also susceptible to large disturbance forces caused by rotor unbalances. A residual unbalance on a rotor can generate disturbance forces synchronous to the rotating speed, causing the rotor to go into a whirling motion. To reduce the effect that the rotor unbalance has on high-speed AMB systems, unbalance compensation or autobalancing methods have been studied and developed over the years. When designed and implemented properly, these methods can significantly reduce the disturbance forces acting on the rotor by allowing it to spin about its center of mass. The interest on rotor unbalance methods has increased rapidly in recent years as high speed AMB applications become more common, and the accessibility to digital controllers makes complex control algorithms easily implementable. A small sample of the literature studying the unbalance compensation problem can be found in Herzog, Buhler, Gahler, and Larsonneur (1996), Setiawan, Mukherjee, and Maslen (2001, 2002); Bi, Wu, Jiang, and Liu (2005), Kuseyri (2012), Tang, Liu, Fang, and Ge (2013), Chen, Liu, and Zheng (2015) and the references therein. On the other hand, unbalance compensation methods have yet to be extended to AMB systems that are subjected to time delay.

This paper investigates an unbalance compensation problem for AMB systems with input delays. In particular, we derive and experimentally validate an unbalance compensation method based on the solution to an equivalent output regulation problem. Precise location and eccentricity of a rotor unbalance are difficult to measure in rotating machines. Instead, the locations of the unbalance forces in our mathematical model are strategically selected to reproduce the relevant rotor vibration patterns. The resulting model based unbalance compensation controller is demonstrated experimentally to significantly reduce the synchronous rotor vibrations and the magnitude of the AMB control input.

The remainder of this paper is structured as follows. The output regulation problem for systems with input delay is first introduced in Section 2, and solutions by both state-feedback and output-feedback are derived here. Next, the unbalance compensation problem for AMB systems is discussed in Section 3, and a control solution is proposed based on the output regulation method developed in Section 2. In Section 4 an AMB test rig with a flexible rotor is introduced. This test rig was constructed to reproduce the dynamics of AMB supported compressors commonly found in the oil and gas industry, and it will serve as the test platform for the unbalance compensation method proposed in this study. Simulation results for the disturbed AMB system with the proposed unbalance compensation method are presented in Section 5, and experimental results obtained from implementing the unbalance compensation method to the AMB test rig are presented in Section 6. Finally, concluding remarks are given in Section 7.

2. Output regulation for time delay system

Output regulation is one of the central problems in control theory. Its objective is to control the plant output such that it tracks a prescribed class of reference signals in the presence of disturbances. The reference signal to track in the output regulation problem, as well as the external disturbance input perturbing the system, is produced by an external generator known as the exosystem. The output regulation problem has been studied extensively since it was formulated by Francis (1977) for linear systems, and by Isidori and Byrnes (1990) for nonlinear systems. A comprehensive treatment of the nonlinear output regulation problem can be found in Byrnes and Isidori (2000), Huang (2004) and Lu and Huang (2015a).

A few works studying the output regulation problem for time delay systems can be found in the literature. The output regulation problem for systems with state delays was discussed in Castillo-Toledo and Núñez-Pérez (2003) and Wang, Wang, Shi, and Wang (2013), where the authors derive the necessary and sufficient conditions for the existence of a solution by employing a similar argument as presented in Francis (1977) for the delay-free case. In the nonlinear setting, Fridman (2003) extends the conditions for solvability of the output regulation problem to systems with state delays. For systems with input delay, Lu and Huang (2015b) introduce a robust solution to the output regulation problem. For linear time-invariant and continuous systems with delays in the states, inputs and outputs, the output regulation problem was studied in Lu and Huang (2014) and Yoon and Lin (2015).

2.1. Definition of the output regulation problem

Consider a linear time-invariant system with input delay,

$$\dot{x}(t) = Ax(t) + Bu(t-\tau) + \mathcal{P}w(t), \tag{1a}$$

$$y(t) = Cx(t), \tag{1b}$$

with state vector $x \in \mathbf{R}^n$, input vector $u \in \mathbf{R}^m$, output vector $y \in \mathbf{R}^r$, and input delay $\tau \geq 0$. The external disturbance $w \in \mathbf{R}^{2s}$ is generated by an exosystem

$$\dot{w}(t) = \mathcal{S}w(t). \tag{2}$$

In general, w could be of any dimension. However, its dimension has been restricted to an even number since the disturbances from the rotor unbalance forces to be considered are sinusoidal. In the output regulation problem studied in this paper, we wish to find a control law that regulates the error signal defined as

$$e(t) = Cx(t) + \mathcal{D}u(t-\tau) + \mathcal{Q}w(t). \tag{3}$$

Then, the objective of our control problem is to find a control law such that

1. the closed-loop system is asymptotically stable when $w \equiv 0$, and
2. for any arbitrary initial conditions of x and w, the error $e(t)$ approaches zero as $t \to \infty$.

Some standard assumptions are made on the system (1) that are required for the solvability of the output regulation problem.

Assumption 1. The eigenvalues of $\mathcal{S}$ have nonnegative real parts.

Assumption 2. The system (1) with $w \equiv 0$ is detectable and stabilizable.

Assumption 1 does not affect the generality of the problem since asymptotically stable eigenvalues of $\mathcal{S}$ do not affect the regulation of the output. Assumption 2 is required for the existence of a control law that asymptotically stabilizes system (1), when $w \equiv 0$.

2.2. Output regulation by state feedback

The following lemma provides a solution to the output regulator problem by state feedback, given that a stabilizing control law exists for the disturbance-free system.

Lemma 1. *Consider the time-delay system (1) satisfying*