

9-1-2006

Further results on active magnetic bearing control with input saturation

F. Mazenc
INRAE's Occitanie-Montpellier Centre

M. S. de Queiroz
Louisiana State University

M. Malisoff
Louisiana State University

F. Gao
Louisiana State University

Follow this and additional works at: https://repository.lsu.edu/mathematics_pubs

Recommended Citation

Mazenc, F., de Queiroz, M., Malisoff, M., & Gao, F. (2006). Further results on active magnetic bearing control with input saturation. *IEEE Transactions on Control Systems Technology*, 14 (5), 914-919. <https://doi.org/10.1109/TCST.2006.876910>

This Article is brought to you for free and open access by the Department of Mathematics at LSU Scholarly Repository. It has been accepted for inclusion in Faculty Publications by an authorized administrator of LSU Scholarly Repository. For more information, please contact ir@lsu.edu.

Further Results on Active Magnetic Bearing Control with Input Saturation*

F. Mazenc[†], M.S. de Queiroz[‡], M. Malisoff[§], and F. Gao[¶]

Abstract

We study the low-bias stabilization of active magnetic bearings (AMBs) subject to voltage saturation based on a recently proposed model for the AMB switching mode of operation. Using a forwarding-like approach, we construct a stabilizing controller of arbitrarily small amplitude and a control-Lyapunov function for the AMB dynamics. We illustrate our construction using a numerical example.

1 Introduction

Active magnetic bearings (AMBs) are being employed in a variety of rotating machines (e.g., compressors, milling spindles, and flywheels) in place of conventional mechanical bearings. Due to the non-contact nature of the magnetic bearings and rotor, AMBs have the unique ability to suspend loads with no friction, operate rotors at higher speeds, and operate in applications where the use of lubricants is prohibited. Since AMBs can be actively controlled, they offer other potential advantages over mechanical bearings, viz., the elimination of vibration through active damping, the adjustment of the stiffness of the suspended load, and the automatic balancing of rotors. AMBs are normally operated with all electromagnets active at all times. An alternative mode of operation is to activate only one electromagnet along each direction at any given time. Although posing more difficulty to the control design, this switching operation prevents opposing electromagnets from producing counteracting forces, and thus helps reduce power consumption.

Typically, an AMB is operated by introducing a sufficiently high, fixed magnetic flux in each electromagnet, which is referred to as the *bias flux*. The bias value is normally set to a fraction of the saturation flux of the electromagnet. This procedure facilitates the design of the AMB ‘control’ flux, which is superimposed on the bias flux. Specifically, this conservative practice allows the system to be modeled by a controllable linear system, thus, enabling the use of linear control design techniques; see for example [1, 7, 9]. Although the bias flux facilitates the control synthesis, it increases electric power losses in the AMB system, causing rotor heating and affecting the machine efficiency. While lowering or eliminating the bias flux is desirable in order to minimize power losses, it enhances the AMB system nonlinearities and may lead to a control saturation¹ or singularity. Due to these conflicting objectives, the design of AMB controllers with reduced power loss is a challenging problem.

In this paper, we consider the problem of low-bias² control of AMBs operating in the switching mode with the constraint that the input voltages are amplitude limited. This problem was previously addressed in [15, 16] using the nested saturation design method of Teel [13, 14]. In addition, an optimal solution was sought to the power-loss minimization problem under voltage saturation in [2]. (A comprehensive literature review of low-, asymptotic-zero-, and zero-bias AMB controllers *without* voltage saturation can be found in [10, 17].) Here, we pursue a different approach to stabilizing the AMB model of [16]. Namely, we use a *forwarding-like* method [8] to design a control law of arbitrarily small amplitude that renders the AMB system globally asymptotically stable (GAS) to the origin. The

*This work was supported in part by NSF grants DMS-0424011 and CMS-0447576.

[†]*Mazenc* is with the Projet MERE INRIA-INRA; UMR Analyse des Systèmes et Biométrie INRA; 2, pl. Viala; 34060 Montpellier, France; Frederic.Mazenc@ensam.inra.fr.

[‡]*de Queiroz* is with the Department of Mechanical Engineering, Louisiana State University, Baton Rouge, LA 70803-6413, de-queiroz@me.lsu.edu. (Corresponding author)

[§]*Malisoff* is with the Department of Mathematics, Louisiana State University, Baton Rouge, LA 70803-4918, malisoff@lsu.edu.

[¶]*Gao* is with the Department of Mechanical Engineering, Louisiana State University, Baton Rouge, LA 70803-6413, fgao1@lsu.edu.

¹Saturation may arise due to limits on the amplitude of the output voltage of the power amplifier driving the electromagnets.

²By *low bias*, we mean an AMB control law where the bias can be set to an arbitrarily small positive constant without affecting the system stability.

main differences between our approach and [16] are: (i) we allow the use of different saturation functions (both ‘hard’ and ‘soft’), thus providing more flexibility in the control implementation, and (ii) we provide an explicit construction for a ‘global’ control Lyapunov function (CLF) for the system. This contrasts with the result of [16], which relies on the standard ‘hard’ saturation and whose Lyapunov-like function is only an ‘asymptotic’ CLF for the system, i.e., a CLF only when the system operates in a certain region of the state space.

The rest of this paper is organized as follows. In Section 2, we introduce the AMB model and motivate our stabilization problem. In Section 3, we prove a lemma that constructs a stabilizing controller of arbitrarily small amplitude and a CLF for a three-dimensional chain of integrators. In Section 4, we use our lemma to construct a CLF and corresponding stabilizing feedback for the AMB model. We provide a numerical example in Section 5, and we close in Section 6 with a summary of our work.

2 AMB Model and Problem Statement

The original nonlinear electromechanical model of the one degree-of-freedom AMB system shown in Figure 1 below can be subdivided into the mechanical subsystem dynamics, the magnetic force equation, and the electrical subsystem dynamics. The mechanical subsystem is governed by

$$m\ddot{y} = \sum_{i=1}^2 F_i(\Phi_i), \quad (1)$$

where m is the rotor mass, $y \in \mathbb{R}$ represents the position of the rotor center, $\Phi_i \in \mathbb{R}$ is the magnetic flux in the i th electromagnet, $F_i(\Phi_i) \in \mathbb{R}$ denotes the force produced by the i th electromagnet, given by [18]

$$F_i = \frac{(-1)^{i+1} \Phi_i^2}{\mu_0 A}, \quad i = 1, 2, \quad (2)$$

μ_0 is the permeability of air, and A is the cross-sectional area of the electromagnet. The electrical subsystem is governed by the equations [18]

$$N\dot{\Phi}_i + R_i I_i = v_i, \quad i = 1, 2, \quad (3)$$

where N denotes the number of coil turns in the electromagnet, R_i is the resistance of the i th electromagnet coil, $v_i \in \mathbb{R}$ is the input control voltage of the i th electromagnet, $I_i \in \mathbb{R}$ is the current in the i th electromagnet which is related to the flux according to [18]

$$I_i = \frac{2(g_0 + (-1)^i y) \Phi_i}{\mu_0 AN}, \quad i = 1, 2, \quad (4)$$

and g_0 is the nominal air gap.

In this paper, we use the new form proposed in [16, 17] for the AMB dynamics in the switching mode of operation. We only outline the model derivation here, and refer the reader to [17] for the details and justification. Consider that the flux is given by

$$\Phi_i = \Phi_0 + \phi_i, \quad i = 1, 2, \quad (5)$$

where $\Phi_0 > 0$ is the constant *bias* flux and ϕ_i is the *control* flux. Let the *generalized* control flux be defined as

$$\phi = \phi_1 - \phi_2, \quad (6)$$

and consider the voltage switching strategy

$$\begin{aligned} v_1 = v, \quad v_2 = 0 & \quad \text{if } \phi \geq 0 \\ v_1 = 0, \quad v_2 = -v & \quad \text{if } \phi < 0 \end{aligned} \quad (7)$$

where v is the *generalized* control voltage. Based on (5)-(7), the AMB model (1)-(3) has the equivalent form

$$\ddot{y} = \frac{1}{m\mu_0 A} (2\bar{\Phi}_0 \phi + \phi |\phi|), \quad \dot{\phi} = \frac{v}{N}, \quad (8)$$

where $\bar{\Phi}_0 = \Phi_0 + \min \{\phi_1(0), \phi_2(0)\}$ and the coil resistance was neglected for simplicity.

Now, consider that the input voltages to the original AMB model are amplitude limited, i.e., $|v_i| \leq v_{\max}$, $i = 1, 2$ where v_{\max} is the known limit. Defining the states $x_1 = y$, $x_2 = \dot{y}$, and $x_3 = \phi$ and the change of input $v = Nu$, the above model becomes

$$\dot{x}_1 = x_2, \quad \dot{x}_2 = \beta_0 x_3 + \beta_1 x_3 |x_3|, \quad \dot{x}_3 = u, \quad (9)$$

where $\beta_0 = 2\bar{\Phi}_0/(m\mu_0 A)$ and $\beta_1 = 1/(m\mu_0 A)$, with the input constraint $|u| \leq v_{\max}/N$.

Our goal in this work is to design a feedback control law $u(x)$, satisfying the above saturation constraint, such that $x = 0$ is GAS where $x = (x_1, x_2, x_3)^\top$. The GAS property means there is a continuously differentiable (C^1) function $V : \mathbb{R}^3 \rightarrow [0, \infty)$ that is radially unbounded and zero only at the origin, and for which the derivative \dot{V} along all trajectories of the system in closed-loop with the controller $u(x)$ is negative definite. A function V satisfying these requirements for some feedback $u(x)$ is called a CLF for (9) [5]. See [17] for a discussion on the relation between the global asymptotic stability of x and the stability of the original AMB states.

3 Preliminary Result

In the following lemma, we use a forwarding-like approach based on [8] to construct a CLF and corresponding stabilizing state feedback of arbitrarily small amplitude for a three-dimensional chain of integrators. We let σ denote the standard saturation projecting \mathbb{R} onto $[-1, +1]$, i.e., $\sigma(s) = s$ when $|s| \leq 1$ and $\sigma(s) = \text{sign}(s)$ otherwise. However, see Remark 1 below for a version of our construction where the hard saturation σ is replaced by a smoother function.

Lemma 1 Consider the chain of integrators

$$\dot{\xi}_1 = \xi_2, \quad \dot{\xi}_2 = \xi_3, \quad \dot{\xi}_3 = \mu, \quad (10)$$

where $\mu \in \mathbb{R}$ is the control input. Let $c_1, c_2 > 0$ be given and

$$\delta \leq \min \left\{ \frac{4}{3}, c_1 \right\}. \quad (11)$$

Define the change of variables

$$z_1 = \delta(c_1 \xi_1 + \xi_2) + \frac{\delta}{c_1} \xi_3, \quad z_2 = c_1 \xi_2 + \xi_3, \quad z_3 = \xi_3 \quad (12)$$

and the functions

$$U(z_2, z_3) = \frac{1}{2} z_3^2 + \int_0^{z_2} \sigma(s) ds \quad (13)$$

$$g(z_1, z_2, z_3) = \frac{\delta}{c_1} \sigma(z_1) + 4(1 + U(z_2, z_3)) \times (z_3 + \sigma(z_2)) - \frac{\delta}{2} (z_2 + z_3). \quad (14)$$

Then the function

$$V(\xi_1, \xi_2, \xi_3) = 4U(z_2, z_3) + 2U^2(z_2, z_3) - \frac{\delta}{2} z_2 z_3 + \int_0^{z_1} \sigma(s) ds \quad (15)$$

is a CLF for (10) since its derivative along the trajectories of system (10) in closed loop with the control

$$\mu(\xi_1, \xi_2, \xi_3) = -c_1 \sigma(z_2) - c_2 \sigma(g(z_1, z_2, z_3)) \quad (16)$$

is negative definite. In particular, the bounded control (16) renders (10) GAS to the origin.

Remark 2 The saturation function σ from Lemma 1 is Lipschitz continuous but not continuously differentiable. We chose this hard saturation for simplicity of analysis. However, one can prove a similar result with smoother saturation functions. For example, if one instead chooses the C^1 function

$$\sigma(s) = \begin{cases} s & \text{if } |s| \leq 1 \\ \text{sign}(s) \left[1 + \frac{1}{\pi} \tan^{-1}(\pi(|s| - 1)) \right] & \text{if } |s| > 1, \end{cases}$$

then the only change in the statement of Lemma 1 is to the right-hand side of the inequality (11). The proof for this saturation is similar to the proof we give below.

Remark 3 Condition (11) in Lemma 1 allows cases where c_1 is arbitrarily large and δ is as small as desired, as well as cases where $\max\{c_1, c_2, \delta\}$ is arbitrarily small, including the case where $c_1 = c_2 = \delta \in (0, 4/3]$.

Proof. We use (12) and $\mu = -c_1\sigma(z_2) + \alpha$, where α is the new control input, to transform (10) into

$$\begin{aligned} \dot{z}_1 &= \delta(z_2 - \sigma(z_2)) + \frac{\delta}{c_1}\alpha \\ \dot{z}_2 &= c_1 z_3 - c_1 \sigma(z_2) + \alpha \\ \dot{z}_3 &= -c_1 \sigma(z_2) + \alpha. \end{aligned} \tag{17}$$

We first perform a Lyapunov-type analysis on the (z_2, z_3) -subsystem using the function

$$V_1(z_2, z_3) = 4U(z_2, z_3) + 2U^2(z_2, z_3) - \frac{\delta}{2}z_2 z_3, \tag{18}$$

where $U(z_2, z_3)$ was defined in (13). By separately considering the cases where $|z_2| > 1$ and $|z_2| \leq 1$, one can easily verify that (18) is positive-definite and radially unbounded for $\delta < 2$. In fact, if $|z_2| \leq 1$, then

$$\begin{aligned} V_1(z_2, z_3) &\geq 4U(z_2, z_3) - |z_2 z_3| \geq 2z_3^2 + 2z_2^2 - |z_2 z_3| \\ &\geq \frac{3}{2}(z_2^2 + z_3^2). \end{aligned} \tag{19}$$

On the other hand, if $|z_2| > 1$, then $\int_0^{z_2} \sigma(s) ds = 1/2 + (|z_2| - 1) \geq |z_2|/2$, so

$$\begin{aligned} V_1(z_2, z_3) &\geq 4 \left(\frac{1}{2}z_3^2 + \frac{1}{2}|z_2| \right) + 2 \left(\frac{1}{2}z_3^2 + \frac{1}{2}|z_2| \right)^2 \\ &\quad - |z_2 z_3| \\ &\geq 2z_3^2 + 2|z_2| + \frac{1}{2}z_2^2 - |z_2 z_3| \geq \frac{3}{2}z_3^2 \\ &\quad + 2|z_2|. \end{aligned} \tag{20}$$

The time derivative of (18) along the trajectories of the (z_2, z_3) -subsystem is given by

$$\begin{aligned} \dot{V}_1 &= 4(1 + U(z_2, z_3))(-c_1\sigma^2(z_2) + (z_3 + \sigma(z_2))\alpha) \\ &\quad - \frac{\delta}{2}(c_1 z_3 - c_1 \sigma(z_2) + \alpha) z_3 \\ &\quad - \frac{\delta}{2}z_2(-c_1 \sigma(z_2) + \alpha) \\ &= -4c_1(1 + U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{2}z_3^2 \\ &\quad + \frac{\delta c_1}{2}\sigma(z_2)z_3 + \frac{\delta c_1}{2}z_2\sigma(z_2) \\ &\quad + [4(1 + U(z_2, z_3))(z_3 + \sigma(z_2)) \\ &\quad - \frac{\delta}{2}z_3 - \frac{\delta}{2}z_2] \alpha. \end{aligned} \tag{21}$$

Since $|\sigma(z_2)| \leq |z_2|$ and $|z_2\sigma(z_2)| = z_2\sigma(z_2)$ give

$$-\frac{1}{4}z_3^2 + \frac{1}{2}\sigma(z_2)z_3 \leq \frac{1}{4}\sigma^2(z_2) \leq \frac{1}{4}z_2\sigma(z_2), \quad (22)$$

(21) becomes

$$\begin{aligned} \dot{V}_1 &\leq -4c_1(1+U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad + \frac{3}{4}\delta c_1 z_2\sigma(z_2) \\ &\quad + [4(1+U(z_2, z_3))(z_3 + \sigma(z_2)) \\ &\quad - \frac{\delta}{2}z_3 - \frac{\delta}{2}z_2] \alpha. \end{aligned} \quad (23)$$

We now distinguish between two cases:

1. $|z_2| \leq 1$. Then $\sigma(z_2) = z_2$, $z_2\sigma(z_2) = \sigma^2(z_2)$, and since $\delta \leq 4/3$, we get

$$\begin{aligned} \dot{V}_1 &\leq -3c_1(1+U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad + [4(1+U(z_2, z_3))(z_3 + \sigma(z_2)) \\ &\quad - \frac{\delta}{2}z_3 - \frac{\delta}{2}z_2] \alpha. \end{aligned} \quad (24)$$

2. $|z_2| > 1$. Then $\sigma(z_2) = \text{sign}(z_2)$, $z_2\sigma(z_2) = |z_2|$, and

$$\begin{aligned} (1+U(z_2, z_3))\sigma^2(z_2) &\geq 1 + \int_0^{z_2} \sigma(s)ds \\ &\geq 1 + \int_0^{\text{sign}(z_2)} sds + \int_{\text{sign}(z_2)}^{z_2} \sigma(s)ds \\ &= 1 + \int_0^{\text{sign}(z_2)} sds + \text{sign}(z_2) \int_{\text{sign}(z_2)}^{z_2} ds \\ &= \frac{1}{2} + |z_2|. \end{aligned} \quad (25)$$

Since $\delta \leq 4/3$, applying (25) to (23) again yields (24). Thus (24) holds for all z_2 .

Finally, we perform a Lyapunov-type analysis on the whole system (17) using the positive definite radially unbounded function V from (15). Since $V(z_1, z_2, z_3) = V_1(z_2, z_3) + \int_0^{z_1} \sigma(s)ds$, where $V_1(z_2, z_3)$ was defined in (18), it follows from (24) that the time derivative of (15) along the system trajectories satisfies

$$\begin{aligned} \dot{V} &\leq -3c_1(1+U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad + \delta|z_2 - \sigma(z_2)| \\ &\quad + \left[\frac{\delta}{c_1}\sigma(z_1) + 4(1+U(z_2, z_3))(z_3 + \sigma(z_2)) \right. \\ &\quad \left. - \frac{\delta}{2}z_3 - \frac{\delta}{2}z_2 \right] \alpha. \end{aligned} \quad (26)$$

We again distinguish between two cases:

1. $|z_2| \leq 1$. Then $z_2 - \sigma(z_2) = 0$, so (26) gives

$$\begin{aligned} \dot{V} &\leq -2c_1(1+U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad + \left[\frac{\delta}{c_1}\sigma(z_1) + 4(1+U(z_2, z_3)) \right. \\ &\quad \left. \times (z_3 + \sigma(z_2)) - \frac{\delta}{2}z_3 - \frac{\delta}{2}z_2 \right] \alpha. \end{aligned} \quad (27)$$

2. $|z_2| > 1$. Then (25) holds and since $|z_2 - \sigma(z_2)| \leq |z_2|$ and $\delta \leq c_1$, we again get (27).

Thus, (27) holds for all z_2 . Using $\alpha = -c_2\sigma(g(z_1, z_2, z_3))$ and (14), (27) becomes

$$\begin{aligned} \dot{V} &\leq -2c_1(1 + U(z_2, z_3))\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad - c_2\sigma(g(z_1, z_2, z_3))g(z_1, z_2, z_3) \\ &\leq -2c_1\sigma^2(z_2) - \frac{\delta c_1}{4}z_3^2 \\ &\quad - c_2\sigma^2(g(z_1, z_2, z_3)) \end{aligned} \quad (28)$$

by separately considering the cases $|g| \geq 1$ and $|g| < 1$, i.e., \dot{V} is negative definite. One can easily verify that the origin is a unique equilibrium point of (17) in closed loop with $\alpha = -c_2\sigma(g(z_1, z_2, z_3))$. Thus, $(z_1, z_2, z_3) = 0$ is GAS [3]. It follows from (12) that $(\xi_1, \xi_2, \xi_3) = 0$ is GAS, and that (15) is a CLF for (10).

4 Main Result

We are now ready to state our main result on the global asymptotic stabilization of (9) with control saturation.

Theorem 4 The control law

$$u(x) = \frac{\mu(x_1, x_2, X_3)}{\beta_0 + 2\beta_1|x_3|}, \quad (29)$$

where $\mu(\cdot)$ was defined in (16) and

$$X_3 = \beta_0 x_3 + \beta_1 x_3 |x_3|, \quad (30)$$

in closed loop with (9) ensures $x = 0$ is GAS, and has arbitrarily small amplitude. Moreover, with the choice (15), the function $x \mapsto V(x_1, x_2, X_3)$ is a CLF for (9).

Proof. We use the change of variable (30) and the change of input (29) to transform (9) into the chain of integrators

$$\dot{x}_1 = x_2, \quad \dot{x}_2 = X_3, \quad \dot{X}_3 = \mu. \quad (31)$$

After setting μ to (16) with $\xi_1 = x_1$, $\xi_2 = x_2$, and $\xi_3 = X_3$, we can invoke Lemma 1 to conclude $(x_1, x_2, X_3) = 0$ is GAS for (31). It then follows from (30) that $x = 0$ is GAS for the system (9) in closed loop with the feedback (29)-(30). The fact that $x \mapsto V(x_1, x_2, X_3)$ is a CLF for the AMB dynamics follows from the proof of Lemma 1.

Remark 5 Notice that the control law (29) has arbitrarily small amplitude since along the closed-loop trajectories,

$$|u(x(t))| \leq \frac{|\mu(x(t))|}{\beta_0} \leq \frac{c_1 + c_2}{\beta_0} \quad \forall t \geq 0. \quad (32)$$

Thus, one can choose c_1, c_2 such that

$$c_1 + c_2 \leq \frac{\beta_0 v_{\max}}{N} \quad (33)$$

to ensure the AMB voltages satisfy the voltage constraint $|v_i(t)| \leq v_{\max}$, $i = 1, 2 \forall t \geq 0$. From (33), one can also see that the control gains can be adjusted to accommodate sufficiently small bias levels due to the direct dependency of β_0 on the bias flux Φ_0 (i.e., a low-bias control). However, one cannot set $\Phi_0 = 0$ since the control may have a singularity.

Remark 6 It is worth comparing our construction from Theorem 4 with the AMB controller from Section VI of [16], where the stabilizing controller took the form of nested hard saturations. In [16], the proof that the control stabilizes the AMB system is based on the method of [13], which uses the hardness of the saturation σ in an essential way. The argument shows that the nested hard saturations cause the AMB dynamics (9) to assume a simplified form after sufficiently large time. Then one shows that this new system of ‘asymptotic’ equations is GAS using a Lyapunov-like analysis. Unfortunately, the Lyapunov function used in the analysis of [16] is not a CLF for the AMB dynamics (9). On the other hand, our construction is not restricted to the standard hard saturation as explained in Remark 1, and thus can lead to smoother stabilizing controllers. Also, the Lyapunov function from Theorem 4 is negative definite along the closed-loop AMB trajectories with the feedback (29) for all time, and thus is a CLF for the AMB dynamics (9).

Remark 7 Knowing a global CLF $V(x)$ and corresponding globally stabilizing feedback $u(x)$ for the AMB dynamics, we can construct a feedback $K(x)$ that renders the system input-to-state stable (ISS) to exogenous disturbances [11]. Choosing $V(x)$ and $u(x)$ from our theorem, and letting $\dot{x} = F(x, u)$ denote the open-loop AMB dynamics, it follows from [9, Theorem 1] that the system $\dot{x} = F(x, K(x) + d)$ is ISS relative to any measurable locally essentially bounded (e.g., locally bounded piecewise continuous), exogenous disturbance $d(t)$ under the combined feedback $K(x) = u(x) - \partial V(x)/\partial x_3$. This is because the term $\partial V(x)/\partial x_3$ in the feedback is the Lie derivative of V in the direction of the constant vector field $x \mapsto (0, 0, 1)^\top$ that multiplies the input in the AMB dynamics. Note that in this case the feedback $K(x)$ is not necessarily saturated. This is because if $K(x)$ were any saturated feedback rendering $\dot{x} = F(x, d)$ ISS, and if \bar{K} were a positive global bound on $K(x)$, then the third component of the dynamic $\dot{x}_3 = K(x) + d$ would have unbounded trajectories when the disturbance is for example $d(t) \equiv 2\bar{K}$, thus violating the ISS requirement. Hence, there is no globally saturated feedback that renders the AMB dynamics ISS to exogenous disturbances. Moreover, the CLF allows us to construct a feedback $\tilde{K}(x)$ rendering the noisy system $\dot{x} = F(x, \tilde{K}(x + e) + d)$ ISS with respect to the disturbance d for small measurement errors $e(t)$ in the controller [12]. In the context of AMBs, d could represent rotor unbalance or vibrations transmitted through the bearing foundation while e could represent inaccuracies in sensing displacement, velocity, and/or flux.

5 Numerical Example

The proposed control law from Theorem 4 above was simulated on the same high-fidelity model of the one degree-of-freedom magnetic levitation system [4, 6] used in [16]. The model includes flux leakage, magnetic material saturation, coil resistance, voltage saturation, and flexible modes, and thus is a fairly accurate representation of the actual system test rig [6]. We refer the reader to [6] for a complete description of the system model.

As in [16], the system was simulated with $\Phi_0 = 10 \mu\text{Wb}$, $v_{\max} = 10 \text{ V}$, and initial conditions set to $y(0) = 0.15 \text{ mrad}$, $\dot{y}(0) = 0 \text{ mrad/s}$, $\Phi_1(0) = 20 \mu\text{Wb}$, and $\Phi_2(0) = 60 \mu\text{Wb}$. The above flux values are for the *total* flux in the magnetic levitation system, i.e., including gap flux and flux leakage. The control parameters c_1, c_2, δ were selected according to (33) and (11) to yield the fastest convergence possible for the state y . This resulted in the following parameter values: $c_1 = 5465$, $c_2 = 5300$, and $\delta = 4/3$. The simulation results for the system states y, \dot{y} , and Φ_{gi} ($i = 1, 2$), and for the control voltages v_i ($i = 1, 2$) are shown in Figure 2 below, where Φ_{gi} denotes the gap flux. When compared with the simulation of the controller from Section VI of [16] (see Figure 8 of [16]), the our control yields similar closed-loop performance although it can be tuned to produce a faster response as seen from Figure 2.

6 Conclusion

We constructed a stabilizing controller and control-Lyapunov function for low-bias active magnetic bearings (AMBs) with voltage saturation. The AMB dynamics used in the construction is borrowed from a recently-developed model for AMBs operating with only one electromagnet active at any given time. Our construction is based on a new forwarding-like approach to stabilizing a three-dimensional chain of integrators with input saturation. The proposed AMB control law has arbitrarily small amplitude and the flexibility of being implemented with different saturation-like functions.

References

- [1] M. Fujita, K. Hatake, and F. Matsumura, "Loop Shaping Based Robust Control of a Magnetic Bearing," *IEEE Control Syst. Mag.*, Vol. 13, No. 4, pp. 57-65, 1993.
- [2] T. Hu, Z. Lin, and P.E. Allaire, "Power-Loss Minimization in Magnetic Bearing Systems," *Proc. IEEE Conf. Decision and Control*, pp. 854-859, Las Vegas, NV, 2002.
- [3] H. Khalil, *Nonlinear Systems*, Upper Saddle River, NJ: Prentice Hall, 2002.
- [4] C. Knospe, "The Nonlinear Control Benchmark System," *Proc. American Control Conf.*, pp. 2134-2138, Chicago, IL, 2000.
- [5] M. Krstic, I. Kanellakopoulos, and P. Kokotovic, *Nonlinear and Adaptive Control Design*, New York, NY: John Wiley & Sons, 1995.

- [6] J.D. Lindlau, *Dynamic Force Biasing of Active Magnetic Bearings via Feedback Linearization*, M.S. Thesis, University of Virginia, 1999.
- [7] F. Matsumura and T. Yoshimoto, "System Modeling and Control Design of a Horizontal-Shaft Magnetic-Bearing System," *IEEE Trans. Magnetics*, Vol. MAG-22, No. 3, 1986.
- [8] F. Mazenc and L. Praly, "Adding Integrations, Saturated Controls, and Stabilization for Feedforward Systems," *IEEE Trans. Automatic Control*, Vol. 41, No.11, pp. 1559-1578, 1996.
- [9] A.M. Mohamed and F.P. Emad, "Conical Magnetic Bearings with Radial and Thrust Control," *IEEE Trans. Automatic Control*, Vol. 37, No. 12, pp. 1859-1868, 1992.
- [10] N. Motee and M.S. de Queiroz, "A Switching Control Strategy for Magnetic Bearings with a State-Dependent Bias," *Proc. IEEE Conf. Decision and Control*, pp. 245-250, Maui, HI, 2003.
- [11] E.D. Sontag, "Input-to-State Stability: Basic Concepts and Results," in *Nonlinear and Optimal Control Theory*, Springer Lecture Notes in Mathematics, to appear, <http://www.math.rutgers.edu/~sontag/papers.html>.
- [12] E.D. Sontag, "Clocks and Insensitivity to Small Measurement Errors," *ESAIM: Control, Optimisation, and Calculus of Variations*, Vol. 4, pp. 537-557, 1999.
- [13] A. Teel, "Using Saturation to Stabilize a Class of Single-Input Partially Linear Composite Systems," *Proc. IFAC Nonlinear Control Systems Design Symp.*, pp. 224-229, Bordeaux, France, 1992.
- [14] A. Teel, "A Nonlinear Small Gain Theorem for the Analysis of Control Systems with Saturation," *IEEE Trans. Automatic Control*, Vol. 41, No. 9, pp. 1256-1270, 1996.
- [15] P. Tsiotras and E. Velenis, "Low-Bias Control of AMB's Subject to Saturation Constraints," *Proc. IEEE Conf. Control Appl.*, pp. 138-143, Anchorage, AK, 2000.
- [16] P. Tsiotras and M. Arcak, "Low-Bias Control of AMB Subject to Voltage Saturation: State-Feedback and Observer Designs," *IEEE Trans. Control Syst. Tech.*, Vol. 13, No. 2, pp 262-273, 2005.
- [17] P. Tsiotras and B.C. Wilson, "Zero and Low-Bias Control Designs for Active Magnetic Bearings," *IEEE Trans. Control Syst. Tech.*, Vol. 11, No. 6, pp 889-904, 2003.
- [18] H.H. Woodson and J.R. Melcher, *Electromechanical Dynamics - Part I: Discrete Systems*, New York, NY: John Wiley & Sons, 1968.

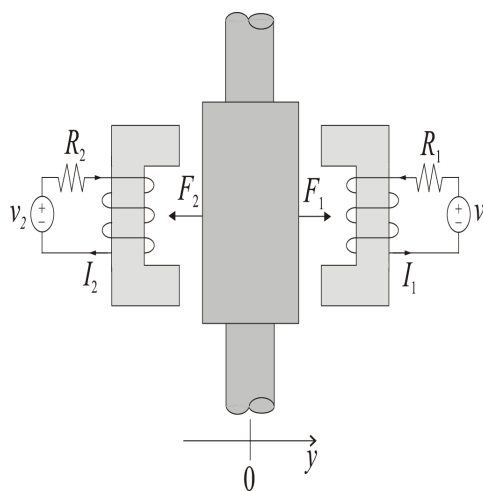


Figure 1: Schematic of the AMB system.

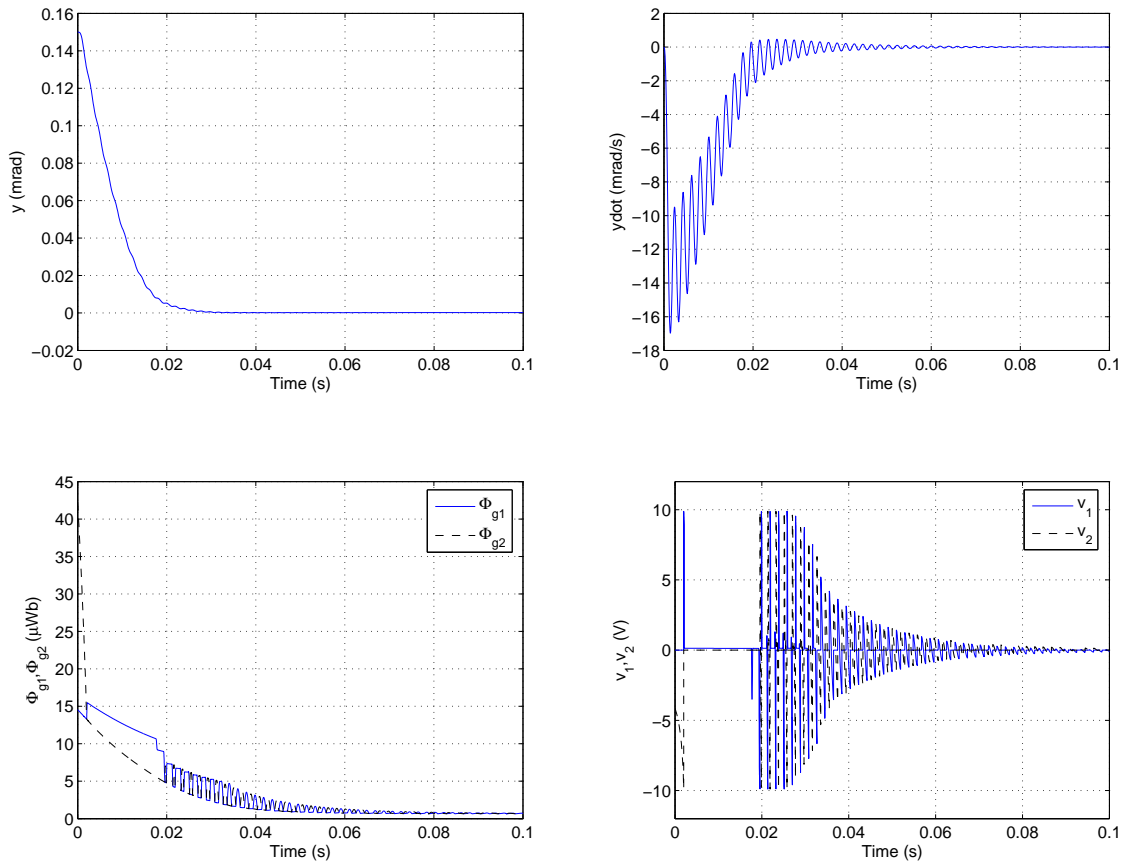


Figure 2: State trajectories and control voltages.