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ACTIVE MAGTNETIC BEARING CONTROL WITH ZERO STEADY-STATE POWER LOSS

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ABSTRACT

Active magnetic bearings (AMBs) are experiencing an increased use in many rotating machinery applications (e.g., compressors, milling spindles, flywheels, etc.) as an alternative to 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 at higher speeds, and operate under environmental constraints that prohibit the use of lubrication. Furthermore, since AMBs can be actively controlled, they offer other potential advantages over conventional mechanical bearings, such as eliminating vibration through active damping, adjusting the stiffness of the suspending load, or providing an automatic rotor balancing capability. See [3] and the references therein for previous work on AMB control. Typically, an AMB is operated by introducing a "high", constant *bias magnetic flux* (or electrical current) in each electromagnet. This conservative practice allows the system to be modeled by a controllable linear system, thus, facilitating the application of standard linear control design techniques (see, for example, [2,6]). On the other hand, the bias flux increases coil and journal power losses which may cause rotor heating and affect the machine efficiency [4]. For example, ohmic (i.e., coil) losses, which arise from the flow of current in the electromagnet coils, are proportional to square of the flux. While lowering or eliminating the bias flux will result in reduced ohmic power losses, it will also enhance the AMB nonlinearities and may lead to a control singularity as was shown in [7]. As is clear from this discussion, the design of AMB controllers that reduce ohmic power losses is a challenging problem. Constant low-bias nonlinear controllers using the integrator backstepping technique were proposed in [7,8] with no discussion about their implication on power losses. In [4], a gain-scheduled linear controller was developed with a low bias current. A low-bias control scheme was recently proposed in [11] using the small-gain theorem. Zero-bias control approaches can be found in [1,5,12]. Unfortunately, these zero-bias results have the common drawback of potentially producing unbounded voltage control inputs. In this paper, we propose a solution to the problem of AMB control with reduced ohmic power losses. Specifically, our goal is to design a control law with the following three attributes: regulates the rotor position to zero, eliminates the steady-state bias flux, and contains no control singularities. The starting point for the proposed control law is the low-bias nonlinear control structure presented in [7]. We modify the controller of [7] by introducing a time-varying bias flux in the form of an *exponentially decaying* function. In the steady state, this will produce zero bias flux, and hence, reduce the ohmic power losses. The proposed controller is shown to ensure the exponential stability of the closed-loop system with the rate of convergence dependent on control gains. This fact facilitates the avoidance of control singularities by allowing us to force the rotor position and velocity to converge to zero faster than the bias flux. The basic premise behind the proposed control/bias flux design can be physically explained as follows. After the rotor is centered in the bearing system, there is no need for the AMB electromagnets to apply forces on the rotor; thus, the electromagnets can be de-energized by turning off the bias flux. We will address the above-described control problem for two different modes of operation of the AMB system. Initially, we consider the standard AMB mode of operation where all electromagnets are active at any given time. We will refer to this operating mode as "full-flux" (FF). Next, we will consider the mode of operation commonly known as "complementary-flux" (CF) [12] where only one electromagnet along each direction is active at any given time. As explained in [12], this reduces the total flux in the AMB system (and hence, helps reduce the ohmic power losses) since the electromagnets do not produce counteracting forces. Unlike what is normally presented in the literature, we provide a rigorous treatment of the CF mode of operation inclusive of a stability analysis, switching strategy, and circuit implementation

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REFERENCES

1. Charara and B. Caron, "Magnetic Bearings: Comparison Between Linear and Nonlinear Functioning," *Proc. Int. Symp. Magnetic Bearings*, pp. 451-460, Alexandria, VA, Jul. 1992.M
2. . 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, Aug. 1993
3. IEEE Transactions on Control Systems Technology, *Special Issue on Magnetic Bearing Control*, Vol. 4, No. 5, Sept. 1996
4. C. Knospe and C. Yang, "Gain-Scheduled Control of a Magnetic Bearing with Low Bias Flux," *Proc. Conf. Decision and Control*, pp. 418-423, San Diego, CA, Dec. 1997
5. J. Levine, J. Lottin, and J.-C. Ponsart, "A Nonlinear Approach to the Control of Magnetic Bearings," *IEEE Trans. Control Syst. Tech*., Vol. 4, No. 5, pp. 524-544, Sept. 1996.
6. 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, Dec. 1992
7. M.S. de Queiroz and D.M. Dawson, "Nonlinear Control of Active Magnetic Bearings: A Backstepping Approach," *IEEE Trans. Control Syst. Tech*., Vol. 4, No. 5, pp. 545-552, Sept. 1996
8. M.S. de Queiroz, D.M. Dawson, and H. Canbolat, "A Backstepping-Type Controller for a 6-DOF Magnetic Bearing System," *Proc. IEEE Conf. Decision and Control*, pp. 3370-3375, Kobe, Japan, Dec. 1996
9. M.S. de Queiroz, D.M. Dawson, S. Nagarkatti, and F. Zhang, *Lyapunov-Based Control of Mechanical Systems*, Cambridge, MA: Birkhauser, 2000
10. J. Slotine and W. Li, *Applied Nonlinear Control*, Englewood Cliff, NJ: Prentice Hall Co., 1991
11. Tsiotras and E. Velenis, "Low-Bias Control of AMB's Subject to Saturation Constraints," *Proc. IEEE Conf. Control Appl*., pp. 138-143, Ancorage, AK, Sept. 2000
12. P. Tsiotras, B. Wilson, and R. Bartlett, "Control of a Zero-Bias Magnetic Bearing Using Control Lyapunov Functions," *Proc. IEEE Conf. Decision and Control*, pp. 4048-4053, Sydney, Australia, Dec. 2000
13. H.H. Woodson and J.R. Melcher, *Electromechanical Dynamics - Part I: Discrete Systems*, New York, NY: John Wiley & Sons, 1968.