Guest Editorial

Introduction to the Special Issue on Magnetic Bearing Control

An active magnetic bearing (AMB) is a collection of electromagnets used to suspend an object via feedback control. The obvious feature of AMB's is noncontact motion control, which offers many advantages and opportunities for a wide variety of industrial, medical, and scientific applications. AMB applications often require solution of very interesting and formidable control problems. The 12 papers comprising this issue provide a broad survey of the challenges presented by this exciting technology and explore interesting directions for meeting these challenges. We hope that these papers will provide the reader with an introduction to and an appreciation of this dynamic field. For those new to AMB's, a brief discussion of the applications and current trends is presented in this introduction.

Traditionally, the term *magnetic bearing* has referred to devices for the suspension of a rotor. Commercial applications include pumps, compressors, flywheels, milling and grinding spindles, turbine engines, and centrifuges. Magnetic suspension offers a number of practical advantages over conventional bearings such as lower rotating losses, higher speeds, elimination of the lubrication system and lubricant contamination of the process, operation at temperature extremes and in vacuum, and longer life. The active nature of magnetic bearings permits a much higher degree of control of rotor vibration, positioning, and alignment, as well as diagnostic and load measurement capabilities. While this potential has not yet been fully exploited [the typical feedback employed is decentralized proportional integral derivative (PID)], there are, as will be seen in this issue, several promising new directions for AMB control in rotating machinery applications.

Magnetic suspensions have also been applied to nonrotating objects (sometimes referred to as *flotors*) for applications as varied as precision motion platforms, wind tunnel model levitation, vibration isolation systems, and the treatment of brain tumors. While some of the control issues are different for rotating and nonrotating applications (e.g., gyroscopic effects and vibration due to imbalance), others may appear in both (e.g., gap nonlinearity, actuator saturation, and hysteresis).

The simplest form of a magnetic bearing consists of a pair of opposing horseshoe electromagnets. The attractive force each electromagnet exerts on the levitated object is proportional to the square of the current in each coil and is inversely dependent on the square of the gap. The coil is highly inductive and the rate of change of the current is limited. Commonly, a switching amplifier is used to drive each coil and often it contains a servocontrol loop so that it may be considered as a current source. Sensors measure the position of the object for feedback control. The controller commands the amplifiers and closes the feedback loop. In most applications, the bearing coils have a bias current that is applied when no net force is to be exerted. To create a desired force, the current in one of the electromagnets is increased from the bias value while the opposing coil current is decreased. This results in a net force that is linear in the perturbation current. Without this bias, the net force is quadratic in the coil current. In this case, when the force is small, the applied force cannot be changed quickly (a low force slew rate). Conversely, operation with a bias current yields a much larger force slew rate and rate saturation can be ignored in modeling and design. Because of the bias current, the open-loop system is unstable as the object is drawn to one side.

Future AMB control technologies are likely to be driven by:

- higher operating speeds;
- lower power loss;
- greater use of available clearance;
- generalized actuation, sensing, and control.

The 12 papers in this issue address many of these trends. To introduce the papers, a brief discussion of these trends and their implications for control theory and design is presented below.

Higher Operating Speeds: Magnetic bearings already permit much higher operating speeds than conventional bearings. However, demand for even greater speed is likely to be strong, e.g., for energy storage flywheel systems for electric vehicles. Higher rotating speed implies a greater rotor gyroscopic effect which results in the plant being linear parameter-varying (LPV). Matsumura *et al.* explore gain scheduled $H\infty$ control for management of both the gyroscopic effects and rotor unbalance response. Their simulations and experimental results indicate the need for further investigation into stability and performance of gain scheduled approaches when the rotor is accelerating or decelerating rapidly. Ahrens *et al.* examine the impact of gyroscopic effects upon control system design for a flywheel application. Their "cross feedback" control method is computationally simple and can improve the stable operating speed range of most controllers when applied to a rigid rotor. Extension of this technique to flexible rotors and for improving the robustness of gain scheduled controllers are interesting possibilities. Finally, recent research into self-scheduled controllers for LPV systems may be important for high-speed applications.

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Because of mechanical design limitations, higher rotational speed will result in more flexible rotors and operation over a greater number of rotor vibration modes. Increased attention to the design of multivariable controllers to dampen these flexible rotor modes will be required. Nonami and Ito apply μ-synthesis to the control of a flexible rotor and demonstrate that significant improvements in stability robustness can be achieved using D-K iteration.

Lower Power Loss: The need for lower power loss is especially acute for high-speed applications since rotation of the journal in the supporting magnetic field can cause significant losses. These result in both reduced machine efficiency and excessive rotor heating. For some applications, rotating losses can be reduced significantly if the AMB is operated without a bias flux. However, this gives a low (zero) minimum force slew rate and has an obvious impact on both rotor stabilization and disturbance rejection. Two papers offer promising approaches for addressing this problem. Charara *et al.* apply input–output linearization to the magnetic bearing regulator problem. Levine *et al.* examine differential flatness concepts to design trajectories without bias currents. In both papers the control equations are developed for a rigid rotor and experimental results are presented. Interesting and challenging problems remain, e.g., the control of flexible rotor modes and the rejection of transient disturbances.

Greater Use of Available Clearance: Most industrial magnetic bearing systems use only a small portion of the available clearance during operation. A larger clearance (e.g., 1 mm) results in greater actuator linearity near the centered position and thus simplifies control design and tuning. However, to reduce bearing size, weight, and power consumption, it is desirable to use a larger portion of the available clearance during operation. For some applications, such as precision positioning platforms, the required motion may be large and use of only part of the available clearance would be impractical. Four papers address the control of a levitated object with this position dependence nonlinearity. De Queiroz and Dawson use a backstepping method to design a controller for a planar rotor disk to obtain exponential position tracking over the entire clearance. Ludwick *et al.* present a six degree-of-freedom precision motion stage with 0.3 nm position accuracy and 100 μm of travel using a straightforward application of feedback linearization. The aforementioned papers of Charara *et al.* and Levine *et al.* also examine control methods that compensate for the position dependence nonlinearity. For many applications, the use of a greater portion of the clearance would also require the design of a controller which satisfies constraints on peak displacements (available clearances) in response to a bounded transient disturbance load.

Generalized Actuation, Sensing, and Control: Usually for every axis of motion there has been a devoted sensor, actuator, amplifier, and control system. That is, each function of a magnetic suspension has had its own dedicated component. Recently, there has been a shift away from this approach. For example, magnetic actuators are used to inductively sense position as well as to apply forces. Motor and bearing functions are achieved with a single actuator. And, direct digital control of amplifier switching is used to eliminate the separate amplifier servocontrol loop, thus uniting the amplifier and rotor controllers. The advantages of these generalized actuation, sensing, and control methods are reduced cost and increased design flexibility. Two papers examine such techniques.

Okada *et al.* propose a new combined motor-bearing design which features an internal permanent magnet and a simple feedback control; experimental performance suggests significant advantages for this design over alternatives. The maximum speed achieved, however, was quite low due to an approximation used in describing the shape of the magnetic flux distribution. A more accurate description of the magnetic field should provide greater performance, but the control required would become significantly more complex.

Mizuno *et al.* explore the design of self-sensing magnetic bearings in which the actuators also act as inductive sensors. This is an area of much current research. These authors show that for laminated bearings, a reduced-order observer will result in an unstable controller. This suggests that alternative demodulation approaches may be required for flexible rotor applications. When solid iron core bearings are used, eddy currents may result in full-order observer based controllers being unstable. As the authors point out, this intriguing result may explain the great difficulty that researchers have had with observer-based methods for solid iron core bearings.

Control of Unbalance Response: The remaining papers consider the control of rotor unbalance response, an area of intense research over the last decade. This is a considerably more mature area and substantial laboratory and industrial experience already exists. Generally, the goal has been to reduce either the applied forces or the rotor vibration. Herzog *et al.* propose a generalized notch filter which can be inserted into a multivariable feedback loop to reduce the control system's response to rotor imbalance so as to avoid actuator saturation. Synthesis of a gain matrix for the notch is discussed and experimental results on a 32 000 r/min turbo expander are presented. The paper also discusses some common links between notch filter and adaptive feedforward approaches to this problem. Ahrens *et al.* also apply the generalized notch technique and examine the effect of gyroscopics.

Lum *et al.* propose a new method of "adaptive autocentering" for reducing the control response to imbalance. This involves on-line estimation of the center of mass position and velocity and incorporation of these into a feedback control. This has the advantage that the estimation can be discontinued after convergence and the values so determined can be used over a range of operating speeds. At this time, the method is applicable to rigid rotors. This paper also contains some interesting parallels to the work of Herzog *et al.* as well as the literature on adaptive feedforward methods.

Rundell *et al.* examine a continuous state feedback controller with a sliding mode observer for a linear model of a gyroscopic vertical rigid rotor with two radial active magnetic bearings. The control objective is to reject rotor vibration while tracking a reference position. The goal is to reduce the measured rotor vibration rather than the actuator force as in the previous papers of Herzog *et al.* and Lum *et al.* This results in rotation about the rotors geometric axis as opposed to its inertial axis. This type of control action would be appropriate for low force, machine tool applications such as a grinding spindle. The performance is quite robust with respect to the rotors angular velocity, an interesting contrast to the results obtained by Matsumura *et al.* In that work, inaccuracy in the measurement of rotor speed, combined with the narrowness of the notch employed, resulted in imperfect attenuation of rotor synchronous vibration. Some directions suggested by this paper include extension of the work to consider actuator nonlinearities and rotor flexibility and implementation of voltage control via the sliding mode (i.e., direct control of amplifier switching).

Thirty papers were submitted for this issue in October 1995 by authors from 12 countries. More than 80 reviewers contributed their efforts to the evaluation of these papers. We would like to gratefully acknowledge their contribution. Thanks also to the TRANSACTIONS Editor, B. Krogh for all of his assistance. Finally, we are very grateful for the efforts of T. Herndon, the secretary of the Center for Magnetic Bearings.

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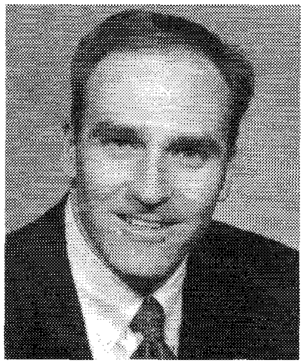

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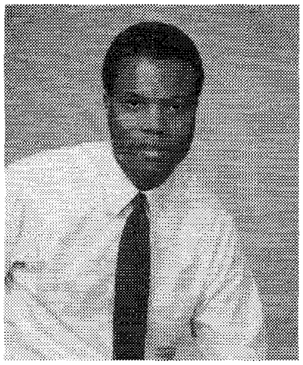

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