actuators

MDPI

Editorial

Actuators for Active Magnetic Bearings

Eric H. Maslen

Department of Integrated Science and Technology, James Madison University, Harrisonburg, VA 22807, USA; masleneh@jmu.edu; Tel.: +1-434-973-4563

Received: 17 October 2017; Accepted: 25 October 2017; Published: 27 October 2017

Keywords: actuators; active magnetic bearings; magnetics; control

---

The literature of active magnetic bearing (AMB) technology dates back to at least 1937 when the earliest work that clearly describes an active magnetic bearing system was published by Jesse Beams [1]. Progress on the technology was modest until the late 1970s, when commercial development began to emerge as, for instance, described by Haberman and Liard in 1977 [2]. The state of the art in 1988 is well-represented by the many technical papers compiled in the Proceedings of the First International Symposium on Magnetic Bearings [3].

In 1988, active magnetic bearings were still largely a novelty, and the literature of that time reflects this. Applications were relatively few, and producers of rotating machinery generally regarded the technology as a scientific curiosity. Most papers considered variations on the same theme: eight pole or "E"-core radial stators and single slot thrust stators with some form of transconductance control of the currents. Touch-down bearings were viewed as a necessity but were also feared as a likely source of failure: contacting a TDB seemed likely to mean a failure only narrowly short of catastrophic. Control was nearly always decentralized Proportional-Integral-Derivative (PID) and high-fidelity modeling of the combination of AMBs with a realistic, flexible rotor was at best in its infancy.

It is immensely gratifying to see this technology blossom from this beginning into a successful and mature technology with wide industrial acceptance and use. This special issue includes eleven contributions covering a wide range of topics related to the actuators of AMB systems as well as their control. Reflecting the maturity of the technology, these papers are generally concerned with practical refinements rather than the fundamentals of the technology.

The conventional concept of a radial magnetic bearing actuator is a sequence of coil-driven electromagnets arranged with alternating polarity around a rotor. Significant energy savings may be realized along with some simplification of the coil drive if the magnet array incorporates permanent magnets to provide biasing flux and arranges the poles in multiple planes so that the field does not alternate in the circumferential direction but, instead, in the axial direction. Such an arrangement is referred to as a *homopolar* structure. Filatov et al. [4] have provided an interesting and comprehensive view of the experience and design considerations that have led to the modern industrial implementation of homopolar magnetic bearings.

Further departures from the conventional four-quadrant magnet scheme are explored in [5,6]. Meeker [5] considers control of general n-pole radial magnetic structures *without biasing*. Unbiased control is of interest because of potential reductions in power consumption. Further, as discussed in [5], there are some radial magnet configurations which fundamentally cannot be bias linearized but can still be acceptably controlled with a generalized quadratic method. David et al. [6] consider the special case of controlling the currents in a four-pole radial magnetic stator, of particular interest in small AMB applications.

Continuing in the vein of using permanent magnets to reduce power consumption, Ishibashi et al. [7] explore the use of a mechanically actuated flux return path in an actuator energized only by a permanent magnet. Such an arrangement achieves magnetic suspension and control without the high coil currents required in a conventional electromagnet-based scheme. The authors propose this approach particularly for applications where air gaps must be very large: they discuss a suspension with an air gap of 20 mm (40 times larger than the typical AMB gap of 0.5 mm) and point to wind tunnel suspensions as an example.

When the rotor is large in diameter relative to its length (as for example in certain kinds of pumps and flywheels), it becomes suited to some specialized actuator topologies. Gruber et al. [8] look at a class of radial stators that can accomplish both active radial suspension and motoring in combination with semi-passive tilt and axial control for pancake-shaped rotors used in numerous pumping applications. Ishino et al. [9] explore a different topology that achieves more active control of the tilt degrees of freedom—particularly useful in applications that anticipate strong tilt perturbations such as operation in air- or sea-borne conditions.

Spangler et al. [10] develop and explore a technique for characterizing the magnetic properties of an AMB in situ. This allows compensation for manufacturing tolerance and misalignment between mechanical coordinates and centers and magnetic coordinates and centers during the commissioning process of an AMB. It also promises a useful means to characterize more complex actuators either in laboratory experimental settings or in the field.

Departures from conventional magnet coil drives are explored in [11,12]. Koehler et al. [11] look at using conventional motor drive components—available in mass production a relatively low cost—as drives for AMB coils. This work recognizes that the volume of drive needs for motors current far exceeds that of AMB, so the mass-produced drives for motors are likely to be much less expensive than speciality drives for AMB for a long time, offering substantial cost savings by reconsidering how the coils are controlled to fit them to motor drives. Ferreira et al. [12] discuss the motives and issues involved in replacement of transconductance amplifiers with transpermeance amplifiers in AMB systems, illustrating that the control of transpermeance amplifiers is likely simpler than that of transconductance amplifiers if only because the feedback sensor requirements are of lower bandwidth while the resulting performance is better by most practical metrics.

Control algorithms for AMB have taken many directions, including conventional PID control, $\mathcal{H}_\infty$, μ, fuzzy logic, sliding mode, and back-stepping. References [13,14] explore some specific practical directions of control. Pesch et al. [13] look at the problem of recovery from momentary contact with the touch-down bearing, using a robust μ-synthesis approach. Anatachaisilp et al. [14] explore the use of fractional order control (as opposed to more familiar integer-order control) to achieve desired control shaping with substantially reduced controller complexity.

Taken together, these papers present a nice picture of some of the directions that AMB technology is taking, revealing a nuanced comprehension of the various ways that the technology can adapt to meet the economic pressures acting on the technology as well as the specialized requirements of specific applications.

Acknowledgments: I would like to thank all of the authors for their willingness to support this Special Issue and for sharing their interesting and excellent work. I am also very grateful to the many reviewers who agreed to support this Special Issue by conducting thoughtful, rigorous and constructive reviews of the papers. Finally, I wish to express my appreciation to the editorial board for their gracious and attentive management of the entire process from soliciting contributions through managing reviews to getting the finalized papers into publication. I am particularly grateful to Lily Sun.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Beams, J.W. High Rotation Speeds. *J. Appl. Phys.* **1937**, *8*, 795–806.
2. Habermann, H.; Liard, G. Le palier magnétique active: un principe révolutionaire. SKF Rev. Roulements: Montigny–le–Bretonneux, France. 1977, No. 192. (in French)
3. Schweitzer, G. (Ed.) *Proceedings of the First International Symposium on Magnetic Bearings*; Springer: Berlin, Germany, 1988.
4. Filatov, A.V.; Hawkins, L.; McMullen, P. Homopolar Permanent-Magnet-Biased Actuators and Their Application in Rotational Active Magnetic Bearing Systems. *Actuators* **2016**, *5*, 26, doi:10.3390/act5040026.

5. Meeker, D.C. A Generalized Unbiased Control Strategy for Radial Magnetic Bearings. *Actuators* **2017**, *6*, 1, doi:10.3390/act6010001.
6. David, D.F.B.; Santisteban, J.A.; Gomes, A.C.N. Modeling and Testing Strategies for an Interconnected Four-Pole Magnetic Bearing. *Actuators* **2017**, *6*, 21, doi:10.3390/act6030021.
7. Ishibashi, N.; Mizuno, T.; Ishino, Y.; Yamaguchi, D.; Hara, M.; Takasaki, M.; Yamada, K. The Proposal of Magnetic Suspension Using Laterally Control Flux-Path Mechanism. *Actuators* **2017**, *6*, 11; doi:10.3390/act6010011.
8. Gruber, W.; Radman, K. Modeling and Realization of a Bearingless Flux-Switching Slice Motor. *Actuators* **2017**, *6*, 12, doi:10.3390/act6020012.
9. Ishino, Y.; Mizuno, T.; Takasaki, M.; Hara, M.; Yamaguchi, D. Development of a Compact Axial Active Magnetic Bearing with a Function of Two-Tilt-Motion Control. *Actuators* **2017**, *6*, 14, doi:10.3390/act6020014.
10. Spangler, D., Jr.; Prins, R.; Kasarda, M. A System Identification Technique Using Bias Current Perturbation for the Determination of the Magnetic Axes of an Active Magnetic Bearing. *Actuators* **2017**, *6*, 13, doi:10.3390/act6020013.
11. Koehler, B.; Denk, J.; Van Maanen, G.; Lang, M. Applying Standard Industrial Components for Active Magnetic Bearings. *Actuators* **2017**, *6*, 8, doi:10.3390/act6010008.
12. Ferreira, J.; Maslen, E.; Fittro, R. Transpermeance Amplifier Applied to Magnetic Bearings. *Actuators* **2017**, *6*, 9, doi:10.3390/act6010009.
13. Pesch, A.H.; Sawicki, J.T. Active Magnetic Bearing Online Levitation Rrecovery Through μ-Synthesis Robust Control. *Actuators* **2017**, *6*, 2, doi:10.3390/act6010002.
14. Anantachaisilp, P.; Lin, Z. Fractional Order PID Control of Rotor Suspension by Active Magnetic Bearings. *Actuators* **2017**, *6*, 4, doi:10.3390/act6010004.