Self–sensing for active magnetic bearings: overview and status

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***Abstract*— Self–sensing approaches permit active magnetic bearings to dispense with the usual position sensor and, instead, extract rotor position information from the voltage and current histories for the actuator coils. Mirroring the development of back–emf sensing of angular position in brushless DC motors, this technology has been a long time coming (more than 15 years) but has begun to be applied to commercial products. This review paper describes the process by which this emergence has occured and outlines some interesting problems that remain to be solved.**

I. INTRODUCTION

After many years of promoting the notion of self–sensing as a route to a simpler hardware realization for magnetic bearings, it is now possible to simply quote the December 2005 newsletter of the prominent AMB vendor, S2M:

> One of the key issues here, and a major challenge in terms of innovation, is the selfsensing bearing technique, where the position sensor and the bearing actuator form a single component. This leads to a far more simple design, with no sensor at all, and fewer connections and related cabling. The cost reduction for a typical bearing is substantial, representing a very strong product differentiation compared to a standard magnetic bearing.[3]

Self-sensing magnetic bearings are no longer primarily a research concept but now find commercial application to turbomolecular pumps [3] and elevator guideways [27].

This paper reviews the state of the art of self–sensing AMB technology both with regard to technical developments and also relative to its commercial status. A short survey of outstanding problems is then provided as a stimulus to future research in the area. Finally, an extensive list of references is provided as a partial guide to the literature on self–sensing AMBs.

II. CONCEPTS

The essential concept of a self–sensing AMB is to eliminate the position sensing device normally associated with active magnetic bearings [64]. The function of this sensor is then replaced by some form of signal processing which extracts information about the rotor position from available actuator current and voltage waveforms, as suggested in Fig. 1. This is possible because the actuator inductance is a function of rotor position. Referring to Fig. 2, voltage u applied to the magnet induces magnetic flux Φ according to

$$u = N\frac{d\Phi}{dt} + iR \tag{1}$$

in which i is the coil current, R is the coil resistance, and N is the number of turns on the coil. The first term in (1) is due to Faraday's law while the second is due to Ohm's law.

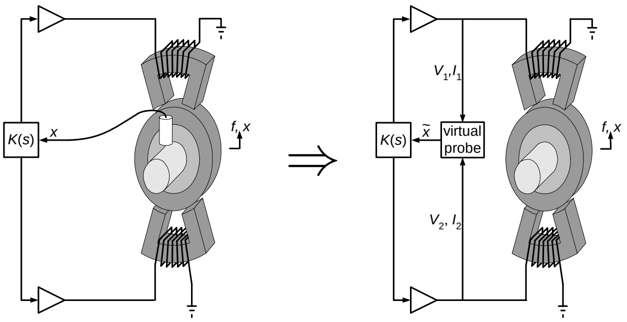

Fig. 1. Changing from a conventionally sensed AMB configuration to a self–sensing configuration.

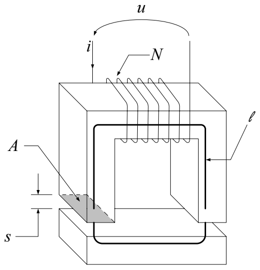

Fig. 2. A gapped electromagnet: the simplest actuator for an AMB.

Neglecting eddy currents, leakage/fringing effects, and assuming that the flux density is distributed uniformly throughout the magnet core and air gap, the flux in the magnet is related to the coil current by

$$\Phi = A\frac{\mu_0 N i}{2s + \frac{\ell}{\mu_r}} \tag{2}$$

in which A is the magnet cross sectional area, s is the length of the air gap, ℓ is the iron length, and μ_r is the relative permeability of the magnet iron.

Combining (1) and (2) produces the relationship

$$u = \frac{\mu_0 N^2 A}{2s + \frac{\ell}{\mu_r}} \frac{di}{dt} - 2\frac{\mu_0 N^2 A i}{\left(2s + \frac{\ell}{\mu_r}\right)^2} \frac{ds}{dt} + iR \tag{3}$$

Clearly, the electrical relationship between the coil voltage and resulting current is strongly dependent on the length of the air gap and its rate of change. With perfect knowledge of the voltage and current, one might reasonably expect to be able to reconstruct the gap and, hence, determine the rotor position.

The implication is that it should be possible to construct an AMB which uses no explicit position sensor. Such an AMB, which extracts position information from measurements of coil voltage and current, is referred to as *self–sensing*.

III. MOTIVATION

There are numerous reasons for wishing to build self–sensing AMBs, rather than conventional sensor based devices. The most obvious motives relate to the hardware itself: it is common to monitor coil currents in AMB systems so converting to self–sensing will eliminate the cabling, physical sensing device, drive electronics, and signal processing hardware associated with each discrete rotor position sensor while replacing them only with signal processing hardware or software to interpret the coil current and voltage signals. Potentially, this realizes some cost savings but, perhaps more importantly, it reduces the amount of hardware in the machine environment (hot, cold, wet, vacuum, etc.) and the amount of cabling between the machine and the drive cabinet. This has substantial potential to increase reliability of these systems if the dynamics of the resulting system are not compromised in the process.

In addition, when the flexibility of the supported rotor is significant[1], then axial displacement of the sensor relative to the actuator (sensor/actuator noncollocation) can produce substantial difficulties in stabilizing the system. In particular, if the node of a flexible mode lies between an actuator and its associated sensor, then the modal phase from actuator to sensor is reversed. Of course, the controller can be designed to take this phase reversal into account, but small changes in system parameters can easily displace this modal node so that it is no longer between the sensor and actuator. In this case, a system which has been stabilized by carefully accounting for the modal node location becomes abruptly unstable: the system robustness is poor. Self–sensing AMBs avoid this problem because the sensor and actuator devices are identical: self–sensing AMBs are *always collocated.*

IV. CONTROL APPROACHES

Although (3) suggests a structure for interpreting coil current and voltage to determine rotor position, a mathematically simpler approach was developed in [77] which first introduced the notion of the self–sensing AMB. This work examined the problem of control of a single axis AMB with an opposed pair of magnets, as described in Fig. 3.

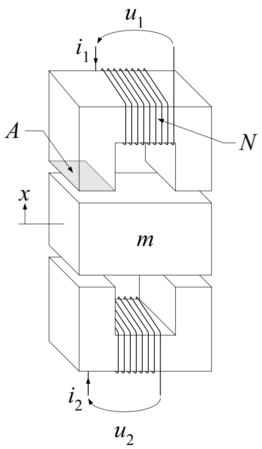

Fig. 3. Opposed electromagnets: a single axis AMB supporting a mass M.

A. State–space solution

The approach developed in [77] and numerous subsequent papers focuses on the fundamental controllability and observability of the bias linearized model of the system in Fig. 3 in which the coil currents of the opposing magnets are assumed to be perturbed symmetrically about some fixed (bias) point. The resulting model is linear with time invariant coefficients so the implied control problem can be attacked using the broad array of analysis and synthesis tools available for such systems.

The controller derived using such a methodology may be separated into a state estimator acting to generate estimates of rotor position and velocity followed by a state feedback controller – the standard LQG controller structure. Thus, the state estimator functions as a virtual probe, extracting position and velocity from coil voltage and current.

The problems endemic to this approach are explored in numerous publications, especially [31], [14], [50], [70] and their antecedents. The central problem is that the transfer function from input voltage to output current has a pole–zero pair in the right half plane and this makes the feedback stabilization problem very difficult. While such systems can be levitated and can provide some useful performance, they are sensitive to parameter drift.

An interesting commercial implementation of an extension of this approach is described in [27] in which the problems in robustness are managed by real time re–estimation of the system parameters most responsible for the problemmatic sensitivity. Physical experience with this interesting implementation clearly indicates that this is a useful direction to pursue.

B. High frequency perturbations

A number of researchers have explored the practical implications of high frequency perturbations to the coil

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[1] Here, “significant” means that the first bending mode of the flexible rotor is within or at least near to the small signal bandwidth of the sensor / amplifier / controller ensemble.

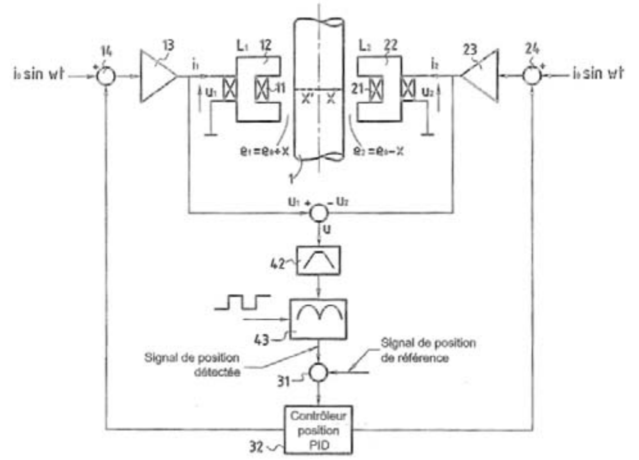

Fig. 4. Schematic of the S2M self–sensing scheme [73].

currents in AMB systems, using these perturbations to estimate the actuator inductance and, hence, the gap length. An excellent example of this approach is provided by [19] in which the instantaneous slope of the current is measured explicitly (using very high rate signal sampling) and compared to the instantaneous coil voltage to determine the gap length statically. Some theoretical underpinnings for this approach are explored in [45], [21], [60] which attempt to reconcile the theory of [50] with experimental results such as those obtained by [63].

Some early results, such as [14], [15], [20] used specialized signals applied to the coils to provide the self-sensing function, but more recent work has attempted to exploit the natural ripple that arises from the normal switching amplifier function; see, for example, [36], [56].

Generally, the solutions that rely on high frequency perturbations derive their position estimates either from direct demodulation of the current ripple or through some form of parameter estimation process. The former methods are simpler than the latter but require specific coil voltage conditioning.

In either case, either a demodulator or a parameter estimator takes coil voltage and current signals and from them forms an estimate of gap length. This estimate is then provided to a typical AMB controller, treating the signal as a replacement for the position signal normally provided by a discrete position sensor. Controllers are typically some variant on PID, but the signals are amenable to other methods such as $\mathcal{H}_\infty$ or $\mu-$synthesis derived MIMO controllers.

Experimental results presented by numerous researchers for high frequency perturbation based self-sensing systems show good performance and strong potential for commercial application. The method employed by S2M is, interestingly, of the type advocated in [14] and is depicted schematically in Fig. 4. In [3], the performance of this system is reported as completely satisfactory for turbomolecular pump application and plans to apply a similar scheme to "light" turbomachinery are reported.

V. PROBLEMS

Despite the emergence of real commercial applications of self-sensing AMB technology, there remain a number of problems that should continue to stimulate academic and industrial research.

A. *Ripple Amplitude*

A key result presented in [21], [60] is that the robustness of self–sensed AMB systems, regardless of the signal processing method employed, hinges on the amplitude of the switching ripple. The robustness does not go to zero in the event that the switching ripple is eliminated (as in [77]) but is very substantially diminished. As a result, self-sensing systems will tend to work better when the coil currents exhibit a lot of high frequency ripple.

This observation is signficant because switching amplifier technology for AMB systems has moved from early approaches that used only two output states ($+V_{ps}$ or $-V_{ps}$) to use of three output states ($+V_{ps}$, 0, $-V_{ps}$). The reason for this is that the amplifier becomes more efficient and eddy current losses and acoustic emissions from the AMB are reduced.

However, with three state drive, the amplitude of the switching ripple is substantially reduced (sometimes by a factor of 10 or so) so that self–sensing with three state amplifiers is difficult. Of course, solutions such as that proposed originally by [14] and implemented in [73] sidestep this problem by injecting a special signal into the power amplifier intended to achieve sufficient ripple amplitude to obtain adequate system robustness. However, this is only accomplished at the expense of much of the efficiency targeted by the three state switching operation.

This limitation appears to be fundamental and probably means that robust self-sensing AMB systems will typically be somewhat less efficient (in terms of electrical power) than the equivalent discretely sensed AMB. Approaches are likely to be a combination of accepting higher losses combined with methods such as presented in [27] to mitigate the modest robustness achieved at lower ripple levels.

B. *Eddy Currents*

Eddy currents pose a special problem, particularly in unlaminated actuators such as thrust bearings. The primary consequence of eddy currents is an effective reduction in iron permeability at high frequencies (see [26] for instance). This means that the variation in actuator impedance with changes in gap – the sensitivity of the device as a position sensor – is poor at high excitation frequencies. It further means that the shape of the current ripple waveform may not be the clean triangle anticipated by [19].

Figure 5 illustrates a typical eddy current waveform in response to 2–state switching. The cusps in the current waveform that appear at each switching instant are controlled almost entirely by eddy currents in the actuator iron. The size of these cusps can be quite large: for an unlaminated thrust actuator, they can be 20 or 30 percent of

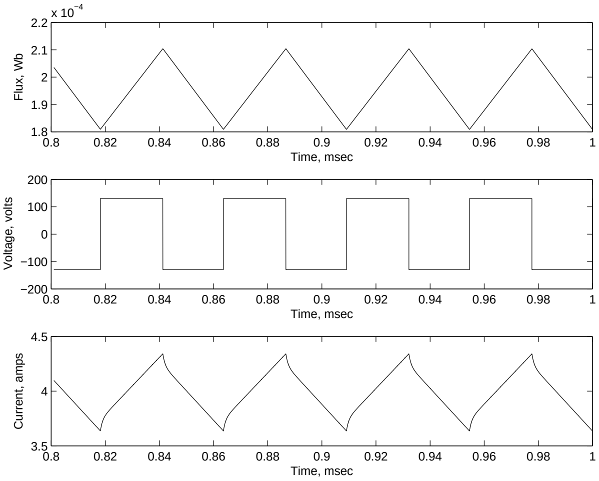

Fig. 5. AMB waveforms for 2-state switching with eddy current production.

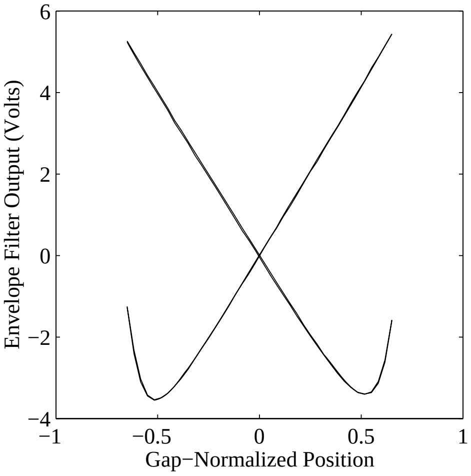

Fig. 6. Switching waveform amplitude *vs* rotor position for two opposing AMB sectors. From [45].

the bias current level, depending on the amplifier switching voltage. The problem with these cusps is that they are not affected by changes in air gap length so they represent a substantial loss in sensitivity of the waveform to air gap.

The primary solution to this problem is to reduce the frequency of the excitation signal – go to lower switching rates (and also lower switching voltages) or use a special interrogation signal. In [73], this issue is addressed by recommending use of a special interrogation signal whose frequency is selected to be just a bit above the effective bandwidth of the actuator. This bandwidth is determined, in part, by the eddy current production. Therefore, linking the interrogation frequency to the actuator bandwidth attempts to preserve sensitivity to gap by minimizing production of eddy currents by the sensing process.

In methods such as [19] which rely on the instantaneous slope of the waveform to determine gap length, a sampling delay needs to be inserted between the switching instant and the sampling interval. This delay should be proportional to the eddy current time constant: the decay time of the cusps in Fig. 5.

Parameter estimation methods, such as [56], should add an eddy current model to the embedded electrodynamic simulation in order to account for this effect.

C. *Saturation*

Perhaps the most vexing problem facing researchers in self-sensing is that of magnetic saturation. This problem has been acknowledged since some of the earliest work in self-sensing [20]. The issue is that saturation reduces the permeability of the actuator iron at high flux densities and this changes the sensitivity of the actuator to air gap dramatically. In particular, if the actuator current is held constant and the air gap is changed, then the slope of the switching ripple will diminish with decreasing gap until the iron begins to saturate. At this point, further reduction in air gap produces two results: a reduction in circuit reluctance due to the narrowing gap and an *increase* in circuit reluctance due to iron saturation. The result is summarized in Fig. 6 which shows that the sensitivity (slope of the curve) actually reverses at some point and a simple demodulation scheme will actually produce an ambiguous signal: the same output can arise at two different rotor positions.

A number of solutions to this problem have been posited. In [20], the actuator has an excess of poles (six horseshoe pole pairs rather than the usual four). In this case, it is possible to momentarily reduce the flux density in selected pole pairs to ensure a fixed level well away from saturation. The current in this pair is then perturbed to estimate the gap length. The principal drawback to such an approach is that the amplifier voltage required to rapidly de-saturate the pole pair, interrogate the gap, and bring the pole pair back into saturation can be substantial: well in excess of the nominal requirement of the system. Another solution is proposed in [55] in which all of the pole gaps are simultaneously estimated in a MIMO parameter estimation scheme. In this case, it is shown that such a scheme can be robust to short periods of actuator saturation and still yield a reliable position estimate. The literature on self–sensing since [55] has generally stayed away from the saturation problem so this appears to be a relatively ripe area for continued research.

VI. CONCLUSIONS

Self–sensing AMB technology now presents a commercially viable alternative to using discrete position sensors in AMB systems. This alternative offers significant cost savings and the potential for dynamics advantages due to its fundamental sensor-actuator collocation. Several technical approaches are available: linear system based, linear system with parameter identification, switching ripple based, and interrogation signal based. Of these, the linear system with parameter estimation and interrogation signal based approaches have been developed as commercial products. Generally, the existing commercial products make modest demands on the system sensing performance: in order to realize products with more aggressive requirements, a number of lingering technical hurdles remain to be crossed.

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