

# Active Magnetic Bearings for Frictionless Rotating Machineries

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## Abstract

Active magnetic bearing (AMB) systems can support a rotor without physical contact and enable users to precisely control rotor position and vibration as function of time or other parameters. These frictionless and programmable features have made AMB suitable to meeting the demand for higher speed, higher efficiency and reliability of rotating machineries in many industrial application including oil and gas production, power generation and energy conservation, clean manufacturing and transportation. This paper reviews the components and working principles of AMB, which requires basic understanding of rotordynamics, electromagnetisms, power electronics and control theories. Several configurations and applications of AMB are presented including design and cost issues. The capabilities of several major AMB world manufacturers are evaluated. The paper concludes with the summary of investigation topics at several leading AMB research centers. It is hoped that this paper can provide an up-to-date, brief and yet comprehensive introduction of the AMB technology for potential users and industrial communities in general.

**Keywords :** Control, magnetic bearing, magnetic levitation, rotordynamics

## 1. Introduction

Active magnetic bearings have several attractive advantages over conventional bearings because magnetic bearings levitate rotors and therefore have no physical contact with the spinning rotors. The use of magnetic bearings can significantly eliminate the frictions that usually exist in conventional bearings. Thus, in rotating systems, magnetic bearings can contribute to efficiency in energy, longer life, and the ability to operate at very high RPM. Other advantages include the elimination of mechanical maintenance of the bearing and lubrication, suitability for clean or vacuum room operation. The programmable feature typically includes the ability to adjust stiffness, damping, and periodic force as function of time or other parameters such as bearing temperature, RPM and angular acceleration.

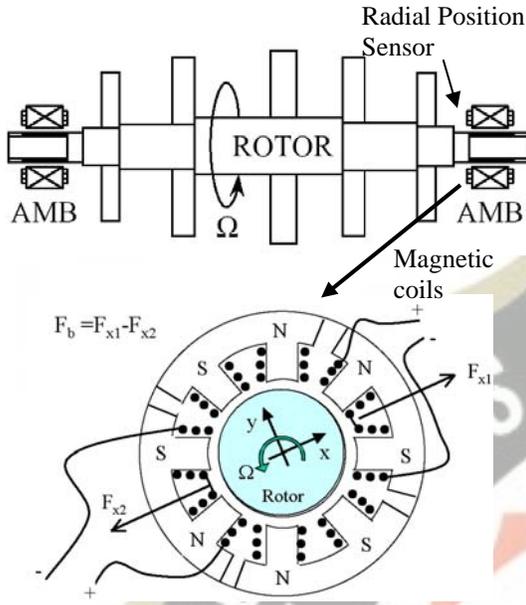
Active magnetic bearings have been implemented in rotating systems in a variety of industrial applications. These applications include flywheel energy storages, momentum wheels, turbomachineries, precision

machineries, vacuum pumps, and medical devices.

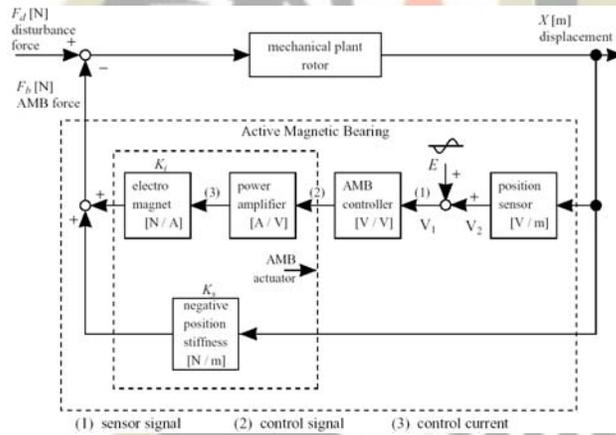
This paper reviews the components, working principles and characteristics of active magnetic bearing (AMB) systems. The most popular configuration as shown in Fig.1 is introduced [1-8] in which the AMB provides radial forces generated by four poles magnetic coils that are driven by power amplifiers operating in current mode.

## 2. AMB Components

The design of AMB systems requires the knowledge of several disciplines including rotordynamics, electromagnetisms, power electronics and control feedback theories. This is driven to the fact that the components of AMB systems include position sensors with signal conditioning, switching-power amplifiers, either analog circuits or Digital Signal Processor (DSP), and magnetic coils/electromagnet as the actuators. The connection of AMB components are shown by the block diagram in Fig. 2.



**Figure 1.** Rotor equipped with Radial AMB



**Figure 2.** AMB system block diagram

### 3. Modeling

The integration of a feedback control in AMB systems shown in Fig. 2 must carefully consider the dynamics of the rotor. This is due to the fact that a rotor, supported by magnetic bearings is an open-loop unstable system as will be shown in this section. Thus, an accurate model of the system is always needed for stabilization.

The dynamic of the rotor can be simplified by focusing on the rotor motion along  $x$  axis shown in Fig. 1. The equation of motion becomes,

$$m\ddot{x} = F_b - m\bar{g} + F_d \quad (1)$$

where  $m$  is the effective mass of the rotor seen in the  $x$  axis,  $x$  is the rotor position, and  $F_b$  is the bearing force

$$F_b = k \left[ \left( \frac{i_{10} + i_c}{l - x} \right)^2 - \left( \frac{i_{20} - i_c}{l + x} \right)^2 \right] \quad (2)$$

$k$  = magnetic force constant

$l$  = nominal air gap

$i_{10}, i_{20}$  = bias currents in the top and bottom electromagnets

$i_c$  = control current

$\bar{g}$  = acceleration along  $x$  axis due to gravity

The nonlinear bearing force in Eq. (2) can be linearized about  $x=0$  and  $i_c=0$ , thus

$$F_b = K_s x + K_c i_c \quad (3)$$

where

$$K_s = \frac{2k(i_{10}^2 + i_{20}^2)}{l^3} \quad ; \text{ position stiffness}$$

$$K_c = \frac{2k(i_{10}^2 - i_{20}^2)}{l^2} \quad ; \text{ current stiffness}$$

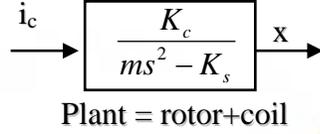
For simplicity, we can assume the sensor runout  $E=0$  in Fig. 2 and the unbalance force  $F_d=0$  in Eq. (1). Proper choice of  $i_{10}$  and  $i_{20}$  can be made to cancel the gravity term in Eq. (1) while  $K_s$  and  $K_c$  can be set to preferable values. Thus, we can write the plant transfer function as shown in Fig. 3. The plant is an unstable system. The simplest way to stabilize the plant is by closing the loop with a proportional-derivative (PD) controller shown in Eq. (4).

$$i_c = -(K_p x + K_d \dot{x}) \quad (4)$$

The closed-loop system dynamic then can be represented by Eq.(5). As long as the

effective damping,  $K_c K_d > 0$  and the effective stiffness,  $(K_c K_p - K_s) > 0$  the system is stable.

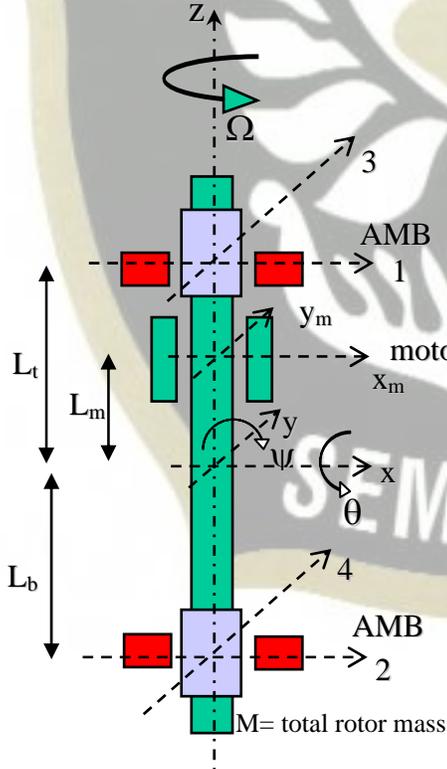
$$m\ddot{x} + K_c K_d \dot{x} + (K_c K_p - K_s)x = 0 \quad (5)$$



**Figure 3.** Single-DOF AMB Plant Transfer Function

A more accurate AMB model consider the gyroscopic coupling in the rotor and also other external forces ie. the unbalanced magnetic pull (UMP) of motor,  $K_m$  as shown in Eq.(6) and Fig. 4.

$$\begin{aligned} M\ddot{x} - K_m x_m &= F_1(i_1) + F_2(i_2) \\ M\ddot{y} - K_m y_m &= F_3(i_3) + F_4(i_4) \\ I_T \ddot{\theta} + I_p \Omega \dot{\psi} - L_m K_m y_m &= L_t F_3(i_3) - L_b F_4(i_4) \\ I_T \ddot{\psi} - I_p \Omega \dot{\theta} - L_m K_m x_m &= L_t F_1(i_1) - L_b F_2(i_2) \end{aligned} \quad (6)$$



**Figure 4.** Model of Rigid Rotor with AMB

For robustness, a state feedback controller (centralized control) is generally implemented in AMB systems, especially for high RPM operation and when  $I_p/I_T$  (polar inertia over transverse inertia) is not negligible. Additionally high order filters or compensators are usually needed in each axis in order to avoid resonances and instabilities at rotor bending frequencies.

#### 4. Design, Cost & Performance Issues

Currently, there is still no industrial or international standard for AMB design procedures and performance requirements. The International Organization for Standardization (ISO) and International Electrotechnical Committee (IEC) are still preparing a draft of ISO 14839 for this purpose. The AMB ISO 14839 draft can be accessed at an internet address shown in reference [9].

There are several variations in the AMB systems configuration. These variations exist because of the need for lower hardware cost and more fault tolerant AMB systems. For example, an AMB system which is so called “self-sensing”, does not require position sensors which means lower hardware cost. However, the stability margin and robustness can easily degrade. So does the AMB system that only has 3 poles of electromagnets in each bearing.

A redundant system which is more fault tolerant usually can cause the cost of production. to increase significantly ie. at least by 4 times. Two examples of redundant AMB systems are shown in Fig. 5.

The design of AMB systems need to consider the worst case scenario such as loss of control due to faulty hardware/software components, and due to large external disturbances such as an earthquake or other vibrations. For this purpose, auxiliary bearings are always incorporated as a back-up. The diameter of auxiliary bearings is sized such that the

electromagnets are well protected during the “crash” and during power start-up and termination.

It is a common practice to generate an accurate Campbell diagram of free-free beam mode of rotors that will be supported by AMB systems. A Finite element software can be used to create a Campbell diagram that shows the location of rotor eigen-frequencies at different spin speed including the rigid body and bending modes. In practice AMB can still be designed to support a rotor that spins near or above the first rotor bending mode. However, this design demands a more powerful DSP in order to perform more complex computation to accommodate higher order compensators. If possible the operation near or above the first bending mode should be avoided because it increases control design complexity and cost.

An example of hardware cost in the year of 2006 for typical AMB systems is shown in Table 1 assuming a mass production ie. at least a thousand AMB units for a vertical rotor with mass of 250 kg, diameter about 5 cm, maximum speed about 25 thousand RPM, distance between bearings about 0.5 meter, and maximum force per axis about 250 N.

**Table 1.** AMB components cost estimate

<b>AMB components</b>	<b>Estimated cost (US Dollar)</b>
2 electromagnets+ position sensors	300-500
8 PWM power amplifiers, @ 50 watt max	400-800
DSP+electronics +power supplies	750-1500
wiring	100-200
2 auxiliary bearings	50-200
<b>Total</b>	<b>1700-3200</b>

It is worth noted that in some designs and applications, the total electrical loss of AMB systems may be higher than the power loss due to mechanical friction of conventional bearings. The wiring of power lines from power amplifiers to electromagnets should be made as short as possible in order to reduce electrical resistance. However, in many applications the other benefits of AMB already overcome this electrical loss such that AMB is still an attractive choice.

Adaptive Vibration Control (AVC) feature in AMB systems is useful after a certain RPM. Using a gradient method to minimize cost function of influence efficient matrix, AVC can “on-the-fly” reduce or eliminate synchronous vibration due to mass unbalance. Because of its great advantage, this feature is almost always incorporated in the AMB systems.

The stiffness and damping of AMB systems can be adjusted by changing the bias currents or the feedback control gains as shown previously in Eqs (3-5). For example, due to a “gyroscopic stiffening effect” in rotors with  $I_p/I_r < 1$ , the AMB stiffness or bias current in equivalent can be decreased after certain high speed; thus the AMB power consumption is reduced.

## 6. Major Players in AMB Technology

There have been numerous AMB manufacturer in the world [10-12]. The two most industrious ones are S2M in France and Revolve in Calgary, Canada. S2M has sold thousands AMB systems primary for compression systems for oil and gas production industry. Another AMB company, Synchrony focuses on “high grade” fault tolerant AMB systems that can be used by aerospace industries and future aircraft engines. One of Synchrony’s approach is to use redundant AMB and multiple DSP as shown in Fig. 5.

Due to the rapid progress in electronics including DSP technology, there are abundant

of avenues for further research in AMB. Performance improvement, cost reduction, and additional design objectives within specific applications are some of the examples. In the recent years, researchers working on magnetic bearings have been aggressively focusing in areas such as (1) studies to utilize modern control methods including multi-variable controls, robust controls, non-linear controls, and adaptive controls in order to minimize rotor vibration; (2) studies of levitating more flexible rotors; (3) studies of self-sensing magnetic bearings; (4) studies on the joint use of magnetic bearings for levitation and motor-stators for rotation; (5) hybrid passive and AMB; and (5) studies on zero-power magnetic bearings using superconductor materials. Most of the above research topics are conducted at the three most notable AMB research and academic centers in the world [13-15]: (1) Rotating Machinery and Controls Laboratory (ROMAC) at the University of Virginia, Virginia, USA; (2) The International Center for Magnetic Bearings (ICMB) at The Institute of Robotics, ETH Zurich, Switzerland; and (3) Institute for Machine Dynamics and Measurements (MTMD), Viena University of Technology, Vienna, Austria.

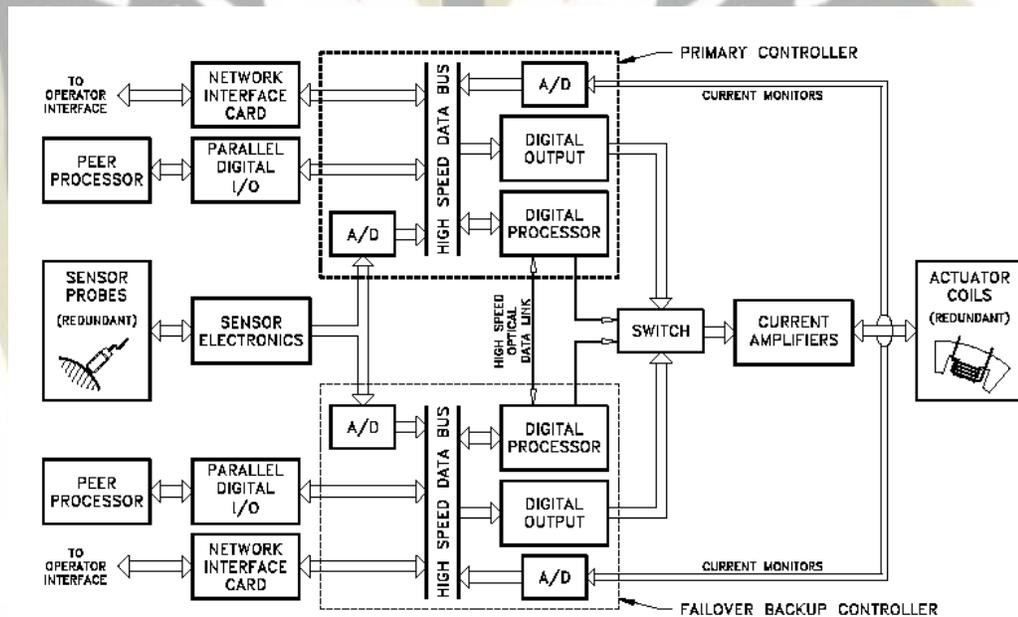
## 6. Conclusions

The AMB technology has been briefly reviewed including its advantages, components, working principles, cost and performance. Some design and implementation issues have been also discussed. The authors believe that AMB systems are still relatively more expensive than conventional mechanical bearings; therefore the massive used of AMB in industries is still prohibitive despite of the many benefits offered. The AMB will still not completely replace conventional bearings in rotating machineries in the near future. However, AMB can find its place well in a limited volumes of high performance rotating machines.

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**Figure 5.** Redundant AMB System with multiple Digital Signal Processors (DSP), Courtesy of Synchrony Inc.