Applications and Research Topics for Active Magnetic Bearings

Gerhard Schweitzer

ETH Zurich
SWITZERLAND
www.mcgs.ch
e-mail: g.schweitzer@ggaweb.ch

Abstract More than thirty years of research and application experience have lead to active magnetic bearings (AMB), which allow unique applications for rotating machinery with excellent performance. The paper will briefly discuss the state of art by giving historic examples and actual industrial applications. The main part is devoted to recent research topics, as a challenge to young researchers in rotor dynamics, mechatronics design and control. As an outlook, novel applications for nuclear and underwater environment, and for a superconductive bearing are addressed.

Key words: magnetic bearings, active magnetic bearings, research topics, rotor dynamics

1 Introduction

Magnetic bearings offer a novel way of solving classical problems of rotor dynamics by suspending a spinning rotor with no contact, wear and lubrication, and controlling its dynamic behavior. In a general sense such an *Active Magnetic Bearing - AMB* is a typical mechatronics product. Figure 1 presents the main components and explains the function of a simple bearing for suspending a rotor just in one direction. The suspension of a full rotor of course needs several magnets, which are connected to one another by a multivariable controller. The built-in software determines its main characteristics, which allows to control the dynamics. Thus, the control law of the feedback is responsible for the stability of the hovering state as well as the stiffness and the damping of such a suspension. Stiffness and damping can be varied widely within physical limits, and can be adjusted to technical requirements. They can also be changed during operation. Theory, design and application are detailed in [13], which is the reference to several figures of this survey and to further research

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topics as well. Standards and guidelines on practical issues are given in [1]. After a brief glance on history the paper shows examples of recent industrial applications for turbomachinery and flywheels. It concentrates on actual research topics such as high speed issues, control of elastic rotors, touch-down dynamics, and the potential of using AMB as a key element for smart rotating machinery. An outlook on future applications, such as in nuclear and underwater environments, concludes the survey.

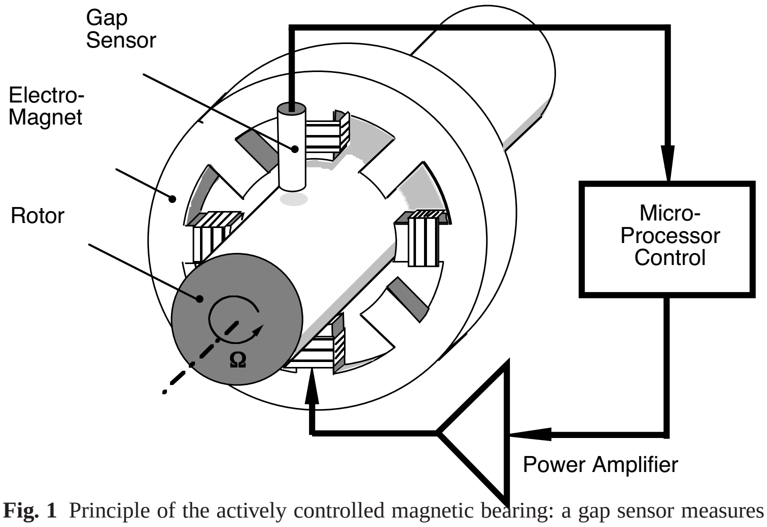

Fig. 1 Principle of the actively controlled magnetic bearing: a gap sensor measures the displacement of the rotor from its reference position, a microprocessor derives a control signal from the measurement, a power amplifier transforms this signal into a control current, and this current generates the magnetic field forces within the actuating electromagnet in such a way that the rotor remains in its hovering position.

2 A Glance on History

First investigations on the physics of suspending a body freely by magnetic field forces go back to Earnshaw (1842, [4]) and Braunbek (1939, [3]). A patent of Kemper (1937, [9]) showed the potential of AMB for magnetically levitated vehicles, and the experiments of Beams demonstrated a spectacular high speed application, where mm-sized steel balls were rotated freely with up to 300 kHz until they burst [2]. First industrial-like applications of AMB were initiated by Habermann [8] for aerospace momentum wheels. The potential for the active control of rotor dynamics was shown in 1974, see Fig. 2. The interest in AMB grew with the implementation of digital control with microprocessors [15], emphasizing the role of software as a prominent element within the machine, eventually leading to the concept of smart machines [6], Sect. 4. The industrialization, about 20 years ago, came with

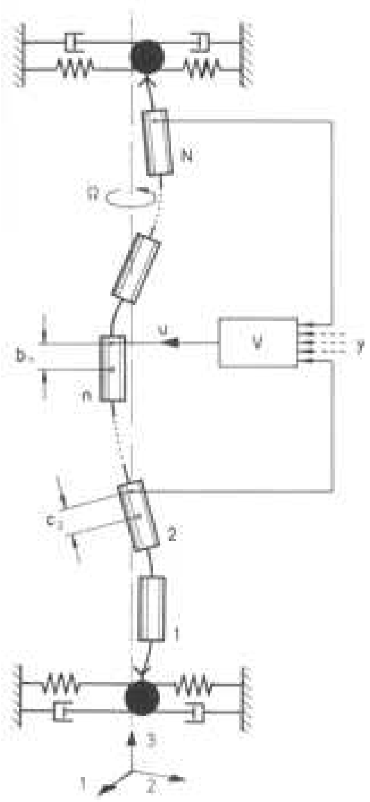

Fig. 2 Active damping: vibration control of a high-speed rotor by AMB was demonstrated in theory and experiment for a multibody centrifuge [12]. The lateral displacements of the rotor elements are measured in some selected locations, the signals are used to derive a control signal for generating suitable damping forces, which act on a specific rotor. In such a way it is possible to cross various bending resonances, and to extend the operational speed beyond the initial stability limit caused by internal damping effects.

the availability of design tools for modeling rotor dynamics and control, and with the advances of hardware for power electronics.

3 Industrial Applications

The state of art in industrial applications will be shown by a few typical examples, Figs. 2 to 6. The description of the examples is given in the captions. The actual emphasis is on turbo-machinery, but of course, there are other promising areas as well, such as machine tools, high-speed motors and generators, flywheels, momentum wheels, or centrifuges. The main features are not only high speed, high power density, or the control of rotor dynamics. Other features, such as the absence of contamination by lubrication or mechanical wear, low energy consumption, and low maintenance costs are prevailing now. Furthermore, the use of AMB as a key to smart machinery allows the integration of the machine into the control of a whole production process and to manage safety and maintenance issues.

Fig. 3 Turbo-blower: cooling gas compressor (CO_2) for a power laser, cutting metal sheets up to 25 mm. The laser needs uncontaminated gas. The speed is 54000 rpm, the rotor mass 3.6 kg, the motor power 12 kW, the radial bearing 48 mm in diameter, the bearing force 230 N (courtesy TRUMPF/MECOS).

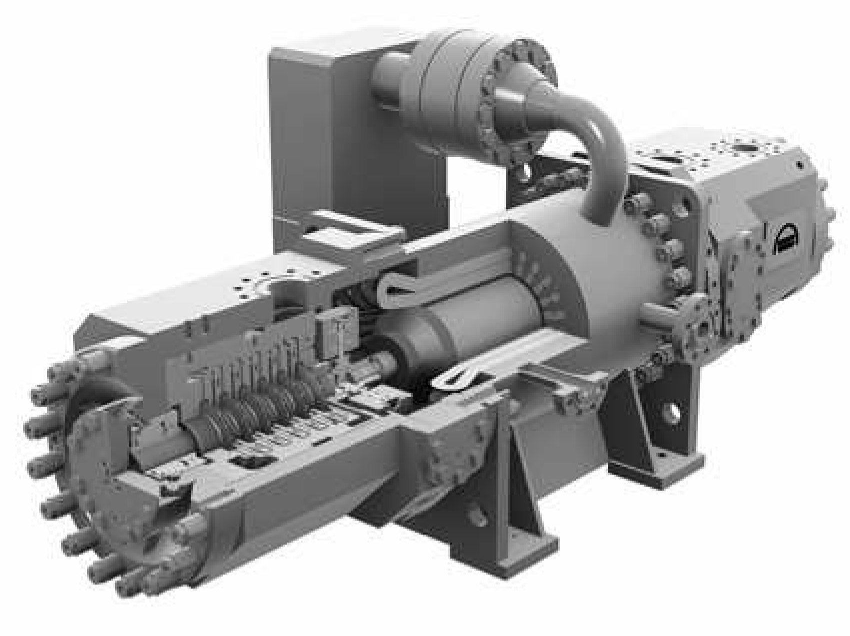

Fig. 4 Pipeline compressor HOFIM for natural gas: integration of direct drive and magnetic bearing in the turbomachine, 6 MW, 9000 rpm (courtesy MAN Turbo/S2M).

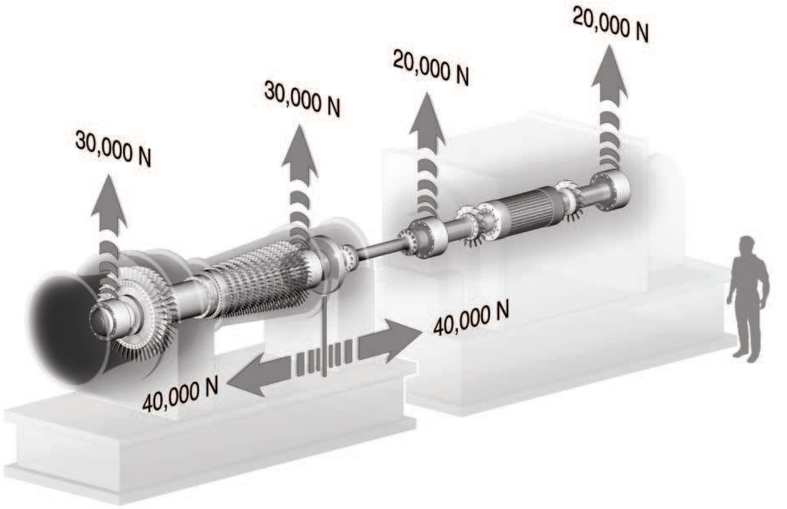

Fig. 5 Gas-turbine/Generator for power generation: 4 radial bearings and 1 thrust bearing, 6010 rpm, 9000 kW, bearing diameter 400 mm (courtesy S2M).

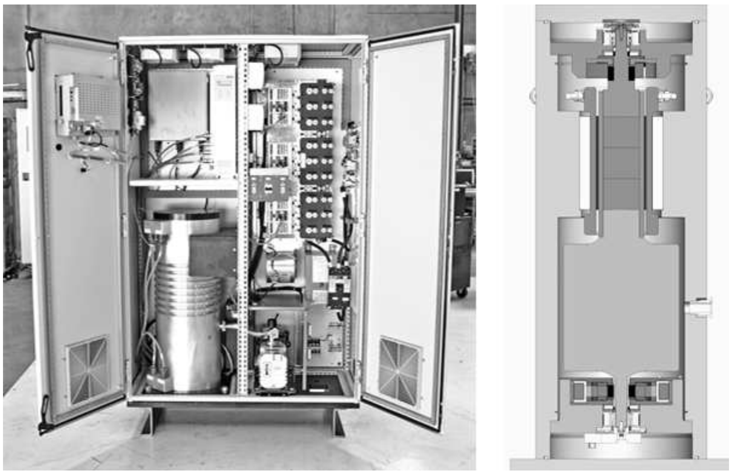

Fig. 6 Flywheel [11]: the 140 kW energy storage flywheel has been developed to provide 15 seconds of ride-through power and UPS service in conjunction with a diesel generator set. The flywheel operates in a vacuum. In the cabinet the flywheel is on the lower left, the magnetic bearing controller is at upper middle, motor/generator and system controller on upper left, and motor/generator power electronics on the right. The right figure shows the cross-section of the flywheel: total energy storage 1.25 kWh at 36000 rpm for delivery of 140 kW for 15 s (0.58 kWh), flywheel rotor mass 109 kg. The flywheel has a steel hub, a 2-pole brushless DC motor/generator, and permanent magnet biased magnetic bearings (courtesy CALNETIX).

4 Research Topics

This survey will focus on 5 research topics, which actually appear to be most challenging, and which are illustrated in exemplary figures:

High-speed Rotors In industrial applications the speed usually is limited not by the bearings themselves, but by the mechanical design of the motor drive, Fig. 7. Critical elements are the usually complex structure of the motor/generator part and the laminated bushes on the rotor with their shrink fits, under the magnetic bearings. Research shows that rotor speeds of up to 340 m/s in the bearing area can be reached with iron sheets from amorphous metal (metallic glass), having good magnetic and mechanical properties. For high speeds permanent magnet synchronous drives are used, where the rotor is wound with carbon fibres, allowing speeds of about 300 m/s. As the cooling of the rotor, in particular in vacuum applications, is limited, high efficiency of the drives and optimized thermal design is essential.

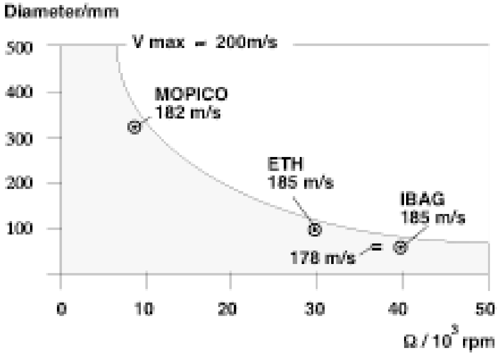

Fig. 7 Examples for the maximal diameter of the (asynchronous) motor drive in function of the rotor speed, which has been achieved in various conventional AMB applications. The (x) indicates a rotor broken at 178 m/s. The circumferential speed is a measure for the centrifugal load and leads to specific requirements on design and material.

Control of Elastic Rotors ”There are two reasons why flexible systems present more of a challenge to the control system designer than does a rigid rotor. The first is the simple matter that a flexible rotor has a much wider mechanical bandwidth than does a rigid rotor. This means that the mechanical response to high frequency forcing is much larger for a flexible rotor than for a rigid rotor and, as a result, the dynamic behavior of the feedback controller at high frequencies is much more important for flexible rotors than for rigid rotors. The second reason is that, when the sensors and actuators are not collocated axially along the rotor, then it is always true that at least one undamped flexible mode shape will exhibit a node between a sensor-actuator pair. If this mode has a frequency within the bandwidth of the controller, then it poses special dynamics problems for the system. Both of these issues must be attended to either explicitly or implicitly in the design of an AMB controller for a flexible rotor (cited from Maslen in [13]).” Figures 8 and 9 show a simple example. For a real elastic rotor, on an elastic foundation, with several actuators and sensors,

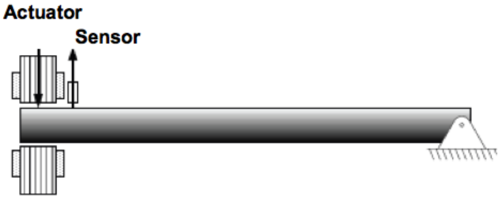

Fig. 8 A pinned, flexible beam controlled at the free end by an active magnetic bearing. Sensor and actuator are not collocated (courtesy Maslen).

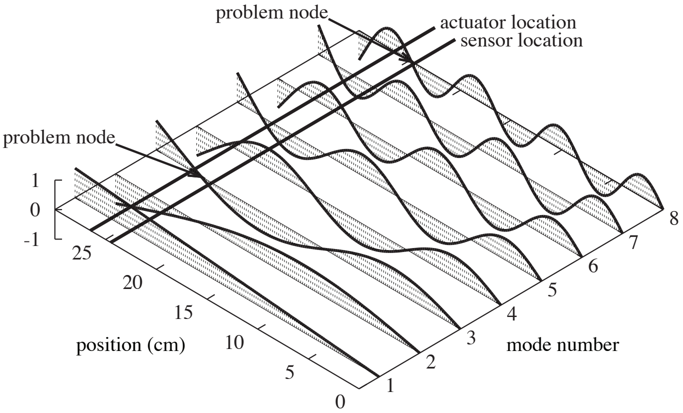

Fig. 9 Modeshapes of the flexible beam of Fig. 8. The mode numbers 3 and 8 show that the displacements measured at the sensor location are out of phase with the ones at the actuator location, causing stability problems. For this simple single input/single output control, compensation of the phase lag can be achieved classically. For real rotors more advanced concepts are necessary (courtesy Maslen)

a multiple input/multiple output control has to take into account uncertainties, and it has to be robust.

Touch-down Dynamics Contact between a rotor and a stator can lead to violent vibrations. As a back-up, in order to avoid potential damage, AMB supported rotors are equipped with touch-down bearings. These are an additional set of conventional bearings, and the rotor will only come into touch with them in extraordinary situations. These bearings should be able to support the rotor for a limited time period until the normal operating mode can be recovered or until the rotor can be run down safely. Dynamics of the touch-down are inherently nonlinear, with strong dependence on initial conditions, and with chaotic phases, Fig. 10. The backward whirl is the most dangerous one, generating very high contact forces. The optimal design of retainer bearings still relies mostly on experience, and a systematic, generally accepted design procedure has yet to be developed. Open research questions include the choice of material, the physical insight into high-speed contacts, i.e. for contact speeds above 200 m/s, the running down through critical speeds in retainer bearings, and control aspects in critical contact situations.

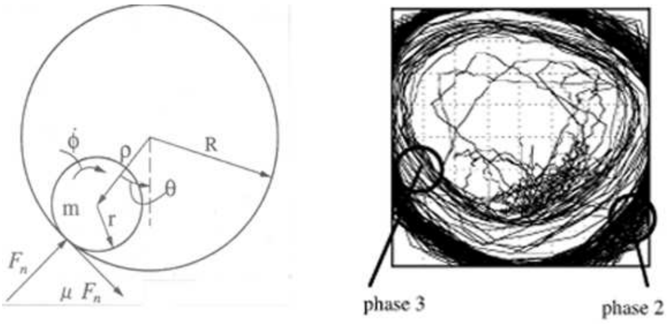

Fig. 10 Left: Variables for describing the touch-down dynamics of the rotor within the stator: rotor speed $\dot{\Phi}$, whirl velocity $\dot{\theta}$, air gap ρ, mass of the rotor m, normal force F_N and friction force μF_N. Right: motion of the rotor center within a circle with the radius of the airgap (0.3 mm). The backward whirl is initiated by a drop down of the rotor, [7].

Smart Machines Machines can be termed *smart* when their internal capability of sensing, actuating and information processing is used in an extensive way. This leads to better functionality with features such as self-calibration, self-diagnostics, self-tuning, self-corrections, and eventually, it leads to less maintenance and higher safety. The smart machine in Fig. 11 consists of three main parts. One is the *Actual Mechatronic System*, the real machine with its process, sensors, actuators and the controller. The second part is the *Mechatronic System Model*, a software representation of the real machine, built up by using identification techniques. The model, or a part of it, will be used for designing, modifying or reconfiguring the control of the real machine. The third part describes the *Smart Machine Management*. It indicates the additional functions that can be incorporated into the system by making smart use of the available information. Figure 12 shows the application of the smart machine concept to an AMB system, which has been built as a test rig for developing self-tuning procedures for its basic control loop.

The potential of AMB/rotor systems to become fault-tolerant is seen as a general feature of smart machinery, contributing to the already very impressive, but still growing, safety and reliability features of AMBs.

Advanced Applications Advanced applications are a challenge for actual AMB research, promising novel and attractive solutions. Examples are given in Fig. 13 for a nuclear power plant, and in Fig. 14 for the use of high temperature superconductors. AMB’s in aero-engines would lead to the futuristic all-electric, or rather oil-free, airplane [5]. Related research problems on high temperature materials are addressed and referenced in [13]. For the deep-sea exploration of natural gas, compressors will be needed that work autonomously and with minimal maintenance, and AMB equipped machinery is offering such performance [14].

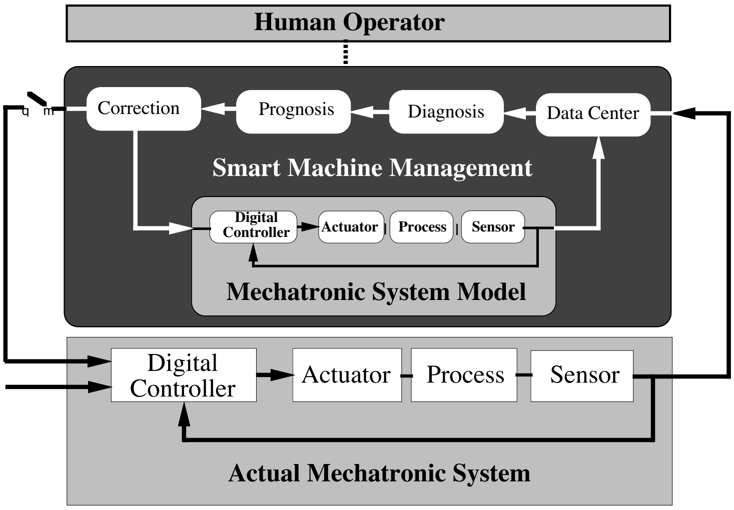

Fig. 11 Structure of a smart machine

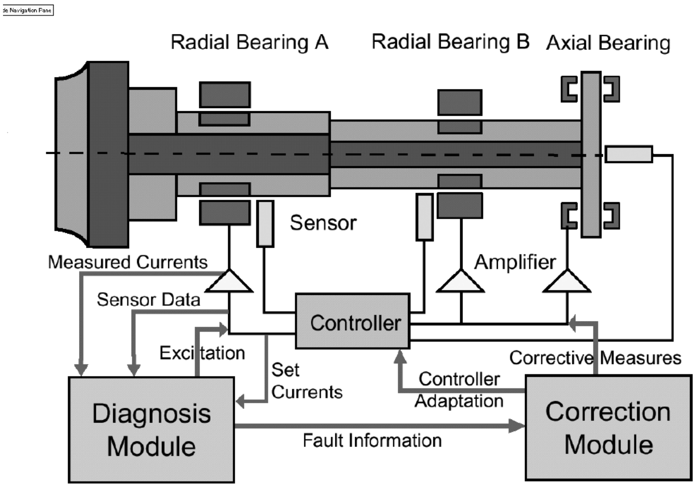

Fig. 12 Rotor in AMB with additional smart machine modules for diagnosis and correction

5 Conclusions

The survey shows, after a brief glance on history and trends, the state of the art for industrial applications of active magnetic bearings in rotating machinery. Main areas are turbo-machinery, most often coupled to directly driven motor/generator units. The advantages are, next to vibration control and high power density, the

Fig. 13 Schematic cross-section of a turbo-generator for a nuclear power plant, the first pebble-bed high temperature gas-cooled test reactor with the gas turbine in the direct cycle (HTR-10GT, under construction, Chinese government key project): 6 MW, 15000 rpm, vertical rotor axis, 4 radial bearings, 2 axial bearings, length of turbine 3.5 m, mass of turbine 1000 kg. (photo courtesy Institute of Nuclear and Novel Energy Technology INET, Tsinghua University, Beijing, [16]).

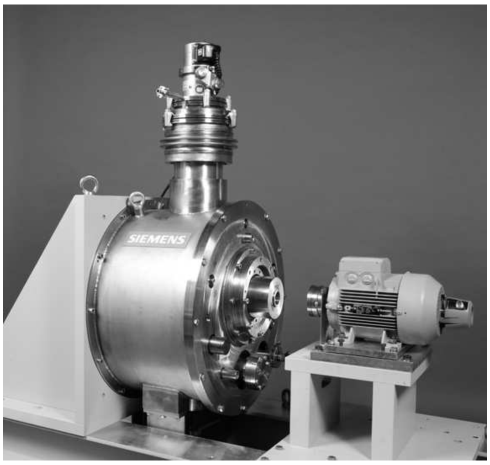

Fig. 14 Test rig for a superconductive bearing designed for a 4 MVA HTS synchronous generator, bearing capacity 500 kg, maximum speed 4500 rpm. In the temperature range below 60 K the bearing capacity remains almost constant. The bearing, initially cooled down to 28 K, can still be operated for additional 2 hours without cooling (photo courtesy SIEMENS, [10]).

absence of contamination by lubrication and mechanical wear, low costs for energy and maintenance, and high lifetime.

Five research topics are addressed and illustrated by examples: high-speed rotors, the control of elastic rotors, touch-down dynamics, the smart machine concept, and advanced applications. These include applications of AMB for nuclear power generation, superconductive bearings, aeroengines, and underwater compressors for natural gas exploration.

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