State of the Art of Magnetic Bearings*
(Overview of Magnetic Bearing Research and Applications)

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Magnetic bearings levitate, suspend and guide rotors by magnetic forces without physical contact. The non-contact support offers many advantages and opportunities for a wide variety of applications. Since the First International Symposium on Magnetic Bearings was held in Zurich in 1988, this field of research has expanded, and competition in research and development has been very keen. This review presents the recent trends in applications, control methodologies, sensorless controls, bearingless motors, unbalance control, problems of flexible rotors, eddy current properties and power amplifiers.

Key Words : Magnetic Bearing, Modeling, Measurement and Control, Electromagnetic Actuator, Rotary Machinery

1. Introduction

Magnetic bearings levitate, suspend and guide rotors by magnetic forces without physical contact. They are constructed in various ways. The non-contact support offers many advantages and opportunities for a wide variety of applications.

Studies of magnetic bearings started in the 1930's, and since the 1980's active control type magnetic bearings have been investigated vigorously. Since the First International Symposium on Magnetic Bearings was held in Zurich (1988), which encouraged the exchange of information among scientists, this field of research has expanded, and competition in research and development has been very keen.

In 1996, the Fifth International Symposium on Magnetic Bearings was held in Kanazawa, Japan, at which the latest results of investigations were presented(1).

This review presents recent trends in magnetic bearing research.

2. Applications

Because magnetic bearings support rotors without physical contact, they have many advantages, e.g. frictionless operation, less frictional wear, low vibration, quietness, high rotational speed, usefulness in special environments and low maintenance. On the other hand, disadvantages of magnetic bearings include the expense of the equipment, the necessity of countermeasures in case of a power failure, and instability in their control systems. However, there are many applications which utilize the above merits.

Examples of applications are : turbomolecular pumps, high-speed spindles for machine tools, textile spindles, hydroelectric plants, flywheels for energy storage, reaction wheels for artificial satellites, magnetic optical bearings, gyroscopes, optical choppers,

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disc drives for data storage, optical scanning devices for instruments, centrifuges, centrifugal compressors, turbo compressors, turbo expanders, cryogenic turbomachines, high temperature blowers, gas turbine engines, LNG pumps, blood pumps, fluid pumps, water pumps in site ion exchange effluent plants (SIXEP) and water treatment compressors.

3. Control Methodology

Magnetic bearings are essentially unstable, multivariable and time varying mechatronic systems, whose properties cause various problems, e.g. stabilization, gyroscopic effect, imbalance vibrations, rotor elasticity, estimation/sensing. Suitable control approaches are required to combat each problem, and magnetic bearings also provide exciting opportunities from the point of view of theoretical studies of control.

In fact, various control methods have been applied to magnetic bearing systems, and they are classified into several categories, e.g. robust control, modern control, nonlinear control, adaptive control, classical control and digital control.

3.1 Robust control

Recent advances in robust control have enabled us to design controllers for multivariable systems that are more forgiving of uncertainties and perturbations in models. The use of the H_∞/μ approach for control designs in magnetic bearing systems has been investigated by Nonami, Knospe, Herzog, Bleuler and the authors of this review, and as a result of their efforts, the robustness of the systems seems to have improved.

For flexible rotor magnetic bearings, Nonami has extensively applied advanced robust control theory, e.g. LMI-based gain scheduled H_∞ control(2), mixed H_2/H_∞(3) and μ-synthesis(4). Knospe and Fujita utilized μ-synthesis to design a robust controller for AMB systems(5),(6). Matsumura scheduled the H_∞ controller gain by using the free parameter to reject imbalance vibration(7),(8).

3.2 Modern control

Because active magnetic bearings are multivariable systems, a state-space approach is effective to control interference from the gyroscopic effect.

Ahrens designed control systems for a flywheel by LQR and compensated for the gyroscopic effect(9),(10). Lee utilized frequency-shaped optimal control to improve the unbalance response(11), and Mizuno designed an observer-based regulator and constructed a self-sensing magnetic bearing(12).

3.3 Nonlinear control

The magnetic force shows hysteresis and nonlinearities. Hence nonlinear control and linearization methods have been investigated with keen interest.

Charara examined both input-output linearization and sliding mode control to compensate for the nonlinearity of the magnetic force in a simple magnetic suspension system(13). Using the property of flatness, Lévine proposed a novel differential geometrical approach for controlling magnetic bearings(14). Queiroz modeled a magnetic bearing as a nonlinear system and designed a nonlinear controller using a backstepping approach to achieve global exponential rotor position tracking(15). Further, applications of sliding mode control and VSS observer have been studied by Rundell(16), Nonami(17) and Tian(18).

3.4 Adaptive control

Multivariable and complicated properties of magnetic bearings makes identification and model validation more difficult. Lum presented an adaptive autocentering control to compensate for rotor imbalance(19).

3.5 Classical control

We cannot deny that the classical frequency shaping approach is still a powerful approach for practical industrial use.

To avoid vibrations due to imbalance, Herzog extended a generalized notch filter that is inserted into the multivariable feedback(20).

3.6 Digital control

Recently there have been significant developments in the digital control of magnetic bearing systems, due to advances in high-speed and high-accuracy digital and parallel processors.

Knospe and co-workers discussed the details of multitasking implementation for digital controllers by using floating-point DSP(21). Ponsart(22) and Zhou(23) utilized a transputer and constructed parallel processing environments, and Bühler discussed the merits/demerits of various combinations of input/output signals(24).

4. Sensorless (Self-sensing) Control

To reduce sensor cost, physical space and non-collocation problems between the actuator and sensor, a new idea of using the magnetic actuator as gap sensor has been introduced. The basic idea had been proposed in the early period of the research. However, a major impact was made by Visher and Bleuler(25) who used the voltage driven magnetic bearing to measure the resulting current. Both signals are fed into the observer to estimate the gap displacement. A state-space model of a magnetic bearing is shown in Fig. 1. The idea was extended by Mizuno et al. to include a sinusoidal disturbance observer(26). A practical application to the turbo-molecular pump has also been tested(27).

Instead of using a direct displacement

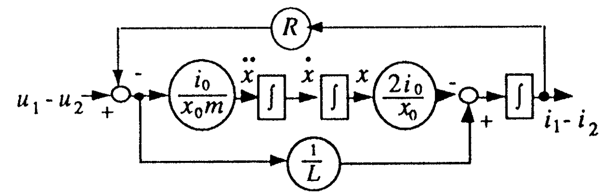

Fig. 1 Transformed state-space model of the SISO-plant for sensorless operation

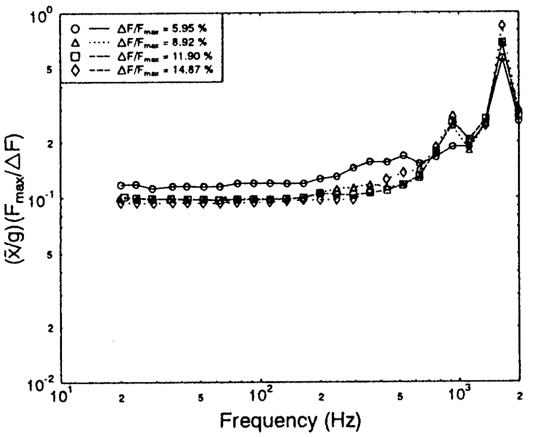

Fig. 2 Estimation error due to duty cycle change of the U. VA. type self-sensing

measurement, the flux is measured to estimate the gap displacement(28). This is not strictly sensorless control, but the goals of reducing the cost and solving the non-collocated problems are very similar. A hole-effect sensor is used to measure the flux, but the biggest problem is that the hole-effect sensor is not reliable.

A high power magnetic bearing is usually controlled by changing the duty ratio of the PWM power amplifier. An electromagnet changes its inductance according to the gap displacement. A PWM carrier frequency component is used to estimate the gap displacement(29). This technique has been further developed by Noh and Maslen, who improved its dynamic response and accuracy(30),(31). The estimation error due to duty cycle is shown in Fig. 2. The dynamic response is close to 1 kHz and the accuracy is very good. The first application of their technique is its installation in the implantable artificial blood pump(32). A magnetically levitated centrifugal pump is highly sought for the blood pump. The sensor is better to be removed by a self-sensing technique. A novel idea using a hysteresis amplifier has been proposed by Mizuno et al.(33),(34). The technique uses a hysteresis PWM amplifier as shown in Fig. 3. An electromagnet changes its inductance according to the size of the airgap, and hence the PWM frequency of a hysteresis amplifier is a function of the airgap. This frequency

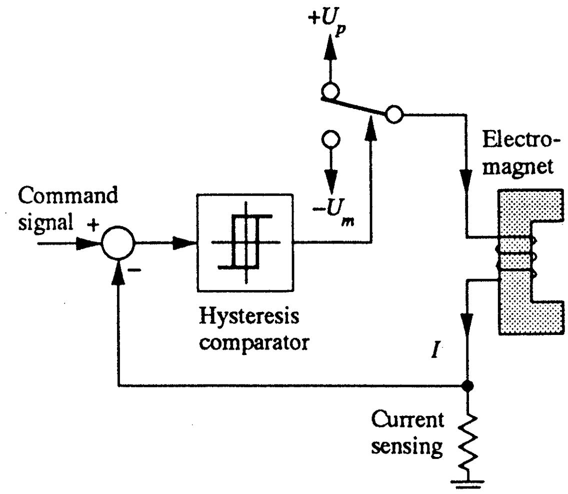

Fig. 3 Schematics of hysteresis amplifier driving circuit

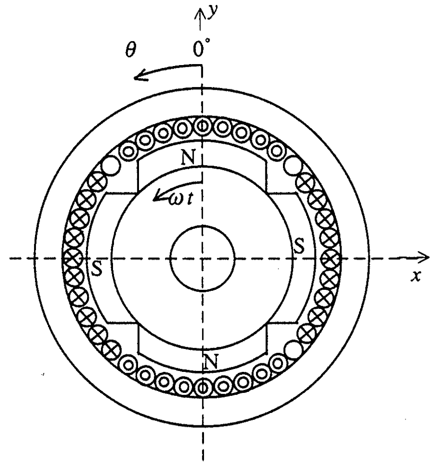

Fig. 4 Schematics of the PM motor with current sheet stator

information is used to control the magnetic bearing.

A differential transformer self-sensing technique has been developed by Matsuda and Okada(35). The technique is intended to be operated with the bearingless motor.

5. Bearingless (Magnetically Levitated) Motor

A new technique of combining a magnetic bearing and an AC motor has been proposed. The first successful report is a description of a PM type synchronous motor by Bichsel(36). Similar work has begun on a reluctance motor by Chiba(37) and also on a PM motor by Okada(38) and an induction motor by Schöb(39). The fundamental theory for this is as follows: Suppose an N pole pair motor and a stator are a current sheet which can produce an arbitrarily distributed magnetic flux. The PM type motor in which $N=2$ is shown schematically in Fig. 4. This N pole pair current in the stator imparts a rotating

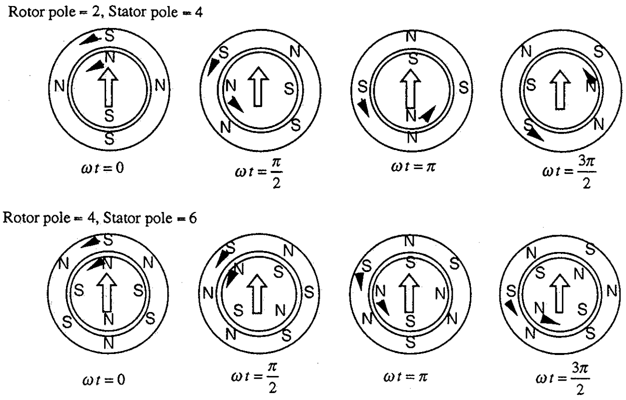

Fig. 5 Two examples of the generalized solution which imports a levitation force to the stator

torque to the rotor, while the $N+1$ or $N-1$ pole pair current in the stator produces a levitation force at the rotor[38]. Two examples of the PM motor are shown in Fig. 5.

This technique has generated much interested among researchers, and the technical improvements are progressing rapidly. However, the efficiency and the top speed of the bearingless motor are still insufficient. Several papers were reported at the Fifth Int. Symp. on Magnetic Bearings[40)-(46]. Among them, the improvement of the motor and achieving a more powerful and faster motor are the main topics[41),(42),(44)-(46]. But applications to real machines were also reported[40),(43]. The most interesting report is the application of the motor to the artificial blood pump[40]. A constant flow type centrifugal pump is eagerly sought for the artificial heart pump. However, the contact point must be removed to prevent thrombosis. An important feature of a bearingless motor is its ability to drive and support a pump without physical contact[40]. However, the proposed pump is planned for use outside the human body and only during operations[40]. An implantable blood pump for life-long use has become an important subject of research. For this purpose, a bearingless motor is planned to support and rotate the pump impeller[47]. Other interesting studies reported before this symposium include the developments of a very small bearingless motor[48] and an electrostatic suspended motor[49].

6. Unbalance Control

Vibration due to unbalance is one of the most serious problems to be solved in the area of magnetic bearing control. An unbalance in the rotor mass can not completely be removed. Hence vibration always exists in rotating machines. Two major methods are available to solve the problems caused by unbalance.

The first method is to compensate for the forces arising from the unbalance by generating magnetic forces that cancel those forces. Nonani and Sivrioglu have investigated the gain-scheduled H_∞ control technique against the problem of unbalance using an LMI approach[2]. Matsumura changed the H_∞ controller gain with respect to the rotational speed of the rotor using the free parameter to possess high gain at the rotational frequency[7),(8].

The second method is to make the rotor rotate around its axis of inertia (automatic balancing). No unbalance forces are generated in this case. Herzog proposed a generalized narrow-band notch filter that is inserted into the multivariable feedback[20]. This approach is very practical and effective to compensate for unbalance.

7. Flexible Rotor

A magnetic bearing is considered adequate to support a flexible rotor. This is not true in practice. The reason for this is that the supporting force is weak and hence the bearing must be larger. The rotor tends to become strong and solid. The actuator response is insufficient to control high frequency vibrations. In the symposium, there were several papers related to the control of flexible rotors. Some of them are related to modeling and identification of the rotor[50),(51]. However, the main area of research is how to control the higher frequency vibrations[3),(17),(18),(52)-(54]. The most common approach is to treat the higher modes of vibration as an error in the model and to apply robust control theory[3),(17),(18]. Two interesting related approaches are to apply the robust controller to attenuate a specific point response[53] or to apply disturbance attenuation[54]. These topics are still the most interesting area of research, and the number of papers appearing is expected to remain high for the future.

8. Eddy Current Properties

Magnetic flux in the iron core of magnetic bearings varies with rotation and radial vibrations of the rotor, as well as with changes in the exciting current. This flux variation produces an eddy current in the iron core, which induces damping efficiency and delays in the control response.

The standard 5-axis controlled magnetic bearing employs laminated sheets for radial bearings and solid cores for axial bearings. The laminated core of radial bearings generates very low eddy currents, but this current imparts a vibration damping to the rotor vibration. This damping is very small, but the vibration is a serious problem when the rotor is used in a vacuum vessel, or if rotors are used in a flywheel energy storage device.

Matsumura[55] studied the relationship between magnetic pole arrangements of radial magnetic bearings and magnetic loss by Fourier analysis of magnetic fields. Two magnetic pole arrangements, NSNSNSNS and NSSNNSSN, were compared, and the analytical and experimental results showed the loss in NSSN is considerably smaller than that in NSNS.

Applying modern magnetic analysis theory strictly, Meeker[56], Ahrens[57] and Rockwell[58] presented analytical results for the loss caused by eddy currents in the Fifth International Symposium on Magnetic Bearings. Allaire[59] investigated the power loss in heteropolar and homopolar machines experimentally and concluded the loss in homopolar machines is smaller than in the heteropolar.

The delay of magnetic flux for magnetic voltage and/or current is a very important subject to achieve stability and high stiffness in the system. It is well known that eddy currents in the iron core may be strictly modeled by a distributed parameter system. But the lumped parameter model of the system is convenient for the design of control systems.

Yukitake[60] proposed a novel expression of the eddy current as shown in Fig. 6(a) and evaluated its effect by comparing the results of the simulations with those of the experiments. Experimental values agreed well with the theoretical results only in the low frequency range. They did not agree at high frequencies. Hence further improvement is expected.

Meeker[61] derived an equivalent circuit by considering eddy current, leakage flux and fringing effects. The result is an infinite chain constructed with resistances and inductances, and he assumed the circuit can be represented by the finite state variable model shown in Fig. 6(b). For control system design, however, he employed a simple 1st order model with

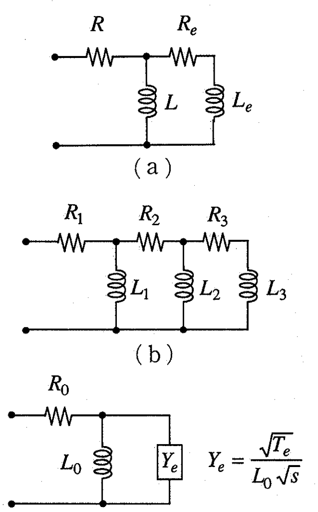

Fig. 6 Models of eddy current

R and L and proposed to treat L as a parameter that varies with frequency.

Miyashita[62] proposed another equivalent circuit to represent the effect of eddy current (Fig. 6(c)). This equivalent circuit agrees relatively well with the experimental system in all frequency ranges, but the design of the feedback controller for this model is difficult.

To achieve stable and high speed responses if eddy currents exist, dynamic studies in this field are needed. Hara[63] proposed a flux feedback method using a search coil signal or an electromagnetic voltage signal with a 1st order low-pass filter and showed an improvement in dynamic response.

9. Power Amplifier for Magnetic Bearings

Electromagnets usually have a large inductance and a small resistance. To power them, two types of amplifier, a switching amplifier or a linear power amplifier, are usually utilized.

Almost all switching amplifiers employ PWM methods having two or three voltage levels. As a novel approach, 1-bit $\Sigma-\Delta$ modulation was proposed by Higuchi[64] using digital control.

A class A linear power amplifier has the advantage of noiseless operation in the high frequency range, but electric power is inefficient. On the contrary, a class G power amplifier employs a power supply with two different voltage levels, and the power efficiency is thereby improved. Carabelli[65] proposed a modified class G power amplifier which also improved the power efficiency.

10. Superconducting Magnetic Bearings

Recently high temperature superconductors were discovered and have been developing rapidly. Applications of supercoducting magnetic bearings have become a center of attention.

Takahata[66] discussed a hybrid system constructed with active magnetic bearings and superconducting magnetic bearings which are composed of permanent magnets and superconducting devices, and applied this system to a flywheel energy storage system with 1 kWh. More detailed research is expected to determine if this system can be constructed with only permanent magnets and superconducting devices.

11. Conclusion

Recent trends and an overview of magnetic bearing research and development are discussed in this paper. Research on control methods, methods of suspension and rotation, and various properties has made remarkable progress. However, applications have not yet been expanded to a similar extent.

Continued fundamental scientific investigation of magnetic bearings is expected. On the other hand, we sincerely hope that all possible effort will be applied to solving the practical problems and reducting production costs.

We will be pleased if this review contributes to the continued development of magnetic bearings.

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