特 集 3
研究解説
UDC 62-5.5：537.3

Magnetic Levitation: A Challenge for Control Design in Mechatronics
磁気浮上：メカトロニクスにおける制御設計の試み

Hannes BLEULER*
ハネス ブロイレル

Magnetic levitation is classified and it is shown that the industrially apploed active levitation is a typical mechatronics system. The important control problems for active magnetic bearings are then presented and current research areas are indicated.

1. Introduction: Magnetic Levitation, Active Magnetic Bearings and Mechatronics

The connection between magnetic levitation and mechatronics may not seem obvious at first sight. In view of current industrial applications, however, this connection is not only very strong, but active magnetic levitation actually is an excellent example to illustrate what mechatronics is all about.

In section 2 many different magnetic levitation principles are shortly presented. There are passive ones (levitation without control) and active ones (those which require closed-loop control to stabilize the levitation). In todays industrial applications the active types by far outnumber the passive types precisely because of their mechatronics specific character.

Therefore, from the application point of view, "magnetic levitation" has become almost synonym with "active magnetic bearing" (AMB), the topic of this report. The term bearing is usually used for rotor bearings, where most applications are found, although other applications of magnetic levitation are important as well. Magnetic levitation for vehicles is usually called MAGLEV, there are much less comercial realizations of MAGLEV than of AMBs. The basic levitation principles are the same for MAGLEV and AMBs, although in application oriented engineering the two fields have grown distinctively different. For instance, MAGLEV are usually larger in size, use larger air gaps, have different disturbance forces and use acceleration sensors on the levitated object. Passive levitation schemes are sometimes applied for MAGLEV, almost never for rotor bearings. Future developments might see some more applications of passive magnetic levitation. MAGLEV is not the main topic of this report.

What characterizes the AMB as a typical mechatronics system? The AMB contains mechanical, electrical and electronic components. The electronic components treat the information about mechanical variables obtained from sensors and they act on the mechanical system through actuators, the power amplifiers and the electromagnets.

The main difference between a mechatronic system and a simple electro-mechanical system is the information processing capability built into the electronics and the embedding of this capability in the sensor-controller-actuator feedback path. The controller, now usually digital, contains the "intelligence" of the system in its software, i.e. the ability to intelligently react and adapt to operating conditions in the widest sense.

Thus mechatronics can be defined as an electromechanical system with sensors, information processing capability and actuators. To design a mechatronics system, skills in many different fields are necessary. The following list contains the most important ones, the first four being basic to any mechatronic system:

mechanical engineering,
electrical engineering
electronics
control engineering
software engineering
physics
optics

---

*Toshiba Chair for Intelligent Mechatronics

It is seen that AMBs fit perfectly into this definition of a mechatronic system.

The unique advantages of AMBs are the absence of any mechanical contact, controllable dynamics, operation without wear and thus drastically reduced maintenance cost, high rotational speeds, integration of complete systems, new design possibilities. Current industrial applications of AMBs include vacuum and clean room technology, machine tools for high precision and high performance, turbomachines.

After a brief overview of (active and passive) magnetic levitation principles in section 2, this report describes why control design for AMBs is particularily challenging (section 3).

2. Principles of Magnetic Levitation

It is proposed to distinguish eight magnetic levitation principles which can be divided into two main groups$^{1)}$. The first group operates with materials of different magnetic permeability μ. the magnetic force involved is usually called reluctance force. The second group is based direcltly on Lorentz force

$$f = i \times B \qquad (1)$$

with the electric current i and the magnetic flux density B.

The reluctance force devices include what is here called the "classical" AMB with an electromagnet, a gap sensor and a control loop to stabilize the levitated position (Fig. 1). This type (Fig. 2 type 1) has by found most practical applications, the active control loop is to be considered not as a drawback, but as an asset of this levitation system, giving it its unique advantages.

Other types of reluctance force levitation are passive and have thus found far less applications. Repellent forces are achieved either with permanent magnets or with diamagnetic material. Repellent permanent magnets do not allow contact-free support in all six mechanical degree of freedom of a rigid body.

Diamagnetic effects are usually so weak that they are only of academic interest (Fig. 2 type 3). There are two important exceptions: For very small scales or with super conductors, practical diamagnetic levitation is possible. Maybe best known is the Meissner Ochsenfeld effect of super-conductors. This levitation type (Fig. 2 type 4) is a diamagnetic effect, since superconducting material can be described as having zero magnetic permeability.

Tuned LC bearings$^{2)}$: This is a passive electromagnetic bearing (Fig. 2 type 2). It has been extensively used for gyros in aerospace applications in the 1960s. The operation principle is the following: The inductance of an electromagnet varies in function of the air gap between rotor and magnet. This inductance can be included in a LC circuit and excited by an AC power source slightly off

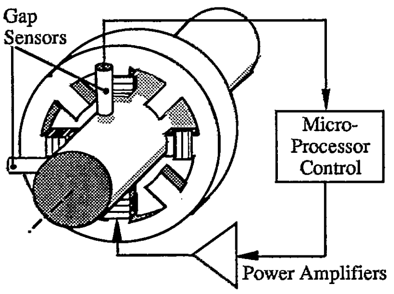

Fig. 1 Functional principle of the classical AMB

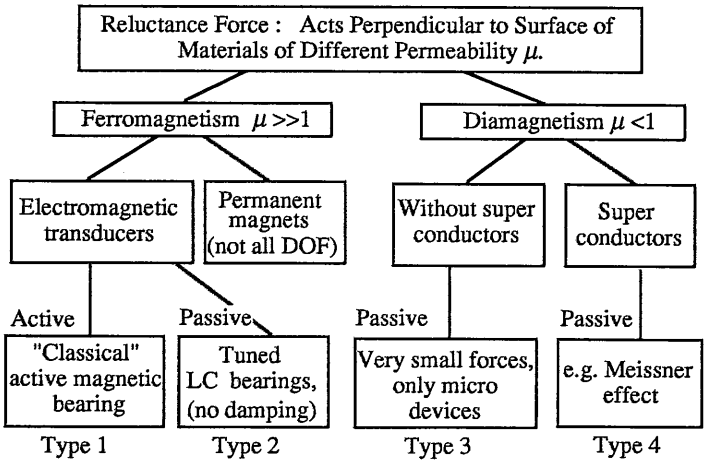

Fig. 2 Reluctance force magnetic levitation principles

resonance in such a way, that it approaches resonance when the rotor moves away from the electromagnet. Approaching resonance will result in a current increase which, in turn, will produce a restoring force on the rotor. A positive stiffness can thus be obtained, although the stiffness is not very high. The main drawback of such bearings has been the complete lack of damping, which is why they have to be externally (mechanically) damped. According to the mechatronics definition above, such a bearing would be an electro-mechanical and not a mechatronics system, similar to an electric motor, as it has no sensors and no information processing.

The active Lorentz-force bearings, in the second group of magnetic levitation devices, work in a manner very similar to most electrical machines. In a synchronous machine the rotor is magmetized and the driving torque (force couple) is composed of Lorentz-force components acting on the current distribution in the stator windings. by changing the arrangement of the stator current flow, it is possible to exert not only a couple, but a radial force component as well (Fig. 3). In order to obtain stable levitation, a gap sensor and a control loop has to be provided, just as for the classical AMB. It is also seen that the distinction between "levitation" and "suspension" (repellent or attractive forces respectively) becomes meaningless for Lorentz forces which are transverse to the air gap. This is why we use "levitation" in a wider sense for all kinds of contact-fee support.

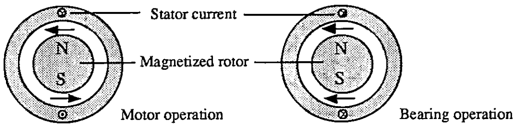

Fig. 3 Active Lorentz-force bearing principle

The control force direction of such bearings depends on the angular position of rotor magnetic flux, an additional rotational phase sensor is therefore necessary and the control algorithm is more complex than in the case of the classical AMB.

Such a bearing has been built[3]. The combination of motor and bearing in a single unit is most interesting for industrial applications as it results in space saving. A similar combination is conceivable for the induction motor. These two bearing types are listed as type 7 and type 8 in fig 4.

Moving coil levitation is of course possible, but it has not been studied for rotor levitation as it would require either a current source and a controller on the rotor or some way of transmitting significant amounts of current to the rotor. A sliding contact would destroy many advantages of contact free levitation.

In addition, there are two passive types of Lorentz-force levitation listed as type 5 and type 6 in Fig. 4. In type 5, levitation occurs only at high relative motion between rotor and stator. This type is intensively investigated for certain MAGLEV vehicles. For this application, low-temperature superconducting magnets are currently necessary on the vehicle in order to achieve sufficient field strengths. Passive levitation starts at about 100 km/h.

The relative motion can be replaced by AC power (type 6). If no superconductors are used, the eddy current

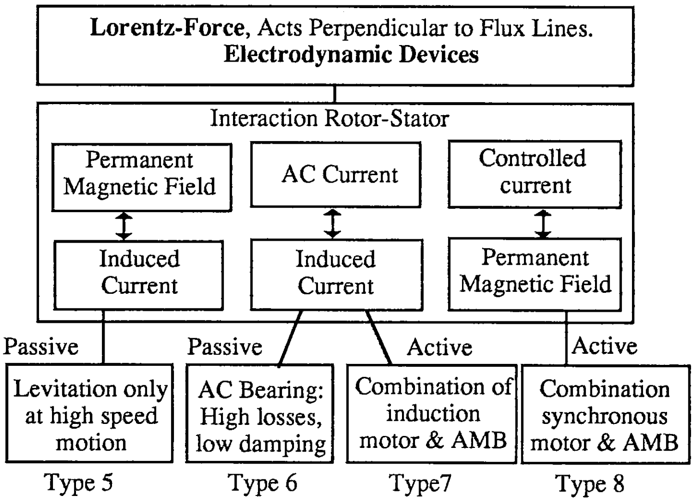

Fig. 4 Lorentz-force levitation priciple

losses of this bearing type are prohibitively high for practical application, levitation takes place only a short time. Induction melting of levitated probes is however possible.

Industrial magnetic levitation is dominated by the type 1 "classical" AMB, that is with an active control loop. The next section shortly describes the control task and its challenges. The other two active bearing types (7 and 8) need a similar control with some additional features not described here.

3. The Control of AMBs

3.1 Stabilizing the Highly Unstable Plant

A conventional mechanical support is characterized by stiffness and damping. Stiffness is the coefficient between displacement and the reaction force of the deformed support, the root of the ratio of stiffness to mass defines an oscillation frequency and the damping (force-velocity factor) quantifies the time-constant of the fading out of the free mechanical vibration.

Mechanical stiffness is a force opposed to displacement. A magnet behaves differently, it attracts a body more the closer it gets. This force, directed in the same direction as the displacement, is the source of the fundamental instability of the equilibrium point of a permanent magnet or an open-loop electromagnet. The controller has to compensate for this destabilizing negative stiffness and then, in addition, provide some positive stiffness of its own. Moreover it has to provide the damping force. Due to nonlinearities, the system with stiffness alone will not behave as a simple spring-mass oscillator, it will instantly go into unstable vibration, especially if high stiffness is desired.

As the sensor usually measures the gap, damping has to be created by differentiating the displacement signal. This is sensitive to noise in the sensor signals and the differentiator has to be carefully designed for good results. Control hardware and cutoff frequency of the controller need to be adapted to given plant and the desired performance.

A better method to obtain a velocity signal is the state estimator, a standard control layout method. AMB control provides a good experimental platform to practice state feedback and state estimation in a "real world" environment. The trade-off of higher complexity versus better performance of the state estimator as compared with a PD control can be investigated and the influence of estimator pole placement can be studied. It is seen how the apparent freedom of design exists only in theory. Once confronted with a practical system, the choices become very limited and great skill is needed to find the design best suited to a given system and controller hardware.

Control realization is mostly digital for obvious reasons. For magnetic bearing systems the influence of time delay is felt very severly because of the importance of the damping force component. This component is a lead-compensator, the velocity signal has a 90° phase lead over the displacement signal. Any delay between input and output (AD-DA conversion, calculation, wait-cycles) directly decreases this phase lead and significantly deteriorates the damping effect of an "ideal" controller.

This is why we have used signal processors for AMB control. The reduction of samping time and time-lag from the range of a few milliseconds to about 100 μ sec is very significant even for relatively heavy mechanical equipment where one would otherwise excpect "slow" time constants.

The linearization is treated in the following manner. As well known, the magnetic bearing characteristics is described by highly nonlinear equations relating force, current and displacement. Neglecting leakage flux and hysteresis and assuming all magnetization energy is concentrated in the air gap, the following basic equation can be obtained:

$$f=\frac{i^2}{(x-x_0)^2} \tag{2}$$

with magnetic force f, coil current i, nominal air gap x_0, displacement x as shown in Fig. 5.

A strict linearization of formula (2) in the controller would require square root functions and a multiplier. This is however not a good solution. The square-root function has infinite slope in the origin, which in practice would require infinite gain in the operating point $i=0$ (or $f=0$). This is of course not realizable, the engineer doing this has pasted over a fundamental hardware problem by software tinkering.

A better approach is to note that the system becomes

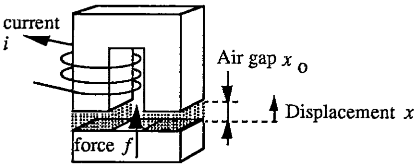

Fig. 5 Variables for magnetic bearing equations

uncontrollable in the point $i=0$. This operating point can be compared to a singular point in robotics kinematics and it is better to redesign the system to avoid such a point. Therefore, magnetic bearings are usually operated with a bias current. Linearization is done around the new operating point without problems, a square-root linearization is then unnecessary although the true force-current characteristics is still a parabola and not a staight line.

3.2 Elastic Rotor, Non-Minimum Phase System

High stiffness means high controller gains which in turn means that potentially much energy is put into the system over the actuator. Realizing high bearing stiffness is therefore sensitive and difficult to realize. The main problem in high stiffness magnetic bearing control comes from the fact that a rigid-body model for the rotor is not suitable. The structural elasticity of the rotor is not neglectable, high stiffness AMBs designed for rigid rotors will excite bending modes of the rotor.

The mechanical model of a rotor including structural bending elasticity increases from order 8–10 to at least 20 or more. Accurate modelling will require a knowledge of FEM techniques and a good feeling for mechanical engineering issues. One has to deal more deeply with modelling and control, for instance order-reduction, spill over effects, identification. State feedback with full-order observer is only a theoretical solution, more generalized output feedback methods with restrictions on controller structure have to be used.

Even modern robust control layout methods such as $H\infty$ quickly show their limits. One of the main difficulties comes from the fact that the transfer function from actuator to sensor or from actuator to effector of an elastic structure is non-minimum phase, i.e. it contains zeros in the complex right half plane. A physical interpretation of this is the following: Exponentially increasing input signals can be found, which, when acting at the actuator, cannot be detected at the output. The control of such systems is known to be especially difficult, even for the most modern and generalized methods, as was recently aknowledged by one of the main authors behind the so-called "post-modern" control theories[4),5)].

3.3 Rotor Dynamics and Unbalance Treatement

The next challenge to AMB control engineer comes from the rotordynamics. Two effects are of special interest. First, the plant model and the eigenvalues depend on rotation sprrd. Second, there are strong, but well structured disturbance forces such as the unbalance effects.

The behavior of a rotor with its forward and backward whirl motion is of course well known in classical rotordynamics. The AMB control engineer must be familiar with the fundamentals of rotordynamics. The possibilities of determining the bearing properties through the controller software opens up a whole field of studies which has an old tradition at the IIS through the works of the Higuchi Lab.

Keywords to be mentioned in this context are periodic learning control, adaptive control, feed-forward compensation. Recent publications are [6)] and [7)]. It is obvious that optimal results are obtained only by five-tuning the controller hardware and software using all the knowledge available.

General procedures are not enough.

3.4 Position-Sensorless Active Bearings

Up to now, coil current i was treated as control variable, i.e. input variable to the plant. Of course, every electrical engineer knows that for the magnetic bearing as an inductive load, the current i is a state variable and not an input variable. It is physically impossible to achive a step in the current. The true input variable is voltage and not current. In an improved modelling, all coil currents are state variables and the order of the system is accordingly increased.

The control engineer thus has to decide, when the simplification of treating the current as input is feasible and when the more complex voltage-input model has to be used. It seems that there are many potential advantages of using voltage as input variable and a thorough assessment of the situation is one of the most pressing issues where very little work has been done.

A most interesting spin-off of voltage controlled bearing is the position sensor-less AMB. It has been found[8),9)] that this plant is observable from current measurement alone. Two such bearings have been realized and they show very promising features such as high static load, minimal hardware and potential for virtual zero-power control. Although once tuned, they are robust to disturbance forces and noise, the tuning of the controller of such bearings is still very difficult and it may be called a true challenge to the control engineer.

4. Conclusion

The purpose of this paper was to show that AMB development is far from being a "closed" chapter. There are several very interesting control issues to be solved and the potential for industrial applications is vast. Among the application areas we are interested in are clean-room and vacuum handling, precision optics, scanning, machining and turbo machines.

New fields of research are emerging such as micro-scale AMBs, in which a project has been started. Other current research includes indentification and control methods and the position sensorless bearing.

Acknowledgment

I would like to express my gratitude to Professor Higuchi for inviting me to Japan and to Toshiba company for financing the Intelligent Mechatronics chair at the IIS.

(Manuscript received, October 5, 1992)

References

1) H. Bleuler, JSME Int. Journ Series III, Vol. 35, No. 3, Sept. 1992
2) T. Higuchi and J. Jin: "Realization of Non-Contract AC Magnetic Suspension", 34th Jap. Joint Automatic Contr. Conf (SICE and IEEE AC Tokyo), Keio Univ, Tokyo 1991
3) J. Bichsel: "Beitraege zum Lagerlosen Elektromotor" PhD thesis, Diss ETH Nr 9303, Swiss Federal Institute of Technology (ETH), 1990
4) J.C. Doyle, Bruce A. Francis, Allen R. Tannenbaum: "Feedback Control Theory", Mac Millan Publishing, 1992
5) J.C. Doyle: Tutorial lecture held at MOVIC Yokohama, Sept. 1992
6) R. Larsonneur et al., Int. Conf. on Rotordynamics IMechE, Bath U.K., Sept 1992
7) H. Bleuler, R. Larsonneur, T. Mizuno: "Periodic Disturbance Treatement for AMB Rotors", Int. Symp. on Theory of Mashines and Mechanisms, Nagoya, Sept 1992
8) D. Vischer: "Spannungsgesteuerte und Sensorlose Magnetlager", Doctor thesis, ETH Zurich, 1988
9) Mizuno, Bleuler, MOVIC Yokohama, Sept. 1992