A Survey of Magnetic Levitation and Magnetic Bearing Types*

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Magnetic levitation has been studied mainly in two distinct fields of application, MAGLEV transportation and rotor bearings. A unified overview, as it is attempted in this paper, reveals that there are many radically different types of magnetic levitation. A systematic classification of these basic levitation principles is proposed. It starts from the fundamental manner to obtain the magnetic force. The systematization derived in this manner aims at including all possible basic magnetic levitation types. As a result some little known levitation types are included, among them Lorentz-force bearings and tuned LC bearings. As a special feature, a new type of active bearing is presented, the so-called self-sensing active bearing using no gap sensor. This remarkable bearing type combines high static load and low hardware costs. Examples of realizations are given.

Key Words : Magnetic Levitation, Magnetic Bearings, Electromagnetic Actuators, Electromechanical Systems, Lorentz Force

1. Introduction

Magnetic levitation has two main fields of application: Transport systems and rotor bearings. Of these two, MAGLEV vehicles may be better known to the public, but rotor bearings are much better established in actual applications. Up to now, there has been only little contact between specialists of the two fields.

Only a few examples of commercial transportation systems applying magnetic levitation are currently operating, although this might be changing in the future.

Magnetic rotor bearings on the other hand have already accumulated more than a decade of actual industrial applications in most various fields ranging from vacuum and space technology to machining, pumps and turbines.

In both fields, MAGLEV and rotor bearings, the engineer can choose from an array of quite different principles of magnetic levitation. Motor-bearing combinations have been proposed. Superconductors can be applied.

A survey of all the different techniques reveals that one specific type of rotor bearings is up to now by far the most successful. This should not detract one from having a close look at all the different levitation principles. The systematic and synoptic overview of the different principles reveals some little known techniques which might have a great potential for future applications.

There have been very few publications up to now⁽¹⁾⁻⁽⁴⁾ attempting to list the various known levitation methods in some systematic manner.

2. Definition of Magnetic Levitation

In accordance with Hollis, Salcudean and Allan⁽⁵⁾⁽⁶⁾, it is proposed to call the levitated object "flotor", since it is not necessarily a rotor. The following empirical definition is proposed: Magnetic levita-

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tion is a stable hovering state without any mechanical contact, where the gravitational force is balanced by magnetic forces only. The position of the flotor has to remain stable when subject to "reasonable" disturbance forces. The contact-free levitation must take place for all rigid body degrees of freedom.

Sometimes⁽¹⁾, a distinction is made between magnetic suspension (referring to systems based on attractive magnetic forces) and magnetic levitation (referring to systems based on repellent magnetic forces). This distinction may seem obvious. However, this restricted sense of the two terms does not cover all types of contact-free magnetic support. Lorentz-force bearings will be introduced, where the force is not *across* the air gap, but *transverse*, i.e. in the direction of the air gap. The distinction between levitation and suspension then completely loses its meaning. Therefore it is suggested to use the term "levitation" in a more general sense, covering all, attractive, repellent and Lorentz-force devices. This broad usage of the term "magnetic levitation" has been common practice in most publications.

3. Two Basic Types of Magnetic Force

A force f on an electric charge Q results according to the basic law

$$f = Q(E + \nu \times B) \quad (1)$$

with the electric field E and Q moving at velocity ν in a magnetic flux density B . The complete form of Eq. (1) was established by the dutch physicist Hendrik Antoon Lorentz (1853–1928)^{*1}.

The energy density of feasible electrical fields in macroscopic technical arrangements is usually smaller by a factor of about 10^5 compared with the energy density of feasible magnetic fields. A similar difference of scales results for forces in the usual, technically reasonable equipment, therefore the electrostatic term is not considered further in this paper, although it becomes important at the micro-technology scale.

The movement of the electric charges can either follow from quantum effects or from a macroscopic current i . In the first case, engineering practice, when not concerned with atomic or subatomic scale, has found a nice way around dealing with quantum physics by describing the media with the magnetization constant $\mu = \mu_r \mu_0$ with μ_r depending on the material. Such materials are subject to a magnetic force called here "*reluctance force*" to distinguish it from the

"*Lorentz force*" obtained in the second case, with the macroscopic current i . In this case, the Lorentz force law is simplified to the familiar cross-product

$$f = i \times B \quad (2)$$

Thus, the term "Lorentz force" is here used only in the restricted sense of Eq. (2), not in the general sense of Eq. (1).

The reluctance force is obtained from the *principle of virtual work* in arrangements of different magnetic permeability μ . The force is computed from

$$f = \partial W / \partial s \quad (3)$$

with the field energy W and a virtual displacement ∂s of the supported body. A magnetic force of this type always arises at the surface of media of different relative permeability μ_r , e.g. iron and air. The force direction is *perpendicular to the surface of the different materials*. The greater the difference of μ_r , the greater the force f . The designation "reluctance force" is common in the literature on electric machines⁽⁷⁾. In German literature on electric machines, this radial force component is sometimes called "Maxwell tension" per surface area of iron⁽⁸⁾. It is proposed to keep the term reluctance force because it contains a hint as to the origin of this type of force. Furthermore, the term is familiar. In contrast to reluctance-force devices, the field energy of Lorentz-force devices is not changed with the geometric displacement of the flotor.

Table 1 sums up the differences of the two force types relevant in our engineering context. The "basic dependence" entries are meant to be only general relationships. The exact formulation depends very much on the given technical arrangement and various operation conditions.

4. Four Basic Reluctance Force Magnetic Levitation Types

Different levitation mechanisms can first be classified according to the value of the relative permeability μ_r of the material involved (ferro-, para- or diamagnetic). Of these, only the ferromagnetic and the Meissner-Ochsenfeld effect are of technical interest. Paramagnetic as well as diamagnetic effects without superconductors produce very small forces and are therefore of academic interest only.

Ferromagnetic devices are realized with electromagnets or permanent magnets, they can be purely passive or actively controlled. All four possible combinations are investigated, i.e. active electromagnets, passive electromagnets, active permanent magnets (by actively controlling the position of the "stator" magnet) and passive permanent magnets. These types are now shortly described. They are found in Table 2 as types 1 through 3.

*1 Actually, the magnetic effects themselves are nothing but a consequence of Einstein's theory of relativity applied to the interaction of moving electrical charges.

4.1 Type 1: Active Magnetic Bearings (AMB) of reluctance force type

The basic setup of this bearing type is well known: Position signals from gap sensors are used by a controller-power amplifier unit to set the appropriate currents and voltages of the electromagnets in such a way, that stable levitation takes place. It is called "active" because it needs the control loop and the actuator for stabilization.

The designation "active" does not refer to the actual force-displacement characteristic realized. It is of course possible to emulate a "passive" force displacement characteristic (i.e. stiffness - damping behavior) with an "active" magnetic bearing. This is

however just one possibility of AMB control layout, there is an unlimited freedom in designing the force-displacement characteristics, e.g. by shaping the frequency domain behavior of the controller or by playing on the sensor positions and the input variables to the controller.

This type of bearings has found the widest range of practical applications among all magnetic levitation types. There have been several international conferences focusing exclusively on this topic⁽⁹⁾⁻⁽¹¹⁾.

An application example (milling spindle, R. Siegwart⁽¹⁰⁾) is given in Fig. 1. The force per bearing surface area when not using superconductors, reaches about 40 N/cm² of bearing surface. Active magnetic

Table 1 The two types of magnetic force computation used in practice.

	Group 1: Reluctance Force	Group 2: Lorentz-Force
basic computation principle	energy in magnetic field, principle of virtual work	cross-product of current and flux density
Computation formula	$f = \partial W / \partial s$	$f = i \times B$
Direction of force	perpendicular to the surface of materials of different μ_r	perpendicular to flux density
Basic dependence on current and air gap	quadratic to current inverse quadratic to air gap	linear when current and flux are not depending on each other, independent of air gap
Other pairs of names found in literature	electromagnetic alignment principle Maxwell Force	electrodynamic interaction principle Lorentz force

Table 2 Classification of magnetic bearings and magnetic levitation

rotor bearings of up to 30 tons load capacity have been built and reported⁽¹²⁾.

The rapid increase of popularity of this type of AMBs has several reasons. On a basic level, one might cite the freely selectable stiffness and damping characteristic and the free positioning of the flotor within the air gap. On the system level, the main advantages might be summarized as follows: An active bearing can adapt itself to operating conditions and can communicate with its environment.

As an example, a rigid body can be made to rotate about its principal axis without transmitting vibrations to its foundation. Bending vibrations of an elastic rotor can be significantly reduced through an appropriately designed active control loop⁽¹³⁾. Precise information on load force, unbalance, vibration amplitude etc. is available on-line, can be stored, processed or sent from a remote site. Rotating machinery is integrated into an industrial process through intelligent interaction. Such advantages have proven decisive for industrial applications.

Research in the field of this bearing type still produces new and surprising bearing types. An example is given in section 6.

4.2 Type 2: Tuned LCR circuit bearings

This bearing type achieves a stable stiffness characteristic in an LC-circuit excited slightly off resonance. The LC-circuit is formed with the inductance of the electromagnetic bearing coil and a capacitor. The mechanical displacement of the flotor changes the inductance of the electromagnet. The LC circuit is operated near resonance and tuned in such a way, that it approaches resonance as the flotor moves away from the electromagnet. This results in an increased current from the AC voltage source and thus pulls the flotor back to its nominal position. The forces and stiffnesses obtained are not very large, but sufficient for certain instrumentation applications. Since it is stable without control loop, it is called "passive", although it dissipates energy. The power supply con-

sists of an AC source operating at a constant frequency.

The main drawback is that there is no damping, i.e. without additional measures such as mechanical damping or active bearings such systems tend to go unstable. They have been used for gyros in aerospace application^{(14),(15)}, but now that powerful controllers can be realized at relatively low costs their main advantage of not using an active control does not balance the drawbacks. This is why they are today a kind of "outsider" although they are still being investigated⁽¹⁶⁾.

4.3 Type 3: Ferromagnetic permanent magnet bearings (without super conductors)

Without active control, passive permanent magnet systems are not able to keep a levitated body's position stable in all degrees of freedom. Such permanent magnet bearings without control loop can only be used to reduce the load of a conventionally borne shaft. They have been widely applied e.g. for household electric energy counters. Some other applications are in combination with active electromagnetic bearings, e.g. turbo-molecular pumps for very high vacuum^{(9),(10),(17)}. In such applications, the disadvantage of relatively low damping of the passive bearing versus the active ones becomes apparent. It is much easier to reduce the vibration amplitude at the active bearing than at the passive one.

An arrangement for indifferent equilibrium is given in⁽⁴⁾, but this has to be considered unstable from the practical point of view. For maglev vehicles, they have been proposed in conjunction with a mechanical magnet position controller on the vehicle using a stator guide rail and guide wheels⁽¹⁸⁾.

It is however possible to achieve true (i.e. stable in all degrees of freedom) magnetic levitation with permanent magnets, when the position of the "stator" magnet is actively controlled with some conventional mechanical motion control⁽¹⁹⁾. As in the type 1 AMB, a gap sensor produces the input variable to the con-

Fig. 1 Example of type 1 AMB application: Rotor of a milling spindle for 40000 rpm, 35 kW, load force at cutting tool 1000N, rotor weight ca. 20 kg, diameter at front radial bearing 96 mm

troller.

4.4 Type 4: Diamagnetic devices and Meissner-Ochsenfeld effect

The fourth type of devices relies on the *diamagnetic* effect ($\mu_r < 1$). Only the diamagnetic effect of superconductors (Meissner-Ochsenfeld effect) is strong enough to produce forces of technical interest. Although at the present time still at the laboratory stage, industrial applications are foreseeable in the not too distant future. Technically interesting arrangements have been proposed and high rotational speeds have been reached by Moon and his co-workers^{(20),(21)}. Current research aims at increasing the mass of the supported object, optimizing the geometry and finding entirely new arrangements, designs and applications. The future looks very promising. Several groups are working in this field.

At present time however, active electromagnetic bearings are a long way ahead as far as industrial applications are concerned. Some of the key advantages of actively controlled bearings can not be matched by purely passive bearings, therefore it does not seem that active electromagnetic bearings will be replaced on a large scale by Meissner-Ochsenfeld effect bearings, although it is safe to predict a significant increase in the application of this type of levitation for both, linear and rotational motion, e.g. in clean room handling devices or related equipment.

This concludes the classification of the reluctance force magnetic levitation devices.

5. Four Basic Lorentz Force Magnetic Levitation Types

The remaining four levitation methods (to the right of table 2) rely directly on the Lorentz-force law. They are grouped according to the source of the macroscopic current i in the cross-product formula (2). This current can be either induced or actively controlled.

In the first case, there are two possible mechanisms of induction: Either there is an interaction between a permanent magnetic field and a moving conductor, or the interaction takes place without relative motion, between a conductor and an AC powered electromagnet. These two basic arrangements are labeled "type 5" and "type 6" in Table 2.

In the second case, the current i in the cross-product formula (2) is an actively controlled current interacting with a magnetic field. There are again two possibilities: Either, the magnetic field is produced by a permanent magnet or there is an interaction between the controlled current and an induced current. These two levitation types are labeled "type 7" and "type 8" respectively. Note that these two levita-

tion types correspond exactly to the basic electric motor types of the synchronous machine (with a permanently magnetized rotor) or an induction motor. In order to produce radial forces instead of torque, the currents must be actively controlled in function of the displacement.

These four basic Lorentz-force levitation devices are now shortly described.

5.1 Type 5: Passive electrodynamic levitation of systems in relative motion

Electrodynamic levitation occurs without active control when high eddy currents are induced at a sufficiently fast relative motion of stator and rotor. Such bearings have been thoroughly studied for high-speed vehicles and occasionally for rotor bearings. Unfortunately, losses seem to be very high when reasonable levitation forces are to be achieved and when normal conductivity is given. In order to obtain the high flux densities necessary for economic operation, superconducting permanent magnets are usually used on the vehicles. This type of levitation is extensively presented in many books, e.g.⁽¹⁾ or⁽³⁾, there are many dedicated conferences⁽²²⁾ and other publications in the field of vehicle levitation are abundant.

A great variety of prototype maglev vehicles has been built, some of them with passive electrodynamic levitation of type 5 and some of them with active electromagnetic suspension of type 1. This seems to be the reason, why it is often assumed, that electrodynamic bearings are passive while electromagnetic levitation is presumed to be active. A look at Table 2 disproves this notion.

5.2 Type 6: Interaction of AC and induced current, passive system

If the relative motion is replaced by an alternating flux, a similar type of passive levitation as type 5 can be obtained. Again, at normal conduction, the levitating force produced by induced eddy currents is relatively weak compared to the power losses. At the same time, such bearings (sometimes called AC-bearings) have poor damping properties^{(9),(23),(24)}. These two major and fundamental drawbacks are the reason, why such bearings are not applied in industry, although a few very special applications are conceivable.

The next two bearing types, belonging to the class of active Lorentz-force bearings, are known in principle^{(5),(6)}, but their full potential as rotor bearings has not yet been realized. Rotor bearings of this type have been pioneered by Bichsel^{(25),(26)}. In his doctor thesis a detailed comparison of the "conventional" (reluctance force) AMB and the Lorentz-force AMB is carried out. As expected, the maximum force depends on a variety of factors very specific to the

actual application.

As general remarks, it can be noted that the capacity of the reluctance force AMB depends mainly on a small air gap and a high saturation flux of the iron while the Lorentz-force AMB needs a high current. A high current means heating up the bearing coils, therefore it can be said, that the Lorentz-force bearing has a high peak force, but in continuous operation a "conventional" AMB will be superior if the air-gap is reasonably small. For an actual machine, the two bearing types seem very roughly equivalent, the final decision over which one is better for a given application depends heavily on the circumstances. The Lorentz-force bearing for rotating machinery is more difficult to realize than a conventional AMB, but the relative price of the control software decreases for large series and large machines. On the other hand, two motor-bearing combinations on one shaft with type 7 or type 8 bearings are shorter than combinations of two classical radial type 1 bearings and a usual electric motor, so here again, the comparison of reluctance-force and Lorentz-force does not lead to a generally valid preference for one or the other type.

5.3 Type 7: Interaction of AC and induced current, active system

The induction motor has a very good efficiency, therefore the tangential force components producing the driving torque have the potential of summing up to efficient radial forces with an appropriate control of the stator currents. Through an elaborate control scheme and/or through additional windings, forces on the rotor can be produced in such a way that the resulting total effect is not only a couple about the rotor axis, but contains also a radial component. This radial component is controlled according to gap sensor signals, just as in the case of the reluctance-force AMB. The efficiency of such a system can be expected to be in the same order of magnitude as the efficiency of an induction motor. It is therefore a dramatic improvement over the type 6 passive levitation.

All desirable properties of active bearings, especially high damping and versatility, can be achieved readily with such a bearing. Application of modern digital control can take care of the appropriate current control. This type of bearing is a Lorentz-force AMB, it is different from a combination of reluctance-force AMB and induction motor as it has been realized by Wehberg⁽²⁷⁾. A combination of the two principles is conceivable.

5.4 Type 8: Interaction of controlled current and static flux

This bearing type is similar to the previous one except the fact, that the induced current of the rotor

is replaced by a permanently magnetized rotor. Such a Lorentz-force AMB has been realized by Bichsel^{(25),(26)} with his synchronous-motor-bearing combination. The device consists mainly of a standard moving-field industrial motor of 2.4 kVA rated power with three pole pairs on the permanently magnetized rotor. The stator was modified and holds the usual windings for driving the rotor and additional windings for creating radial forces. His work proves that practical magnetic rotor bearing designs along the idea of type 7 and type 8 are not only realizable, but that such bearings also have the potential for industrial applications.

A Lorentz-force magnetically levitated robot wrist of levitation type 8 has been proposed by Hollis and Salcudean^{(5),(6)}. This is another interesting application field for such bearings which is completely different from rotating machinery applications.

6. The Self-sensing AMB

Probably the most radical departure of the "classical" active magnetic bearing is the following configuration, which still belongs to the type 1 levitation. It is possible to realize such a bearing *without using a gap sensor*. The theory behind this new bearing type is simple to explain: In place of the current-amplifier (common for type 1 rotor bearings), a voltage amplifier is used. It can be shown theoretically, that the bearing-rotor system is *observable with the bearing current as the only plant output variable*^{(28),(29)}. The current is measured in the amplifier and the rotor can actually be stabilized by using this measurement only. The reason, why this has not been noticed might be the following: The rotor-bearing community is interested in simple control systems, usually a current amplifier is built and it is assumed that the force is proportional to the current. The MAGLEV-community on the other hand is much more concerned about an efficient use of the maximum power of the amplifiers, in that case a voltage amplifier is preferred and the coil inductance is not disregarded in the dynamic model of the system. However, MAGLEV control is very demanding, so that there is not much incentive to remove the gap sensors. On the contrary, in order to improve the quality of MAGLEV support, additional accelerometers are often used.

Using the voltage controlled MAGLEV model a simple one-degree of freedom test model with analog control has been realized. It has some very interesting features. It is robust enough for many applications, although the tuning of the controller is still difficult. But once the correct controller has been found, it is very robust against all kinds of disturbances and it has a very high static load capacity. This is because

the active air-gap under static load is smaller and not larger, as with the conventional AMB. In other words: Pushing down the flotor makes it move up (after an initial drop) and vice-versa. It features an inherent "zero-power" operating point as it is the current and not the position which is brought to zero in the equilibrium. Together with a permanent-magnet bias, this could be most interesting for many energy-critical applications.

A full degree of freedom rotor system with digital control has also been realized as self-sensing bearing, i.e. without gap sensors and research on this bearing type is currently being done.

7. Conclusion

A systematic classification of magnetic levitation methods is proposed. It is based on the type of magnetic effect and on the possible basic technical arrangement for contact-free levitation. Technically interesting solutions for magnetic levitation rely either on active control or on the use of superconductors. Among those two, superconductor devices are still at an early stage of laboratory testing, but the future looks promising. Active bearings on the other hand provide a great variety of very desirable features, *just because they are active*. It is therefore not surprising that this bearing type is being applied on an increasingly significant scale in various industrial machines including large compressors, machining, cryogenic, vacuum and clean-room equipment.

The systematic classification proposed here leads one to consider some basic bearing types which are not well known at the present: Lorentz force bearings (active electrodynamic bearings), as combinations of active bearings and inductance motors or active bearings and synchronous machines. They could have the potential for industrial applications.

The self-sensing bearing has the potential of low cost realization because it needs no sensing hardware at the rotor. At the same time, it has a high static load capability.

References

- (1) Jayawant, B. V., Magnetic Suspension and Levitation, E. Arnold Publishers, London (1981)
- (2) Jayawant, B. V., Electromagnetic Suspension and Levitation, Rep. Prog. Phys., Vol. 144 (1981)
- (3) Sinha, P. K., Electromagnetic Suspension, Dynamics and Control, IEE Control Engineering Series # 30, P. Peregrinus Ltd, London, (1987)
- (4) Jung, V., Magnetisches Schweben, Springer, Berlin, (1988)
- (5) Hollis, R. L. and Salcudean, S. E., On the Design and Control of Magnetically Levitated Robot Wrists, Robotics and Manufacturing, recent trends in research, education and applications, Proc. 3rd Int. Symp. Robotics and Manufact. Vol. 3, ASME Press New York, (1990)
- (6) Hollis, R. L. and Salcudean, S. E., A Six Degree of Freedom Magnetically Levitated Variable Compliance Fine Motion Wrist, 4th Int Symp on Robotics Research, Santa Cruz Ca, Aug. (1987) in Robotics Research, Vol. 4, MIT Press.
- (7) Del Toro, V., Electric Machines and Power Systems, Prentice Hall, (1985)
- (8) Kpfmller, K., Einfhrung in die theoretische Elektrotechnik, Springer, Berlin, (1984)
- (9) Schweitzer, G. (ed), Magnetic Bearings, Proc. 1st Int Symposium on Magnetic Bearings ETH Zurich, Springer, (1988)
- (10) Higuchi, T. (ed), Magnetic Bearings, Proc. 2nd Int. Symposium on Magnetic Bearings, Univ. of Tokyo, (1990)
- (11) Allaire, P. (ed), Proc. ROMAG Conference on Magnetic Bearings and Dry Gas Seals, Washington D.C. (Univ. of Virginia), (1991)
- (12) M. Dussaux in Proc. 2nd Int. Symposium on Magnetic Bearings (10)
- (13) Larssonneur, R., A High Speed Rotor in Active Magnetic Bearings, Proc. 3rd Int. Conf. on Rotordynamics, IFToMM, Lyon, (1990)
- (14) Frazier, R. H., Gilinson, P. J. and Oberbeck, G. A., Magnetic Suspension, MIT Press, (1974)
- (15) Parente, R. B., Stability of a Magnetic Suspension Device, IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-5 No. 3, May, (1969), p. 474
- (16) Higuchi, T and Jin, J., Realization of Non-Contact AC Magnetic Suspension, 34th Jap. Joint Automatic Contr. Conf. (SICE and IEEE AC Tokyo), Keio Univ., Tokyo (1991)
- (17) Bleuler, H. and Bernhardt, H., New Concepts for Contact-free Support of Industrial High Speed Rotors, Proc. 3rd Int. Conf. on Rotordynamics, IFToMM, Lyon, (1990)
- (18) Abe, M. (1989), A Study on Fundamentals of Mechanically Controlled Permanent Magnet Levitation System for Maglev Transport Vehicle, in (22)
- (19) Higuchi, T., Oka, K., (1991), Active Magnetic Levitation Mechanism Using Permanent Magnets with a Fast Servomechanism, Proc. 35th Annual Conf. of Jap. Instrument, Systems, Control & Information Engineers, Kyoto Japan (Abstract English, paper Japanese)
- (20) Moon, F. C., Chang, P.Z. (1990), High-Speed Rotation of Magnets on High Tc Superconduction Bearings, Appl. Physics Lett. 56, 397
- (21) Chang, P.Z. (1991), Mechanics of Superconducting Magnetic Bearings, Dissertation, Cornell Univ., Ithaca N. Y.
- (22) 1st Int. Conf. on Magnetically Levitated Systems and Linear Drives, Maglev' 89, Yokohama, Japan
- (23) Nikolajsen J. L., A Magnetic Bearing based on Eddy Current Repulsion, NASA CP 2443 Rotordynamic Instability Problems in High Perform-

- mance Turbomachinery, (1986), p. 460.
- (24) Nikolajsen, J. L., Palazzolo, A. B., Electrodynamic Force Application in Rotordynamic Research in Electrodynamic Forces and Applications, Proc. 3rd Int. ISEM Symp., Sendai, Jan. 1991, J. Tani and T. Takagi (editors), Elsevier, Tokyo, (1992)
 - (25) Bichsel, J. (1990), Beiträge zum lagerlosen Elektromotor, doctor thesis No. 9303, Swiss Federal Institute of Technology, Zurich
 - (26) Bichsel, J. (1991): The Bearingless Electrical Machine, Int. Symp. on Magn. Susp. Techn., NASA Langley Res. Center, Hampton VA
 - (27) Wehberg, J. (1991), Elektrischer Antrieb und integrierte magnetische Lagerung am Beispiel eines hochtourigen Rotors, doctor thesis, Technical Univ. of Braunschweig, Germany
 - (28) Vischer, D. and Bleuler, H., A New Approach to Sensorless and Voltage Controlled AMBs Based on Network Theory Concepts, Proc. 2nd Int. Symposium on Magnetic Bearings, T. Higuchi (ed.), Univ. of Tokyo, (1990)
 - (29) Bleuler, H. and Vischer, D., Magnetic Bearing Systems with Minimal Hardware Requirement, in Proc. ROMAG Conf. on Magn. Bearings and Dry Gas Seals⁽¹⁾, (1991)

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