Stiffness Of Magnetic Bearings

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1. ABSTRACT
The chance to apply magnetic bearings depends on the possibility, to improve their static and dynamic performance. Intensive considerations on the dynamic performance of magnetic bearings made clear, that the stiffness depends on the dynamic performance of the
- measuring system,
- electronic controller,
- power-electronic devices and
- the eddy currents in the iron core of the bearing.

The paper shows the theoretical description of the dynamic performance of a magnetic bearing. From these are derived demands to the above mentioned components.

2. INTRODUCTION
With frequency controlled inverters it became possible, to increase the rotor speed of asynchronous motors over 3000 rpm. New technologies became of interest.

There was a demand for increasing the speed of bearings.

Magnetic bearings are applicable for a rotor speed, which is with conventional bearings not or only with a high additional expense to be achieved. Magnetic bearings have the advantage, that there are no mechanical contacts. Because there is no mechanical friction only small losses and temperatur rises appear. No sealings and no lubricants are necessary.

The maximum of rotor speed depends only on the strength of the used rotating materials.

Because of this advantages magnetic bearings can be a technical and economical advantageous alternative to mechanical bearings.

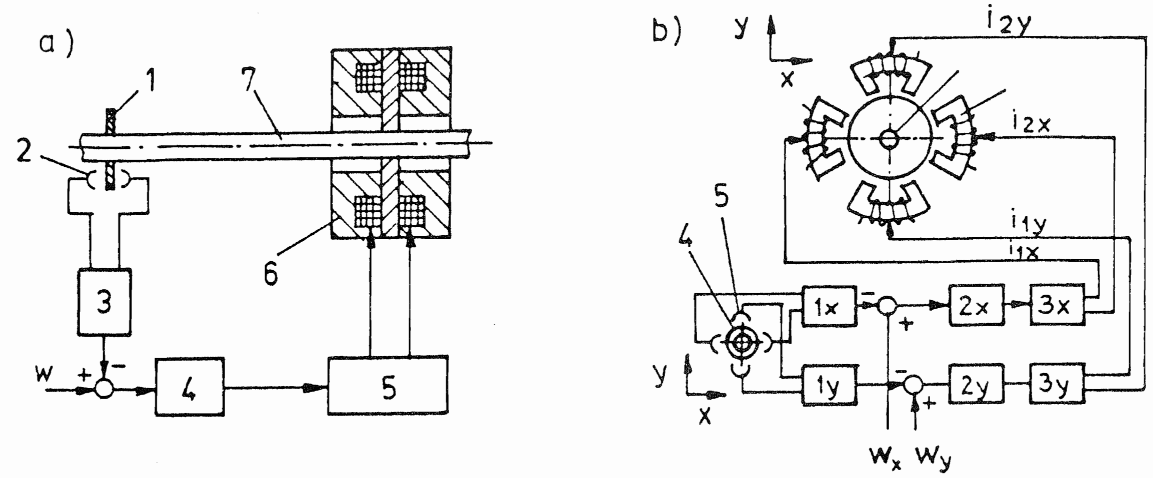
3. PRINCIPLE OF THE CONSIDERED BEARINGS
There are two types of magnetic bearings, active and passive ones. The principle of active magnetic bearings is the contactless influence on the shaft position by electromagnets, which give attractive forces to the rotor. Because the system electromagnet - rotor is instable, it is necessary to stabilize the shaft position with a closed loop system.

In the following are only considered active magnetic bearings. Fig. 1 shows the principal design.

An axial and a radial magnetic bearing with the position-control-loop is to be seen in the figure.

Contactless inductive sensors measure the position of the shaft continously. An electronic equipment controls the forces of electromagnets, that the shaft keeps its centre-position also if there are disturbance forces.

The power amplifiers feed the electromagnets with the control-currents. Because of a high efficiency, transistor pulse amplifiers are used.



1 ... distance measuring system
3 ... power amplifier
5 ... inductive sensor
7 ... shaft

2 ... controller
4 ... measuring trace on the shaft
6 ... stator of electromagnetic system

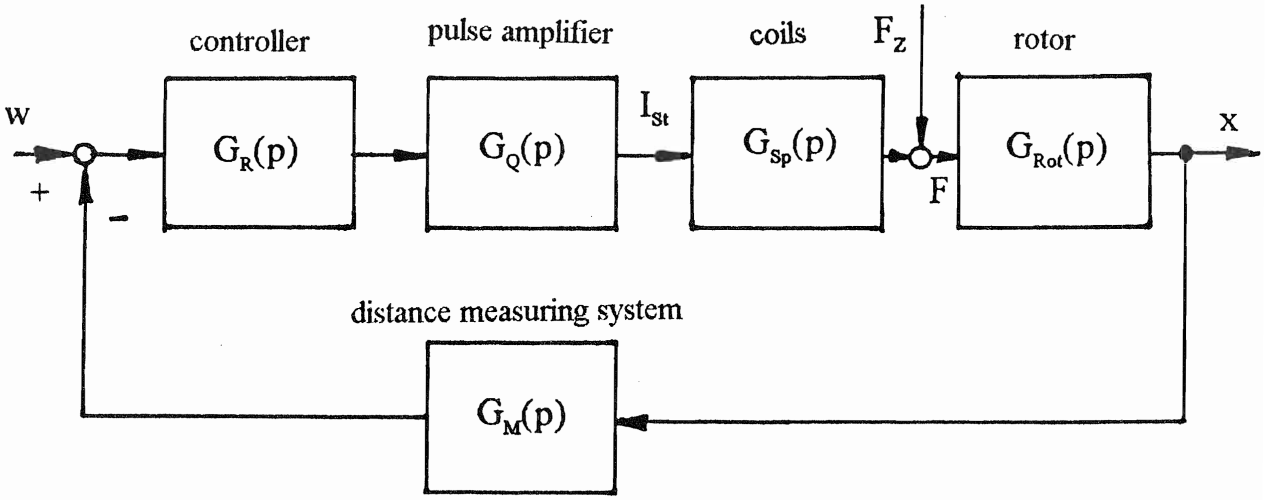
Fig. 1: Principle of an active magnetic bearing
a) axial b) radial

An active magnetic bearing has some advantages in comparison with passive bearings because of the active influence on the bearing force. So the performance of magnetic bearings can be influenced by changing of parametres in the controller, for instance:

- adjustment of the optimal stiffness according to the application
- increasing of shaft centricity even if there is an unballance
- damping of oscillations
- change of shaft position under running conditions.

4. STRUCTURE OF THE CONTROL SYSTEM

For the calculation of the bearing parameters it is necessary to describe mathematically the whole control loop. For this the transition functions of all components are needed. Fig. 2 shows the structure of the control-system.
The distance sensors and the coils are a PT1 - element. The rotor parameters depend on the rotor-geometrie. The current - force - coefficient depends on the electromagnetic design of the bearing.
The achievable gain in the loop significant depends on the time constants of the pulse amplifier T_Q and the coils T_{Fe}.
For small values of T_Q and T_{Fe} is increased the range of stability, the maximum of the pemissible loop-gain and with the last one the dynamic stiffness of the bearing.



Distance measuring system: 20 V/mm, inductive-, capacitive- or eddy-current-measuring system
Controller: PID-structure, analog
Pulse amplifier: current-source, 5 A/V, pulse frequency: 50 kHz

Fig. 2: Structure of the control-loop

5. SPECIAL TRANSITION FUNCTIONS

The transition function of the open control loop is:

$$Go(p) = G_M(p)\, G_R(p)\, G_Q(P)\, G_{SP}\, p)\, G_{Rot}(p) \qquad (5.1)$$

Two special transition functions are of interest for the performance of magnetic bearings:

- the reference input function
- the disturbance error function.

The reference input function shows, how the magnetic suspended rotor follows the reference position signal. It is of interest if the rotor must moved on special traces in the airgap of the bearing. The reference input function reads as follows:

$$Gw(p) = \frac{G_R(p)\, G_Q(p)\, G_{sp}(p)\, G_{Rot}(p)}{1 + Go(p)} \qquad (5.2)$$

The disturbance error function shows, how the magnetic suspended rotor moves if disturbance forces have an influence. The disturbance error function is:

$$Gz(p) = \frac{G_{Rot}(p)}{1 + G_O(p)} \qquad (5.3)$$

The quotient of the bearing force F and the deviation x is the so called stiffness S. It is:

$$S = \frac{dF}{dx} \qquad (5.4)$$

The stiffness also can be calculated as the reciprocal of the absolute value of the disturbance error function:

$$S = \frac{1}{|\,G_z(p)\,|} \qquad (5.5)$$

The stiffness of a bearing depends on the frequency of the disturbing forces. At f = 0 we get the so called static stiffness. Magnetic bearings with an integral part in the controller have a very high static stiffness. It is only limited by the mechanical strength of the shaft.
A static stiffness in the range up to 10000 N/µm has been already measured. Similar ball-bearings or sliding bearings achive values of about 200 N/µm.
If the frequency is f > 0 we get the dynamic stiffness. Values in the range up to 150 N/µm have been already achieved.

6. TIME CONSTANTS IN THE CONTROL LOOP

The effective time-constants in the control-loop-system of an active magnetic bearing have a significant influence on the achievable performance of the bearing. In the following this influence should be investigated and valuated for the example of the dynamic stiffness.

6.1. Time constant of the pulse amplifier

The pulse ampfifier has to drive the control-current through the coils without any delay according to the output of the controllers. Therefore it works in the current-source-mode to decrease the effective time-constant of the exciter coil. The maximum of current rise is determined by the inverter voltage and the inductivity of the coils. It can be derived:

$$\left.\frac{di}{dt}\right|_{max} = \frac{U_{ZK}}{L_{st}} \qquad (6.1)$$

Therefore there is a time constant T_Q which depends on the reference-value of the current. The final pulse-frequency leads to another time delay T_L , which is of dead-time type. It was possible, to get the transition functions by exploitation of the BODE-Diagrams, which were measured for each of the pulse amplifiers.

$$G_Q(p) = \frac{K_Q\, e^{-p\,TL}}{1 + p\,T_Q} \qquad (6.2)$$

with: $T_Q = 150\ \mu s$
(for $U_{ZK} = 300\ V$ and $L_{St} = 2.4\ mH$)
$T_L = 20\ \mu s$ (for $fp = 50\ kHz$)
$K_Q = 5\ A/V$ ($Imax. = 15\ A$)

6.2. Time-constant of the magnetic circuit

Eddy currents damp the alternating magnetic flux in the magnetic circuit. That means, that the magnetic flux in the iron core of the magnetic bearings and the corresponding bearing force can only follow delayed the control-current. This leads to an additional time constant because of the eddy currents in the magnetic circuit. Their influence is to be taken into account by a parallel connected ohmic resistance to the control coils. This resistance must have such a value, that the I^2R losses are equal to the eddy-current-losses in the magnetic circuit.
With the parallel resistance and the inductivity of the control coil the time constant can be calculated:

$$T_{Fe} = \frac{L_{st}}{R_P} \qquad (6.3)$$

This time constant is proportional to the specifical eddy current losses of the iron. In our case it was possible, to realize a time constant of T_{Fe} .= 0.16 ms. The transition function of the coils reads as follows:

$$G_{Sp}(p) = \frac{Ki}{1 + pT_{Fe}} \qquad (6.4)$$

with Ki = 218 N/A and
T_{Fe} = 0.16 ms.

6.3. Time constants of the measuring system

In the control loop of active magnetic bearings appeare other time constants. By use of modern electronic equipment it is possible to keep this time constants small in comparison to the time constants of the magnetic circuit and the pulse amplifiers.

To avoid the differentiation of the distance measuring signals, the radial rotor velocity can be measured as an auxillary control quantity and used to stabilize the control loop. Such a fast auxillary control quantity decreases the effective time constant and leads to a quiet shaft position.

7. SUMMARY

Fig. 3 shows the influence of the time constants of pulse amplifier and magnetic circuit. The maximal achievable dynamic stiffness at the limit of stability of the control loop is to be seen.

The time constants of pulse amplifier and magnetic circuit were varied, whilest all the other parameters were kept constant. Two pulse amplifiers were investigated:

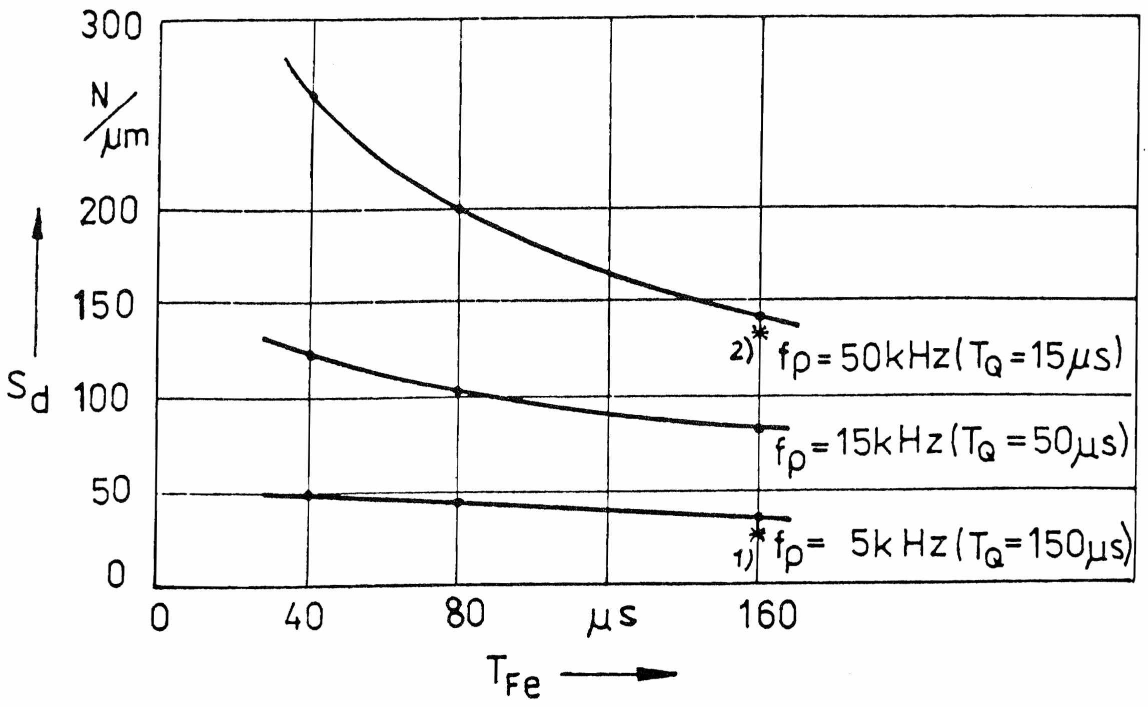


Fig. 3: Influence of the time constants T_Q and T_{Fe} on the maximal achievable stiffness

1*) Pulse amplifier with bipolar transistors, (280 V, 13 A, 5 kHz) Sd = 30 N/µm

2*) Pulse amplifier with POWER-MOSFET, (300 V, 15 A, 50 kHz) Sd = 120 N/µm

The measuring electronic was considered to be free of any delays.
It is to be seen, that the influence of the time constant of the magnetic circuit increases for higher pulse frequencies (that means smaller time constant T_Q). Therefore it is especially by using of fast pulse amplifiers necessary, to make the iron core of material with low specific iron losses and with a small thickness of the laminations.

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