DESIGN OF A MINIMUM CURRENT MAGNETIC BEARING

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ABSTRACT

Current consumption of active magnetic bearings is an essential factor for the running costs and particularly for the acquisition costs. The maximum value of the needed current defines the size of the power amplifier, the diameter of the windings and the size of the slots etc. For the same lifting capacity, size and costs can be reduced significantly by reduction of the current.

This paper analyses the current consumption systematically. At first it shows how the bias current premagnetization can be replaced by permanent magnets. Different constructions are discussed. Furthermore, a control strategy will be presented, which minimizes the DC currents necessary for the support of static loads. The avoidance of currents caused by imbalance compensation has already been discussed in former papers. All three measures together are usable to reduce the current consumption of AMBs significantly. Solely the transient currents are still required.

INTRODUCTION

One criteria to qualify and compare active magnetic bearings is the load capacity in relation to the volume. It is mainly limited by two parameters:

- the losses in the windings
- saturation of the iron in the magnetic circuit

The saturation is a material specific parameter. It can be increased a little by variation of the material. A reduction of percentage of silicon in the iron core material increases the saturation flux density but decreases the specific resistance and causes higher eddy current losses. Materials that include cobalt are very expensive and have a low specific resistance but a saturation density of more than 2T can be reached. Hence the effect of saturation can not be reduced significantly by changing the material without increasing the cost dramatically, the cross-sectional area of the iron has to be enlarged. If the cross-sectional area of the iron is enlarged, there is less space for the copper of the windings. This means less total ampere-turns and less force. The optimal design can only be found iterative. The total ampere-turns are also limited by the specific current density. Because of the cooling conditions, it mostly can not be increased to more than 5-7 A/mm^2.

Reduction of the **power consumption** is the only thing that can be done to increase the load capacity of an AMB at the same volume **overall. Thus, the lifetime cost can be reduced.**

The total power consumption of an magnetic bearing consists of static currents, dynamic and transient currents. Static currents are

- the bias current for premagnetization
- a DC current caused by static loads like the weight of the rotor

the dynamic and transient components are

- a current synchronous to the rotation frequency, caused by unbalance
- transient currents, caused by lifting of the rotor, changes of loads and other transient disturbance forces.

In many cases, the static components have a bigger **share of** the total power consumption than the dynamic ones. If there are mainly static loads, 0.05-0.1 W/N losses are produced because of ohms resistance in the windings[4][5].

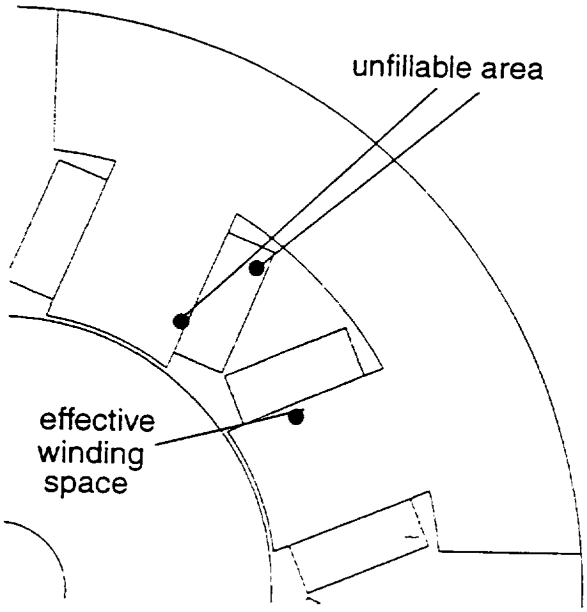


figure 1 Winding space of an AMB

As **already mentioned, the total ampere-turns** depend on the volume that can be filled with copper. As can be seen in *figure 1*, there is some space needed in the slot for isolation and due to the round wire, a bulk factor has to be considered. There is also an area which can not be filled with windings, because the windings are coiled first and than put to the iron core as a unit. Thus, the effective winding space is limited to 75-80% of the slot space [2]. Magnetic bearings with plates from three-phase-motors are coiled slot by slot. Therefore, the whole slot can be filled up with windings and there is nearly no empty space left. This is the reason for higher total ampere-windings of this construction, the effective winding space is more than 90% of the slot space. Together with the availability of this plates, this was the main reason to use this kind of plates in the constructions studied.

All of the named parameters have an influence on the current consumption and load capacity, but do not reduce current consumption as much as the implementation of permanent magnets (PM) does. They can substitute the whole flux generated by the static current. This is mainly the premagnetization, but also static loads con be supported by the permanent magnets. The first is discussed detail in the following three sections, the later is discussed in the section zero DC-current control. **Inbalance** can invoke large amplitudes of harmonic current synchronous to the rotational speed. The reduction of this current by means of unbalance compensation is well known (Herzog et al. [6]). Applying this three measures,

- the **permanent magnetic** premagnetization,
- the zero DC-current control and
- the unbalance compensation,

current will only be needed for dynamic and transient forces and to stabilize the system. Thereby the load capacity per volume relation is significantly increased.

IMPLEMENTATION OF PERMANENT MAGNETS

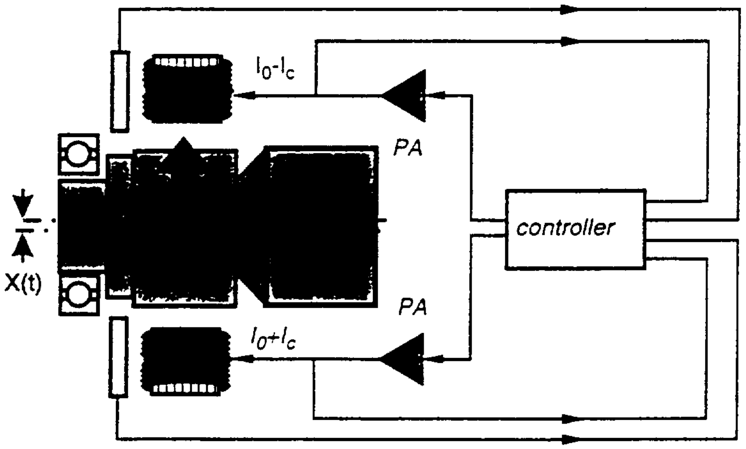


figure 2 principle arrangement of an magnetic bearing

Figure 2 shows the principle arrangement of an magnetic bearing without permanent magnet. There is at least one position sensor to measure the distance between rotor and stator. The position controller drives the current commands to the power amplifier. This allows the rotor to levitate in the desired position. Electromagnetical actuators can only deliver forces in one direction, no matter in which direction the current is driven through the coils. To guarantee correct working of the position control at acceptable dynamic performance, both force directions are needed.

This can be reached by a differential drive of the opposite coils of one axis.

This means that a bias current I_0 is driven **through** both opposite coils of one axis. A positive control current I_c results in a positive force, a negative current results in a negative force for this axis. This arrangement also linearizes the bearing but always needs a bias current which is half of the maximum current, no matter how big the load is.

The constant flux generated by the bias current can also be realized by the implementation of a permanent magnet. This constant flux can be reduced or enlarged depending on the sign of the control current. This results in higher load capacity.

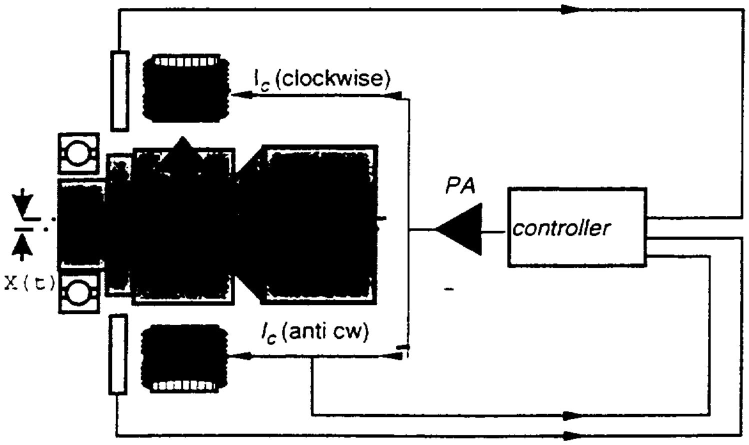


figure 3 principle arrangement of an magnetic bearing with permanent magnet

The permanent magnets can also compensate static forces as described in ZERO DC-CURRENT CONTROL.

Another positive side effect is, that one power amplifier can be economized and for a 4 pole bearing only two power amplifiers are needed, one for each axis.

There are two basic constructions to implement permanent magnets into magnetic bearings: the coplanar and the non-coplanar type. Coplanar means that the flux of the permanent magnet flows in the same plane as the flux generated by the coils. From the analytical point of view, there is a two dimensional problem. Possible arrangements are shown in *figure 8*. The non-coplanar type has fluxes in different planes, this leads to a 3D-problem.

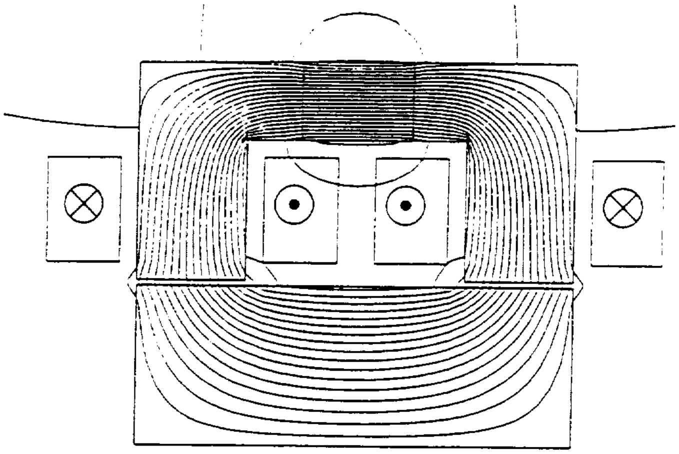


figure 4 finite element calculation of the example shown in *figure 5* with small leakage

As already mentioned, the two fluxes flow in the same plane at an coplanar bearing. Therefore the coil flux has to be driven through the permanent magnets, which are made out of high energy materials like samarium cobalt or neodymium iron boron. This is a problem, because this materials have a very small relative permeability. This means that there is a massive additional air gap for the coil and a higher current is needed to generate dynamic forces.

For coplanar bearings, an easy analytical model can be used to calculate the forces because the flux only flows in two dimensions. *Figure 5* shows the equivalent circuit for coplanar bearing neglecting the nonlinearity of the materials.

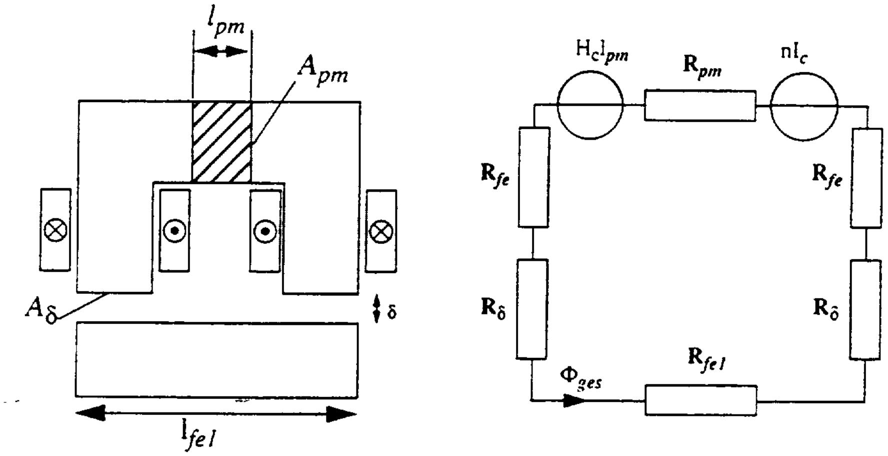


figure 5 equivalent circuit of a coplanar bearing

To calculate the force of such an arrangement, several equations have to be solved. The first Maxwell-Equation

$$\oint \vec{H} d\vec{s} = \iint \vec{S} d\vec{A} \tag{1}$$

can be simplified:

$$\sum Hl = nI + H_c \cdot l_{pm} \tag{2}$$

Together with

$$B_\delta A_\delta = B_{Fe} A_{Fe} S_{Fe} = B_{pm} A_{pm} S_{pm} \tag{3}$$

and

$$B_\delta = H_\delta \mu_0, \quad B_{Fe} = H_{Fe}\mu_0\mu_{Fe}, \quad B_{pm} = H_{pm}\mu_0\mu_{pm}, \quad R_\delta = \frac{\delta}{\mu_0 A_\delta}, \quad R_{fe} = \frac{l_{fe}}{A_\delta \mu_0 \mu_{fe}} \quad \text{and}$$

$R_{pm} = \dfrac{l_{pm}}{A_{pm}\mu_{pm}\mu_0}$ the force can be calculated by the following equation

$$F_B(I_c, B_{pm}) = \frac{A_\delta(2\mu_0 n I_c + B_{pm} l_{pm})^2}{\mu_0\left(2\delta + \frac{A_\delta}{A_{pm}\cdot L_{pm}}\cdot\frac{l_{pm}}{\mu_{pm}} + \frac{A_\delta}{A_{Fe}\cdot L_{Fe}}\cdot\frac{l_{Fe}}{\mu_{Fe}}\right)^2} \tag{4}$$

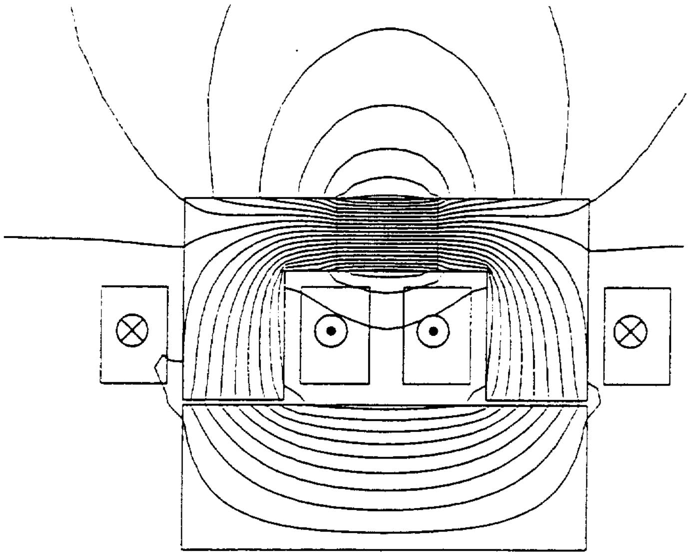


figure 6 massive leakage due to high current density

A_δ is the cross-sectional area of the air gap δ, A_{pm} the cross-sectional area, L_{pm} the leakage factor of this area and l_{pm} the length of the permanent magnet, l_{Fe} the middle length of the whole iron with the relative permeability μ_{Fe} and the flux density B_{pm} of the permanent magnet, n is the number of windings for each coil and I_c the current. As (4) shows, the force can be **increased** with positive currents and can be reduced with negative currents. This is the same effect that can be realized with a bias current in the windings.

Measurements and comparisons with 2D-FE-calculations have shown that the force error of this method can be less than 15%. Depending on the current, the maximum flux density in the iron core and the eccentricity of the rotor, the error can be reduced to 6% by implementation of the geometry specific leakage factor. Less leakage can be seen in *figure 4*, which is without current in the coil then in *figure 6* which is with weakening of the field.

The realization of this kind of bearing is described in COPLANAR DESIGN.

Much more difficult is the calculation of the non-coplanar type. The flux generated by the permanent magnet flows in the r-z-plane, the flux generated by the coils in the r-φ-plane. This means, that a 3D-problem has to be solved.

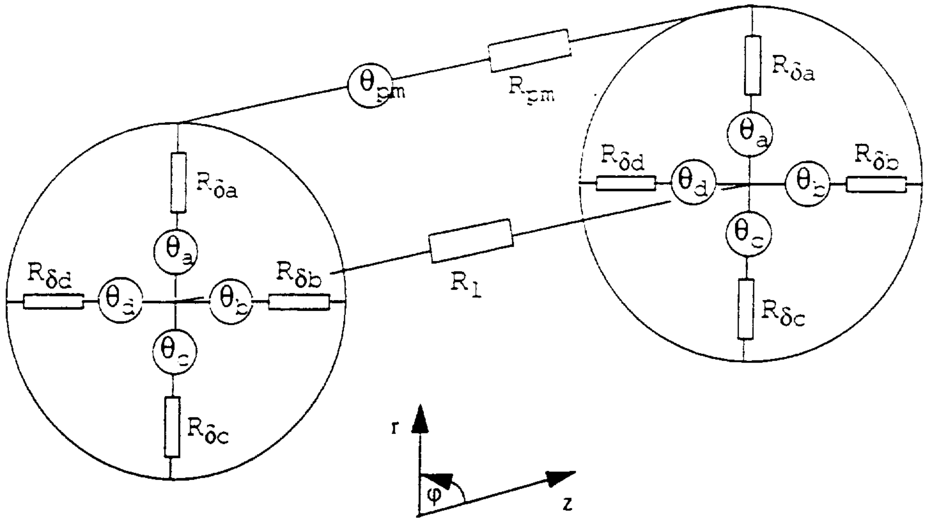


figure 7 equivalation circuit neglecting the resistance of the iron

The simplest model neglecting the resistance of iron, scattering and non-linear effects is shown in *figure 7*, where R_l is the resistance of the isolation of the laminations. Such a model is already explained in [1]. The model becomes difficult to calculate and to evaluate considering the nonlinearities and scattering. Another method is to compute the flux in the air gap generated by the coils in the r-φ-plane and the flux generated by the permanent magnet in the *r-z*-plane separately. The addition of the flux vectors delivers the resulting flux in the air gap and the force can be calculated. The error of this calculation is bigger than 40% in some cases. One reason for this massive error is the other operating point of the B-H-curve if the two fluxes are considered separately. Better results can be expected, if the inner and outer boundary condition is set to dirichlét. This method allows to consider the bias flux as normal flux at the inner and outer boundary. The 3d- finite element method is the only way to get good results. However this method is very time intensive and difficult to handle.

COPLANAR DESIGN

Figure 8 shows possible arrangements of coplanar bearings. The bias flux of the permanent magnets can be realized by axial, tangential or radial polarisation of the permanent magnet. It can be implemented in the stator with polar or cylindric flux direction. An implementation in the rotor is also possible. The most common arrangement is version b).

The coplanar as well as the non-coplanar type of bearing can be realized in 3-pole arrangement as well as in 4-pole arrangement [7]. In opposition to bearings biased by coils, the 3-pole version with permanent magnet does not have the advantage, that one power amplifier can be economized. Experimental studies of three pole bearings without permanent magnets have pointed out that this system has a tendency to become **unstable.**

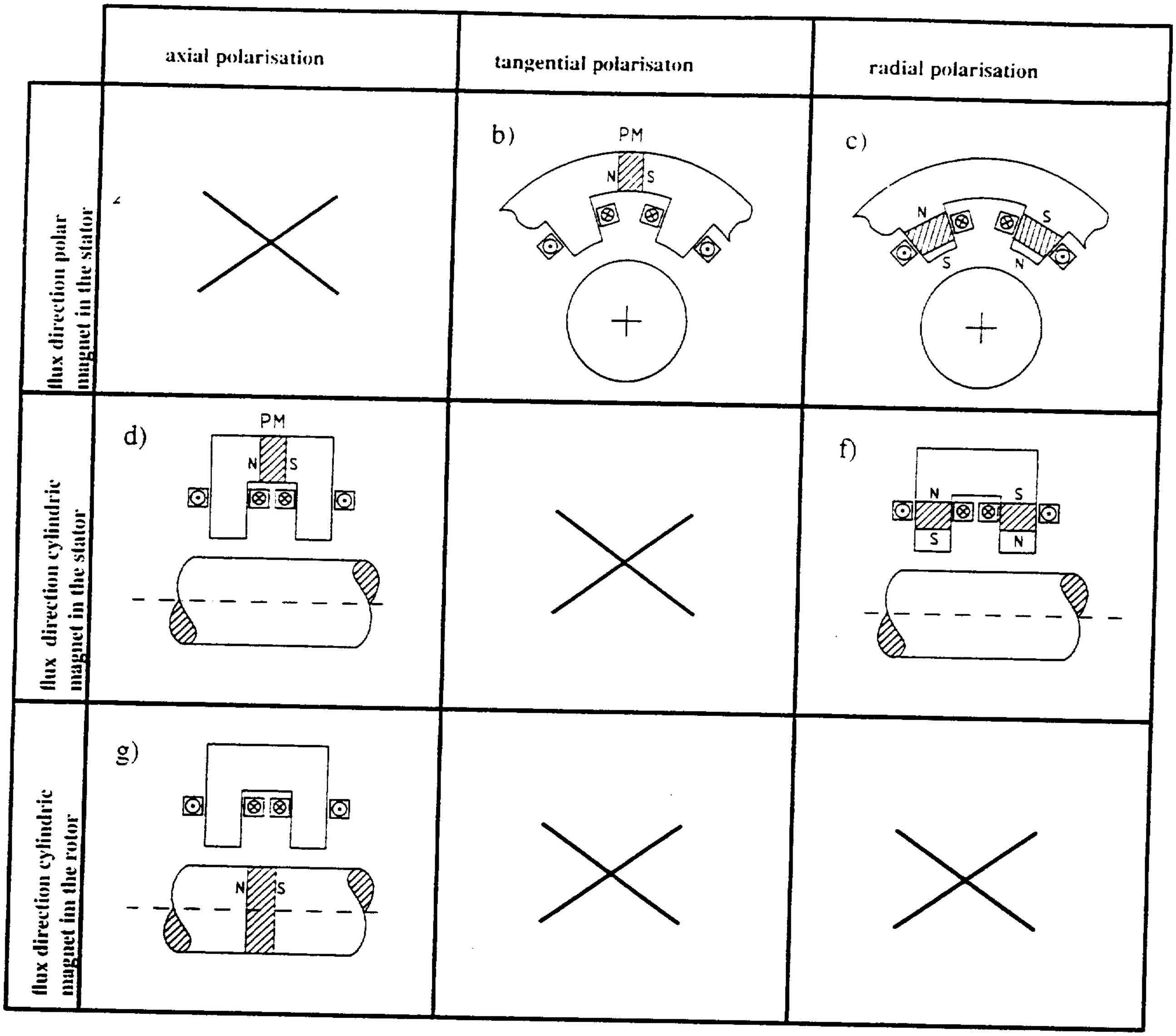


figure 8 Arrangements of coplanar bearings

The reason is the electromagnetical coupling of the axis and due to the accuracy of the fixed point DSP **controller** the inaccurate coordinate-transformation for the three force axis in the 2 dimensional plane. *Figure 9* shows a 4 pole arrangement with two permanent magnets per pole. The plates are of an eight pole AC-motor with 0.25 kW and have the number IEC 80/6-8.80. The outer diameter is 120mm, the inner diameter is 80 mm with an air gap of 0.6 mm. The permanent magnets are made of Sm_2Co_{17} with an energy density of 225 kJ/m^3 and a remanence of 1.1 T.

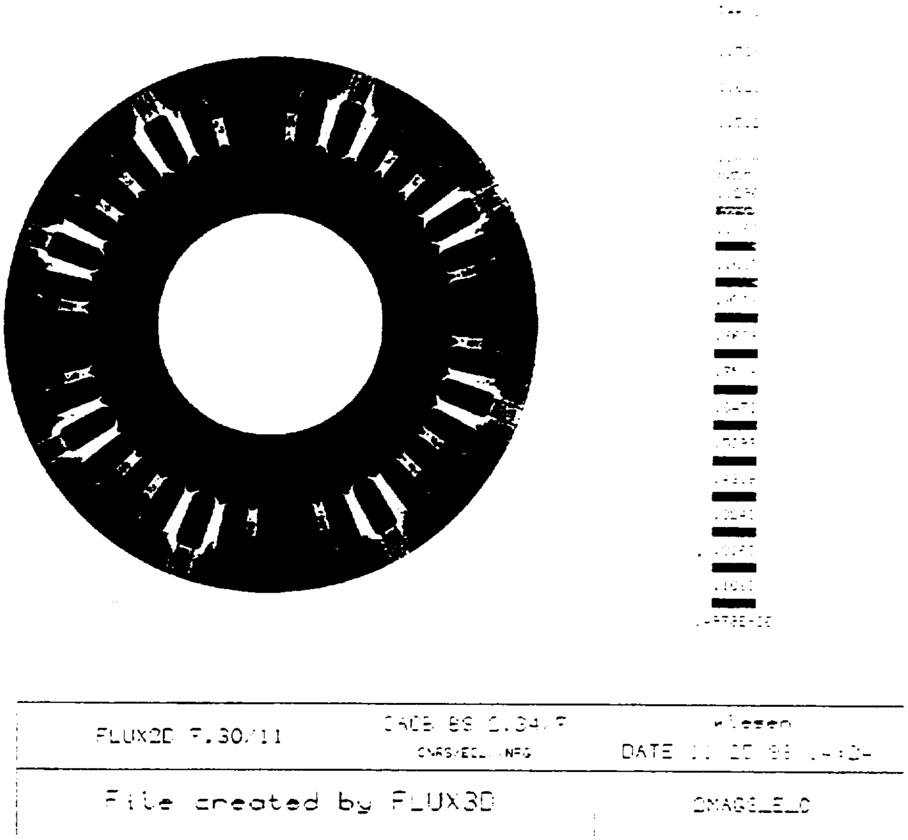


figure 9 Flux density of a 4 pole arrangement without current in the coils

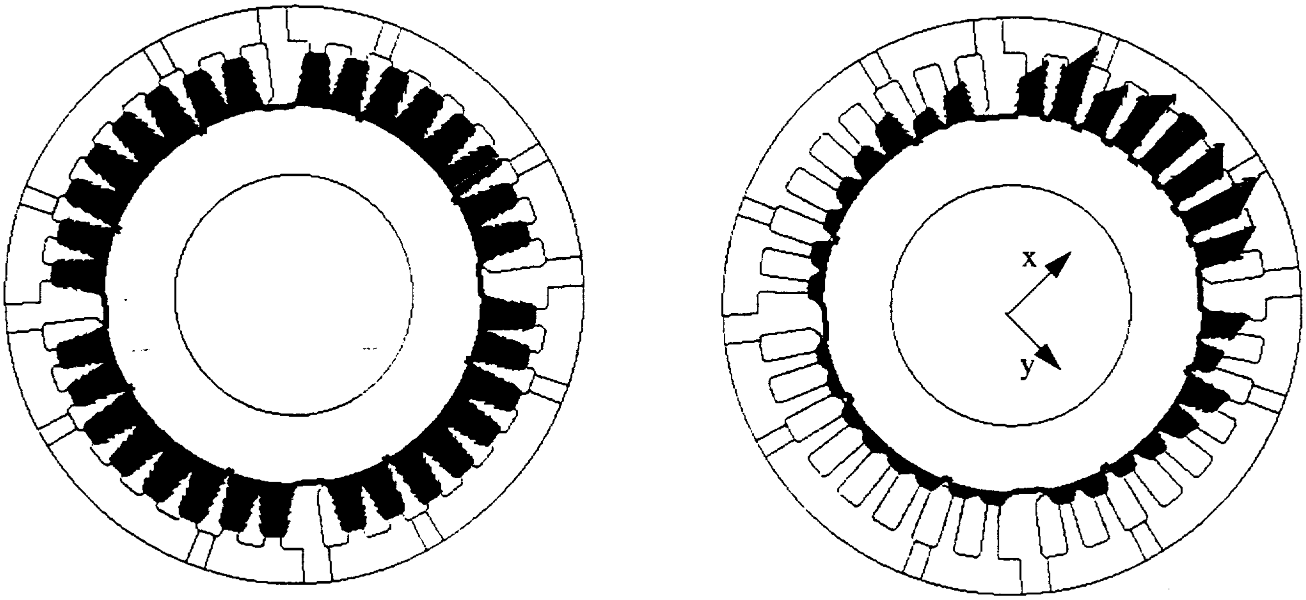


figure 10 magnetic pressure of a centrical and eccentrical rotor

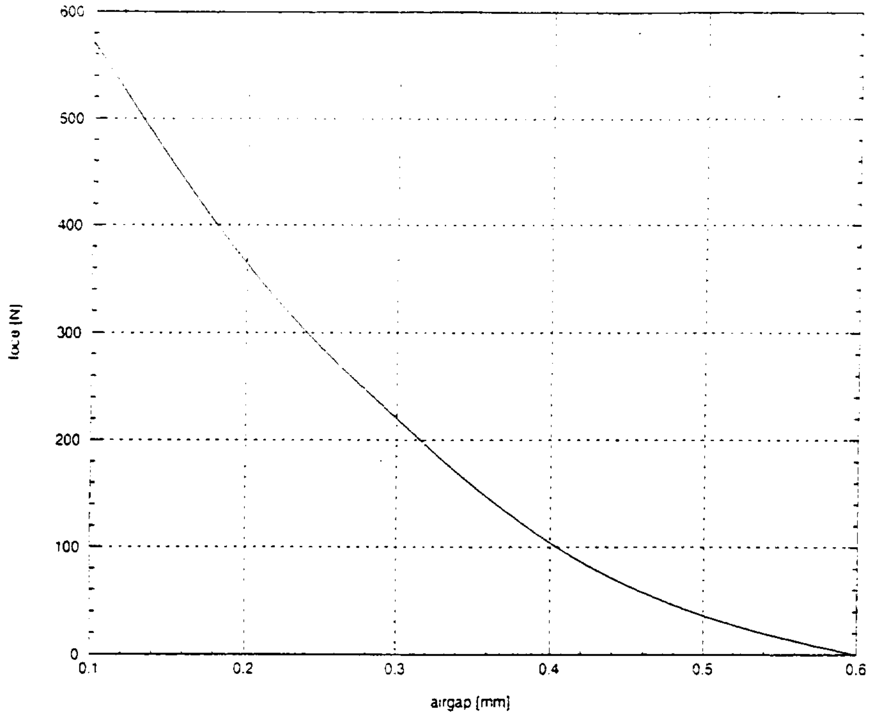


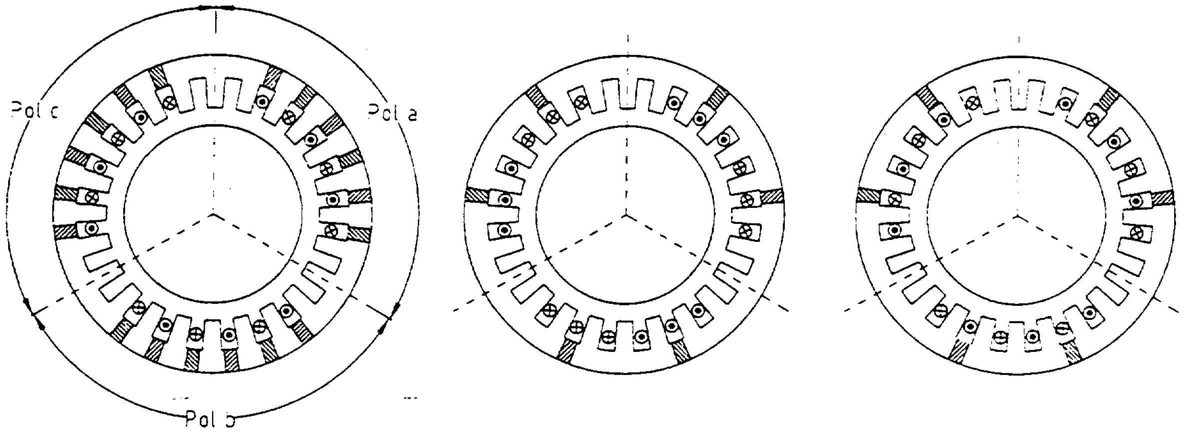
figure 11 rotor force without current

Figure 10 shows the force density that acts on the rotor surface. The force has the same size if the rotor is in centrical position. The resulting force is zero. If the rotor is moved in the direction x, a force results in the same direction.

Figure 11 shows the resulting force if there is no current in the windings.

The force characteristic becomes more linear, if a permanent magnet is implemented in every slot of the plate (variant A in *figure 1*).

Figure 1 shows some possible implementations of permanent magnets for a 3-pole bearing realized with plates of an AC-motor.



variant A

variant B

variant C

figure 1 some arrangements of a coplanar bearing of type b in *figure 8*

Figure 12 shows the results of the FE-calculation of variant A. There is a very good linearity between current and force. The disadvantage of this solution is the high force that still appears, when weakening the field of the permanent magnet. The reason is the high remanence of the permanent magnets. The curve becomes more steep, when the thickness of the magnets is reduced. However this reduction is limited by the stability against demagnetisation of the permanent magnets especially at high temperatures.

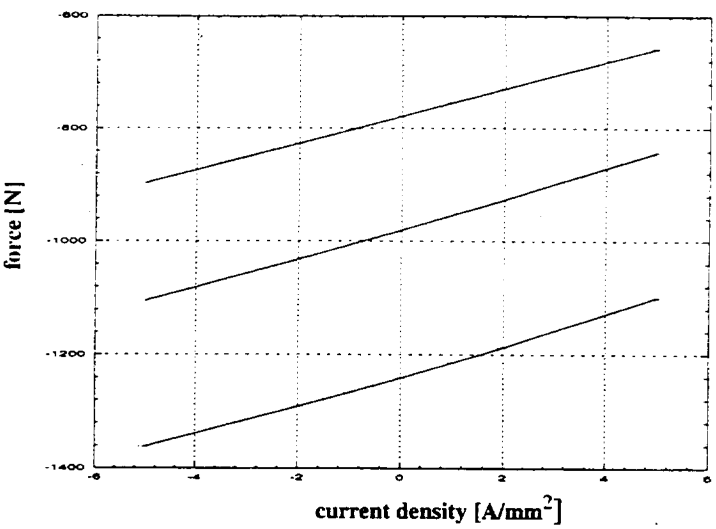


figure 12 characteristic diagram of one pole in *figure 13*

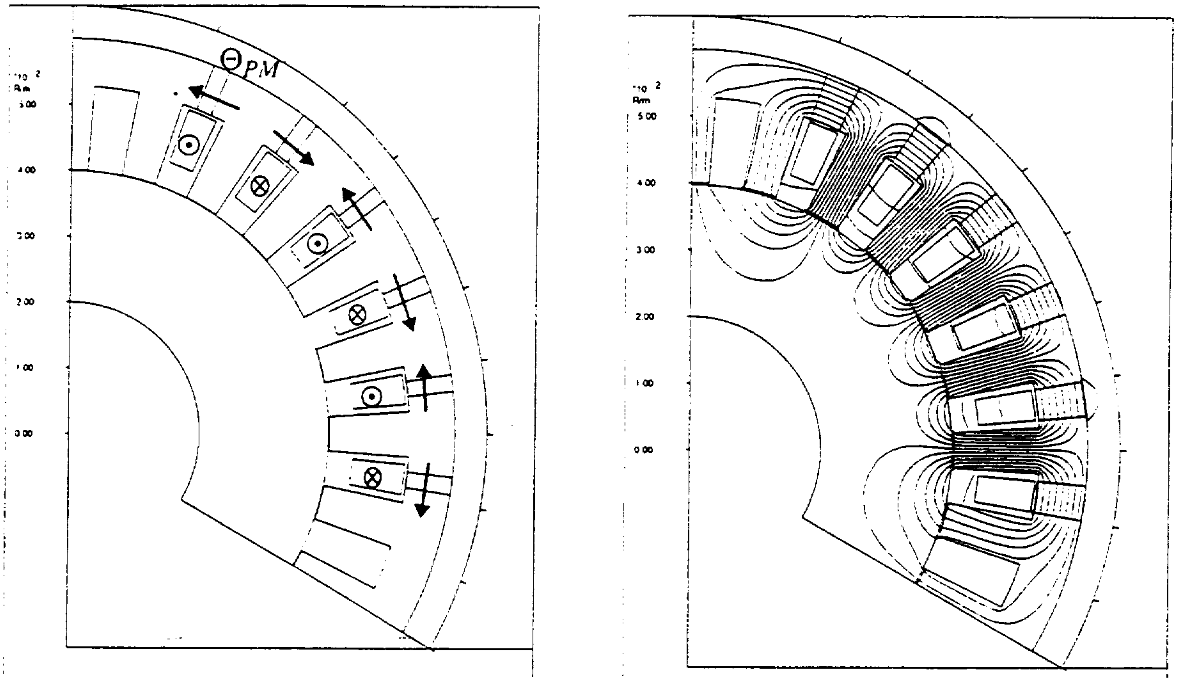


figure 13 computation of variant A with the FD- program ***PROFI***

Figure 14 shows the curves for the variants B and C. The characteristic becomes much more nonlinear. The reason of this effect can be explained with the plots in *figure 15*. If the force is reduced by weakening the field of the permanent magnets, another flux path appears, that generates a force. This effect is bigger for variant C and leads to a bigger nonlinearity. Variant A is the auspicious design for a coplanar bearing with AC-motor-plates. It has a nearly linear characteristic and offers the largest surface for permanent magnets. This means highest forces without current. Beside the high cost for permanent magnets, the main disadvantage is the small current force ratio.

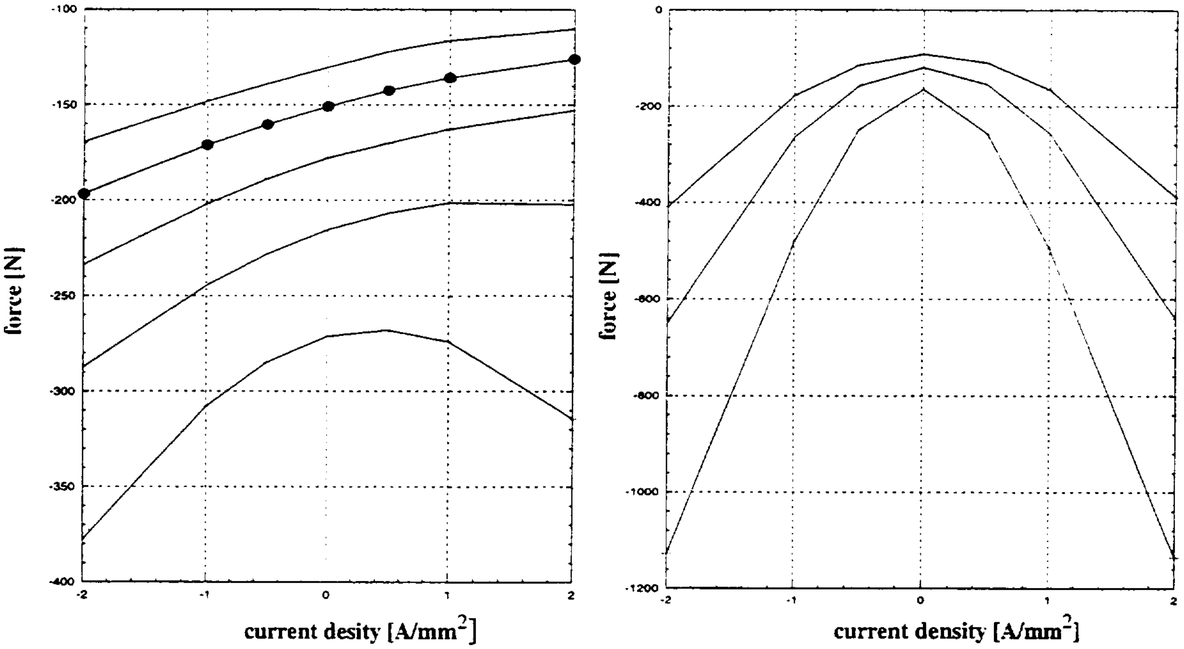


figure 14 characteristic curves of variants B and C

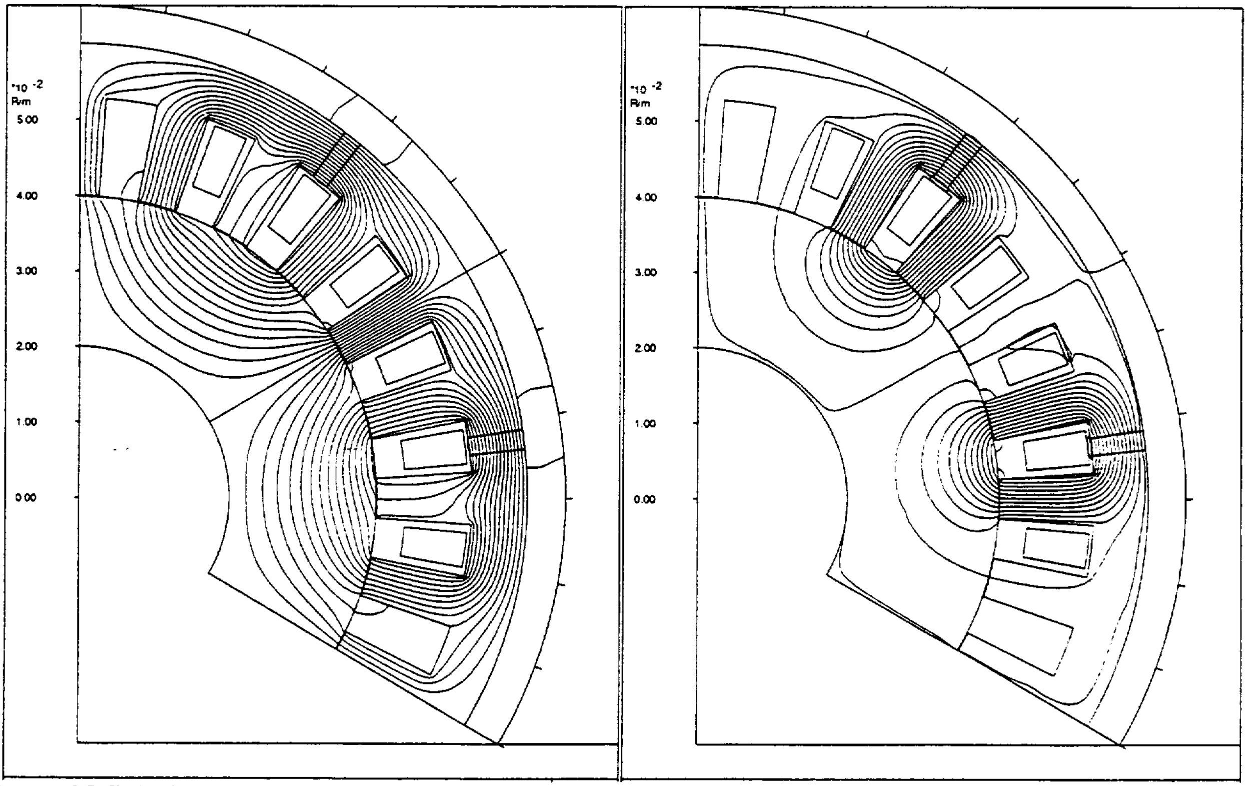


figure 15 fieldlines without current (l) and with weakening of field (r)

Figure 16 shows possible arrangements of non-coplanar bearings. The bias flux of the permanent magnets can be integrated in the rotor or the stator.

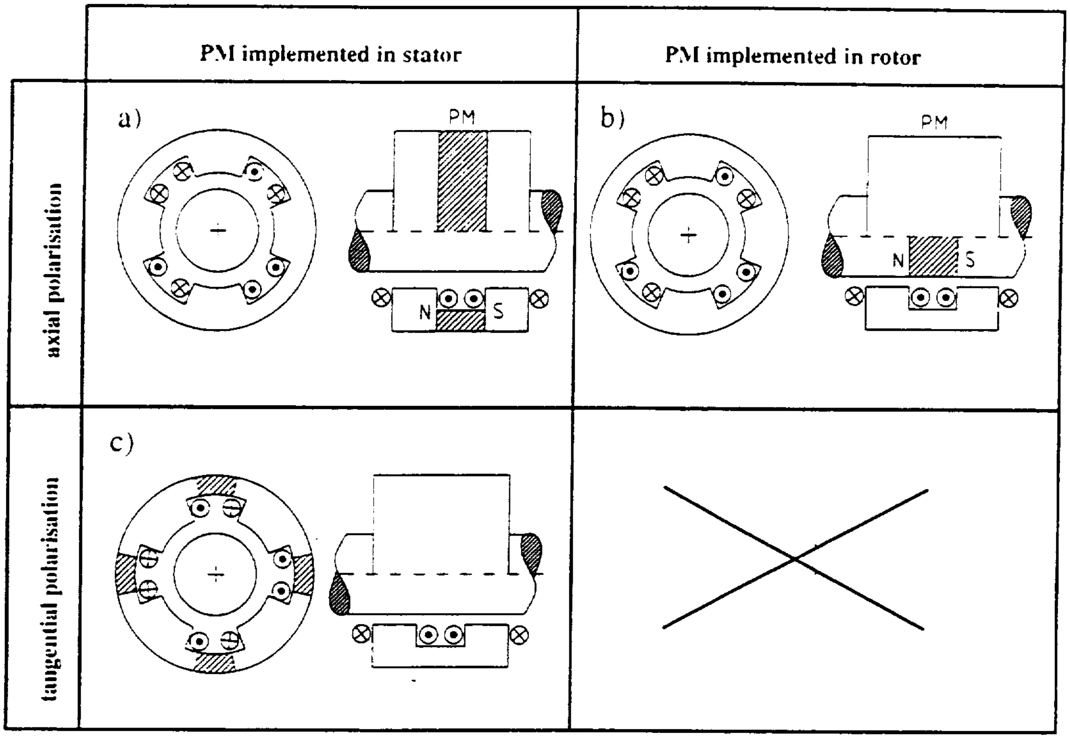


figure 16 arrangements of non- coplanar bearings

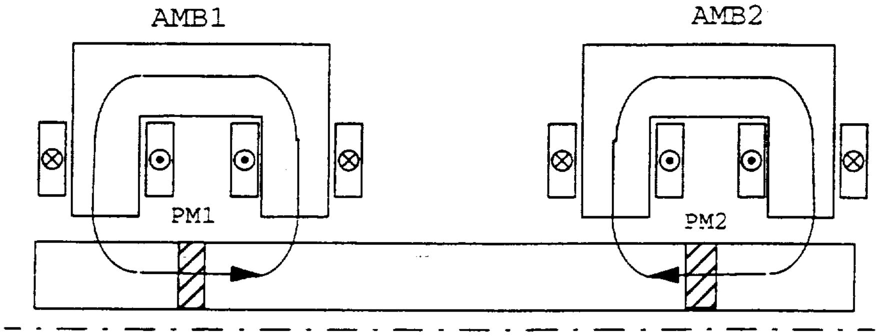


figure 17 arrangement with two bearings and two permanent magnets

Non-coplanar bearings have already been realized as 3 ([3],[7]) or 4 ([2]) pole magnetic bearings. It can be point out as a main technical advantage, that there is no additional resistance from the permanent magnets in the magnetic circuit. There is less current needed to generate the same coil flux as in coplanar bearings. However, the surface to implement permanent magnets is smaller than for coplanar bearings. This means less forces without current but a better current force ratio. Most of the constructions prefer variant a) of *figure 16*. The permanent magnet, which has a thickness of 2 mm only, is very difficult to handle and to obtain for such an construction with permanent magnet in the stator when IEC 80/6-8.80-plates are used.

Beyond it, the surface of the permanent magnet in the rotor is almost **twice** as large as the surface in the stator. These are the main reasons, why an arrangement with permanent magnets in the rotor is preferred. *Figure 17* shows an arrangement with two bearings and one permanent magnet for each bearing. The disadvantage of such a construction is the need of two windings for every axis of the bearing. Thus, the specific load capacity decreases. Another possibility is shown in *figure 18*. The only stator modification, that has to be done is a housing for the two bearings that is made of a ferromagnetic material. The rotor has to be made of two parts to allow the assembly of the permanent magnet disc. If the permanent magnet is made of two halves of a disk, only a slot has do be machined. In this case, the magnet should be fixed with a bandage.

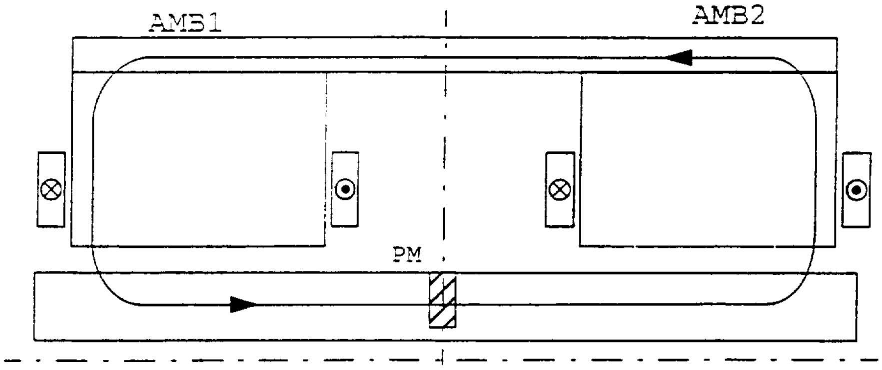


figure 18 arrangement with two bearings and one permanent magnet

As already mentioned, the force of an non-coplanar bearing can only be computed with the 3 dimensional finite element method. For a better oversight, *figure 19* shows only a quarter of the model of such a computation. The complete bearing is shown in *figure 20.*

When we assume, that both bearings have the same load, only one bearing has to be computed, the other one can be considered by symmetry. This reduces the computation time. The length of the rotor is reduced to a minimum due to the same reson.

The force generated in one bearing without current is shown in *figure 21.*

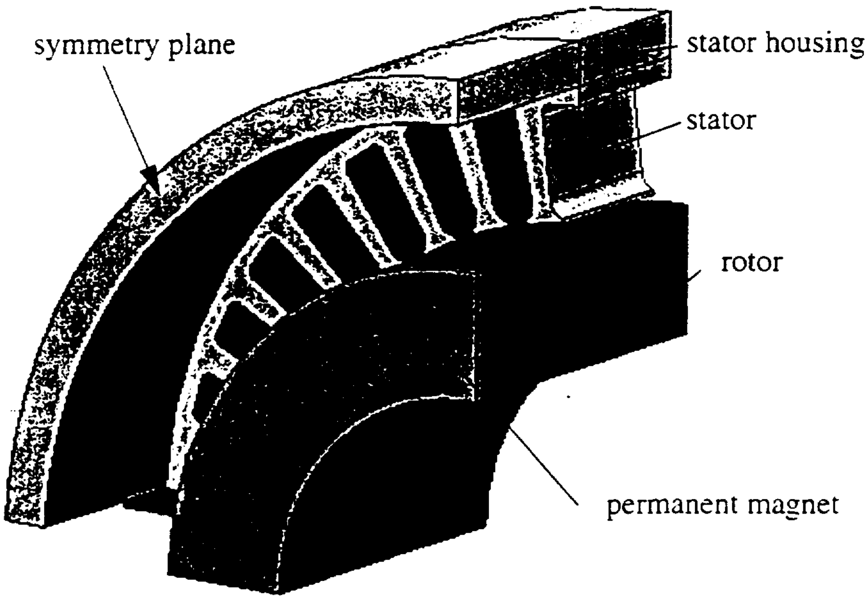


figure 19 one pole of the FE-model of the non-homopolar bearing

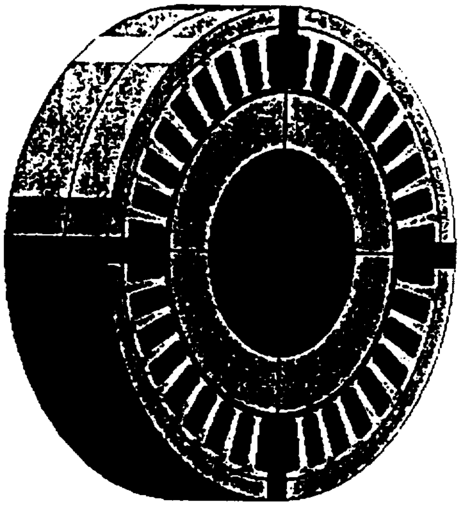


figure 20 model of one complete bearing

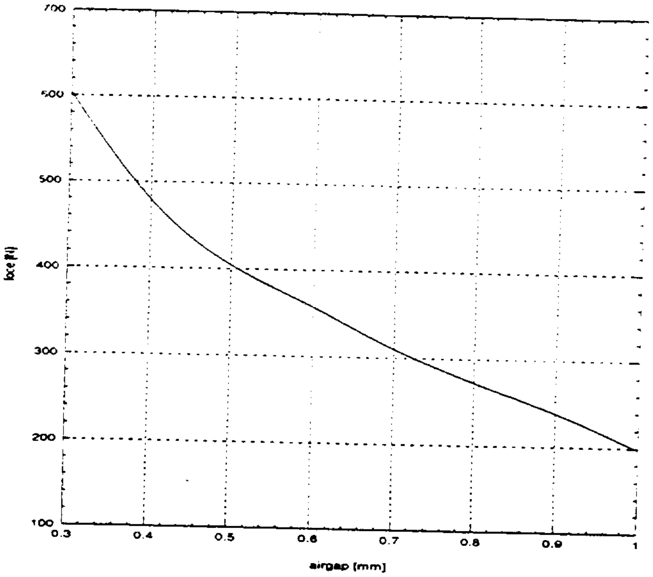


figure 21 loading capacity of one AMB without current

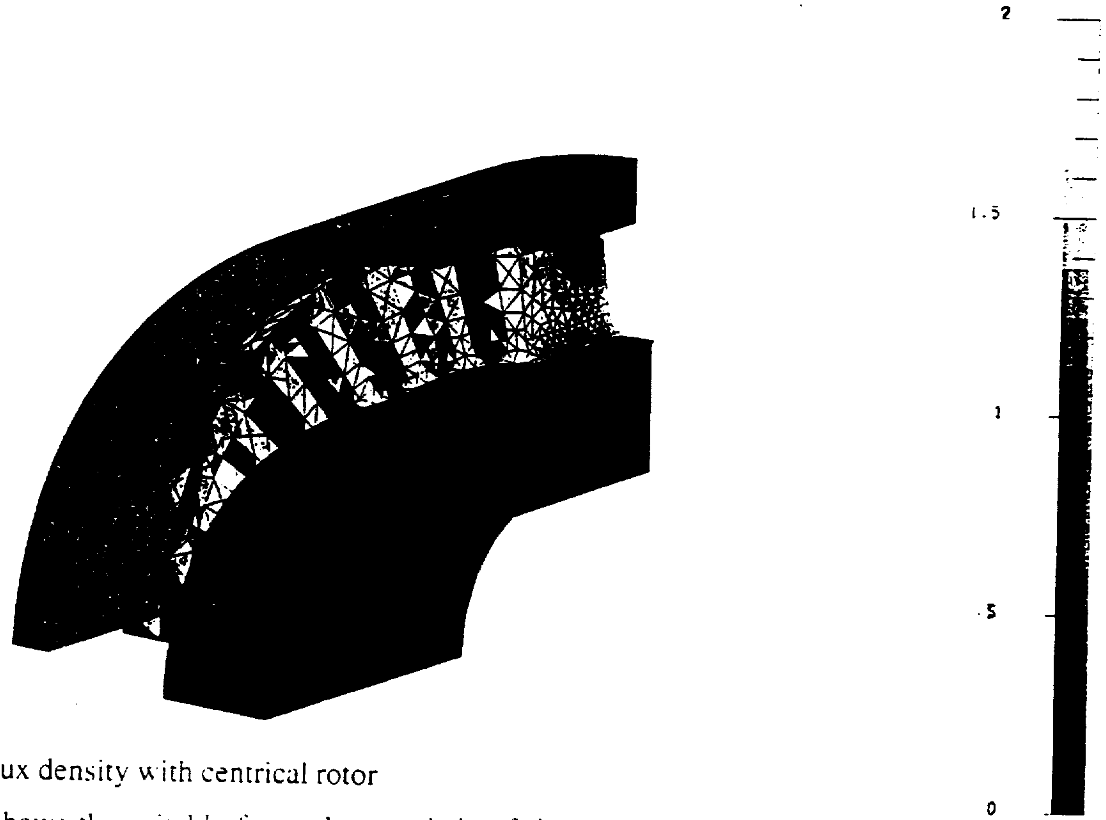


figure 22 flux density with centrical rotor

Figure 21 shows the suitable force characteristic of the non-coplanar bearing. It can deliver more than 500 N per bearing from one permanent magnet only. Although the coplanar bearing has a higher load capacity then the noncoplanar type. The current force ratio of this bearing is higher. Thus, this bearing has a better performance, if the dynamic forces are higher than the static ones.

ZERO DC-CURRENT CONTROL

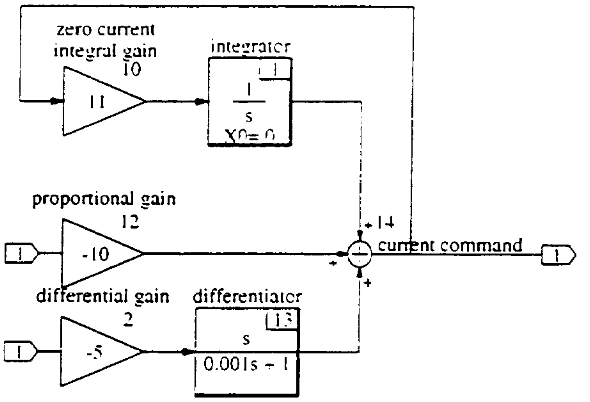


figure 23 modified PID controller scheme for zero DC-current

The usage of permanent magnets already reduces the DC-current significantly. But if the AMB has to support static loads like gravitational loads, a DC-current is still required. This depends on the common control strategy to keep the rotor in the centre of the bearing. As already mentioned, outside the centre of a permanent magnetic premagnetized AMB a position can be found, where the specific static force is supported by the permanent magnets without any current. To move the rotor to this position of force-equilibrium the static behaviour of the position control loop has to be changed. The current and not the position deviation has to become zero for $t \rightarrow \infty$. For the common PID-control this can be realised easily: The input to the integral gain of the PID controller is no longer the position deviation, it now is the current. This scheme is shown in *figure 23*. Stability of the closed loop is reached by a positive sign of the integral feedback. A low gain is desired, because a high gain increases the compliance at low frequencies. If the gain is chosen small, the stability margin of the underlying PD-controller is not touched.

From a practical point of view the range of displacement should be limited in order to avoid contact with the stator and to keep a gap for excursions invoked by dynamic loads. If the rotor exceeds the limits, the control is switched to conventional PID-control with the limit as desired position.

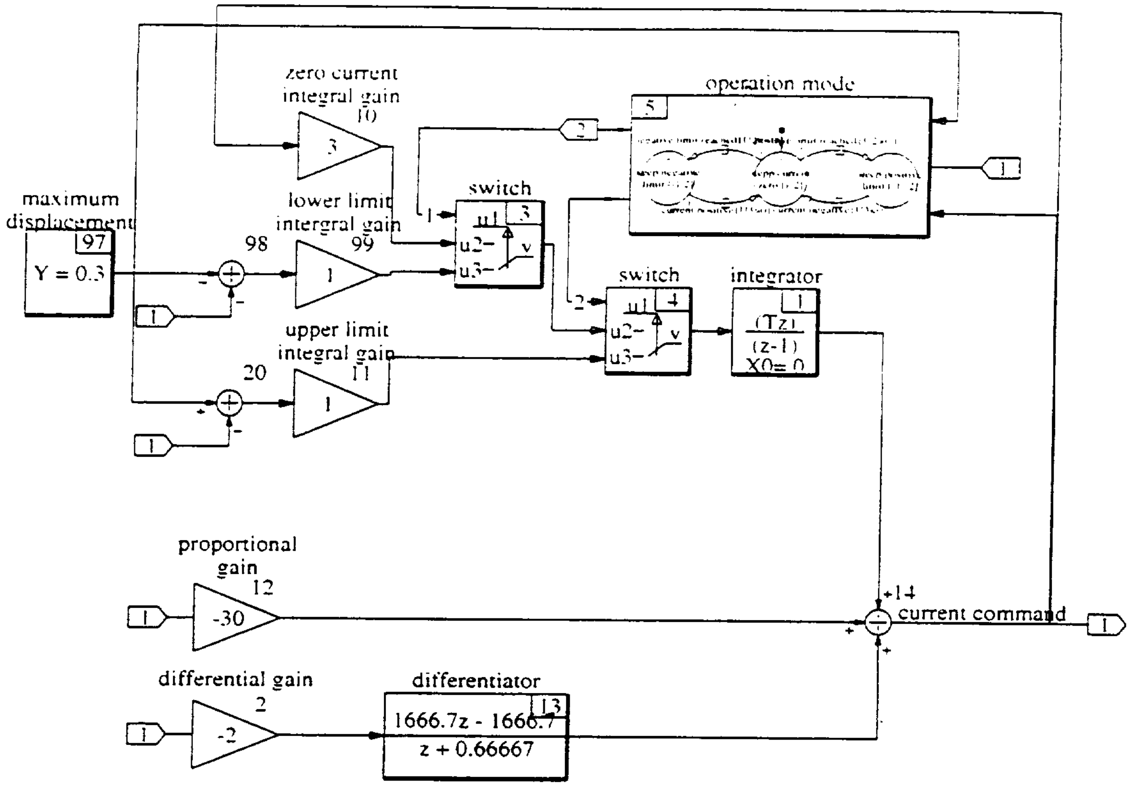


figure 24 controller scheme for zero DC-current with displacement limitation

Figure 24 shows the control scheme with displacement limitation. There are three operation modes: keeping the upper limit, keeping the lower limit and enforcing zero current.

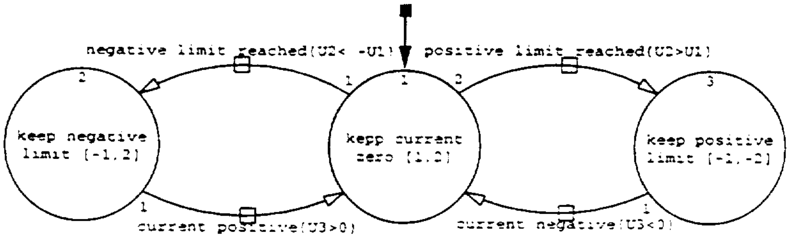


figure 25 controller operation mode switching for displacement limitation

For all three modes one integrator is used and only the feedback paths are switched to the input of the integrator to avoid unsteadiness of the current command. *Figure 25* shows the three operation modes and their switching conditions.

Simulation results are shown in *figure 26*. The load is stepwise increased. As long as the limits are not exceeded the current returns to zero. When the limits are reached, the DC-current increases. The dynamic behaviour to the load steps is not affected by the switching between the operation modes.
The developed control scheme allows static displacement of the rotor within a given range to minimize the DC-current consumption. It has to be checked for each application, whether displacement of the rotor

is tolerable and if so, which range can be allowed. The control strategy can also be combined with other controller types than PID. Stability and performance has to be checked for both operation modes, conventional integral gain and zero current integral gain.

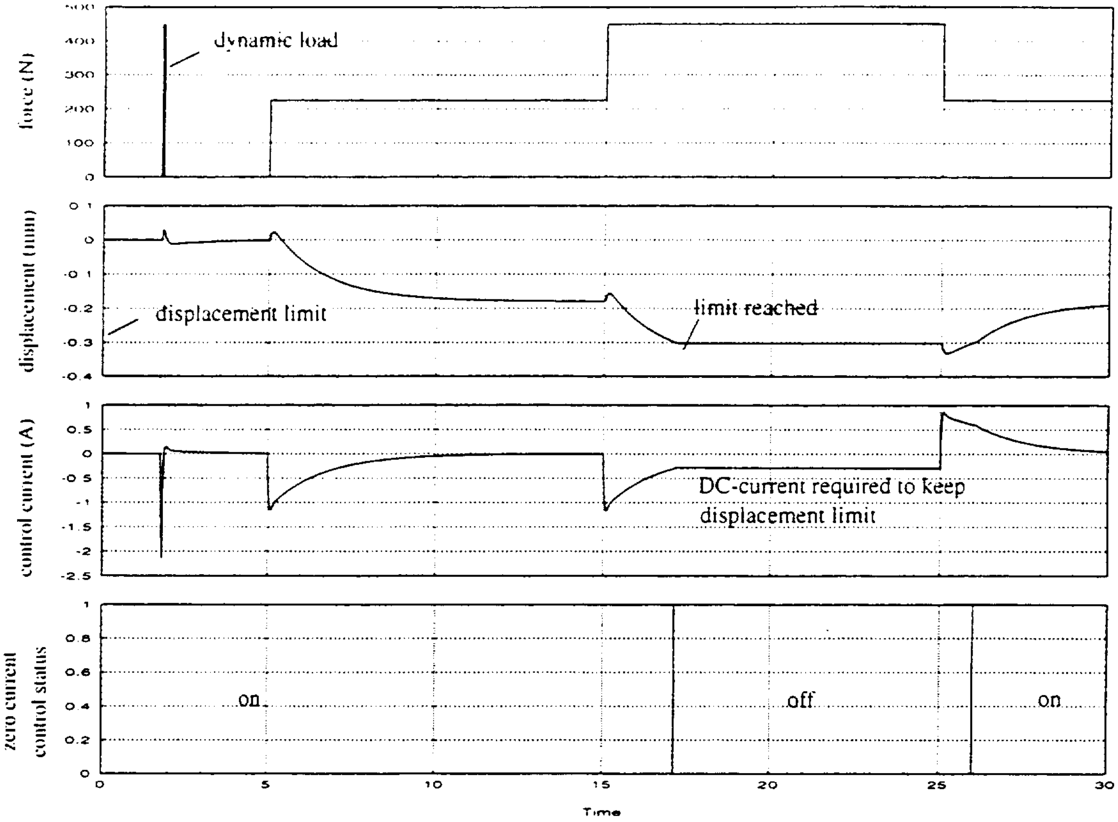


figure 26 operation of the zero DC-current control

CONCLUSION AND OUTLOOK

The power consumption of an AMB has been analysed first. The static currents can be reduced by the implementation of permanent magnets. The realisation of the two principal constructions of AMBs with permanent magnet coplanar and non-coplanar bearings, has been presented. The coplanar bearing delivers higher forces without current in the coils whereas the non-coplanar types have an higher current force ratio. The presented zero-dc-current-controller reduces the static current. This means higher load capacity and reduced life time costs. A coplanar bearing is the preferred construction, if there are mainly static forces. If the dynamic ones are predominantly, the non-coplanar type is the right choice.

These statements are based on simulations. Shortly the rotor with the permanent magnets will be finished and the two kinds of bearings can be compared in experiment.

ACKNOWLEDGEMENT

We would like to thank Mr. Jörg Buchwald for his support and Mr. Martin Ernst for the FE-3D-computation. Beyond it SIMEC GmbH. Germany for providing the software FLUX 3d of CEDRAT and PROFI Engineering GmbH. Germany for the preparation of the software PROFI 2d.

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