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# ACTIVE MAGNETIC BEARING WITH LARGE AIR GAP FOR OPERATION WITH A 3-PHASE POWER CONVERTER

BREAK

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## ABSTRACT

In order to reduce the costs, radial active magnetic bearings have been proposed which consist of only three electromagnets. Unfortunately it is not possible to operate the three coils with a 3-phase power converter, since the sum of the coil currents does not equal zero. Three independent amplifier channels are needed for the control of this arrangement. In this paper a radial magnetic bearing is proposed which can be operated by commercial 3-phase power amplifiers. By the use of an arrangement of permanent magnets it is possible to make the sum of the three phase currents become zero. Some problems related to this bearing arrangement as well as solutions are discussed and shown using the example of two prototype bearings.

## MOTIVATION

In a radial active magnetic bearing, usually four independent electromagnets are arranged around the rotor. They are operated either by four unipolar power amplifiers or by two bipolar amplifiers. A simplification can be achieved by the arrangement of only 3 electromagnets. Such arrangements have been shown for example in [1] and [2]. In this case three independent unipolar power amplifiers are still needed for the control of one radial bearing. Unfortunately, it is not possible to operate the three coils with a 3-phase power converter. However, it would be very attractive to operate magnetic bearings with 3-phase power converters, mainly for two reasons:

- 3-phase converters are used in huge quantities for electrical drives and are therefore available at very low prizes. Today they are even cheaper than dc power amplifiers.
- Modern 3-phase servoamplifiers incorporate high performance digital processors like signal processors. These processors would offer enough calculation power for the control of active magnetic bearings. This means that a 3-phase servo amplifier could be easily transformed into a magnetic bearing controller merely by exchanging software.

In [3] an active magnetic bearing type is shown which can be driven by an industrial 3-phase power converter. However this type needs special coils to assure the premagnetisation needed by the magnetic bearing. Such coils need much space in the bearing stator especially when the air gap between bearing stator and rotor has to be large, as for example in systems where rotor and stator must be canned. For such canned systems (pumps or compressors for industrial operation) it seems desirable to have active magnetic bearings with:

- large air gap (> 1mm)
- no special premagnetisation coils and
- which are still small and compact

## THE NEW APPROACH

In this paper a radial active magnetic bearing is suggested which can be operated by industrial 3-phase power amplifiers and where the premagnetisation flux is created by permanent magnets.

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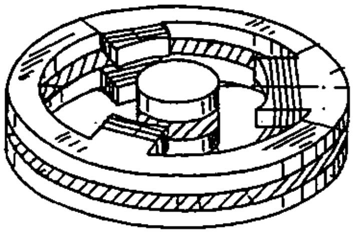

**figure 1: Active magnetic bearing for operation with 3-phase amplifiers and with permanent magnets**

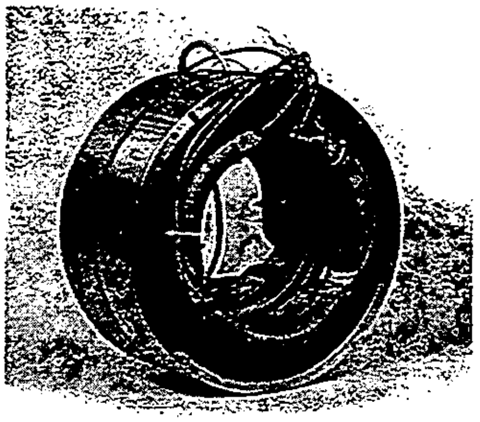

**figure 2: Electrical scheme of the bearing**

In figure 1 and figure 2 and [4] this new bearing type is shown. The bearing itself consists of two iron rings on both sides of the bearing with the coils on it. The permanent magnets which are responsible for the bias flux are between the two iron rings. The corresponding coils of the bearing are connected together. In figure 3 the electrical scheme of such a bearing type is shown.

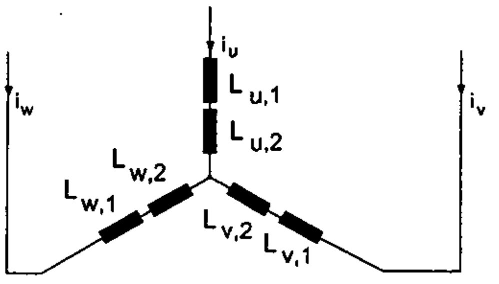

**figure 3: Electrical scheme of the bearing**

There is one major point which has to be considered when feeding the bearing by a 3-phase power converter. In a 3-phase system, the sum of the phase currents must equal zero. This is the case whether the winding coils are connected either in star configuration with a floating star point or in delta configuration. It means that only two out of the three phase currents ($i_u$, $i_v$, $i_w$ in figure 3) can be independently controlled. The third phase current equals the negative sum of the two others. At first glance this seems to be no problem for the radial bearing, since only two degrees of freedom should be controlled.

The equation system which shows the relationship between the magnet forces ($F_u$, $F_v$, $F_w$) of the coils and the resulting forces in the two directions x and y ($F_x$, $F_y$) is undetermined:

$$F_x = F_u - \frac{1}{2}F_v - \frac{1}{2}F_w \tag{1}$$

$$F_y = \frac{\sqrt{3}}{2}F_v - \frac{\sqrt{3}}{2}F_w \tag{2}$$

A further condition is possible, for example that the sum of all magnetic forces equals zero. If the magnetic forces were proportional to the winding currents, the bearing could be easily operated as a 3-phase system. However, this would mean that the electromagnets can generate attractive forces as well as repulsive forces, depending on the sign of the current. But since the magnetic forces are proportional to the power of two to the winding current, only attractive forces can be generated. A better idea is to let the sum of all magnetic forces and therefore the sum of the winding currents equal a constant, positive value. However, in this case the currents no longer form a 3-phase system and the windings cannot be driven by a 3-phase power converter.

The idea is now, to generate a constant magnetomotive force in all of the three electromagnets by the mentioned permanent magnets between the two iron parts of the bearing: the magnetic field of the electromagnets itself and a component from the permanent magnets. In figure 4 the fields between the core teeth of the magnets and the rotor are shown for both bearing rings.

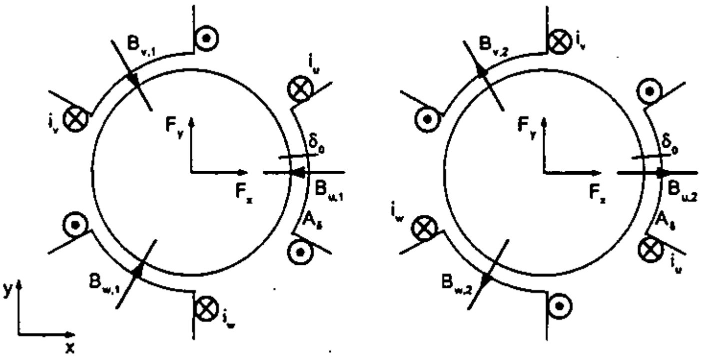

figure 4: Fields in the bearing

The resulting fields can be calculated as follows:

$$B_u = B_{u,1} = B_{u,2} = \frac{\mu_0 \cdot N \cdot i_u}{\delta_0 - x} + \frac{\mu_0 \cdot l_{pm} \cdot A_{pm} \cdot H_{pm}}{2 \cdot A_\delta \cdot (\delta_0 - x)} \qquad (3)$$

$$B_v = B_{v,1} = B_{v,2} = \frac{\mu_0 \cdot N \cdot i_v}{\delta_0 + \frac{1}{2}x - \frac{\sqrt{3}}{2}y} + \frac{\mu_0 \cdot l_{pm} \cdot A_{pm} \cdot H_{pm}}{2 \cdot A_\delta \cdot \left(\delta_0 + \frac{1}{2}x - \frac{\sqrt{3}}{2}y\right)} \qquad (4)$$

$$B_w = B_{w,1} = B_{w,2} = \frac{\mu_0 \cdot N \cdot i_w}{\delta_0 + \frac{1}{2}x + \frac{\sqrt{3}}{2}y} + \frac{\mu_0 \cdot l_{pm} \cdot A_{pm} \cdot H_{pm}}{2 \cdot A_\delta \cdot \left(\delta_0 + \frac{1}{2}x + \frac{\sqrt{3}}{2}y\right)} \qquad (5)$$

| | | |
|---|---|---|
| *$N$* | ... | *number of windings* |
| *$\delta_0$* | ... | *air gap length* |
| *$l_{pm}, A_{pm}, H_{pm}$* | ... | *parameter of the permanent magnet* |
| *$A_\delta$* | ... | *tooth core area* |
| *$x,y$* | | *displacement from the centre point* |

$$F_i = \frac{B^2{}_{i,1} \cdot A_\delta}{2 \cdot \mu_0} + \frac{B^2{}_{i,2} \cdot A_\delta}{2 \cdot \mu_0} = \frac{B^2{}_i \cdot A_\delta}{\mu_0} \qquad (6)$$

( 3 ), ( 4 ) and ( 5 ) represent the field from the electric part and the part from the permanent magnet. The force per core tooth is shown in ( 6 ). ( 7 ) - ( 9 ) show the linearisation of equation ( 6 ), under the assumption of a very small displacement from the centre of the bearing.

$$F_i(i_i) = F_i(i_i = 0) + \frac{\partial}{\partial i_i} F_i(i_i)\Big|_{i_i = 0} \cdot i_i \qquad (7)$$

$$F_i(i_i) = \underbrace{\frac{\mu_0 \cdot {l_{pm}}^2 \cdot {A_{pm}}^2 \cdot {H_{pm}}^2}{4 \cdot A_\delta \cdot {\delta_0}^2}}_{F_{pm}} + \underbrace{\frac{\mu_0 \cdot N \cdot l_{pm} \cdot A_{pm} \cdot H_{pm}}{{\delta_0}^2}}_{k} \cdot i_i \quad \Leftrightarrow x,y << \delta_0 \qquad (8)$$

$$\Rightarrow F_i(i_i) = k \cdot i_i + F_{pm} \tag{9}$$

The resulting forces in x and y direction are calculated as shown in ( 10 ) and ( 11 ) with ( 1 ) and ( 2 ).

$$\begin{aligned} F_x &= F_u - \tfrac{1}{2}F_v - \tfrac{1}{2}F_w \\ &= k \cdot i_u + F_{pm} - \tfrac{1}{2}k \cdot i_v - \tfrac{1}{2}F_{pm} - \tfrac{1}{2}k \cdot i_w - \tfrac{1}{2}F_{pm} \\ &= k \cdot i_u - \tfrac{1}{2}k \cdot i_v - \tfrac{1}{2}k \cdot i_w \end{aligned} \tag{10}$$

$$\begin{aligned} F_y &= \tfrac{\sqrt{3}}{2}F_v - \tfrac{\sqrt{3}}{2}F_w \\ &= \tfrac{\sqrt{3}}{2}k \cdot i_v + \tfrac{\sqrt{3}}{2}F_{pm} - \tfrac{\sqrt{3}}{2}k \cdot i_w - \tfrac{\sqrt{3}}{2}F_{pm} \\ &= \tfrac{\sqrt{3}}{2}k \cdot i_v - \tfrac{\sqrt{3}}{2}k \cdot i_w \end{aligned} \tag{11}$$

Now the condition for a 3-phase system is applicable:

$$i_u + i_v + i_w = 0 \tag{12}$$

With equations ( 10 ), ( 11 ) and ( 12 ), the equations for the three phase currents with the forces $F_X$ and $F_Y$ as parameters can be evaluated:

$$i_{us} = \frac{2}{3}\frac{F_{xs}}{k} \tag{13}$$

$$i_{vs} = \frac{1}{3} \cdot \frac{1}{k}\left(-F_{xs} + \sqrt{3}F_{ys}\right) \tag{14}$$

$$i_{ws} = \frac{1}{3} \cdot \frac{1}{k}\left(-F_{xs} - \sqrt{3}F_{ys}\right) \tag{15}$$

$$\begin{bmatrix} i_{us} \\ i_{vs} \\ i_{ws} \end{bmatrix} = \frac{2}{3 \cdot k}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} F_{xs} \\ F_{ys} \end{bmatrix} \tag{16}$$

If the equation system is written in a matrix form ( 16 ) it is obvious that the currents form a 3-phase system. They can be evaluated by a simple 2- to 3-phase transformation from the setvalues ($X_S$ and $Y_S$) of a position controller. The basic control scheme of the 3-phase bearing is shown in figure 5.

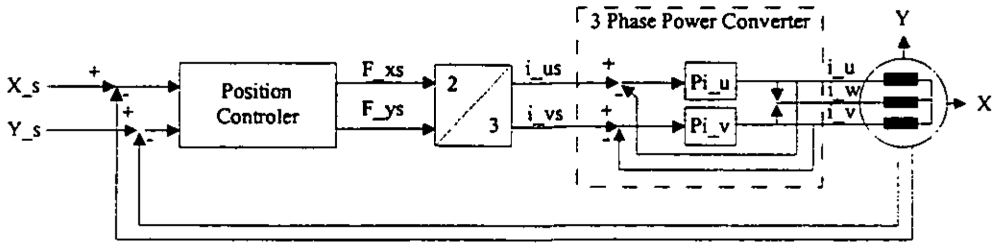

figure 5: Control scheme of the 3-phase radial bearing

The linear equations ( 10 ) and ( 11 ) are based on the assumption that the force changes are directly proportional to the changes in currents. However, this assumption is valid only for small changes of the current and as long as the rotor is placed in the centre of the three electromagnets, which was made during the linearisation of equation ( 6 ). In reality, the magnetic forces are proportional to the magnetomotive forces (which are dependent on the phase currents as well as on the premagnetisation) by the power of two. Also, they are inversely proportional to the power of two of the air gaps. These dependences lead to a non-linear behaviour of the bearing forces for high currents as well as for large displacements of the rotor. In [ 3 ] the effect of the cross-coupling is shown for a 3-phase bearing with electrical premagnetisation. A good solution to the problem of cross-coupling is the design of a symmetrical arrangement of the 3-phase system. One solution could be the turning of one of the iron rings. The modification is shown in figure 6. Such a bearing is perfectly symmetrical to displacements and shows virtually no cross-coupling effects.

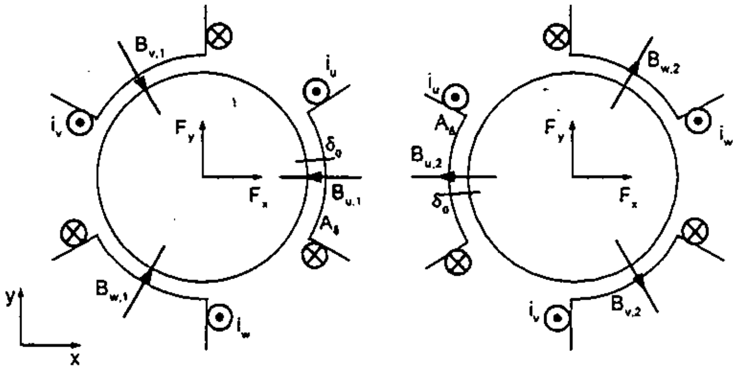

figure 6: Design with one ring turned

A further advantage of the described bearing is the feasibility of large air gaps which is due to the permanent magnet biasing. To obtain the same magneto motive forces which can be achieved already by small volumes of rare-earth magnets by electrical coils, an extremely high winding space would be necessary. Since the price of neodymium-iron-boron magnets felt down drastically in recent years, it is very economic to use permanent magnet biasing.

## APPLICATIONS

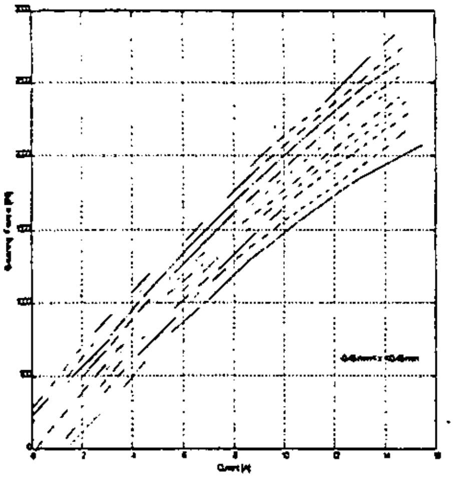

figure 7: load against current

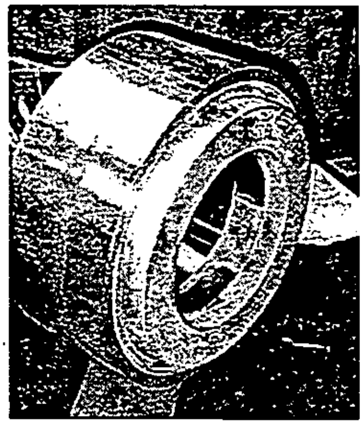

figure 8: 2300 N bearing for a pump

In figure 8 a practical implementation of this bearing type is shown. The bearing is designed for a pump where the whole rotor is within the pump medium. There are no seals and no slide bearings. The maximum load capacity is 2300 N, the stator diameter is 310 mm, the rotor diameter 170 mm and the air gap 2.3 mm.

The bearing rotor must work in aggressive environment (e.g. for the chemical industry). Therefor rotor and stator are capsulated with Hastelloy 0.5 mm thick. In figure 7 the load is shown against the current in the steering winding.

Another application is shown in figure 9. There an outer rotor bearing is shown with a maximal load capacity of 3000 N. The diameter of the rotor is 400 mm, the stator 335 and the air gap 2.5 mm.

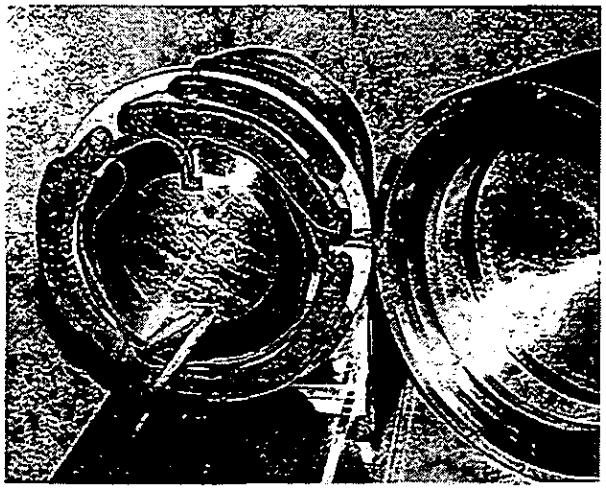

**figure 9: outer rotor bearing (3000 N)**

**figure 10: Magnetic bearing controller based on industrial 3-phase amplifiers**

The bearing in figure 10 is controlled by a commercial 3-phase servo amplifier by Lust Drive Technology. The phase voltage is 380 V and the maximum phase current 16 A. A whole range of such servo amplifiers starting at 1.5 kVA and ranging up to 44 kVA is available in this product family.

In figure 10 a magnetic bearing controller for five spatial degrees of freedom is shown. It is entirely based on commercial 3-phase servo amplifiers by LUST Drive Technology (MC7000 series). The only hardware modification of the 3kVA converters is an additional 2-channel sensor card (for the position sensing of the rotor) which is plugged into an extension slot. Everything else is accomplished by software. All control parameters are stored on a chip card and can be easily set. The controllers can exchange data by a high speed serial link. Several field bus interfaces are available for this system. The power range of the servo amplifiers starts at 1,4 kVA and ends at 44 kVA. The power amplifiers used for this bearing are relatively small compared with classical magnetic bearings, because the main flux of the bearing is produced by the magnets. The currents needed depend only on the changing load of the machine (unbalance, changing load of the outer system).

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