LOW LOSS AND LOW COST ACTIVE RADIAL HOMOPOLAR MAGNETIC BEARING

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ABSTRACT

This paper describes an analytical modeling of a new magnetic bearing with an additional permanent magnet circuit. The suggested design offers various advantages opposite conventional magnetic bearings with regard to the mechanical and electrical expenditure. Using additional permanent magnet circuits the possibility is offered to reduce the required drive power, which is necessary to obtain the radial carrying forces. A simple drive with conventional three-phase current power amplifier becomes practicable. The calculation, design and optimization of the permanent magnetic and electromagnetic circuits is realized by technical and economical point of view. The theoretical executions are concentrated on the calculation of the magnetic forces and the investigation of the coupling of the x- and y-axis. Pure analytical methods are used for this purpose. On the strength of the special arrangement of the stator rings there is a linearization and decoupling of the force characteristics. For the control behavior it leads to, that for example a stabilization of a disturbance force in x-direction causes a negligible force change in the y-axis. At this style there is nearly no coupling of the rotor position. All these influences are shown in diagrams and discussed in detail.

1 INTRODUCTION

Magnetic suspension technology is applied in vacuum technology, machine tools and turbomachines. Special advantage offers their contactless nature, which eliminates friction. Also the controllable dynamic of the magnetic bearings is a great advantage. These characteristic features permit new constructions, operation without of mechanical wear and for that reason less mechanical maintenance as well as high speed with the possibility for vibration reducing. New ideas can be realized at the construction of the magnetic bearings in order to obtain an improvement of the properties (Schweizer, Traxler and Bleuler, 1993).

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A substantial improved utilization of the available electrical energy as well as a reduction of the expenditure of power electronics can be obtained, if there is a superposition of electrical flux and a homopolar permanent magnet flux in the air gap of the magnetic bearing (Hawkins et al., 1997; Meeks at al., 1994).

At the same magnetomotive force a homopolar magnetic bearing generates thus a clear higher carrying force as a comparable electrical magnetic bearing.

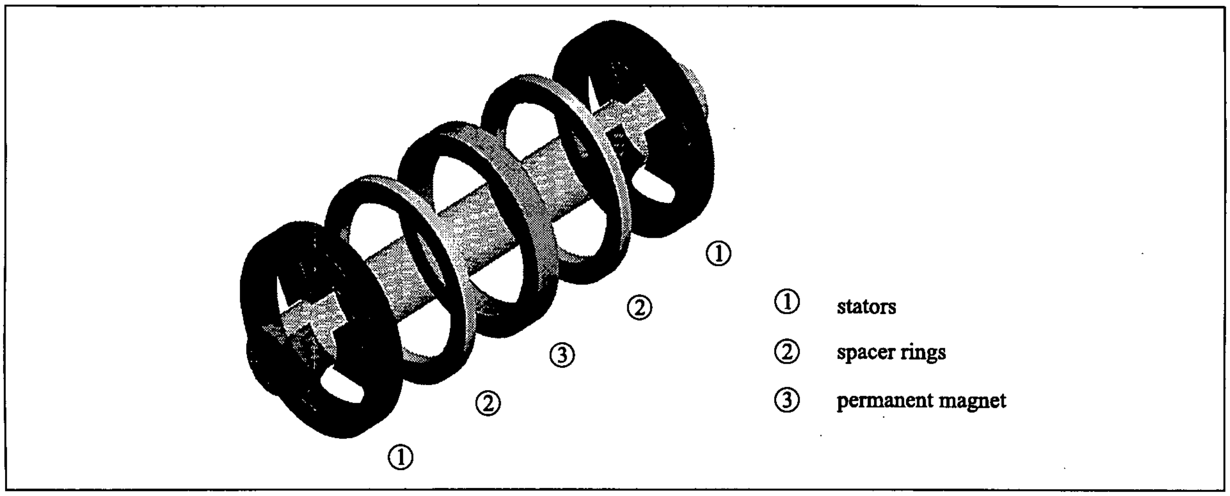

Fig. 1: Components of the magnetically circuit of a homopolar magnetic bearing.

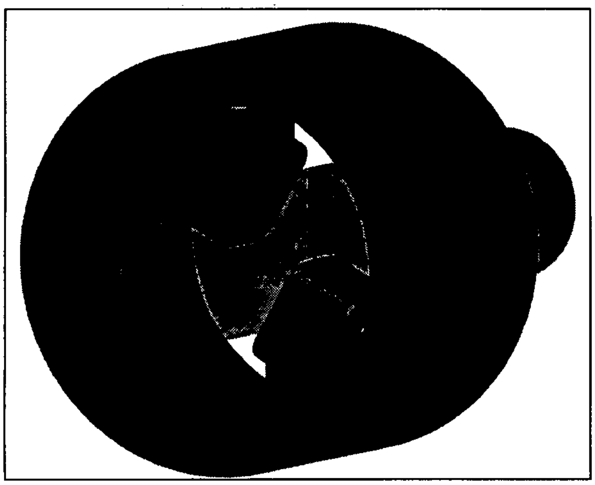

Fig. 2: Principle presentation of a homopolar magnetic bearing.

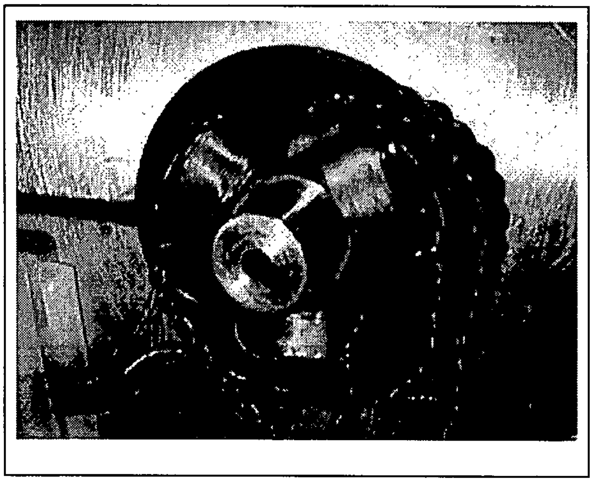

Fig. 3: Realization of a homopolar magnetic bearing.

A particular design of the homopolar magnetic bearing is obtainable, if the electromagnetic poles are developed in form of three concentrated coils, one per phase. Such a design is named a 3T-construction in the theory of electrical machines.

Normally each bedding of a spacial degree of freedom requires an own control circuit with two electromagnets. At a radial bearing for a bedding in x- and y- direction three control coils are sufficient. The control coils, which are split up in two coils for the reason of compactness, are connected in a star point, by which a simple drive with conventional three-phase current power amplifier becomes practicable.

The discrete coils can be wind outside the stator and following inserted as a whole in these. Small armature is possible with the termed construction, and that's why it has exceptional advantage with limited axial dimension. If the three-phase coils of the two stators are connected with opposite winding direction in parallel or in series, therefore the radial magnetic forces at both stators point always in the same direction.

With such an arrangement a radial magnetic bearing with smaller radial dimensions can be realized. The available space in axial direction between both stators, which depends on the armatures, can be used for arrangement of positioning sensors for measuring the rotor position. The advantage of such an arrangement lies in the accordance between the place of the position measuring and the place of the mean force production.

By choosing the diameter of the rotor in the region of the stators slight bigger than in the remaining region, additional to the active radial magnetic bedding a passive axial magnetic bedding can be obtained. The reason for that is the occurring of reluctance forces. With additional concentric slots in the rotor and in the stators this effect can be increased.

2 THEORETICAL BASIC FACTORS TO THE HOMOPOLAR MAGNETIC BEARING

At conventional active magnetic bearings the operating point adjustment of the ferromagnetic circuit results in a static current, which also flows at an unloaded bearing and causes losses in the control coils. Instead of adjusting the required flux for the operating point entirely over a current, at a homopolar magnetic bearing the ferromagnetic circuit is premagnetized with a permanent magnet. The homopolar magnetic bearing produces therefore less static losses in the control coils.

The additional magnetomotive force of the permanent magnet causes a displacement of the operating point to a higher level in the square force-magnetomotive force characteristic (figure 4).

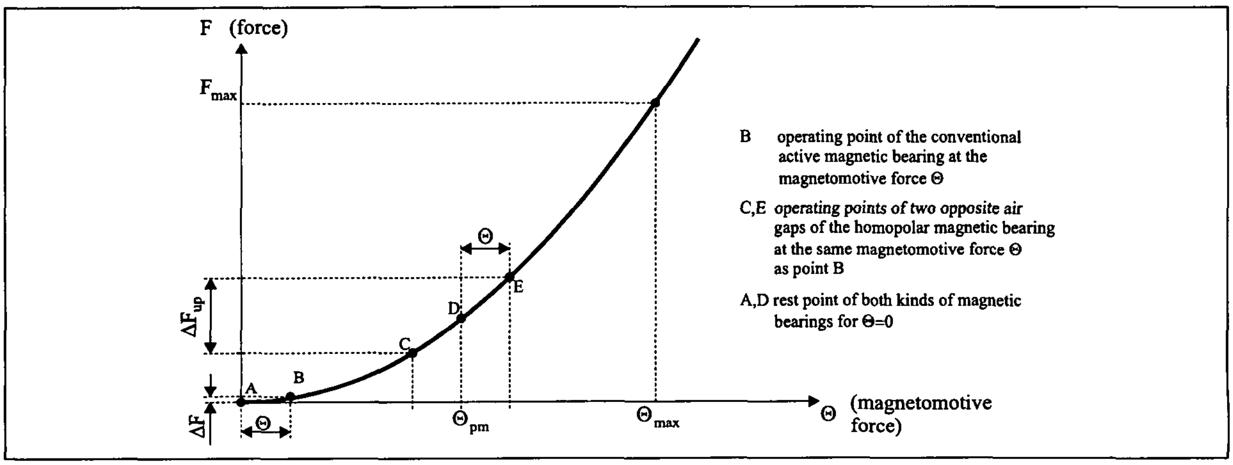

Fig. 4: Force-magnetomotive force characteristic.

The permanent magnet bias design is smaller than the all-electromagnetic bearing because the electromagnet coil window can be smaller since it is used for control only, and consequently, the active magnetic circuit laminated structure can be made smaller (Meeks, DiRusso and Brown, 1990).

3 MODEL OF THE HOMOPOLAR MAGNETIC BEARING

3.1 STATOR EQUIVALENT CIRCUIT DIAGRAM

For the representation of the total equivalent circuit diagram first the equivalent circuit diagram of one stator ring is explained. The stator rings are modeled two-dimensional. The model shown in figure 5 lies in the middle of the stator ring plane (Baumschlager and Binder, 1997).

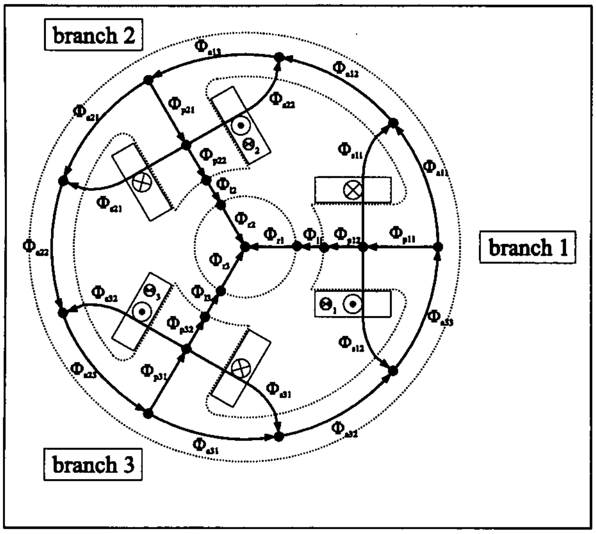

Fig. 5: 2D-model for one stator ring.

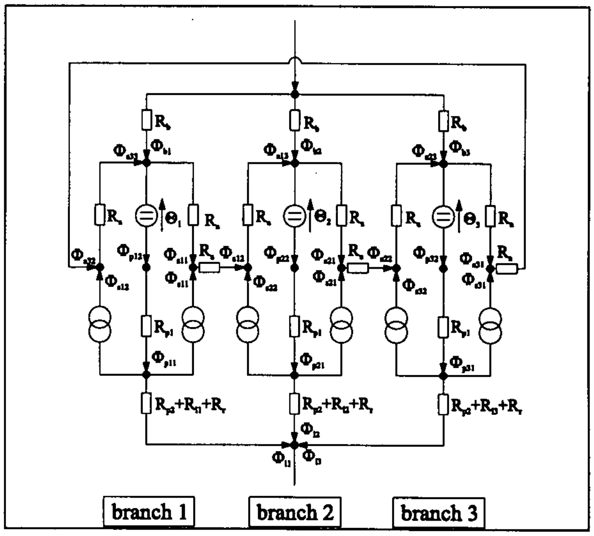

Fig. 6: Magnetic equivalent circuit diagram for one stator ring.

Figure 6 shows the magnetic circuit in the cross section of one stator ring. The iron paths from this plane to the spacer ring have to be considered (compare figure 1). Therefore the resistance's R_b and the fluxes Φ_{b1}, Φ_{b2} and Φ_{b3} are added in figure 6.

3.2 CALCULATION OF THE FORCES

The magnetic forces are given by the following equations:

$$F_{l1l}=\frac{B_{l1l}^2\cdot A_l}{2\mu_0}\qquad F_{l1r}=\frac{B_{l1r}^2\cdot A_l}{2\mu_0} \tag{1}$$

$$F_{l2l}=\frac{B_{l2l}^2\cdot A_l}{2\mu_0}\qquad F_{l2r}=\frac{B_{l2r}^2\cdot A_l}{2\mu_0} \tag{2}$$

$$F_{l3l}=\frac{B_{l3l}^2\cdot A_l}{2\mu_0}\qquad F_{l3r}=\frac{B_{l3r}^2\cdot A_l}{2\mu_0} \tag{3}$$

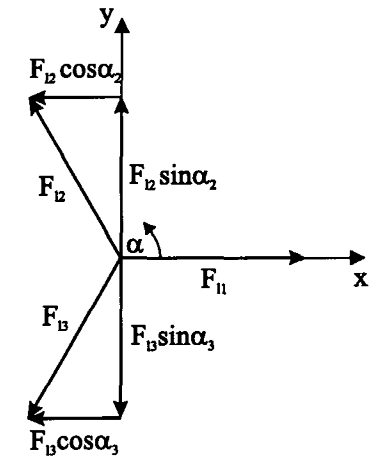

Fig. 7: The magnetic forces.

By vectorial addition we obtain the resultant force components (figure 7) in x- and y-direction in the following equations:

$$F_{xl}=F_{l1l}\cos\alpha_1+F_{l2l}\cos\alpha_2+F_{l3l}\cos\alpha_3 \tag{4}$$

$$F_{yl}=F_{l1l}\sin\alpha_1+F_{l2l}\sin\alpha_2+F_{l3l}\sin\alpha_3 \tag{5}$$

$$F_{xr}=F_{l1r}\cos\alpha_4+F_{l2r}\cos\alpha_5+F_{l3r}\cos\alpha_6 \tag{6}$$

$$F_{yr}=F_{l1r}\sin\alpha_4+F_{l2r}\sin\alpha_5+F_{l3r}\sin\alpha_6 \tag{7}$$

The components of the resultant bearing total force $F_x(x,y,I_1,I_2,I_3)$ and $F_y(x,y,I_1,I_2,I_3)$ are calculated to:

$$F_x(x,y,I_1,I_2,I_3) = F_{xl} + F_{xr} \tag{8}$$

$$F_y(x,y,I_1,I_2,I_3) = F_{yl} + F_{yr} \tag{9}$$

Through the Park-Transformation the three-branch system I_1, I_2 and I_3 is calculated into the two-branch system I_x and I_y.

$$F_x = F_x(x,y,I_x,I_y) \tag{10}$$

$$F_y = F_y(x,y,I_x,I_y) \tag{11}$$

3.3 GRAPHICAL REPRESENTATION

Figure 8 and figure 9 display the obtained functions $F_x(x,y,I_x,I_y)$ and $F_y(x,y,I_x,I_y)$. While figure 8 shows the whole operation area, figure 9 shows the nonlinear functions around the zero point. The following is to realize out of the figures:

If we suppose that the rotor is located in the steady position (x_0=0,y_0=0), so at a small excursion a force is developed, which lead to a higher excursion. The control system is instable and can be stabilized by a controller.

The graphs for the x- and y-direction look same, though the functions are not identical. That at least points to a similar control behavior of the control system in both directions.

In figure 9 the nonlinearity is not recognizable but in figure 8. So it seems that around the zero point a good approximation by a linear function is possible, which above all at higher excursions out of the zero point lose its validity.

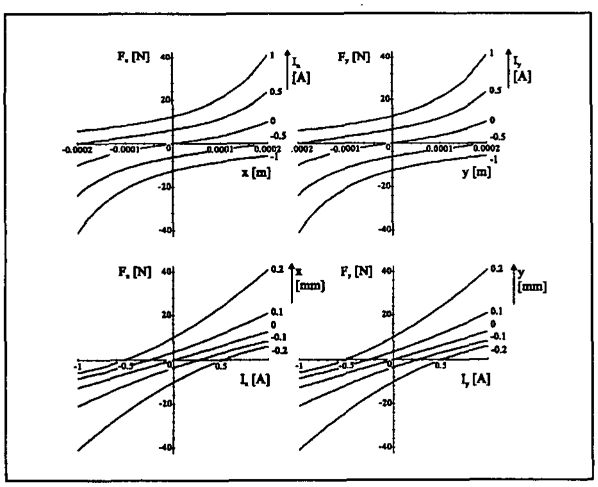

Fig. 8: $F_x(x,y,I_x,I_y)$ and $F_y(x,y,I_x,I_y)$ across the whole operation area.

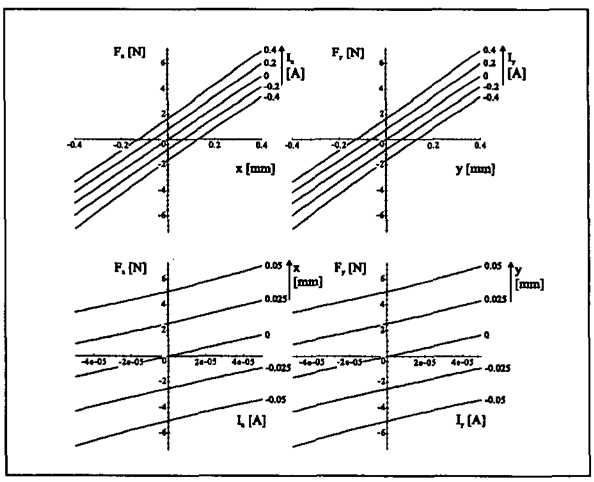

Fig. 9: $F_x(x,y,I_x,I_y)$ and $F_y(x,y,I_x,I_y)$ around the zero point.

4 ANALYTICAL INVESTIGATION OF THE COUPLING

In section 3 a nearly linear course was shown for the magnetic force in dependence of the current (compare figure 9). A further criterion for a linear control is the independence of the force F_x of y and I_y, as well as the force F_y of x and I_x, so that

$$F_x = F_x(x, I_x) \tag{12}$$

$$F_y = F_y(y, I_y) \tag{13}$$

is valid.

This can be obtained by a geometric torsion of the stator rings against each other.

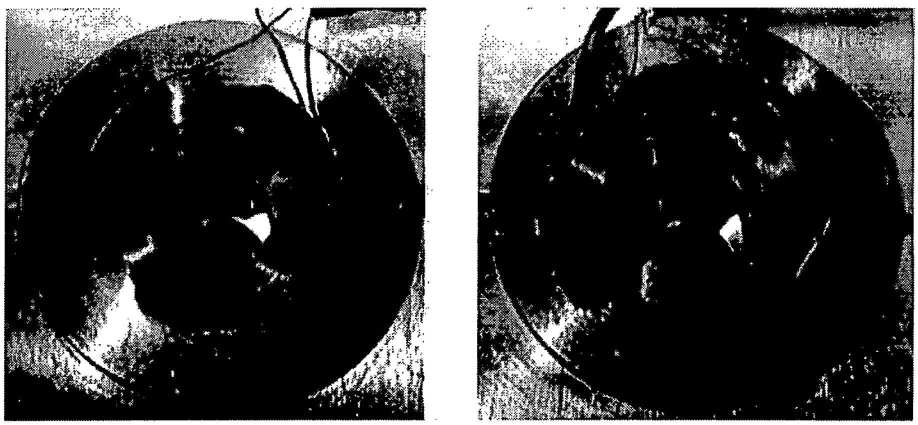

Fig. 10: Homopolar magnetic bearing without and with 180° torsion of the stator rings.

In figure 10 the left picture shows the homopolar magnetic bearing before it was redesigned (Grbeša, 1998; Hahn, 1997). The difference between the earlier style and the new one is clear to see. While at the left homopolar magnetic bearing the pole faces align and one branch of the three-branch system is applied at one rotor side, at the right homopolar magnetic bearing the stator rings are distorted 180°, so that the two in series connected coils of one branch operate at opposing sides of the rotor.

This constructive difference has, as practical experiences and theoretical investigations show, extraordinary effect at the behavior of the bearing. The control behavior is much better and a disturbance force in one coordinate axis causes a negligible influence in the other coordinate.

The forces are illustrated with regard to following parameter variation (Baumschlager and Binder, 1997):

- Course of force F_x over I_x, at variation of I_y (compare figure 11 a)
- Course of force F_y over I_y, at variation of I_x (compare figure 11 b)
- Course of force F_x over x, at variation of y (compare figure 11 c)
- Course of force F_y over y, at variation of x (compare figure 11 d)

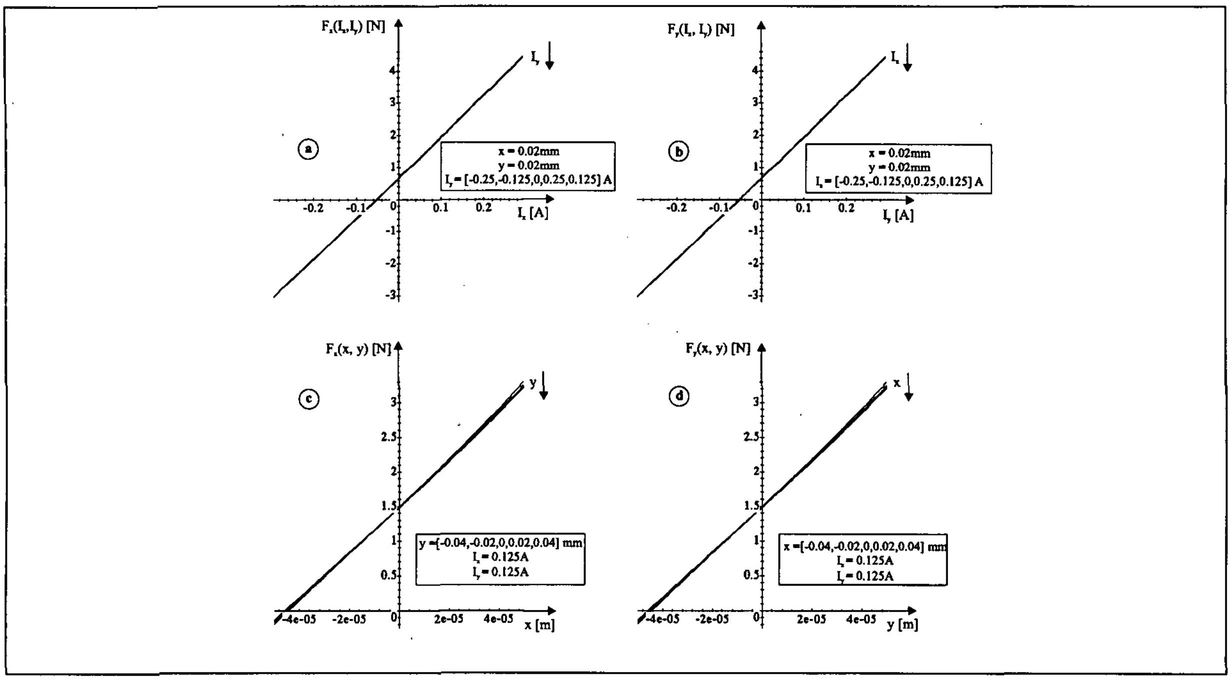

Fig. 11: Coupling effect of a homopolar magnetic bearing with distorted stator rings.

Figure 11 shows the investigation of the coupling at the homopolar magnetic bearing with distorted stator rings. It becomes clear, that a current in x-direction has no effect on the force in y-direction (compare figure 11 b) and reverse (compare figure 11 a). For the control behavior it leads to, that for example a stabilization of a disturbance force in x-direction causes a negligible force change in the y-axis. At this style there is nearly no coupling of the rotor position (compare figure 11 c and d).

This investigation has demonstrated that on the strength of the special arrangement of the stator rings there is a linearization of the force characteristics and a decoupling of the axis. Around the operating point (±0.05mm-environment) the system can be considered as decoupled and a linear, decoupled control structure can be applied.

4.1 INVESTIGATION OF THE COUPLING AT THE HOMOPOLAR MAGNETIC BEARING

The coupling effect is investigated practically at the built-on homopolar magnetic bearing. For this purpose the x-axis of the homopolar magnetic bearing is excited with a rectangular pulse. It becomes clear, that there is a coupling effect, but with

$$|y| < 0.01\text{mm} \tag{14}$$

the coupling effect is very small and negligible. The result of the investigation of the coupling at the homopolar magnetic bearing is shown in figure 12.

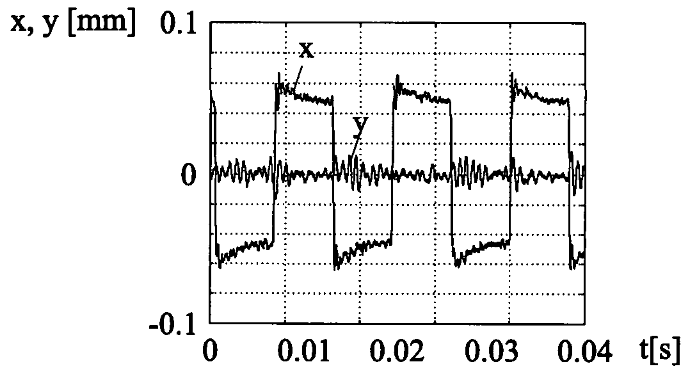

Fig. 12: Coupling of the x- and y-axis of a homopolar magnetic bearing.

Out of the waveform of the coupling reaction it becomes clear that a bounce excites a characteristic vibration (figure 12).

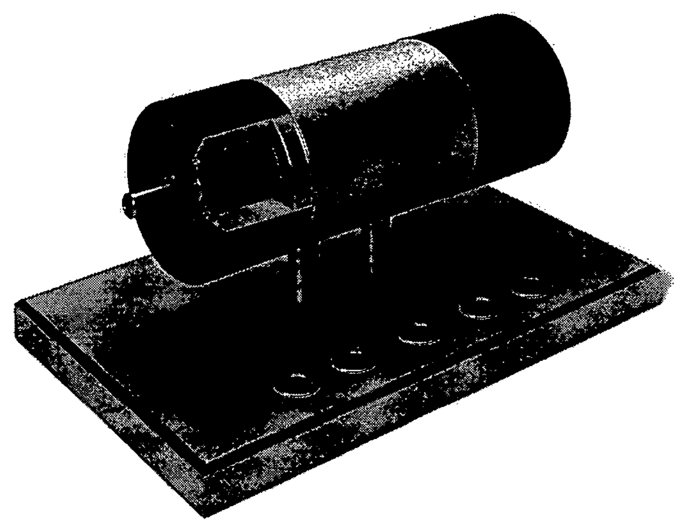

Fig. 13: Electrical drive with homopolar magnetic bearings.

Figure 13 shows an electrical drive with homopolar magnetic bearings. It was built up to test the function of the homopolar magnetic bearing.

5 CONCLUSION

This development has demonstrated that a substantial improved utilization of the available electrical energy as well as a reduction of the expenditure of power electronics can be obtained, if there is a superposition of electrical flux and a homopolar permanent magnet flux in the air gap of the magnetic bearing.

A particular design of the homopolar magnetic bearing is obtainable, if the electromagnetic poles are developed in form of three concentrated coils, one per phase, because at a radial bearing for a bedding in x- and y- direction three control coils are sufficient. That way a simple drive with conventional three-phase current power amplifier becomes practicable.

The investigation of the coupling at the homopolar magnetic bearing is discussed. It becomes clear, that a current in x-direction has an negligible effect on the force in y-direction and reverse, if the stator rings are distorted 180° against each other.

Further work will be required to optimize the mechanical construction and the magnetic circuit. Therefore the FEM- and analytical calculations will be used. The obtained theoretical models are to verify.

ACKNOWLEDGEMENT

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REFERENCES

Baumschlager, R., Binder, A.: Theoretische und experimentelle Untersuchungen von Unipolar-Magnetlagern. Diplomarbeit am Institut für Regelungstechnik und Elektrische Antriebe, Johannes Kepler Universität Linz, 1997.

Grbeša, B.: Modeling of a Homopolar Magnetic Bearing. Proceedings of the PCIM 98, Nuremberg, 1998.

Hahn, J.: Modellierung von Unipolar-Magnetlagern. Diplomarbeit am Institut für Regelungstechnik und Elektrische Antriebe, Johannes Kepler Universität Linz, 1997.

Hawkins, L., Brown, E., Thorp, J., Sloteman, D.: Development of a Homopolar, Permanent Magnet Bias Magnetic Bearing System for an API 610 Pump. Proceedings of MAG 97, pp. 3-14, 1997.

Meeks, C., DiRusso, E., Brown, G.: Development of a Compact, Light Weight Magnetic Bearing. AIAA Preprint 90-2483, presented at AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference, Orlando, 1990.

Meeks, C., McMullen, P., Hibner, D., Rosado, L.: Lightweight Magnetic Bearing System for Aircraft Gas Turbine Engines. Fourth International Syposium on Magnetic Bearings, ETH-Zurich, pp. 429-434, 1994.

Schweitzer, G., Traxler, A., Bleuler, H.: Magnetlager - Grundlagen, Eigenschaften und Anwendungen berührungsfreier, elektromagnetischer Lager. Springer Verlag, Berlin, Heidelberg, 1993.