Nd-Fe-B permanent magnets for passive and hybrid magnetic bearings with extended application temperature range

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***Index Terms*—VACODYM®,VACOMAX® magnetic Bearing, Surface charge model, amperien current density, coulombian representation, FEA**

I. Categories

Digest Categories: Magnetic bearing

***Abstract*—Passive magnetic bearings or hybrid passive magnetic bearings are commonly built up with Sm-Co or with Nd-Fe-B magnets. One of the most important item of those magnets is it's homogeneity in flux density distribution and the precise angularity. A miss-match would cause an undesired displacement. It may therefore be very important to measure these homogeneity's and angular deviation very precisely. Some application call for a higher temperature, thus a need of higher remanence B_r is inevitable and in some cases the temperature coefficient T_k of remanence B_r is also of importance. This may be achieved by applying the Grain Boundary Diffusion GBD. In the following paper we will give an overview of the current development to ensure this future demand. A variation of parameter studies will give an overview of the main influencing factors which act on the bearing forces and stiffness.**

II. Introduction

Turbo molecular pumps for example are equipped with passive magnetic bearings on the high vacuum side. The passive magnetic bearing are to stabilise the turbine shaft radially, while the axial stabilisation is achieved by an active (electric) magnetic bearing or a mechanical bearing. Whenever a parametric analysis of magnetic bearings is conducted, the analytical approach by simulating the magnet with surface charge modules is very convenient, since its results may be very rapidly obtained. The programs used in this field are commonly written in Matlab®/Scilab® or in Mathematica®. Of interest are the forces F_z obtained in a bearing and its stiffness K_z versus displacement. In this paper, we will give a brief introduction of these analytical methods and we will compare those results with Finite Element Analysis FEA. At the same time we will try to show the realistic influences of the variation of dimensions, remanence and the magnetic orientation onto the forces and the stiffness of a magnetic bearing.

III. Analytical approach of axially oriented magnet rings for magnetic bearings

In general let us first try to simulate a magnetic ring by using two surface charged coils which may substitute a ring magnet refer to eqn.(1) and eqn.(2) as used in [1] and [2].

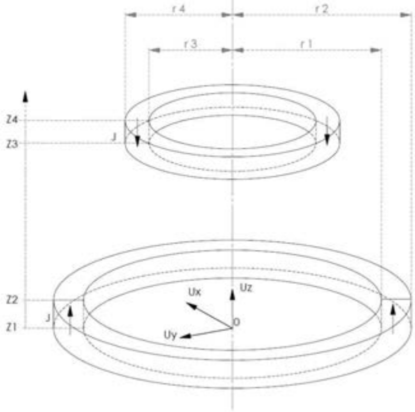

Figure 1. Two axially oriented magnet rings as an axial bearing.

$$F_z = \frac{J_1 J_2}{2\mu_0} \sum_{i=1}^{2} \sum_{j=3}^{4} (-1)^{1+i+j} \left\{ f_z(r_i, r_j) \right\} \quad (1)$$

$$f_z(r_i, r_j) = r_i r_j \int_{z_3}^{z_4} \int_{z_1}^{z_2} \int_{0}^{2\pi} \frac{(\tilde{Z} - Z) cos(\Theta) dz dz d\Theta}{(r_i^2 + r_j^2 - 2 r_i r_j cos(\Theta) + (z - z)^2)^{\frac{3}{2}}} \quad (2)$$

$$F_z = \frac{J_1 J_2}{2\mu_0} \sum_{i,k=1}^{2} \sum_{j,l=3}^{4} (-1)^{1+i+j+k+l} F_{i,j,k,l} \quad (3)$$

with eqn.(2) inserted into eqn.(1)

$$F_{i,j,k,l} = r_i r_j g(z_k - z_l, r_i^2 + r_j^2 + (z_k - z_l)^2, -2 r_i r_j) \quad (4)$$

$$g(a, b, c) = A + S \quad (5)$$

With A and S being:

$$A = \frac{a^2 - b}{c}\pi + \frac{\sqrt{c^2 - (a^2 - b)^2}}{c}(a_1 + a_2) \quad (6)$$

with

$$a_1 = \log\left[\frac{-16c^2}{(c^2 - (a^2 - b)^2)^{\frac{3}{2}}}\right] \quad (7)$$

$$a_2 = \log[\frac{c^2}{(c^2-(a^2-b)^2)^{\frac{3}{2}}}] \quad (8)$$

and

$$S = S_1 + S_2 + S_3 \quad (9)$$

$$S_1 = \frac{2a}{c\sqrt{b+c}}((b+c)E[\Phi_1, m_1] - cF[\Phi_1, m_1]) \quad (10)$$

In eqn.(10) $\Phi_1 = arcsin[\sqrt{\frac{b+c}{b-c}}]$
In eqn.(10) $m_1 = arcsin[\frac{b-c}{b+c}]$

$$S_2 = \frac{2a}{c\sqrt{b+c}\sqrt{\epsilon}}(\frac{c}{\sqrt{\mu}}E[m_2] - c\sqrt{\mu}K[m_2]) \quad (11)$$

In eqn.(11) $m_2 = \frac{b-c}{b+c}$
In eqn.(11) $\epsilon = \frac{c}{c-b}$
In eqn.(11) $\mu = \frac{c}{b+c}$

$$S_3 = \sqrt{\epsilon\beta^{-1}}((b-a^2)K[2\mu] + (a^2-b+c)\Pi[\frac{2c}{b+c-a^2}, 2\mu]) \quad (12)$$

In eqn.(12) $\mu = \frac{c}{b+c}$, $\beta = \frac{b+c}{b-c}$and $\epsilon = \frac{c}{c-b}$

These analytical calculation and formulae of $g(a, b, c)$ in eqn. (10 to 12) contain elliptical integrals $K[m]$, $F[\Phi, m]$, $E[\Phi, m]$, $E[m]$ and $\Pi[m, n]$, $\Pi[n, \Phi, m]$ as described in the following equations (13) to (18):

$$K[m] = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{1-msin(\Phi)^2}} d\Phi \quad (13)$$

Where m in eqn.(13) is valid for $<= 1$.

$$F[\Phi, m] = \int_0^{\Phi} \frac{1}{\sqrt{1-msin(\Phi)^2}} d\Phi \quad (14)$$

$$E[\Phi, m] = \int_0^{\Phi} \sqrt{1-msin(\Phi)^2} d\Phi \quad (15)$$

$$E[m] = \int_0^{\frac{\pi}{2}} \sqrt{1-msin(\Phi)^2} d\Phi \quad (16)$$

$$\Pi[n, m] = \Pi[n, \frac{\pi}{2}, m] \quad (17)$$

$$\Pi[n, \Phi, m] = \int_0^{\Phi} \frac{1}{\sqrt{1-nsin(\Phi)^2}} \frac{1}{\sqrt{1-msin(\Phi)^2}} d\Phi \quad (18)$$

The exact analytical formulation of K_z as in [2] can be expressed in the following equations.

$$K_z = \frac{J_1 J_2}{2\mu_0} \sum_{i,k=1}^{2} \sum_{k,l=3}^{4} (-1)^{1+i+j+k+l} C_{i,j,k,l} \quad (19)$$

where

$$C_{i,j,k,l} = 2\sqrt{\alpha}E[m_4] - 2\frac{r_1^2 + r_j^2 + (z_k z_l)^2}{\sqrt{\alpha}} K[m_4] \quad (20)$$

with $\alpha = (r_i - r_j)^2 + (z_k - z_l)^2$ and $m_4 = \frac{-4r_i r_j}{\alpha}$.

And m in eqn.(14) to (18) and n eqn.(17) and eqn.(18) are valid for $m, n <= 1$ respectively. As the magnet ring is substituted by two surface coils on the inner and outer circumference, the magnetic orientation is fixed to the axial direction, thus any deviation of orientation may not be calculated. This calls for a different approach, which may be found in [3]. In this paper the focus is on a dipole method and gives a 2D representation of permanent magnet bearings. The results differ slightly from the fully analytical approach given by [2] as it is an abbreviation.

$$F_z = p\frac{J_1 J_2}{2\pi\mu_0}\frac{2}{R^3} S_1 S_2 sin(\beta_1 + \beta_2 - 3\Theta) \quad (21)$$

For the axial forces versus axial displacement F_z is calculated and simulated in eqn. (21).

$$K_z = -2K_r = p\frac{J_1 J_2}{2\pi\mu_0}\frac{6}{R^4} S_1 S_2 cos(\beta_1 + \beta_2 - 4\Theta) \quad (22)$$

In eqn. 22 one may observe, that the radial stiffness is half the axial stiffness, i.e. $K_r = -\frac{K_z}{2}$. This is the reason, why in this paper we concentrate on calculating the axial stiffness K_z only.

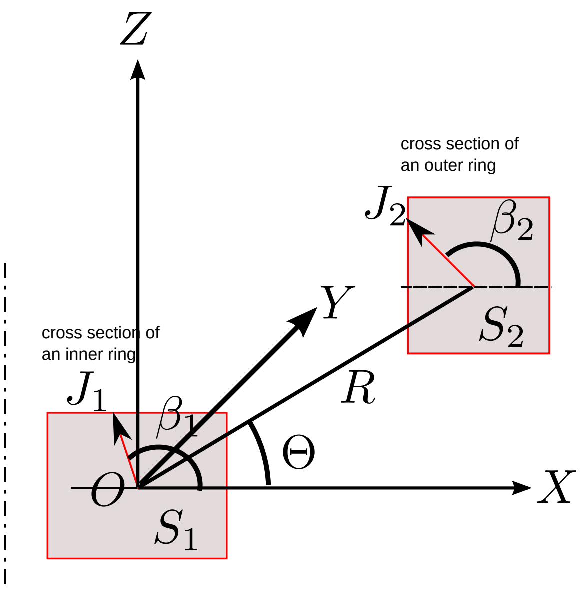

Figure 2. 2D Rings

The bearing stiffness K_z versus the axial displacement is calculated in eqn. (22). The advantage of this approach is, that it allows a deviation of orientation, but only to the extent, that the orientation is uniform over the entire ring. This uniform orientation may give a diverging or converging flux density above or below the rings pole surface, which is also know as “hot”- Side / “cold” - Side effect [4]. As stated in the paper of Bekinal et. al. [3] there will be a slight difference in results compared to the Yonnet et. al. publications [5] and

[2], thus a comparison with 2D FEA [1] calculations is therefore useful. A single angular deviation in one single direction super positioned with the normal axial direction, e.g. X-direction or Y-direction is not possible to simulate using these analytical formulae. This may be done by super positioning a diametrical ring. An analytical approach needs to be elaborated but is not the scope of this paper, thus to obtain any results for this kind of constellation, it would be necessary to calculate those bearings with 3D FEA. [2]

IV. Parameter study of influencing factor on bearing forces and stiffness

All analytical calculations as done by e.g. [5] [2] [6] [7] [8] [9] [10] [11] [12] are a very fast and convenient approach to render results, but do not reflect processing variances of remanence, dimension and orientation deviation. We therefore have undertaken a parameter study to find the most significant influencing factors which act on the bearing forces and stiffness. As a reference we may consider a passive magnetic bearing with the following dimension and magnetic properties, homogeneity and orientation deviation (by angular deviation causing a so called "Hot" and "Cold Side of each magnetic ring. If one would vary the outer and inner ring magnet of an axial bearing by a parameter study, one would need to vary the dimension of the inner ring denoted with suffix $_1$ D_{outer_1}, D_{inner_1},$Height_1$, Br_1 and β_1 and the same for the outer ring denoted by suffix $_2$ D_{outer_2}, D_{inner_2},$Height_2$, Br_2 and β_2 accordingly and keeping each of the five parameter on three levels, i.e. minimal, nominal and maximal. This would need $3^{10} = 59049$ combinations. To run a calculation of so many variations would be a rather endless undertaking. We therefore try to reduce the variation by combining the rings' volume and remanence to its magnetic moment, i.e. $M_{mag_1} = Vol_1 Br_1$ for the inner ring and $M_{mag_2} = Vol_2 Br_2$ for the outer ring. By doing so we now reduce the number of combinations, i.e. M_{mag_1} and β_1 for the inner ring and M_{mag_2} and β_2 for the outer ring, to $3^4 = 81$ combinations.

	Nominal	LSL	USL
Outer Ring outer Dia. [mm]	64.00	63.98	64.02
Outer Ring inner Dia. [mm]	44.00	43.98	44.02
Inner Ring outer Dia. [mm]	40.00	39.98	40.02
Inner Ring inner Dia. [mm]	20.00	9.98	10.02
Height [mm]	10.0	9.99	10.01
Remanence Br [T]	1.00	0.97	1.03
Angle of Orientation [deg]	90	88.5	91.5

Table I
Dimension and properties of inner ring magnet bearing

Tab. I gives an overview of the parametric variation of dimension, magnetic properties and deviation of orientation, which then is reduced to the magnetic moment and the deviation of orientation as shown in Tab. II . This approach simplifies the number of variation significantly.

[1] http://www.femm.info/wiki/HomePage

[2] http://www.ansys.com/Products/Simulation+Technology/Systems+&+Multiphysics/Multiphysics+Enabled+Products/ANSYS+Maxwell

	Nominal	LSL	USL
Magnetic Moment M_{mag_1} inner Ring IR [nVsm]	9.424	8.924	10.001
Magnetic Moment M_{mag_2} outer Ring OR [nVsm]	16.965	16.231	17.714
Angle of Orientation β_1 of IR [deg]	88.5	90	91.5
Angle of Orientation β_2 of OR [deg]	88.5	90	91.5

Table II
Dimension and properties of outer ring magnet bearing

V. Result of parameter study

The analytical result were compared with 2D FEA results to see how good these calculation fit.

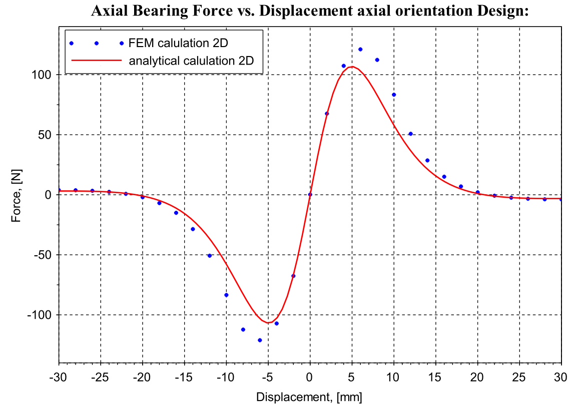

Figure 3. Force Fz vs. axial displacement 2D FEA and analytical calculation

It can be seen in fig. 3 the analytical results (red line) fit well. Only the maximum and the minimum differ slightly, the 2D FEA results (blue dots) show a higher maximum and lower minimum respectively.

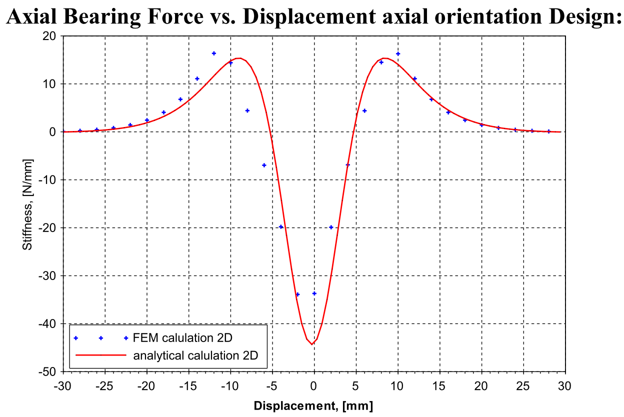

Figure 4. Stiffness Kz vs. axial displacement 2D FEA and analytical calculation

As far as the stiffness is concerned, the 2D FEA results differ slightly from the analytical results, especially with the maxima's fig. 4 as described by Bekinal [3].

First let us look at the influence of varying the magnetic moment and keeping the orientation constant at $90[deg]$.

The forces are symmetrical over the displacement, which can be seen in fig. 5, the maximum in magnetic moment

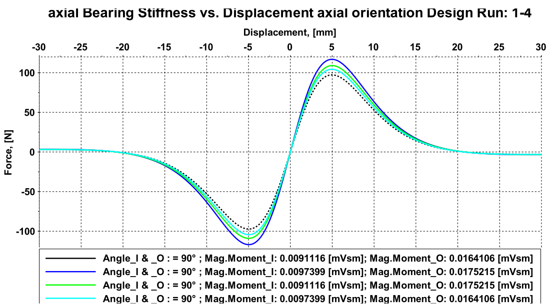

Figure 5. Force Fz vs. axial displacement analytical calculation with orientation 90 [deg] for various magnetic moments

produces the highest force where the lowest force is at $98[N]$ (black line) and the highest $118[N]$ (dark blue line), thus producing a difference of $20[N]$. It also shows, that the smallest inner magnetic moment combined with the highest outer magnetic moment (green line) renders a higher force maximum than the highest inner magnetic moment combined with the lowest outer magnetic moment (light blue line). All in all the maximum force depend very strongly on the magnetic moment only, so the higher the magnetic moment of both rings is, the higher the maximum force.

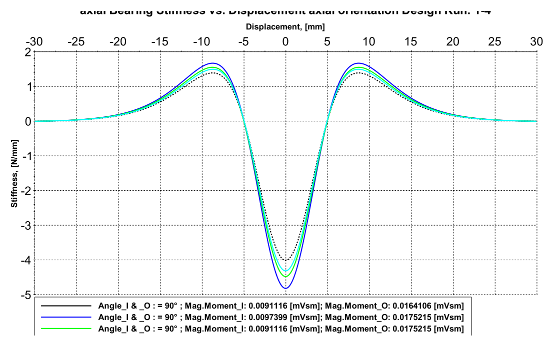

Figure 6. Stiffness Kz vs. axial displacement analytical calculation with orientation 90 [deg] for various magnetic moments

Considering the same with the stiffness Plot fig. 6 a dislocation of the inner magnet ring from the symmetry either in upward or downward displacement with varying magnetic moment renders a difference from $-4.0[\frac{N}{mm}]$ to $-4.7[\frac{N}{mm}]$ in stiffness. Since, according to eqn. 22, the radial stiffness $K_r = -\frac{K_z}{2}$ with the variation of the magnetic moments by a total of appr. $21[\%]$ yields a variation of the radial bearing stiffness by appr. $18[\%]$. The lowest magnetic moment in both rings render the lowest stiffness Kz (black line). The highest magnetic moment renders the highest stiffness Kz (dark blue line). The combination of the lowest inner magnetic moment with the highest outer magnetic moment (green line) renders a higher stiffness than the combination of the highest inner magnetic moment with the lowest outer magnetic moment (light blue line). Again the Stiffness is only correlated with the variance of magnetic moment.

It is important to say, that the respective maxima are symmetrical, thus the forces and stiffness's are the same regardless the displacement in the positive or negative direction from the line of symmetry, where the inner ring is within the outer ring.

Now considering the same analysis by varying the angle of orientation, thus, the so called "hot"- side "cold"- side effect by varying the angle from $90[deg]$ + / - $1.5[deg]$ symmetrical keeping the magnetic moment constant at the nominal value similar plots can be analysed.

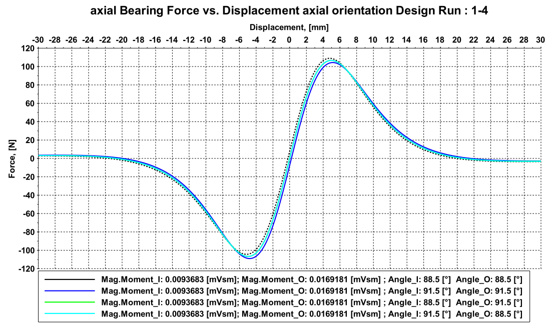

Figure 7. Force Fz vs. axial displacement analytical calculation with varying angle of orientation

When the angle of orientation of the inner and the outer ring are at 88.5 deg (both rings have a diverging field density distribution), the forces shown in fig. 7 are not symmetrical, thus moving the inner ring from the negative to the positive displacement in z-direction on the negative side the forces are less than on the positive side (black line). When the angles of orientation of both rings are at 91.5 deg, thus converging field distribution, the forces are also not symmetrical and on the negative side are higher than on the positive side of the displacement in z-direction (dark blue line). Combining a diverging inner ring (angle 88.5 deg) with a converging outer ring (angle 91.5 deg) renders a symmetrical force (green line). Where as combining a converging inner ring (angle 91.5 deg) with a diverging outer ring (angle 88.5 deg) also renders a symmetrical force and both maxima are on the same level (light blue line). The light blue line covers identically the green line.

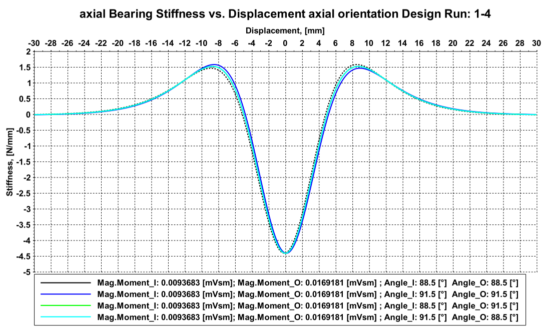

Figure 8. Stiffness Kz vs. axial displacement analytical calculation with varying angle of orientation

As expected from the forces, the stiffness refer to fig. 8 show the same, if both are diverging rings (i.e. angle 88.5 deg) they render on the negative side of the displacement a lower and on the positive side of the displacement a higher stiffness (black line). If both rings are converging (angle 91.5 deg) then the stiffness on the negative side is higher than on the positive side (dark blue line). If the inner ring is diverging and the outer ring converging, then the stiffness is again symmetrical (green line). If the inner inner ring is converging and the outer ring diverging, then the stiffness is on the same level as later.

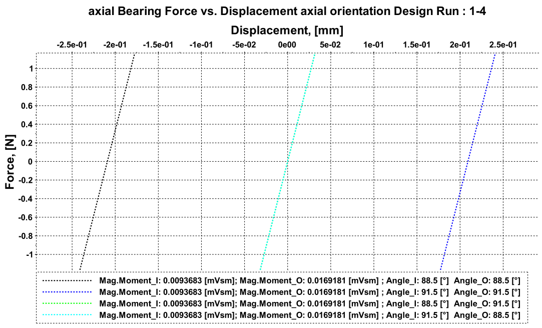

Figure 9. Force Fz vs. axial displacement analytical calculation with varying angle of orientation

The above described influences can be analysed in more detail by magnifying fig. 9 in the vicinity of the origin. In general, one may deduce, that a unsymmetrical force- or stiffness- distribution may be neutralised by combining a "hot side" inner ring with a "cold side" outer ring or vice verse. When two diverging or two converging magnetic rings are combined within a bearing, a so called "parasitic axial force" at $z = 0.0$ is $+/-8[N]$ which can be observed by extrapolating to $z = 0.0$. These parasitc forces may be neutralised by shifting one of the rings in axial direction by $+/-0.21[mm]$ refer 9. So it is important to measure these effect very precisely. This phenomenon was also patented by VACUUMSCHMELZE GmbH & Co. KG (VAC) [3].

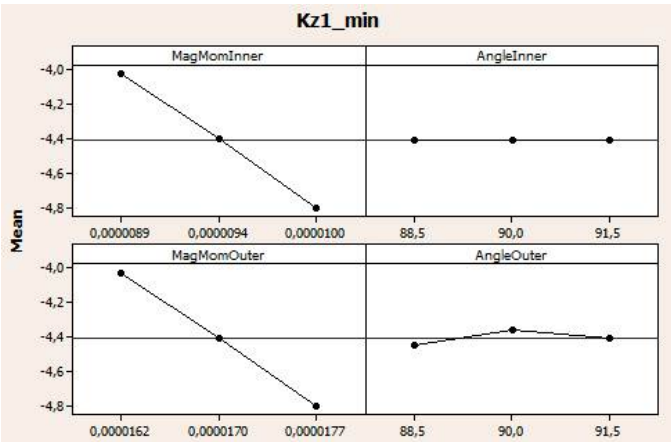

Figure 10. Main Effect magnetic moment acting on stiffness Kzmin. Mean taken over all 81 parameter sets

Analysing the 81 combinations possible, one may deduce, that the magnetic moment is a so called main effect, which acts on the maximum and minimum Force and Stiffness refer to fig. 10.

Where as the symmetrical or unsymmetrical distribution of forces or Stiffness cause a so called "parasitic axial force" and only depends on the angle of orientation fig. 11 or "Hot side"

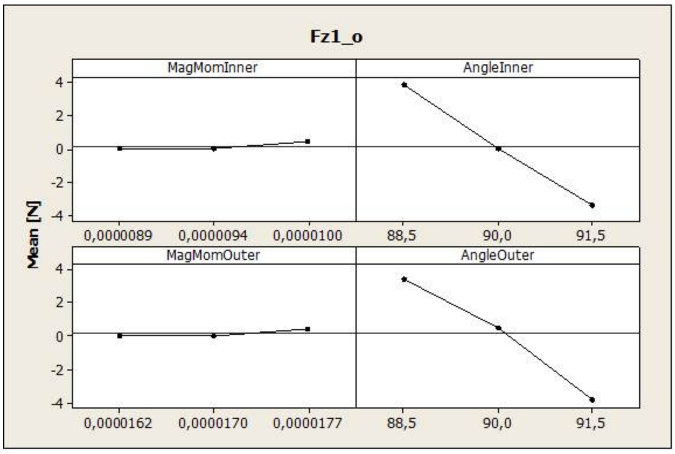

Figure 11. Main Effect angle acting on Fz at z = 0.0. Mean taken over all 81 parameter sets

and "Cold Side" of the ring magnets and it may be neutralised by a sorted and paired combination of rings.

VI. Outlook

Most magnetic baerings are currently equipped with Sm-Co magnets. But resently even Nd-Fe-B magnets are being considered as an alternative solution. With a new family of grades and technologies, one may be able to increase the share of Nd-Fe-B magnets in magnetic bearings, when ever a higher environmental temperature, thus coercivity is needed.

A proposal to meet these demands is to use Grain Boundary Diffusion (GBD) magnets as in fig. 12. By implementing this technology the coercivity may be increased by $> 400\frac{kA}{m}$ and keeping the remanence constant. As shown in fig 12 by the blue line, which represents a typical demagnetisation curve of transversal pressed VACODYM 131 TP, while the black lines shows the increase of coercivity by applying Dy/Tb Grain Boundary Diffusion. By developing new magnet grades using this advanced processing step as described, VACUUMSCHMELZE (VAC) has not only met and fulfilled the demand from the market to reduce the heavy RE content of Nd-Fe-B magnets, but also significantly improved the magnetic properties. Thus, by reducing the heavy RE content, the security of supply of RE elements may be enhanced. These additional process steps of applying RE elements and exposing the magnet to 800 $[degC]$ - 1000 $[degC]$ do have an influence on the production costs. The overall result may not necessarily be cost neutral, depending of course on the level of the raw material prices. However, such a technique demonstrates that new grades can be tailored to meet specific customer and application demands, either in the form of higher H_{cJ} or B_r values, enabling precise optimisation of the magnet grade to the working conditions of the customers application.

VII. Conclusion

In this paper, we tried to find an analytical method, with which we are able to find the main influencing factors which act on a axial magnetic bearing forces and stiffness. By carrying out a parametric variation, we were able to find

[3]Patentschrift DE 103 21 925 B4 2008.10.02

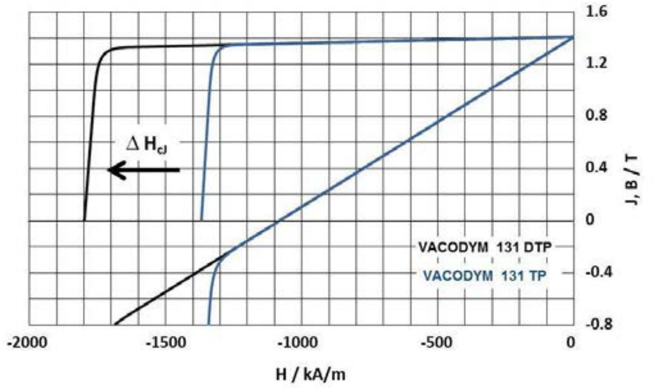

Figure 12. The increase in magnetic properties with diffusion treatment.

that the forces and stiffness not only depend on the mutual magnetic moments of the inner and outer magnetic ring, but also on their mutual so called" "Hot Side" or "Cold Side" effect, which was represented here by the angular orientation. The approaches by Yonnet et. al. [5] [2] through [11] [12] could not be used, because the analytical calculation does not take into account, that a diverging or converging orientation of a ring is possible. Only with the work of Bekinal et. al. [3] it is possible to consider this effect.

We also were able to show that a paired combination of diverging and converging rings may reduce the unsymmetrical force and stiffness distribution of a magnetic bearing.

REFERENCES

[1] V.Lemarquand G.Lemarquand. Passive permanent magnet bearings for rotating shaft : Analytical calculation. *Intech,croatia*, ISBN 978-953-307-148-0:132, 2010.

[2] V. Lemarquand R.Ravaud, G.Lemarquand. Force and stiffness of passive magnetic bearings using permanent magnets. part 1 : Axial magnetization. *IEEE Transactions of Magnetics*, 45,7:2996, 2009.

[3] S. Jana M.I. Peerzade S.I. Bekinal, T.R. Anil. Optimization of halbach magnetized permanent magnet axial bearing. *IJEIT*, 2,1:5, 2012.

[4] M. Weickhmann. Nutzung des Nord- / Sd- Effektes bei permanenter-regten Maschinen. *FEMAG Anwendertreffen, Offenbach*, 2011.

[5] J.P. Yonnet. Permanent magnet bearing and couplings. *IEEE Transaction on Magnetics*, 17:1169–1173, 1981.

[6] R. Ravaud G.Lemarquand. Halbach structure for permanent magnets bearing. *Progress In Electromagnetics Research M*, 14:263–277, 2010.

[7] R. Ravaud G.Lemarquand. Magnetic field produc ed by a parallelepipedic magnet of various and uniform polarization. *Progress In Electromagnetics Research PIER*, 98:207–219, 2009.

[8] G.Lemarquand R.Ravaud. Halbach structures for permanent magnets bearings. *Progress In Electromagnetcs Research M*, 14:263–277, 2010.

[9] V.Lemarqund R.Ravaud, G.Lemarquand. Force and stiffness of passive magnetic bearings using permanent magnets. part 2: Radial magnetization. *IEEETransactions on Magnetics*, 45,9:3334–3342, 2009.

[10] V.Lemarqund R.Ravaud, G.Lemarquand. Force and stiffness of passive magnetic bearings using permanent magnets. part 2: Radial magnetization. *IEEETransactions on Magnetics*, 45,9:3334–3342, 2009.

[11] G.Lemarquand V. Lemarquand. Passive permanent magnet bearing for rotating shaft : Analytical calculation. In *Magnetic Bearings, Theory and Application*, 2010.

[12] Anthony Zander W. Robertson, Ben Cazzolato. A simplified force equation for coaxial cylindrical magnets and thin coils. *School of Mechanical Engineering, University of Adelaide, SA 5005, Australia*, pages 1–5.