3D-FEM ANALYSIS OF A LOW LOSS HOMOPOLAR INDUCTION BEARING

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ABSTRACT

A radial flux homopolar induction bearing has been developed, and is analyzed using a 3D-FEM software in which the Minkowskij transform has been implemented. Results show remarkably low bearing losses, but also a strong and speed dependent cross coupling in the lateral plane stiffness. Parametric optimization of the magnetic circuit has been performed to maximize bearing stiffness with regard to magnet size, losses and stability.

INTRODUCTION

Recent findings on new homopolar designs showing extremely low losses have attracted renewed attention to the study of electrodynamic bearings, EDB, or Magnetic Induction Bearings, MIB, as they are also referred to.

Research on Heteropolar bearings have been carried out for decades by inventors like Richard Post[1] and also by the author[2], usually resulting in bearings with relatively high losses and poor dynamic stability. With the introduction of homopolar designs[3, 4, 5] the losses have been brought to a minimum, the remaining ones mainly resulting from magnet inhomogenities.

Homopolar designs can be divided into bearings where the rotor conductor is either wire wound[3] or consists of a bulk cylinder[5] or plate. The airgap flux can be either axial[3] or radial[5]. Analyzing the forces and the stability of these bearings is a complex task, where it is necessary to fully understand the nature of the induced currents. An extensive analysis was done recently by Filatov[3, 4] who developed and investigated a low-speed, wire wound axial flux bearing, which showed stable operation and very low losses. An advantage when it comes to analyzing wire wound bearings is that once the coil design is done, then the current paths are known, for which the amplitude and phase angle can be calculated.

However, for the bulk conductor designs, which are the preferred designs for high-speed bearings due to mechanical considerations, no paper has yet presented the geometric shape of the currents, here referred to as eddy currents. Neither has anyone proposed a solution to their amplitude and phase.

The purpose of this paper is to present results from many years of 3D-FEM calculations concerning the shape, the amplitude and the phase angle of the eddy currents induced in conducting rotor cylinders in radial flux homopolar induction bearings. These values will then be converted into useful bearing data, such that it can be applied by mechanical engineers for further rotordynamic simulations.

PRINCIPLES OF OPERATION

To visualize the function of the bearing consider the simple homopolar bearing in fig. 1. It consists of a rotating electrically conducting cylinder, and a stator made of two axially magnetized permanent magnets and three iron washers, the latter acting as flux concentrating pole shoes. Note that one half of the stator is removed for clarity.

When the rotor is spinning at a velocity ω around an axis that is displaced from the center of the homopolar flux, two main eddy currents of amplitude *I* are induced in the cylinder. A detailed illustration of the magnetic interactions is given in fig. 2a-e.

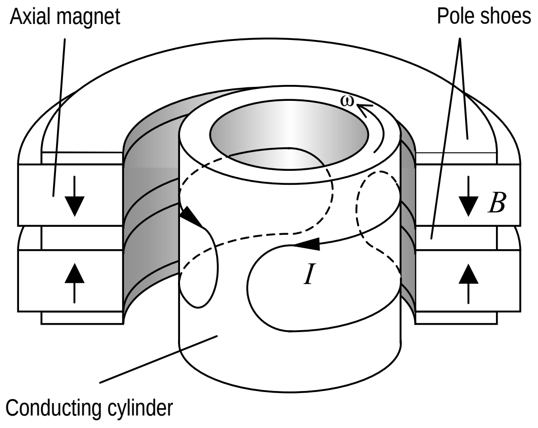

Fig. 1.

In fig. 2a the bearing rotor is spinning in its centered position. The flux from the magnets is concentrated via the pole shoes into a radial homopolar flux finally penetrating the rotor surface. Since no flux changes are present on the surface, no currents are induced and no ohmic losses are generated.

The rotor is now displaced a distance Δr_0 in the negative y-direction, fig. 2b. A point A on the rotor surface will see a sinusoidally alternating flux. The flux derivative is maximum in the position of A shown in fig. 2c. A voltage is induced trying to create a current circulating this point. However, due to inductance the current is phase delayed and does not reach its maximum until point A has reached the position in fig. 2d. The currents consist of the active currents I^+ and I^- and the short cirquit currents I_{sc}. The latter are dashed since they do not occur in this particular plane cut. The Lorenz force distribution $dF = JB$ is acting along the eddy currents, and on this cut the contributions from the active parts of the currents are shown.

The short circuit currents live deeper down in the cylinder, in the same plane as the magnets, fig. 2e. In this plane the flux is axial, both through the magnets and through the cylinder. It is interesting to note that the Lorenz force is actually larger on the short cirquit currents than on the active currents, since the former are much longer, which can best be seen in the perspective view in fig. 1.

In fig. 1f the resulting Lorenz force

$$F = \int_{Cyl} J \times B \, dV$$

acting on the cylinder is shown, and the force angle θ is defined related to the y-axis.

The force component acting in the y-direction $F \cdot \cos\theta$ is the desired lift force, and the force acting in the x-direction $F \cdot \sin\theta$ is a destabilizing side force causing forward wirl if not properly damped. Engineers involved in tribology should immediately recognize the similarities between this bearing and a conventional fluid dynamic bearing.

NUMERICAL METHODS

The results presented in this paper have been achieved using the 3-dimensionsional finite element method, 3D-FEM. Since the computational task is not trivial, the first sections will be devoted to the choice of software and to the methods used.

A homopolar magnetic flux is only possible to achieve in a 3-dimensional magnetic circuit, so the problem could not be solved with any of the 2D-codes available on the market in 1995 when the project started. Also, 3D-FEM calculations are, even today, very time consuming, so much effort was put into selecting the software, and building fast Linux servers.

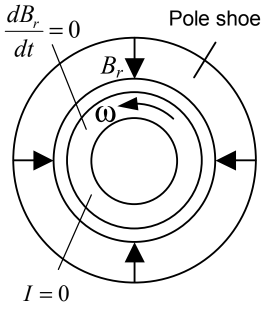

Fig. 2a.

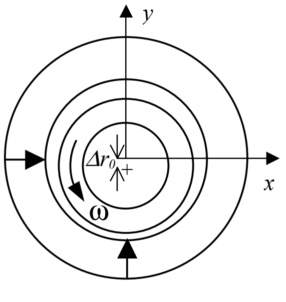

Fig. 2b.

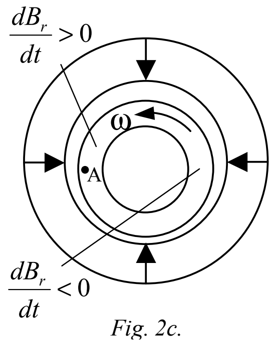

Fig. 2c.

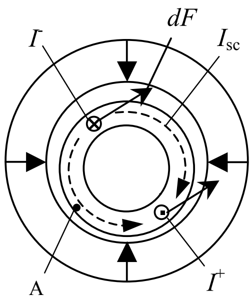

Fig. 2d.

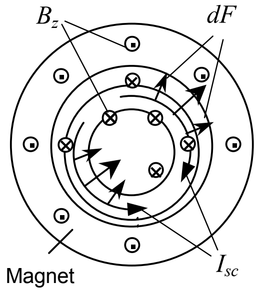

Fig. 2e.

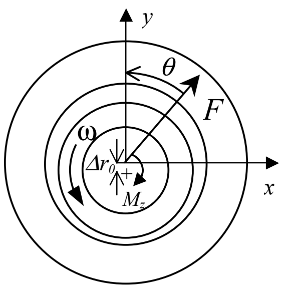

Fig. 2f.

Eddy current problems involving spinning rotors can be solved either by using several time steps, or be transformed into steady state using the Minkowskij transform which is then solved in one single calculation.

Software

The only 3D-code which had implemented the Minkowskij transform was the MEGA-code, at that time recently developed by the Univesity of Bath.

The Minkowskij transformation increases the number of equations in the eddy current elements by a factor of two. Since about 30% of the elements are used to build up the mesh of the conducting rotor, this

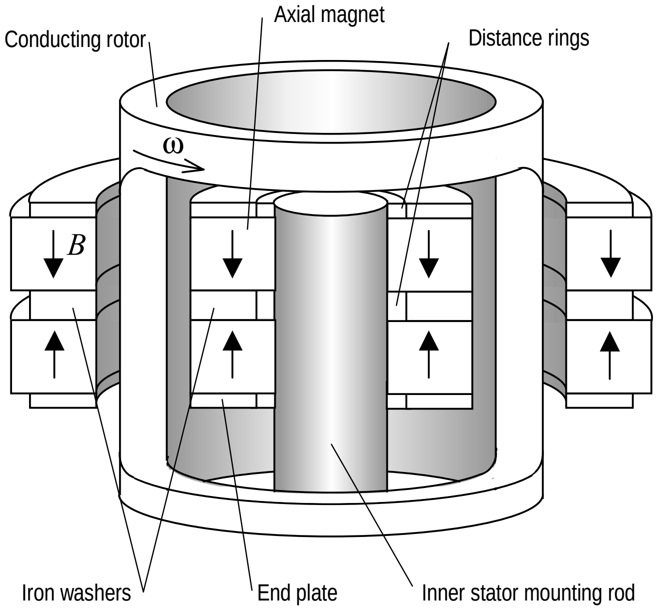

Fig. 3. Intermediate rotor bearing.

means tha the total number of equations are increased approximately 30%, which in turn increases the calculation time 69% compared to the time to solve one single time step. Since a large number of time steps are necessary, the timesavings using the Minkowskij transform instead of time steps is considerable. In normal configuration Mega is not optimized for 30% eddy current elements, so the team at Bath had to modify the software. Nevertheless, when using the Minkowskij transform the solver gets unstable at low rotational speeds below approximately 10–15,000 RPM depending on model geometery. Thus low speed operation can not be calculated.

Platform

Mega is run on a 32 bit Linux server using 1 GByte RAM memory, dual 550 MHz pentium processors and 2 parallell SCSI hard disc drives. The maximum allowed number of equations in this configuration is 250,000. To solve more equations a 64 bit processor would be needed. Normally the model size is 150,000 equations which takes about one hour to solve as long as hard disc swapping is not required.

Model Geometry

In the result section a slightly more advanced design will be simulated than the inner rotor bearing in fig. 1, which was described previously. Magnets and pole shoes will now be mounted inside as well as on the outside of the rotor cylinder, see fig. 3. Such a bearing will be referred to as an intermediate rotor bearing. This doubles the airgap surface, which increases the stiffness approximately a factor of two. It also affects the inductance, so that low speed stability is improved by reducing the force angle θ.

Calculations have been performed both with and without pole shoes.

In the result section diagrams, bearings with two axially stacked sets of magnets are denoted 2-row bearings, a term borrowed from the ball bearing industry.

Material	**Dimension**	**Unit**
Outer magnet	38×30×4	mm
Inner magnet	24×16×4	mm
Outer washer, middle	38×30×4	mm
Inner washer, middle	24×16 ×4	mm
Outer end plates	38×30×4	mm
Inner end plates	24×16×4	mm
Copper cylinder	29×25×9	mm
Airgap	0.5	mm
Useful airgap (due to emergency bearing)	0.25	mm

Property	**Value**	**Unit**
Remanence	1.0	T
Rel. permeability, magnets	1.0	
Rel. permeability, iron	300	
Conductivity	$6\cdot 10^{6}$	$(\omega m)^{-1}$

Table 1. Bearing model data.

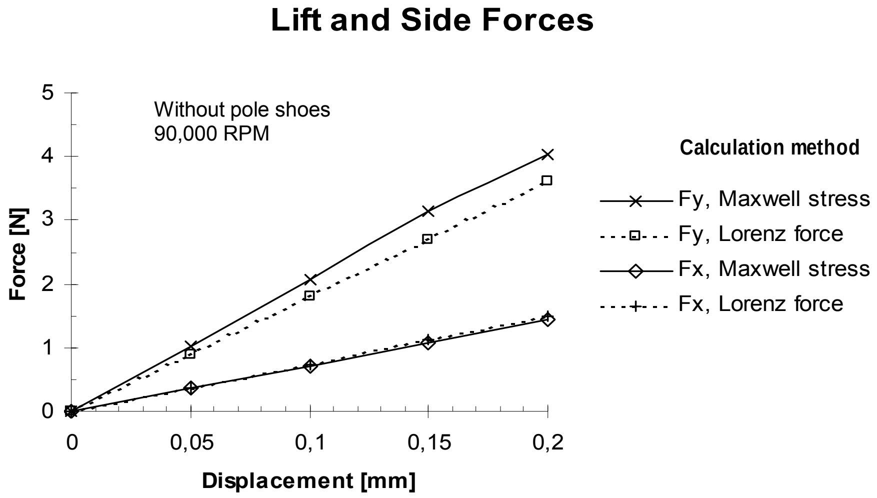

Fig. 4. Lift force F_y and side force F_x calculated using different methods.

Mesh Generation

A very important aspect of this work is to find a way to create a mesh, which will generate results that are accurate enough. When doing parametric changes to the geometry, we want to be sure that the change in the calculated forces is a result from the change in the parameters and not from the change in the mesh. Thus the mesh was designed manually and then fixed. After it had been fixed the only allowed changes was to move individual nodes. We also found that we could not use any triangular elements in or close to the eddy current regions, otherwise additional eddy currents would be induced purely related to the bad mesh and with no physical significance.

Post Processing

In Mega there are basically four methods to calculate forces. They all have some advantages and disadvantages. The methods are:

- Volume integral of Lorenz forces
- Surface integral of Maxwell stresses
- Magnetic potential energy difference
- Volume integral of Joule heat

The volume integral of Lorenz forces is very accurate since it involves a lot of elements. It does though become less accurate at very high speed due to the skin effect, which reduces that number. The surface integral of Maxwell stresses does not have this problem, since the air gap surface area is constant at all speeds. The disadvantage of Maxwell stress is that for a bearing with more than one air gap, like the intermediate bearing, the surface integral has to be calculated twice in the post processor. However, if ferromagnetic materials are used in the rotor, Maxwell stresses have to be used, since Lawrence forces does not take the attractive and destabilizing force between iron and magnets into consideration. In fig. 4 and 7 results using different methods are compared.

RESULTS

The results are presented in diagrams 4, 6 and 7. Diagram 4 shows the linear relationship versus displacement for the x- and y-components of the bearing force, and in diagram 7 the corresponding brake torque is shown.

The brake torque is also shown in fig. 6c, where it has been plotted against speed for constant eccentricity. In fig. 6a the in-plane stiffness, as defined by Filatov[3], has been calculated. Fig. 6b shows the corresponding force angle θ.

From the torque curve in fig. 6c, the losses can be calculated, which are plotted agains speed in diagram 6d given a certain eccentricity. However, constant load is often a more realistic operating condition, and this is shown in fig. 6e. Here the eccentricity is allowed to vary, and at low speed the rotor will finally touch the emergency bearing, which is assumed to occur when the eccentricity e reaches 50% of the airgap.

Finally, fig. 6e shows an example of a parametric optimization. Here the relationship between bearing stiffness and bearing length has been optimized with regard to the magnet axial thickness. It is found that the optimum bearing geometry is strongly speed dependant.

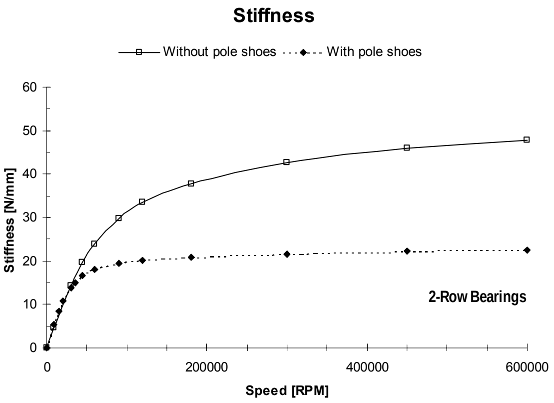

Fig. 6a.

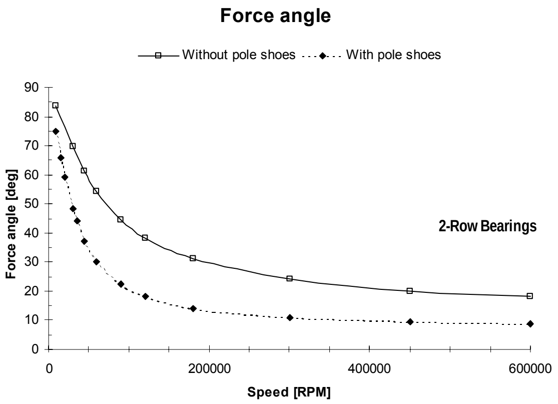

Fig. 6b.

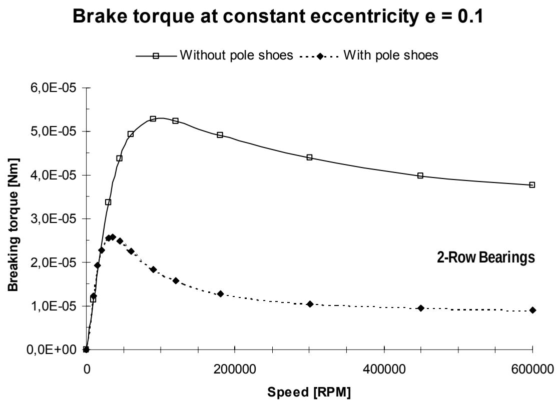

Fig. 6c.

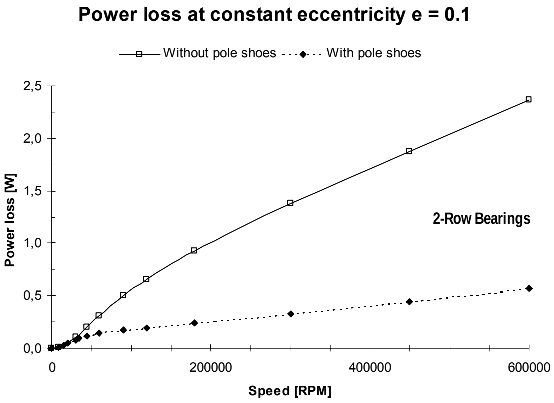

Fig. 6d.

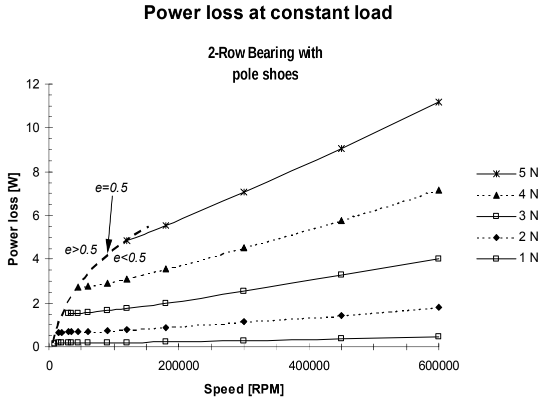

Fig. 6e.

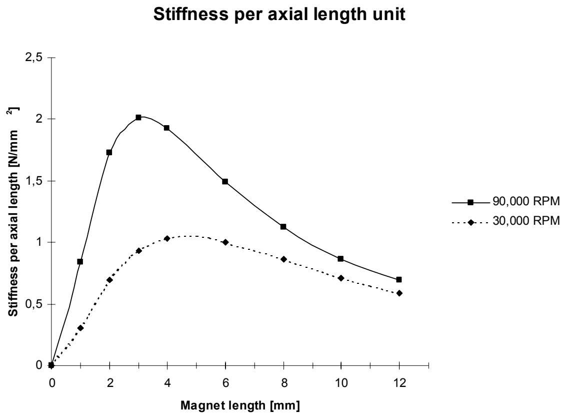

Fig.6f.

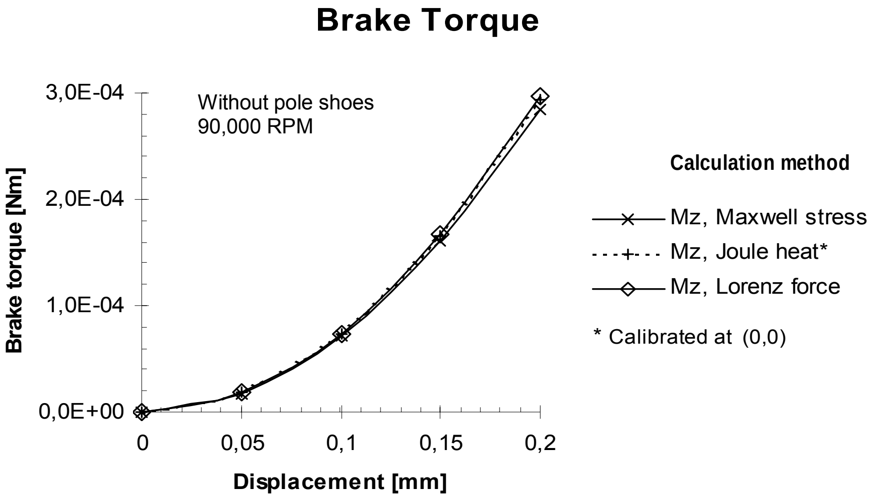

Fig. 7. Brake torque versus displacement calculated using different methods.

DISCUSSION AND CONCLUSION

Despite the fact that the study of homopolar bearings is a fairly new research area, we are able to find similarities with other research areas. The induced currents do for instance not vary much from currents in induction generators. And the resulting forces correlate in principal very well to the ones found in conventional fluid film bearings, though the order of magnitude is different. On the other hand, high load capacity is often not required in high-speed machines since they by nature have a lower weight to surface relationship due to their smaller size. For mechanical engineers it might be so that in the future they will have easier to adapt to this new technology than to conventional active magnetic bearings, since the latter suffer from a higher degree of complexity and show different properties than what they are used to.

However, research on homopolar bearings has barely started and much work remains to be done before a product can be launched. For instance, this paper only focus on currents induced by eccentric operation provided that the whirl is zero. There is a second kind of currents induced by non-synchronous whirl. To simulate them a mesh is required capable of allowing the rotor mesh to crash into the stator mesh. Such software codes are being developed, and might result in interesting research projects in the future. Such a code could also be used to optimize non-rotating eddy current damping. Until then, the author intends to build up an analytical model of the bearing, which includes these effects.

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