Proceedings of the Conference „Advances in Magnetics“ (AIM 2016), Bormio, Italy, March 14-16, 2016

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M. Schuck,
J. Schäfer,
T. Nussbaumer,
J. W. Kolar

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Marcel Schuck[1], Jannik Schäfer[1], Thomas Nussbaumer[2], and Johann W. Kolar[1]

[1]Power Electronic Systems Laboratory, Swiss Federal Institute of Technology, Zurich, Switzerland
[2]Levitronix GmbH, Zurich, Switzerland
schuck@lem.ee.ethz.ch

***Abstract*—The ongoing miniaturization trend of electric machines demands for higher rotational speeds to provide a required power level at decreased size. The goal of this project is to develop new concepts for bearingless machines with rotational speeds exceeding 25 million rotations per minute (Mrpm), which is the highest rotational speed ever achieved. A passive magnetic bearing for a spherical rotor of small size is presented, which generates a restoring force if the rotor is displaced from its equilibrium position. The achievable bearing forces are calculated analytically and verified through simulations and experiments.**

***Index Terms*—asynchronous machine, levitating sphere, passive magnetic bearing, ultra-high speed.**

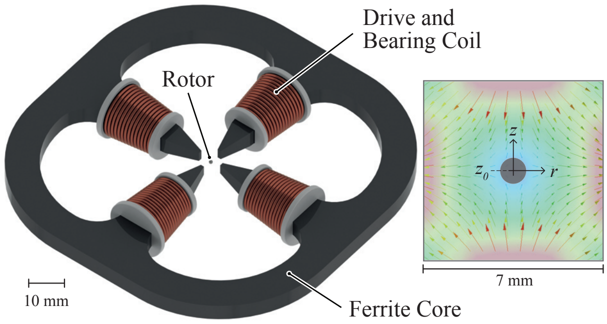

Fig. 1: Setup of the ultra-high speed motor.

I. Introduction and Setup

Magnetic bearings provide effective means to reduce bearing friction in an electrical machine, thus facilitating the achievement of high rotational speeds. The latter are beneficial in applications such as gyroscopes, centrifuges and drilling devices, as well as in materials science research. By eliminating air friction losses at the rotor, rotational speeds beyond 20 Mrpm have been achieved with small spherical steel rotors in the past [1], but could not be verified in more recent studies [2]. Such ultra-high rotational speeds can be used in material testing applications. The goal of this project is to extend the limits of electrical machines and overcome the challenges in regard to power density and controlability of highly dynamic systems. The achievable rotational speed is ultimately limited by the centrifugal load that the rotor can withstand, which scales as $\omega_{\mathrm{r,max}} \sim 1/a$, where $\omega_{\mathrm{r,max}}$ is the angular frequency and a is the rotor radius. This means that the rotor has to be as small as possible to achieve ultra-high rotational speeds, making it difficult to actively control the rotor position, which has been considered in [3]. Therefore, this study investigates a passive radial electrodynamic bearing (EB) which *by design* exerts a force on the rotor in case of a displacement from its equilibrium position.

The setup of the ultra-high speed motor is shown in Fig. 1. The active magnetic bearing (AMB) in radial direction which counteracts the gravitational force acting on the rotor has been omitted in the depiction. Applying an EB in axial direction as well is theoretically possible but entails high rotor and stator losses as the required bearing force is relatively high. The rotor is placed in the center of a ferrite core, which holds four combined bearing and drive coils located apart by 90°. The magnetic flux density as generated by the EB in the vicinity of the rotor is depicted in the inset. A cylindrical coordinate system as displayed is used to obtain analytical results for a single stator tooth, which are valid for all teeth due to the symmetry of the setup.

II. Analysis of the Electromagnetic Problem

To calculate the repulsive Lorentz force that acts on the sphere, the external magnetic flux density $\vec{B}(r, \phi, z)$, which has a radial component $B_r(r, z)$ and a component in z direction $B_z(r, z)$, is used. The eddy currents inside the sphere are mainly induced by the z-component of this field, and an analytical solution is only obtainable if $B_z(r, z) \approx B_0$ is assumed. The validity of this assumption is verified below through simulation results. After significant mathematical effort and consideration of the applying boundary conditions, the eddy current density inside the sphere due to the homogeneous external magnetic flux density can be found from a suitable magnetic vector potential $\vec{A}$ in spherical coordinates as (cf. [4])

$$\vec{J}(r, \theta) = -\sigma \frac{\partial \vec{A}}{\partial t} = -\frac{1}{2} B_0 \sigma \omega r \cdot \mathrm{Re}\left\{ jF(r) \sin(\theta) \cdot \vec{e}_\varphi \cdot \mathrm{e}^{j\omega t} \right\}, \tag{1}$$

where σ, ω, and r denote the conductivity of the rotor material, the angular frequency of the applied external field and the radial position inside the sphere, respectively. $F(r)$ is the solution to the differential equation which is valid inside the sphere based on the chosen ansatz of the magnetic vector potential. As the current flow inside the sphere is directed in φ direction in a spherical coordinate system with its origin at the center of the rotor, the resulting Lorentz force $\vec{F} = \vec{I} \times \vec{B}$ is mainly generated from the interaction with $B_r(r, z)$ and, therefore, acts as a repulsive force. Its magnitude is obtained as

$$F_{l,z}(z_0) = \int_V J_\varphi(r, \theta, z_0) \cdot B_r(r) r \sin(\theta) \mathrm{d}V, \tag{2}$$

where z_0 denotes the center position of the sphere.

A. *Verification through Simulations*

To verify the analytically obtained results, a comparative analysis with FEM simulations was carried out for various operating conditions. Figure 2 shows the current density on a cross-sectional plane through the equator of a sphere with 0.8 mm in diameter, a conductivity of $\sigma = 4.5 \times 10^6\ \mathrm{S \cdot m^{-1}}$, and a current of 25 ampere-turns at a frequency of $f = 500$ kHz flowing in one of the stator coils. The resulting magnetic flux density at the center of the rotor is ≈ 5 mT, for a rotor displacement of 1.5 mm from the center of the setup towards the coil. It can be observed that the results are in good agreement. The slight rotation of

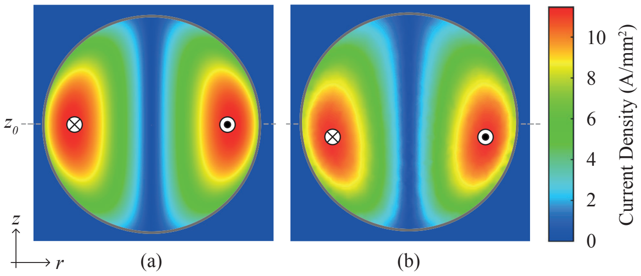

Fig. 2: Analytically calculated (a) and simulated (b) eddy current density inside the sphere.

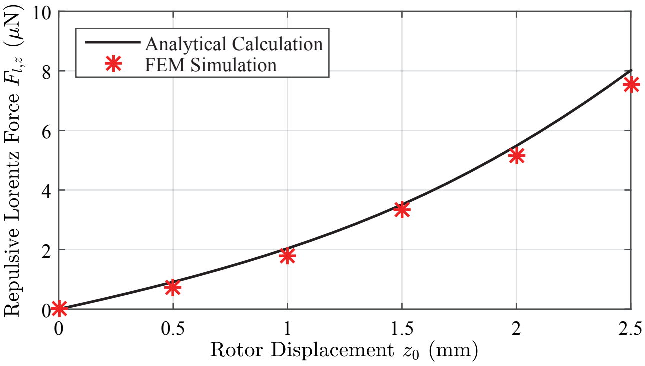

Fig. 3: Calculated and simulated repulsive Lorentz force for varying rotor displacement.

the current density in the simulated results originates from the contribution of $B_r(r, z)$ to the generation of the eddy currents, which has not been accounted for in the analytical solution.

Similarly, a comparative analysis of the force as calculated using (2) and obtained through simulations was carried out for different radial displacements of the rotor under equal operating conditions. The result is shown in Fig. 3, where an increasing repulsive Lorentz force can be observed for higher displacements.

B. Rotor Losses

The eddy currents inside the sphere cause ohmic losses, which can be calculated as

$$P_{\mathrm{loss}} = \frac{1}{\sigma} \int_V J_\varphi^2(r, \theta, z_0) \mathrm{d}V, \tag{3}$$

and cause an increase of the rotor temperature T_{r}, which can cause it to melt at high currents [5], [6]. The final rotor temperature depends on the conditions under which the motor is operated. As the required forces are small for the given setup, rotor temperatures are below 200°C in the presence of thermal convection under ambient pressure conditions, but can reach significantly higher values under vacuum conditions, where the only possibility for heat transfer is radiation.

C. Comparison to the Reluctance Force

The attracting reluctance force acting on the sphere in z direction counteracts the Lorentz force and, thereby, impairs the functionality of the EB. It can be obtained as [3]

$$F_{r,z} \approx \frac{4\pi a^3}{\mu_0} \left(\frac{\mu_r - 1}{\mu_r + 2} \right) \cdot B_r(r, z_0) \cdot \frac{\partial B_r(r, z_0)}{\partial r}, \tag{4}$$

where μ_r denotes the relative permeability of the rotor material and $B_r(r, z_0)$ is the radial component of the external flux density at the center of the rotor without considering the influence of the rotor itself. The ratio $\kappa = F_{l,z}/F_{r,z}$ has been calculated for the previously considered 0.8 mm sphere and is depicted in Fig. 4 for a variable frequency of the coil current. It can be observed that a resulting repulsive force is obtained only above a certain frequency.

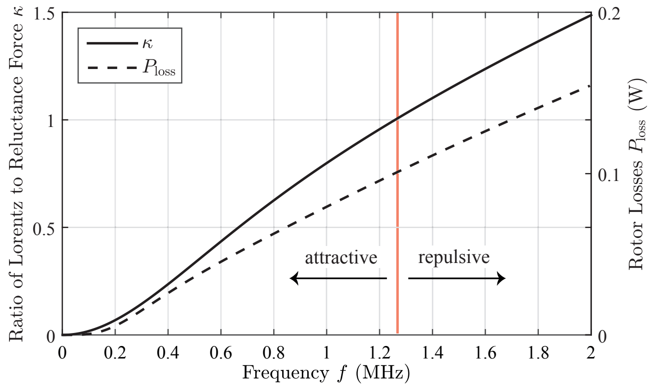

Fig. 4: Ratio of Lorentz and reluctance force and losses for different frequencies.

III. Results and Conclusion

Analytic models for assessing the performance of an EB for an ultra-high speed motor have been provided and verified through simulations. It represents a promising approach for passive radial stabilization of the rotor without the requirement for active control and position sensing, which is especially advantageous for very small rotors as required in the given applications. The EB is a feasible option as the required forces are small, yielding limited eddy current losses inside the rotor. The verification of the analytically obtained result for the current density inside the sphere through FEM simulations and the complete calculation of the resulting force on the sphere exceed the scope of the existing literature [7], [8], [9]. The results are universally applicable and offer valuable design guidelines. More detailed considerations, along with the experimental verification of the findings using the existing motor prototype, will be presented in the final paper and have been omitted here due to space constraints.

References

[1] J. W. Beams, J. L. Young, and J. W. Moore, "The production of high centrifugal fields," *Journal of Applied Physics*, vol. 17, no. 11, pp. 886–890, 1946.

[2] A. Boletis and H. Bleuler, "Achieving ultra-high rotating speeds," in *8th International Symposium on Magnetic Bearing, Mito, Japan*, 2002, pp. 539–542.

[3] M. Schuck, T. Nussbaumer, and J. W. Kolar, "Electromagnetic suitability analysis and characterization of ultra-high speed spherical steel rotors," in *Joint MMM-Intermag Conference, to be published*, 2016.

[4] T. Reichert, T. Nussbaumer, and J. W. Kolar, "Complete analytical solution of electromagnetic field problem of high-speed spinning ball," *Journal of Applied Physics*, vol. 112, no. 10, pp. –, 2012.

[5] E. Fromm and H. Jehn, "Electromagnetic forces and power absorption in levitation melting," *British Journal of Applied Physics*, vol. 16, no. 5, p. 653, 1965.

[6] U. B. Sathuvalli and Y. Bayazitoglu, "The lorentz forces on an electrically conducting sphere in an alternating magnetic field," *Magnetics, IEEE Transactions on*, vol. 32, no. 2, pp. 386–399, 1996.

[7] W. Brisley and B. Thornton, "Electromagnetic levitation calculations for axially symmetric systems," *British Journal of Applied Physics*, vol. 14, no. 10, p. 682, 1963.

[8] W. Smith, "Electromagnetic levitation forces and effective inductance in axially symmetric systems," *British journal of applied physics*, vol. 16, no. 3, p. 377, 1965.

[9] G. Lohöfer, "An electrically conducting sphere in a three-dimensional, alternating magnetic field," *IMA journal of applied mathematics*, vol. 68, no. 1, pp. 1–21, 2003.