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Force Measurements on a Shielded Coreless Linear Permanent Magnet Motor

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This paper compares force measurements on a shielded coreless linear permanent magnet motor with 2-D models. A 2-D semianalytical modeling method is applied, which is based on Fourier modeling and includes force calculations. The semianalytical modeling correctly predicts the behavior found in the measurements, disregarding the saturation effects in the shield. The proposed semianalytical modeling method gives a good preliminary indication of the forces, which makes it a valuable modeling technique during design.

Index Terms—Analytical models, magnetic shielding, mode matching methods.

I. INTRODUCTION

Predictability and controllability of motors and actuators are required in the high-precision industry. For this purpose, a single-sided coreless linear permanent magnet motor is commonly applied [1]. Unfortunately, these single-sided coreless linear permanent magnet motors have the drawback of a large magnetic stray field due to the absence of the back-iron on the secondary side. The magnetic stray field reduces the applicability of permanent magnet-based actuators and other magnetic sensitive devices in the proximity of the single-sided coreless linear permanent magnet motors.

A strong reduction of the magnetic stray field and its influence on a magnetic sensitive device in its proximity is achieved by applying magnetic shielding on the single-sided coreless linear permanent magnet motor. Since the shielding applied will be moving along with the secondary, its weight must be kept as low as possible, which results in a shield with finite dimensions. Usually, the design of shielding with finite dimensions is done using finite element analysis [2] or Schwarz–Christoffel mapping [3]. Unfortunately, both of these modeling methods are time-consuming, therefore, no full parameter sweeps are possible and the obtained insight during the design is limited.

A (semi) analytical modeling method is preferred during the initial design stage, since a fast modeling tool enables a more thorough investigation for the different parameters. A semianalytical modeling method capable of including the finite dimensions of the magnetic shielding is Fourier modeling extended with mode-matching [4]–[6]. In [7], a semianalytical modeling method based on Fourier modeling was applied on a coreless linear permanent magnet motor.

This paper presents force calculations in the semianalytical model obtained by Fourier modeling. The model is used to investigate the forces experienced on a permanent-magnet-based actuator, represented by a permanent magnet, in the vicinity of a shielded coreless linear permanent magnet motor. The results of the semianalytical modeling method are compared with measurements and with a 2-D finite element model.

II. TOPOLOGY

The topology considered in this paper consists of one single stator side of a Tecnotion UXX ironless series motor [8]. One triplet of coils of the same series is used and is fixed above the permanent magnet plate. A magnetic shield with finite dimensions is centered above the coil triplet of the motor. Above the magnetic shield, a permanent magnet is located on which the force is calculated. Although the measurements are on a 3-D situation, the translation to a 2-D periodic situation is made, which is common for linear permanent magnet motors. The cross-sectional view of the geometry, which is used for the semianalytical model, is shown in Fig. 1.

In the semianalytical model, an even periodicity is used with a width of $x_p = 228$ (mm). This periodicity is a necessity for the semianalytical modeling method and is chosen to be twice the width of the coil triplet, such that the influence of the adjacent periods is negligible. The dimensions and material properties used for the modeling are specified in Table I. The origin $O$ of the used $xz$-coordinate system is located at the bottom left of the backiron.

III. SEMIANALYTICAL MODELING

The magnetic flux density in the semianalytical model is described using spatial harmonics, i.e., Fourier
In each region, the harmonic description is given by

\[
B^i_z = B^i_{z0}(z) + \sum_{n=1}^{\infty} \left[ B^i_{zsn}(z) \sin (\omega_n x^i) + B^i_{zecn}(z) \cos (\omega_n x^i) \right]
\]

where \( i \) is the region indicator, \( B^i_{z0} \) is a possible DC value for the magnetic field in the \( x \)-direction, \( S^i_{zsn} \) and \( S^i_{zecn} \) are source terms for the current source, \( M^i_{zsn} \) and \( M^i_{zecn} \) are the sine and cosine terms which describe the magnetization, where \( q^i_n, r^i_n, s^i_n, \) and \( t^i_n \) are constants to be determined, and where \( x^i \) is the \( x \)-position in region \( i \) (\( x^i \) includes an offset with respect to the global coordinate system to ensure that the \( x^i = 0 \) coincides with the left edge of that region).

All source terms are directly calculated based on the geometry of the sources, while \( B^i_{z0}, q^i_n, r^i_n, s^i_n, \) and \( t^i_n \) have to be determined by boundary conditions. On the interfaces between the regions, the boundary conditions are applied. In principle, on all boundary interfaces, continuity of the field strength in the \( x \)-direction and continuity of the magnetic flux density in the \( z \)-direction should be applied. Due to the application of the mode-matching, however, this will not be possible on the interfaces between regions VII and VIII, since the mode-matching method will assume a boundary on the edges that results in a magnetic field that is purely in the \( z \)-direction. The boundary of regions VII and VIII with the regions located above is a piecewise continuous boundary, while the boundary conditions at the bottom of region I and the top of region XI ensure that the magnetic field will vanish for \( z \rightarrow \pm \infty \).

With all boundary conditions applied and, therefore, with all constants known, it is possible to calculate the force using the Maxwell stress tensor \([9]\). The force is described according to

\[
F = \frac{1}{\mu_r \mu_0} \iiint_V \nabla \cdot T \, dV
\]

where \( T \) is the actual Maxwell stress tensor. Using Gauss’s theorem results in

\[
\vec{F} = \frac{1}{\mu_r \mu_0} \oiint_S \hat{n} \cdot \vec{T} \, dS
\]

where \( S \) is the surface enclosing the volume \( V \) and \( \hat{n} \) is the outward normal vector on this volume. The volume \( V \) or surface \( S \) can be chosen freely around a soft magnetic material.
as long as it only encloses this soft magnetic material and air or vacuum.

Since there are only 2-D situations considered, the closed surface volume integral will be reduced to four line integrals on the edges of the volume considered in the 2-D domain. For the 2-D domain under consideration, the Maxwell stress tensor is given by

\[ T = \begin{bmatrix} T_{xx} & T_{xz} \\ T_{xz} & T_{zz} \end{bmatrix} = \left[ \begin{array}{cc} \left( \frac{1}{2} B_x^2 - \frac{1}{4} B_z^2 \right) \frac{B_x B_z}{B_z} & \left( \frac{1}{2} B_x^2 - \frac{1}{4} B_z^2 \right) \frac{B_x}{B_z} \\ \frac{B_x B_z}{B_z} & \left( \frac{1}{2} B_z^2 - \frac{1}{4} B_x^2 \right) \frac{B_z}{B_x} \end{array} \right] \]

where \( B_x \) and \( B_z \) are given by (1) and (2).

Using (10) in (9) for the observed 2-D situation gives

\[ F_x = \frac{1}{\mu_0 \mu_r} \left\{ - \int_{C_b} B_x B_z \, dx - \int_{C_t} \left( \frac{1}{2} B_x^2 - \frac{1}{4} B_z^2 \right) \, dz \right\} 
+ \int_{C_l} B_x B_z \, dx + \int_{C_t} \left( \frac{1}{2} B_x^2 - \frac{1}{4} B_z^2 \right) \, dz \]

\[ F_z = \frac{1}{\mu_0 \mu_r} \left\{ - \int_{C_b} \left( \frac{1}{2} B_z^2 - \frac{1}{4} B_x^2 \right) \, dx - \int_{C_t} B_x B_z \, dz \right\} 
+ \int_{C_l} \left( \frac{1}{2} B_z^2 - \frac{1}{4} B_x^2 \right) \, dx + \int_{C_t} B_x B_z \, dz \]

where \( C_b, C_l, C_t, \) and \( C_r \) are the bottom, left, top, and right edges of the integration domain. These force integrals can be calculated either analytically or numerically. The force is calculated by the semianalytical model within 2 s rather than the minute calculation time of finite element methods.

**IV. MEASUREMENTS**

The forces obtained from the semianalytical model are compared with measurements, which are performed on the setup shown in Fig. 3.

Using a positioning device, the top permanent magnet is moved in the \( x \)-direction over a full period. The positioning device is equipped with \( \mu \)m accurate linear encoders, which ensures an accurate placement of the permanent magnet. Between the permanent magnet and the positioning device, a load cell is mounted to obtain the force on the magnet.

On the nonmagnetic mounting plate, half of the stator of a Tecnotion UXX ironless series motor [8] is placed. Above the stator, a coil triplet of the same series, the UXX3S, is placed, such that the coils will not displace if they are excited. On a fixed distance of the coils, a shield is located; this shield is centered above the coil triplet and is supported to prevent bending by the reluctance forces.

In principle, three separate force effects are expected in the measurements. First of all, the forces obtained from the permanent magnet array and the coil triplet on the moving magnet, for which a sinusoidal force behavior is expected. The second effect of the forces is the reluctance force of the shielding on the moving magnet. The third effect is the actual shielding of the magnetic field originating from the magnet array and the coils. This effect is a local reduction of the sinusoidal forces that are originating from the sources when the moving magnet is close to and above the shield.

The results of the measurements for different shield widths are shown in Fig. 4 for a movement of the magnet over a full period in the \( x \)-direction and the coils excited as specified in Table I. In the top of the figure, the force measured in the \( x \)-direction is given, underneath the differences between the measurements and the semianalytical model are given according to \( \Delta F = F_{ANA} - F_{\text{meas}} \), the analytical force results minus the measured forces. In the bottom of the figure, the \( F_z \) and \( \Delta F_z \) are given in an equal way. For the line where no shield is present, the expected sinusoidal characteristic is clearly visible in \( F_x \) and \( F_z \). For all shielded situations, the sinusoidal behavior is also visible in the beginning and the end of the measurements, in case the magnet is away from the shield. For \( F_x \), the reduction of the forces by the shield is clearly visible around \( x_{mc} = 114 \) (mm), where all shielded measurements show a lower force than the unshielded situation. The reluctance force of the shield on the magnet is visible in \( F_z \) around \( x_{mc} = 114 \) (mm), where more force in the negative \( z \)-direction is found for the shielded situations.
When comparing the differences between the semianalytical model and the measurements, $\Delta F_x$ and $\Delta F_z$ in Fig. 4, it is visible that the semianalytical model gives an accurate description away from the shield. The forces predicted by the semianalytical model show a much larger difference if the magnet is located near or above the shield. To further analyze, the differences found, the measurements on one of the shields is investigated more thoroughly.

In Fig. 5, the results of the measurements for a shield with a width of $w_3 = 100.2$ (mm) are highlighted. Besides the measurements, the results of the semianalytical model are given in the same figure. Furthermore, the results of two 2-D finite element analysis model, using Cedrat’s FLUX2D software [10], are given as well, one with a linear permeable material in the shield and other with a nonlinear permeable material. The finite element model with a linear permeability assumed in the shield (the circular markers in Fig. 5) gives a perfect agreement with the semianalytical results. This indicates that the semianalytical model is correctly describing the modeled topology and that the modeling assumptions are causing the differences between the model and the measurements. The assumption of the linear material and the assumption of a 2-D description are the major contributors to the differences. In the area where the shield is located, the measurements and all models give a strong reduction of the sinusoidal characteristics. However, the semianalytical model and the 2-D FEA model with linear material show no sinusoidal behavior remaining, while the measurements show that part of the sinusoidal effects remains.

The remainders of the sinusoidal behavior emerge above high flux density locations in the shield, locations that are saturated. The saturation causes a local reduction of the permeability of the shielding material, which results in a larger penetration of the magnetic field originating from the magnet plate and the coils through the shield. Therefore, the nonlinear magnetic permeability of the shielding material is the cause of the remaining sinusoidal force characteristics. The 2-D finite element analysis model with nonlinear shielding material has an initial permeability equal to the linear material and has a saturation point of 1.5 (T). The results are shown by the square markers in Fig. 5, where it is clearly visible that more sinusoidal behavior is remaining compared with the model with a magnetically linear shielding material.

For the forces in the $x$-direction, the results of the nonlinear finite element model reveal an equal behavior as is found in the measurements. Only some minor amplitude differences (which are caused by differences in material parameters between model and measurements, and deviations between individual magnets) are visible. For $F_z$, the remaining sinusoidal behavior is also clearly present in the nonlinear model.

The measurements show a larger attracting force toward the magnetic shield, which is not covered by the nonlinear finite element model or either of the 2-D models with a linear permeability assumed. Therefore, it is concluded that this difference is caused by the fact that the shield is larger than the permanent magnet in the $y$-direction, a difference that is not incorporated in any of the presented 2-D models.

V. Conclusion

The semianalytical modeling method presented in this paper includes force calculations and is applied on the movement of a magnet above a (shielded) coreless linear permanent magnet motor. The forces predicted by the semianalytical model are in perfect agreement with the 2-D finite element analysis model with a linear permeability in the shield. By comparing the modeling results with the measurements, large differences are visible. These differences are caused by the nonlinearity of the shielding material used and by the assumption of the 2-D domain. Even though significant differences are found, the proposed semianalytical modeling method is a valuable tool during the design stage of a shielded coreless linear permanent magnet motor.

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