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**Citation for published version (APA):**

Jansen, J. W., Lomonova, E. A., & Rovers, J. M. M. (2009). Effects of eddy currents due to a vacuum chamber wall in the airgap of a moving-magnet linear actuator. *Journal of Applied Physics*, 105(7), 07F111-1/3. [07F111]. <https://doi.org/10.1063/1.3076421>

**DOI:**

[10.1063/1.3076421](https://doi.org/10.1063/1.3076421)

**Document status and date:**

Published: 01/01/2009

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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# Effects of eddy currents due to a vacuum chamber wall in the airgap of a moving-magnet linear actuator

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(Presented 14 November 2008; received 21 September 2008; accepted 28 December 2008; published online 6 March 2009)

This paper discusses the effects of eddy currents induced in an electrically conducting plate which is placed in the airgap of a linear synchronous actuator with moving permanent magnets. The eddy currents induced in this plate, which is part of a controlled atmosphere chamber, cause not only damping but also deteriorate the actuator performance by disturbing the position measurement with Hall sensors. Furthermore, feed-forward controllers are less effective due to the suppression of high frequent armature fields. These effects are analyzed with an analytical model and verified with finite element simulations and measurements. © 2009 American Institute of Physics. [DOI: 10.1063/1.3076421]

## I. INTRODUCTION

Brushless linear permanent magnet (PM) actuators are commonly applied in fully automated product lines because they combine high speeds and high position accuracy. In long production lines, a linear actuator solution with moving magnets and stationary coil arrays can be advantageous because there are no cables to the moving translators.<sup>1,2</sup> When vacuum or controlled atmosphere processes are involved, the coil arrays are often placed outside the processing chamber for maintenance reasons, while the translator with the PMs moves inside the chamber. As a result, an electrically conducting plate, which is part of the controlled atmosphere chamber, is present in the airgap of the linear actuator. For construction reasons, the plate material is often aluminum.

Figure 1 shows an overview of such a positioning system with a conducting plate in the airgap. Usually these systems have multiple coil arrays to increase the stroke. The desired position accuracy is 0.1–1 mm and the speed is 2 m/s or higher. Especially at these relatively high speeds, the induced eddy currents influence the system performance.

This paper presents an analysis of the effects of the conducting plate in the airgap of the linear motor on the magnetic flux density distribution. The analysis is carried out with an analytical model which is based on the magnetic vector potential and complex Fourier series. Contrary to, e.g., Refs. 3 and 4 not only the eddy-current damping is investigated but also the effects on the position sensors and the frequency response of the armature field. The model and the discussed phenomena are compared with experiments and finite element simulations.

## II. ANALYTICAL MODEL OF THE LINEAR ACTUATOR

To analyze the electromagnetic behavior and the eddy currents, an analytical model of the magnetic fields inside the linear actuator is derived. Contrary to the real actuator, which

is shown in Fig. 1, the model is derived for an infinitely long actuator. Furthermore, instead of a slotted stator structure, the coils are modeled by current sheets in the airgap. An overview of the model is shown in Fig. 2. The dimensions are summarized in Table I.

Both the magnetization of the PMs  $\mathbf{M}$  and the current densities ( $J_r, J_s, J_t$ ) in the coils with concentrated windings (three-phase star connection) are expressed as complex Fourier series. The flux density  $\mathbf{B}$  is calculated using the vector potential  $\mathbf{A}$ , i.e.,

$$\mathbf{B} = \nabla \times \mathbf{A}. \tag{1}$$

The governing equations for the five regions indicated in Fig. 2 are, respectively,

$$\begin{aligned} \nabla^2 A_{z1} &= -\mu_0 \frac{\partial M_y}{\partial x}, \\ \nabla^2 A_{z2} &= 0, \\ \nabla^2 A_{z3} &= \mu_0 \sigma \frac{\partial A_{z3}}{\partial t}, \\ \nabla^2 A_{z4} &= 0, \\ \nabla^2 A_{z5} &= \mu_0 (J_r + J_s + J_t), \end{aligned} \tag{2}$$

where  $\sigma$  is the conductivity of the aluminum plate in the airgap.<sup>5</sup>

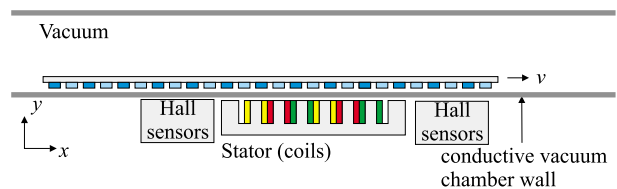


FIG. 1. (Color online) Overview of the studied moving-magnet linear motor with aluminum vacuum chamber wall in the airgap.

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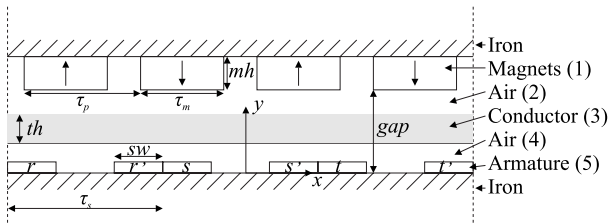


FIG. 2. Infinitely long model of the moving-magnet linear actuator. The concentrated windings are modeled by current sheets  $rr'$ ,  $ss'$ , and  $tt'$ .

The iron parts are assumed to be infinitely permeable, hence  $A_z(y=0)=A_z(y=gap+mh)=0$ . Besides these boundary conditions, also the boundary conditions  $A_z(y=-\infty)=A_z(y=gap+mh)=0$  have been considered to analyze the magnetic flux density in the Hall sensors (which do not have back iron) and to calculate the damping force on the part of the translator which is not above the stator coils.

The model (with the first set of boundary conditions) has been validated using finite element simulations in FLUX2D. Figure 3 shows the magnetic flux density in region 2, while the magnets move with  $v=2$  m/s. Figure 4 shows the magnetic flux density in region 2 by the armature coils ( $f=83.33$  Hz,  $t=36$  ms, and current amplitude  $I=1$  A turn). Both the analytical model and the finite element simulations without slotting are in good agreement. However, neglecting the slotting of the stator results in an error (10%–15%) in the armature field, as shown in Fig. 4.

III. DAMPING

When the magnet array moves, eddy currents are induced in the stationary conductor in the airgap. Consequently, it behaves as an eddy-current brake. For low speeds, the force can be considered to be proportional to the speed, i.e.,  $F=Dv$ , where  $D$  is the damping. The damping has been obtained by integrating the Maxwell stress tensor at the center of region 2. Because the stator is shorter than the translator, it covers only 42% of the translator. The damping for this part has been calculated with the analytical model and the first set of boundary conditions and is equal to 49 N s/m. For the other part of the translator, a damping of 46 N s/m has been calculated with the second set of boundary conditions. As a result, the total damping is equal to 95 N s/m. During experiments, a damping of 90 N s/m was measured. The experimental setup is shown in Fig. 5.

TABLE I. Dimensions and parameters of the model of the moving-magnet linear actuator.

Pole pitch $\tau_p$	12 mm
Magnet pitch $\tau_m$	8 mm
Magnet height $mh$	4 mm
Remanence magnet $B_r$	1.2 T
Slot pitch $\tau_s$	16 mm
Slot width $sw$	5 mm
Gap	5 mm
Thickness conductor $th$	2 mm
Conductivity (aluminum) conductor $\sigma$	$3.43 \times 10^7$ S/m
Depth model	60 mm

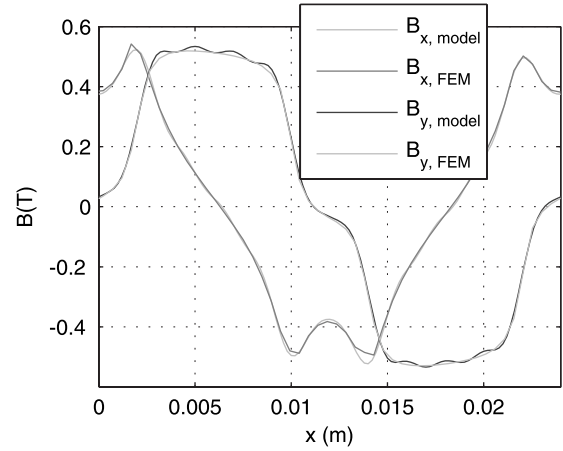


FIG. 3. Simulated magnetic flux density waveform of the PMs in region 2 ( $v=2$  m/s and 11 harmonics included in the simulation).

IV. POSITION MEASUREMENT USING HALL SENSORS

The position of the translator is measured without contact by two sets of two Hall sensors which are located on both sides of the translator. The Hall sensors are indicated in Fig. 1 and on the photo of the experimental setup in Fig. 5. Due to the eddy currents induced in the plate by the PMs, the magnetic field measured by the Hall sensors will lead in phase compared to the situation without eddy currents. Consequently, an incorrect distance is measured. Figure 6 shows the prediction of the phase delay with the analytical model and the delay measured at several speeds. The delay was measured using an optical linear encoder with 1  $\mu$ m resolution as reference.

V. FREQUENCY RESPONSE OF THE ARMATURE FIELDS

Besides eddy currents induced in the conducting plate by the PMs, also eddy currents will be induced as a result of the armature currents. In the controller of servo systems, usually a flat frequency response of these magnetic fields is assumed. Due to the eddy currents, high frequency magnetic fields will

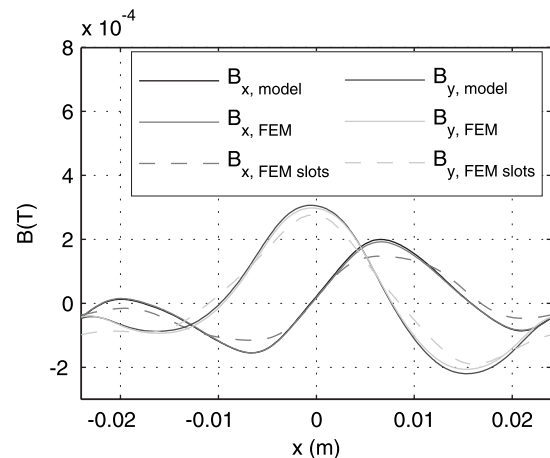


FIG. 4. Simulated magnetic flux density waveform of the armature coils in region 2 ( $f=83.33$  Hz,  $t=36$  ms,  $I=1$  A turn, and 11 harmonics included in the simulation).

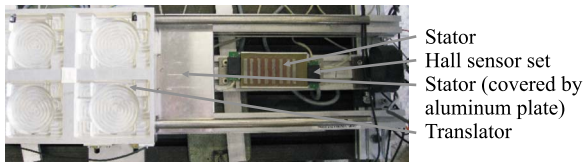


FIG. 5. (Color online) Experimental setup. Below the aluminum plate another stator segment is mounted.

be suppressed. This will mainly affect the actuator at high speeds, especially the high-frequency feed-forward controllers.

Figure 7 shows the frequency response of the armature measured in region 2 at  $x=16$  mm and a current amplitude  $I=1$  A (which is equivalent to 100 A turns). The magnetic field components were measured with a Lakeshore model 460 gaussmeter with a three-axis probe. The phase was measured with respect to the current in phase  $ss'$ . The aluminum plate causes significant phase delay and damping of the armature fields from 100 Hz. The difference between the measured and modeled response is caused by the fact that eddy current in the slotted iron stator structure cause additional damping. To demonstrate this effect, also the response without the aluminum plate is shown. The phase difference for the  $B_x$  component in the phase response has been verified to be caused by the slotting of the translator.

VI. CONCLUSIONS

The effects of eddy currents due to a vacuum chamber wall in the airgap of a moving-magnet linear actuator have been analyzed by both simulations and experiments. The induced eddy currents cause damping forces, incorrect position measurements, and suppression of high-frequency armature fields. The damping forces and the phase lead of the mag-

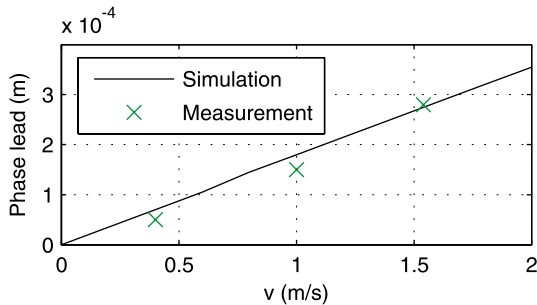


FIG. 6. (Color online) Measured and simulated phase lead of the Hall sensors.

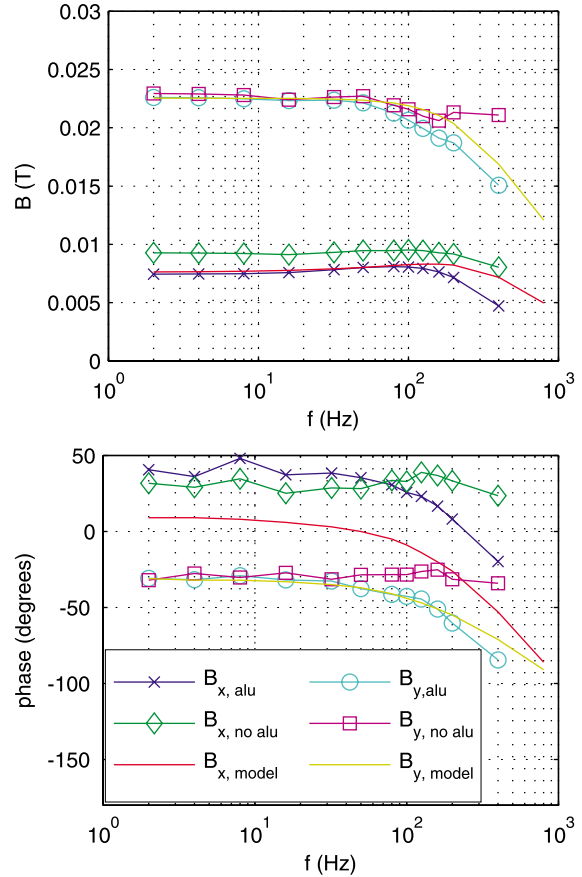


FIG. 7. (Color online) Measured and modeled frequency response of the field of the armature windings measured at  $x=16$  mm in region 2 with and without aluminum plate in the airgap ( $I=100$  A turns).

netic flux density of the PMs measured by the Hall sensors can be accurately predicted with the analytical model based on complex Fourier series. The predictions of the field of the armature windings and its frequency response are less accurate because they are influenced by the stator slots and eddy currents in the stator iron itself.

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<sup>5</sup>J. A. Tegopoulos and E. E. Kriezis, *Eddy Current in Linear Conducting Media* (Elsevier, Amsterdam, 1980).