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# Simulation of a ferrofluid-supported linear electrical machine

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**The force magnification of ferrofluids used in the airgap between the two acting magnets in electrical machines has been investigated with the theoretical method of orthogonal expansion. This theoretical substantiation is necessary for a comprehensive judgement of the measurements on a ferrofluid-supported electric motor. The method itself and the results are presented. Copyright © 2004 John Wiley & Sons, Ltd.**

**KEYWORDS:** ferrofluids; linear electric motors

## INTRODUCTION

Electric motors, linear or rotating, have an airgap between the acting magnets, e.g. stator and rotor in a rotating machine. To reduce the magnetic resistance the airgap is filled with a ferrofluid to enlarge the forces in a linear electrical machine and the torque in rotating electric machines. Besides experiments, such configurations can be simulated theoretically using the method of orthogonal expansion. A process model of a linear electric machine is presented here.

## CALCULATION OF MAGNETIC FIELDS

Figure 1 shows the planar geometry. The boundary conditions for the walls at $x = \pm w$ are chosen to guarantee that the lines of forces are closed. This minimizes the influence of these boundaries. In each subspace a trial solution is made. Two representative examples for the vector potential $A_z(x,\ y)$ are given here:

**subspace 3**

$$A_{z,3}(x,\ y) = \sum_{j=1}^{n_3} \cos[k_{3,j}(x - b_1)]\{\exp[k_{3,j}(y - g_o)] \times A_{3,j} + \exp[-k_{3,j}(y - f_o)]A_{3,j}\}$$

$$k_{3,j} = \frac{0.5(2j-1)\pi}{-w - b_1} \tag{1}$$

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**subspace 7**

$$A_{z,7}(x,\ y) = \sum_{j=1}^{n_7} \sin[k_{7,j}(x + w)]\{\exp[k_{7,j}(y - e_o)] \times A_{7,j} + \exp[-k_{7,j}(y - e_o)]A_{7,j}\}$$

$$k_{7,j} = \frac{0.5j\pi}{w} \tag{2}$$

The magnetic fields are calculated as follows:

$$H_x = \frac{1}{\mu}\frac{\partial}{\partial y}A_z \tag{3}$$

$$B_y = -\frac{\partial}{\partial x}A_z \tag{4}$$

Between each of the subspaces one has to formulate boundary conditions, which guarantee the continuity of the fields in the whole geometry. The number of equations has to be the same as the number of coefficients. Some of them are given here as an example:

**subspaces 1 to 2,4**

$$B_{y,1}(x,\ p_o) = \begin{cases} B_{y,2}(x,\ p_o) & -w < x < b_1 \\ B_{y,4}(x,\ p_o) & o_1 < x < +w \end{cases} \tag{5}$$

$$H_{x,1}(x, p_o) = \begin{cases} H_{x,2}(x,\ p_o) & -w < x < b_1 \\ 0 & b_1 < x < c_1 \\ H_{x,4}(x,\ p_o) & c_1 < x < +w \end{cases} \tag{6}$$

**subspace 2 to 3**

$$B_{y,2}(x,\ g_o) = B_{y,3}(x,\ g_o) \qquad -w < x < b_1 \tag{7}$$

$$H_{x,2}(x,\ g_o) - H_{x,3}(x,\ g_o) = I_a \qquad -w < x < b_1 \tag{8}$$

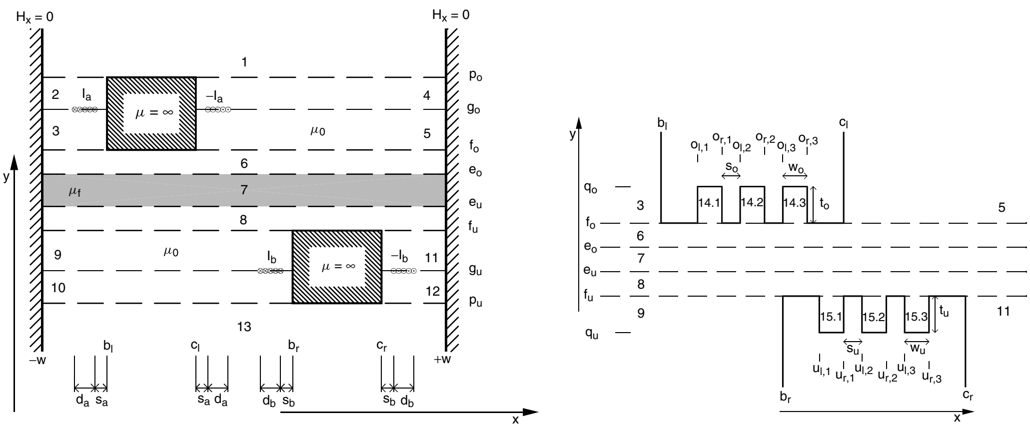


**Figure 1.** Geometry of the linear electric motor (left) and grooved magnet surfaces for stepping motor simulation.

The orthogonal sums representing the fields are inserted into these boundary conditions. Here, the method of orthogonal expansion is applied. This yields a system of linear equations, which has to be solved to obtain the coefficients.

## REALIZATION OF COILS

The exciting currents are represented as a current distribution between two spaces, as can be seen in Fig. 2. To realize massive coils, several geometries with varied current distributions as described in Fig. 2 are overlaid.

## DETERMINATION OF FORCES

The total force acting on a body imbedded in a medium can be calculated with a volume integral over the material force density **f**, which acts on all points inside the body:

$$\mathbf{F} = \int_V \mathbf{f}\, \mathrm{d}V \tag{9}$$

Another interpretation is that the forces act on the surface of the treated body, which leads to a surface integral enclosing the body over the stress tensor **p**:

$$\mathbf{F} = \oint_{Sv} \mathbf{p}\, \mathrm{d}S \tag{10}$$

Equations (9) and (10) can be transformed into each other with the theorem of Gauss. The calculation of forces on the basis of Maxwell's tensions are founded on the relation[2]

$$\mathbf{p} = (\mathbf{Bn})\mathbf{H} - 0.5(\mathbf{BH})\mathbf{n} \tag{11}$$

Unlike Maxwell, who found this relation through the principle of virtual shift, Hofmann[3–5] used a method where the total force acting on a body inside a magnetizable fluid can be calculated from the sum of the direct force and the buoyancy, which leads to the ponderomotoric force

$$\mathbf{F}_{\mathrm{pond}} = \mathbf{F}_{\mathrm{direct}} + \mathbf{F}_{\mathrm{buoyant}} \tag{12}$$

in Figure 3 explains how the surface integral works in the case treated here, where the force upon the upper magnet is determined.

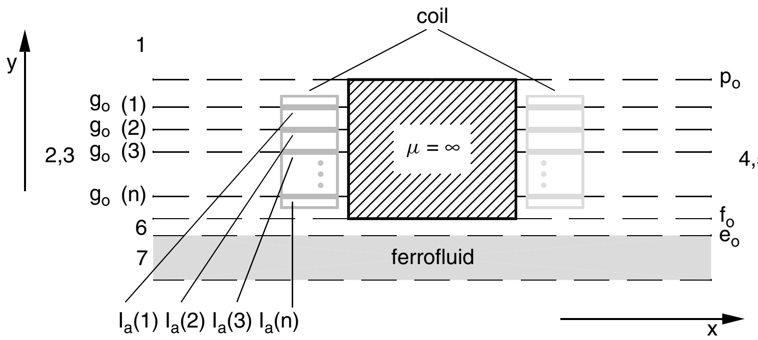


**Figure 2.** The representation of thick coils as layers of current distributions.

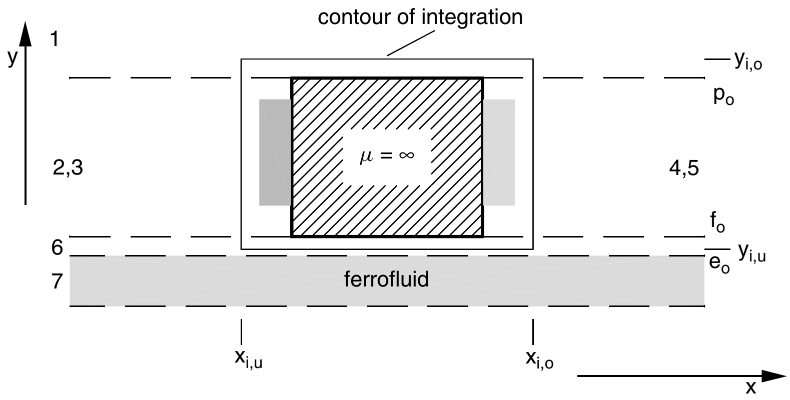


**Figure 3.** Calculation of forces using the Maxwell tensions applying a surface integral.

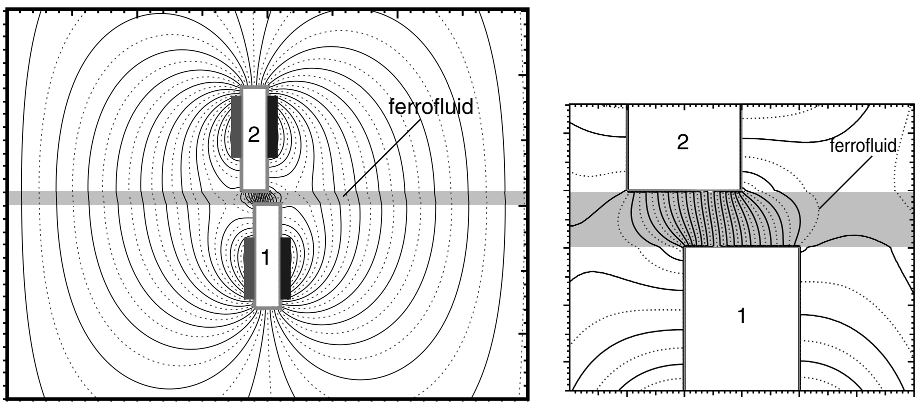


**Figure 4.** Lines of forces in the whole area of calculation (left) and between the two magnets (right) (1: lower magnet; 2: upper magnet).

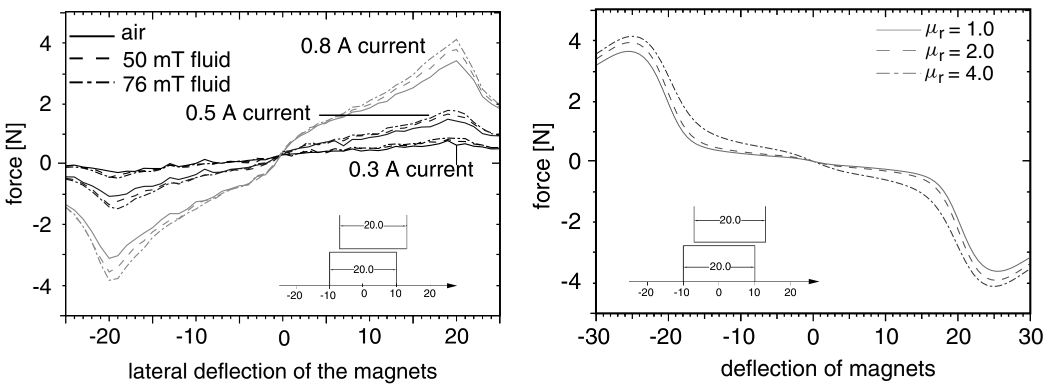


**Figure 5.** Lateral force between the two magnets shown for three values of $\mu_r$ as a result of the calculation (left) and the measurement result (right), where the curve for a current of 0.8 A correspond to the calculation.

## RESULTS AND COMPARISON WITH MEASUREMENTS

The area over which the calculations were performed is shown in Fig. 4. Then, comparing the measurements from Fig. 5(left) with the results of calculation shown in Fig. 5(right) the excellent correspondence is obvious. One can see that the calculated curves have a more pronounced kink at a lateral deflection of *ca* ±17 mm compared with the measurements. The reason is that the fluid in the fluid bath of the measurement setup[6] is not confined just to the gap, as it is in the calculation. Thus, the measurement curves are subject to some smoothing effects. In addition, one has to keep in mind that the calculations are done for a planar geometry (two-dimensional), whereas the real machine is three-dimensional.

## CONCLUSIONS

The calculations correspond very well with the measurements. This is an important confirmation of the improvement of electrical machines by using ferrofluids. Thus, one has a promising application of this new and fast-progressing technology of magnetic fluids. This theoretical approach also provides a practical tool for evaluating some aspects of the problem that are not easy accessible by experiments.

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