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Numerical simulation and magnet system optimization for the Lorentz Force Velocimetry (LFV) of low-conducting fluids

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Abstract

The present paper describes the first steps towards investigating the magnet system which will be used for the Lorentz Force Velocimetry (LFV) of low-conducting fluids. Two types of magnet systems were considered: a) two permanent magnets; b) two permanent magnets and an iron yoke. The FEM packages Maxwell and Comsol were used for the analysis. The validation of the FEM models was done using experimental data and by comparing the numerical results obtained in the two programs. A parametrical analysis of the magnet system was done to define the optimal dimensions of magnets for a given channel geometry.

Introduction

LFV is a contactless method to measure the flow rates of electrically conducting fluids such as liquid metals [1]. This method is based on the interaction of the transversal permanent magnetic field with the fluid flow. In this case, the eddy currents are induced in the flow. By interacting with the primary magnetic field these currents cause the Lorentz force, which brakes the flow. According to Newton's law, the same force acts on the magnet system, but in the opposite direction. In other words, the force acting on the magnet system has the same direction as the flow. This force is proportional to the flow rate. Therefore, it is possible to define the flow rate by measuring this force.

The main advantage of LFV is that it avoids the direct contact with the flow, allowing us to measure the flow rates of very hot and chemically aggressive fluids like melts.

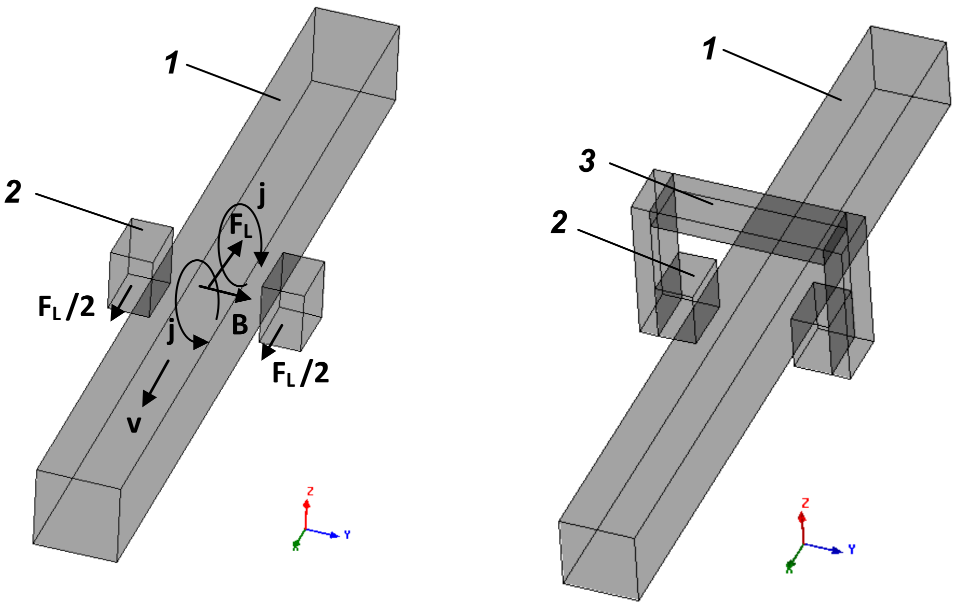
The LFV theory was discussed in detail in [2]. Here it was found that the force acting on the magnet system is proportional to the flow velocity, the electrical conductivity of the fluid, and the squared magnetic flux density.

The goal of our project is to optimize the magnet system for the LFV of low-conducting fluids like liquid glass. The electrical conductivity of liquid glass is several orders less than that of liquid metals. This corresponds with the Lorentz force, resulting in very strict requirements to both the measurement system and the magnetic system. First, the Lorentz force must be higher than 10^{-5} N. Second, the weight of the magnet system must be less than 10 kg. Third, the ratio of the Lorentz force to the weight of the magnet system must be as high as possible.

1. Problem definition

For the first prototype of the LFV of low-conducting fluids the following initial conditions were stated: the cross-section of the electrolyte is S=40x40 mm^2; the electrical conductivity of the electrolyte is σ=4 S/m; the velocity of the electrolyte is v=5 m/s. Assuming that the wall thickness of the channel is 5 mm, the distance between each magnet and the electrolyte was fixed at 6 mm.

The working principle of the LFV is shown in Fig. 1*a*. The fluid flow moves through the transversal permanent magnetic field with velocity **v**. It causes the eddy currents **j** in the flow. The interaction of the eddy currents with the primary magnetic field **B** leads to the Lorentz force $\mathbf{F_L}$, which brakes the flow. According to Newton's law, the same force acts on the magnets, but in the opposite direction.



a *b*

Fig. 1. Illustration of the apparatus and working principle the LFV for low-conducting fluids (*1* - electrolyte; *2* - permanent magnet; *3* - iron yoke).

So far, we have considered the translational motion of the solid body instead of the fluid flow motion, because it considerably simplifies the numerical model and allows us to perform a parametrical analysis relatively quickly. Nevertheless, the fluid flow motion is to be taken into account in the later phase of our investigation, because it considerably affects the eddy currents and the Lorentz force. It should be mentioned that the small magnetic Reynolds number allows us to assume that the magnetic field deformation due to the induced magnetic field is negligible.

Two magnet systems were analyzed: one containing two permanent magnets (Fig. 1*a*) and another containing two permanent magnets and an iron yoke (Fig. 1*b*). The material of the permanent magnets is NdFeB. Steel 1008 is the material for the iron yoke. The nonlinear relative permeability of steel 1008 was taken into account.

2. Description of numerical models

The FEM packages Maxwell and Comsol were used for our investigation. The transient analysis was performed using Maxwell and the steady-state analysis was performed using Comsol. In spite of the different approaches, the results obtained for the same problem were in very good agreement, as shown below.

In the Maxwell package we used the time step and the path length for the analysis. After several test calculations we found that the parameters had no effect on the resulting force if the Courant number was less than one:

$$Co = \frac{\mathbf{v} \cdot \Delta t}{\delta} < 1 \tag{2.1}$$

Here **v** is the bar velocity, Δt=0.001 s is the time step and δ=0.01 m is the mesh size in the bar.

The transient solver in the program Maxwell calculates the field parameters at each time step. The moving bar is surrounded by a band. The mesh in this band is newly generated at each time step to bind the bar mesh with the air region mesh. The mesh in all other regions doesn't change. In all regions we used free mesh consisting of tetrahedral elements.

With Comsol the following equations are solved in the bar region:

$$\nabla \cdot \left(-\sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + \sigma \nabla V\right) = 0 \tag{2.2}$$

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A}\right) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + \sigma \nabla V = 0 \tag{2.3}$$

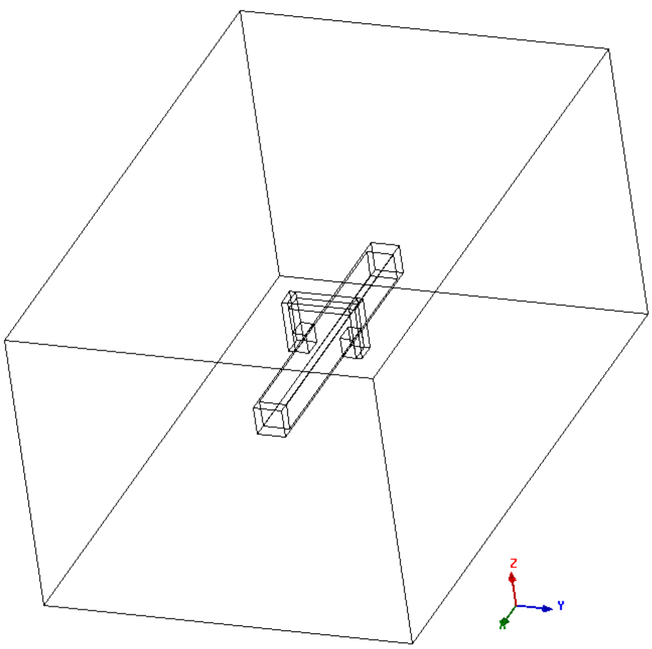


Fig. 2. Regions of the FEM model of the LFV.

Here **A** is the magnetic vector potential and V is the electric scalar potential. The regions of the FEM model the LFV are shown in Fig. 2. This model corresponds to the magnet system which includes an iron yoke. The boundary conditions at the external boundaries of the model are: **A**=0; **n**×**A**=0, and at the surface of the bar: **n**·**j**=0. The mesh sizes used in the bar, magnets, and iron yoke regions were smaller than 10 mm. The mesh was generated using tetrahedral elements (free mesh). We used approximately the same mesh sizes in both programs. The detailed comparison of the two models is described below.

3. Validation and comparison of the numerical models

To validate our numerical models we used the experimental results from [3]. The numerical transient analysis was performed using Maxwell. The experimental and numerical results are in good agreement (see Fig. 3). The difference between calculated and measured forces was approximately 10%. This difference is caused by the unavoidable difference of the material properties of the iron yoke and the permanent magnets in the experiment vs. the numerical model. Moreover, the electrical conductivity of the aluminum bar in the numerical model was chosen to be $2.73 \cdot 10^7$ S/m. The real electrical conductivity in the experiment was not measured and can deviate from the value used in the numerical model.

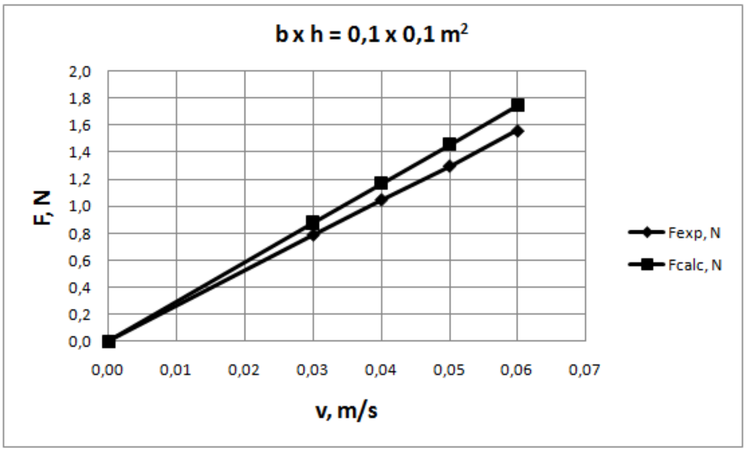


Fig. 3. Comparison of the experimentally and numerically obtained Lorentz force.

We also compared the results obtained in the two programs. We simulated both magnet systems with and without an iron yoke. Table 1 shows the properties of the models as well as the numerical results for the magnet system without an iron yoke. In this model, two permanent magnets were used with dimensions Lmx=0.04 m; Lmy=0.025 m; Lmz=0.05 m along the x, y and z axis, respectively. Other initial data are given in section 1. The difference between two calculated forces is less than 3%.

Table 1. Comparison of the FEM models: Magnet system without an iron yoke.

	Maxwell (transient)	Comsol (steady-state)
Number of elements	375981	371748
Calculation time, s	3038	130
Force, N	$1.154\cdot10^{-5}$	$1.186\cdot10^{-5}$

Table 2 shows the parameters of the FEM models for the magnet system with an iron yoke as well as the results obtained in both programs. In this model, we have simulated permanent magnets with the following dimensions Lmx=Lmz=0.04 m and Lmy=0.025 m. The difference between the two calculated forces is less than 5%.

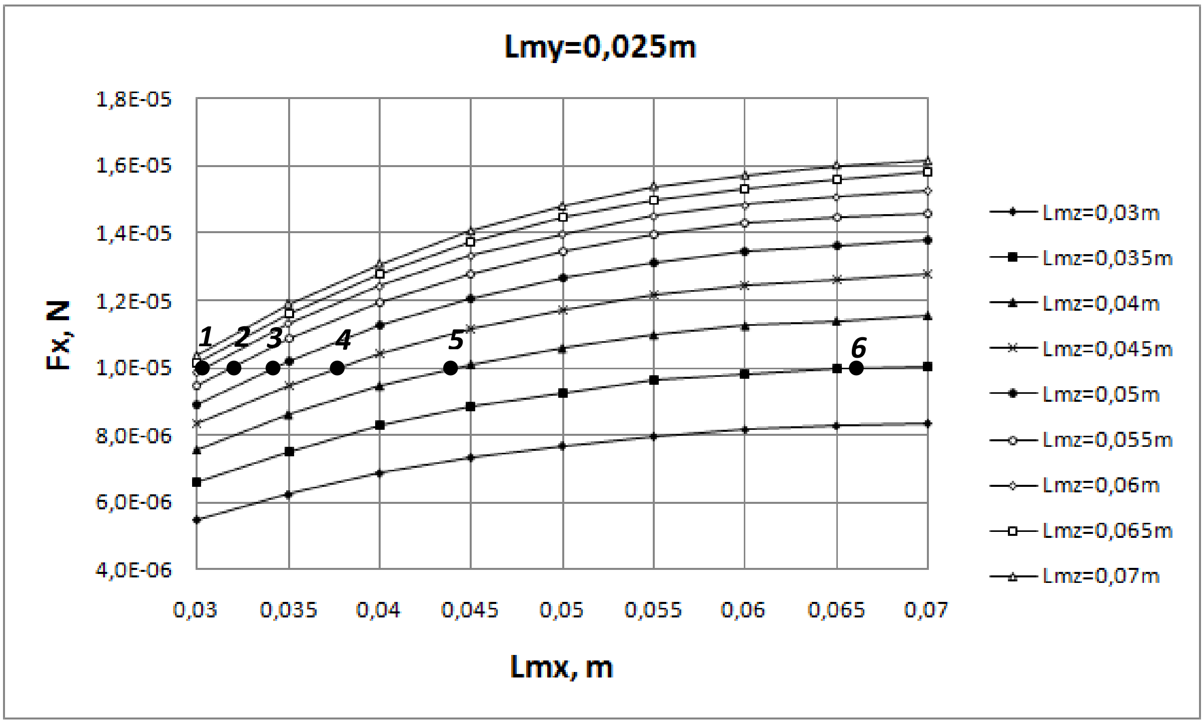
Table 2. Comparison of the FEM models: Magnet system with an iron yoke.

	Maxwell (transient)	Comsol (steady-state)
Number of elements	68712	72400
Calculation time, s	2021	398
Force, N	$1.327\cdot10^{-5}$	$1.394\cdot10^{-5}$

The comparison of the results shows that the calculated Lorentz forces are in very good agreement. Comsol is more suitable for the parametrical magnet system analysis because much less computational time is necessary.

4. Numerical results

After the numerical models were validated and optimized we performed the parametrical analysis of the magnet system. Figure 4*a* shows how the Lorentz force depends on the length of the permanent magnets Lmx by the fixed thickness Lmy and for the different height Lmz of the magnets. We used the initial data from section 1. From these curves it is easy to find the optimal permanent magnet dimensions. The analogous dependencies were obtained for the magnet system with an iron yoke. It was found that the ratio of Lorentz force to magnet system weight is approximately 2 times smaller for the system with an iron yoke. Therefore, the magnet system without an iron yoke is much more efficient for the LFV of low-conducting fluids. The optimal dimensions for the permanent magnets are Lmx=0.038 m; Lmy=0.025 m, Lmz=0.045 m (see point 4 in Fig. 4). The resulting weight of the magnet system is about 0.65 kg.



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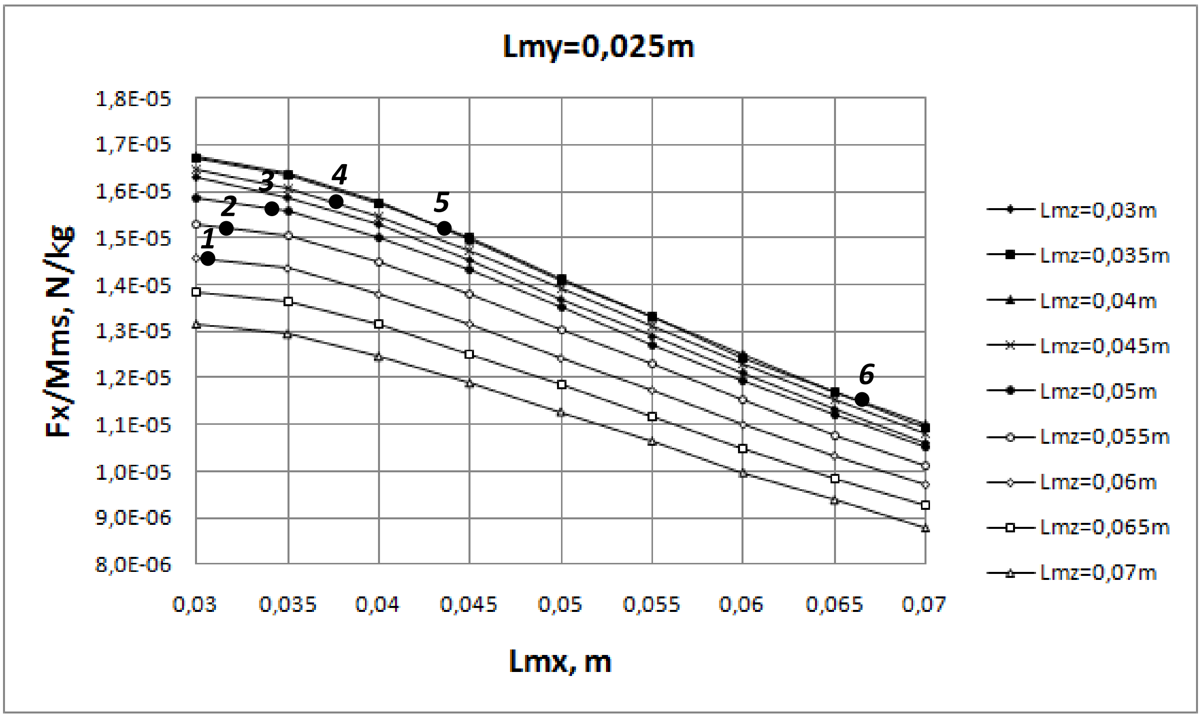

b

Fig. 4. Lorentz force and its ratio to the weight of the magnet system.

Figure 4 shows two of several diagrams obtained for different permanent magnet thicknesses Lmy: 0.02 m; 0.025 m; 0.03 m; 0.035 m and 0.04 m. It was found that the ratio of the Lorentz force to the weight of the magnet system without an iron yoke is highest when Lmy=0.025 m. It should be mentioned that we used the criterion $F_L=10^{-5}$ N (see Fig. 4*a*) to find the optimal permanent magnet dimensions.

Conclusions

The numerical LFV models were developed using the programs Maxwell and Comsol to analyze the magnet system. These numerical models were validated using the experimental data and by comparing the results. The parametrical analysis was performed to define the optimal dimensions of the magnet system for the given dimensions of the channel cross-section. It is necessary to further develop the numerical model to take into account the velocity profiles in the channel.

References

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