EXPERIMENTAL INVESTIGATION OF THE LORENTZ FORCE RESPONSE TO THE TIME-DEPENDENT VELOCITY INPUT WHILE CONSIDERING FINITE MAGNETIC REYNOLDS NUMBER

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Abstract: The Lorentz force velocimetry is a set of well-known techniques which are used to investigate velocity profiles or mass flux in channels filled with a liquid metal [1]. The technique is based on a linear dependence between Lorentz force and a conductor velocity. Usually, magnetic Reynolds number has to be small enough to keep this dependence linear. An increase of magnetic Reynolds number gives rise to the magnetic field distortion that makes Lorentz force velocimetry complicated. The presentation explains the dynamics of the Lorentz force at finite magnetic Reynolds number and shows the results of the magnetic field sweeping measurements.

1. Introduction

When an electrically conducting material moves across magnetic field lines, eddy currents are induced in the conductor. These currents carry an additional magnetic field which leads to a deformation of the applied magnetic field lines [1], [2]. As a consequence, the conducting material experiences a braking Lorentz force. The key point is that the Lorentz force is proportional to the conductor velocity. It means that having measured this force the velocity can be calculated. Although the method is very promising because it is accurate and contactless, it can be applied only if a primary magnetic field is not affected by a conductor. If the velocity is high, a secondary magnetic field created by eddy currents becomes strong enough to change the initial magnetic field distribution that leads to a nonlinear Lorentz force - velocity dependence. This phenomenon can be characterized by the magnetic Reynolds number Re_m which is finite in that case. The goal of this work is to study experimentally an error in the Lorentz force velocimetry due to finite Re_m effects as well as to show that the Lorentz force can be a powerful instrument to study an MHD task.

2. Problem definition

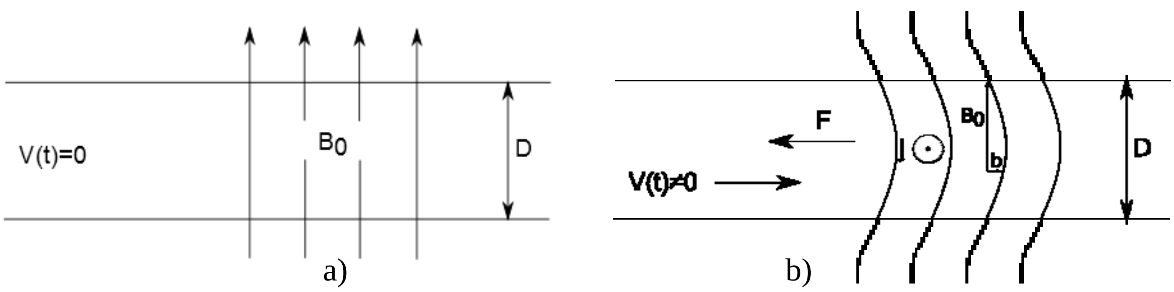


Figure 1: Sketch of the problem.

A problem studied here is sketched in fig. 1. A solid rod moves with a time-dependent velocity through a transverse magnetic field B_0, created by permanent magnets. If the rod experiences no motion, the applied magnetic field is not distorted (fig. 1a). In case of nonzero velocity, eddy currents j ensue that leads to a primary magnetic field disturbance by the induced magnetic field b (fig. 1b).

An interaction between the induced magnetic field and eddy currents gives rise to the Lorenz force F, which opposes the flow. The effects of magnetic field perturbation can be observed if magnetic Reynolds number Re_m is high enough. One possibility to obtain finite Re_m is to increase rapidly the velocity of the rod which moves through a transverse magnetic field, so that the acceleration (advection) time t_{adv} is several times smaller than the diffusion time, i.e.:

$$\mathrm{Re}_m = \frac{\mu\sigma D^2}{t_{adv}} \sim 1, \qquad (1)$$

where μ is a magnetic permeability, σ is an electrical conductivity and D is a characteristic length (fig. 1b).

3. Experimental setup

The experimental setup (fig. 2) consists of two thick aluminium plates with a piezoelectric force sensor mounted between them. On the top plate there is a magnetic Halbach array which creates a constant transverse magnetic field in the range from 0 to 1 T depending on the distance between magnets. A hole 20 cm in diameter was made in the centre of the plates so that a thick massive solid rod could easily go through. Additionally, an array from 7 Hall sensors was installed in the area between the magnets and the rod for the induced magnetic field measurements. The velocity of the rod is controlled by a computer with 1 kHz frequency so that it can be changed from 0 to 1 cm/s within 60 ms (fig. 3a). By this setup we can measure simultaneously the Lorentz force acting on the rod and the magnetic field distortion by the induced magnetic field.

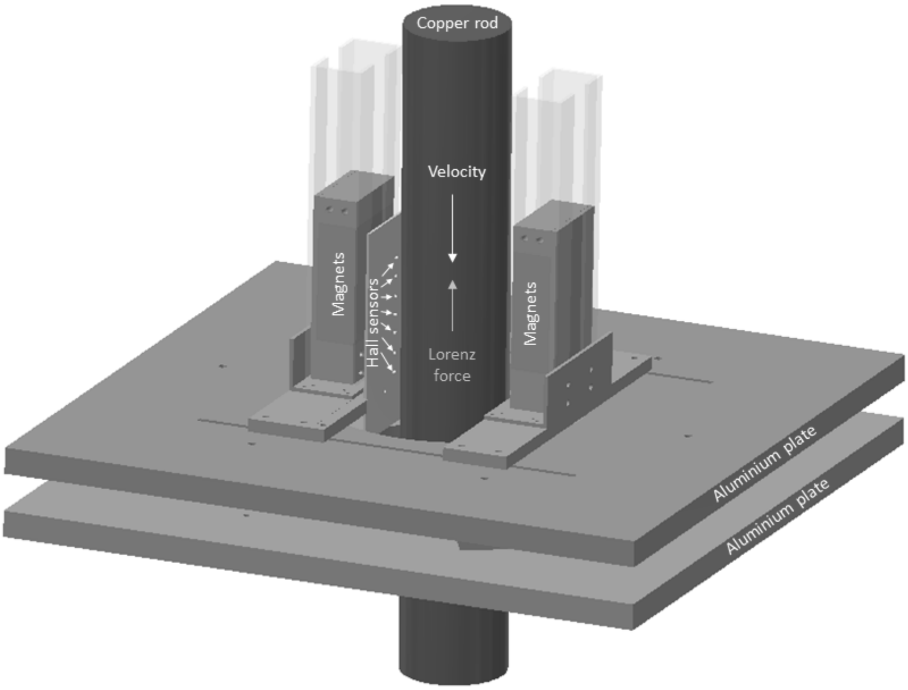
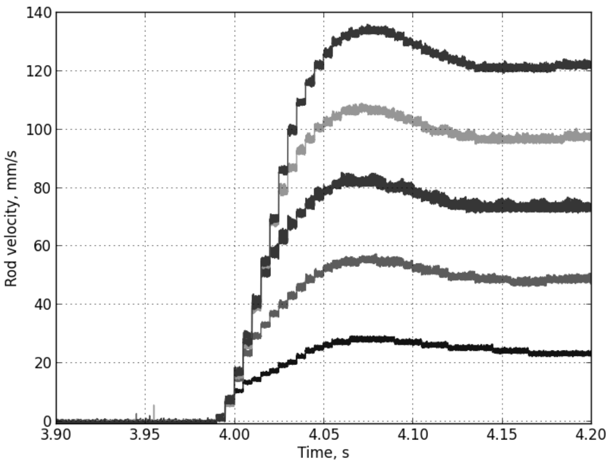


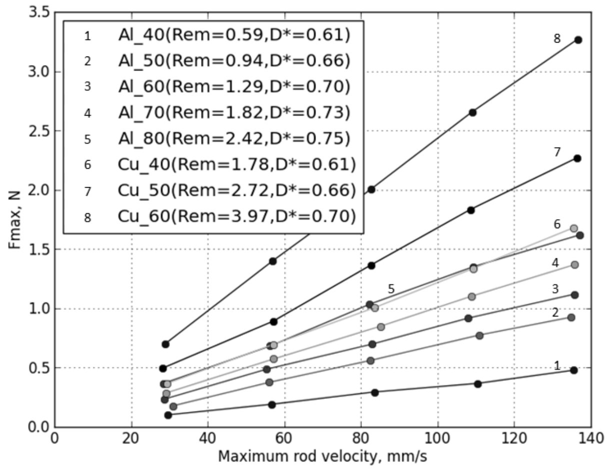
Figure 2: Experimental setup.

4. Measurement results

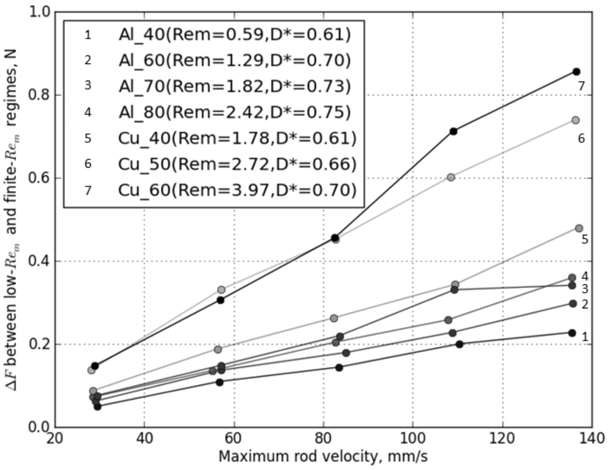
We measured Lorentz force as a function of the maximum rod velocity at different magnetic Reynolds numbers Re_m and different aspect ratios $D^* = D/L$ (L is the distance between magnets) for copper and aluminium rods (fig. 3b). The time response of Lorentz force is in good agreement with an analytical model developed in [3]. A decrease in Lorentz force at finite Re_m is explained by the magnetic field distortion due to the influence of the induced magnetic field b generated by eddy currents which circulate mainly in the area, where the magnetic field is non-uniform.



a)



b)



c)

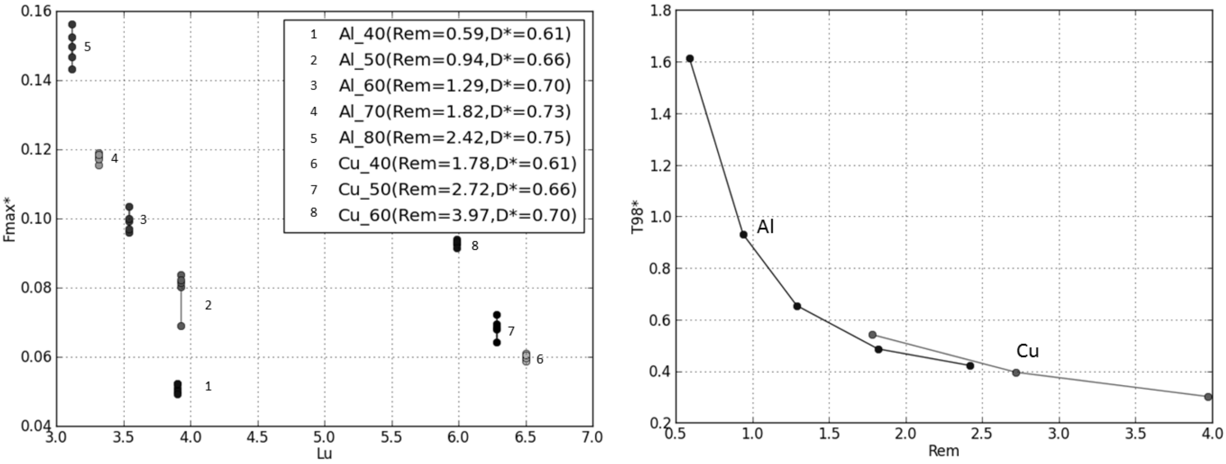
Figure 3: 5 different signals of the rod velocity (a), the maximum Lorentz force acting on the rod as a function of velocity at different Re_m and D* (b), and the difference between low-Re_m and finite-Re_m cases (c).

The actual force was compared with the values obtained at low-Re_m regime (fig. 3c). As we expected, due to the magnetic field distortion, there is a drop of the Lorentz force in comparison with low-Re_m case. This difference increases if Re_m becomes higher.

Fig. 4a shows that by means of the Lorentz force it is possible to measure the energy which is dissipated inside the conductor:

$$\frac{d}{dt}\int \rho v^2 dV = -\frac{1}{\sigma}\int j^2 dV \sim F_L \cdot v \qquad (2)$$

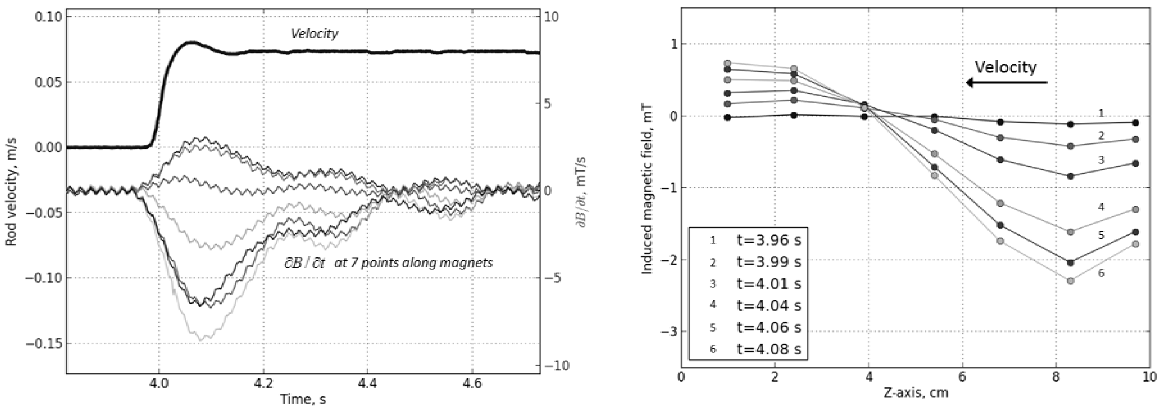
We note that a higher Re_m leads to a smaller time response of the system. The response is measured by non-dimensional reaction time T98* which shows how fast the Lorentz force rises from 0 to 98% of its asymptotic value. It was shown that T98* strongly decays as a function of Re_m (fig. 4b). This stems from a general concept of a frozen state of magnetic field lines in a conductor when Re_m becomes finite or big.



a) b)

Figure 4: The maximum of the nondimensional Lorentz force as a function of the Lundquist number at different Re_m and D* (a) and the nondimensional saturation time T_{98}* for different Re_m (b).

We have also measured $\partial B / \partial t$ (fig. 5a) which is linked with the eddy currents in the rod. Before the onset of the motion there is no induced magnetic field. But as soon as the rod starts to move, eddy currents ensue giving rise to the Lorentz force and to the induced magnetic field which deforms the applied one.



a) b)

Figure 5: Time-derivative of the induced magnetic field (a) and its evolution in time (b).

The evolution in time of the induced magnetic field is shown on figure 5b. It was observed that the rod drags magnetic field lines until the equilibrium between magnetic field advection and diffusion is achieved.

5. Conclusion

The Lorentz force response for a solid conductor to a time-dependent velocity input at finite magnetic Reynolds number has been studied. It was shown there is a difference between the values of the force in low-Re_m and finite-Re_m cases. The difference is explained by the fact that eddy currents create the induced magnetic field which distorts the primary one. This distortion has been measured by an array of Hall sensors and it was observed that the conductor drags the magnetic field lines along the travelling direction.

6. References

[1] Thess, A.; Votyakov, E.; Kolesnikov, Y.: Lorentz Force Velocimetry, Phys. Rev. Lett. 96 (2006) 164501.
[2] Weiss, N.: The expulsion of magnetic flux by eddies, P. Roy. Soc. A-Math. Phy. 293 (1966) 1434.
[3] Weidermann, Chr.; Sokolov, I.; Thess, A.: Lorentz force and Joule heat induced in an electrically conducting plate moving with time-dependent velocity under the influence of a homogeneous magnetic Field, IEEE Transactions on Magnetics, (2014) (in press).