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New developments on Lorentz force velocimetry for weakly conducting fluids

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Abstract

We report on the progress of the Lorentz force velocimetry (LFV): a contactless non-invasive flow velocity measurement technique. This method has been developed and demonstrated for various applications in our institute [1] and in industry [2].

At applications for weakly conducting fluids such as electrolytes with conductivities in the range of 1 – 10 S/m the challenging bottleneck is the detection of the tiny Lorentz forces in the noisy environment of the test channel. For the force measurement a state-of-the-art electromagnetic force compensation balance is used. Due to this device the mass of the Lorentz force generating magnets is limited. For enabling larger magnet systems and for higher force signals we have developed and tested a buoyancy based weight force compensation method which will be presented here.

Key words: Lorentz force velocimetry, weakly conducting fluids, force measurement, non-invasive

Introduction

As it is well known from liquid metal MHD, characterized by relatively small magnetic Reynolds numbers [3], Ohm's law for a moving liquid can be written in the following form:

$$\mathbf{j} = \sigma (-\nabla\Phi + \mathbf{v} \times \mathbf{B}_0) \quad (1)$$

Here σ is the electrical conductivity, \mathbf{j} denotes electric current density, Φ is the electric scalar potential, \mathbf{v} is the velocity of the melt, and \mathbf{B}_0 denotes the magnetic field. Ohm's law expresses the fact that in electrically conducting liquid, eddy currents are induced by the movement of the liquid through a magnetic field and the action of a curl-free electrical field, defined by the gradient of its scalar potential. Due to the solenoidal nature of \mathbf{B}_0 , charge conservation and the mutual interaction of the eddy currents and the applied magnetic field, Lorentz force is generated, which density \mathbf{f} defined by the relation $\mathbf{f} = \mathbf{j} \times \mathbf{B}_0$. We now insert the characteristic values \mathbf{v} , \mathbf{B} , and L for velocity, magnetic induction, and length, respectively, and, upon integrating over the volume affected by the magnetic field we find the following important scaling relation for the induced Lorentz force.

$$\mathbf{F} \sim \sigma \mathbf{v} \mathbf{B}^2 L^3 \quad (2)$$

According to formula (2), the Lorentz force linearly depends on the product of electrical conductivity and conductor's velocity, hence measuring of the force under predefined conditions allows an estimation of the velocity, as it is described

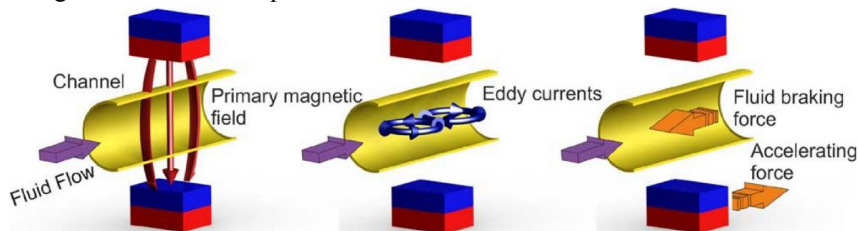


Fig. 1: Principle of Lorentz force velocimetry: The fluid flow gets interspersed by a static magnetic field and hence, eddy currents with a secondary magnetic field are generated. According to the laws of electrodynamics, the resulting force on the source of the primary magnetic field is an accelerating force in the direction of flow. This force is called Lorentz force.

by [4].

Experimental setup

The investigations are made at a closed loop channel (see fig. 2) where tap water is used as a working fluid. Its electrical

conductivity can be set easily by adding sodium chloride. Hence, the conductivity can be adjusted from 0.03 S/m up to 20 S/m. A centrifugal pump is driving the flow and enables average fluid velocities up to 4 m/s in the test section. The nozzle and a set of mesh and honeycomb filters provide a piston shaped velocity profile at the nozzle's outlet. To decouple vibrations from the pump the force measurement setup is placed at a separate fundament. Further, a fluid temperature control system keeps the temperature of the fluid constant with a peak to peak deviation of ± 25 mK. Hence, the electrical conductivity that varies about 2 %/K at room temperature can be kept constant sufficiently. As a velocity reference a commercial magneto-inductive-flowmeter is used which enables the calculation of a calibration factor between Lorentz force and fluid velocity respectively volume flow.

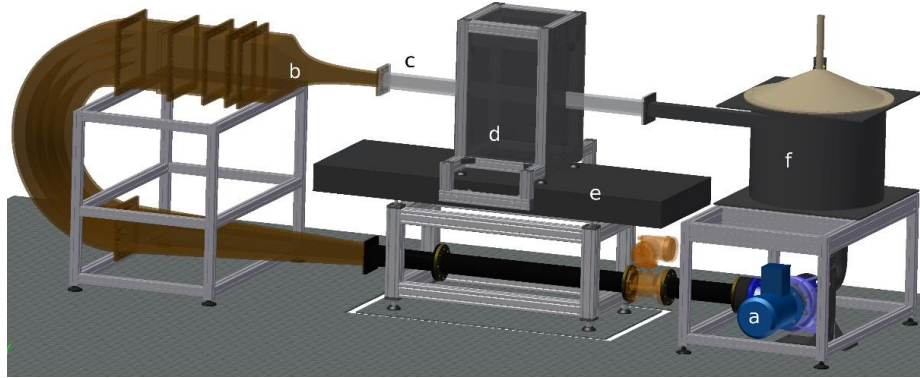


Fig. 2: Schematic illustration of the test channel with (a) pump, (b) nozzle, (c) test section / duct, (d) mounting for Lorentz force velocimeter, (e) mechanical decoupling and (f) relax vessel.

A state-of-the-art electromagnetic force compensation (EFC) balance is used in a 90° rotated orientation for measuring the Lorentz forces of the horizontal flow.

On the one hand the EFC balance allows high force resolution but on the other hand the mass of the magnet system that is hanged on its load bar is limited to approximately 1 kg to avoid breaking of its thin and very fragile solid state joints. Even with rare-earth high-field magnet systems and numerical optimizations of the geometry of the magnets there unveils an upper limit in available Lorentz force and thereby a lower limit for the electrical conductivity of the fluid and generally a limited measurement resolution due to this mass restriction.

It has been decided to test the compensation by buoyancy to use the above mentioned advantages of this concept: float bodies at both sides of the magnet system are placed in two tanks ($\approx 380 \times 110 \times 100 \text{ mm}^3$) which are filled with a fluid (water and oil). The float bodies are mounted by side arms to the magnet system. For testing the setup in operating conditions of larger magnet systems, the mass of the magnet system has been increased from 1.008 kg to 3.01 kg by gluing 4 cuboids from flint glass ($\approx 500 \text{ g}$, $77 \times 46 \times 41 \text{ mm}^3$) symmetrically so that the center of mass of the magnet system stays unvaried. In terms of magnetic field those glass bodies are only dead mass and they do not contribute to the generation of Lorentz force. This important condition needs to be considered in the evaluation later. The choice of dead mass instead of additional magnets have been made to allow a direct comparison of the noise levels with and without the new parts because here the amplitude of the Lorentz force is not changed in general.

The lift force of the float bodies has to compensate the additional weight of the glass cuboids of about 20 N and of course the weight of themselves and of the side arms. Water and paraffin oil have been selected and compared as buoyancy media in the tanks because they have a low electrical conductivity to avoid interaction with the Lorentz force measurements. Especially the last-mentioned substance has a relatively high viscosity and a moderate heat conduction coefficient and hence temperatures differences will lead only to low thermal convection.

Overcoming limitation for the size of the magnet systems: Buoyancy compensated magnet systems

For applying the LFV for weakly conducting fluids such as electrolytes with an electrical conductivity of 10 S/m and less the force measurement is the main problem because the occurring forces are in the same range smaller as the conductivities are: six orders of magnitude. In a $50 \text{ mm} \times 50 \text{ mm}$ duct and a fluid velocity from 0 to 3.5 m/s the force resolution has to be less than $1 \mu\text{N}$ in the rather noisy environment of the flow channel. Forces can only be resolved by an electromagnetic force compensation balance (EFC balance). This value equals 10^{-7} of the weight force of the magnet system and hence the force measurement system is mounted on a separate footing. Due to this necessary type of balance the weight force of the magnet system hanging on it is limited to 10 N. Larger magnet systems cannot be used without a compensation of the vertical acting force.

The idea of weight force decreasing by using buoyancy would enable larger magnet systems and higher resolution for force and hence higher velocity resolution. As a side-effect this force has only a component in the opposite direction of the gravitational force without any horizontal components that would disturb the force signal. Fig. 3 and fig. 4 show the setup that has been built for using this effect with large float bodies, which have been constructed for water and oil as

buoyancy media and with respect to the stability criteria for swimming objects [5].

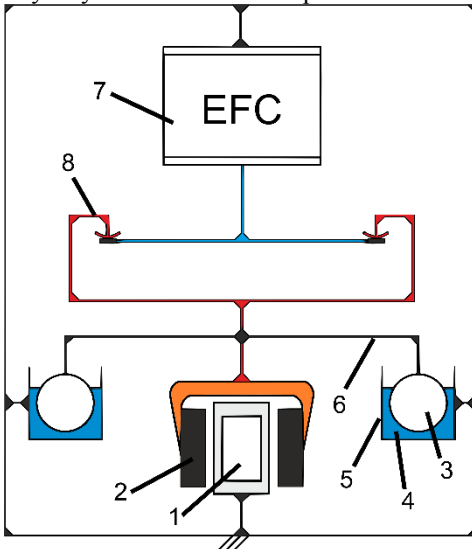


Fig. 3: Principle setup of buoyancy compensation.

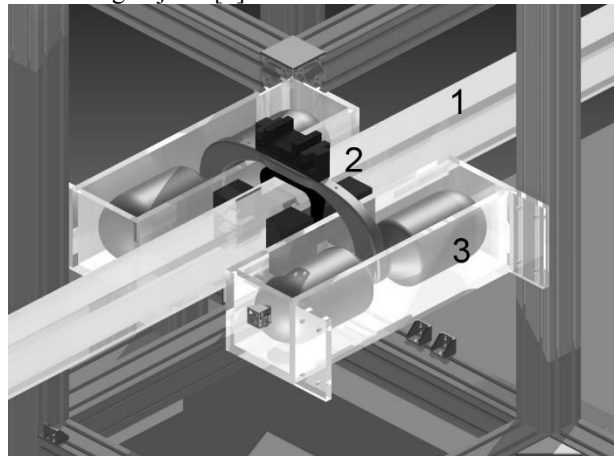


Fig. 4: Sketch of the casting flow problem with magnet pole faces and numerical grid for the simulations.

Measurement results

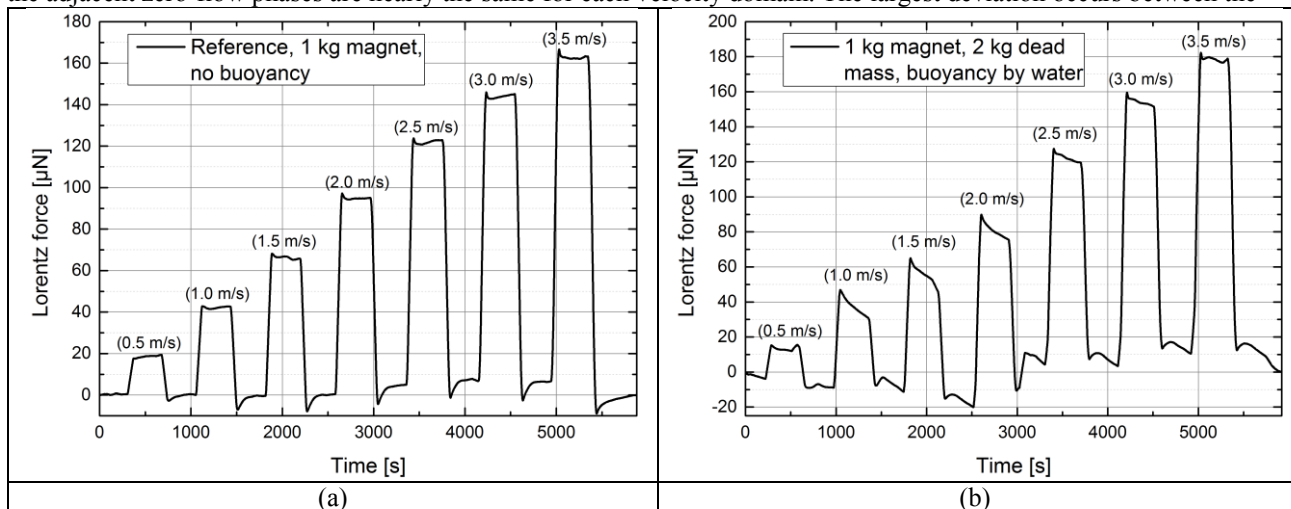
As a reference for the evaluation of the concept of compensating weight by buoyancy a “dry” measurement series with the conventional setup has been made without the glass dead mass and without the float bodies and side arms. The gained data can be compared with two measurement series for the compensation setup: one with water and one with paraffin oil as buoyancy media, each with the additional dead mass which gets compensated now. At all measurements the working fluid in the channel (saltwater) had a fixed electrical conductivity of 10 S/m and a temperature of 21 °C.

At first, it can be seen obviously that the new compensation concept is suitable for detecting and resolving the occurring Lorentz forces for both buoyancy media.

The concern of too much noise due to thermal convection in the float bodies or from other sources can be invalidated, as the data in (fig. 6-a) to (fig. 6-c) show clearly.

For the compensation with water the measurement data (fig. 6-b) show a strong drift of the ground state (zero fluid velocity) that could not be removed completely by detrending. By the analysis of the setup there has been a noticeable increase in the weight of the float bodies due to leakages coming from small cavities in the mesh structure of the 3D printing process. In comparison to that, the drift of paraffin oil (fig. 6-c) is more linear and can be removed as good as in the reference measurement (fig. 6-a). In general there is a drift superimposing the Lorentz force signal which comes from small tilting of the setup due to small temperature changes and other effects.

For quantifying the results, the changes in Lorentz force have to be plotted over the related changes in fluid velocity by determining the heights of the flanks in (fig. 6-a) to (fig. 6-c). Results are shown in (fig. 6-d). It can be seen clearly, that there is no damping or distortion of the force for both buoyancy media, because the amplitudes between the plateaus and the adjacent zero-flow phases are nearly the same for each velocity domain. The largest deviation occurs between the



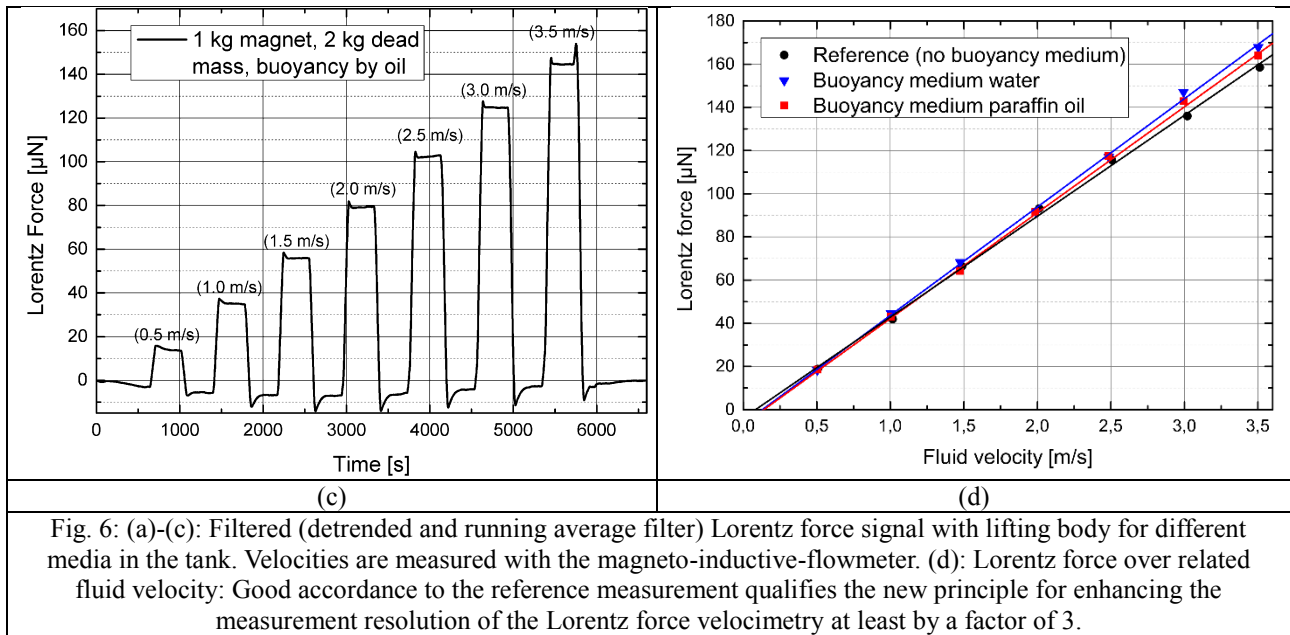


Fig. 6: (a)-(c): Filtered (detrended and running average filter) Lorentz force signal with lifting body for different media in the tank. Velocities are measured with the magneto-inductive-flowmeter. (d): Lorentz force over related fluid velocity: Good accordance to the reference measurement qualifies the new principle for enhancing the measurement resolution of the Lorentz force velocimetry at least by a factor of 3.

reference measurement and the measurement with water: 5.6 % (fig. 6-d). This means that the measurement series for water and paraffin oil have a fairly good accordance with the reference measurement.

The noise that remains after detrending and averaging can be quantified by analyzing the standard deviation (STD) of the signals. By extending the setup as it is described here the noise level of the force signal stays unvaried after applying our standard data processing: Even if the noise level of the raw data increases from 1.5 % in the reference setup up to 7 % in the compensation setup for fluid velocities of 3 m/s the filtered data show a STD for all setups in the range below 1 %. Hence, no influence of using the principal of buoyancy compensated magnet systems to the noise level has been measured.

Conclusion and Outlook

We demonstrated that the concept of buoyancy compensation is a feasible method which enables large scale magnet systems for Lorentz force velocimetry at weakly conducting fluids. The initially unknown effects of the additional float bodies like damping of force amplitudes or higher noise level have been measured: There is no negative influence to the measurement resolution – on the contrary there is completely no amplitude modification and the additional noise can be eliminated by the yet used moving average filter. Thus, a comprehensively positive evaluation of the concept can be given. Replacing the dead mass that have been used for the simulation of a higher magnet weight force would result in an at least 3 times higher force signal and hence in a much better SNR. Therefore, the results shown here are only an underestimation of what would be possible with a real full size magnet system.

Accordingly, this technique is able to improve the resolution of the Lorentz force Velocimetry at least by a factor of 3 too. In general, there is no limitation for using even larger magnet systems such as Halbach magnet arrays with 10 kg weight to get an increase of resolvable fluid velocity or a decrease of electrical conductivity of the fluid of a factor of 10. Here, 90 % of the magnet system's weight force needs to be compensated. Further, new technologies like superconducting magnet systems in cryostats which definitely exceed the mass restriction became possible applications for the Lorentz force velocimetry.

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