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Anwendung der Lorentzkraft-Techniken für Durchflussmessungen

Application of Lorentz force techniques for flow rate measurement

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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 (e.g. Ebert et al. 2013) and in industry (Weidermann 2013). Using the LFV the electrical conductivity of the fluid needs to be known to evaluate a velocity from the force signal. This constraint can be avoided with the time-of-flight method, whose feasibility for velocimetry has been demonstrated for liquid metal flows. This method and the results will be demonstrated here in detail. Furthermore, 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 as well.

Introduction

As it is well known from liquid metal MHD, characterized by relatively small magnetic Reynolds numbers (Moffatt 2000), Ohm’s law for a moving liquid can be written in the following form:

$$j = \sigma(-\nabla\Phi + \mathbf{v} \times \mathbf{B_0}). \tag{1}$$

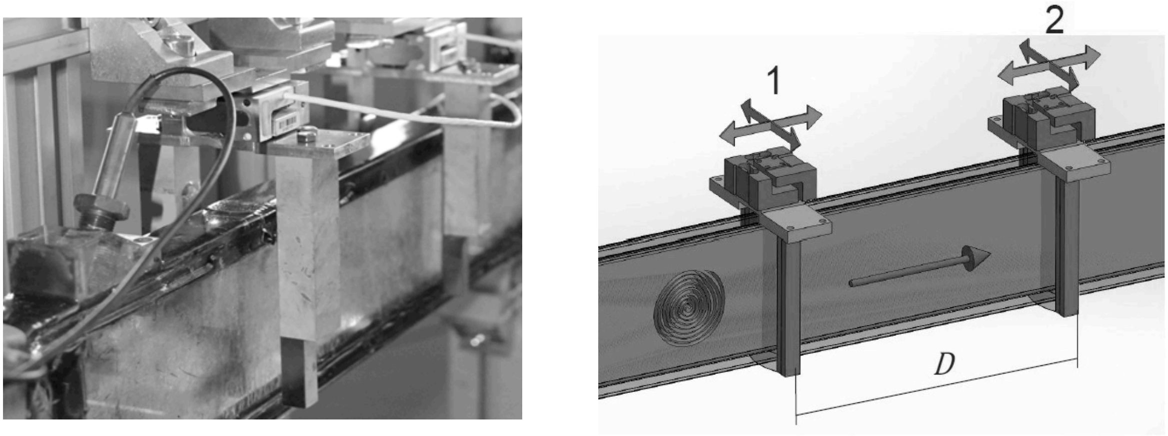
Here σ is the electrical conductivity, j denotes electric current density, Φ is the electric scalar potential, $\mathbf{v}$ is the melt velocity, and $\mathbf{B_0}$ denotes the magnetic field. Ohm’s law expresses the fact that in electrically conducting liquid, eddy currents are induced by the movement 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 f defined by the relation $f = \mathbf{j} \times \mathbf{B_0}$. We now insert the characteristic values v, 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 (Shercliff 1962).

$$F \sim \sigma v B^2 L^3. \tag{2}$$

According to (2), Lorentz force linearly depends on the product of electrical conductivity and conductor's velocity, hence measuring of the force under predefined conditions makes possible velocity estimation, as it is described by Thess et al. 2007. For accurate velocimetry, outer conditions and fluid's parameters should be known and controlled precisely, because slight temperature variations influence on electrical conductivity of fluid as well as on the strength of magnetic field.

Time-of-flight Lorentz force velocimetry

The time-of-flight LFV method (Jian, Karcher 2012) can be used to bypass these restrictions; the technique can be successfully applied when electrical conductivity is not precisely known or under changeable outer conditions. The last reason makes time-of-flight LFV especially important for industry application.
According to time-of-flight LFV (Fig. 1) two measurement systems are mounted one-by-one on a channel.



(a) (b)

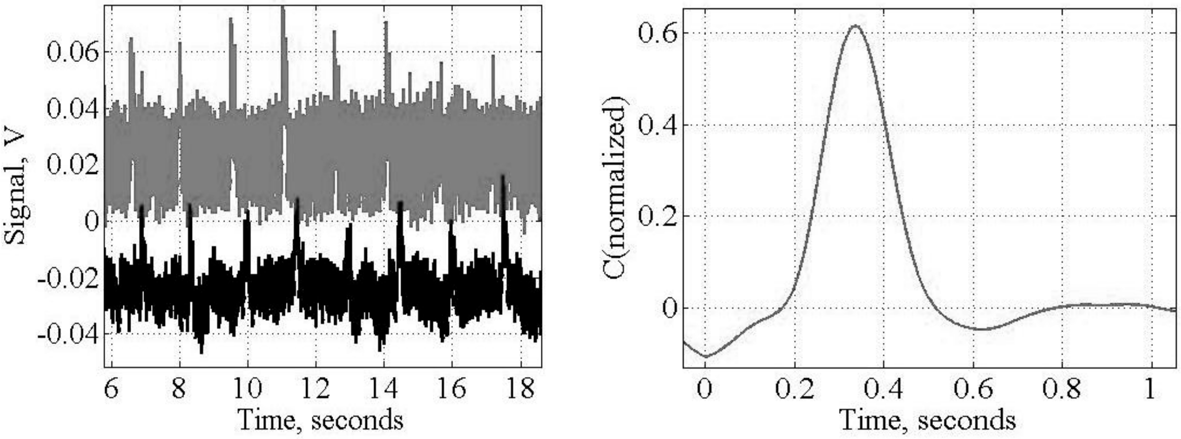
Fig. 1: Experimental equipment (a) and principle scheme (b) of for time-of-flight LFV. In (a) velocity is determined by measurement of torque, caused by Lorentz force within the flow. In (b) velocity is estimated by measurement of vortex' passing time (time-of-flight) across two magnetic systems and dividing the distance between flow meters per obtained time-of-flight

Elements of time-of-flight technique are presented here on the example of created in TU Ilmenau closed channel with Galinstan – alloy of gallium, indium, and stannum (Latin for "tin"), which is liquid under room temperature. Each of flow meters comprises of a permanent magnet pair and an attached force sensor. The measurement systems are mounted along the experimental channel and separated by a certain distance *D* in the direction of the flow. Within the flow, artificial vortices are generated up-stream in relation to the measurement systems. Before reaching measurement zone of a channel, flow passes artificial vortex generator that induces strong disturbances in it. Reynolds number inside the channel is proportional to 10^4, so Karman's street is forming after artificially created barrier. And vortices, which are generated within the Karman's street, provide changing in force signal by passing of every measurement system. When vortex fluctuation reaches magnetic field of measurement system we can observe a peak on its force-time signal of one force sensor while second system still measures stable flow. The vortices are passing both pairs of magnets one-by-one, which gives us serial change of measured Lorentz force signals due to flow disturbances. Here, upon finding a normalized cross-correlating coefficient *C* of the two force signals, we determine the time-of-flight τ of the generated vortex structure passing the both flow meters. The data can be used to determine the desired mean velocity v of the melt as distance-time dependence (standard definition of velocity):

$$v \propto D/_{\tau}. \tag{3}$$

To get exact and accurate value of velocity v it is necessary to multiply (3) to some empirical coefficient k_L, which could be obtained by calibration of time-of-flight LFV with application of such widely used techniques as Ultrasound Doppler Velocimetry (UDV) or local electro-potential probe – Vives-probe (Ricou, Vives 1982); the results of calibration show strong temperature-dependent behaviour of k_L, which indicates necessity of qualitative temperature control of liquid in the experiment.

Measurements of time shift τ are based on obtaining normalized cross-correlation coefficient C of two force signals (fig 2a, b), which are registered by magnetic measurement systems as a result of disturbance by the passing vortex (in fluid experiment) or copper plate (in dry test).



(a) (b)

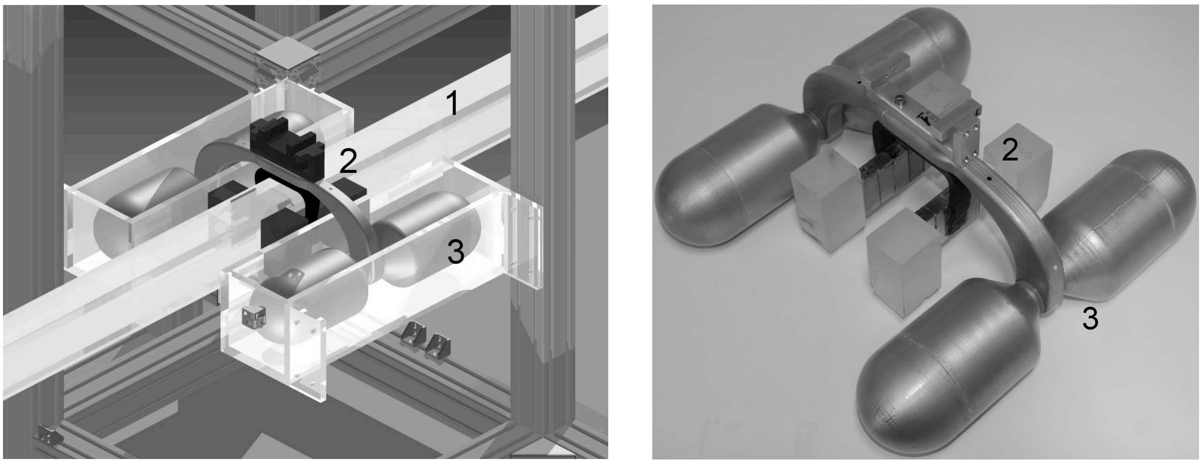
Fig. 2: Dry test's time-of-flight LFV results. Force signals with clear peaks (a), caused by copper plate passing through magnetic field of measurement systems and normalized cross-correlation coefficient *C* of the signals (b), which shows time-of-flight value

To ensure correct working of flow meters it is necessary to provide dry tests before fluid experiment. The main goal of dry tests is to register signals that prove operating performance of measurement scheme. During the test solid material – copper plate – is used instead of moving vortex and, because σ of solid copper is about twenty times higher than σ of the melt GaInSn, the Lorentz force induced by its movement is likewise twenty times higher and clear peaks are observed on both signals without significant noise influence. As well as in fluid experiment with generated vortices, copper plate is moved serially through the magnetic field of both flow meters with a known velocity and two peaks are observed in each trial. Normalized cross-correlation function of the force signals (fig. 2b) shows maximal value at time point that corresponds to the time delay τ between two series of peaks.

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. In a 50 mm x 50 mm duct and a fluid velocity from 0 to 3.5 m/s the force resolution has to be less than 1 µN 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 velocity. As a side-effect this force has only a component in the opposite direction of the gravitational force without any horizontal components that would be disturb the force signal. Figure 3 shows 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 (White, 2011).



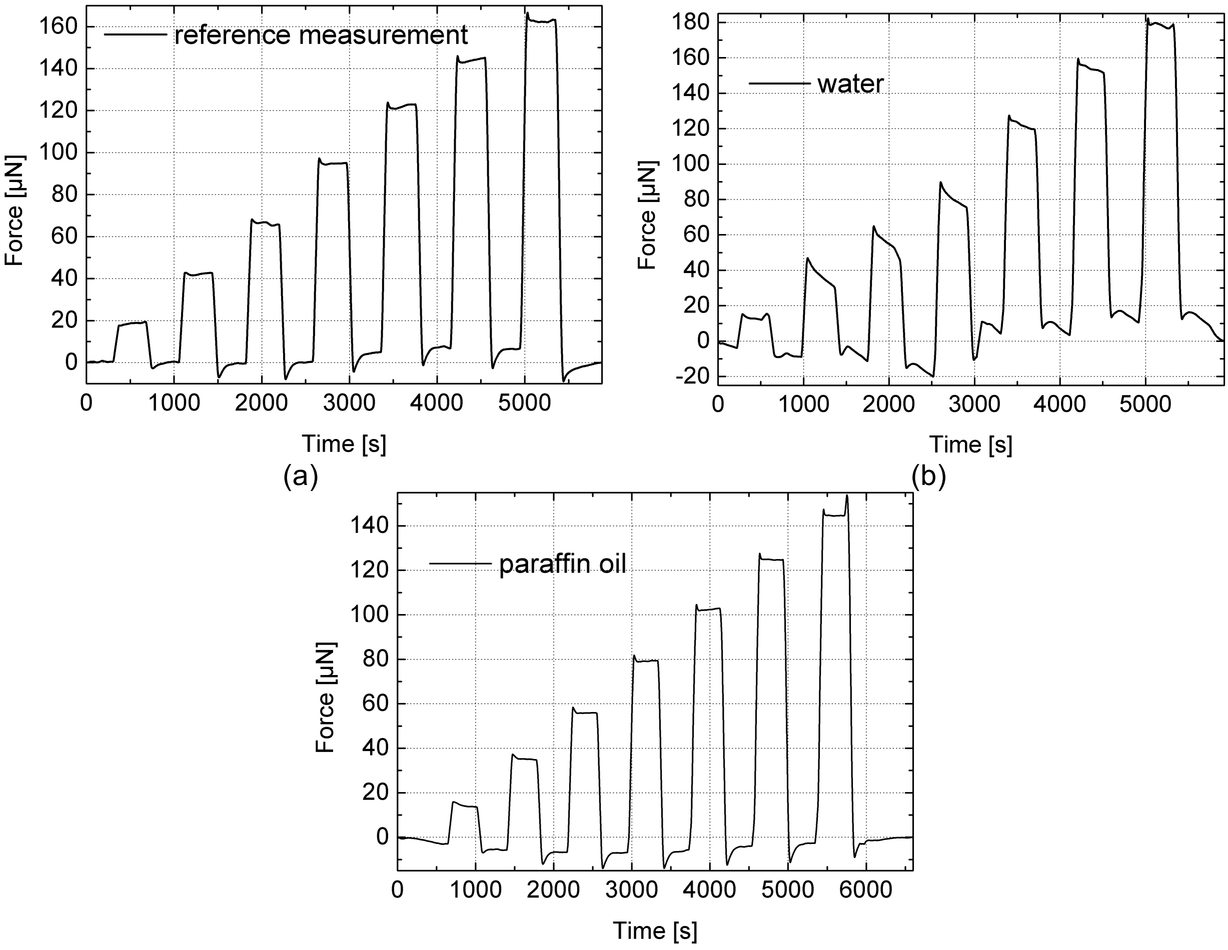
(a) (b)

Fig. 3: Experimental setup of the magnet system with buoyancy compensated weight force. 1: low channel, 2: magnet system with additional dead-mass, 3: float bodies, (a) schematic view of the setup (b) implemented construction

For simulating a larger magnet system 2 kg of dead-mass made from glass have been added to the magnets. The buoyancy from the float bodies shall compensate the resulting additional weight force (≈ 20 N) and their own weight force (≈ 7 N). They have been produced by 3-D printing technology with a design that has been optimized for stability and low weight. Due to thermal convections induced by temperature differences two different media and hence two different Rayleigh-Numbers have been tested: water and paraffin oil.

The main criteria for evaluating this concept are the noise level and the damping of the force amplitudes caused by viscosity of the buoyancy media. The reader may keep in mind, that the mass of the magnet system including dead-mass has increased by a factor of three and that the occurring forces would increase by at least the same factor if the dead-mass would be replaced by magnets. This decreases the signal to noise ratio of a large system consisting no dead-mass compared to the setup that is shown here.

Figure 4 shows the results of the measurements for different flow velocities and with salt water as an electrolyte with an electrical conductivity of 10 S/m. The measurement frequency has been 25 Hz and a detrend filter for the plateaus with zero velocity and a moving average filter (length: 1200) have been used for decreasing the thermal drifts and (statistical) noise. It can be seen clearly that both buoyancy media are not damping the force signal at all. Further, the resulting noise and the response times are in the same range as without the buoyancy construction.



(a) (b)

(c)

Fig. 4: Lorentz force signals for the fluid velocities: 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2.5 m/s, 3 m/s and 3.5 m/s with salt water (electrical conductivity: 10 S/m).
(a) reference measurement without buoyancy setup, (b) buoyancy medium: water, (c) buoyancy medium: paraffin oil.

Conclusion

Time-of-flight LFV is a prospective techniques for aggressive liquid's velocity and volumetric flow rate measurements, especially in relation to its industry applications. Our investigation shows that proposed method of flow rate measurement can be applied in cases of unstable temperature liquid metal examination.

The first experiment for evaluating the concept of buoyancy compensated magnet systems has given positive results. Both tested media are very feasible for new setups with larger magnet systems. This opens up new ways for high precision force measurement and new large magnet systems e.g. heavy high-field superconducting magnets in cryostats at the same time and facilitates the research progress towards very weakly conducting fluids such as tab water.

Acknowledgements

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