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Electromagnetic technique for liquid metal flow measurement by force time-of-flight principle

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Abstract

Flow rate and velocity measurement in opaque and aggressive liquids such as metal melts is a challenging task in scopes, where flow should be controlled. Optical measurement techniques as well as submerging probes or control units cannot be applied in this highly severe environment; hence, contactless methods are of interest for practical flow control. One branch of such techniques is flow rate estimation by measurement of electromagnetic parameters. In this paper we present working principle and experimental results of a such contactless electromagnetic technique – time-of-flight Lorentz force velocimetry (LFV), which allows determine the flow rate of liquid metals. The principle is based on measurement of Lorentz force that generated inside liquid metal under its motion through magnetic field, because the force linearly depends on flow rate. The method needs neither additional calibration nor information about fluid properties and magnetic field magnitude.

Key words: flow rate, liquid metal, Lorentz force

Introduction

According to the principles of magnetohydrodynamics, videlicet that as a result of the relative movement of an electrically conducting liquid in an externally applied magnetic field, Lorentz force F_L is induced. The induced forces act on both: the conductor and the system producing the magnetic field, they tend to slowdown the relative motion and are proportional to mean velocity v and magnetic field B [2]:

$$F_L = qv \times B \quad (1)$$

where $B = B_0 + b$ – applied and induced values of magnetic field; q – the charge, which is carried with liquid. And $qv = j$ represents eddy currents within the flow, initiated by magnetic field. According to Ohm's law for moving conductive liquid:

$$j = \sigma(E + v \times B), \quad (2)$$

where σ – electrical conductivity of liquid; E – electric field.

Eddy currents are followed by creation of Lorentz force, which opposes the flow. By virtue of the fact that permanent magnets are caused appearance of the force and in accordance with the third law of Newton, a reaction force, equal in magnitude and opposite in direction to Lorentz force, acts on magnets. The reaction force is measured by commercial force sensors, which are rigidly coupled with permanent magnets.

Hence, according to (1), (2), by applying Faraday's law, measured Lorentz force can be also estimated by [4], where only mean velocity v or volumetric flow rate Q_v are unknown:

$$F_L \propto \sigma v B_0^2 L^3, \quad (3)$$

where L – characteristic length of system magnets-liquid.

Working principle

Time-of-flight Lorentz force velocimetry (Fig. 1) allows to measure the flow rate in liquid metal and the technique is unaffected by physical properties of fluid or by outer conditions. The time-of-flight principle [4] is based on correlation of two Lorentz force measurements. Two flowmeters consist from a pair of permanent magnets and force sensor each. The sensors detect reaction of Lorentz force on magnets. Sensors are mounted on a duct at a certain distance D between each other. A vortex moves sequentially through magnetic field of both flowmeters and disturbs flow and, hence, measured force. Correlation of the signals gives time delay value τ that vortex needs to pass distance between flowmeters. The distance between sensors per time difference give mean velocity of liquid metal within a duct with cross-section area A , which, in turn, allows get liquid metal flow rate Q :

$$Q = vA = A \frac{D}{\tau} \quad (4)$$

3D strain gauge sensors are used for force measurements, the measurement range of each direction is 2 N, so magnet holding system should be as light as possible to not overload strain gauge component in gravity direction. The goal was reached by applying standard aluminum profiles for construction. Besides this, new magnet holding system allows mount permanent magnets with 1 mm distance to the duct, which increased sensitivity of force measurement. The model experiments described here demonstrate that time-of-flight LFV is feasible non-contact electromagnetic technique for measuring and control of volumetric flow rates in turbulent liquid metal flow.

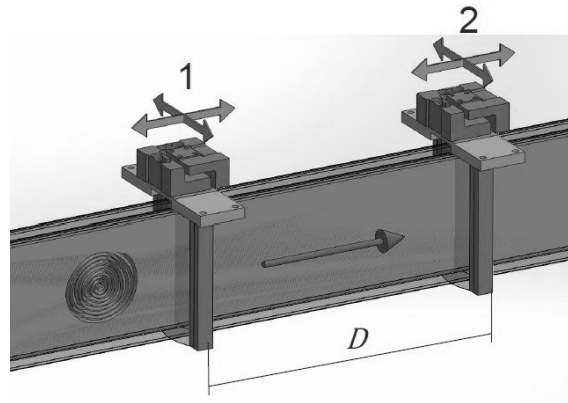


Fig. 1: Working principle of time-of-flight LFV. Two identical flowmeters, consist of permanent magnets pair and force sensor each, measure Lorentz force to calculate flow rate.

Results

To validate time-of-flight LFV method before liquid application, dry test with a copper plate was provided. The plate was moving through the gap between permanent magnets of flowmeters (fig. 2a,b). The test's results demonstrate the highest value of normalized correlation coefficient C at time equal 0.32 sec, what with the distance 0.15 m between flowmeters gives us rough estimation of mean velocity of plate 0.47 m=sec and proved that method is working and can be applied for more physically complicated liquid flow.

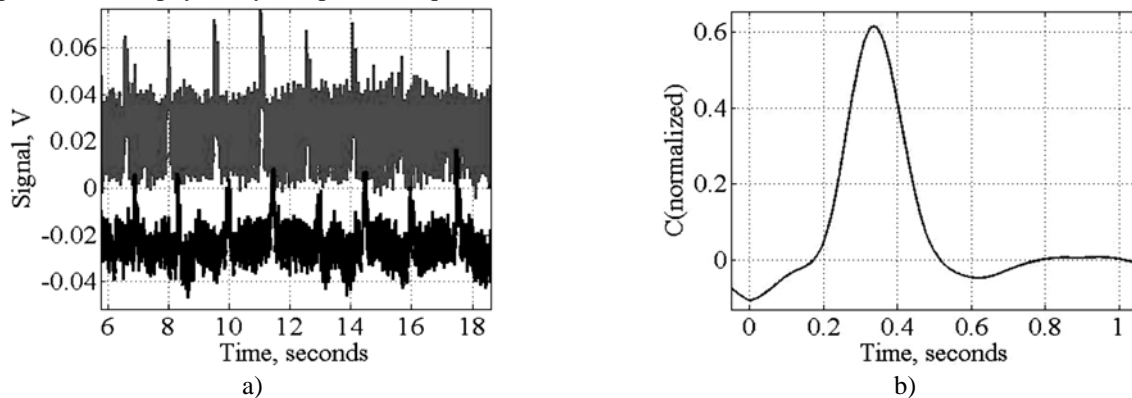


Fig. 2: Dry test's time-of-flight LFV results. Force signals with clear peaks (a), caused by copper plate passing through magnetic field of measurement systems and normalized cross-correlation coefficient C of the signals (b), which shows time-of-flight value

Measurement system and signal processing enabled to estimate mean velocity of liquid metal in the duct (Fig. 3). Electromagnetic pump creates flow within the duct, so its rotation frequency is used as horizontal coordinate to refer to velocity.

The measurement results show high error value, as one can see by error bars on both diagrams. This is observed due to low signal-to-noise ratio. More specifically, signal is getting lost against the background noise, what is easy to see by comparison between cross-correlation function of two signals and their autocorrelation functions: if peaks of cross- and auto-correlations coincide we are able detect only noise.

Another observation, that can be made due to presented diagrams – the time-of-flight velocity value mostly lays lower

than measurement results of Vives-probe [5]. This can be explained by the velocity difference between mean flow in the duct center and moving vortices or other disturbances that are slowed down according to their size and direction either by boundary layers or by internal friction in liquid mostly.

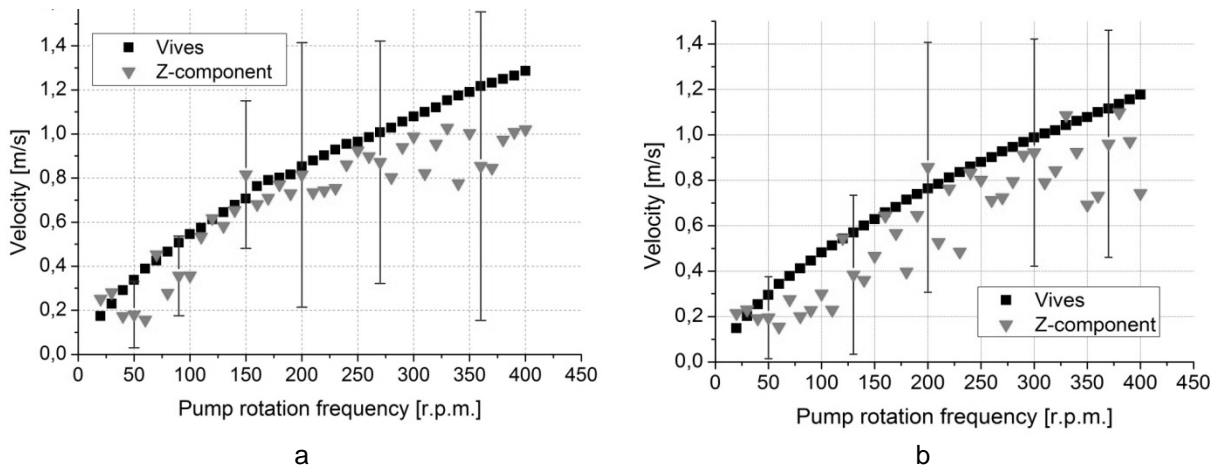


Fig. 3. Time-of-flight measurements results in comparison with reference method – Vives-probe. Velocity on (a) and (b) are presented for normal position of sensors with and without artificial vortex generation correspondingly

The time delay values, calculated by cross-correlation of x- and y-directions, don't represent clear change of velocity with increase of pump rotation frequency and, thus, cannot be used in velocity estimation. In x-direction constant bulk flow force is in evidence and it is a complicated task to distinguish useful signal from strong turbulent disturbances. In y-direction case flow is parallel to magnetic field lines and if this occurs there is no Lorentz force generation possible. The only component, that shows visible change of time delay during experiment, is z-component of force, so the mean velocity was estimated by this component.

Conclusions

Experimental research of time-of-flight Lorentz force velocimetry is very challenging and interesting task. And the method itself is a prospective technique for mean velocity and volumetric flow rate measurements especially in relation to its industrial applications. This method is successfully used in laboratory conditions for velocimetry of turbulent liquid metal and gained results show sufficient correlation between time-of-flight and reference velocity estimation without applying any additional calibration. The time-of-flight Lorentz force velocimetry does not directly depend on physical properties of liquid metal and gives wide opportunities to investigate behavior of vortices of different nature in turbulent duct flow under moderate and high Reynolds number.

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