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FORCE MEASUREMENTS BY STRAIN GAUGE SENSORS AS PART OF TIME-OF-FLIGHT FLOW RATE CONTROL

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ABSTRACT

Contactless techniques are the most promising methods for liquid metal flow rate control and some of these methods are based on electromagnetic induction of breaking force acting on an electrically conductive fluid which is moving through a static magnetic field. Providing flow analysis in case of aggressive and hot liquids is a complicated task, especially when liquids composition and, hence, its physical properties, are unknown. One of the techniques is time-of-flight Lorentz force velocimetry (LFV). By using the method one can estimate volumetric flow rate without knowing of electrical conductivity, magnitude of magnetic field or characteristic dimension. The most important and crucial challenge within the technique is detection of small fluctuations of Lorentz force value. In this article we will focus on special aspects of application of highly sensitive strain gauge force sensors within the framework of time-of-flight LFV.

1. INTRODUCTION

There are existing many kinds of multiply origin forces like compression, tension, bending, gravity and many others. Measurement of these forces is in sphere of vivid interest of present-day science and industry. Different working principles are applied for the purpose [1]: comparison with well-known force (scales), force effect on elastic element (strain gauge), change of the pressure (pneumatic load cells), etc. Moreover, nowadays force measurements are used not only for direct force determination, but also for investigation values in different fields, such as bioengineering (bacterial adhesion study [2]) or material science (atomic force microscope [3]). It is also common to use force measurement for flow rate control of conductive [4] and non-conductive materials [5].

One of the flow control's method which is based on force measurement is Lorentz force velocimetry (LFV). It is an up-to-date contactless technique for control of volumetric flow rates of hot, opaque, and aggressive fluids, where neither contact nor optical method can be applied. Since metal melts are excellent electrical conductors, the employment of electromagnetic flow measurement devices are favorable. LFV is based on the fundamental principles of magentohydro-dynamics (MHD) [6], [7]. The theory of this MHD effect was well described by Shercliff in 1963 [8]. When an electrically conducting material passes the magnetic field lines stretched by an arrangement of permanent magnets, eddy currents are induced inside the moving material. These eddy currents interact with the applied magnetic field and, as a consequence, Lorentz forces are generated within the material. The generated force opposes liquid's movement and, according to the Newton's third law, the same value of force is acting in the opposite direction on the source of magnetic field - permanent magnet. Because the force depends on velocity, it provides a velocity dependent force signal for flowmeter applications. According to Thess [4], the flow velocity has a linear influence on the resulting Lorentz force F_L, hence it can be estimated by measuring the force:

$$F_L \sim \sigma v B_0^2. \tag{1}$$

A drawback of the technique is that the measured force is not just the function of volumetric flow rate, but also depend on such factors as electrical conductivity σ of the melt, magnitude of the applied magnetic field B_0, which difficult to control precisely during the experiment due to their temperature dependence.

2. TIME-OF-FLIGHT LFV

To circumvent the deficit of accurate properties data, improved LFV technique - time-of-flight [9] method - is suggested. Feasibility of the method to determine flow parameters without probes and signal particles is significant under condition of industrial manufacture. Time-of-flight LFV allows to control flow rate of liquid metal and is unaffected by physical properties of fluid or by outer conditions. According to the technique (Fig. 1a), two identical measurement systems are mounted along a liquid metal channel one by one. Each of flow meters comprises of a permanent magnet pair and an attached strain gauge force sensor, so inducing of Lorentz force and measurement of the reaction force are made simultaneously. The measurement systems are separated by a certain distance D in the direction of the flow. Electromagnetic pump, based on permanent magnets, is used for pumping the flow in the channel. Within the flow, up-stream to the measurement systems, artificial vortices are generated. A generator of vortices is located in such way, that created by it fluctuations can move with a liquid through magnetic field of permanent magnets. The vortices are passing both pairs of magnets one-by-one, which gives us serial change of measured Lorentz force signals because of flow disturbances. Here, upon finding a cross-correlating function of the two force signals, we determine the time-of-flight τ of the generated vortex structure passing the both flow meters. Then, according to the time

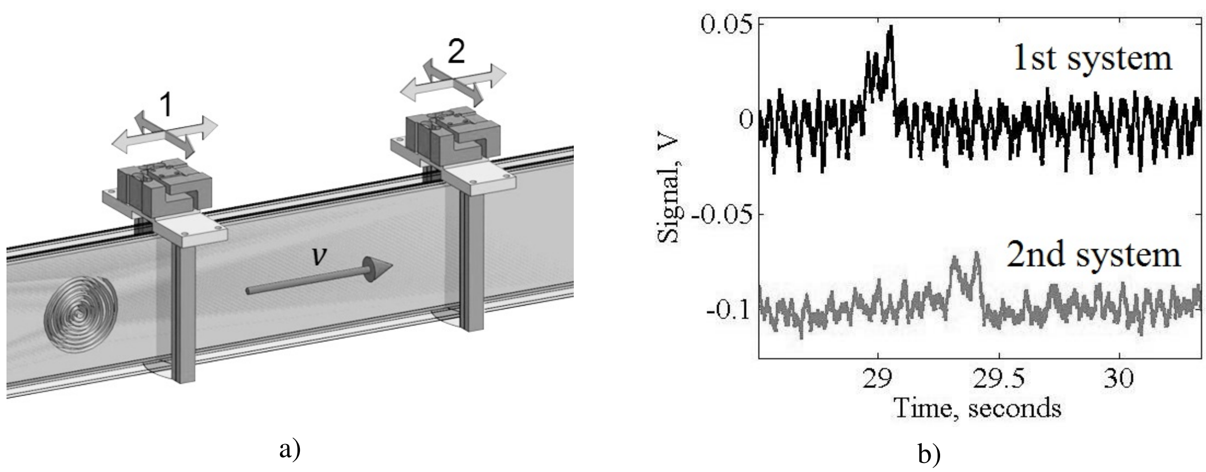


Figure 1: *Working principles of time-of-flight LFV (a) and signals of time-of-flight LFV (b). Velocity is determined by the measurement of time delay between peaks, caused by Lorentz force disturbance within the flow due to a moving vortex.*

between peaks τ and the distance D between measurement systems, observer can estimate mean velocity and, hence, flow rate Q_v of the liquid (k - empirical coefficient):

$$Q_v \quad = \quad kD/\tau. \tag{2}$$

The experimental facility consists of a closed channel with rectangular cross-section of height per width = 80 x 10 mm^2. The entire duct is made of acrylic glass. The flow velocity is limited by the water pump and can reach fluid flow velocities in the range of up to $v = 1.0m/s$. The channel is filled with eutectic alloy of Gallium, Indium and Tin – Galinstan – which is liquid under room temperature and has electrical conductivity in order 10^6. To increase the rate of turbulence within the channel, to create long-life vortex structures and to increase the rate of usable signals, a vortex generator is mounted into the flow. Several methods can be used for vortex generation: contact way – by immersed solid body, or contactless way – by magnetic obstacle, that are created by permanent magnets or electromagnetic influence. Application of solid body as the vortex generation provides good qualitative results in creation of Karman's street in case of laboratory conditions, but as a contact method it cannot be used in case of aggressive or hot medium, so magnetic obstacles were tested as well.

3. FORCE MEASUREMENTS SYSTEM

Simultaneous measurement of Lorentz force by two identical flowmeters is the main idea of time-of-flight LFV. Thereto in practice different force sensors can be used: load cells [10] and electromagnetic force compensators [11], optical systems [12,13]. Core requirements to the sensors for laboratory tests by LFV: high sensitivity and accuracy in low forces measurement range, because level of Lorentz force in our laboratory conditions doesn't exceed 10^{-2}...10^{-1}N. In case of time-of-flight LFV applied sensors have to be even more sensitive, because flow disturbances as a result of vortex movement are lower than 10^{-3}N. In order to satisfy the requirements commercial three-dimensional strain gauge sensors were chosen with declared sensitivity value 40μN and measurement range 2N. The principle of the force sensor is the measurement of voltage alteration due resistance changes under the application of force or strain. Standard strain gauges can sense the displacements as small as 5 m, what makes them capable to detect small changes of force. As sensors material aluminum was selected because of its non-magnetic nature and smooth stress-strain behavior in measured force range.

Every force sensor is connected with a pair of permanent magnets 10 x 10 x 90 mm^3, as it shown at Fig. 2. The magnet system is equipped with two high-energy magnets made of NdFeB and reaches maximum magnetic flux density of the order of 300 mT within the channel between magnets. Top side of both sensors is rigidly fixed to loaded aluminium construction to avoid displacement damping due to bending stresses of coupling elements and mounting system itself. The whole measurement setup is fixed

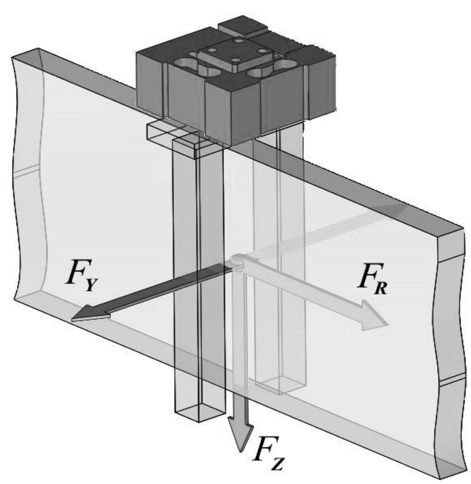


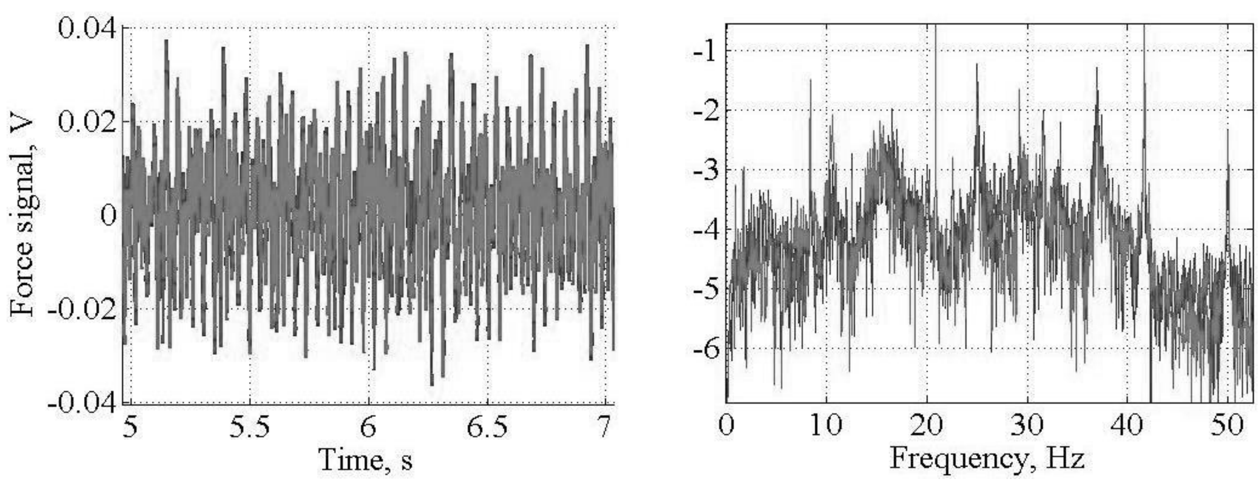
Figure 2: *Force measurement system of time-of-flight LFV (one of two). Force F_R, caused by system reaction on interaction of conductive liquid flow and space variable magnetic field, F_Y – multidirectional turbulence and magnets disaligment, F_Z – gravitational force.*

on a stone block and embedded in a box filled with sand in order to suppress the effects of vibrations of the surrounding building. The magnets are emplaced symmetrically to the channel both in vertical and horizontal (orthogonal to the flow) directions. The Lorentz force that is generated within intersection of applied magnetic field and conductive flow, have effect on both magnets at the same time as consequent reaction force. The main component of measuring force – resulting force F_R – acts at the middle point between centers of permanent magnets along the flow. Orthogonal component of the reacting force F_Y is caused by multidirectional turbulent fluctuations within the flow and the imperfection of magnets positioning according to flow: disalignment or asymmetry. Value of F_Y could reach significant values, up to 10% of F_R, so accurate mounting of the sensors is necessary for qualitative force signal. Vertical component F_Z is caused mostly by gravitational force due to the weight of fastening system with permanent magnets which is equal 2,56N. Asymmetry in vertical positioning of the magnets according to the height of the channel has insignificant effect on F_Z (less than 0,1% of gravitational force).

The voltage change due to the sensors' resistance alterations are measured in complex with commercial strain gauge amplifiers from the force sensor's producer and with a high resolution digital data acquisition system Agilent. The influence of primary strain, caused by outer conditions, temperature, mutual influence of forces in supplementary directions and so on are neutralized by preparatory tarring of amplifiers so preliminary state doesn't have significant effect on the measurement result.

4. RESULTS

To illustrate practical results of time-of-flight LFV we used cylindrical solid body to generate strong turbulence fluctuations within the flow. The cylinder has diameter 5mm and is mounted in the middle of the channel, 10cm before the first measurement system. Every test endures up to three minutes, so impact of the change of surrounding conditions with time is neglected. because of high density and, hence, inertia forces of investigated liquid, it takes one minute for it to stabilize the flow after starting of the pump. Two force signals were measured simultaneously and the results are presented at Fig. 3.



a) b)

Figure 3: *Typical force signals of time-of-flight LFV (a) and their power spectrum (b). Combination of two force signals, obtained during experiments with closed rectangular channel. The signals are very noisy due to mechanical vibration of the channel and measurement system, power spectrum of signals shows intensity of different frequency spectrum components*

Time-of-flight LFV measurements results show high level of noise of different nature, primarily due to mechanical vibrations within system itself, electromagnetic pump and oscillations in the channel; as well as electromagnetic noise due to electrical networks (50Hz peak on power spectrum diagram). Another significant source of noise is natural frequency of strain gauge force sensors. Though declared value of the frequency is $180Hz$, due to heavy magnets and their fastening system high level of dead load effects, that decreases value of sensors natural frequency to $\sim 30Hz$.

The distance between the sensors is estimated as $15cm$ with uncertainty $\pm 0{,}1mm$. To detect the time delay in a noise-corrupted sequence, the normalized cross-correlation function of two force signals was applied (Fig. 4). Cross correlation is a standard method of estimating the degree to which two series are correlated. The maximal value of the function shows the time delay value between investigated curves. Under normalized cross-correlation the range of the data is -1 to 1 such that the closer the cross-correlation value is to 1, the more closely the information sets are.

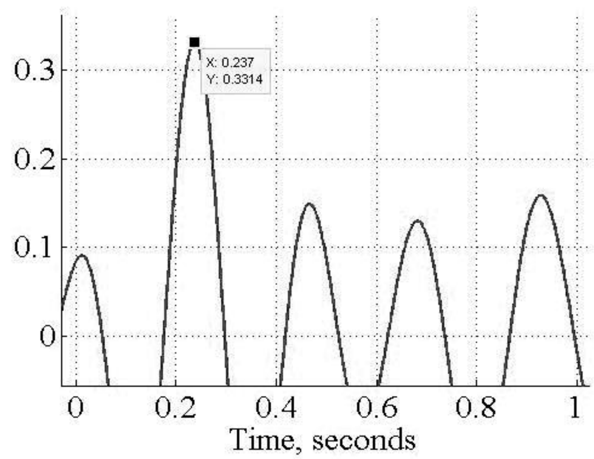


Figure 4: *Normalized cross-correlation function of two force signals of time-of-flight LFV. The highest peak has shown at time point 0,237s due to alternate effect of vorticies within the flow. The fluctuation were created by solid cylindrical obstacle.*

Within described experiment time delay value $0{,}237s$ is obtained which with the distance $15cm$ between sensors gives us mean cross-sectional velocity $0{,}633m/s$ without applying of any calibration coefficient, at the time as potential probe measured $0{,}809m/s$ in the middle of the channel.

Our experiment procedure results in evaluating the travelling speed of any vortex structure within the flow. We observe that the raw signals are very noisy and the cross-correlation is weak, so proper filtering of raw signals is necessary. The improvements of filtering technique is a part of the future investigation, directed on decreasing noise-to-signal ratio at the frame of time-of-flight LFV.

5. CONCLUSIONS

The feasibility of time-of-flight LFV for flow rate measurements of liquid metals in closed channel has been successfully demonstrated under laboratory conditions as fully contactless method. There is no need in mechanical contact of probes and liquid or in additional information about physical properties of the media and material. The present technique measures the transit time of tagging vortieces that are transported by the flow and registered by two Lorentz force flow meters that are arranged in a certain distance between each other. The flow rate determination is based on cross-correlation function between two simultaneously measured force signals and is independent of liquid properties and magnetic field strength. Strain gauge force measurement system, that was applied for the tests, is sufficiently sensetive to detect small changes of Lorentz force due to moving vorticies within the flow. Experimental results are well compared with the results of local velocimetry technique - potential probe; the difference between measured results is primarily caused by the difference of mean and bulk velocity values in channel flow.

6. ACKNOWLEDGEMENTS

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