APPLICATION OF A MULTI-DEGREE-OF-FREEDOM SENSOR IN LOCAL LORENTZ FORCE VELOCIMETRY USING A SMALL-SIZE PERMANENT MAGNET SYSTEM

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ABSTRACT

Local velocity or even mass flow measurement of liquid metals is still an unsolved issue in the steel industry. Lorentz force velocimetry is a contactless measurement technique for flow rate and local velocity in electrically conductive fluids like liquid metals. In this technique, permanent magnets generate magnetic field lines which penetrate the flowing metal melt and according to the principles of magnetohydrodynamics, eddy currents and a total Lorentz force are generated inside the melt. This braking Lorentz force is proportional to the velocity of the flow. In the case of local Lorentz force velocimetry, the permanent magnets are significantly smaller in comparison with the cross-section of the flow allowing local velocity measurements. Additionally, by connecting the magnet system to a 6-Dof force/torque sensor, we are able to measure locally the force and torque acting on the magnet system allowing the estimation of both the local streamwise velocity as well as its gradient.

1. INTRODUCTION

In Lorentz force velocimetry, the magnetic field lines produced by permanent magnets are spanned by the flowing electrically conductive liquid. According to the principles of magneto hydrodynamics, eddy currents are generated inside the fluid giving rise to a secondary magnetic field. The interaction between the secondary and the first magnetic field give rise to Lorentz forces within the fluid but in the direction opposite to the flow ("braking effect"). According to Newton's third law, there is a counter force of the same magnitude in streamwise direction acting on the permanent magnet system which is fixed to a force sensor. Given that the magnetic field lines penetrate the entire cross-section of the flow, the measured force F_L is proportional to the flow rate Q or velocity V, the applied magnetic field B_0 to the power of two and to the electrical conductivity σ of the liquid metal [7]:

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

or

$$F_L \sim V\sigma B_0^2 \tag{2}$$

But in the case of local Lorentz force velocimetry where the permanent magnets are significantly small in comparison to the cross section of the flow, we are able to have a qualitative assessment of the local velocity of volume subset of the flow owing to the rapid decay of magnetic fields. With this technique Dr. Christiane Heinicke was able to locally identify mechanical obstacles inside the flow and their wake behind them with a spatial resolution of 3 cm with a 10 mm permanent magnet [5]. The model experiments were performed in the experimental facility GALINKA (Figure 1) having as test fluid GaInSn in eutectic composition. Dr. Heinicke carried out force measurements with an interference optical force measurement system measuring locally only the streamwise force (Figure 2).

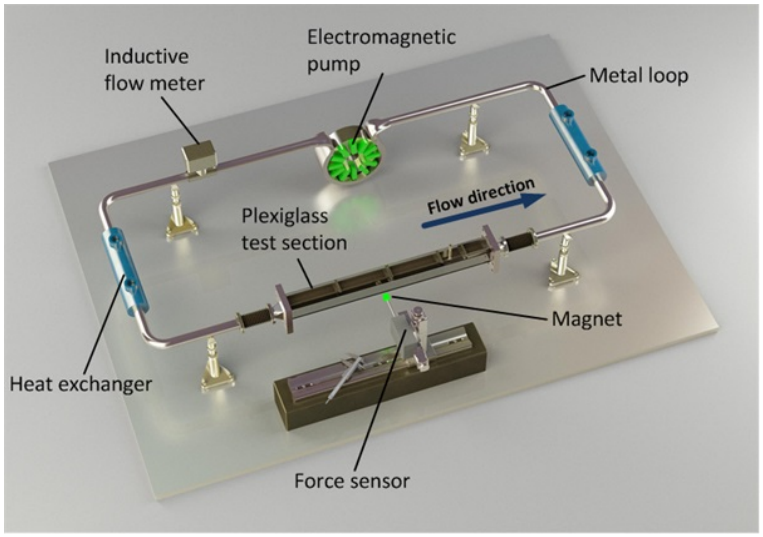

Figure 1: Experimental facility GALINKA. The liquid metal loop consists of stainless steel pipes and an 80cm long plexiglass rectangular (50mm x 50mm) test section. The GaInSn is pumped by the electromagnetic pump and flows though the test section where the force sensor is placed beside and measures the resulting streamwise force acting on the magnet.

2. PROBLEM DESCRIPTION

The present aim is to increase the spatial resolution of the force by reducing the volume subset of the flow which is interacting with the magnetic field by using smaller magnets, e.g. 5mm cubic magnets. However, the expected force will be too small for the current interference optical force measurement system (Figure 3) to be able to detect, as demonstrated by Dr. Heinicke's parametric study with magnets of different size (5, 10 and 15mm cubic magnets) [4]. In order to have a measurable force with higher spatial resolution, a novel arrangement of small-size permanent magnet system is proposed as shown in Figure 2. The design of the magnet system takes also into account a future use of a multi-degree-of-freedom sensor which is currently being developed in the A-2 project of the RTG Lorentz Force Velocimetry and Eddy Current Testing (Figure 3) [2]. This enables us to measure all the torque components acting on the magnet system in addition to the Lorentz force components while measuring velocity fields with local gradients. This in turn, allows for the estimation of both the local streamwise velocity as well as its gradient.

3. RESULTS

We start the analysis of the problem by finding the magnetic field distribution of the new permanent magnet system. Additionally, its volume should be limited to the volume of the old one (10 mm cubic magnet) for a direct comparison between them. Finally, the magnetic field distribution and the total Lorentz force would be compared given a velocity profile of liquid metal inside the duct (not scope of this paper).

3.1 Magnetic field distribution

The magnetic field B produced by a bar permanent magnet (Figure 4) can be obtained analytically using the charge model in which the magnet is reduced to a distribution of an equivalent "magnetic charge". With

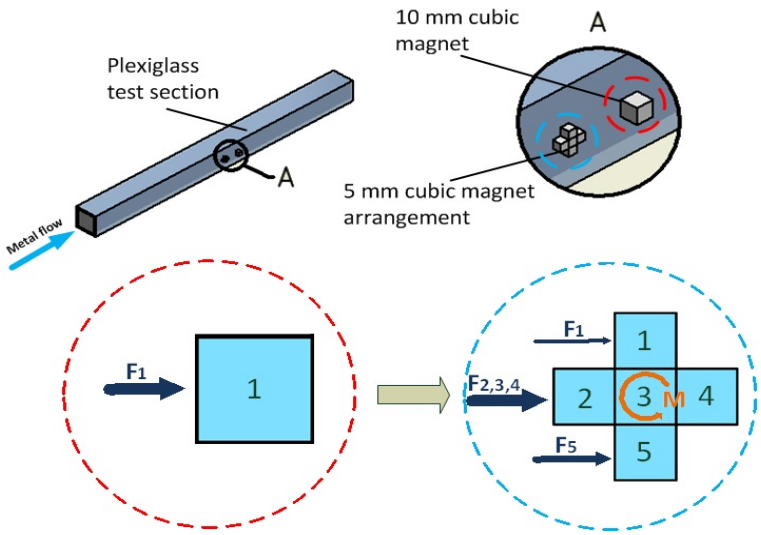

Figure 2: Proposal of replacement of a 10 mm cubic permanent magnet with a small-size permanent magnet system. For better visualization, the plexiglass duct and the current (10 mm cubic magnet) and proposed magnet systems are shown for comparison. In the current configuration, the IOFS (interference optical force sensor) is fixed to the outer face of the magnet and measures a streamwise force F_1. In the case of the proposed magnetic system which is fixed to the magnet 3, the streamwise force F_s=F_1+F_2+F_3+F_4+F_5 and a net torque M on the magnet arrangement will be measured by a multi-degree-of-freedom sensor. The force is proportional to the velocity of the flow and the torque would be a measure of the velocity gradient on the measuring point. The dimensions of the magnet arrangement shown in this picture are for explanation purpose.

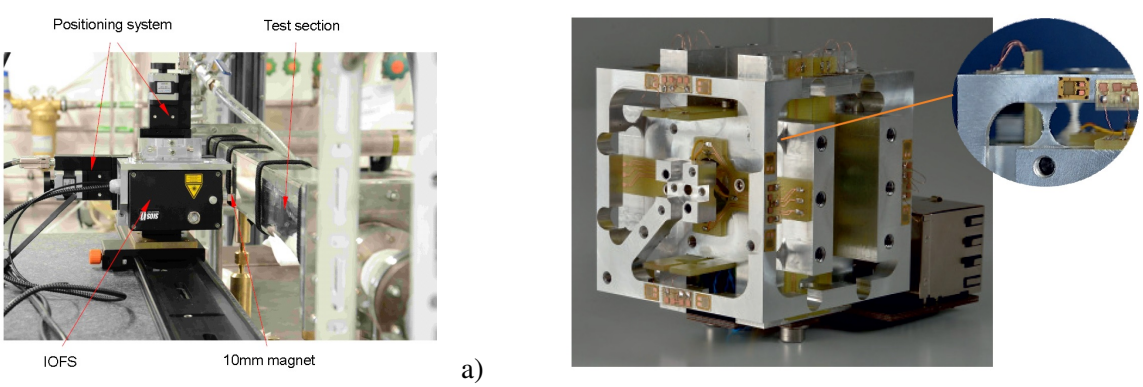

Figure 3: **a)** Close-up of the measurement system (interference optical force measurement system), the positioning system, and the duct [4]. **b)** Monolithic (60x60x60 mm^3) 6-DoF Force/Torque sensor with strain gauges and electrical connections [6].

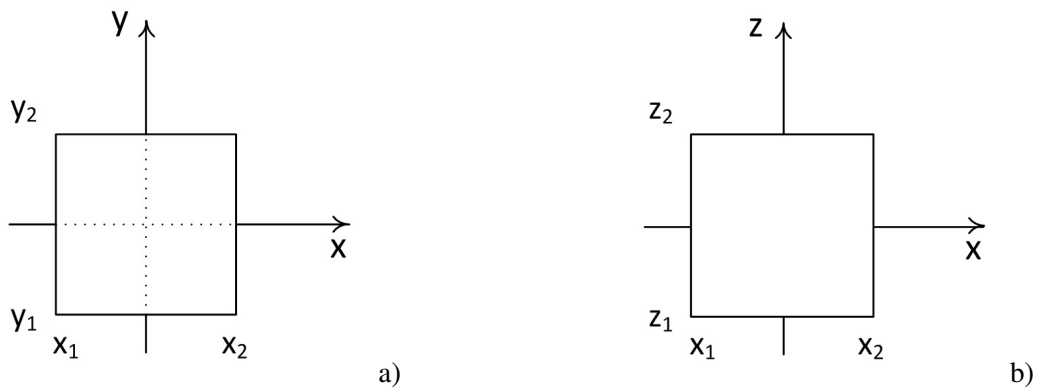

Figure 4: Cross-sectional views of a bar magnet with reference frame: **a)** *x* - *y* plane; and **b)** *x* - *z* [3].

this model and assuming that the magnetization is **M** = M_s $\hat{\mathbf{z}}$, the magnetic field outside the magnet can be calculated as follows [3]:

$$B_x(x,y,z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{m=1}^{2} (-1)^{k+m} ln[F(x,y,z,x_m,y_1,y_2,z_k)], \tag{3}$$

where

$$F = (x,y,z,x_m,y_1,y_2,z_k) = \frac{(y-y_1) + [(x-x_m)^2 + (y-y_1)^2 + (z-z_k)^2]^{1/2}}{(y-y_2) + [(x-x_m)^2 + (y-y_2)^2 + (z-z_k)^2]^{1/2}}, \tag{4}$$

$$B_y(x,y,z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{m=1}^{2} (-1)^{k+m} ln[H(x,y,z,x_1,x_2,y_m,z_k)], \tag{5}$$

where

$$H = (x,y,z,x_1,x_2,y_m,z_k) = \frac{(x-x_1) + [(x-x_1)^2 + (y-y_m)^2 + (z-z_k)^2]^{1/2}}{(x-x_2) + [(x-x_2)^2 + (y-y_m)^2 + (z-z_k)^2]^{1/2}}, \tag{6}$$

and

$$B_z(x,y,z) = \frac{\mu_0 M_s}{4\pi} \sum_{k=1}^{2} \sum_{n=1}^{2} \sum_{m=1}^{2} (-1)^{k+n+m} tan^{-1} \left[\frac{(x-x_n)(y-y_m)}{z-z_k)} g(x,y,z;x_n,y_m,z_k) \right], \tag{7}$$

where

$$g = (x,y,z;x_n,y_m,z_k) = \frac{1}{[(x-x_n)^2] + [(y-y_m)^2 + (z-z_k)^2]^{1/2}} \tag{8}$$

As explained before, for a direct comparison of the new and the old magnet systems and assuming a constant density (same material), the mass and the volume of both systems hast to be the same. That means that the volume of the 10 mm cubic magnet has to be the same as the volume of the 5 permanent magnet arrangement:

$$Vol_{10mm} = (10mm)^3 = 1000mm^3 = \sum_{i=1}^{5} B_i = 5 * a * b * c \tag{9}$$

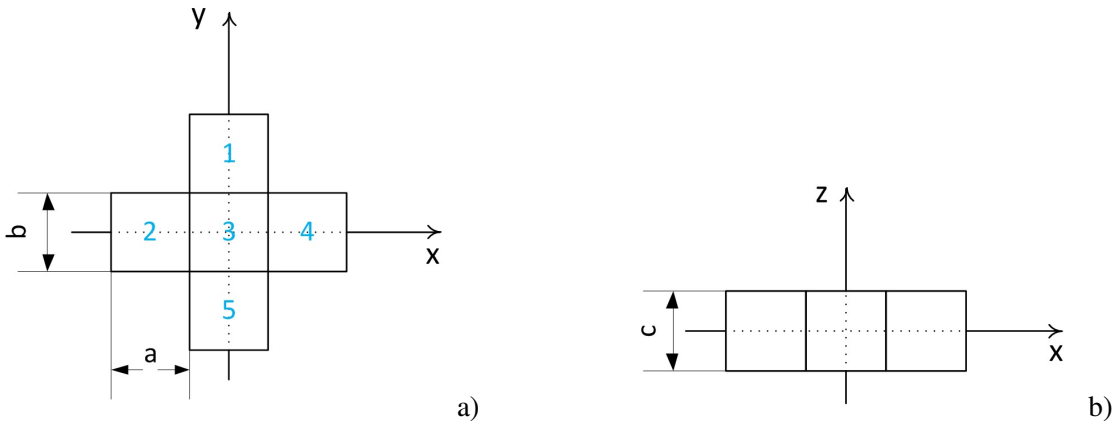

Figure 5: Cross-sectional views of the small-size permanent magnet arrangement composed by 5 magnets with reference frame: **a)** x - y plane; and **b)** x - z. The volume of each of the 5 permanent magnets is: $Vol = a*b*c$.

A comparison of the B_z component of the magnetic field of the old and the new magnet system (a = 5 mm, b = 5 mm, c = 8 mm) at different distances (z = 0.5, 5 and 10 mm) were obtained using the previous equations. B_z is perpendicular to the duct and is responsible for the Lorentz force in x direction which is the same one of the flow (Figure 6).

3.2 Experiments

2D local velocity measurements on the Mini-LIMMCAST facility will be taken place in October at the *Helmholtz Zentrum Dresden Rossendorf (HZDR)* in Dresden [1]. The old measurement system will be used for this task and these results will be compared afterwards with the new magnet system attached to a multi-degree-of-freedom force sensor [6].

4. Conclusions

The strongly dependence of the magnetic field with the distance restricts our velocity measurement to a small subsection of the flow next to the wall. Nevertheless, it was already been proven by Heinicke in [5] the possibility of local velocity assessment using a 10 mm cubic magnet. In the current case, the geometry of the magnet system and well as distance to the liquid metal are very critical for the magnetic field distribution in the liquid metal. An optimal magnetic field distribution on the duct is critical for a successful local streamwise velocity and velocity gradient measurement. Experiments will be performed investigating the force and torque on the magnet system while changing the distance to the liquid metal.

Acknowledgements

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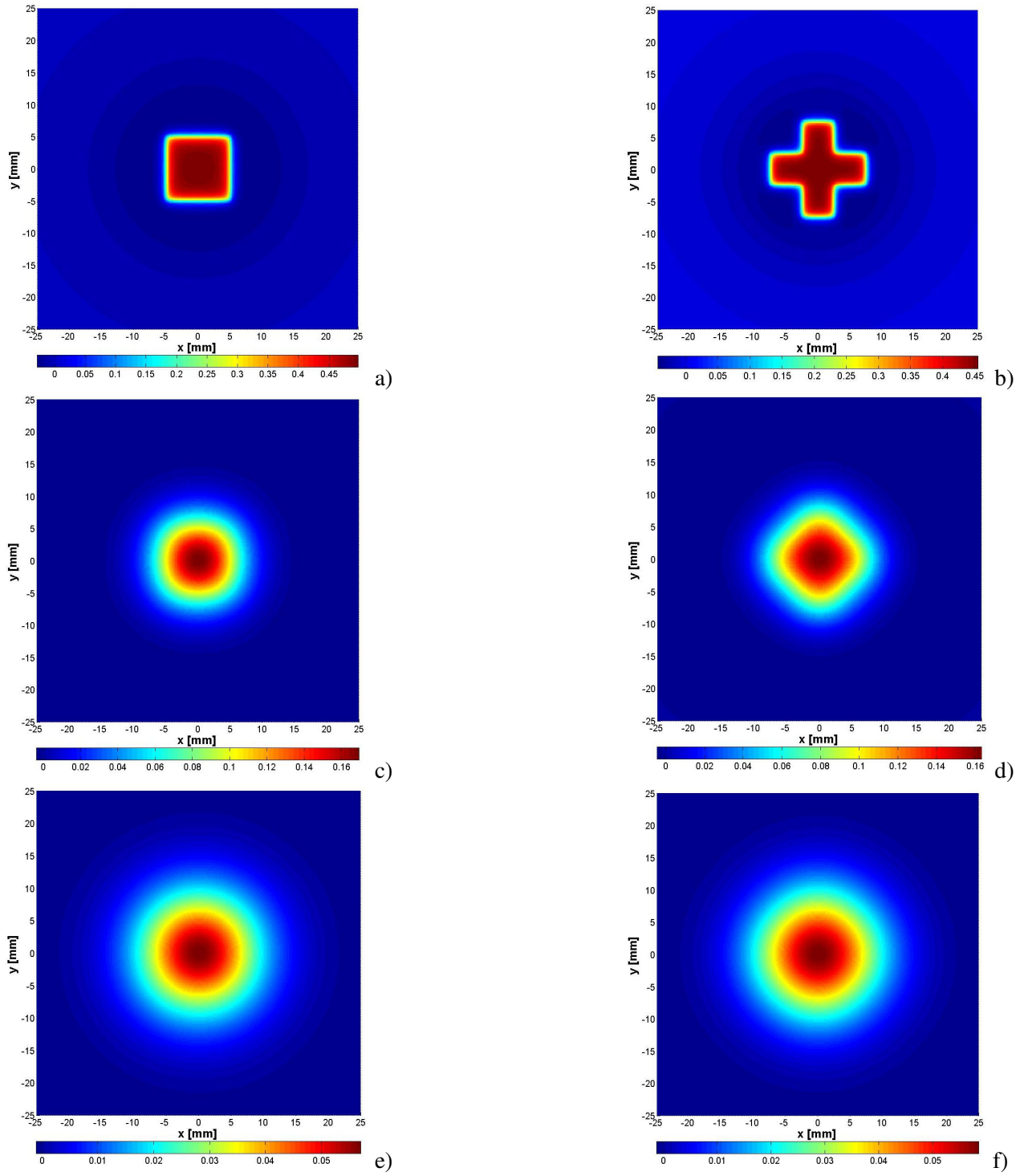

Figure 6: B_z *[T]* component of the magnetic field of the old (*left*) and the new (*right*) magnet systems on a 50 x 50 mm^2 window at different distances: **a , b)** $z = 0.5\ mm$, **c , d)** $z = 5\ mm$ and **e , f)** $z = 10\ mm$. The old magnet system is composed of a 10 mm cubic magnet and the new magnet system of an arrangement of 5 permanent magnets (Figure 5). The magnetization direction in both cases is $\mathbf{M} = M_s\ \hat{\mathbf{z}}$ where M_s is 1 x 10^6 A/m. The influence of the geometry of the magnet systems decays very strongly within the distance. $z = 5mm$ is the minimum distance available in the experiment due to the thickness of the walls of the plexiglass rectangular duct.

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