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Local Lorentz force flowmeter at a continuous caster model using a new generation multicomponent force and torque sensor

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Abstract

Lorentz force velocimetry is a non-invasive velocity measurement technique for electrical conductive liquids like molten steel. In this technique, the metal flow interacts with a static magnetic field generating eddy currents which, in turn, produce flow-braking Lorentz forces within the fluid. These forces are proportional to the electrical conductivity and to the velocity of the melt. Due to Newton’s third law, a counter force of the same magnitude acts on the source of the applied static magnetic field which is in our case a permanent magnet. In this paper we will present a new multicomponent sensor for the local Lorentz force flowmeter (L2F2) which is able to measure simultaneously all three components of the force as well as all three components of the torque. Therefore, this new sensor is capable of accessing all three velocity components at the same time in the region near the wall. In order to demonstrate the potential of this new sensor, it is used to identify the 3-dimensional velocity field near the wide face of the mold of a continuous caster model available at the Helmholtz-Zentrum Dresden-Rossendorf. As model melt, the eutectic alloy GaInSn is used.

Keywords: liquid metals, magnetohydrodynamics, Lorentz force, flow measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

Velocity measurement in liquid metals like liquid steel still remains a big challenge in many industrial applications. The opaqueness of the melt hinders the utilization of well-established optical methods like particle image velocimetry (PIV). Moreover, the high temperature and the chemical aggressiveness of those melts makes it difficult to apply non-optical flow measurement techniques, like ultrasound doppler velocimetry (UDV), pressure and electric potential probes. Therefore, a contactless method for flow measurement would be highly desirable for the investigation of industrial processes.

For instance in continuous casting, which has been the most relevant steel casting technology in the last decades, the flow field in the mold has a great influence on the quality of the produced steel. A lot of effort has been spent on simulation and optimization of this process [12]. A schematic sketch of a typical continuous casting installation is depicted in figure 1. The liquid steel is provided by the ladle from where it flows into the tundish which acts as a reservoir. From the tundish the liquid steel pours through the submerged entry nozzle (SEN) into the water-cooled mold where it starts to solidify. At the outlet of the mold the metal has a solid shell of some centimeters in thickness while the interior is still liquid. Afterwards,
the slab is cooled further and solidifies completely. The casting speed is controlled by the position of the stopper rod which regulates the flow through the SEN into the mold.

The quality of the produced steel depends on the flow regime in the upper part of the mold. Typical flow-related problems are slag entrainment and surface quality problems. In general, a steady and symmetric double-roll flow structure with inward flow at the meniscus, as indicated in figure 1, is assumed ideal since it promotes impurities and bubbles to the free surface so that they are not entrained into the solid steel [5, 17]. In view of these problems any measurement technique for investigating the flow in the mold would be highly desirable.

Contactless flow measurement techniques for liquid melts are typically based on the principle of Faraday’s induction exploiting the relative movement of electrically conducting liquid melts in magnetic fields. The working principle relies on measuring the flow-induced perturbations of an externally applied magnetic field like in contactless inductive flow tomography (CIFT), where the velocity field is obtained by measuring the perturbations of the applied magnetic field [9]. Another of these measurement techniques is Lorentz force velocimetry (LFV) [10, 11] which measures the force or torque on a permanent magnet. This technique can be extended to measure not only the flow rate [14, 15] but also to detect the flow velocity near the wall in the vicinity of the magnet by miniaturizing its size [2–4]. By using a permanent magnet with a volume much smaller than the fluid domain, only the flow near the wall in the region adjacent to the magnet contributes to the total force signal. Due to its localized nature, we define this subdivision of LFV as local Lorentz force velocimetry and the measuring device, the local Lorentz force flowmeter (L2F2). Placing the sensor sequentially at different positions, the measured forces correspond to the spatial distribution of the flow field. The first generation L2F2 sensor was only capable of measuring one component of the force at a time [4]. In order to record the second component, the sensor had to be rotated 90 degrees increasing the measurement error. The force component normal to the wall was not accessible at all. The new generation multicomponent sensor presented in this paper is capable to measure all three components of the force and of the torque simultaneously. This enables us to access all three local velocity components at the same time by either the force or the torque signals. After its calibration [7, 8], we applied this sensor to investigate the three-dimensional velocity structure near the wide face of the mold of a continuous casting model. The Mini-LIMMCAST facility (LIquid Metal Model for continuous CASTing of steel) uses GaInSn as test melt being liquid at room temperature [13]. The new L2F2 is placed in front and scans the wide face of the mold using a 3-axis linear stage. In every position the force and torque signals are recorded simultaneously. The 2D force distribution parallel to the wide face of the mold shows the expected double-roll flow structure, whereby the component of the force normal to the wide face provides an insight into the velocity component directed towards the wall. Additionally, the measured torque also shows to be less sensitive to perturbations in the environment due to ferromagnetic materials.

The paper is structured as follows: after a short description of the basics of the Lorentz force velocimetry in section 2, we will present the model of a continuous caster, the Mini-LIMMCAST facility, and the new force and torque measurement system in section 3. In section 4 we will show the results of the measurements and compare them with an UDV measurement. Finally, section 5 reviews the main conclusions.

2. Lorentz force velocimetry

Lorentz force velocimetry is a non-invasive velocity measurement technique for electrically conductive liquids. In this technique, as shown in figure 2(a), a static magnetic field \( B \) is applied to a moving liquid with velocity \( \vec{v} \) and conductivity \( \sigma \). According to Ohm’s law for moving conductors, the current density

\[
\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B})
\]

is induced (see figure 2(b)), where \( \vec{E} \) is the electric field. This current density \( \vec{j} \), in turn, induces the so-called secondary magnetic field \( \vec{b} \) (see figure 2(c)). In general, the magnetic field \( \vec{B} \) is the sum of the applied magnetic field \( \vec{B}_0 \), generated by the permanent magnet, and the secondary magnetic field \( \vec{b} \). The ratio between \( |b| \) and \( |B_0| \) is proportional to the magnetic Reynolds number, defined as

\[
R_m = \frac{\mu_0 \sigma l v}{|B_0|}
\]

where \( l \) and \( v \) denote characteristic length and velocity scales of the fluid, respectively. In most industrial applications, \( R_m \) is much smaller than 1, so that \( \vec{B} \approx \vec{B}_0 \). Under influence of the magnetic field \( \vec{B}_0 \) the current density \( \vec{j} \) generates a Lorentz force density

\[
\vec{j}_L = \frac{\vec{j} \times \vec{B}_0}{|\vec{B}_0|}
\]
inside the fluid which counteracts the flow (see figure 2(d)). The integral value of the Lorentz force density in the fluid is given by the volume integral over the fluid domain

$$ F_L = \int_{\text{Vol}} j \times B_0 \, dV. $$

Due to Newton’s third law, there is also a force $F_m$ of the same magnitude acting on the magnet system. This force on the magnet can be expressed in terms of the secondary magnetic field $\vec{b}$ by

$$ F_m = (\vec{m} \cdot \nabla) \vec{b} $$

at the position of the permanent magnet which can be modeled by a corresponding magnetic dipole $\vec{m}$ [10]. Additionally, the torque $\vec{T}$ on the magnet can be calculated by

$$ \vec{T}_m = \vec{m} \times \vec{b}. $$

By measuring the force $F_m$ and/or the torque $\vec{T}_m$ on the permanent magnet the mean velocity of the flow in the liquid metal can be inferred. For Lorentz force flowmeters usually only the streamwise component of the flow is recorded, because the flow in the duct has one dominating flow direction. However, in case of local Lorentz force velocimetry all six force/torque components are of interest. The L2F2 sensor of the first generation recorded only one component of the force [2]. In order to get two components of the flow the sensor has to be rotated. With this setup the two-dimensional stationary flow structure in the vicinity of the wall of a confined vessel could be reconstructed [4]. Unfortunately, we are assuming in both cases that the flow is fairly stationary and also introducing another source of error by positioning the magnet one more time in the measuring grid. In order to overcome this limitations faced with the former L2F2, the new generation sensor described in section 3.2 is capable to simultaneously record all three components of the force $F_m$ as well as of the torque $\vec{T}_m$.

In order to calculate the velocity from the force, a calibration factor is used which depends on the distance between the magnet and the liquid metal and the strength of the magnetic field. The amplitude of the force acting on the magnet $F_m$ for the mean velocity $v$ in its vicinity can be estimated by [11]

$$ F_m \sim \alpha v B_0^2 h^{-3}. $$

In this case $h$ is the distance between the permanent magnet and the liquid metal.

For a quantitative estimation of the force and the torque, we assume an infinite conductive layer moving with velocity $v e_x$ and a permanent magnet approximated by the magnetic dipole $\vec{m}$ pointing orthogonal to the moving conductive layer at a distance $h$. Then, we can analytically express the force and torque acting on the dipole with the following relationships [10]

$$ F_m = \frac{\mu_0 \sigma v m^2}{128 \pi h^2} e_x $$

and

$$ \vec{T}_m = -\frac{\mu_0 \sigma v m^2}{128 \pi h^2} e_y. $$

3. Experimental setup

3.1. Mini-LIMMCAST facility

The Mini-LIMMCAST facility had been set-up in order to investigate a variety of flow phenomena as they are typical for the continuous casting process. In this facility, methods to control the flow field in the mold are also developed where GaInSn in eutectic composition is used as working fluid [13]. Its electrical conductivity is $3.3 \cdot 10^3 \pm 3 \cdot 10^2 \, \text{S m}^{-1}$ at 20°C [6] and figure 3 depicts a photograph of the set-up. The tundish is represented by a stainless steel cylinder which contains about 5–6 l of the melt. The melt is discharged through a submerged entry nozzle (SEN) made of acrylic glass, with an inner diameter of 10 mm, into the mold with a rectangular cross section of $140 \times 35 \, \text{mm}^2$ (also made of acrylic glass). The flow rate through the SEN is controlled by the vertical position of the stopper rod. From the bottom of the mold the liquid metal flows through flexible tubes to a dam and is conveyed to a storage vessel afterwards. The vertical position of the dam controls the surface level in the mold. From this tank
the liquid metal is pumped back to the tundish by an induction pump. The liquid level in the tundish and the mold are monitored using a laser and an ultrasonic distance sensor, respectively. The experiments were performed in continuous mode. By controlling the flow rate of the pump the level of the melt in the tundish is kept constant. As a consequence, a stationary flow is produced in the mold. The accompanying UDV measurements were done in a once-through manner. In all experiments the stopper rod was lifted 20 mm, which leads to a flow rate of $0.12 \text{l s}^{-1}$ through the SEN. The force and torque sensor was mounted on a positioning system that was located near the wide face of the mold, as seen in figure 3.

### 3.2. Multicomponent force/torque sensor

A high-precision measurement system is needed for the multicomponent measurement of small Lorentz forces. These forces and torques created by the interaction of the permanent magnet and a liquid metal flow are in the range of mN and in $\mu \text{Nm}$, respectively. A reliable measurement of the small forces is still a challenging task and such a device is commercially not available. For the simultaneous sensing of three force and three torque components a sensor was designed [7] which is shown in figure 4. Here, the design parameters and the sensors elastic materials have been chosen to fulfill the required measurement ranges. The flexure hinges have a radial shape and a minimum thickness of 0.4 mm. Figure 5 shows a picture of the sensor fixed to a mounting base and a permanent magnet attached to the force-feed-in for Lorentz force velocimetry applications.

The sensor is made from a monolithic aluminum structure with dimensions of $60 \times 60 \times 60 \text{ mm}^3$, consisting of six parallel spring mechanisms which are deforming under the influence of forces and torques. Those deformations are measured using strain gauges connected in form of full-bridge circuits. The output signals are captured with a measurement amplifier and digitized with a frequency up to 50 kHz per channel. For protection from external influences the force-feed-in is equipped with an overload protection system and the entire device is enclosed in a housing made from acrylic glass. Under stable laboratory conditions the metrological parameters, shown in table 1, are obtained by the experimental calibration procedure described in [8]. By using a magnet with different mass in comparison with the one used in the modal analysis, the eigenfrequencies of the sensor may be slightly shifted. Additionally, during experiments we will see in the measured signals the damped eigenfrequencies caused by the damping effect of the liquid metal.

By the design of the sensor, the output signal vector representing the readings of the channels of the measurement amplifier $\vec{U} = [U_1, U_2, U_3, U_4, U_5, U_6]^T$ linearly depends on the force and torque components combined in the vector $\vec{F} = [F_x, F_y, F_z, M_x, M_y, M_z]^T$. The relationship is given by the equation

$$\vec{U} = \mathbf{C} \cdot \vec{F}, \quad (10)$$

where $\mathbf{C}$ is the calibration matrix determined experimentally by application of well-known forces and torques while measuring the resulting output signals. After calibration, the vector $\vec{F}$ is obtained by inverting equation (10) according to the relation

$$\vec{F} = \mathbf{C}^{-1} \cdot \vec{U}. \quad (11)$$

The center of the sensor coordinate system is likewise defined by calibration. The measured torques $\vec{M}_0$ can be transformed from the calibration coordinate system to the torques $\vec{M}_c$ at another reference coordinate system by using

$$\vec{M}_c = \vec{M}_0 - \vec{F}_0 \times \vec{I}, \quad (12)$$

where $\vec{F}_0$ is the measured force vector and $\vec{I}$ the distance vector between the calibration point and the reference point. As the distance between the channel and the magnet and the
2010 $k$ is the vacuum permeability, $(10^80\ 10^3)\ Hz...284\ Hz\ Nm\ FF\ F$. $73Hz...119Hz\ m\ 15\ 15\ 15\ mm^3\ →\ rad$, and $→\ →\ 1$. $M\ MM\ N\ 1\ 48x524$ force velocimetry. permanent magnet attached to the force-feed-in for use in Lorentz of the integral Lorentz force. Our next step is to experimentally obtain the distance vector from the sensor coordinate system to the point of application was used. $cubic\ permanent\ magnet\ with\ the\ properties\ shown\ in\ table\ 2$ was used.

### Table 1. Metrological parameters of multicomponent force/torque sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Force</th>
<th>Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>$F_x, F_y, F_z$</td>
<td>$M_x, M_y, M_z$</td>
</tr>
<tr>
<td>Range</td>
<td>$\pm 2\ N$</td>
<td>$\pm 0.12\ Nm$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\pm 19\cdot 10^{-6}\ N$</td>
<td>$\pm 1.4\cdot 10^{-6}\ Nm$</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$0.51\ mV/V/N$</td>
<td>$6.8\ mV/V/Nm$</td>
</tr>
<tr>
<td>Eigenfrequencies</td>
<td>$73\ Hz...119\ Hz$</td>
<td>$176\ Hz...284\ Hz$</td>
</tr>
<tr>
<td>Maximum deformation</td>
<td>$\pm 0.37\ mm$</td>
<td>$\pm 5.5\cdot 10^{-3}\ rad$</td>
</tr>
</tbody>
</table>

### Table 2. Parameters of the permanent magnet.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>$15 \times 15 \times 15\ mm^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>NdFeB</td>
</tr>
<tr>
<td>Grade</td>
<td>N48</td>
</tr>
<tr>
<td>Magnetization density $\bar{M}$ in A m$^{-1}$</td>
<td>$1080 \times 10^3$</td>
</tr>
</tbody>
</table>

mounting position of the magnet on the sensor are not known exactly, the correct point of application of the integral Lorentz force on the sensor is unknown. In order to decrease sources of uncertainty, the results presented in this paper are obtained using the main diagonal of the calibration matrix. Here, the main sensitivities of the sensor are defined and correspond to the center of the sensor coordinate system with $l = [0, 0, 0]m$. Our next step is to experimentally obtain the distance vector from the sensor coordinate system to the point of application of the integral Lorentz force.

### 3.3. Magnetic field distribution

For the measurements at the Mini-LIMMCAST facility, one cubic permanent magnet with the properties shown in table 2 was used.

$$B_0(x, y, z) = \mu_0 M \frac{\epsilon^2}{4\pi} \sum_{k=1}^{2} \sum_{n=1}^{2} \sum_{m=1}^{2} (-1)^{k+n+m} .$$

$$\tan^{-1}\left\{\frac{(x-x_0)(y-y_0)(z-z_k)^{-1}}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_k)^2}}\right\} . \quad (13)$$

Here $\mu_0$ is the vacuum permeability, $M$ the magnetization density and $x_0, y_0, z_k$ are given by the magnet dimensions: $x_1 = y_1 = -7.5\ mm, \ x_2 = y_2 = 7.5\ mm, \ z_1 = -15\ mm$ and $z_2 = 0\ mm$.

By solving equation (13) for a $8.4\ mm$ distance in the $z$-direction we obtain figure 6. The $x$ and $y$ components of the flux density as shown in figure 7 are given by following equations

$$B_{0x}(x, y, z) = \mu_0 M \frac{\epsilon^2}{4\pi} \sum_{k=1}^{2} \sum_{n=1}^{2} \sum_{m=1}^{2} (-1)^{k+n+m} .$$

$$\ln\left\{\frac{(y-y_1)(x-x_0)^2 + (y-y_2)(z-z_k)^{-1} + (z-z_k)^{1/2}}{(y-y_2)(x-x_0)^2 + (y-y_2)^2 + (z-z_k)^{1/2}}\right\} . \quad (14)$$

$$B_{0y}(x, y, z) = \mu_0 M \frac{\epsilon^2}{4\pi} \sum_{k=1}^{2} \sum_{n=1}^{2} \sum_{m=1}^{2} (-1)^{k+n+m} .$$

$$\ln\left\{\frac{(x-x_1)(y-y_0)^2 + (y-y_1)^2 + (z-z_k)^{1/2}}{(x-x_1)(y-y_1)^2 + (y-y_1)^2 + (z-z_k)^{1/2}}\right\} . \quad (15)$$

The magnetic fields $B_{0x}$ and $B_{0y}$ together with $B_{0z}$ lead to a force in the direction opposite to the flow.

### 3.4. Measurement procedure

In order to assess the flow structure near the wide face of the mold, the force sensor described in section 3.2 was placed close to the acrylic glass wall of the wide face. Figure 8(a) shows...
the total scanning area of the measurement. At the beginning of the experiment, the magnet was placed at (0,0) as shown in figure 8(b). Then, the magnet follows a zig–zag movement maintaining a step size of 10 mm in both x and y directions (figure 8(a)). When the magnet reaches 140 mm in x, it takes an additional step of 5 mm in order to cover the entire width of the acrylic glass mold. In this zig–zag movement, we cover an area from (0,0) to (145,−160) having 16 × 17 = 272 measuring points. In each point we obtain the respective average from each of the 3 force and the 3 torque signals acting on the magnet in a time slot of 5 s (Fx′, Fy′, Fz′, Tx′, Ty′, Tz′). The selection of the time interval of 5 s is a compromise between measurement time for averaging at each position and run time of the entire scan, during which the flow has to be stationary. Previous UDV measurements confirm that the flow in the mold is almost steady [13].

One complete measurement of the force field across the 272 measuring points takes about 2 h. In total two measurements are carried out: First, the force measurement was performed without any fluid flow, in order to determine the local offset of the signals. This is needed to take the deviations of the forces and torques into account which are caused by the presence of ferromagnetic materials in the vicinity. In the second experiment, the Mini-LIMMCAST facility was operated in continuous mode. By controlling the flow rate of the pump the level of the melt in the tundish was kept constant during the entire experiment time of 2 h. This leads to a constant flow rate through the SEN and to a stationary flow in the mold. Finally, we subtract the offset of the measured signal obtaining Fx, Fy, Fz, Tx, Ty and Tz.

4. Measurement results

The results of the force and the torque measurements are shown in figures 9 and 10, respectively. In both figures, the three components are summarized in contour and vector plots. For a better visualization of the results, we have introduced equally-spaced interpolated points between the measuring data using cubic splines. As a result of this step, we have increased the data to be plotted from 272 points to 990 points, or in other words, x from 0 to 145 mm and y from 0 to −160 mm with a grid resolution of 5 mm.

In figure 9(a), a vector plot composed by Fx and Fy is plotted over a contour plot of their magnitude (Fmag = |Fy|). As a consequence, we can have access to local information such as the direction and magnitude of the flowing liquid metal inside the mold. For instance, the known four-vortex structure in the mold of Mini-LIMMCAST, like in continuous casting processes, could be clearly identified. Additionally to this information, the force in the perpendicular direction Fz (figure 9(b)) provide us an insight into the velocity perpendicular to the acrylic glass wall. For example, the two positive peaks in the area around x ≈ 0 mm and y ≈ 145 mm with y ≈ −100 mm, show where the jets reach the side walls. As a consequence, they strongly diffuse generating velocity component in the z-direction and split into upper and lower vortices. In order to check the measured forces, we used a CFD simulation of the stationary flow in the mold of the Mini-LIMMCAST facility as described in Wondrak et al [16] and calculated the force and the torque at four locations: (20, −140), (20, −60), (60, −140) and (60, −60). We found a good agreement between the measurement and the simulation. For example, at (20, −140), the measured force in y-direction is Fy = −5.4 mN, whereas the simulated force was Fy = −6.5 mN. The difference between the measurement and the simulation can be attributed to a slight difference in the distance of the sensor to the fluid. However, more experiments and simulations have to be carried out in order to have a better understanding of the spatial resolution of our measurements.

Regarding the measurements of the torques, the results are shown in figure 10 as vector and contour plots analogue to figure 9 for comparison. The vector and contour plot (figure 10(a)) are based on Tx and Ty, where Tmag is the magnitude of these two components (Tmag = |Ty|). However, in the case of the vector plot, we use the information of −Tx in x direction and Ty in y direction. This can be easily explained that a force \( \vec{F} = F_y \hat{e}_y \) at a distance \( \vec{r} = r \hat{e}_x \) generates a torque in y direction (\( \vec{T} = \vec{r} \times \vec{F} = -T_y \hat{e}_z \)).
As a consequence, the resulting vector plot of the torques is almost identical to the vector plot of the forces presented before. This tight similarity was expected according to equations (8) and (9), where the torque differs from the force just by the exponent $h$ that is the distance between the dipole and the liquid metal. The results also suggest that this $h$ may be relatively constant across the mold. Whereas the torques presented in this paper refer to the center of the sensor coordinate system instead of the center of the magnet, they will still show the same trend. Finally, regarding $T_z$, a correlation can be seen between the vector and contour plots of $T_x$ and $T_y$, but no visible pattern was identified referring to the flow structure. This situation can be explained by a possible slight misalignment between surface of the magnet and the liquid, causing that $T_z$ will also have a percentage of both $T_x$ and $T_y$. $T_z$ is expected to be much more smaller than the two dominant components.

One of the advantages of measuring the torques acting on the magnet is that they are less sensitive than the force components in the presence of ferromagnetic materials in the environment. In the case of the measurements in the MiniLIMMCAST facility, the vector plot of the force signal
without taking the local offset (figure 11) into account is disturbed probably by the influence of ferromagnetic parts like the driving motors of the positioning system. As a result, the component \( F_x \) of the force deviates considerably and we are not able to identify the four-vortex structure of the velocity profile. On the other hand, in regard to the vector plot of the torque signal, the results are very similar in comparison to the ones obtained in figure 10, where the local offset was subtracted from each measurement. Despite this fact, the overall magnitude of the torque deviates in 2% but the general tendency of the vector plot remains nearly identical.

In order to validate the force measurements, we additionally performed independent UDV measurements which recorded the velocity near the wall. 10 UDV probes with a vertical distance of 10 mm were mounted at the narrow face and their center was 4 mm away from the wide face of the mold. In this configuration, the velocity close to the wall of the wide face could be recorded. Owing to the rapid decay of magnetic fields, this is the place of the highest contribution of the measured Lorentz force. The comparison between \( V_x \) and \( F_x \) is presented in figure 12 and are normalized for a qualitative assessment. Here, the measuring grid for \( V_x \) is defined from \((5, -10)\) to \((135, -160)\). Both UDV and LFV measurements present similar behavior, showing the places where the liquid metal enters the mold and indicating the horizontal velocity components of the upper and lower vortices (red and blue areas). The difference in the measurement results can arise from different measurement volumes of the two
techniques. The UDV has a good spacial resolution in the direction of the ultrasonic beam of about 1 mm (x-direction) in the present operating conditions. The lateral extension of the UDV measurement volume is related to the spreading of the ultrasonic beam along the measurement line, which depends on the sound velocity, emitting frequency and the diameter of the US emitter. In the present setup the lateral extensions starts with a radius of about 3 mm at the sensor side and increases with the distance to a radius of about 7.5 mm at the opposite side. In case of the local Lorentz force velocimetry, the sensitivity is determined by the spatial distribution of the magnetic field of the permanent magnet (see figures 6 and 7). In addition to the spatial resolution discrepancies, there are differences in the temporal resolution as well. UDV is able to measure one component along the line of the ultrasound beam in one instant of time. Operating 10 ultrasonic transducers in multiplexer-mode, one can scan a 2D-plane with a time resolution of 6 Hz (depending on the measurement conditions and the configuration of the measurement device). In contrast, LFV is a point measurement, which has to scan the entire wide face of the mold. In this configuration a full scan of the wide face needs about 2 h. This gives a difference in the averaging principle between both measurement techniques. For the UDV measurement we get a time average of the velocity at all locations over the same time interval. In contrast, for LFV we have different instants of time for each location due to the scanning of the wide face of the mold, but the same averaging length of 5 s.

5. Conclusion

With the presented multicomponent force sensor we were able to obtain a qualitative assessment of the 3-dimensional velocity structure of GaInSn near the wide face of the mold of a continuous caster model. The known double-roll structure was clearly identified in the area around the two jets. By the multicomponent sensing of forces and torques acting on the small-size magnet, as a step further in local Lorentz force velocimetry, we could also have an insight into the velocity component perpendicular to the wall by measuring the force in this direction. Additionally, as Lorentz force velocimetry predicts, we can also have access to the 2D velocity field at the Mini-LIMMCAST based on the measured torque signals. The torque sensing showed to be less sensitive to perturbations in the environment in comparison with the force signal. In conclusion, we could have access to the velocity information of the liquid metal in the mold of a continuous caster model by either the force or the torque signals acting on the permanent magnet.

Despite the volumetric nature of Lorentz force velocimetry, where the measured forces correspond to a determined volume subset of the flow spanned by the applied magnetic field, we were able to have a resolution of the force in the order of 10 mm with a 15 mm cubic magnet. A good agreement was found with UDV measurements close to the wide face of the mold. However, in order to compare the magnitude of the velocity for both measurement techniques, a calibration factor between the measured force and a reference velocity has to be determined which will be our focus for the future work.

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