**1. Introduction**

Compared to transparent fluids, liquid metals and semiconductor melts pose serious problems for the reliable determination of local velocities or integral flow characteristics [1]. Even the widely used ultrasonic Doppler velocimetry (UDV) faces difficulties when it comes to its application in very hot and/or chemically aggressive fluids, such as liquid steel or silicon. Fortunately, the high electrical conductivity that is responsible for the opaqueness of those fluids allows the utilization of magnetic inductive methods.

These methods bear on applying magnetic fields to the flowing fluid and measuring appropriate features, e.g. amplitudes, phases, or forces, of the flow induced magnetic fields. In the contactless inductive flow tomography (CIFT), entire three-dimensional flow fields are reconstructed from induced field amplitudes that are measured at many position around the fluid, to which one or a few external magnetic fields are applied [2, 3]. A recently developed flow rate sensor relies on the determination of magnetic phase shifts due to the flow [4]. In the Lorentz force velocimetry (LFV) [5] one measures the force acting on a permanent magnet close to the flow, which results as a direct consequence of Newton’s third law applied to the braking force acting by the magnet on the flow. With this technique, it is now possible to measure velocities of fluids with remarkably low conductivities, such as salt water [6].

A common drawback of all these methods is that the measured signal is not only dependent on the sought flow velocity, but also on the conductivity of the fluid. Usually, the signals are proportional to the so-called magnetic Reynolds number $Rm = \mu_0 \sigma V L$, where $\mu_0$ is the magnetic permeability constant, $\sigma$ the conductivity of the liquid, and $V$ and $L$ denote typical velocity and length scales of the relevant fluid volume. In most cases, the signal depends also on geometric factors, so that the measuring system has to be calibrated anyway. Further to this, the use of permanent magnets (for LFV) or of magnetic yoke materials (for the phase-shift method) set limitations to the ambient temperature at the position of the respective sensors.

The goal of the present paper is both to circumvent the necessity to calibrate the measurement system, and to mitigate the temperature limitation problem. The measurement system to be presented belongs to a wider class of time-of-flight methods that utilize the existence of some traceable pattern in the fluid which is being advected by the flow. By measuring the time of flight of the advected pattern between two positions along the flow one can infer the flow velocity.

In one realization of this principle, the role of the pattern is played by some (unspecified) turbulence elements moving close to the wall of the fluid. If the flow direction is known, one can apply external magnetic fields at two positions and infer the flow speed from correlations of the magnetic signals induced by the turbulence elements that are passing by [7]. A similar correlation technique is presently under investigation in the time-of-flight LFV [8].

Another realization had already been developed in the 1960s by Zheigur and Sermons [9]. In their ‘pulse method’, the role of the traceable pattern is played by an eddy current system that is imprinted into the conducting medium by switching on or off the current in one excitation coil, and by
registering the flow advected pattern by another coil situated downstream the flow. The instant at which the current in this detection coil crosses zero indicates the passing-by of the center of the eddy current system. The flow velocity is then determined by dividing the distance between the two coils by the measured time interval.

In [9], the method had been shown to allow to measure velocities of an aluminum bar from 20 m s$^{-1}$ down to 1 m s$^{-1}$, but not significantly lower. One reason for this limitation was the exclusive focus on identifying the instant of vanishing current in the detection coil by means of an oscillograph. For small velocities (or, more exactly, for small $R_m$), when the decay of the eddy current is much faster then its advective velocity, the determination becomes less and less reliable.

In the present paper, we will apply a modern data acquisition system and appropriate analysis methods in order to infer the velocity from the complete data sets of the induced current in three detection coils, rather than only one particular instant in one single coil. With a view to measuring the entire transient signal after switching, we dub this method ‘transient eddy current flow metering’ (TEC-FM). After explaining the measuring principle and technical realization, we will apply it to the determination of the velocity of a rotating aluminum disk, and to the flow of GaInSn in a circular tube. The paper closes with some outlook for future improvements and for possible industrial applications.

2. Measuring system and principle

The heart of our measuring system consists of three small detection coils embedded into one larger excitation coil (see figure 1). The excitation coil is installed parallel to the boundary of the fluid, so that the three detections coils are arranged in one row in direction of the flow.

The block wiring diagram is shown in figure 2. The signal for the excitation coil is produced by an AGILENT 33200A waveform generator and then amplified by a Rohrer PA2166 precision power amplifier. The advantage of using a current source, instead of a voltage source, is that it leads to a well-defined time dependence of the excitation magnetic field, independent of the inductance of the utilized coil. The induced signals measured by the three detection coils are amplified by FEMTO DLPVA-100-B-D amplifiers and then digitized with a TEKTRONIX DPO7104 oscilloscope. Here, the high input impedance of the dc-coupled signal path ensures a very weak back-reaction on the magnetic field of the eddy currents can be neglected.

In the following, we will focus on the case that the current in the excitation coil is on for $t < 0$, and is being switched off at $t = 0$ (note that the contrary case that the current is switched on at $t = 0$ is not completely equivalent: the subtle differences will be discussed elsewhere). With our excitation technique we achieve a smooth and non-oscillatory decay with a typical fall time of approximately 100 $\mu$s. By this pulse, a ring-like eddy current system is induced in the nearby moving conductor. For a conducting half-space at rest, the evolution of this eddy current system can be given in a quasi-analytic form [10], which was also experimentally confirmed in a liquid metal experiment [11]. Here, we illustrate the ring-like eddy current system for the case of a solid electrical conductor moving to the right. Figure 3 shows the result of corresponding simulation with ANSYS multiphysics. The excitation coil is indicated below the body.

This eddy current, in turn, produces a magnetic field $b_\text{out}$ outside the fluid, whose $b_x$-component (in the flow direction) is zero exactly below the center of the (advected) eddy current ring. Close to this point, $b_x$ can be considered linear in $x$. If the detection coils are situated within this linear region, their signals can be exploited to identify the point of vanishing $b_x$ which represents the (moving) pole of the eddy current ring.

The use of three coils enables us to verify the linearity of the function $b_x(x)$. Yet, for the sake of simplicity, the following theoretical considerations will be restricted to the simpler two-coil system (figure 4).

Shortly after switching off the current in the excitation coil, the $b_x$ component along the flow direction $x$ can be
parametrized in the following way (from here on, we replace \( b_x \) by \( b \)): 

\[
(b(x,t)) = -b(x_1,t) + b(x_2,t) \cdot \frac{x(t) - x_1}{x(t) - x_2},
\]

with the decay function

\[
m(t) = m_0 \exp(-t/\tau)
\]

where \( \tau \) is the typical decay time of the eddy current system in the liquid. These equations can be made comprehensible by assuming the eddy current to be impressed instantaneously into a solid metallic block, where it decays with a decay time \( \tau \) while the block itself moves along the trajectory \( x_p(t) \). In this sense \( x_p(t) \) represents the time-dependent pole position of the flow-advected eddy current system which can, in turn, be interpreted as the time integral over the velocity of the fluid:

\[
x_p(t) = \int_0^t v_p(t) \, dt.
\]

Hence, the velocity of the pole of the eddy-current related magnetic field can be determined as

\[
v_p(t) := \frac{dx_p(t)}{dt}.
\]

The pole position \( x_p \) at a given instant can be determined from the values \( b(x_1,t) \) and \( b(x_2,t) \) measured at the two detection coil positions \( x_1 \) and \( x_2 \), respectively:

\[
x_p(t) = x_1 - \frac{b(x_1,t)(x_2 - x_1)}{b(x_2,t) - b(x_1,t)}.
\]

This system of equations would be sufficient if the magnetic fields were indeed measured by Hall or Fluxgate sensors. However, since we are using pick-up coils (also with a view to later high-temperature applications), our measured signal is actually the voltage in the detection coil which is proportional to the time derivative of the magnetic fields rather than the magnetic field itself.

The equation for this time derivative of the magnetic field,

\[
\dot{b}(x,t) = m(t)(x - x_p(t)) - m(t)\dot{x}_p(t)
\]

can be obtained from equation (1). The corresponding pole \( x_{pp} \) of this time derivative is derived from setting the rhs of equation (6) to zero, and utilizing the relations \( m(t)/m(t) = \tau \), and \( \dot{x}_p = v_p(t) \):

\[
x_{pp}(t) = x_p(t) + \tau v_p(t).
\]

The velocity of this pole of the magnetic field derivative results then as

\[
v_{pp} := \dot{x}_{pp}(t) = \dot{v}_p(t) + \tau v_p(t).
\]

We see that the velocity of the pole of the derivative \( v_{pp} \) is identical to the velocity \( v_p \) of the pole of the field itself as long as the latter is time-independent. In our method, we will trace indeed the pole of the time derivative, which is for every instant given by

\[
x_{pp}(t) = x_1 - \frac{\dot{b}(x_1,t)(x_2 - x_1)}{\dot{b}(x_2,t) - \dot{b}(x_1,t)}.
\]

quite in analogy with equation (5).
3. Rotating aluminum disks

In this section we will validate the TEC-FM method at a simple model for which the velocity is well known. For this purpose we choose a rotating aluminum disk of radius 165 mm and thickness 10 mm, and apply our sensor at a radius of 145 mm (see figure 5). The lift-off is 2 mm, so that the distance between the disk and the center of all coils is 8 mm.

The velocity at this radius can be pre-adjusted by the disk rotation rate. Figure 6 shows the time evolution of the signals at the three detection coils, for 11 chosen velocities between 0 m s$^{-1}$ and 5 m s$^{-1}$. A slight asymmetric positioning within the excitation coil leads, shortly after switching off, to signals $u_1$ and $u_3$ which are not perfectly antisymmetric. Fortunately, the velocity inference method of TEC-FM is largely insensitive to such an imperfection.

From these data we estimate the position of the pole (figure 7) for the first 2 ms after switching off the current. The black lines, drawn for comparison, would correspond to a perfect movement of the pole of the eddy current with the rotating disk. The strong divergence of the pole position, as appearing for high velocities and beyond 1.5 ms, results from the increasing failure of the linear interpolation scheme in case that the pole position leaves the space between the detection coils.

At least during the first 1 ms, the signal is very clean and allows us to determine the speed of the pole. This is shown in figure 8, for which we have made an additional average over 50 pulsing events with an interval of 10 ms between them (so that we obtain one velocity value every 500 ms). As evidenced by the error bars, the velocity can be recovered with high accuracy.

4. Flow of GaInSn in a pipe

After having validated the method at a solid rotating disk, we apply it now to the case of a liquid metal flow in a pipe. We consider a flow of the eutectic alloy GaInSn (with the electrical conductivity $\sigma = 3.3 \times 10^6$ S m$^{-1}$) in a circular plastic pipe of inner radius 27.3 mm (for more details of the test rig, see [12]). The distance between the boundary of the liquid metal and the center of the coils is now 9 mm. Figure 9 shows again the signal of the three coils for 15 different flow velocities (measured by an independent flow meter). Note that the magnetic field decay is much faster than in the aluminum case with its much higher conductivity, since the decay time is roughly $\tau = \frac{\mu_0 \sigma d}{2}$, with $d$ a typical length scale of the order of the coil distance. This lower decay time would allow us to provide velocity values approximately every 50 ms.

Again, the time-dependence of the pole position $x_{pp}$ (figure 10) and the resulting velocities $v_{pp}$ are shown (figure 11). Given the turbulent character of the pipe flow it is not surprising that the pole trajectory in figure 10 is much more noisy than the corresponding pole trajectory for the aluminum disk. Consequently, we obtain also larger error bars of the final velocity data (figure 11). Yet, the overall agreement with the pre-given velocity $v_x$ is quite reasonable, and might even be improved by a refined data analysis.

5. Outlook

We have modified, and significantly enhanced, the pulse method of Zheigur and Sermons [9] by using a compact
design of three small detection coils embedded into a larger excitation coil, and by exploiting the complete signals measured at these coils for the determination of the flow velocity. This one-sided sensor can be easily applied to the flow in open and closed pipes and vessels, but of course also to solid conductors.

This TEC-FM has been validated at a rotating aluminum disk. First experiments at a flow of GaInSn, in the velocity range 0.2–1.5 m s$^{-1}$, show the applicability of the method for liquid metals. The extension of the method to lower and higher flow speeds, as well as a detailed comparison with other flow measurement techniques, has to be left for future work.

The method is calibration-free since it does not depend on the conductivity of the moving body (at least, as long as the signals are still strong enough). A further advantage of the sensor system is the avoidance of any magnetic material. Indeed, only air coils are used which can easily be adapted even to very hot environments such as for slab casters or within the pullers of Czochralski crystal growth. The velocity inference method makes TEC-FM largely insensitive to imperfections in the positioning of the detection coils within the excitation coil. Similarly, the method is rather robust against changes of the lift-off, as long as the distance to the fluid is not excessively larger than the distance between the detection coils. A more critical role is played by inclination angles between the central axis of the excitation coil and the normal vector of
Therefore, a reasonable alignment of both directions is recommended.

A straightforward extension of the principle is to measure two-dimensional flow structures close to the wall, just by adding two additional receiver coils orthogonal to the existing ones.

As mentioned above, there are subtle differences between switching on and switching off the current. These have to do with the $\mathbf{v} \times \mathbf{B}$ induction term which adds a weak $\infty$-shaped current system to the present ring-like one (as shown in figure 3). A detailed study of these differences, and of their potential to infer also the conductivity of the fluid, is left for future work.

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