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Two-dimensional ultrasound Doppler velocimeter for flow mapping of unsteady liquid metal flows

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ABSTRACT

We present a novel pulsed-wave ultrasound Doppler system for fluid flow investigations being able to determine two-dimensional vector fields of flow velocities. Electromagnetically-driven liquid metal flows appear as an attractive application field for such a measurement system. Two linear ultrasound transducer arrays each equipped with 25 transducer elements are used to measure the flow field in a square plane of 67×67 mm^2. The application of advanced processing methods as a multi-beam operation, an interlaced echo signal acquisition and a segmental array technique enable high data acquisition rates and concurrently a high spatial resolution, which have not been obtained so far for flow measurements in liquid metals. The extended pulsing strategy and essential operation principles such as the multiplexing electronic concept will be presented within this paper. The capabilities of the measuring system make it suitable for investigations of non-transparent, turbulent flows. Here, we present measurements of liquid metal flows driven by a rotating magnetic field for demonstration purposes. The measuring setup realized here reveals details of the swirling fluid motion in a horizontal section of a cube. Frame acquisition rates up to 30 fps were achieved for a complete two-dimensional flow mapping.

1. Introduction

The development of innovative liquid metal technologies, in particular the optimized flow control by tailored electromagnetic fields, requires a detailed knowledge of the flow structure and, hence, the availability of efficient and reliable measurement techniques for liquid metal flows. Well-proven laser-based methods [1] as usually used for flow measurements in transparent fluids will obviously fail for this specific case owing to the fluid's opacity. Since the first pioneering work of Takeda in the late eighties [2,3] the pulsed-wave ultrasound Doppler velocimetry (UDV) has been continuously developed to become a powerful tool for flow investigations in non-transparent liquid metal flows. Numerous studies have already been published reporting successful measurements in single and two-phase metallic flows for different applications and temperature ranges (see [4] for a review). The existing UDV technique provides instantaneous profiles of the velocity component aligned with the direction of ultrasound propagation. The enhancement of the capabilities towards a multidimensional flow mapping with high frame acquisition rates and high spatial resolution would be exceedingly desirable for the examination of complex turbulent flows as occurring e.g. during electromagnetic stirring of metals. For instance, the use of modulated AC magnetic fields as recently proposed by [5] generates three-dimensional flows with transient vortical structures. Detailed investigations of such flows and a validation of respective numerical simulations require a multidimensional acquisition of the flow field with a reasonable temporal and spatial resolution. Imaging techniques become more and more important for detailed explorations of three-dimensional turbulent flows, in particular with respect to the generation of a suitable experimental data base for an efficient validation of respective numerical simulations.

The development of ultrasound imaging methods was started by several research groups coming mainly from the biomedical field (see for instance [6–8]). The need for considering complex flow patterns motivated several researchers to use multi-transducer Doppler systems. For instance, Fox [9] proposed a concept of a multiple crossed beam technique for obtaining three-dimensional velocity vectors of the flow field. The operational principle of a so-called vector Doppler system based on continuous-wave Doppler was introduced by Fox and Gardiner [6] in order to reconstruct real vector velocities irrespective of the particular angle between the ultrasound beam direction and the flow. Overbeck et al. [7] used a single transmitter and two receivers in a pulsed-wave Doppler system to resolve orthogonal velocity components. A similar measuring system composed of a constant-beam-width emitting transducer and up to four receiving transducers was developed by Hurther and Lemmin [10] to conduct 3D flow measurements across the cross section of an open water channel. Scabia et al. [8,11]

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presented a real-time 2D vector Doppler system based on a 128-element linear transducer array with electronic focusing.

First attempts have already been made to realize a flow mapping of liquid metal flows by the pulsed ultrasound Doppler technique. Takeda and Kikura [12] investigated the mercury flow in a mockup liquid metal target of a spallation neutron source. A semi-circular arrangement of 20 single transducers allowed them to reconstruct two-component (2C) flow vectors at discrete nodes inside the hemispherical two-dimensional (2D) window region. The measurement rate of the flow mapping amounted to 2 fps. A mapping of a steady liquid metal channel flow impacted by an inhomogeneous DC magnetic field has been carried out by Andreev et al. [13]. The authors generated a sophisticated mesh of superposed beam lines by consecutive measurements using one transducer at different positions and under various inclinations with respect to the channel axis. Time-averaged 2C velocity vectors were calculated at the crossing points of the measurement lines. More recently, measurements of a submerged liquid metal jet have been reported by Timmel et al. [14]. A horizontal adjustment of 10 transducers provided a two-dimensional visualization of the horizontal velocity component.

These references outline the demand for spatially as well as temporally highly resolved, multi-dimensional UDV measurements which are not covered by the current state-of-the-art. Our paper presents an ultrasound Doppler measurement system using two linear ultrasound transducer arrays each equipped with 25 transducer elements. The orthogonal arrangement of the transducer arrays allows to measure two-dimensional flow fields composed of the in-plane velocity components. Realized acquisition rates of several ten vector maps per second meet the requirements for measurements of highly turbulent flows. For demonstration purposes velocity measurements have been performed in a liquid metal cube exposed to a rotating magnetic field (RMF) driving a swirling flow.

2. Vector field UDV system

2.1. Ultrasonic sensor design

A time-dependent flow mapping requires the application of transducer arrays allowing a fast electronic traversing of the ultrasonic measuring beam. The sensor system used here consists of two identical linear transducer arrays in an orthogonal arrangement spanning a square measuring plane of 67 mm by 67 mm (see Fig. 1). The transducer elements allow for the measurement of the velocity component aligned with the direction of the ultrasonic beam, particularly, the array aligned with the direction of the *x*-axis measures the *y*-component of the flow velocity and vice versa. The arrays span a mesh of profile lines in the square measuring plane. The flow field is reconstructed by determining the velocity vectors from the measured components at each crossing point.

Each array consists of 25 elements (size 2.4 mm $\times$ 5 mm) with an element pitch of 2.7 mm [15]. The dimensions are depicted in Fig. 2a. The ultrasound arrays are designed to operate as segmental arrays. Segmental arrays can be actuated in groups of elements to achieve a lower beam divergence (resulting in a sufficient high spatial resolution along the entire measuring depth) on the one hand and a small beam line pitch (resulting in a higher measuring line density) on the other hand [16,17]. For the present sensor design the vertical extent of an array element is twice the horizontal extent. The elements are operated in pairs of two transducers resulting in an active square transducer area with an almost identical lateral resolution in the vertical and the horizontal direction. This square transducer can be traversed by half of its edge length that corresponds to one element pitch. The procedure is shown in Fig. 2b in general. The succession of excitation of the transducer elements as used here will be described in the next section. As a consequence of the element binning, the segmental operation principle provides 24 measuring lines per array [15]. The resulting acoustic field was estimated by sound field simulations and is shown in Fig. 3. The area where the slope of the intensity is less than -6 dB can be defined as measuring volume. This gives us a lateral resolution of approximately 3 mm at the near field distance of 25.4 mm, which is in the same order of magnitude as the element pitch. More details regarding the characteristics of the sound field can be found in [15].

The emitting frequency of $f_0 = 8$ MHz was chosen for the demonstration measurements presented within this paper. The ultrasound pulses are composed of $N_C = 8$ harmonic wave cycles yielding an axial resolution of approx. 1.4 mm inside the liquid metal alloy GaInSn. For a more detailed description of the sensor design the authors refer to [15].

2.2. Operation principle

Previous applications of multiline Doppler systems for velocity measurements in liquid metals (for instance [12]) used sequential multiplexers to actuate several transducers and to record various measuring lines in succession. Depending on the signal-to-noise ratio and the desired measurement uncertainty a number of 20 to 100 bursts, designated as emissions per profile, are necessary for each transducer to determine the respective velocity profile. The subsequent recording of the profiles from each measuring line by conventional multiline systems results in a distinct time lag between scanning the first and the last measuring line which complicates the simultaneous acquisition of the complete flow field. This problem aggravates with increasing number of measuring lines making such multiline systems apparently not applicable for measurements of turbulent flows which require a high temporal resolution.

Two novel approaches are implemented in the pulsing strategy to overcome this problem. The first method concerns a multi-beam operation. The basic idea is to scan as many ultrasonic beams (respectively transducer pairs) in parallel as possible. However, this concept is restricted by the beam divergence since the ultrasound beams may overlap and induce a crosstalk between the different measuring lines. This problem can be solved by selecting a sufficient distance between the transducer elements being active at the same time. Experimental investigations revealed a tolerable crosstalk of less than -40 dB for the current array design if a distance of 4 inactive array elements is chosen between the active element pairs [15]. For our array comprising 25 transducer elements such a spacing permits the parallel operation of four transducer pairs (see also Fig. 4).

The second improvement of the temporal resolution results from an efficient segmentation of the overall acquisition time. As already mentioned above, the reconstruction of the velocity profiles relies on the analysis of many consecutive echo signals excited by a sequence of equidistant ultrasound pulses. The related parameter N_{EP} denotes the number of pulse emissions per velocity profile. The time between consecutive ultrasound pulses, the pulse repetition time (T_{PR}), defines the effective velocity range to be measured.

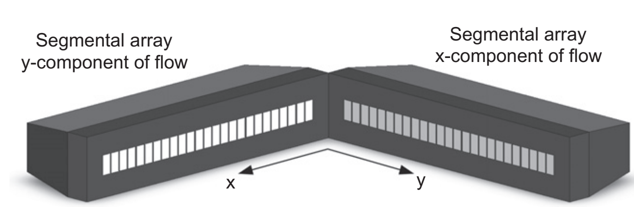

Fig. 1. Sensor setup for vector field measurements.