2d-2c Ultrasound Doppler Array Velocimeter for Flow Investigations in Liquid Metals

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A novel ultrasound Doppler measurement system for investigating the velocity field in electromagnetically driven liquid metal flows is presented. Two orthogonally arranged ultrasound sensor line arrays facilitate a two-dimensional measurement of two velocity components (2d-2c) within a square area of 70 x 70 mm². The array elements are controlled by a specific time multiplex technique in order to achieve both a high spatial and a high temporal resolution. The design of the sensor, the multiplex electronics and the operation mode of the measurement system are described. First velocity field measurements of liquid metal flows in a cubic vessel driven by a rotating magnetic field were performed and will be presented.

Keywords: Ultrasound Doppler Velocimetry, Flow Field Measurements, Ultrasound Sensor Array, Liquid Metals, Magnetohydrodynamics, Rotating Magnetic Field

1 INTRODUCTION

Magnetohydrodynamics (MHD) provides manifold possibilities of electromagnetic flow control in industrial processes (e.g. continuous casting). Beside ongoing numerical simulations a comprehensive understanding of the interactions between liquid metal flows and different kinds of applied magnetic fields requires also detailed experimental investigations. Reliable and precise data about the velocity structure are necessary for the validation of the theoretical computer models. Model experiments using low melting point liquid metals (e.g. GaInSn) are considered as an important tool to investigate the flow structure and related transport processes in liquid metal flows [1]. Because of the opaqueness of the fluid the instrumentation of respective experiments is challenging. Powerful optical methods like Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) as used for measurements in transparent liquids can obviously not applied in opaque melts.

The pulsed wave ultrasound Doppler velocimetry (UDV) offers an attractive possibility to measure flow velocities in opaque fluids [2, 3]. Also two-dimensional flow mapping of stationary flows were performed with UDV using multiple transducers [4]. However, measurements with a high number of scanning lines as well as a high temporal resolution are desired for investigations of highly turbulent, three-dimensional flows occurring, for example, during the electromagnetic stirring of metal melts.

Few commercial UDV instruments are available on the market, however, merely providing measurements of one velocity component along one line. An upper limit of ultrasound transducers which can be controlled simultaneously by these instruments and an inadequate arrangement of the transducers restrict an efficient flow mapping.

For this reason, a novel pulsed wave UDV measurement system currently in development is presented, which provides 2d-2c flow field measurements with high temporal and spatial resolution using two linear sensor arrays.

2 MEASUREMENT SYSTEM

The UDV system deploys two linear ultrasound transducer arrays each equipped with 25 transducer elements [5]. Figure 1 shows an orthogonal arrangement of these arrays allowing a 2d-2c measurement of the flow pattern in a square plane of 70 x 70 mm². Thereby, each array facilitates the measuring of one of the two velocity components (2d-1c). The design of the linear arrays is determined by several requirements which are described next.

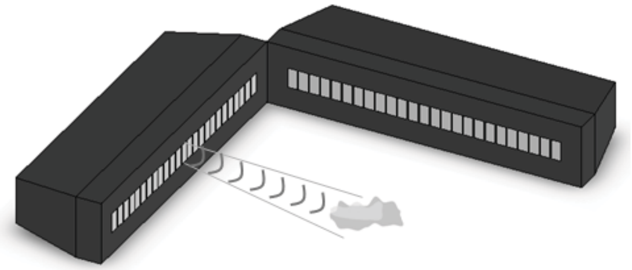


Figure 1: Two linear ultrasound transducer arrays arranged orthogonally for 2d-2c flow field measurements

The detection of small flow structures requires a high spatial resolution of the measurements. A high axial resolution necessitates a high ultrasound transmission frequency as well as a large transducer bandwidth. The lateral resolution also increases with higher transmission frequencies, since the angle of ultrasonic beam divergence in the far field becomes smaller with higher frequencies. However, the transmission frequency can not be chosen arbitrarily high as a result of acoustic attenuation inside the liquid metal which increases with rising frequency. For the present design the compromise of these considerations is found in an ultrasound transmission frequency of 8 MHz for the piezo elements with a -3dB-bandwidth of 2.5 MHz.

Regarding the size of the piezo elements opposite demands have to be considered. On the one hand, a small size of these elements is preferable to scan the flow field with a small lateral spacing. On the other hand, a low divergence of the ultrasound beam requires dimensions of the piezo elements being much larger than the ultrasound wavelength [6]. Hence, a specific sensor structure for the linear arrays was designed to meet both requirements. The sensor arrays consist of rectangular transducer elements with a cross section of 2.5 x 5 mm² (fig. 2). The elements are separated by a gap of circa 0.3 mm caused by the production process. Thus, the entire sensitive array length is about 70 mm. In operation adjacent rectangular piezo elements are driven in pairs acting as single piezo element with an effective square area of 5 x 5 mm² which can be shifted by 2.8 mm. This results in 24 controllable transducer pairs.

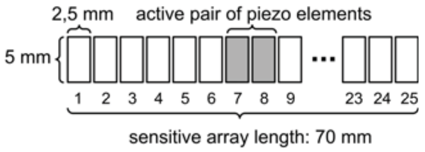
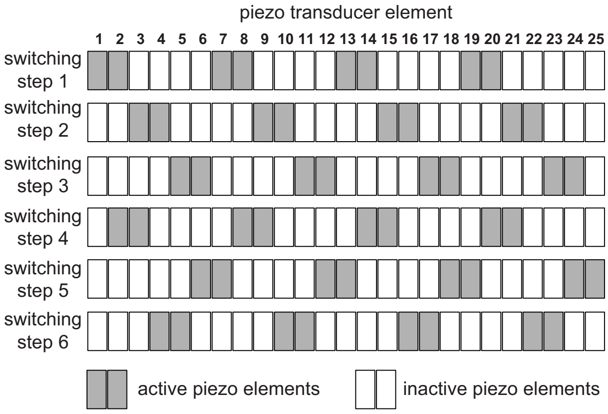


Figure 2: Design of a linear ultrasound array with 25 transducer elements

The requirement of a high temporal resolution is contrary to the demand of a high spatial resolution since the duration for sequentially scanning the entire flow field increases directly with a growing number of array elements. The idea for achieving a high temporal resolution despite the high number of array elements is to parallelize the measurement as much as possible. Thereby, the spacing between the active piezo pairs is chosen in such an extent that crosstalk can be neglected. The optimum spacing for the present measurement system was determined by sound field simulations and crosstalk investigations. Their results allow driving four piezo pairs in parallel reducing the scanning time by a factor of 4. This is implemented in the multiplex control scheme in figure 3. It features to scan the entire flow field in n = 6 switching steps. In order to minimize artefacts in the velocity profiles by multiple backplane echoes the control scheme ensures that no piezo element operates at two consecutive switching steps.



piezo transducer element

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
switching step 1	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	☐
switching step 2	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐
switching step 3	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐
switching step 4	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐
switching step 5	☐	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨
switching step 6	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐	☐	☐	▨	▨	☐	☐

▨▨ active piezo elements ☐☐ inactive piezo elements

Figure 3: Transducer control scheme of 4-channel parallel operation mode

The measurement setup for one linear ultrasound array is shown in figure 4. The main component is a self-developed high speed, high voltage capable multiplexing electronics implementing the entire control scheme. The burst signal generated by an arbitrary function generator is amplified by a high voltage RF amplifier. Afterwards the high voltage burst is distributed by the transmitting multiplexer among the transducers being active in the respective switching step. The transmitting/receiving (T/R) switch separates the burst signal from the echo signal received by the particular transducer. The receiving multiplexer of the switching electronics transfers the amplified echo signals of the active transducers to four summing amplifiers. They sum the echo signals of the elements of each active transducer pair as well as filter and amplify the signals. A personal computer (PC) equipped with a four-channel data acquisition (DAQ) card acquires the echo signals with a sampling rate of 25 MS/s. A microcontroller controls the transmitting and receiving multiplexer as well as generates the trigger for the burst signal and the DAQ card.

For 2d-2c operation two measurement setups (compare figure 4) are required. Thereby, the linear arrays have to be driven alternating to prevent crosstalk due to diffuse scattering. For this reason, the multiplexing circuits of both linear arrays are synchronized.

The echo signals are processed offline in MATLAB after acquiring the data. A software-based digital quadrature demodulation provides the “I” and “Q” signal of each channel which are filtered afterwards [2, 7]. The flow velocity is estimated with the frequency-domain autocorrelator, see [8]. However, the acquisition of the full bandwidth signal also allows applying the time-domain cross-correlation technique to achieve higher temporal resolution for flow mapping [9].

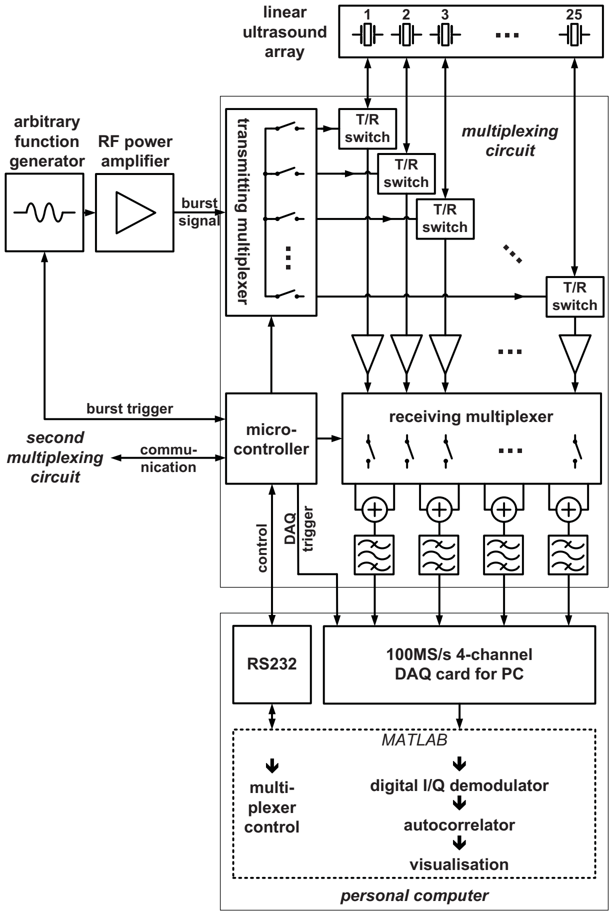


Figure 4: Measurement setup with multiplexing circuit to implement the control scheme

3. MEASUREMENTS

Up to now the measurement system features two-dimensional measurements of at first one velocity component (2d-1c). The second component is currently implemented.

First measurements were performed to validate the parallel operation mode and characterize the measurement system.

3.1 Measurement Setup

The experimental setup shown in figure 5 applies a magnetic field stirrer to drive a liquid metal flow inside a cubic vessel. The stirrer consists of a system of induction coils generating a rotating magnetic field (RMF). The cubic vessel with an inner edge length of 70 mm is made of acrylic glass and filled with the metal alloy GaInSn (c = 2740 m/s) which is liquid at room temperature. It is placed centrically in the magnetic stirrer.

The flow is generated as follows: The RMF rotates around the vertical vessel axis and induces electric currents inside the liquid metal. These currents interact with the imposed magnetic field and generate a dominating angular component of the magnetic field which drives a swirling flow of the melt [10].

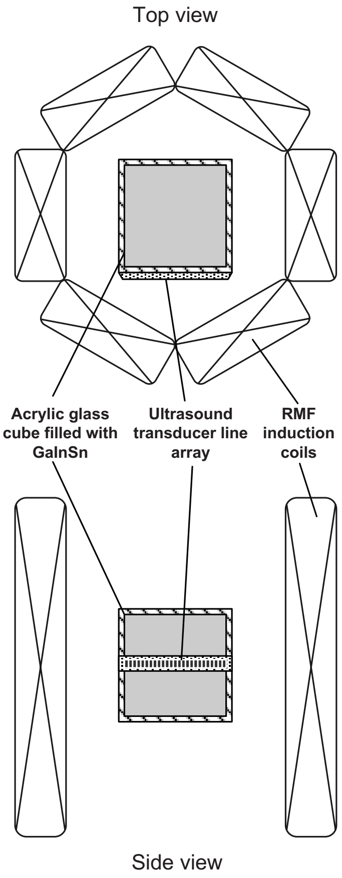


Figure 5: Experimental setup: Acrylic glass cube filled with GaInSn in a RMF stirrer

3.2 Spatial and temporal resolution

The number of wave cycles is a trade-off between a high axial resolution (i.e. a low number of cycles), transducer bandwidth and high acoustic energy or rather a high signal-to-noise-ratio (i.e. a large number of cycles). For the present investigations ultrasound bursts of 8 sinusoidal wave cycles at a frequency of 8 MHz are deployed. From this follows an axial resolution of $\Delta z \approx 1.4$ mm in GaInSn.

The lateral resolution of ultrasound transducers is defined as the -6 dB intensity width in the focal point (or rather the near field depth) of the sound beam. The sound field simulation of a square transducer of 5 x 5 mm² yields a lateral resolution of $\Delta x \approx 3$ mm in GaInSn for the applied measurement system. Hence, the lateral resolution is approximately equal to the traversing step width of 2.8 mm.

The temporal resolution of the flow mapping is determined by the burst repetition frequency which depends on the measurement depth. A depth of the cube of 70 mm results in a calculative repetition frequency of maximum 3.2 kHz related to the control scheme shown in figure 3. Due to technical reasons (i.e. switching time and programming time of the transmitting and receiving multiplexer; see figure 4) the maximum burst repetition frequency is set to 1.6 kHz. In the prospective 2d-2c operation the linear arrays will be driven alternately which leads to half of burst repetition frequency above.

3.3 Measurement results and discussions

For mapping the swirling flow in the cube the linear array is mounted in the vessel wall as depicted in figure 6. There, the measurement plane coincides with the x-y-plane of the cubic vessel at z = 35 mm.

Figure 7 shows one single frame of a 2d-1c flow mapping. There, the y-axis equals the alignment of the array and the velocity component according to the x-axis is measured. A flow toward the transducers is depicted as negative velocity and a flow away from the transducers as positive velocity. As a conclusion figure 7 presents a clockwise rotating vortex flow (compare with figure 6).

For this full frame 50 emissions per profile with a burst repetition frequency of 830 Hz were used which results in a duration of merely 63 ms for capturing the entire flow structure. This corresponds with a frame rate of 16.6 fps.

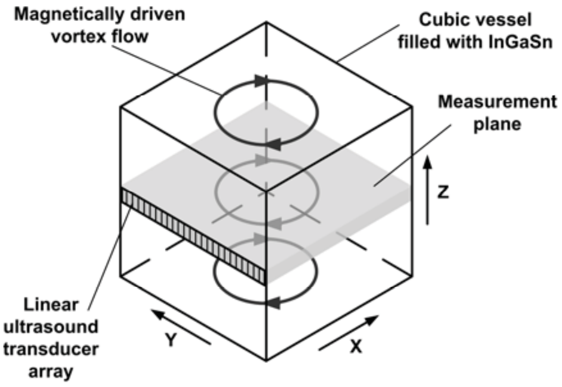


Figure 6: Measurement configuration for visualization of flow field (2d-1c) in the plotted measurement plane

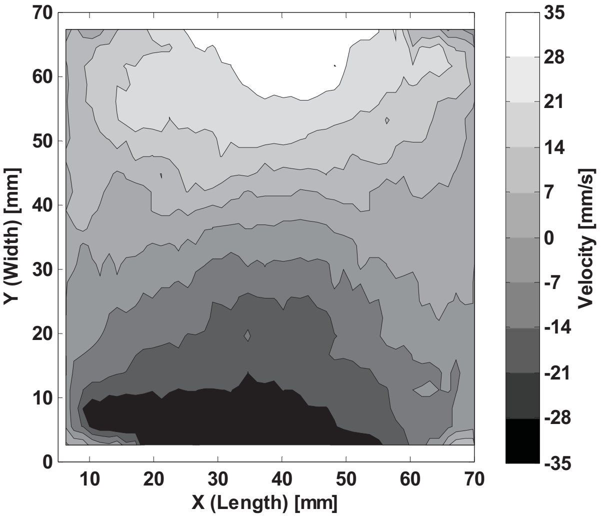


Figure 7: Single frame (Δt = 60 ms) of RMF-driven clockwise vortex (f = 50 Hz; B = 1.4 mT); the velocity component in x-direction is measured

By applying the maximum burst repetition frequency of 1.6 kHz (50 emissions per profile) frame rates up to 33 fps were achieved. Reducing the number of emissions the frame rate may be increased further.

4 SUMMARY

A 2d-2c ultrasound Doppler velocimeter for measuring flow fields in liquid metals is developed. There, two linear ultrasound transducer arrays each with 25 elements are arranged orthogonally to each other to cover a measurement plane of 70 x 70 mm². A specific array design and a parallelized operation mode facilitate a high temporal resolution contemporary with a high number of transducer elements.

Preliminary 2d-1c flow mappings of a RMF-driven liquid metal alloy were successfully performed achieving a full frame rate of up to 33 fps. Prospectively the second velocity component will be implemented and the frame rate will be increased further by faster signal processing methods.

ACKNOWLEDGEMENT

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