Modular ultrasound array Doppler velocimeter with spatial self-calibration for flow mapping in liquid metals

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Investigating the complex interaction of electrically conductive fluids and magnetic fields is relevant for a variety of applications from basic research in magnetohydrodynamics (MHD) to modeling industrial processes involving metal melts, such as steel casting and crystal growth. However, experimental studies in this field are often limited by the performance of flow instrumentation for opaque liquids. We present an ultrasound array Doppler velocimeter (UADV) for flow mapping in opaque liquids near room temperature. It is modular and flexible regarding its measurement configuration, for instance it allows capturing two velocity components in two planes (2d-2c) of 220x220 mm^2 with a frame rate of 8 Hz. It uses four linear arrays with 42 ultrasound transducers each driven in a parallelized time division multiplex (TDM) scheme. A FPGA-based signal processing allows a continuous and near-realtime operation of the measurement system. Further postprocessing combines the single-component velocity data to a 2d-2c flow field. This necessitates precise knowledge of the relative geometric position of the transducer arrays. We present a novel method that performs a spatial self-calibration by a mutual time of flight measurements, significantly reducing alignment errors.

The UADV is applied to experiments in the context of manufacturing crystalline silicon ingots for photovoltaics. A measurement example of a magnetically stirred flow of GaInSn in a rectangular container is given.

Keywords: Flow-Mapping, Ultrasound Doppler Velocimetry, Liquid Metals, Magnetohydrodynamics, Spatial Self-Calibration

1 INTRODUCTION

Flow control is the key to improve quality and energy-efficiency of a multitude of industrial processes involving liquid metals, for instance steel production or melt growth of semiconducting crystals for use in microelectronics or photovoltaics. By applying a time-dependent magnetic field the melt flow can be influenced in a contactless manner via Lorentz forces. To understand the complex interactions between magnetic fields and the flows induced in an electrically conductive fluid, experimental flow investigations are indispensable complementing numerical simulations. It is common practice to conduct scaled model experiments in low melting alloys, for example gallium-indium-tin (GaInSn, melting point approx. 10 °C) [1]. A suitable way of instrumenting the flow in the opaque fluids is the ultrasound Doppler velocimetry (UDV) [2,3], but commercial off-the-shelf devices are often limited in the amount of transducers and their multiplexing speed. This is contrary to the requirements that arise for flow mapping of complex and unsteady flow phenomena.

We present an ultrasound array Doppler velocimeter (UADV) system for liquid metal flows at room temperature that uses up to nine linear ultrasound (US) sensor arrays and enables high temporal and spatial resolution suitable to investigate complex transient flows. It is flexible regarding the measurement setup and its parameterization. We give an example of a setup for measuring a two-component flow field in two planes. The sensors are custom-tailored to instrument a container with a 220x220 mm^2 base. This corresponds to a so-called first generation (Gen1) crucible, which represents the research scale for modeling the melt flow in photovoltaic silicon crystal growth.

2 MEASUREMENT SYSTEM

2.1 Sensors

The measurement system utilizes multiple linear US-arrays to obtain a one-component velocity measurement in a plane. The UADV supports multiple sensor variants, which vary in geometrical dimensions, element count and frequency and can be chosen according to the measurement requirements. For example an 8 MHz array consisting of 42 single element piezo transducers (5 x 5 mm^2) with a total sensitive length of 218 mm is shown in Fig. 1. The transducers are excited with a burst signal of eight sine periods at $f = 8$ MHz, which results in an axial resolution of about 1.4 mm in GaInSn [4]. This sensor array is customized for capturing the flow in containers with a square cross-section of 220x220 mm^2. Its acoustical impedance is matched to borosilicate glass, which enables measurements through the containers walls.

2.3 Electrical Design

The UADV employs a modular design that consist of an arbitrary function generator (AFG), a power amplifier, an electronic switching matrix (the multiplex module) and an analog-digital converter

(ADC) module for each sensor array (Fig. 2 and 3). The AFG generate a burst signal, which is amplified and routed to the active transduces in one linear array. The received echoes are separated from the burst signals, amplified by a variable gain amplifier (VGA) and converted into digital signals. The echo amplification is determined by a voltage ramp that is chosen to compensate for increasing attenuation with increasing time of flight of US-pulses in fluids (time gain compensation, TGC) [4,5].

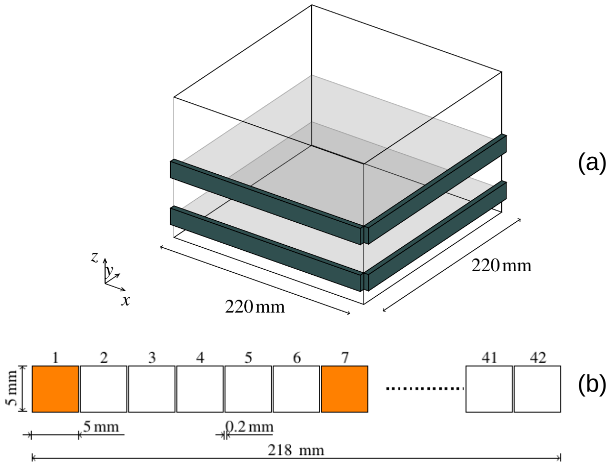

Figure 1: 2d-2c measurement setup (a) using four linear ultrasound arrays (b) with 42 transducers each; the marked elements are active in the first switch step of the TDM scheme.

To achieve a higher temporal resolution, the measurement process is parallelized over the line-arrays. A time division multiplex (TDM) scheme is used to drive several transducer pairs simultaneously in order to measure multiple lines at once. That allows scanning a plane in $N_s = 6$ time steps with a typical frame rate of 30 Hz [4]. Mutual exclusive driving of sensor arrays is possible in setups, where the beams of different sensor-arrays cross, as for instance in two-componential velocity measurements.

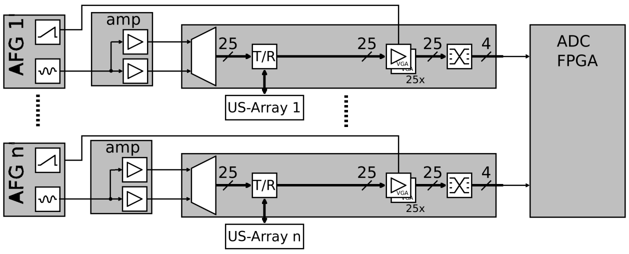

Figure 2: Block diagram of the UADV system; from left to right: signal generator, power amplifier, multiplex module, digitizer and FPGA

2.4 Signal Processing

The UADV captures US echoes on up to 32 receive-channels simultaneously. The analogue signals are digitized in parallel via a 32-channel ADC-module (NI 5752) at 32 MSamples/s. The mean total digital bandwidth of the system typically amounts to 1.2 GB/s, which is beyond the sustainable limit of nowadays storage facilities, if long-duration measurements are desired. Therefore parts of the signal processing are offloaded to an FPGA module (NI PXIe-7965R) which is well suited to highly parallel tasks.

The velocity-estimation is performed by the Kasai-autocorrelation algorithm [6, 7]. A complex Doppler signal is derived by creating an analytical signal and sampling at specific time instances relative to the ultrasound burst emission. Its mean Doppler frequency is directly proportional to the velocity of the corresponding scatterer particle.

The FPGA module implements a finite impulse response (FIR) bandpass filter with 8 MHz center frequency and 0.3 MHz bandwidth, a delay module to form a 90° phase-shifted signals and an IQ-demodulation stage. After the preprocessing, which decimates the amount of data (leading to a typical mean throughput of 120 MB/s); a PC performs the autocorrelation and velocity estimation.

Figure 3: UADVs multiplex unit; the 9 multiplex modules support 25 transducer elements each and can be aggregated to drive larger sensor arrays with e.g. 42 elements.

2.4 Spatial Self-Calibration and Post-Processing

To obtain a spatial velocity profile, the information of all linear arrays has to be combined according to their respective geometric positions and directions. The post-processing algorithm is flexible regarding the sensor configuration and allows for instance two-component multi-plane measurements (2d-2c) or three-component measurements along a line (1d-3c) [8].

The correct superposition of velocity components heavily depends on the precise knowledge of the relative position of the linear arrays. But in a majority of measurement setups, especially for clamp-on/ through-the-wall measurements, a reproducible relative alignment of the sensors is hard to achieve.

Therefore we implemented a spatial self calibration algorithm that allows an in-situ determination of these geometric relations. It is based on mutual time-of-flight (TOF) measurements between all transducer elements for linear arrays spanning the same plane (see Fig. 4). The strong directivity of the transducers and the assumption of equally distributed point-scatters in a rectangular reflective container allows distinguishing the following geometric sound paths with their respective lengths:

Direct: Sender to scatterer to receiver

$$l_{i,j} = i \cdot \Delta x + j \cdot \Delta y + x_0 + y_0 \qquad \text{(Eq. 1)}$$

Indirect: Sender to container wall to scatterer to receiver

$$l^{(R)}_{i,j} = 2L_x - i \cdot \Delta x + j \cdot \Delta y - x_0 + y_0 \qquad \text{(Eq. 2)}$$

The calibration algorithm evaluates the response of the receiving elements and determines the TOFs corresponding to the direct and indirect path length by peak detection of the signals envelope. This gives the matrices $l_{i,j}$ and $l^{(R)}_{i,j}$, which are substituted into Eq. 1 or 2 respectively. The resulting overdetermined system of equations is solved by a least square approximation to yield the unknown quantities x_0 and y_0. Reference measurements for an orthogonal pair of 67 mm sensors with 25 elements each show a combined uncertainty of typically 0.4 mm (k_p=1, according to GUM).

In subsequent flow mapping, the relative sensor positioning is incorporated into the post-processing, significantly reducing the alignment errors for multi-component measurements.

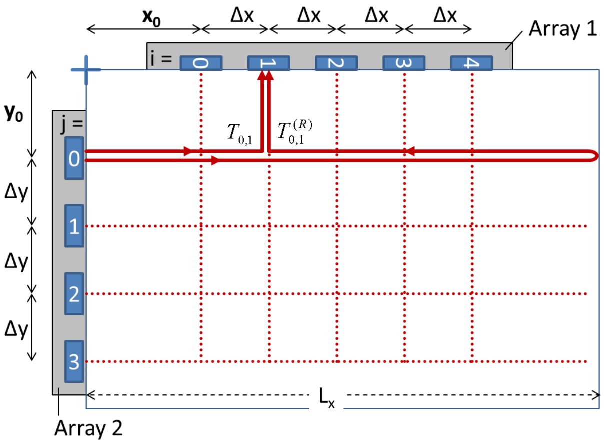

Figure 4: Spatial self calibration algorithm: The relative position of the orthogonal arrays 1 and 2, x_0 and y_0, can be deduced from the direct ($T_{i,j}$) and indirect ($T^{(R)}_{i,j}$) TOF.

3 MEASUREMENTS IN LIQUID METALS

To demonstrate the capabilities of the UADV system, an example of a measurement in GaInSn in a container with a 100x100 mm² base is given in Fig 5. It uses a previous sensor configuration that differs from the sensors described in Sec. 2.1 in the number of 25 transducer elements (25), the elements dimension (2.5x5 mm^2) and the active length (67 mm). In the dual-plane setup, four sensor arrays span two measurement planes to allow simultaneous capturing of two velocity components (2c). A US pulse repetition frequency of 570 Hz (resulting in an upper velocity limit of v_{max} = 48.8 mm/s) was used to obtain 52 velocity profiles each, which are temporally averaged subsequently. The flow is driven by a vertical traveling magnetic field with a frequency of 450 Hz [5]. A complex flow pattern emerges with a radially outward flow near the bottom wall of the container and a predominant –y component in the middle plane. For the given parameterisation, a measurement uncertainty contribution of the UADV system of <1% · v_{max} (k_p=1, according to GUM) was estimated.

4 OUTLOOK

Because of the modular approach of the UADV system it can be applied to a variety of measurement setups in MHD model experiments. We plan to use the customized sensors described in Section 2.1 in a near-room-temperature model of the crystal growth process in the photovoltaic industry. This allows investigating the interaction of the flow with time-dependent magnetic fields. The extended temperature range of the sensors (0-100 ℃) will enable non-isothermal measurements that involve temperature gradients and liquid-solid phase changes. This gives a more accurate model of the solidification process of liquid silicon in the photovoltaic industry.

An extension of the measurement modalities provided by the UADV towards detection of liquid-solid interfaces in the measurement volume is planned.

5 SUMMARY

Experimental studies are of great interest in MHD-research to complement and refine numerical models and increase the knowledge of the interaction between magnetic fields and conductive fluids. We aim to provide an enhanced flow instrumentation that is suitable for mapping complex transient flows.

We presented a modular UADV system for mapping flows in opaque liquids near room temperature. Its flexible design enables multi-plane and multi-component measurements. A spatial self calibration algorithm allows accurate overlaying of velocity components. A time-division-multiplex scheme and a FPGA-based signal processing allows high frame rates of up to 30 Hz sustained over long measurement durations. A sensor setup customized for a 2d-2c flow measurement in a 220x220 mm^2 borosilicate glass container was shown.

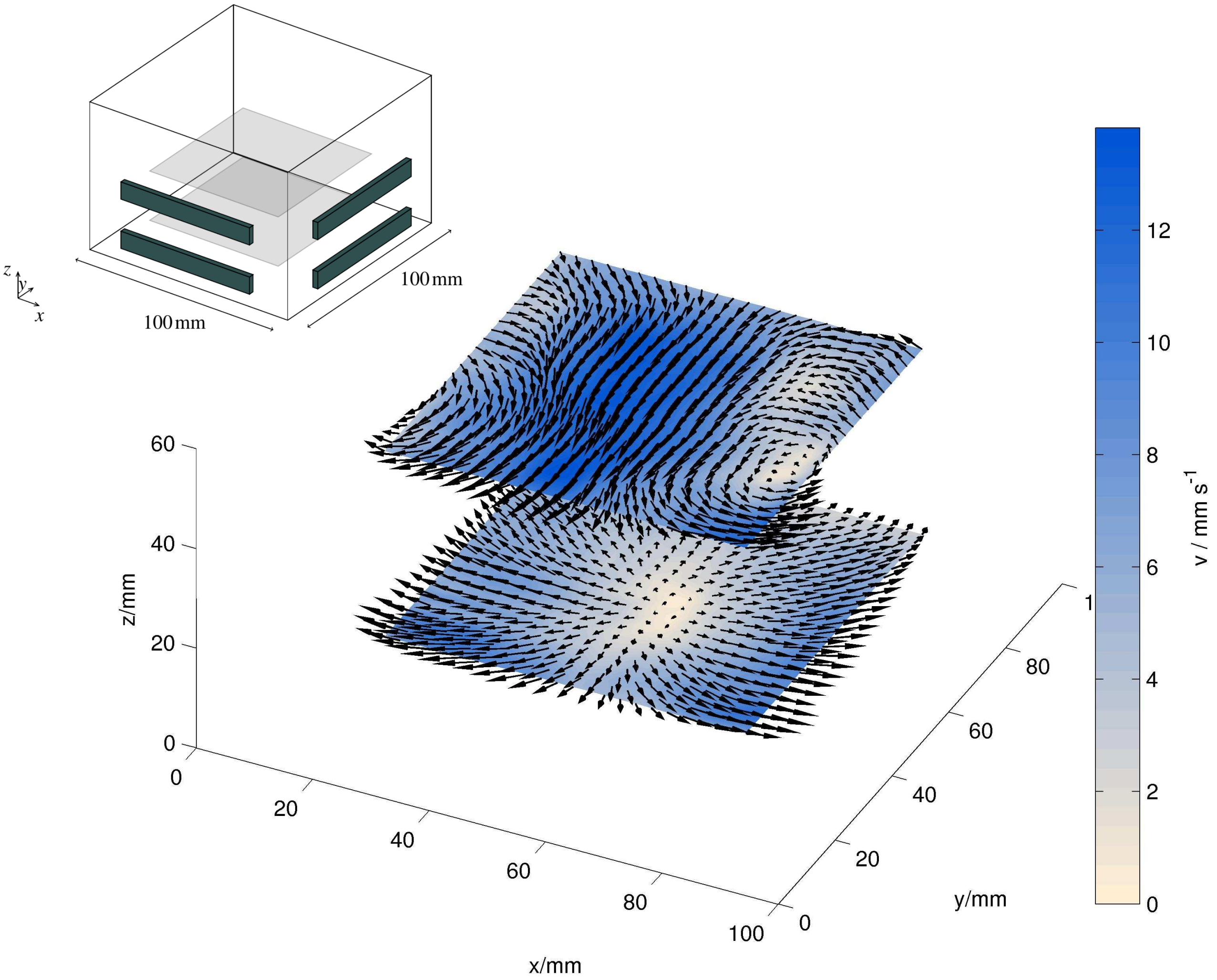

Figure 5: Dual-plane flow mapping (2d - 2c): Measurement setup and results for magnetically stirred GaInSn in a cubic 100x100 mm² container. Arrays with a length of 67 mm and 25 transducer elements were used [5]

ACKNOWLEDGEMENT

The authors like to thank the Federal Ministry for the Environment (BMU) for the funding received within the grant 0325646A (project ENOWA), as well as Kathrin Niemietz for conducting the experiment and Paul Bönisch for fruitful discussions.

REFERENCES

[1] Eckert S, Gerbeth G, Räbiger D, Willers B, Zhang C: Experimental modeling using low melting point metallic melts: Relevance for metallurgical engineering, Steel Res. Int. 78 (2007), 419-425.

[2] Eckert S, Cramer A, Gerbeth G: Velocity measurement techniques for liquid metal flows, in Magnetohydrodynamics - Historical Evolution and Trends, Molokov S, Moreau R, Moffatt HK (Eds.), Springer-Verlag, Dordrecht (2007), 275-294.

[3] Takeda Y: Development of an ultrasound velocity Profile monitor, Nucl. Eng. Design 126 (1991), 277-284.

[4] R. Nauber, M. Burger, L. Büttner, S. Franke, D. Räbiger, S. Eckert, J. Czarske: Novel ultrasound array measurement system for flow mapping of complex liquid metal flows, The European Physical Journal Special Topics, 220 (2013), 43–52.

[5] R. Nauber, M. Burger, M. Neumann, L. Büttner, K. Dadzis, K. Niemietz, O. Pätzold, J. Czarske: Dual-plane flow mapping in a liquid-metal model experiment with a square melt in a traveling magnetic field, Experiments in Fluids, 54 (2013), 1502-1513.

[6] Jensen JA: Estimation of blood velocities using ultrasound, Cambridge University Press, Cambridge (1996).

[7] Kasai C, Namekawa K, Koyano A, Omoto R: Real-time two-dimensional blood flow imaging using an autocorrelation technique, IEEE Trans. Sonics. Ultrason. 32 (1985), 458-464.

[8] L. Büttner, R. Nauber, M. Burger, D. Räbiger, S. Franke, S. Eckert, J. Czarske: Dual-plane ultrasound flow measurements in liquid metals, Meas. Sci. Technol. 24 (2013), 055302-055314