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# Modular Ultrasound Array Doppler Velocimeter with FPGA-based Signal Processing for Real-time Flow Mapping in Liquid Metal

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**Abstract**

Investigating the complex interaction of 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 the crystal growth process in the photovoltaic industry. This enables targeted optimizations of the melt flow and allows to significantly increase the yield and energy efficiency of industrial processes. 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 at room temperature. It is modular and flexible regarding its measurement configuration, for instance it allows capturing two velocity components in two planes ($2d-2c$). It uses up to 9 linear arrays with a total element count of 225, driven in a parallelized time division multiplex (TDM) scheme. A FPGA-based signal pre-processing allows to handle the massive data bandwidth of typ. 1.2 GB/s and enables a continuous and near-realtime operation of the measurement system. The capabilities of the UADV system are demonstrated in a basic MHD research experiment with a metal melt (GaInSn) in a cubic container of $(67\,\text{mm})^3$. The flow induced by a rotating magnetic field is captured with a temporal resolution of 250 ms for the horizontal and vertical central cross-section of the cube.



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*Keywords:* Flow-Mapping, Ultrasound Doppler Velocimetry, Liquid Metals, Magnetohydrodynamics, Flow Control, FPGA

## 1. Introduction

Controlling the flow of molten metals is a key to improvements in various industrial processes, such as continuous steel casting or silicon crystal growth in the photovoltaic industry. Time-varying magnetic fields allow to influence the flow of conductive liquids contactlessly via Lorentz forces. A significant increase of energy-efficiency and yield for such process can be achieved, if the interactions of liquid metal flows and magnetic fields are well understood. This motivates the research in the field of magnetohydrodynamics (MHD), where scientific insights are usually gained by a combination of numerical simulations and experimental investigations. The latter require a flow instrumentation for

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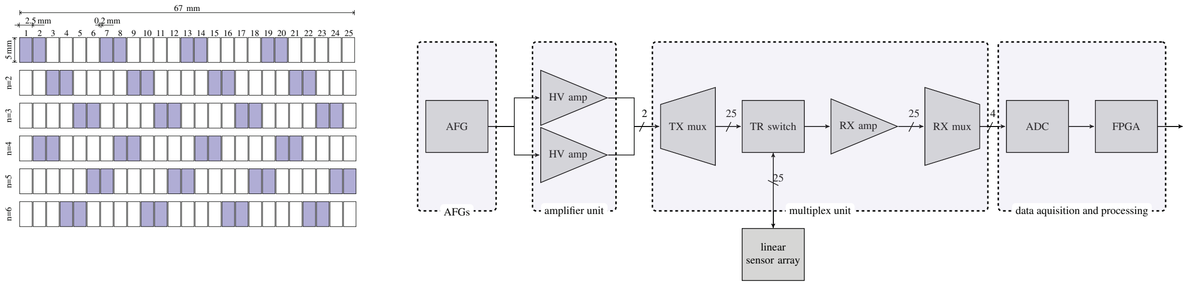


(a) (b)

Fig. 1. Geometric dimensions of a custom linear sensor array with 25 elements and the excitation pattern for scanning a plane (a); Block diagram of a single module (of up to 9) in the UADV system, each module is capable of driving 25 transducer elements (b).

opaque liquids that is able to visualize complex transient flow structures. For experiments in low melting metals near room temperature, for instance in the eutectic alloy GaInSn (melting point 10 °C), the ultrasound Doppler velocimetry (UDV) is a well suited, non-invasive instrumentation principle [2, 7]. However, available commercial off-the-shelf UDV devices are often limited to measurements with a few single element transducers in a strictly sequential multiplexing and therefore provide insufficient time-resolved imaging capability. We present an ultrasound array Doppler velocimeter system (UADV) for instrumenting liquid metal flows at room temperature. It uses linear sensor arrays with a total of up to 225 transducers and is flexible regarding the measurement setup and its parameterization. We demonstrate the capabilities of the UADV system by instrumenting an experiment of magnetically stirred GaInSn in a cubic vessel in two perpendicular planes.

## 2. Measurement system

### *2.1. Sensors and time division multiplex*

The UADV employs multiple linear ultrasound arrays, whose geometrical dimensions, element counts and frequencies can be chosen according to the measurement requirements. An example of a probes geometry is depicted in Fig. 1a. The customized probe is a linear array consisting of 25 single element piezo transducers (center frequency 8 MHz, $2.5 \times 5\,\mathrm{mm}^2$) with a total sensitive length of 67.5 mm. The transducers are excited in pairs, which results in an effective sensor surface of $5 \times 5\,\mathrm{mm}^2$. To increase the temporal resolution over strictly sequential scanning, the measurement process is parallelized over the linear arrays. A time division multiplex (TDM) scheme is used to drive four transducer pairs simultaneously in order to measure multiple lines at once (Fig. 1b). This allows scanning a plane in $N_{sw} = 6$ time steps with a typical frame rate of 30 Hz [5]. Mutual exclusive driving of sensor arrays is possible in setups, where the beams of different sensor-arrays intersect, as for instance in two-componential velocity measurements.

### *2.2. Electrical design*

The UADV employs a modular design that is scalable to 9 modules supporting 25 transducers each. The modules can drive single sensor arrays or can be aggregated for driving larger sensors, e.g. with 50 elements [5, 6]. The UADV hardware consists of arbitrary function generators (AFGs) and power amplifiers that create parameterizable burst signals. These are routed through an electronic switching matrix to the active transducer elements according to the TDM scheme. The received echoes are separated from the burst signals and amplified by a variable gain amplifier (VGA) to compensate for the time-of-flight dependent attenuation in the fluid (time gain compensation, TGC).

### 2.3. Signal processing and post processing

The UADV digitizes echo signals on 32 receive channels simultaneously through an ADC-module (NI 5752, 32ch) at 32 MSamples/s. The mean total digital bandwidth of the system amounts to 1.2 GB/s for typical configurations, which is beyond the sustainable limit of nowadays storage facilities. This would prevent long-duration measurements, because the data can only be transferred from a fast temporary memory to a persistent storage discontinuously. Therefore a realtime data compression is necessary, which is achieved by offloading parts of the signal processing to a field-programmable gate array (FPGA) module (NI PXIe-7965R), which is well suited to massively parallel tasks.

The velocity estimation is performed by the Kasai-autocorrelation algorithm [3, 4]. A complex Doppler signal is obtained by creating an analytical signal and sampling at specific time instances relative to the burst emission. The mean Doppler frequency is directly proportional to the velocity of the corresponding scatterer.

The FPGA module implements a finite impulse response (FIR) bandpass filter with 8 MHz center frequency and 0.3 MHz bandwidth and a delay module to form 90° phase-shifted signals for subsequent IQ-demodulation. The preprocessing allows to reduce the amount of data by 10 : 1, followed by autocorrelation and velocity estimation on a personal computer (PC).

To obtain a spatial velocity profile, the information of all linear arrays is combined according to their respective geometric positions and directions in the post-processing algorithm. For example, two componential flow measurements (2d-2c) can be achieved by arranging two sensors perpendicular to each other, spanning a common measurement plane [1].

## 3. Measurements in liquid metals

To demonstrate the capabilities of the UADV system, an example of a measurement for a basic MHD research experiment is given (Fig. 2). An acrylic glass container of $(67\,\text{mm})^3$ is filled with liquid GaInSn and four linear sensor arrays are arranged to instrument the centric horizontal and vertical cross section of the cube. A pulse repetition frequency of 551 Hz results in an upper velocity limit of $v_{max} = 47\,\text{mm/s}$ and a temporal resolution of 250 ms. The flow is driven by a horizontally rotating magnetic field with a frequency of 50 Hz. This induces a vortex in the horizontal plane (primary flow) and four distinct vortices in the vertical plane near the cubes corners (secondary flow). For the given parameterization, a measurement uncertainty of the UADV system of $< 1\,\% v_{max}$ ($kp = 1$, according to GUM) was estimated from a reference experiment with a linear stage.

## 4. Summary and outlook

We presented a modular UADV system for multi-plane flow mapping in opaque liquids near room temperature. It is flexible regarding the parametrization and measurement setup and can be applied to a variety of experiments, e.g. models of industrial processes like photovoltaic crystal growth and continuous steel casting or basic research investigations. By employing a time-division-multiplex scheme and a FPGA-based signal processing the UADV allows frame rates of up to 30 Hz sustained for a (practically) unlimited measurement duration. An example of an UADV measurement in a cubic container driven by a rotating magnetic field was shown.

In the future we plan to apply the UADV system to crystal growth model experiments including a significant temperature gradient and a liquid-solid state change. A further reduction of the amount of data will be necessary for simultaneously tracking the phase boundary and capturing the fluid flow in multi-hour measurements.

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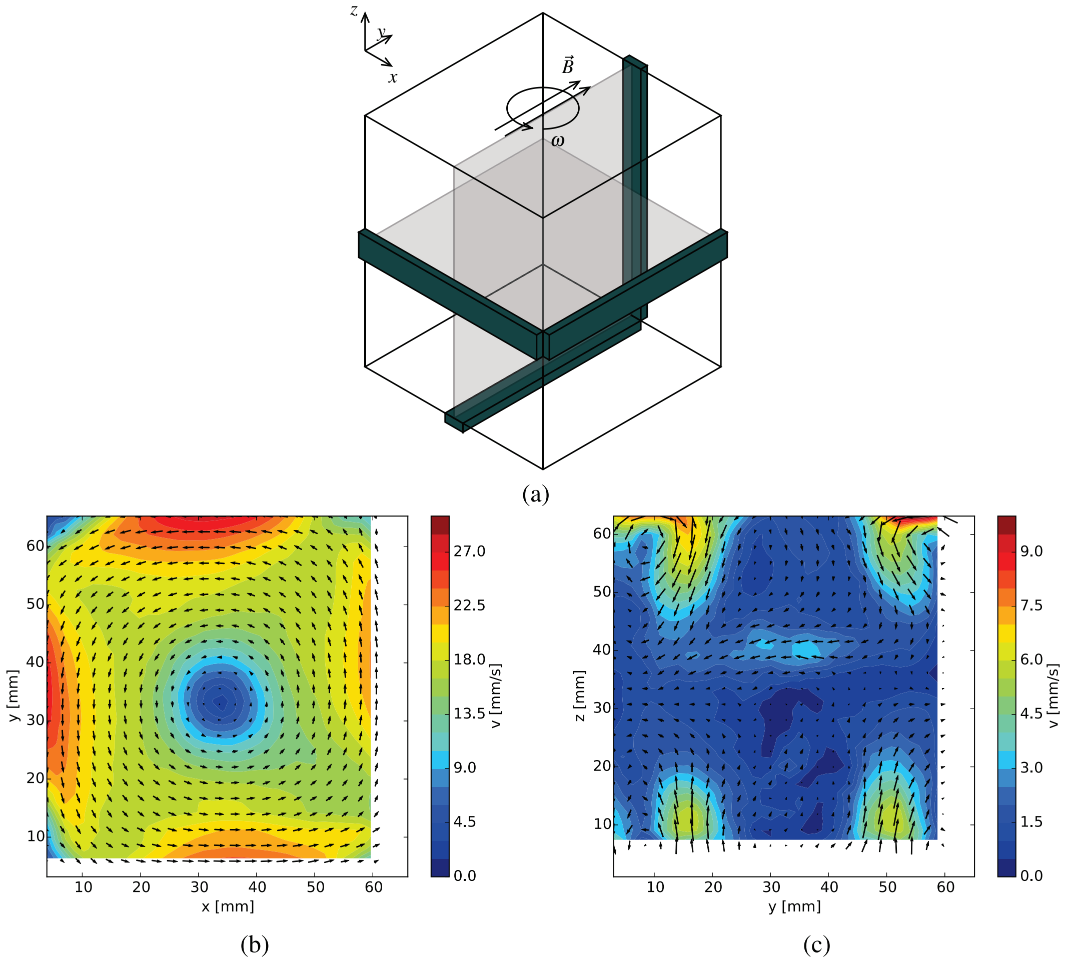


Fig. 2. Dual-plane flow mapping (2d - 2c) in two perpendicular planes: Measurement setup (a) and results for magnetically stirred GaInSn in a cubic $(67.5\,\mathrm{mm})^3$ container. The velocity maps in the horizontal plane (primary flow, b) and the vertical plane (secondary flow, c) are obtained quasi-simultaneously.

## References


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

[2] Eckert, S., Cramer, A., Gerbeth, G., 2007. Velocity measurement techniques for liquid metal flows, in: Magnetohydrodynamics. Springer Netherlands. volume 80 of *Fluid Mechanics and Its Applications*, pp. 275–294. doi:10.1007/978-1-4020-4833-3 17.

[3] Jensen, A., 1996. Estimation of blood velocities using ultrasound: a signal processing approach. Cambridge University Press.

[4] Kasai, C., Namekawa, K., Koyano, A., Omoto, R., 1985. Real-time two-dimensional blood flow imaging using an autocorrelation technique. Sonics and Ultrasonics, IEEE Transactions on 32, 458 – 464. doi:10.1109/T-SU.1985.31615.

[5] Nauber, R., Burger, M., Büttner, L., Franke, S., Räbiger, D., Eckert, S., Czarske, J., 2013a. Novel ultrasound array measurement system for flow mapping of complex liquid metal flows. The European Physical Journal Special Topics 220, 43–52. doi:10.1140/epjst/e2013-01795-1.

[6] Nauber, R., Burger, M., Neumann, M., Büttner, L., Dadzis, K., Niemietz, K., Pätzold, O., Czarske, J., 2013b. Dual-plane flow mapping in a liquid-metal model experiment with a square melt in a traveling magnetic field. Experiments in Fluids 54, 1–11. doi:10.1007/s00348-013-1502-x.

[7] Takeda, Y., 1991. Development of an ultrasound velocity profile monitor. Nucl. Eng. Des. 126, 277 – 284. doi:10.1016/0029-5493(91)90117-Z.