Dual-plane Ultrasound Array Doppler Velocimeter for Flow Investigations in Liquid Metals

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A dual-plane, dual-component ultrasound array Doppler velocimeter for investigating transient complex flow phenomena in liquid metals is presented. It utilizes four sensor arrays consisting of 25 single element transducers along a line of 67 mm. The system combines a spatial resolution of approx. 3 mm with a temporal resolution of up to 30 Hz using electronic beam traversing and time division multiplex. The modular realization of the measurement system allows flexible sensor configuration, e.g. four planes can be measured with one velocity component, two planes with two components or two lines with three components. Those capabilities are demonstrated by measurements in a magnetically stirred metal melt at room temperature.

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

1 INTRODUCTION

Metal melts and the flows therein are of outstanding importance for a variety of technological processes, especially for steel production (continuous casting process) and crystal growth (Czochralsky method, etc.). In recent developments, the application of magnetic fields is investigated to influence the melt-flow in a defined way and to optimize the quality of the resulting product. Experimental flow investigations are indispensable to understand the interaction between the magnetic fields and the induced flows. It is common practice to conduct scaled model experiments in low melting alloys, for example gallium-indium-tin (GaInSn) [1]. Ultrasound pulse wave Doppler is an appropriate method for flow investigations [2,3], but commercial off-the-shelf devices often employ only a limited number of transducers and are hardly suitable 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 four ultrasound (US) arrays and provides high temporal and spatial resolution suitable to investigate complex transient flows. The capabilities of the UADV system are demonstrated by two measurements in magnetically stirred GaInSn.

2 MEASUREMENT SYSTEM

2.1 Sensors

The measurement system utilizes US line arrays in order to obtain a one-component velocity measurement in a plane. An array consists of 25 single element piezo transducers (2.5 x 5 mm) with a total sensitive length of 67 mm (fig. 1). The active elements are driven pairwise to form a square transducer of approx. 5 x 5 mm. Those dimensions are the result of a trade-off between element size and beam divergence and determine the lateral resolution to approx. 3 mm in GaInSn. This corresponds with the pitch of 2.7 mm that transducer pairs of the line array can be traversed electronically. The piezo-transducers are excited by 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].

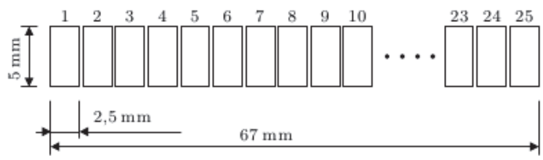

Figure 1: Linear ultrasound array with 25 transducer elements [5]

2.2 Time Division Multiplex

To obtain a high temporal resolution it is necessary to parallelize the measurement process along the line array. Therefore a time division multiplex (TDM) scheme is used to drive several transducer pairs simultaneously in order to measure multiple lines at once. It has been determined that a spatial distance of four inactive transducers and a temporal separation of one time step is sufficient to neglect cross-talk in GaInSn [4]. The outcome is an excitation pattern (fig. 2) that allows to scan a plane in N_s = 6 time steps with an overall frame rate up to 30 Hz [5].

In order to obtain two or more velocity components, multiple sensor arrays measure in overlapping planes and are driven mutually exclusive. This is achieved by interleaving the excitation patterns of the sensor arrays. To measure a two-component (2c) velocity field along two planes (2.5d) for instance, two arrays are arranged orthogonally per plane and are electronically traversed in an alternating manner. Therefore twice the time is needed to completely capture a plane in a two-component configuration.

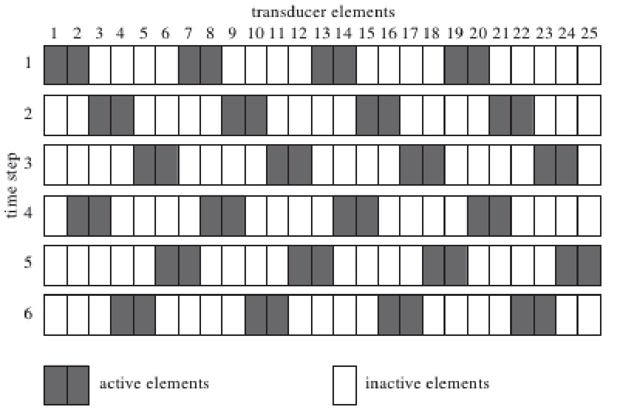

Figure 2: Time division multiplex scheme for a single array

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 and an analog-digital converter (ADC) card for each sensor array. Each AFG generates a burst signal, which is amplified and routed to four transducer pairs in one line array. The received echoes are separated from the burst signals, amplified with variable gain 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).

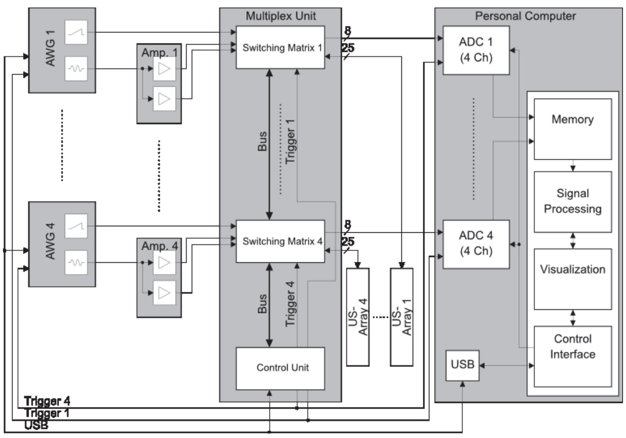

Figure 3: Block diagram of the UADV system

2.4 Signal Processing

The digitized echo signals are processed offline after acquisition by four ADC-cards to obtain the flow velocity profiles. The time-domain signal is processed through a finite impulse response (FIR) bandpass filter with 8 MHz center frequency and 0.3 MHz bandwidth. Subsequently the real-valued signal is complemented by a 90° phase shifted imaginary part to form an analytic signal via the Hilbert transform. By sampling at specific time instances relative to the ultrasound burst emission a complex Doppler signal is derived. The mean frequency and directional information are subsequently estimated via an autocorrelation algorithm [6, 7]. The velocity of the fluid in the corresponding depth relative to the transducer is directly proportional to its Doppler frequency.

To obtain a spatial flow profile, the information of all line-arrays is combined according to their respective geometric positions and directions. A post-processing algorithm allows all orthogonal sensor configurations and provides the flexibility to measure for example multi-plane one (1c) and two-component (2c) velocity profiles as well as three velocity components (3c) along a line of three intersecting planes.

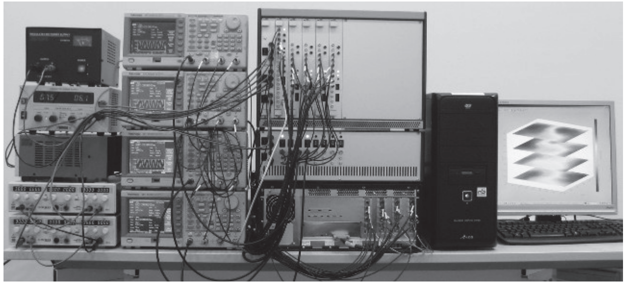

Figure 4: Deployment of the UADV system, from left to right: power supplies; arbitrary function generators (AFG); modular multiplex electronics, power amplifiers and signal acquisition; standard PC

3. Measurements in Liquid Metals

To demonstrate the capabilities of the UADV system, measurements are performed in magnetically stirred GaInSn. The metal melt is contained in a cubic vessel of 67x67x67 mm that has several mounting options for US line arrays. A US pulse repetition frequency of 538 Hz is used to obtain 30 profiles of 50 echoes each, which are temporally averaged subsequently.

In a dual-plane setup, four sensor arrays span two measurement planes to allow quasi-simultaneous capturing of two velocity components (2c). Arrays spanning the same plane are driven mutually exclusive, the crosstalk between two planes can be neglected ($\Delta z \geq 15$ mm). The resulting 2.5d-2c flow field is depicted in fig. 5.

Three velocity components (3c) can be measured by intersecting three orthogonal single-component planes. With four available sensor arrays, three-component measurements along two lines are possible. Fig. 6 shows the experimental setup and the obtained flow field.

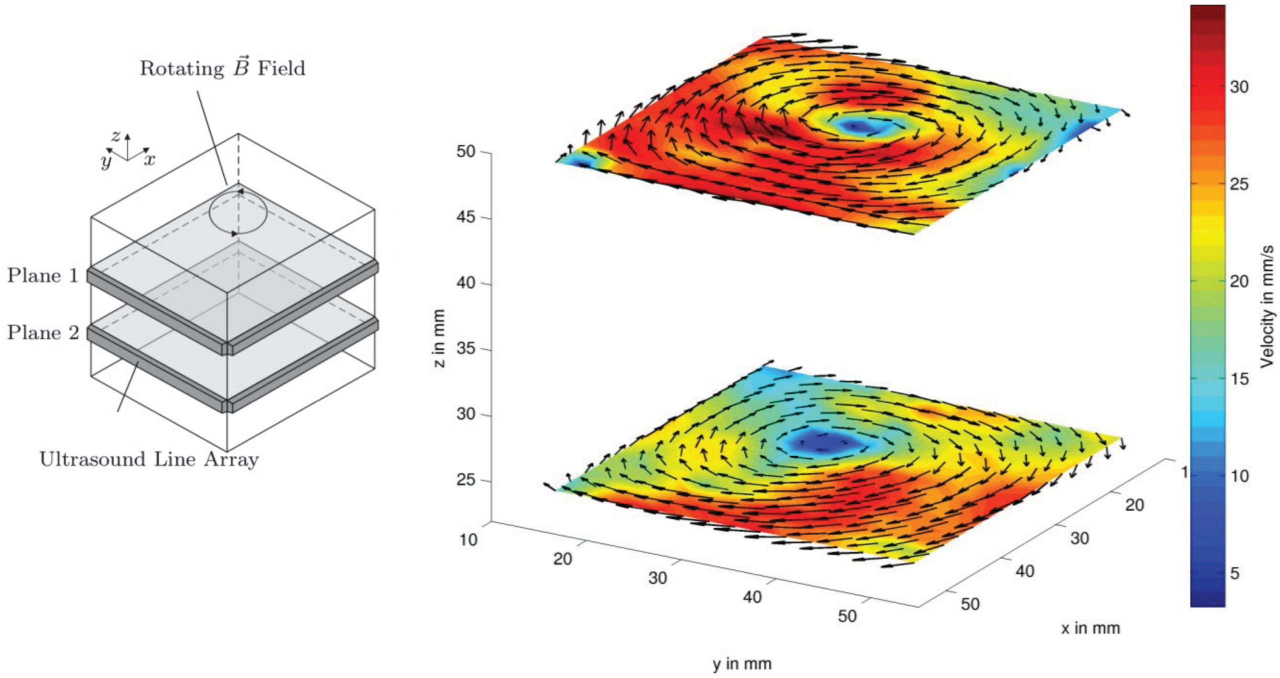

Figure 5: Dual-plane measurement (2.5d - 2c): Measurement setup and results for magnetically stirred GaInSn in a cubic vessel

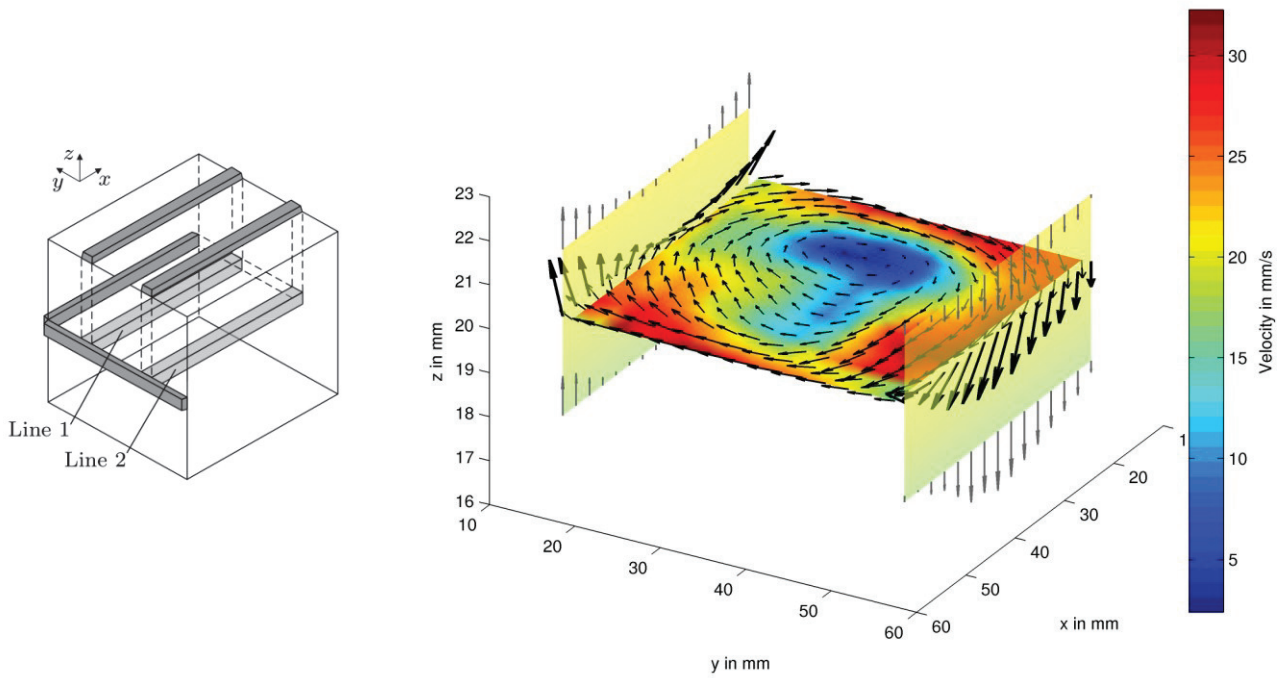

Figure 6: Dual-line measurement (1.5d - 3c): Measurement setup and results for magnetically stirred GaInSn in a cubic vessel; three-component vectors along two intersection lines are drawn bold

4 OUTLOOK

As the UADV system has proven usefully for complex flow mapping, a variety of applications arise. It is planned to apply the system to a scale-model of continuous steel casting in order to characterize the influence of magnetic fields to the melt flow [8]. Contactless mixing of metal melts by different means of magnetic fields [9] is studied as well, using the capabilities of the UADV system to simultaneously obtain primary and secondary flows. Further investigations of directed solidification process of silicon will be conducted in isothermal models that are especially relevant for the photovoltaic industry [10].

5 SUMMARY

We have presented a flexible UADV system to capture complex transient flows in liquid metals. Its modular design allows for multi-plane and multi-component flow mapping. A time division multiplex scheme ensures high temporal resolution (up to 30 Hz) while optimized ultrasound-beam characteristics determine a spatial resolution of approx. 3 mm. The system is demonstrated by a dual-plane (2.5d-2c) and a three-component (1.5d-3c) velocity measurement in a low melting liquid metal alloy.

The development of a capable UADV system poses great potential for the field of MHD and a profound understanding of the interaction between electromagnetic fields and conductive fluids.

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