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Ultrasound Imaging in Hot Melts with Time Reversal Virtual Arrays

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***Abstract*—Industrial processes, such as silicon crystal growth for the photovoltaics industry, continuous steel casting, plastics and aluminum extrusion, involve hot, opaque liquids. Non-invasive inline monitoring is desirable to improve the quality of the products and the resource efficiency of the process. However, ultrasound-based imaging methods are severely limited by the transducer's resistance to high temperatures.**

We propose a method for imaging hot liquids using an ultrasound phased-array probe attached to a multi-mode waveguide (MMWG) for thermal decoupling. The complex wave propagation through the MMWG leads to a strongly distorted image, which is addressed with a time reversal virtual array (TRVA). The TRVA method performs a system identification and compensates the distortions based on the time-reversal invariance of sound propagation. We demonstrate planar imaging with this method in liquid tin at $\approx 300\,^{\circ}\mathrm{C}$, well above the destruction limit of the transducers. The characterization of the imaging properties of the system showed a spatial resolution better than $1.6\,\mathrm{mm}$.

The proposed method for imaging through MMWG may open a new window into a variety of technical and industrial processes involving hot, opaque liquids in harsh environments.

***Index Terms*—in-process monitoring, multi mode waveguides, computational ultrasound, liquid metals, time reversal, TRVA**

I. Introduction

Non-invasive online monitoring is crucial for improving of the resource efficiency of industrial processes, such as silicon crystal growth for the photovoltaics industry, continuous steel casting and plastics extrusion. However, it is very hard to image structures and flows in those processes due to harsh environmental conditions, as high temperatures and the opaqueness of the involved fluids. Especially ultrasound-based imaging methods are limited by the transducer's susceptibility to high temperatures and corrosion. One approach to overcome these limitations is to spatially separate the transducers from the measurement volume using an acoustical waveguide. Single line measurements of velocity profiles and structures in hot liquids have been achieved using single mode waveguides [1], [2]. However, single mode waveguides are mechanically complex, strongly attenuating and do not provide the capability for imaging.

For in situ process imaging of hot melts, we propose using a multimode waveguide (MMWG) in combination with the time reversal virtual array (TRVA) method. A MMWG can carry the information of a complete, two-dimensional image, yet it is scrambled due to the complex sound propagation. TRVA exploits the time invariance of the wave equation in linear media [3] to focus on a set of pre-calibrated points on the far (distal) end of the waveguide with a phased array transducer at the near (proximal) end. These points are combined to form a virtual array, which allows transmit and receive beamforming into the measurement volume [4]. We demonstrate this method in liquid tin at $\approx 300\,^{\circ}\mathrm{C}$ and experimentally characterize the imaging properties of this system.

The computational ultrasound approach of TRVA allows to trade mechanical complexity for advanced signal processing, thereby gaining the ability for flow and structure imaging. This may overcome a severe limitation of ultrasound imaging regarding high temperatures and potentially extend its usage to a new class of applications in the industrial field.

II. Materials and Methods

We use the TRVA method as described by Kalibatas, Nauber, Kupsch and Czarske for compensating the propagation through a cuboid waveguide [4]. An ultrasound array is placed at the proximal end, while the distal end is brought in contact with liquid tin (cf. Fig. 1a). Multiple plane waves with different tilts are emitted using the phased-array ultrasound Doppler velocimeter (PAUDV) platform [5]. The relevant parameters are given in Tab. I.

The system identification step of TRVA is performed through an in situ calibration. A stainless steel needle with a diameter $d = 1\,\mathrm{mm}$ is traversed laterally in front of the distal end of the MMWG. The received signals are subtracted from a measurement without scatterer, temporally cropped and time reversed (cf. Tab. II). This gives a pattern for each position, that can be convolved with the received signals an the proximal end in order to estimate the signal at that position, effectively placing a virtual transducer there [4]. While the calibration procedure is invasive, further measurements are non-invasive. After transforming the signals of the ultrasound array at the proximal end to the TRVA, delay-and-sum beamforming with plane wave compounding is performed [6].

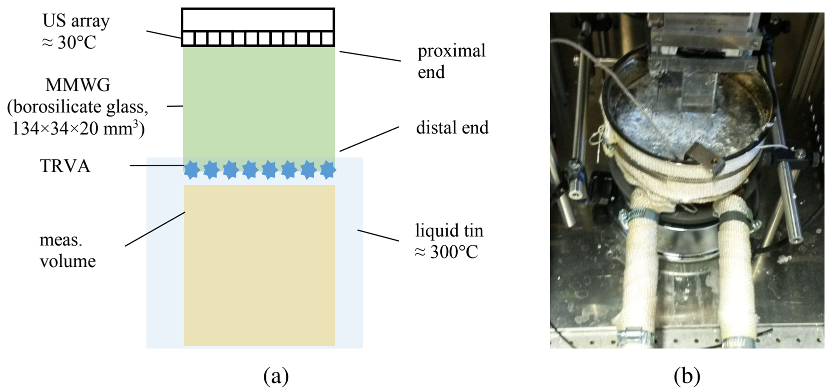

Fig. 1: Schema (a) and photograph (b) of the experimental setup.

Ultrasound Transducer Array	
type	SNX 140623 ME128-LMP10 (Sonaxis SA, France)
element count	$N_{\mathrm{el}} = 128$
element pitch	$\Delta x_{\mathrm{el}} = 0.5\,\mathrm{mm}$
height	$h = 5\,\mathrm{mm}$
center frequency	$f = 3.1\,\mathrm{MHz}$
band width ($-6\,\mathrm{dB}$)	$f\mathrm{bw} = 1.4\,\mathrm{MHz}$
Ultrasound Generation	
wave form	rectangular pulse, one period
plane wave tilt	$\alpha = \{0°, 8.6°, -8.6°\}$
frequency	$f_0 = 3\,\mathrm{MHz}$
electrical amplitude	$A = 20\,\mathrm{V}$
repetitions	$N = 32$
Ultrasound Detection	
gain	$43.5\,\mathrm{dB}$
samples	$N_{\mathrm{samp}} = 3576$
sampling frequency	$f_{\mathrm{samp}} = 30\,\mathrm{MHz}$

TABLE I: Parameters for ultrasound generation and detection using the PAUDV platform [5].

III. Experimental Characterization of the Imaging Properties in Liquid Tin

We determine the point spread function (PSF) of the system by imaging a point-like scatterer (the needle described in the previous section) in liquid tin at $\vartheta \approx 300\,°\mathrm{C}$. We quantify the following characteristics: The peak-to-background ratio (PBR) calculated from the intensity at the scatterer's position in relation to the mean background intensity. Furthermore, the full width at half maximum (FWHM) is determined for an axial and lateral cross section of the PSF. Fig 2 shows the PSF of the system imaging through a MMWG with and without compensation for two positions. Without compensation, the complex sound propagation through the MMWG distorts the PSF to an extend that makes spatially resolved measurements infeasible (PBR < 1). By applying the compensation with the TRVA method, focusing with PBR > 10 and a lateral $\mathrm{FWHM}_{\mathrm{lat}} < 2\lambda$ is achieved. It can be seen, that both characteristics degrade with increasing distance to the center of the distal end of the waveguide at $P_0(x = 0\,\mathrm{mm}, y = 0\,\mathrm{mm})$.

Waveguide	
material	Borosilicate glass
wavelength	$\lambda_{\mathrm{wg}} = 2.02\,\mathrm{mm}$
length	$L = 84\,\mathrm{mm}$
width	$W = 34\,\mathrm{mm}$
height	$H = 20\,\mathrm{mm}$
speed of sound (longitudinal)	$c_{\mathrm{wg}} = 6050\,\mathrm{m\,s^{-1}}$ [7]
shear wave speed	$c_{\mathrm{wg,shear}} = 3690\,\mathrm{m\,s^{-1}}$ [7]
density	$\rho = 13.5\,\mathrm{kg/m^3}$ [7]
specific acoustic impedance	$Z_{\mathrm{wg}} = 13.5\,\mathrm{MPa\,s\,m^{-1}}$ [7]
TRVA	
element count	$N_{\mathrm{VA}} = 64$
element pitch	$\Delta x_{\mathrm{TRVA}} = 0.539\,\mathrm{mm}$
time window	$t \in [27.8\,\mathrm{\mu s}, 52.1\,\mathrm{\mu s}]$
Measurement Field	
fluid	liquid tin
temperature	$\vartheta \approx 300\,°\mathrm{C}$
speed of sound	$c_{\mathrm{tin}} = 2471\,\mathrm{m\,s^{-1}}$
wavelength	$\lambda = 0.82\,\mathrm{mm}$
geometry	$x \in [-21\,\mathrm{mm}, 21\,\mathrm{mm}]$
	$y \in [2\,\mathrm{mm}, 25\,\mathrm{mm}]$
grid spacing x	$\Delta x = 0.10\,\mathrm{mm}$
grid spacing y	$\Delta y = 0.10\,\mathrm{mm}$

TABLE II: Parameters of TRVA imaging.

IV. Conclusion and Outlook

Ultrasound imaging of structures in liquid tin at $\vartheta \approx 300\,°\mathrm{C}$ is demonstrated by using a MMWG in combination with the TRVA method. Despite the complex propagation, a spatial resolution of $\mathrm{FWHM}_{\mathrm{lat}} < 2\lambda$ with PBR > 10 has been achieved. It is planned to apply this method to the solidification of liquid metals, thereby tracking the liquid-solid interface directly in a metallurgical process. Furthermore, in-process imaging of complex flow structures in hot liquids, such as plastics, will be attempted. This may extend the scope of ultrasound imaging to a new class of applications in harsh, industrial environments.

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(a) PBR $= 0.2$

(b) PBR $= 0.7$

(c) PBR $= 81.4$, FWHM$_{\text{lat}}$ $= 1.34\,\text{mm} = 1.6\lambda$

(d) PBR $= 17.3$, FWHM$_{\text{lat}}$ $= 1.54\,\text{mm} = 1.9\lambda$

Fig. 2: PSF of the ultrasound intensity at $P_1(x = 13\,\text{mm}, y = 13\,\text{mm})$ (c, a) and at $P_2(x = 3\,\text{mm}, y = 21\,\text{mm})$ (d, b) with (c,d) and without (a, b) compensation through the TRVA; experimentally determined by imaging a scatterer ($d = 1\,\text{mm}$); the white cross identifies the location; the lines above and right of the plot give the lateral and axial cross section.

experimental setup. This research was funded by Deutsche Forschungsgemeinschaft, grant number Cz 55/43-1.

References

[1] S. Eckert, G. Gerbeth, and V. Melnikov, "Velocity measurements at high temperatures by ultrasound doppler velocimetry using an acoustic wave guide," *Experiments in Fluids*, vol. 35, no. 5, pp. 381–388, 2003.

[2] T. Ihara, N. Tsuzuki, and H. Kikura, "Application of ultrasonic doppler velocimetry to molten glass by using broadband phase difference method," *Flow Measurement and Instrumentation*, vol. 48, pp. 90–96, 2016.

[3] M. Fink, "Time reversal of ultrasonic fields. I. Basic principles." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 39, no. 5, pp. 555–566, 1992.

[4] M. Kalibatas, R. Nauber, C. Kupsch, and J. Czarske, "Flow field imaging with ultrasonic guided waves for exploring metallic melts," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, no. 1, pp. 112–119, 2018.

[5] K. Mäder, R. Nauber, V. Galindo, H. Beyer, L. Büttner, S. Eckert, and J. Czarske, "Phased array ultrasound system for planar flow mapping in liquid metals," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 64, pp. 1327–1335, 2017.

[6] G. Montaldo, M. Tanter, J. Bercoff, N. Benech, and M. Fink, "Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 56, no. 3, pp. 489–506, Mar. 2009.

[7] N. K. Bourne, L. C. Forde, J. C. F. Millett, and J. E. Field, "Impact and Penetration of a Borosilicate Glass," *Journal De Physique IV*, vol. 7, no. 1 997, pp. 1–6, 1997.