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Uncertainty comparison of velocity estimators for ultrasound flow imaging in narrow channels

Messunsicherheitsvergleich von Geschwindigkeitsschätzern der Ultraschallströmungsbildgebung in schmalen Kanälen

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Abstract: Ultrasound Imaging with a linear phased array allows measuring turbulent vector profiles in two dimension with two components (2D2C). This is interesting in narrow channels for the application in battery cells or research in magnetohydrodynamics (MHD), where the access to the opaque fluid is often restricted. There are two main velocity estimation methods applicable: the Ultrasound Doppler Velocimetry (UDV) or the Ultrasound Image Velocimetry (UIV).

In this work, these methods were evaluated by their attainable measurement uncertainty for the application in narrow channels, where the acquisition of the lateral velocity component is crucial. With a calibration rig, UIV could achieve a total measurement uncertainty of 9.9 % and UDV 17.6 %. As UIV reaches a 44 % lower measurement uncertainty, it is the preferential method to measure lateral flows in narrow channels. In future work, the calibration rig will be adapted to optimize and characterize the flow instrumentation in opaque liquid metals.

Keywords: Measurement uncertainty, flow imaging, ultrasound.

Zusammenfassung: Ultraschallbildgebung mit linearen Phased Arrays erlaubt Messungen turbulenter Strömungsvektoren in zwei Dimensionen mit zwei Komponenten (2D2C). Das ist interessant für die Applikation in schmalen Kanälen für Batteriezellen oder für Grundlagenforschung im Bereich der Magnetohydrodynamik (MHD), wobei der experimentelle Zugang zum opaken Medium oft eingeschränkt ist. Hierbei sind zwei hauptsächliche Geschwindigkeitsschätzer einsetzbar: die Ultraschall-

Doppler-Velozimetrie (UDV) oder die Ultraschall-Image-Velozimetrie (UIV).

In dieser Arbeit wurden die Verfahren anhand ihrer erreichbaren Messunsicherheit in der Anwendung an schmalen Kanälen charakterisiert. An einem Kalibrierstand konnte eine totale Messunsicherheit von UIV mit 9,9 % und von UDV mit 17,6 % erreicht werden. Da UIV eine um 44 % geringere Messunsicherheit erreicht, ist es das bevorzugte Verfahren für die Bildgebung von lateralen Strömungen in schmalen Kanälen. In zukünftiger Arbeit wird der Kalibrierstand angepasst um die Strömungsbildgebung in opaken Flüssigmetallen zu optimieren und zu charakterisieren.

Schlüsselwörter: Messunsicherheit, Strömungsbildgebung, Ultraschall.

1 Introduction

Ultrasound flow imaging in narrow channels is a promising technique for the application in battery cells [1], crystal growth [2] or for fundamental research in the field of magnetohydrodynamics (MHD) [3] that use opaque fluids. The ultrafast method with the linear phased array adaptive focussing allows imaging of turbulent vector flow profiles. The experiments require two-dimensional plane scanning of two-component velocity vectors (2D2C) by only one acoustical access.

Within narrow channels, measuring the lateral velocity component is crucial. Recent studies showed promising results by means of the Ultrasound Doppler Velocimetry (UDV) [2]. This method can be adapted with the crossed beam method to measure 2D2C [4]. One further method is the application of Ultrasound Image Velocimetry (UIV) [5].

The aim of this work is to characterize the attainable measurement uncertainty and choose the more appropriate method. This is done by comparing the methods of UIV and UDV as described in Section 2 on the grounds of their attainable measurement uncertainty. Therefore, a

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calibration setup was build, as more thoroughly specified in Section 3. The results of the velocity estimators are presented and discussed in Section 4.

2 Ultrafast phased array velocimetry

2.1 Imaging

The Ultrafast Imaging method uses a plane wave excitation by means of a phased array probe and simultaneous recording of occurring echoes [6], as depicted in Fig. 1. The echoes are localized by digital parallel beamforming. Therefore, the delay-and-sum method is used, which means delaying, windowing and summing up each transducer signal according to its expected travelling time to a certain focus point.

Fig. 1: Principle of the ultrafast plane wave scan with a phased array. (a) Plane wave excitation; (b) receiving of the backscattered echoes; (c) successive delay-and-sum beamforming for localization of echoes.

2.2 Velocimetry

The localized echoes comprise the vector flow information of the medium. As mentioned in Section 1, UDV and UIV can be utilized to estimate the velocity with pulsed ultrasound signals [5].

Doppler Velocimetry

With Ultrasound Doppler Velocimetry (UDV), the phase difference of signals is used to estimate flow velocities [2]. It offers a higher spatial resolution and more computational efficiency than UIV. For 2D2C profile measures, the phased array is divided into two sub-apertures [4]. Each one has a separate Doppler sensitivity direction, which are crossing in a certain manner for every focus point in the 2D-plane. By means of a coordinate transform, the velocities can be reconstructed to 2C-vectors. However, the sensitivity directions are roughly estimated. Scattering of the sound field and masking of transducers introduces an unknown systematic deviation.

Image Velocimetry

Ultrasound Image Velocimetry (UIV) is based on the correlation of local intensity distributions [1]. Interrogation windows of subsequent planar 2D-images are being correlated. Usually, window sizes of multiple wavelengths are necessary. It thus has a lower spatial resolution than UDV, but is not as sensitive to wavefront distortions as UDV [1].

3 Laminar calibration rig

3.1 Concept

The main goal of the calibration rig is to estimate the measurement uncertainty and the spatial resolution of the flow imaging. In conformity with the guide to the expression of uncertainty in measurement (GUM), the standard measurement uncertainty u_v consists of a systematic deviation $u_{v,\text{sys}}$ and a random deviation $u_{v,\text{rand}}$:

$$u_v = \sqrt{u_{v,\text{sys}}^2 + u_{v,\text{rand}}^2}. \quad (1)$$

$u_{v,\text{rand}}$ is given by the empirical standard deviation of the mean value s_v with

$$u_{v,\text{rand}} = \frac{s_v}{\sqrt{N}}. \quad (2)$$

$u_{v,\text{sys}}$ can be obtained by the difference to a reference. As $u_{v,\text{sys}}$ can only be obtained for this reference, the systematic deviation is unknown for any other flow rate. Following the principle of maximum entropy of GUM, the systematic deviation equals

$$u_{v,\text{sys}} = \frac{v - v_{\text{ref}}}{\sqrt{3}}. \quad (3)$$

3.2 Calibration setup

To obtain a reference velocity, a setup with a flow cell that provides a laminar flow is used. The setup is shown in Fig. 2. The measurement region in the setup has a range of $10 \text{ mm} \times 12 \text{ mm}$ ($x \times y$). It is indicated by the blue rectangle in Fig. 2. A velocity gradient in the elevation direction introduces random deviations. In order for this matter to be negligible, the measurement region is placed in the middle and the flow channel has a width of $w = 30 \text{ mm}$, ten times the element height of the array probe. The wall on top is 5 mm thick and made of acrylonitrile butadiene styrene (ABS). The material couples the ultrasound into the glycerol with a similar acoustical impedance to avoid reflections.

A pump with a pulseless head drives the flow. Glycerol (purity 99.9%, density 1.261 g/cm^3 , viscosity 1.412 Pa s) with $0.5 \text{ vol\%}$ added scattering particles is used as fluid. Based on the channel dimensions and the flow rate, the mean velocity can be calculated as:

$$\bar{v} = \frac{\dot{V}}{A} = \frac{\dot{V}}{w \cdot h}. \quad (4)$$

$\bar{v}$ is used as input variable for a CFD simulation with OpenFOAM to calculate the reference velocity profile in the channel geometry. The uncertainty of the simulation is negligible compared to the uncertainty of the input variable $\bar{v}$. Therefore, the calibration rig has a mean uncertainty of $u_{\bar{v}} = 0.065 \text{ mm/s}$, see the budget in Tab. 1. Hence, the uncertainty of the reference is negligible compared to the uncertainty of the velocity measurement.

As the reference is zero at the borders, the mean velocity of Eq. 4 is employed to calculate the relative uncertainties:

$$F_v = \frac{u_v}{\bar{v}}, \quad F_{v,\text{sys}} = \frac{u_{v,\text{sys}}}{\bar{v}}, \quad F_{v,\text{rand}} = \frac{u_{v,\text{rand}}}{\bar{v}}. \quad (5)$$

Fig. 2: The flow imaging setup for the calibration.

Table 1: Measurement uncertainty budget for the calibration rig.

Quantity	Uncertainty	Estimated through
$\dot{V} = 80 \text{ ml/min}$	$u_{\dot{V}} = 1.38 \text{ ml/min}$	OEM calibration
$w = 30 \text{ mm}$	$u_w = 0.029 \text{ mm}$	max deviation
$h = 12 \text{ mm}$	$u_h = 0.029 \text{ mm}$	max deviation
$\bar{v} = 3.7 \text{ mm/s}$	$u_{\bar{v}} = 0.065 \text{ mm/s}$	error propagation

Table 2: The specifications of the phased array probe used.

Manufacturer	Imasonic
Element pitch	0.3 mm
Element height	3 mm
Number of elements	128
Center frequency	4 MHz
Relative bandwidth	$\approx 70 \%$

3.3 Flow field imaging

The phased array with the specifications given in Tab. 2 is utilized for the imaging. It is done with the parameters given in Tab. 3. There are slight differences between UIV and UDV. The excitation signal of UDV has a longer pulse width with 4 periods excitation. The processing of UDV requires a smaller bandwidth and a mid-frequency below the side lobe criteria of the phased array. The correlation window size is three times smaller and therefore the spatial resolution three times higher.

4 Measurement uncertainty analysis

4.1 Characterization results

Calibration measurements were conducted with a flow rate of 80 ml/min as given by Tab. 1. 60 profiles were measured over time. The mean value of the profile in the middle of the 2D-plane is shown in Fig. 3 for UIV and UDV compared to the reference. The coloured areas around the curves indicate the standard deviation of the mean value. The reference is depicted as an orange line. $F_{v,\text{sys}}$, $F_{v,\text{rand}}$ and F_v are calculated from these results and depicted in Fig. 4.

The total measurement uncertainty is calculated as a mean value over all measured points N_y in y :

$$\bar{F}_v = \frac{1}{N_y} \sum_y F_v(y). \quad (6)$$

Table 3: The flow imaging parameters for the procedure, the excitation signal and the signal processing of both UIV and UDV.

Measurement parameters	UIV	UDV
Number of us elements	32	32
Pulse repetition frequency	600 Hz	600 Hz
Emissions per profile	500	500
Measured profiles N	60	60
Excitation frequency	6 MHz	6 MHz
Signal length	2 periods	4 periods
Signal processing parameters		
Processed frequency range	3 to 7.2 MHz	3.6 to 4.4 MHz
Processed window size	$3\lambda = 0.96$ mm	$1\lambda = 0.32$ mm

Here, UIV reaches a total value of $\overline{F}_v = 9.9\%$ and UDV 17.6%.

4.2 Discussion

Random deviation

As depicted in Fig. 4, UDV has a significant lower random deviation than UIV. One reason may be that outliers occur in the UIV processing due to a low signal to noise ratio (SNR) of the correlation maximum [7]. This can be improved with an outlier filter. Furthermore, the lower spatial resolution of UIV leads to greater random deviations, when dissolving a gradient in the velocity profile. This can be improved with adaptive correlation of win-

Fig. 3: The measured profiles of UIV and UDV against the reference. The coloured area around the curves indicates the standard deviation.

dow sizes [8], Plane Wave Compounding [9] or the use of Particle Tracking [10].

Overall, there is an increasing random deviation with the measurement depth for both methods. This corresponds to a lower SNR due to the acoustical attenuation of the medium and to a decreasing spatial resolution of the beamformed focus points in larger distance. In the case of UDV, the sensitivity direction tends towards the axial velocity component with increasing measurement depth. This too can cause increasing random deviations.

Systematic deviation

From Fig. 3 and 4 it can be obtained, that UIV has a lower mean systematic deviation than UDV. There are several possible reasons. As mentioned in Section 2, there is a systematic deviation in the estimation of the sensitivity directions. Each transducer signal of the phased array is superimposed with a directivity pattern. This is neglected in the estimation of the sensitivity directions, leading to a spatial dependent deviation in transforming the measured velocity into the 2D-plane. Further investigations on adap-

Fig. 4: The relative systematic deviation $F_{v,sys}$ (top), the relative random deviation $F_{v,rand}$ (middle) and the relative measurement uncertainty F_v (bottom) of UIV and UDV.

tive apodization of the transducers could help decreasing this deviation.

Besides, there is an increasing measured mean value in advancing measurement depth y with UDV, which appears as a shifted profile in Fig. 3. The used Doppler frequency estimation with autocorrelation is sensitive to wavefront distortions in the medium [1]. The distortions occur more likely, when the wavefront passes more particles, leading to an increasing systematic deviation. Furthermore, the deviation by the sensitivity direction estimation may increase with the depth.

Considering $F_{v,\text{sys}}$ in the range of 1 mm to the wall, there is a similar effect visible within UIV and UDV. Both methods overestimate the velocity in this region, almost to a constant value. This may be caused by two effects: an insufficient spatial resolution within the velocity gradient and scattering effects caused by the boundary layers. The effect increases especially on the back wall, where the signal may additionally be distorted by reflections. However, UIV has a lower systematic deviation in this region. This concludes that it is more robust against near wall distortions in this setup.

Measurement uncertainty

From Fig. 4 it can be obtained, that $F_{v,\text{sys}}$ has the main impact on the measurement uncertainty F_v for both methods. Comparing the mean values shows, that UIV reaches a 44 % lower F_v than UDV. This concludes that UIV is the more appropriate technique for the imaging of lateral flows in narrow channels.

5 Conclusion

With this work, the performance of UIV and UDV on flow imaging in narrow channels was investigated. To do so, the measurement uncertainty was characterized in a calibration rig with a lateral laminar flow. In this setup, UIV reached a total measurement uncertainty of 9.9 %, lower than UDV with 17.6 %. The measurement uncertainty analysis showed that the systematic deviation has the main impact to the measurement uncertainty of both methods. This may be caused by wavefront distortions of the imaging methods.

For research in MHD, the calibration rig will be adapted to be capable of running experiments with GaInSn to optimize the flow instrumentation in liquid metals. Then, the local distributed measurement uncertainty will

be used as a figure of merit for systematic optimization. This will be advantageous for fundamental research or applications in energy storages in liquid metal batteries in the future.

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References

- [1] C. Kupsch, D. Weik, L. Feierabend, R. Nauber, L. Büttner, and J. Czarske. Vector flow imaging of a highly laden suspension in a zinc-air flow battery model. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 66(4): 761–771, Apr. 2019. 10.1109/TUFFC.2019.2891514.
- [2] N. Thieme, M. Keil, D. Meier, P. Bönisch, K. Dadzis, O. Pätzold, M. Stelter, L. Büttner, and J. Czarske. Directional solidification of gallium under time-dependent magnetic fields with in situ measurements of the melt flow and the solid-liquid interface. *Journal of Crystal Growth*, 522: 221 – 229, Sept. 2019. 10.1016/j.jcrysgro.2019.06.034.
- [3] Y. Tasaka, K. Igaki, T. Yanagisawa, T. Vogt, T. Zuerner, and S. Eckert. Regular flow reversals in rayleigh-bénard convection in a horizontal magnetic field. *Phys. Rev. E*, 93: 043109, Apr. 2016. 10.1103/PhysRevE.93.043109.
- [4] 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*, 64(9): 1327–1335, Sept. 2017. 10.1109/TUFFC.2017.2693920.
- [5] C. Poelma. Ultrasound imaging velocimetry: a review. *Experiments in Fluids*, 58(1):3, Dec. 2016. 10.1007/s00348-016-2283-9.
- [6] M. Tanter and M. Fink. Ultrafast imaging in biomedical ultrasound. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 61(1):102–119, Jan. 2014. 10.1109/TUFFC.2014.2882.
- [7] C. Poelma, R. Van der Mijle, J. Mari, M.-X. Tang, P. Weinberg, and J. Westerweel. Ultrasound imaging velocimetry: Toward reliable wall shear stress measurements. *European Journal of Mechanics-B/Fluids*, 35:70–75, 2012.
- [8] R. Theunissen, F. Scarano, and M. Riethmüller. An adaptive sampling and windowing interrogation method in PIV. *Measurement Science and Technology*, 18 (1), 18, Jan. 2007.
- [9] 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*, 56(3):489–506, Mar. 2009.
- [10] C. Errico, J. Pierre, S. Pezet, Y. Desailly, Z. Lenkei, O. Couture, and M. Tanter. Ultrafast ultrasound localization microscopy for deep super-resolution vascular imaging. *Nature*, 527(7579):499, 2015. 10.1038/nature16066.