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**Publication date**

2016

**Document Version**

Final published version

**Published in**

Proceedings of the 18th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics

**Citation (APA)**

Poelma, C., & Gurung, A. (2016). Instantaneous velocity field measurement in densely-laden two-phase flows using Ultrasound Imaging Velocimetry. In *Proceedings of the 18th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics* Instituto Superior Técnico.

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# PROCEEDINGS

OF THE

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FLUID MECHANICS

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# Instantaneous velocity field measurement in densely-laden two-phase flows using Ultrasound Imaging Velocimetry

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**Keywords:** PIV, ultrasound, turbulence, two-phase flows

## ABSTRACT

Ultrasound Imaging Velocimetry (UIV, also known as 'echo-PIV') has, since its introduction a decade ago, been regarded as a promising tool to characterize non-transparent flows. Prime application examples are particle-laden flows and (in vivo) blood flow. Virtually all studies so far have been validation/comparison studies in laminar flow. In this contribution, we show that the technique has matured to a state where also unsteady, turbulent flows can be characterized. We do this by performing measurements in a fully-developed (single-phase) turbulent pipe flow at a Reynolds number of 5300. The outcome agrees with literature data. Subsequently, we demonstrate that the technique can measure in the same flow, but now with a moderate volume fraction of particles; such flows are beyond the capabilities of conventional, optical techniques. This opens up a wide range of application areas, such as studies into turbulence modification and sediment transport.

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## 1. Introduction

Two-phase flow phenomena play a key role in many processes in both industry and nature. Despite their importance, the understanding of their underlying physics - a necessity for proper modelling - is somewhat limited. This can be attributed to the fact that the current *de facto* standard methods used in research laboratory are based on optical measurement techniques: in particular LDA and PIV in its various incarnations. As soon as there is an appreciable volume fraction of a dispersed phase, the resulting turbidity of the fluid invalidates the optical approaches. Volume loads as low as 0.5% have been reported to be the practical limit of PIV in two-phase flow (Poelma et al., 2006).

In recent years, several techniques have been proposed to study turbid, particle-laden flows. Examples include flow measurements based on Magnetic Resonance Imaging and X-Ray imaging. A third alternative, with a much lower barrier of entry, is ultrasound imaging velocimetry (UIV or "echo-PIV"; Kim et al., 2004; Poelma et al., 2011). In this technique, particle



image velocimetry algorithms are applied to images obtained using echography (instead of cameras and lasers). Since its introduction, many studies have appeared focusing on validation, by comparing the outcome with e.g. optical PIV or theoretical results. At the same time, applications start to appear, e.g. to characterize intraventricle flow (Cimino et al., 2012) or determine non-Newtonian rheology in opaque fluids (Gurung et al., 2015). However, virtually all of the studies so far have only used either qualitative interpretation or time-averaged flow statistics (with the use of phase-averaging for periodic flows). To date, no study has attempted to determine quantitative flow statistics on instantaneous images.

In this study, it is demonstrated that UIV has matured enough that it can reliably obtain statistics in turbulent two-phase flows, even at moderate volume fractions (here approximately 5%).

## 2. Turbulence statistics in single-phase and two-phase flows

First, the measurement system and facility are validated using a well-described single-phase reference flow: fully-developed turbulent pipe flow at  $Re = 5300$  (Eggels et al., 1996). The data is acquired using a SonixTouch echography machine with a 128-element linear transducer, providing a typical field-of-view of  $4 \times 4 \text{ cm}^2$ . Data is processed using in-house software. The mean velocity, as well as 2<sup>nd</sup> order statistics (in particular  $\langle uu \rangle$ ,  $\langle vv \rangle$  and  $\langle uv \rangle$ ) correspond well with the literature data; see e.g. Figure 1, which shows the root-mean-square of the streamwise and radial velocity fluctuations together with the reference values. In the near-wall region ( $r/D \sim 0.45$ ) the fluctuations are overestimated due to measurement errors, in particular for the streamwise velocity component. This is due to the relatively poor resolution of UIV in the streamwise direction, as compared to the radial direction (Poelma et al., 2012). Nevertheless, the main features of the flow are captured with sufficient accuracy.



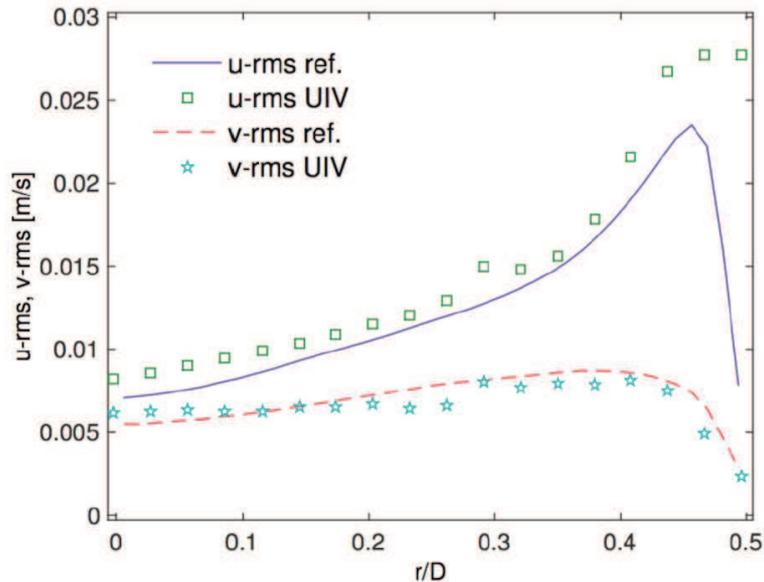


Figure 1: single-phase validation of ultrasound imaging velocimetry (symbols); comparison with literature reference data (lines) for fully-developed turbulent pipe flow at  $Re = 5300$ .

In the second part of the study, turbulent particle-laden flow is studied. In figure 2, two snapshots of the flow are shown with a volume fraction of 5% particles (3M Zeeospheres G-850; density  $2.1 \text{ g/cm}^3$ ,  $D_{50} = 40 \text{ }\mu\text{m}$ ,  $95\% < 160 \text{ }\mu\text{m}$ ). The left hand side shows a mobile bed, with a laminar-like flow above it. Note the gradual decrease of the velocity near the top of the bed (middle dashed line), with non-zero velocities extending in the top of the bed. In the right hand side, the flow rate is increased. This fully suspends the particles and the velocity field is a flattened, turbulent profile. Note that the velocity profiles are based on UIV vector fields (averaged in time and along the width of the field-of-view). Based on the local intensity, it is even possible to obtain a semi-quantitative estimate of the particle concentration.

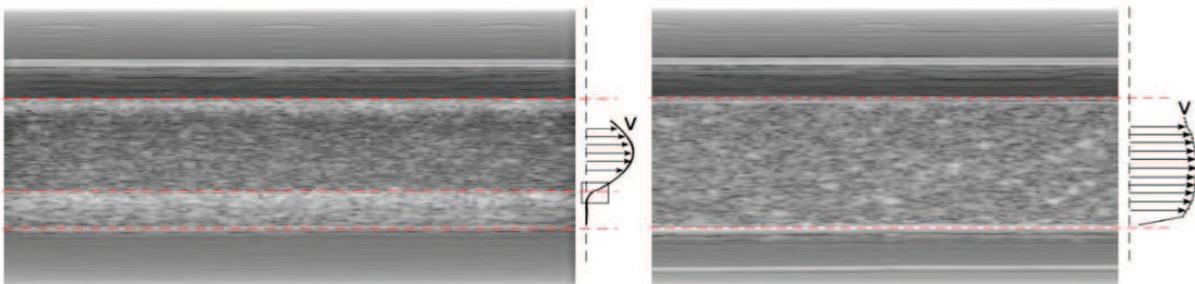


Figure 2: Snapshot of the flow in two situations: slower flow leads to a mobile bed with a laminar velocity profile above it. A higher velocity suspends the particles and leads to a flattened, turbulent velocity profile. The mean velocity profiles have been averaged over the width of the vector field.



In figure 3, the turbulence statistics are reported for the particle-laden flow at a Reynolds number of approximately 6800 (mean, fluctuations and Reynolds stress  $\langle uv \rangle$ ). Note that there is no reference data available for this case. No very significant changes are expected with respect to the single-phase (due to the low Stokes number of the dispersed phase particles), apart from an increased relative density. The statistics indeed resemble the reference data for the single-phase flow. However, the streamwise fluctuations are likely to be strongly affected by noise, and are overestimated to a great extent near the walls.

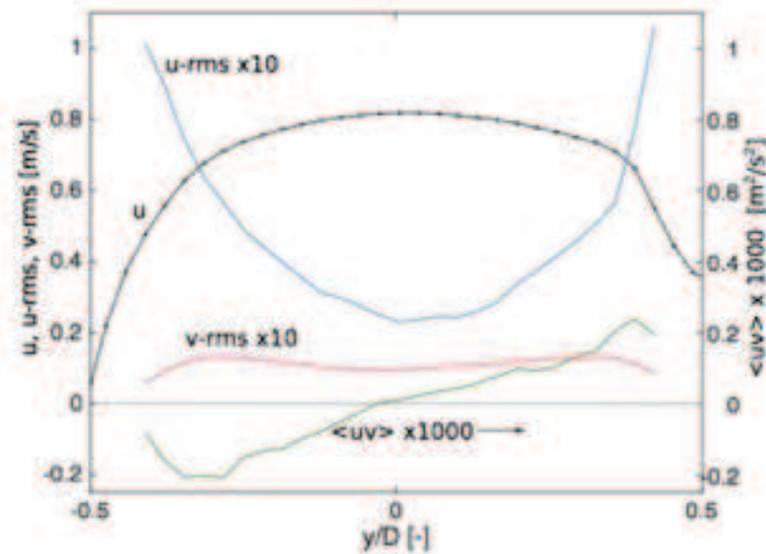


Figure 3: turbulence statistics in a flow with a volume load of approximately 5% and a Reynolds number  $Re = 6800$ .

The accuracy of the technique and restrictions with respect to volume fraction are studied in a mock-up (a small capped pipe section, which allows for rapid change in particle type and load) using time-resolved measurements. By evaluating the temporal variation of the velocity at each point (for a simple, agitated flow), an estimate for the measurement uncertainty can be obtained. At a volume load of 10%, an estimated error of 3.5 mm/s in the streamwise and 0.51 mm/s in the radial direction are obtained. For the case of single-phase case at  $Re = 5300$ , this would translate to an error of 2.6% and 0.37% of the bulk velocity.

These proof-of-principle measurements show that UIV is a powerful tool that will enable the study of turbid two-phase flows that have hitherto eluded experimental investigation. Future work will concentrate on systematic studies of the effects of various particle sizes, densities and loads on turbulent flows. This will shed light on the underlying physics of these important flows.



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