

Large-Volume Pressure from Tomographic PTV in a Surface Mounted Cylinder Near-Wake using HFSB Tracers

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1 Introduction

Particle image velocimetry (PIV) is used as a standard tool for aerodynamic studies in wind-tunnels, as it allows the simultaneous measurement of the velocity field in a planar domain. The use of a tomographic PIV system extends the approach to a three-dimensional measurement volume, in turn helping to characterize complex turbulent flows. However, the use of tomographic PIV in aerodynamic wind tunnels is hampered by the fairly limited size of the measurement volume (few cubic centimeters), mostly due to the low intensity of the light scattered by micron-size tracers.

Recent advances of tomographic PIV using Helium-filled soap bubbles (HFSB) as tracers have shown that the measurement volume can be significantly increased (up to several thousands cubic centimeters) for velocity measurements in air [1, 2]. The present work builds upon the above mentioned capabilities and applies tomographic PIV using HFSB as tracers to measure the instantaneous flow field pressure in a measurement volume of several liters. The resulting method is interesting in that it significantly simplifies pressure measurements over extended surfaces.

The experiments are conducted simultaneously with surface pressure measurements intended as ground truth to estimate the accuracy of the proposed measurements. The sample problem chosen for the experiments is that of a truncated cylinder installed on a flat plate, which features both wall bounded turbulence as well as large scale unsteady flow separation.

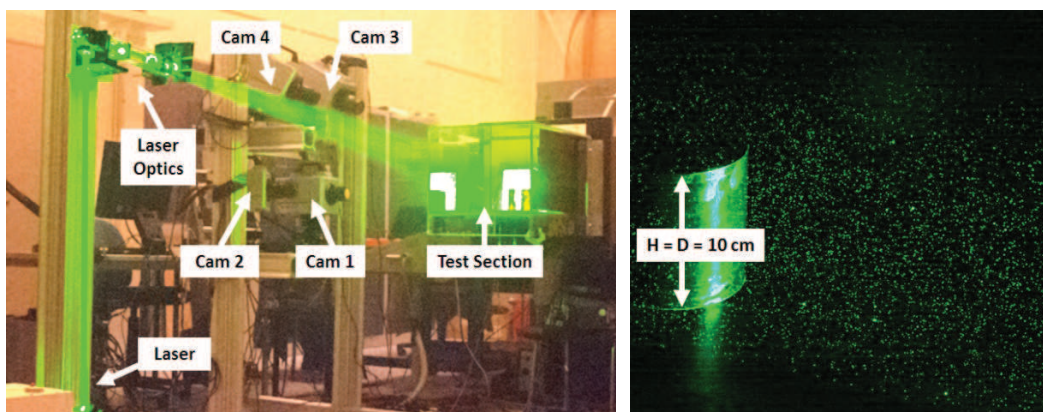


Fig. 1. Arrangement of the experimental setup (left) and an instantaneous image captured by camera 4 (right) of the wall-mounted cylinder ($H=D=10$ cm) with seeding (HFSB)

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The present flow topology was considered in a variety of studies [4], and offers relevant aerodynamics applications, such as acoustic noise generated by protrusions or appendices (car side mirror or landing gear, among others). Measurement of the instantaneous pressure in this flow case has proven to be a challenge, with recent studies employing wind tunnel models equipped with up to 179 simultaneously operated pressure taps [5].

2 Experimental setup and processing procedures

The experiments are conducted in the W Tunnel of TU Delft. The wind tunnel has an open-return-circuit with an open test section of $40 \times 40 \text{ cm}^2$. A cylinder of 10 cm diameter and height is installed on a flat plate. The boundary layer is tripped to ensure a turbulent boundary layer. Measurements are conducted at a free stream velocity of 5 m/s ($Re_D = 3.6 \times 10^4$). Figure 1 (left) illustrates the experimental setup.

To capture the near-wake of the cylinder a measurement domain is selected. The achievement of the present measurement domain, which is two orders of magnitude larger than conventional tomographic experiments [3], was possible only through the use of neutrally buoyant HFSB with a diameter of approximately $300 \text{ }\mu\text{m}$ as tracers. Images were recorded with a particle density of 0.7 bubbles per cm^3 . Illumination is provided by a Quantronix Darwin-Dwo Nd:YLF laser, which has a nominal pulse energy of $2 \times 25 \text{ mJ}$ at 1 kHz. The imaging system consists of four Photron Fast CAM SA1 cameras (CMOS, 1024×1024 pixels, 12-bit, pixel dimension $20 \text{ }\mu\text{m}$). The cameras are equipped with 105-mm Nikkor objective at aperture setting of $f/16$. The optical magnification is $M = 0.26$ and the observed region is $20 \times 17 \times 18 \text{ cm}^3$. Ten sequences of 2000 single-frame images are acquired at 2 kHz to obtain a time-resolved measurement. The recorded images were pre-processed using a minimum subtraction filter and subsequently Gaussian smoothing with a $3 \times 3 \times 3$ pixels kernel. The particle images (see e.g. Fig. 1, right) are reconstructed using the FastMART algorithm in the LaVision *Davis* 8.2 software package. The domain is discretized into $1018 \times 725 \times 783$ voxels. Particles are identified in the volumes by peak-finding in a $5 \times 5 \times 5$ vox neighbourhood and sub-voxel accuracy of particle location is obtained by fitting of a 3D Gaussian through their intensity distribution. A particle-tracking algorithm based on Malik et al. [7] is used to calculate particle tracks (Fig. 2, left). A five-snapshot track length is employed, through which for increased accuracy a third order polynomial is fitted. The time-derivative of each polynomial yields velocity at the particle locations. Velocity is subsequently calculated on a grid ($70 \times 60 \times 60$ vectors) by the adaptive Gaussian windowing technique with $\sigma = 10 \text{ mm}$.

Instantaneous pressure is calculated by solving the Poisson equation for pressure (see e.g. [6]),

$$\nabla^2 p = -\rho \nabla \cdot \frac{D\mathbf{u}}{Dt} + \mu \nabla \mathbf{u}, \quad (2)$$

with Neumann boundary conditions from the momentum equation on all volume boundaries except the top boundary, where a Dirichlet boundary condition calculated from the Bernoulli equation is specified. The velocity material derivative is evaluated from the velocity measurements through a Lagrangian approach as outlined in Pröbsting et al. (2013).

Time-averaged pressure is evaluated using the time-averaged approach outlined in [5],

$$\nabla^2 \bar{p} = -\rho \nabla \cdot (\bar{\mathbf{u}} \cdot \nabla) \bar{\mathbf{u}} - \rho \nabla \cdot \nabla \cdot (\overline{\mathbf{u}'\mathbf{u}'}). \quad (3)$$

To obtain the time-averaged velocity field and the turbulence statistics, all instantaneous velocity vectors found from the PTV procedure are combined and averaged using Gaussian interrogation windows with $\sigma = 5 \text{ mm}$.

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For validation of the technique, reference instantaneous and time-averaged pressure measurements are taken at the surface using respectively four LinearX M51 microphones and a 2101 Mensor. To allow for direct comparison to the pressure reconstruction from the proposed technique, the microphone measurements are made simultaneous with the tomographic measurements.

3 Time-averaged velocity and pressure

The mean surface pressure is plotted in Fig. 2. The left figure shows the reference surface pressure measurement and the right figure the result obtained from the tomographic experiment. As can be seen, the two pressure minima around $x = 100$ mm are approximated accurately. In addition, the streamwise pressure evolution is accurately predicted as can be seen in Fig. 3, which shows the mean surface pressure along the centerline $y = 0$ mm and along the line $y = 40$ mm.

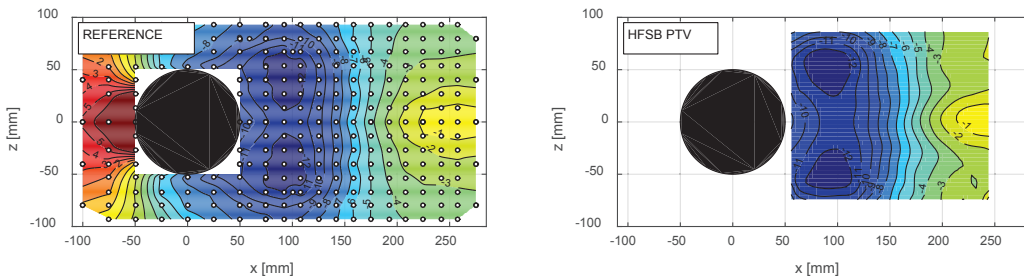


Fig. 2. Mean surface pressure; reference surface pressure measurements (left) and tomographic PTV (right).

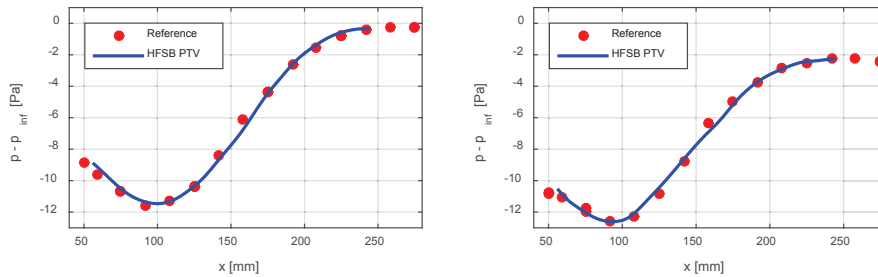


Fig. 3. Time-averaged surface pressure along $z = 0$ mm (left) and $z = 40$ mm (right)

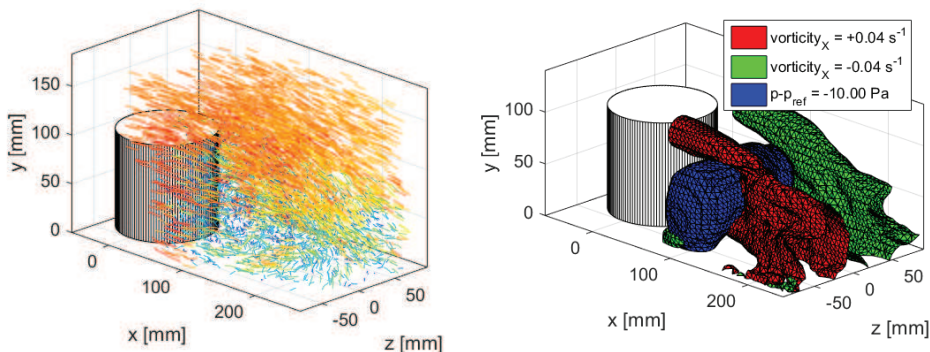


Fig. 4. Visualization of particle tracks (colored by velocity magnitude for clarity, left) and the mean flow field (right)

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In addition to surface pressure, the pressure reconstruction also provides pressure in the volume. Figure 4 (right figure) shows the resulting and expected low-pressure region (blue) in near-wake region, in relation to the two counter-rotating tip vortices.

4 Instantaneous pressure

Fig. 5 (left) shows a short sequence of the resulting pressure evolution in the plane $z = 20\text{mm}$, where an expected vortex shedding event can be identified from the low pressure structure separating from the wake region. For more quantitative assessment of instantaneous pressure, the microphone surface pressure measurement at $x = 150\text{mm}$, $z = 20\text{mm}$ is compared to the reconstruction pressure fluctuations at the same location in Fig. 5-right. The truncated time-series indicates correlation between the two. Full assessment and calculation of the correlation coefficients is left as a topic for future study.

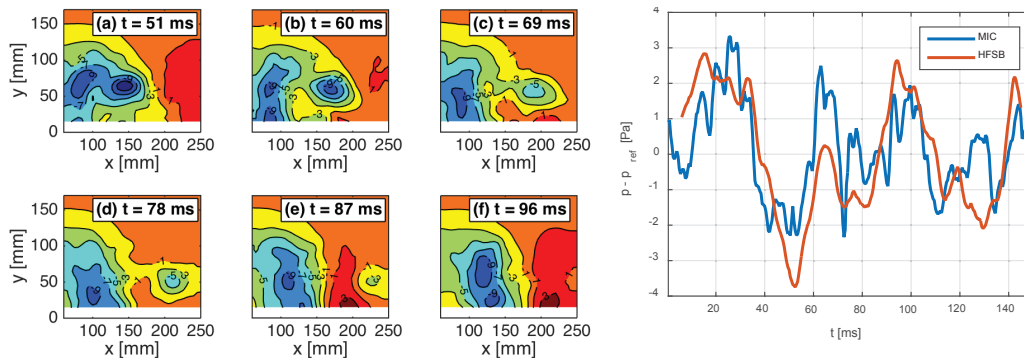


Fig. 5. Time-series of instantaneous pressure in the plane $z = 20\text{mm}$ (left) and time series of pressure at the location of microphone 3 ($x = 150\text{mm}$, $z = 20\text{mm}$; right)

5 Conclusions

Time-resolved tomographic PTV measurements in the near-wake of a low aspect-ratio surface mounted cylinder have been realized over a large measurement volume (6 liters) by use of HFSB as tracers. An algorithm based on PTV is used to estimate the velocity and its material derivative. By invoking the momentum equation, the mean and instantaneous pressure in the flow field is computed in the measurement volume. The results are compared to reference surface pressure measurements for the time averaged as well as fluctuating component. The former are found in excellent agreement and the latter returns a level of correspondence similar to recent studies in the literature (Ghaemi et al. 2012; Probsting et al. 2013). In conclusion, the Pressure-from-PIV approach has been extrapolated and shown viable also for large-scale experiments based on HFSB.

References

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