

Application of Helium Filled Soap Bubbles and STB for 3D PIV investigations of large-scale passive flow control devices

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ABSTRACT

The paper deals with application of large-scale PIV for investigation of flow field over structured surfaces used for flow control. The aim of the work was to demonstrate the feasibility of Helium Filled Soap Bubbles for investigation of passive flow control in wind tunnel at real-world scale and flow speeds. The flow control strategy relies on creating vortex formations in the boundary layer with use of dimples. To match the Reynolds number representative for automotive and general aviation aerodynamics the measurements were performed in low-speed wind tunnel with test section diameter of 5 m at flow speeds 20, 30 and 40 m·s⁻¹. Application of HFSB enabled for 3D PIV measurements in large volume of 0.5 m³ and revealed change in flow topology over structured surface.

1. Introduction

Passive flow control with use of structured dimples might prevent turbulent separation, intensify heat transfer, and reduce drag (Ali et al., 2024)(Butt et al., 2014). Visualization of flow topology near the wall surface is beneficial to understand the relation between the geometrical parameters and flow control capabilities of this devices (van Campenhout et al., 2018). Due to unsteady and three-dimensional nature of vortices induced by passive flow control devices it is desirable to capture instantaneous 3D flow field in the boundary layer. Therefore, techniques capable for volumetric velocity measurements near the wall at high Reynolds numbers are beneficial for both theoretical and practical studies dedicated to finding passive flow solutions.

Advances in effective generation of sub-millimetre size naturally buoyant seeding in form of Helium Filled Soap Bubbles (Scarano et al., 2015) and volume self-calibration (Wieneke, 2018) together with advanced particle tracing algorithms such as Shake-the-Box STB (Schanz et al., 2016) allowed for performing 3D PIV measurements in large volumes (Hysa et al., 2023)(Grille Guerra et al., 2024). The feasibility of HFSB for investigations of wall bounded turbulence was investigated by (Faleiros et al., 2018). Recently, the capabilities of 3D Lagrangian Particle Tracking with use of STB for was demonstrated in near wall flow at various Reynolds numbers by (Schröder et al., 2024).

In this study we investigate the feasibility of large-scale PIV with use of STB particle tracing and HFSB for investigation of flow topology above structured surface at Reynolds numbers representative for automotive and general aviation aerodynamics.

2. Materials and methods

The test was conducted in the Łukasiewicz Research Network – Institute of Aviation T-3 wind tunnel, in an open test section with a diameter of 5 m. The test object was a flat plate (400 mm × 500 mm × 5 mm) featuring a row of dimples (40 mm × 10 mm) arranged with alternating skew angles of -35° and $+35^\circ$ (see Figure 2, left). The HFSB injector was positioned at the exit of the wind tunnel nozzle.

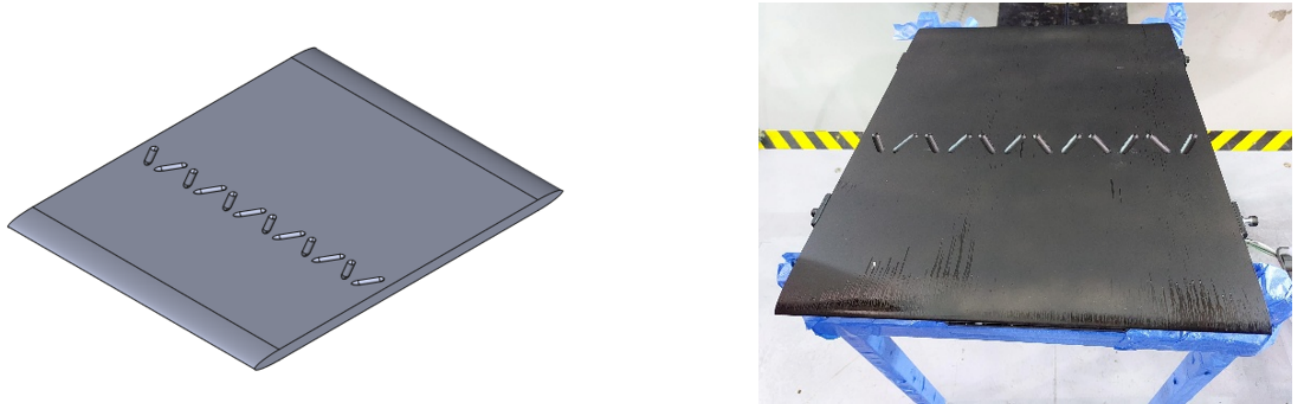


Figure. 1 (left) CAD model of the test object surface with dimples. (right) Test object in WT test section. Soap accumulation at the leading edge can be observed.

The test object was placed downstream of the WT/HFSB flow at the end of the test section, as shown in Figure 2. Tests were performed at freestream velocities of $20 \text{ m}\cdot\text{s}^{-1}$ and $30 \text{ m}\cdot\text{s}^{-1}$. The resulting Reynolds number was $6,65 \cdot 10^5$ and $1 \cdot 10^6$ respectively.

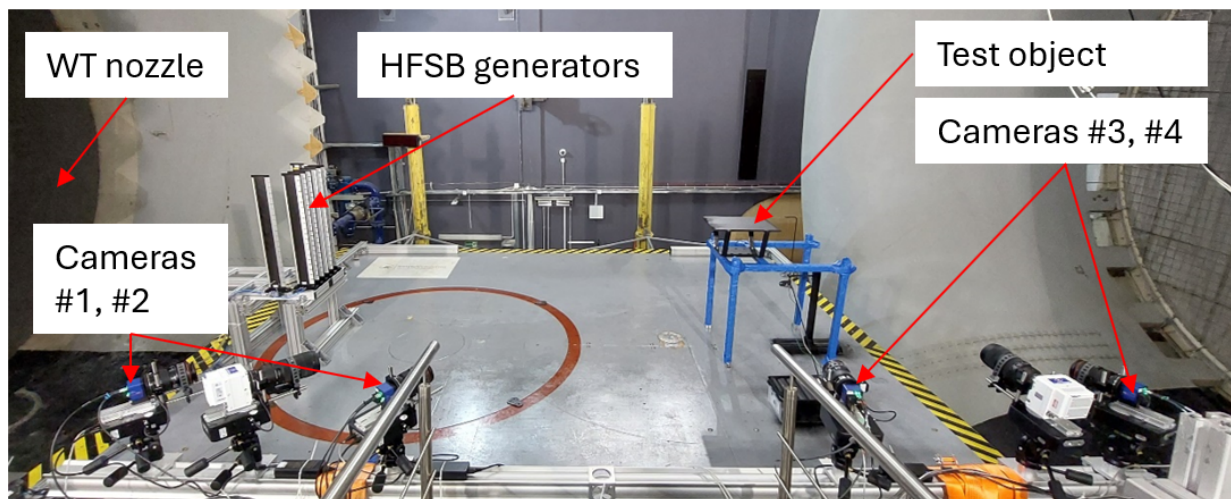


Figure. 2 HFSB 3D PIV STB system in T-3 test section.

2.1. Velocity measurements

The PIV system consisted of a Nd:YAG laser (400 mJ at 15 Hz) and four Imager CX3 cameras with 16 Mpx COMS sensors with high quality lenses (f ca 24 mm). The volume of $0,6 \times 1,2 \times 0,8$ m³ was calibrated with use of flat dotted calibration target. The Volume Self-Calibration with single image correction was applied to compensate the errors due to cameras vibrations during the image acquisition. All raw images were pre-processed by subtracting sliding minimum of 2 pixels and sliding Gaussian smoothing filter (3x3) for removing double glare at some particles images. The particle positions and displacement were detected in domain $640 \times 200 \times 450$ mm with double pulse Shake the Box (Novara et al., 2023), STB algorithm implemented in DaVis software from LaVision. An average of 85 000 particle tracks per recording was captured. This resulted in relatively low particle image densities of 0,005 particles per pixel. For the instantaneous velocity field, sufficient quality of the interpolated velocity data on a Cartesian grid was achieved using a binning procedure with a bin size of 10 mm, resulting in a Dynamic Spatial Range DSR of 64. To increase the spatial resolution, ensemble particle tracks from 1,000 measurements were interpolated using a subvolume size of 64 voxels with 75% overlap, resulting in a grid size of 3,439 mm (DSR = 232). The Dynamic Velocity Range calculated for ensemble PTV measurement (Agüera et al., 2016) was DVR = 125.

3. Results

Figure 3 and Figure 4 shows the 3D velocity field over test object with the dimples. The isosurfaces of ω_z vorticity at the outer edge of the boundary layer is displayed for both cases.

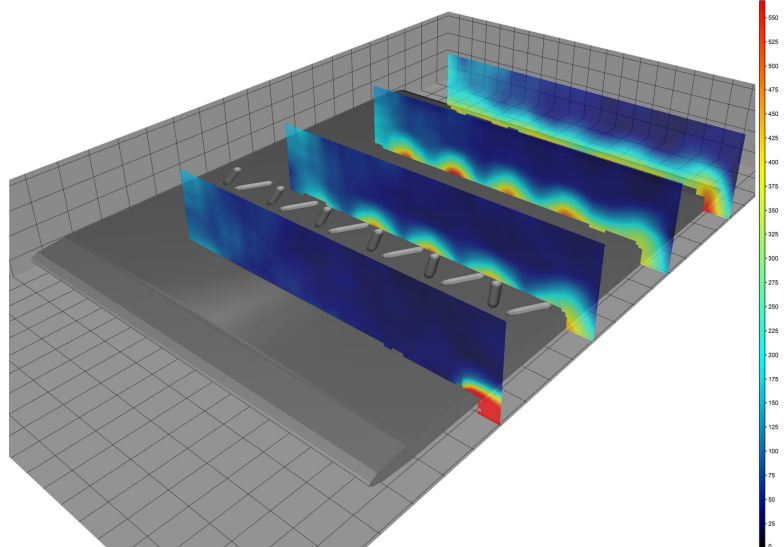


Figure. 3 2D cross-sections of 3D vorticity field.

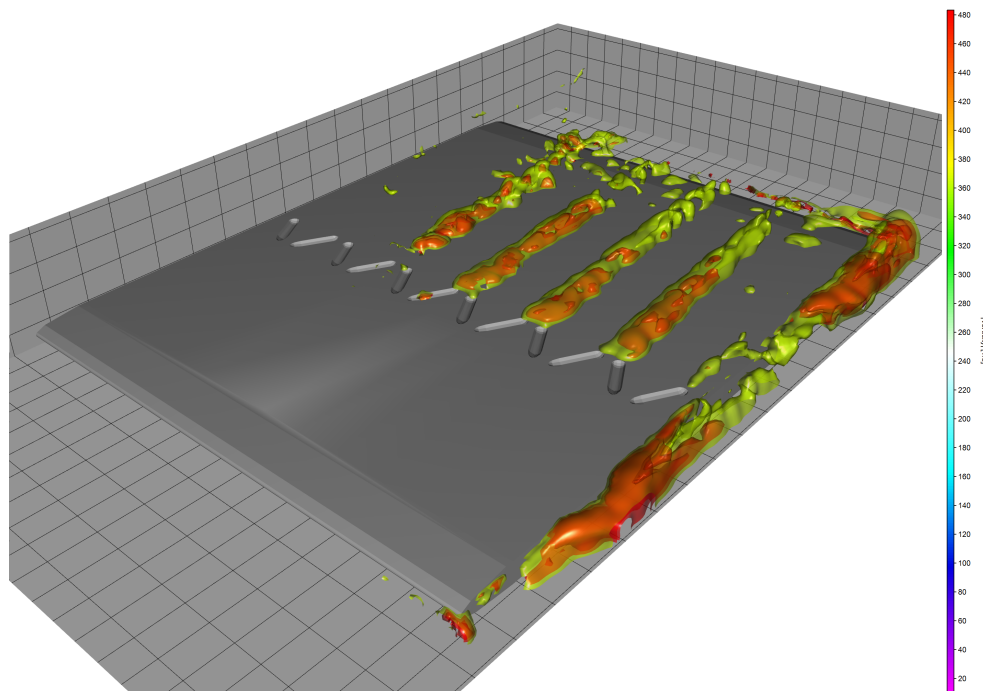


Figure. 4 The isosurfaces of constat value of vorticity ω_z .

Mean streamwise velocity profiles for two locations 150 mm and 300 mm from leading edge are presented in Figure 5. The velocity profiles in 80% of BL thickens was captured starting from $y/\delta = 0,2$.

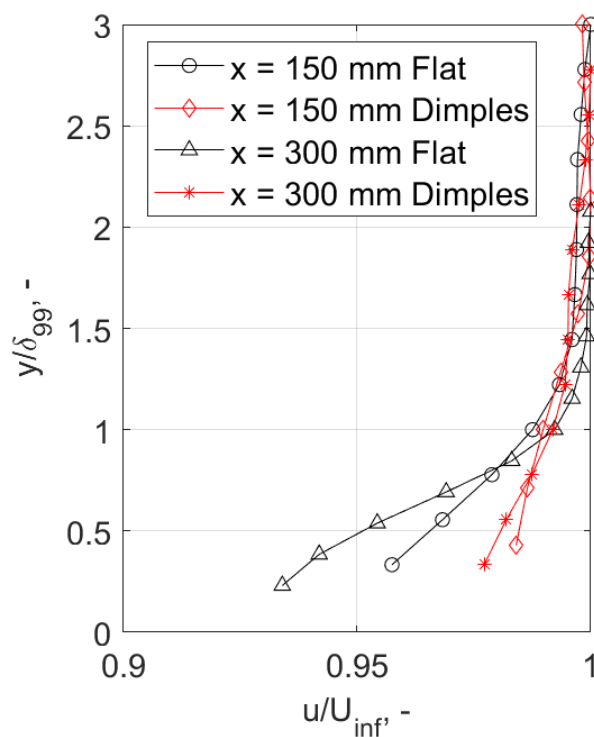


Figure. 5 Mean streamwise velocity profiles, $x = 0$ is located at leading edge of the plate

4. Conclusions

Application of HFSB allowed for capturing 3D velocity field in outer border of the boundary layer. The mean streamwise velocity profiles in case of structured surface are steeper than in the case of flat surface. The HFSB emitter placement at the WT nozzle exit gives slightly higher DSR than in case of placement in the settling chamber (Scarano et al., 2015b). Nevertheless, the further experiments will be conducted with LNA array placed in the settling chamber for the sake of introduction less flow disturbances in the test section. The test show capabilities for volumetric measurements at industrial scale in Łukasiewicz – Institute of Aviation T-3 wind tunnel.

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