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## 3D Lagrangian Particle Tracking within transitional flows

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The development and production of laminar flow wings is one important goal in Europe’s challenges to significantly reduce the fuel burn and the emission of future transport aircraft. For the aerodynamic design of laminar flow wings (NLF or HLFC), the understanding of the boundary layer transition process is essential and the further improvement of numerical prediction tools is necessary. The understanding of the effect of surface imperfections on the laminar boundary layer is still vague. Both the effect of roughness (e.g. due to small rivet heads or insects) and the effect of surface steps (e.g. between two adjacent wing panels) are important.

Two different types of imperfections were studied by 3D Lagrangian Particle Tracking (LPT, Schröder & Schanz 2023) experiments. First, the transitional flow downstream of a backward facing step (BFS) of height  $h = 5\text{mm}$  at several Reynolds numbers ( $Re_h \approx 850 - 4150$ ) was investigated. On the other hand, the BFS was replaced by a small cube (1.5 mm sides). In both cases, the incoming boundary layer was kept laminar, such that a transition occurs in the wake of the step and the cube. It is known that the flow around these imperfections depends on various parameters such as the dimension ratios ( $L/h$ ),  $(\delta/h)$  and  $(\theta/h)$ , the Reynolds number, the free stream turbulence and its specific spectral distribution, etc. The transition of the boundary layer can be caused downstream due to the growth of Tollmien-Schlichting-waves in two-dimensional boundary layers or, in addition, by crossflow instabilities in three-dimensional boundary layers. The investigation of the development of disturbances due to instabilities requires the measurement of highly resolved velocity fields both in space and in time and, preferably, the skin friction distribution on the surface. For a related publication, see (Schröder et al. 2020).

The experiments were performed in the low speed water tunnel (THBV) at ONERA Lille, which is a gravity-driven, closed-loop water tunnel. The measurement volume was illuminated using a Photonics Industries DM200 2\*150 W high-speed laser, operated at around 25 mJ per pulse at a frequency of 2.25 kHz. The light sheet was cut to a rectangular shape of  $80 \times 10\text{mm}^2$  (see Fig. 1). The water was seeded using  $30\text{ }\mu\text{m}$  polyamide particles (*Orgasol*) and the particle images were observed using a system of seven high-speed cameras (6 \* Photron V2640, 1\* Photron V640L). 12,597 time-steps were recorded per run; for the relevant cases up to 15 runs were performed.

Here we only show results for the BFS-case at free-stream-velocity of 0.45 m/s ( $Re_h \approx 2250$ ). Variable-timestep-Shake-The-Box (VT-STB) was applied using the DLR implementation (Schanz et al. 2016, Schanz et al. 2021); in the final pass, around 80,000 to 100,000 particles were tracked instantaneously. See Fig. 2 for various cuts and a result of the application of FlowFit data assimilation (Gesemann et al. 2016).

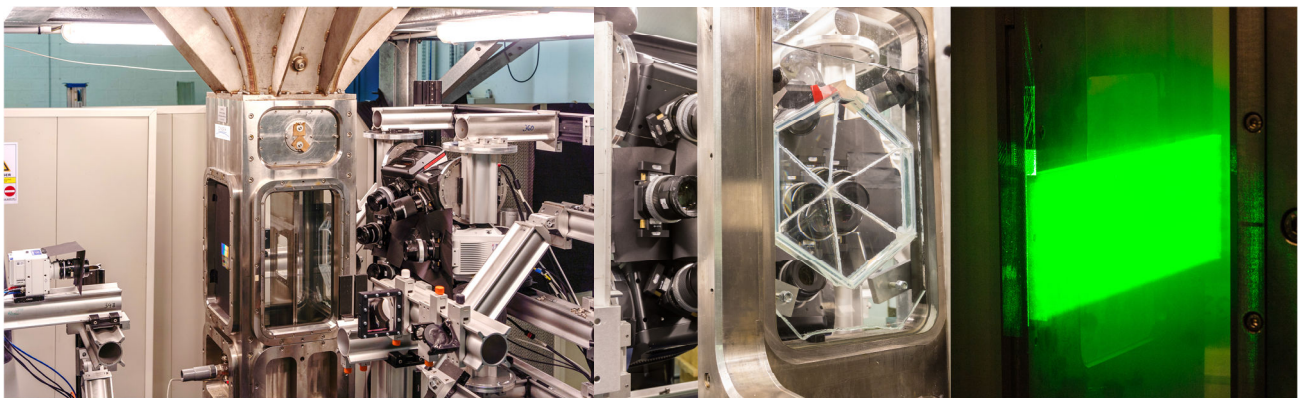


Fig. 1: (Left, Middle): Six cameras viewing through a six-faced prism, a seventh camera from behind. Flow from top to bottom. (Right): The BFS-model being illuminated by the laser sheet ( $80 \times 10\text{mm}^2$ ).

It can be seen how the laminar flow convects over the step and transitional structures develop due to instabilities in the shear layer between the quiet recirculation zone and the fast incoming flow. Vortical structures, which are mostly oriented in streamwise (stw) direction, can already be identified in the particle representation. The FlowFit result clearly shows these as systems of hairpin-shaped vortices that are created by large spanwise (spw) instabilities, stemming from the shear layer, which can be identified as extended tubular regions of negative pressure.

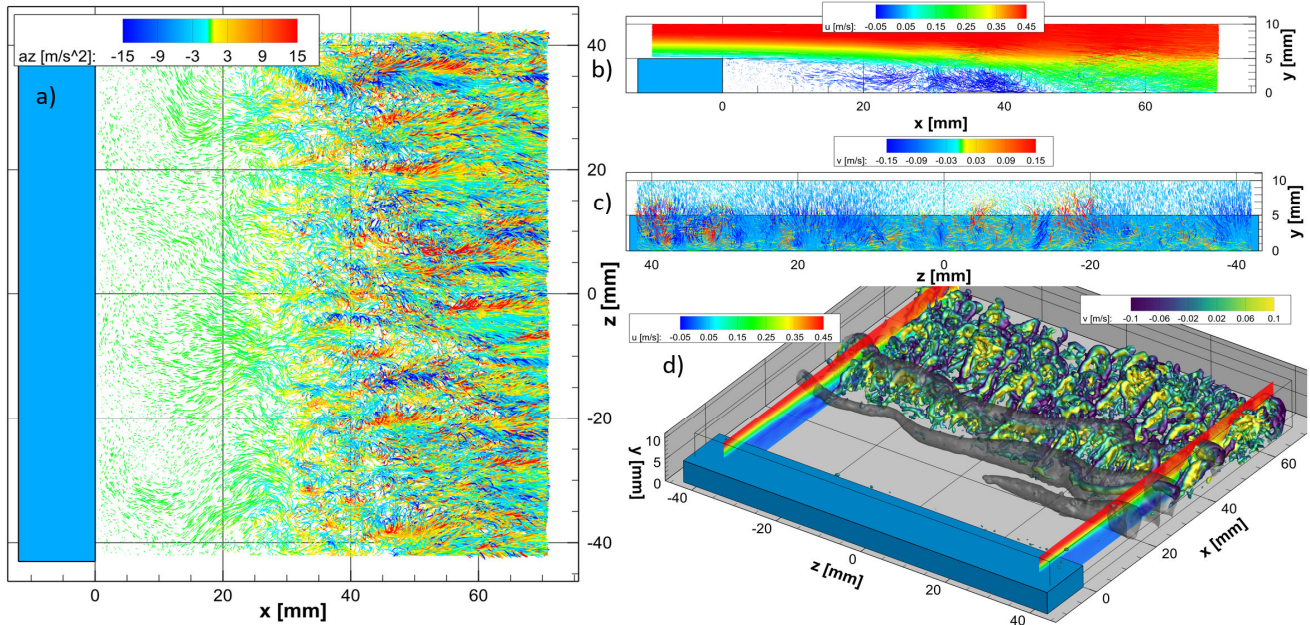


Fig. 2: STB and FlowFit results for a BFS-flow, laminar boundary layer at  $Re_h \approx 2.250$ : (a) Top view on near-wall tracks (up to 2.5 mm above the wall), cc. by spanwise acceleration. (b) 10 mm spanwise slice, cc. by streamwise velocity. (c) 10 mm streamwise slice ( $x = 50 - 60$  mm), cc. by wall-normal velocity. (d) Instantaneous FlowFit result, showing isosurfaces of  $Q$  ( $5000/s^2$ , cc. by wall-normal velocity) and of negative pressure (grey).

Fig. 3 displays statistical results from a binning process. It can be seen that the recirculation zone extends until approx. 45 mm (9 h) behind the step, where the turbulent flow reattaches to the wall. A second, counter-rotating circulation bubble is resolved close to the foot of the step, extending approx 4 mm in streamwise direction.

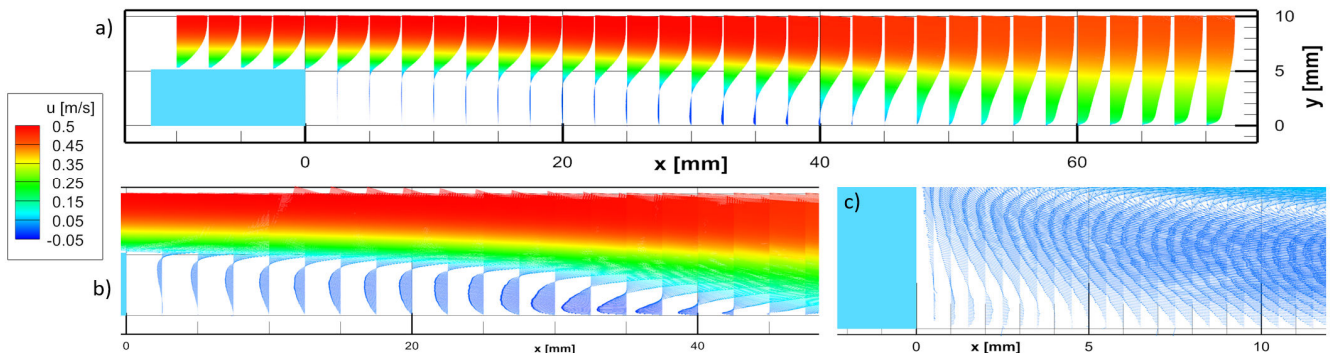


Fig. 3: Average of the particle properties in small bins ( $500 \mu\text{m}$  streamwise,  $50 \mu\text{m}$  wall-normal, full span-wise extent) at three scalings with relative vector length of 1 (a), 10 (b) and 40 (c).

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