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Shake-The-Box particle tracking with variable time-steps in flows with high velocity range (VT-STB)

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Abstract

In recent years, Lagrangian Particle Tracking (LPT) has become more and more important in the field of 3D flow measurements, largely due to the introduction of the methods of Iterative Particle Reconstruction (IPR, Wieneke 2013) and Shake-The-Box (STB, Schanz et al. 2016). Applying the STB algorithm, particles can be tracked in large numbers, with a nearly complete suppression of ghost particles. The ability of the STB algorithm to discern real particles from ghost particles is largely stemming from the observation that for real particles the change of acceleration is small between time-steps, while ghost particles are generated in quasi-random locations all over the measurement volume. However, this assumption only holds if the particles exhibit a certain amount of movement relative to each other, such that the ambiguities 'de-correlate' within few time-steps. In many flows this assumption holds, however flows with a high velocity range can exhibit regions in space with only very little movement of the particles (e,g, jet flows). As the time separation has to be chosen such that the fastest particles are reliably tracked, particles in the surrounding flow might move only a fraction of a pixel in the same time. Another potentially problematic effect of slowly moving particle clouds is that situations of overlapping particle images are retained over several time-steps.

We see that a slowly moving particle field is detrimental to the tracking process in multiple ways. In this work we propose an extension to the standard STB evaluation, which applies multiple iterations of particle tracking with variable time-separation. The idea is to start the evaluation with a time separation such that the slowest particles of the flow can be optimally tracked. From there, the time-separation is iteratively reduced, tracking faster and faster particles with every iteration. Finally, the original time-separation of the recording is reached, where only the fastest particles - whose velocity initially determined the recording rate - remain to be tracked. The involved steps are detailed in the following

1. Choose a suitable temporal $\Delta_{s,i=1}$ such that the *slowest particles* move at least one particle image diameter from image to image, where $\Delta_{s,i=1}$ is the number of omitted snapshots.
2. Perform *particle tracking* on the selected subset of snapshots.
3. *Filter* the gained trajectories using a fitting method with a suitable kernel-size.
4. Choose a *finer temporal resolution* $\Delta_{s,i+1} < \Delta_{s,i}$ for the next iteration.
5. *Interpolate* the filtered trajectories from $\Delta_{s,i}$ to the time-steps given by $\Delta_{s,i+1}$
6. Perform *particle tracking* on the snapshots given by $\Delta_{s,i+1}$, while feeding the interpolated particle clouds from the previous iteration as a partial pre-solution to the reconstruction of each snapshot
7. Repeat steps from 3 to 6 until $\Delta_{s,i+N} = 1$ is reached.

The VT-STB approach is applied to an experimental dataset, measuring the flow of a small diameter jet impinging on a circular cylinder. The setup is placed in a regular cylindrical 16-faces glass tank (see Fig. 1). A jet is generated by a nozzle of diameter $d = 3$ mm and is impinging onto a circular cylinder with diameter $d_C = 52$ mm at an angle of 45°.

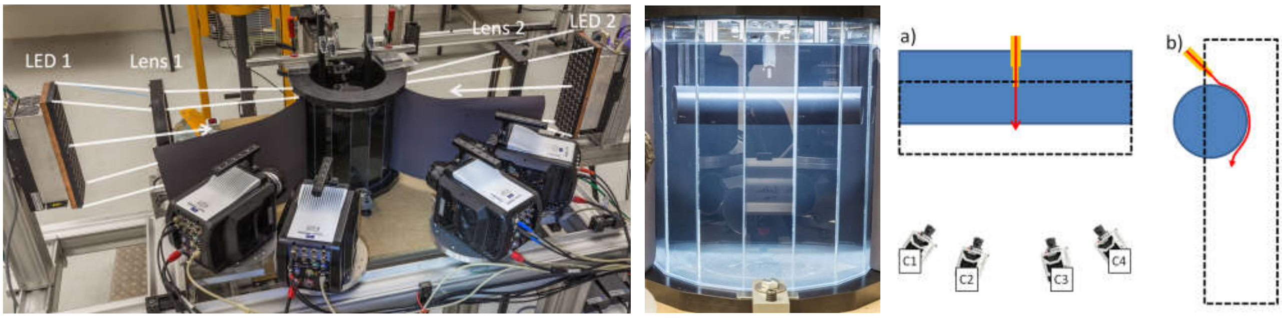

Fig. 1: Left: Setup for the water jet experiment. with four Phantom V2640 cameras viewing into the water tank, which is illuminated from two sides by high-power white LED arrays. Middle: 16-face water tank with submerged cylinder ($d_c = 52$ mm) and d = 3mm nozzle at 45° impinging angle. Right: Schematical experimental setup from top view (a), and side view (b). Cylinder in blue, nozzle in yellow, centerline flow in red and the illuminated area as a dashed line.

The maximum jet velocity was v_{MAX} = 6 m/s, corresponding to a Reynolds number of 17,875. For a more detailed description, see (Kim et al. 2018), where a comparable setup was employed in air.

VT-STB was applied in the following fashion: 5 iterations were performed, starting with a time separation of $\Delta_{s,1}$ = 79 time-steps (the slowest particle move approx. 2.4 pixel in this interval, corresponding to approx. one particle image diameter). The following iterations feature time separations of $\Delta_{s,i}$ = [36, 14, 6, 1] time-steps.

The operating principle of VT-STB is illustrated in Fig. 2, left. For each iteration, a 10mm - thick slice of the volume, centered around the nozzle is visualized, showing particle tracks over approx. 500 time-steps (based on the original sampling; the effective length varies slightly due to the different time separations). The particles tracked at $\Delta_{s,1}$ = 79 (see Fig. 2 left, top) are located in the entrainment region and below the cylinder, far from the wake of the jet. Maximum velocities of approx. 0.12 m/s are attained. When moving to iteration 3 ($\Delta_{s,3}$ = 14, Fig. 2 left, middle), maximum velocities of 0.7 m/s can be tracked. Large parts of the wake region below the cylinder appear in the tracking system. Finally, when $\Delta_{s,5}$ = 1 is reached in iteration 5 (Fig. 2 left, bottom), the remaining fast particles from the jet and its direct surroundings are tracked. Maximum velocities of 6 m/s are seen, as expected.

In order to assess the benefits of VT-STB over regular processing using Δ_s = 1, the results are compared to a normal STB evaluation over 1,000 images. Fig. 2 (right) shows comparisons between the two reconstructions in two selected subvolumes. Both evaluations correctly capture the vast majority of the tracks, however for STB a relevant amount of tracked particles appears within the cylinder, indicating ghost tracks (not shown here). For VT-STB this region is nearly completely void. When focusing on a smaller region (see Fig. 2, right, top) it is obvious that the normal STB-result is interspersed with both outliers, as well as a sizeable number of tracks with velocities close to zero, appearing in regions with visibly higher flow velocity. The VT-STB result is free of both types of abnormal particle tracks. At the same time, the tracks of slow particles exhibit less noise, as the filtering is carried out on a broader kernel, minimizing the effects of long-lasting overlap situations.

Similar pheneomena are seen when looking at a x-z plane located on the upper edge of the measurement volume, above the jet (viewing from top, see Fig. 2 right, bottom). The STB evaluation shows clear signs of 'line-of-sight'-tracks, where particles follow the viewing direction of a singular camera, as their intensity is mostly supported by a peak on that specific camera. Furthermore it can be seen that some of the particles in the center of the vortex that are present for VT-STB are missing for the STB evaluation.

For the examined flow, VT-STB processing shows profound advantages; however it has to be stressed that this case represents an extreme in terms of velocity range and volume ratio of fast and (very) slow moving particles. For most experimental investigations, normal STB evaluations will show significantly less ghost particles, still we expect benefits of VT-STB processing in many flows.

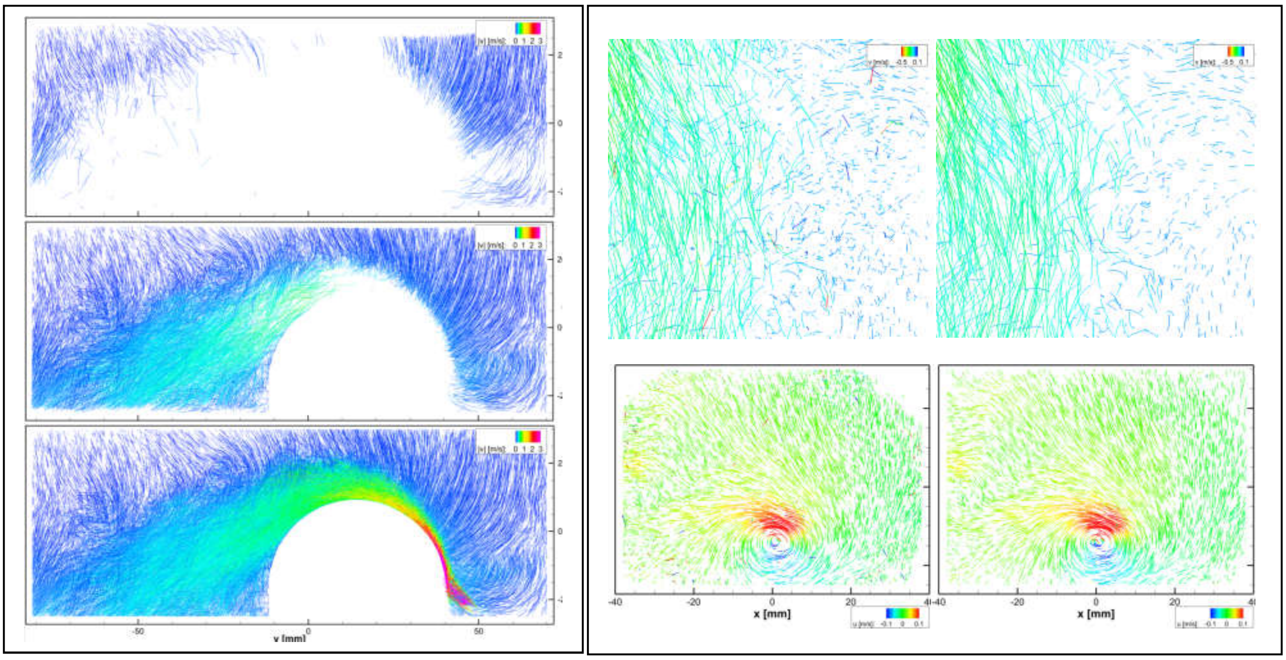

Fig. 2: Left: VT-STB tracking with 5 iterations, showing iterations 1, 3 and 5 with time separations of $\boldsymbol{\Delta_s}$ = 79, 14 and 1 time-steps. Right: STB processing (left) vs. VT-STB processing right) in two exemplary regions.

References

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