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# Comparative experimental assessment of velocity, vorticity, acceleration and pressure calculation using time resolved and multi-pulse Shake-the-Box and Tomographic PIV

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## Abstract

From volumetric time-resolved experimental data, 2-pulse and 4-pulse data is constructed. In this way, time-resolved and multi-pulse analysis techniques for instantaneous volumetric flow measurements can directly be compared. At the same time, correlation based tomographic-PIV and dense particle tracking (Shake-the-Box) are compared according to their performance for velocity, vorticity acceleration and pressure (pressure from PIV) measurement. Different schemes for converting track data to a grid are examined: binning and fine-scale-reconstruction using an advanced vortex-in-cell approach (VIC#). In general, all methods perform reasonably well for the given task of velocity, vorticity acceleration and pressure calculation. However, there are some methods that show particular higher qualities in the results, usually at the expense of higher computation time. Remarkably is the ability of 2-pulse Shake-to-Box to deliver very convincing pressure results for the experimental flow investigated in this study.

## 1 Introduction

Optical volumetric flow measurement has enjoyed several important breakthroughs in the last years (among others): Tomographic PIV [Elsinga et al. (2006)], Motion Tracking Enhancement (MTE) [Novara et al. (2010)] and Sequential MTE (SMTE) [Lynch and Scarano (2015)], Shake-the-Box (STB) [Schanz et al. (2016)], 4-pulse STB [Novara et al. (2016)] and 2-pulse STB [Jahn et al. (2017)], Pressure from PIV [van Oudheusden (2013), van Gent et al. (2017)], data assimilation techniques like FlowFit [Gesemann et al. (2016)] and VIC+/# [Schneiders and Scarano (2016), Jeon et al. (2018)]. Each of these contributions had considerable impact on volumetric flow measurement. At the same time, it made it harder for the experimentalist to choose from the given techniques or to find the optimal measurement technique for a task at hand. Many studies focus on the introduction of new concepts or on the application of one or the other technique for a specific task. Studies comparing directly the capacities of different techniques in depth with the same data set are rare and require considerable effort. Moreover, the only study so far comparing e.g. Tomographic PIV and Shake-the-Box (including pressure calculation) was based on synthetic data only and did not include the additional challenges from experimental data [van Gent et al. (2017)].

In this study experimental data from time-resolved volumetric recordings of a free jet in water is used as an experimental test case [Violato and Scarano (2011)]. A rare feature of this data set is the

availability of recordings in a wide range of seeding densities (0.001 particles per pixel (ppp) up to 0.17 ppp) allowing the selection of an optimal seeding density for this study.
2-pulse and 4-pulse data is assembled from the time resolved recordings to study multi-pulse STB. In this way the results from virtual double frame cameras can be compared directly to the original time resolved results. The analysis techniques described above are combined in multiple ways to finally get velocity, vorticity, acceleration and pressure results in many different ways (e.g. STB + VIC#, see Fig. 1). Results are qualified in terms of the quality of reconstructed features (e.g. vortex rings, pressure minima etc.), temporal coherence, noise content and also computation time. This matrix allows the selection of an optimal set of operations for different requirements, e.g. the fastest solution with acceptable computation time or the solution with the overall best quality (which turns out to be the slowest in terms of computation time).

# 2 Experimental Data

**Time resolved** measurement of a circular jet in water at Re = 5000 [Violato and Scarano (2011)] are recorded. Nozzle exit diameter is 10 mm, exit velocity of the jet is 0.42 m/s. Polyamide particles are seeded with a concentration of 0.001 ppp to 0.17 ppp and illuminated by a 25 mJ Quantronix Darwin-Duo Nd-YLF laser. Four LaVision HighSpeedStar 6 CMOS cameras operate in 1.3 kHz to obtain series of 200 images each at a resolution of 1024 x 1024 pixel. The maximum particle displacement is about 5 pixel in a single timestep. A recording with a particle density of 0.04 ppp is used in this paper.
Multi-pulse data (2-pulse and 4-pulse) is simulated from these recordings. Multi-pulse is designed to overcome the limitation of time resolved analysis, which only allows the measurement of low to modest flow velocities, but cannot be applied at really high flow velocities, limited by camera frame rates and available laser power.
**2-pulse** data is created by combining two consecutive images to pairs of double frames, mimicking double frame PIV cameras.
**4-pulse** was introduced recently [Novara et al. (2016), Jahn et al. (2017)]. Two double pulse lasers create four laser pulses (at times $t_1$ to $t_4$) and double frame cameras acquire **two illuminations** in each frame (e.g. $t_1$ and $t_2$ in the first frame and $t_3$ and $t_4$ in the second). Particle tracks with four time-steps are retrieved, allowing the calculation of velocity and acceleration.
4 pulse data is created by adding image intensities of two time steps for each of two double frames. Different strategies for time separations ($dt_1=t_2-t_1$, $dt_2=t_3-t_2$, $dt_3=t_4-t_3$) have been proposed. Here, longer time separations within a frame and a shorter time separation between frames is used: $dt_1= dt_3=$ 2 time-steps and $dt_2=$ 1 time-step. Particle density for 4-pulse data is twice as high as for 2-pulse and time resolved data, being a disadvantage for the 4-pulse case. However, only this way instantaneous flow features can be compared directly.

# 3 Measured Quantities

Particle image recordings allow the calculation of important and useful measurement quantities for fundamental research and technical applications, including velocity, vorticity, acceleration and pressure. Velocity vectors on a regular grid are already the primary result of correlation-window based Tomo-PIV. From that, vorticity and acceleration are readily derived, with acceleration requiring time-resolved data. Pressure gradient and finally pressure is calculated from velocity and acceleration by pressure gradient integration or application of a Poisson solver [van Oudheusden

(2013)]. Particle positions over time (particle tracks) are the primary result from particle tracking (STB). Velocity and acceleration are calculated at particle locations. Different techniques (see below) are applied to obtain velocity, vorticity, acceleration and pressure on a regular grid from the scattered particle data.

# 4 Analysis Techniques

Techniques applied in this paper for velocity, vorticity, acceleration and pressure calculation are presented in figure 1. Calculating acceleration directly from finite differences leads to noisy acceleration fields. Therefore, the more noise resistant **pseudo Lagrangian tracking** [van Gent et al. (2017)], is used here, where a 2$^{nd}$ order polynomial is fitted iteratively at each grid point to match the velocity fields from several time steps (7 in this study). Velocity and acceleration are then determined analytically from the polynomial fit.

For the conversion of STB data on a regular grid, two different methods are applied: **binning** and **fine-scale-reconstruction (FSR)**. For binning, a polynomial of 0, 1$^{st}$ or 2$^{nd}$ order is fitted to velocity or acceleration values of all particles contributing to a bin. Fine-scale-reconstruction by VIC# [Jeon et al. (2018)] is used as a data assimilation approach to convert particle tracks to a grid, yielding velocity, acceleration and pressure in a single optimization process. Whenever fine-scale-reconstruction is not used (fig. 1), pressure is calculated using a Poisson solver, where divergence-free-filtering for velocity and curl-free-filtering for the pressure gradient are applied. Note that there is a path from 2-pulse to pressure via STB and FSR, so that pressure can be obtained from double frame recordings, where no acceleration is available!

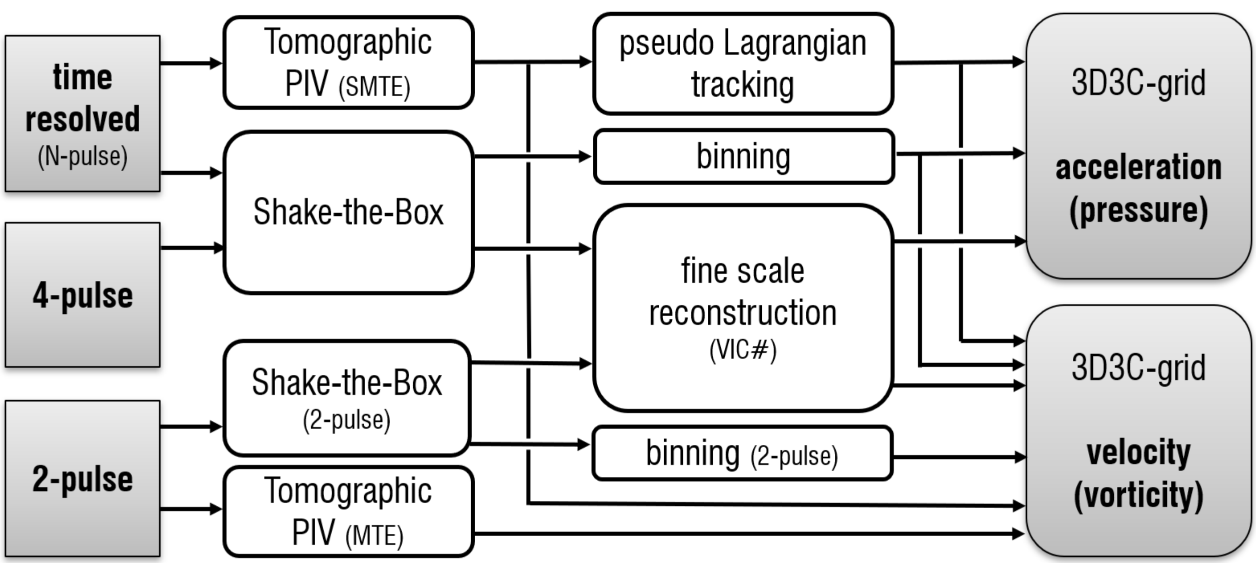


Figure 1: Processing chains, that lead from particle image recordings (left) to measured quantities on a regular grid (right).

# 5 Results

For Tomo-PIV and binning, a (final) interrogation volume size of 48 x 48 x 48 voxel at 75% overlap has been applied, yielding 64 x 88 x 62 vectors. Fine-scale-reconstruction utilized the same resulting grid size of 12 x 12 x 12 voxel, so that results can be compared directly. Results are displayed either as a single plane from the center of the measurement volume or as a time history plot of a single point in space. This point is located on the jet centerline for velocity results or on the radial position of the vortex rings for all other measures. Both points are about 3 diameters downstream from the jet exit. Table 1 summarizes the abbreviations used in the following result figures. Results from 2-pulse Tomo-PIV (MTE) are not presented as they were very similar to time resolved results.

Table 1: Abbreviations

| | | |
|---|---|---|
| **Tomo**: Tomographic PIV | **Ps. Lag. tr.**: pseudo Lagrangian tracking | **STB Ord=N**: Shake-the-Box + binning with polynomial of order N |
| **FSR grid=N:** Fine Scale Reconstruction using VIC# with a grid size of N voxel | **2-pulse, 4-pulse**: STB results from 2-pulse or 4-pulse data | **tr**: time-resolved data is used for analysis, also if neither 2-pulse nor 4-pulse is mentioned |

## 5.1 Velocity Results

Inspecting individual particle tracks (fig. 2) from time resolved STB reveals, that particle trajectories are very smooth over many time steps for the current flow, and that no high frequency noise is present, as expected for the relatively low Reynolds number (5000). Consequently, any high frequency noise (spatially or temporally) is very likely to originate from measurement errors rather than reflecting real flow properties. This assumption is important for interpretation of the analysis results.

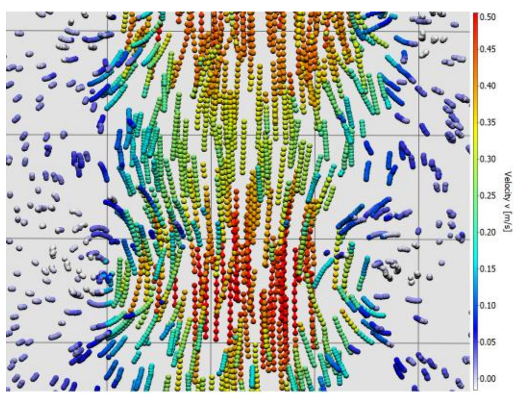


Figure 2: Particle tracks from Shake-the-Box

All time resolved (fig. 4) and multi-pulse (fig. 5) velocity results look very similar at first glance and clearly reveal the principal velocity distribution correctly. Among time-resolved analysis (fig. 4) Tomo-PIV with pseudo Lagrangian tracking (b) and STB + fine-scale-reconstruction with a grid of 12 voxel (f) show the overall best quality, exhibiting smooth flow feature with a high dynamic range (no damping) and very little spatial noise.
2-pulse STB results with binning and order 0 or 1 (fig. 5, a+b) show very similar results. 4-pulse results (fig. 5, bottom) present some bias error in the outer regions (dark blue areas). In general, results from binning with an order of 2 show higher spatial noise, but potential higher spatial resolution and peak amplitudes.
Velocity profiles over time (fig. 6) look most reasonable for Tomo-PIV with pseudo Lagrangian tracking (top, left). The dynamic range (peak to peak) is high and the curve is smooth.

Time-resolved STB and FSR results (top, right) appear more noisy. The amplitudes are damped if the order for binning is low (0 or 1), also for FSR with a grid of 12. FSR with a grid of 8 and binning with an order of 2 exhibit higher amplitudes but also more temporal noise. The same holds true for 2-pulse and 4-pulse STB (fig. 6, bottom). The multi-pulse results are in general more noisy than the time resolved ones, especially the 4-pulse results from binning with an order of 2 is showing strong noise spikes in the time plot.

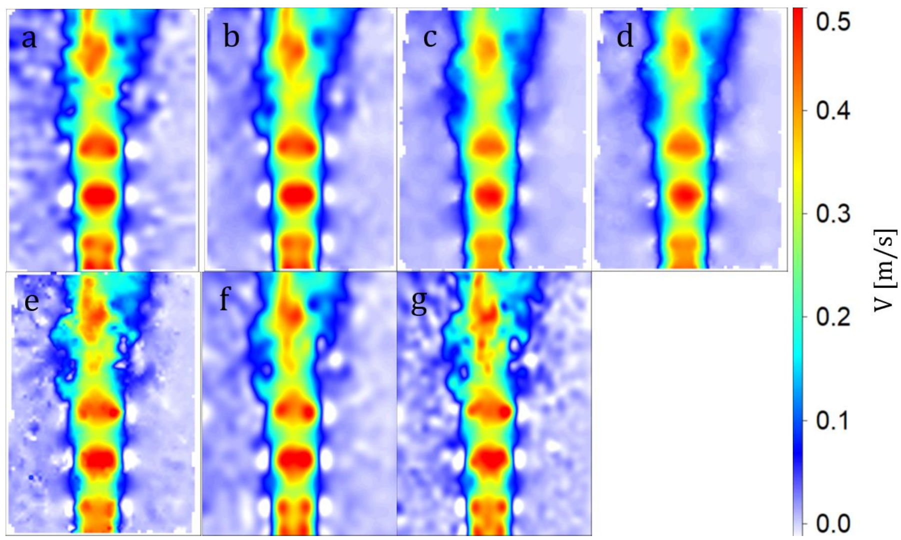


Figure 4: vertical velocity component v for time resolved analysis. a) Tomo; b) Tomo ps. Lag. tr.; c) STB Ord=0; d) STB Ord=1; e) STB Ord=2; f) FSR grid=12; g) FSR grid=8

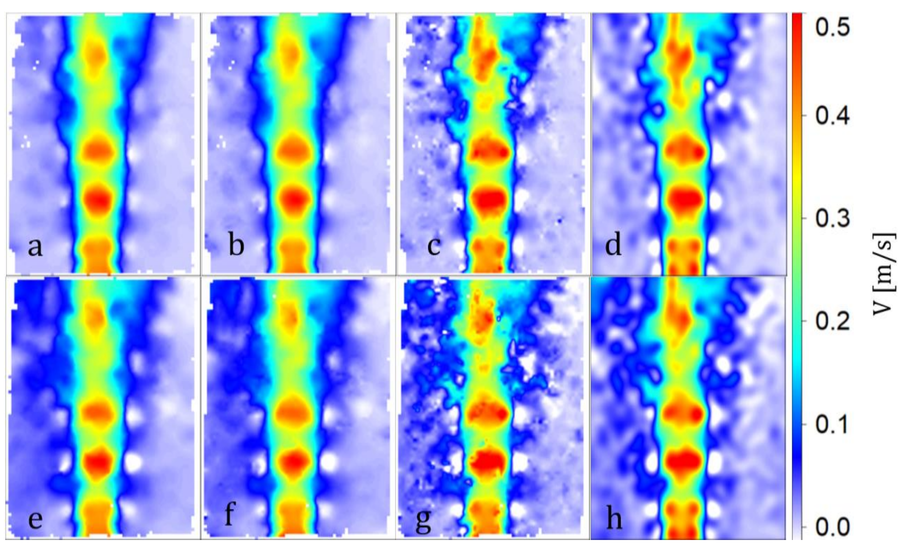


Figure 5: vertical velocity component v for 2-pulse STB (top) and 4-pulse STB (bottom) analysis. a+e) Ord=0; b+f) Ord=1; c+g) Ord=2; d+h) FSR grid=12

## 5.2 Vorticity Results

Fine-scale reconstruction results in the highest peak vorticity (figs. 7-9). Tomo-PIV with pseudo Lagrangian tracking is getting close and shows the most convincing time plot with little temporal noise and high peak amplitudes (fig. 9, top left). 2-pulse and 4-pulse results appear more noisy in general. FSR and binning with an order of 2 achieve the highest peak amplitudes in the vortex cores.

## 5.3 Acceleration Results

Acceleration results are quite reasonable and very similar for Tomo-PIV and all FSR cases (fig. 10, a, e, f, g, k), exhibiting clear acceleration maxima at vortex locations and very little noise in the outer

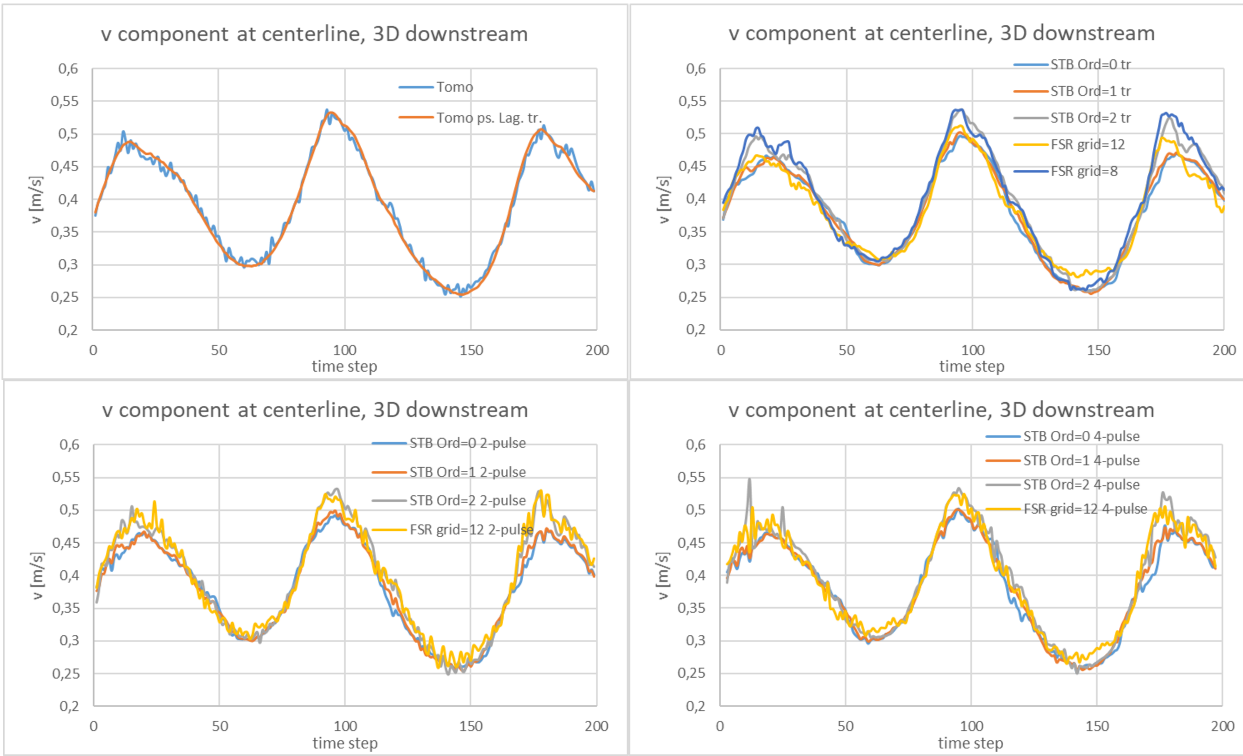


Figure 6: vertical velocity component v at centerline, 3 diameters downstream

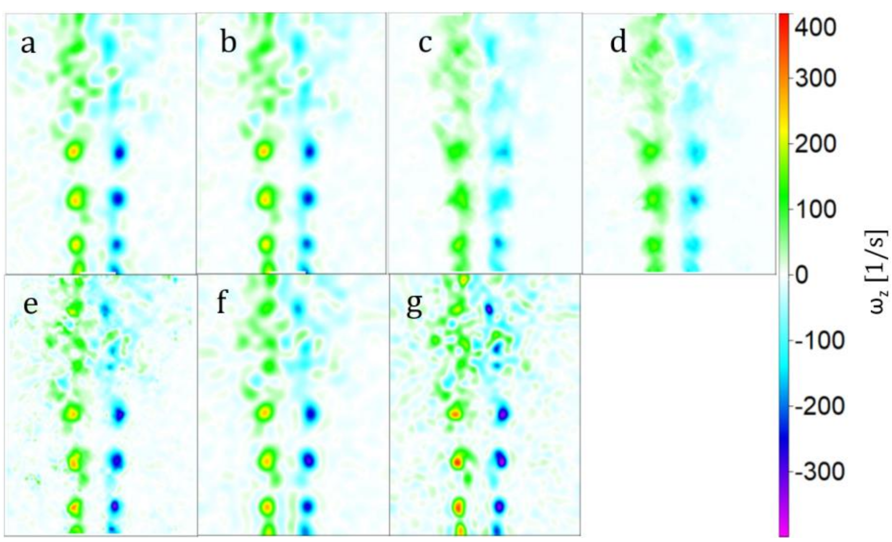


Figure 7: vorticity z-component for time resolved analysis. a) Tomo; b) Tomo ps. Lag. tr.; c) STB Ord=0; d) STB Ord=1; e) STB Ord=2; f) FSR grid=12; g) FSR grid=8

region. Acceleration noise right at the borders for Tomo-PIV is likely to result from clipping effects of pseudo Lagrangian tracking. Amplitudes are damped for binning with low order (fig.10, b, c, h, i). Acceleration noise is strong, especially in the outer regions for time resolved binning of any order (fig.10, b, c, d) and very strong for time resolved and 4-pulse with order 2 (fig.10, d, j).

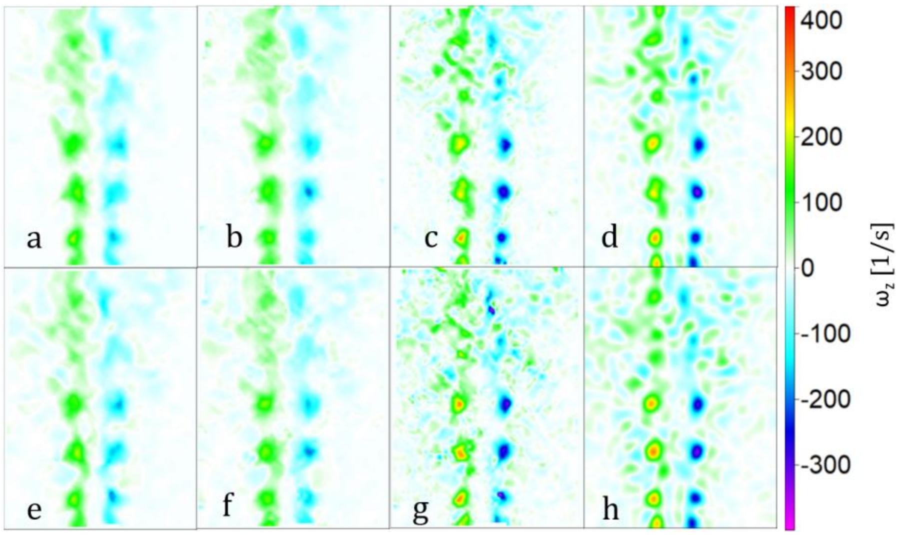


Figure 8: vorticity z-component for 2-pulse STB (top) and 4-pulse STB (bottom) analysis. a+e) Ord=0; b+f) Ord=1; c+g) Ord=2; d+h) FSR grid=12

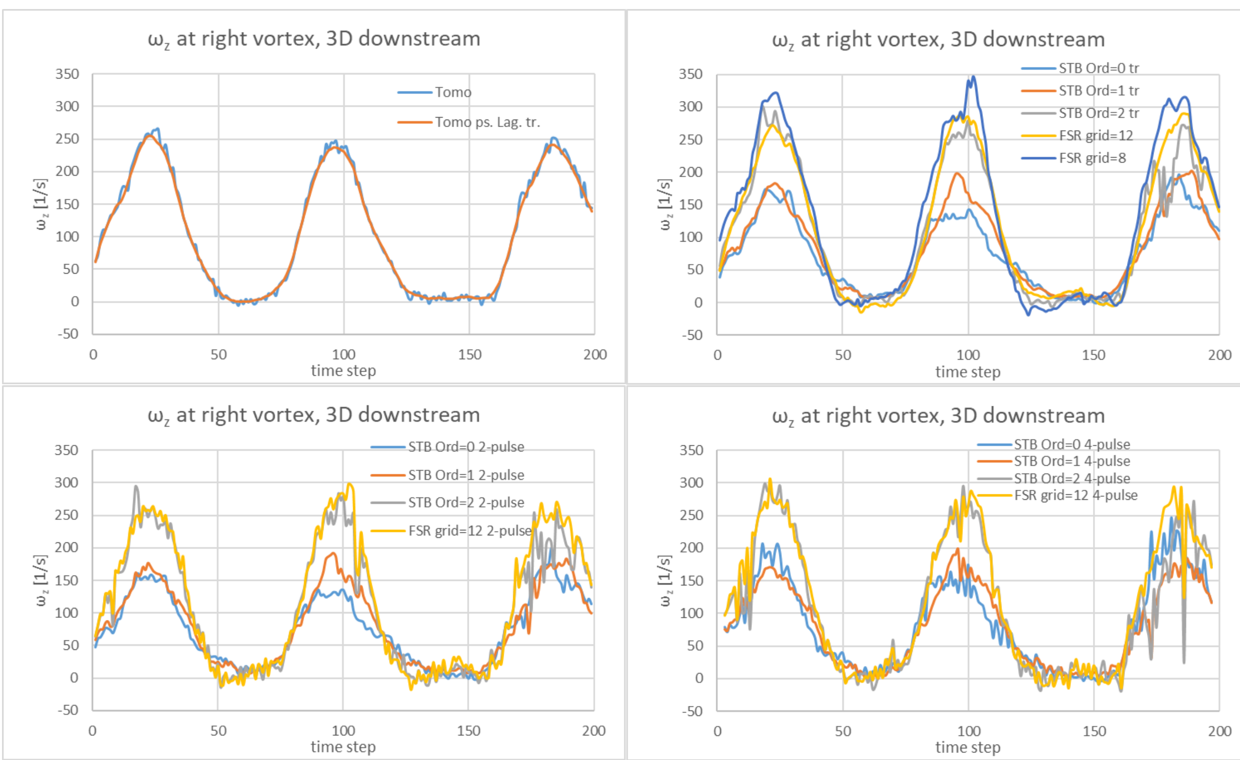


Figure 9: vorticity z-component at right vortex, 3 diameters downstream

Similar findings are observed for the temporal evolution (fig. 11) where all FSR results show the highest peak amplitudes. Peak amplitudes for Tomo-PIV are smaller but the curve is comparably smooth. 2-pulse and 4-pulse results (fig. 11, right) are again more noisy, especially for 4-pulse binning with order 2. Note how acceleration is very accurately reconstructed with little noise from 2-pulse STB with FSR (fig. 10, g and fig. 11, right, light blue).

## 5.4 Pressure Results

Results from acceleration are directly reflected, as expected, in pressure results (fig. 12, 13). Again, Tomo-PIV and all FSR results (fig. 12, a, e, f, g, k) exhibit very reasonable pressure structures at highest peak amplitudes and little noise. Pressure structures and peak amplitudes are poorly resolved for 4-pulse without FSR (fig. 12, h, i, j) with unphysical pressure fluctuation in the outer regions. Time resolved STB with binning yields more reasonable pressure structures in the center (fig. 12, b, c, d) but also exhibits unphysical pressure fluctuation in the outer regions.

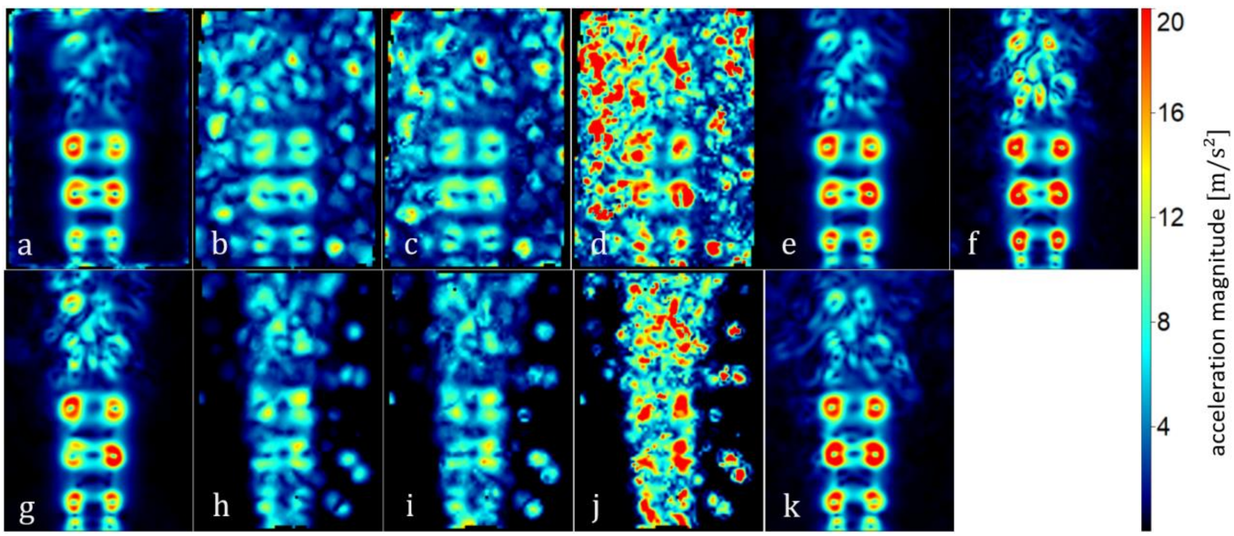


Figure 10: acceleration magnitude. a) Tomo ps. Lag. tr.; b) STB Ord=0; c) STB Ord=1; d) STB Ord=2; e) FSR grid=12; f) FSR grid=8; g) STB 2-pulse FSR; h) STB 4-pulse Ord=0; i) STB 4-pulse Ord=1; j) STB 4-pulse Ord=2; k) STB 4-pulse FSR

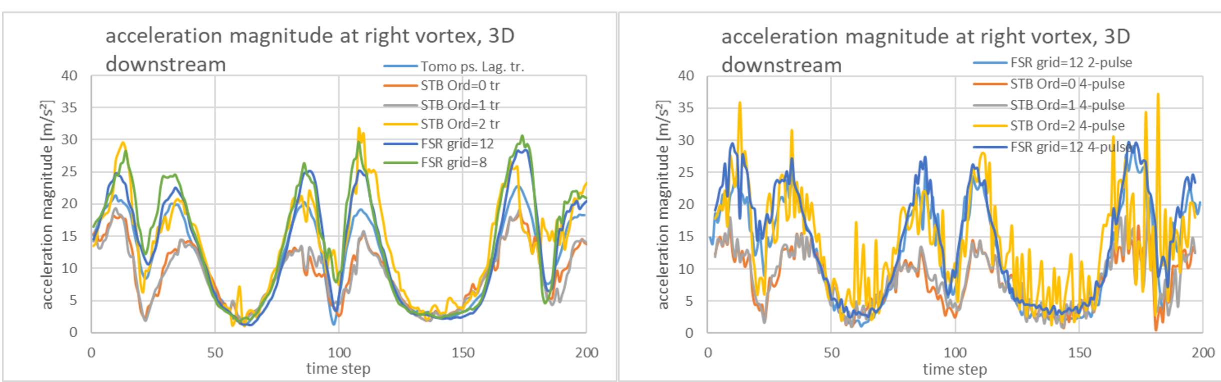


Figure 11: acceleration magnitude at right vortex, 3 diameters downstream

Strong amplitude damping becomes visible in the time plot for STB with binning and order 0 or 1 (fig. 13). FSR results show the highest peak amplitudes and Tomo-PIV and binning with order of 2 are in between these extremes. For time resolved cases (fig. 13, left) all curves are comparably smooth, multi-pulse data exhibits more temporal noise (fig. 13, right). Again, it should be noted how pressure is very accurately reconstructed with little noise from 2-pulse STB with FSR (fig. 12, g and fig. 13, right, light blue).

# 6 Conclusion and Discussion

Despite previous finding that particle tracking is superior for pressure estimation for **synthetic** data [van Gent et al. (2017)], for the **experimental** data presented here, Tomo-PIV with pseudo Lagrangian tracking showed very convincing results for all measurement values.

Shake-the-Box with binning allows fast calculation (5-10 times faster than Tomo-PIV), but either shows amplitude damping (order 0 or 1) or increased noise (order 2). STB results for time resolved data has a higher quality than multi-pulse data.

STB + fine scale reconstruction is yielding very good results in all cases and for all measures. Also, in this case, the quality for time resolved data is even higher than for multi-pulse. Improvements of VIC# are possible (and investigated) taking the time history into account (VIC##). Computation time for FSR is even about 20% to 50% higher than for Tomo-PIV

4-pulse data could not show a clear advantage here over 2-pulse data. The advantage of being able to directly calculate acceleration is potentially cancelled out by the disadvantage of the higher effective particle density.

The most notable result for this experimental data, is, to the authors opinion, the high quality of reconstructed velocity, vorticity, acceleration and especially pressure data from 2-pulse STB in combination with fine-scale-reconstruction. It seems counter intuitive, that measures that are related to acceleration can be retrieved from 2-pulse data. The vortex-in-cell (VIC) method is responsible for the surprising behavior as it allows to calculate acceleration from vorticity transport. This finding opens new experimental opportunities for pressure evaluation from high velocity flows with dual frame PIV-cameras.

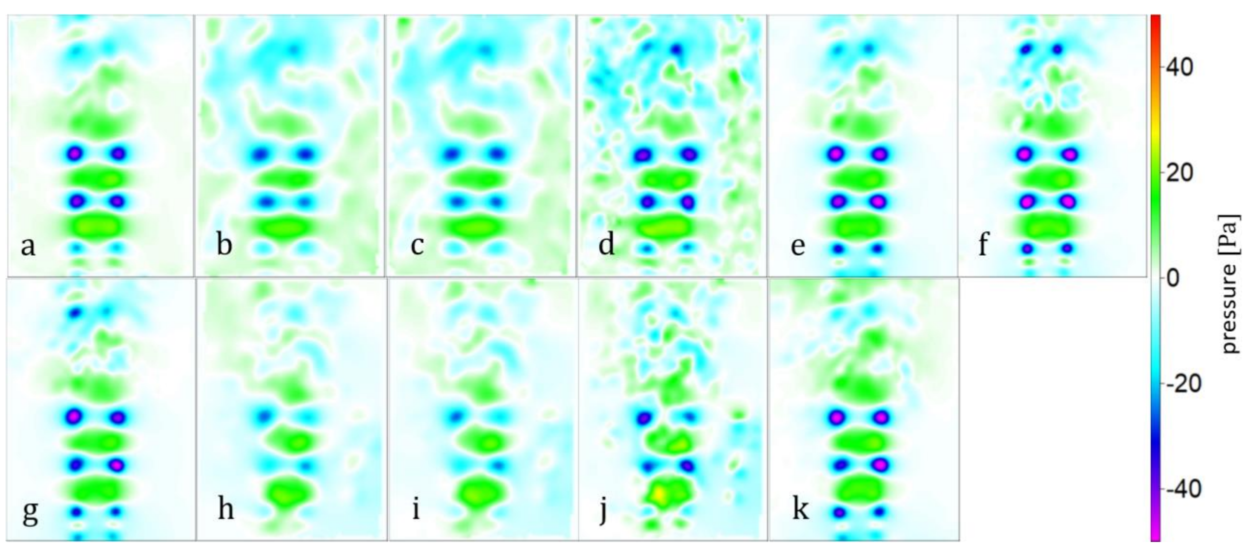


Figure 12: relative pressure. a) Tomo ps. Lag. tr.; b) STB Ord=0; c) STB Ord=1; d) STB Ord=2; e) FSR grid=12; f) FSR grid=8; g) STB 2-pulse FSR; h) STB 4-pulse Ord=0; i) STB 4-pulse Ord=1; j) STB 4-pulse Ord=2; k) STB 4-pulse FSR

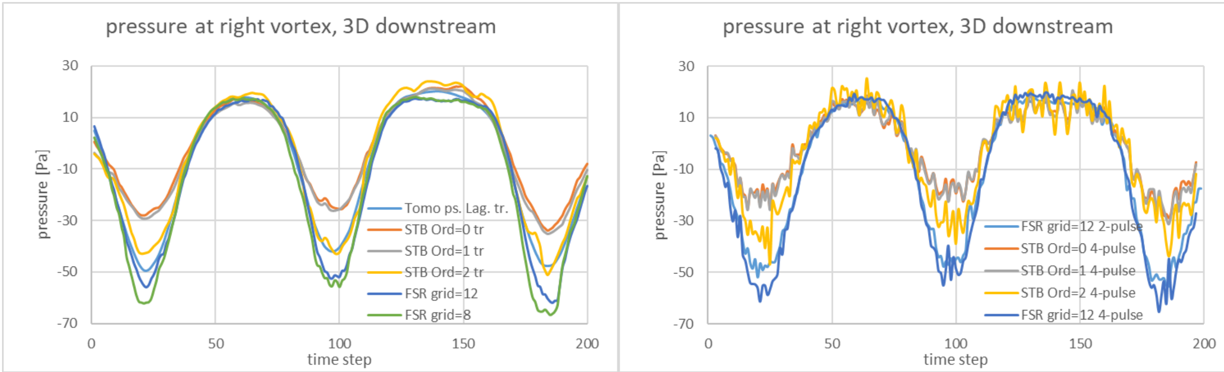


Figure 13: relative pressure at right vortex core, 3 diameters downstream

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