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4D Particle Tracking Velocimetry measurements in a Von Karman turbulence experiment

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Abstract

This study presents details of a time-resolved three-dimensional particle tracking velocimetry in a Von Karman turbulence experiment facility using four high-speed cameras and a high-speed laser. The first set of measurements are conducted within a volume of $45 \times 40 \times 6$ mm^3 with several particle seeding concentrations. The measurements are then replicated with a half-thick volume in the depth of focus direction. Acquired images are processed using Shake-The-Box (Lavision) method to obtain trajectories of particle positions in the measurement volume. The spatial concentration of tracked particles is compared for all cases. Concerning both measurement volumes, results show that by increasing the seeding concentration, the number of tracked particles is gradually converging to a maximal value after which, by seeding more particles, the number of tracked particles decreases. The maximum achievable spatial concentration of tracked particles is considerably higher for half-thick measurement volume, compared with the full-thick volume case. For half-thick measurement domain, tracked particles concentration reaches seven particles per mm^3 resulting in a mean distance of about 500 μm between particles. This value is approximately four times larger than the Kolmogorov length scale of the flow. Moreover, spectral analysis on the Lagrangian trajectories of particle positions shows that noise level of particle positions is inversely proportional to the ratio of the number of tracked particles to the total number of seeded particles in the measurement domain.

1 Introduction

The present experimental study is performed as a part of a unique project trying to understand the origin of the drag force. In turbulent flows, the drag phenomenon is mostly caused by the dissipation induced by moving objects. Consequently, flow measurements at small scales become crucial to get a better understanding of the properties of the dissipation and its consequences, such as intermittency corrections to the Kolmogorov spectrum. In this context, previously conducted stereoscopic particle image velocimetry measurements well resolved Kolmogorov length scales, but missing information on gradients in the third direction (perpendicular to SPIV plane) makes it hard to have a reasonable estimation of dissipation (Saw et al. (2016)). Moreover, traditional three dimensional tomographic PIV measurements have not been satisfying enough in terms of spatial resolution (Kuzzay et al. (2017)).
This study aims to push the limits of three-dimensional fluid motion measurements in terms of spatial resolution. Recent developments in optical diagnostics techniques have resulted in new methods such as Shake-The-Box (STB) introduced by Schanz et al. (2013). This method is a combination of 3D Particle Tracking Velocimetry and Tomographic PIV, resulting in several significant advantages on both such as higher accuracy, higher applicable particle image densities between 0.03 and 0.06 ppp (factor of 10 higher compared to classical 3D-PTV), and less computational effort (Raffel et al. (2018)). It is crucial to note that STB method only works with time-resolved data sets as it makes use of temporal information to predict the next position of tracked particles (Schanz et al. (2016)). Considering the mentioned advantages, we utilized STB method

for the current study.
A summary of previous 4D-PTV measurements performed in water with Shake-The-Box method is presented in Table 1. Schröder et al. (2015) applied STB measurements in a periodic hill experiment with a measurement volume of $90 \times 94 \times 6$ mm^3 in water. They were able to track $136,000$ particles for each time-step with a particle image density of 0.04-0.06 ppp. Tracked particles spatial concentration was about 0.8 particles/ mm^3. For Schanz et al. (2016) the perceived particle image density varies between 0.01 and 0.05 ppp in a water jet experiment resulting $12,600$ tracked particles with a spatial concentration of about 0.1 particles/ mm^3. Neeteson et al. (2016) conducted free ball fall experiment tracking about $21,000$ particles in a cylindrical volume with a diameter of 80 mm and a height of 68 mm resulting in a 0.06 particles/ mm^3 spatial concentration. Within these three studies, the minimum achieved mean distance between tracked particles is about 1 mm for Schröder et al. (2015).

Table 1: Previous 4D-PTV "Shake-The-Box" measurements in water

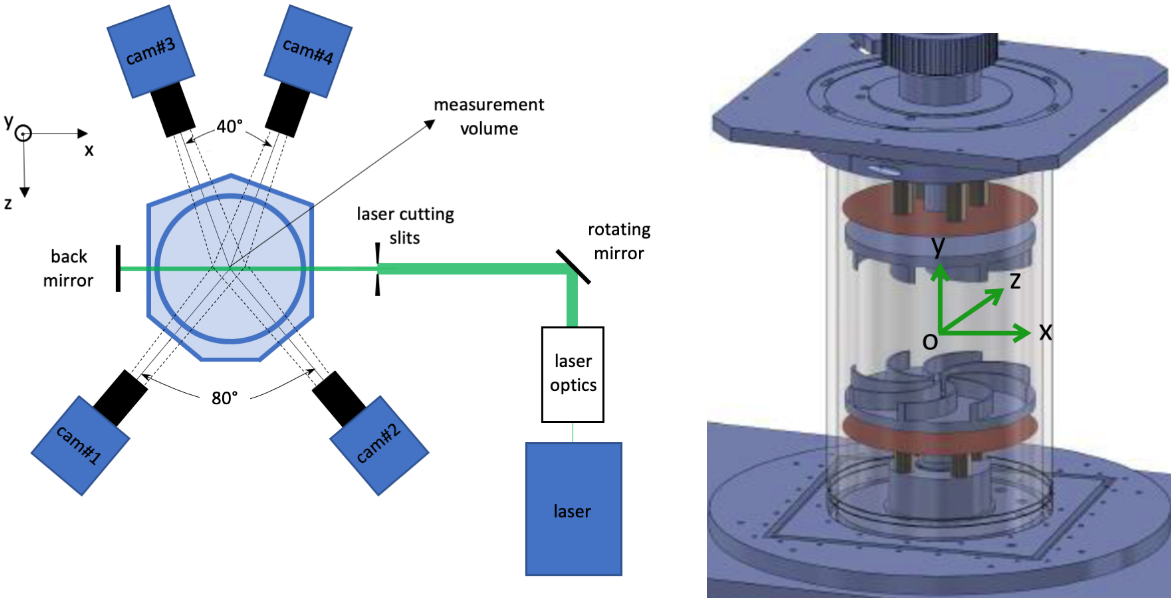
Reference	Volume [mm^3]	Image particle density [ppp]	Tracked particle concentration [particles/ mm^3]	Mean distance between particles [mm]
Schröder et al. (2015)	$90 \times 94 \times 6$	0.04-0.06	0.8	1
Schanz et al. (2016)	$\Pi \times 25^2 \times 53$	0.01-0.05	0.1	2
Neeteson et al. (2016)	$\Pi \times 40^2 \times 68$	-	0.06	2.5

2 Experimental Setup

Measurements are conducted at center of a Von Karman experiment in two different volumes of $45 \times 40 \times 6$ mm^3 and $45 \times 40 \times 3$ mm^3. The tank has a diameter of 0.2 m and a height of 0.47 m filled with water as the working fluid. The fluid is stirred by two counter-rotating impellers implemented to upper and lower ends of the tank capable of rotating in desired frequency. Imaging is performed through four high-speed cameras with planar positioning and a high-speed laser. Schematic of the experimental setup and the Von Karman facility, as well as a picture of the camera setup around the tank, are shown in Fig. 1(a-c), respectively. It is possible to perform measurements over a wide range of Reynolds numbers based on impeller's diameter and tip speed from 6,000 to 150,000 by changing the rotation frequency. For the current study, the rotation frequency is 0.5 Hz, which corresponds to a Re number of 30,000. Each camera is installed on a Scheimpflug device to obtain a uniform focus of particle images in the measurement volume. As shown in Fig.1(a), to allow the cameras to image the illuminated volume perpendicular to the air/glass interfaces, the cylindrical tank is located inside a heptagon shape tank, and the interface is filled with water without particles. 10 μm hollow-sphere glass particles are used for seeding. A mirror is placed after the tank to send back the laser to the measurement volume to minimize the effects of differences in forward and backward scattering of the particles with respect to the cameras. Details of the experimental setup are summarized in Table 2.
Kolmogorov length (η) and time (τ) scales based on ε the mean energy dissipation per unit mass, are calculated as 120 μm and 14 ms, respectively, using equation 1 & 2. Average dissipation (ε) has been measured through global torque measurements. (Kuzzay et al. (2015)).

$$\eta = (Re^3 \times \varepsilon)^{-\frac{1}{4}} r \tag{1}$$

$$\tau = (Re \times \varepsilon)^{-\frac{1}{2}} \frac{1}{2\pi f} \tag{2}$$



(a) Schematic of the experimental setup (b) Schematic of the utilized Von Karman facility

(c) Camera setup around the tank

Figure 1: Experimental setup

Table 2: Experimental setup details

Seeding	10 μm hollow-sphere glass particles
Illumination	Quantronix high speed laser, 2.5 mJ/pulse
Recording device	4 high-speed Miro, chip size:1600 × 1600 pixels
Imaging	Nikon objectives f = 105 mm, f# = 11, M=0.4
Acquisition frequency	1.2 kHz
Measurement volume	$45 \times 40 \times 6\ \mathrm{mm}^3$ & $45 \times 40 \times 3\ \mathrm{mm}^3$
Impellers rotation frequency	0.5 Hz
Reynolds number (based on impeller tip speed)	$30,000$
Kolmogorov length scale	120 μm
Kolmogorov time scale	14 ms

Each sequence of measurement is acquired with a frequency of 1.2 kHz for 2.7 seconds (3226 time-steps). Data were obtained and analyzed via Davis10 (Lavision) software. Post-processing has been done with home-made routines developed in Matlab©. Measurements are made with different particle densities in two different volume thicknesses. Volume thickness is in the direction of depth of focus of the cameras. Other conditions like laser pulse energy and Shake-The-Box analysis parameters are the same for all measurement sequences. Table 3 summarized the STB parameters.

Table 3: Shake-The-Box parameters

Threshold for 2D particle detection	110 counts			
Allowed triangulation error	0.5 voxels			
Refine particle position and Intensity	4 iterations			
Shake particle position	0.1 voxel			
Median filter for track detection	Iterations 4	Number of neighbors 10 particles	Standard deviation 2	Maximum range 120 voxels
Velocity limit (displacement)	Vx = 25, Vy = 25, Vz = 25 voxels			

3 Results

4D-PTV "Shake-The-Box" measurements are performed in a Von Karman experiment aiming highest possible spatial concentration on tracked particles. Measurements are repeated with increasing particle seeding concentration in two different domains to see the effects of volume thickness in the cameras' depth of focus direction. Results with moderate to highest manageable particle image densities are presented and compared for both full-thick and half-thick volumes. Fig. 2 presents a sample of 3-dimensional instantaneous trajectories of tracked particles for 21 consecutive time-steps in the full-thick measurement volume ($45 \times 40 \times 6$ mm^3) with 0.043 ppp particle image density.

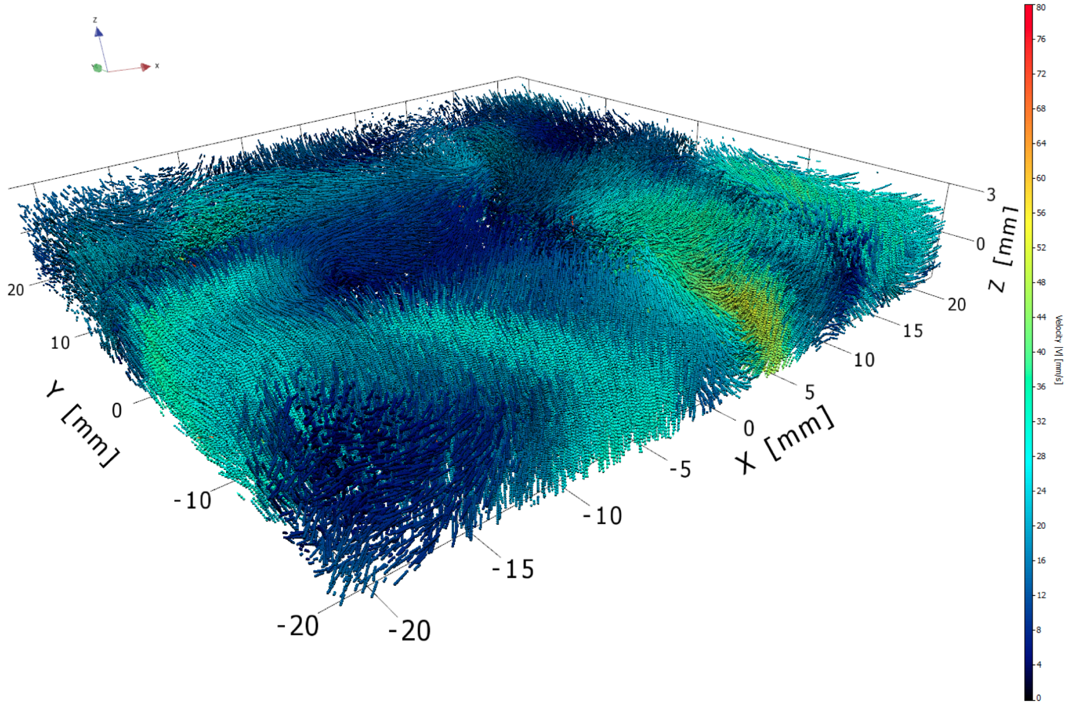


Figure 2: A sample of 3-dimensional instantaneous trajectories of tracked particles at Re=30,000, with 21 time-steps plotted for each track (0.043 ppp & $45 \times 40 \times 6$ mm^3).

The number of tracked particles in each time-step are plotted for different cases in Fig. 3. Full-thick volume case with 0.043 ppp particle image density has the maximum number of tracked particles of about $50,000$. It is crucial to note that after 0.043 ppp, measurements were conducted with 0.048 ppp, and it is not possible to get appropriate results from STB analysis. 0.043 ppp is then the maximum concentration achievable for full-thick volume. For half-thick case, the maximum achievable number of tracked particles is about $40,000$ for 0.05 ppp. As the number of the tracked particle is nearly constant between case 0.045 and 0.050 ppp for the half-volume case, the saturation of seeding concentration for this case appears around 0.050 ppp.
Fig. 4 demonstrates the effects of measurement volume thickness and amount of particle seeding on the spatial concentration of tracked particles. Seeding quantity could be investigated either as particle image density or as the physical concentration of seeded particles. In the former case (see Fig. 4(a)), we see that by decreasing the measurement volume thickness, it is still possible to obtain good STB results with slightly higher particle image densities. In the latter case (see Fig. 4(b)), by decreasing volume thickness, it is possible to obtain acceptable STB results with extremely higher spatial concentration for seeded particles. For full-thick volume (0.043ppp) the best achievable tracked particle spatial concentration is around 4.5 particles/ mm^3 corresponding to a mean distance between tracked particles of about 600 μm. For the half-thick volume case, it is possible to achieve a nearly doubled physical concentration (seven particles/ mm^3) of tracked particle compared to full-thick case. The mean distance between tracked particles reduces to about 500 μm at 0.05ppp for half-thick volume case. It is important to note that the particle image density magnitudes and consequently, particle seeding concentrations are obtained with the Davis10 software.

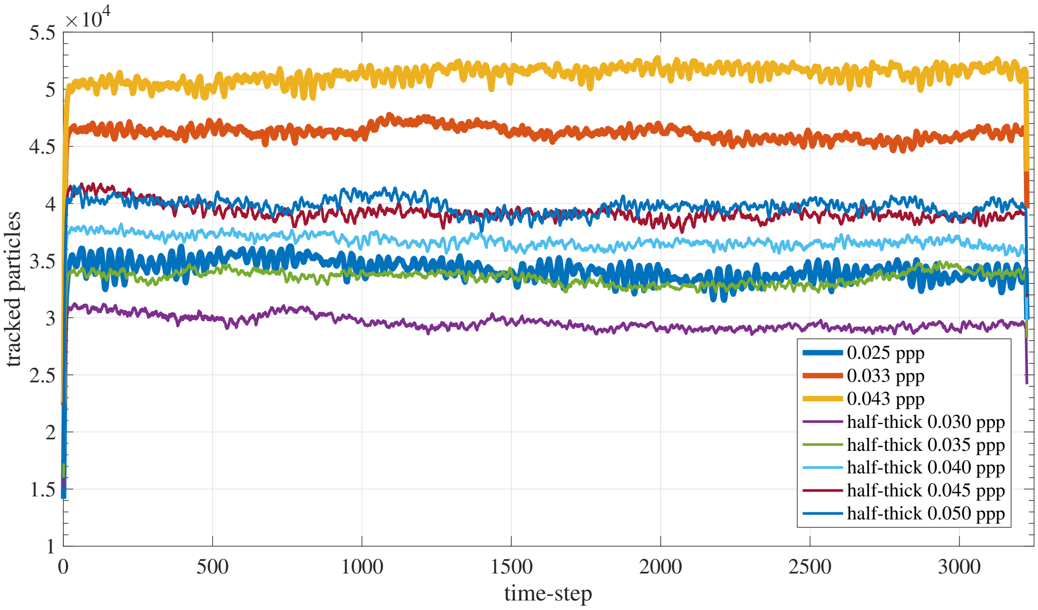
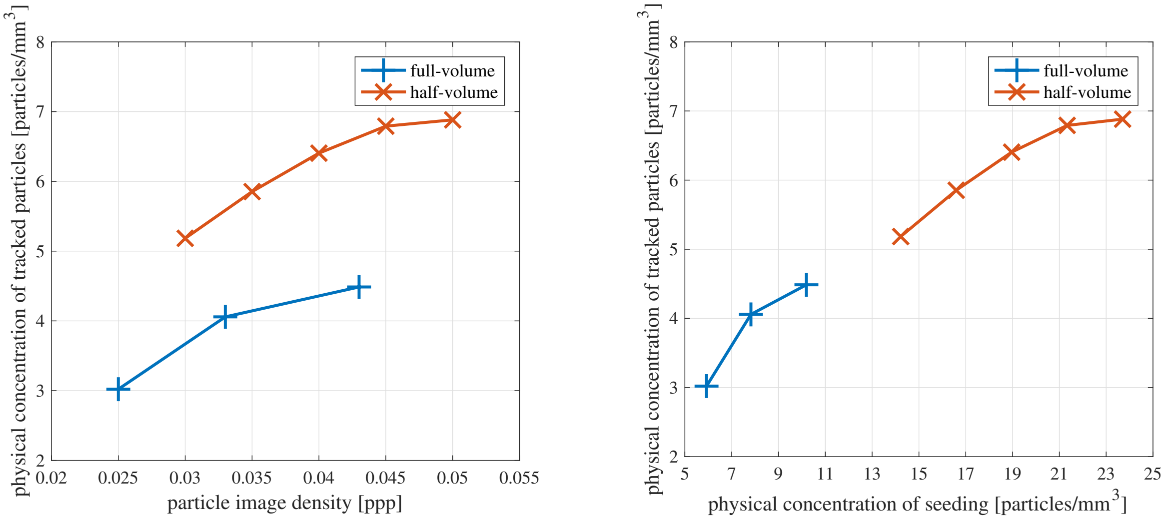


Figure 3: Number of tracked particles in each time-step

Fig. 5 shows track length histogram for all measurement sequences. As one would expect, longer tracks (up to 700 time-steps) are observed for full-thick measurement domain due to less out of plane lost in the transverse direction with thicker volume. Moreover, for the half-thick case, longer trajectories are tracked for lower particle image densities. In general, for all cases, nearly more than 40% of the tracks are longer than 20 time-steps.
Fig. 6 presents the power spectrum density of x-position of the tracked particles averaged for tracks with a length of 100 time-steps. For the flat part, which could be a good indicator for the noise level in the measured position of the particles, all cases display similar behavior except minor differences as shown in the magnified box. It is interesting to notice that the level of noise shown at high frequency in spectrum data is inversely proportional to the ratio of tracked particles to the overall number of seeded particles in the volume ($\frac{N_{tracked}}{N_{total}}$) shown in Fig. 7. Either by increasing particle image density or decreasing the volume

thickness (to track more particles), the ratio ($\frac{N_{tracked}}{N_{total}}$) decreases, and consequently, the error increases.



(a) tracked particles concentration vs. particle image density

(b) tracked particles concentration vs. seeding concentration estimated from the particle image density and the depth of the light sheet

Figure 4: Effects of measurement volume thickness and seeding quantity on the spatial concentration of tracked particles

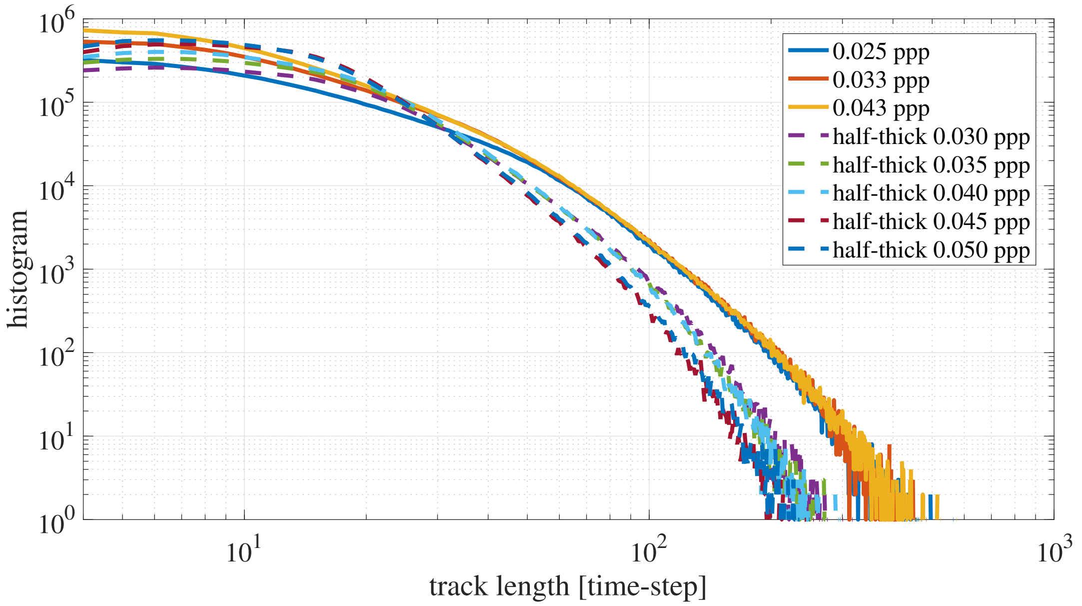


Figure 5: Track length histogram

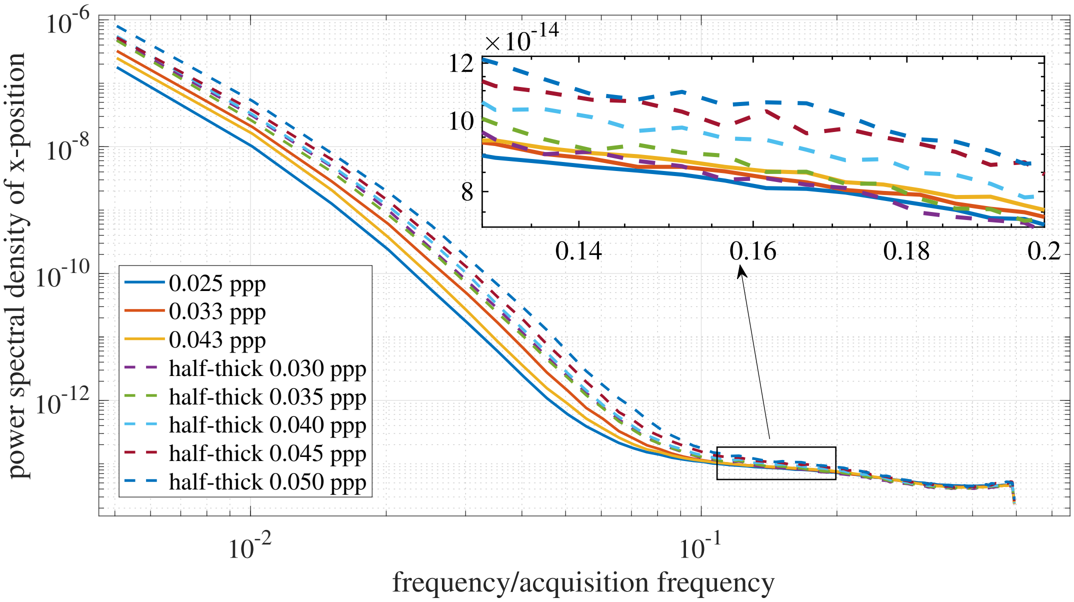


Figure 6: PSD of x-position of tracks with length of 100 time-steps

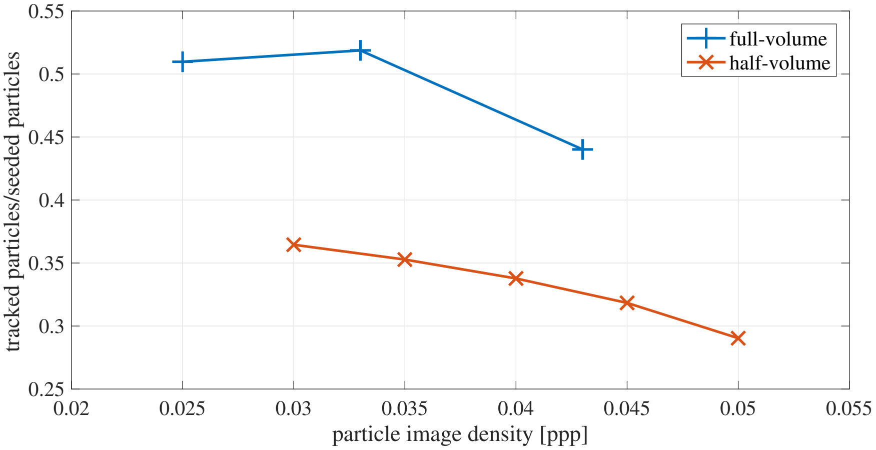


Figure 7: Ratio of the number of tracked particles to the number of overall seeded particles in the measurement domain ($\frac{N_{tracked}}{N_{total}}$).

4 Conclusion

Details of a time-resolved three-dimensional particle tracking velocimetry (4D-PTV) in a Von Karman turbulence experiment is discussed exploring highest achievable spatial resolution. Measurements are conducted in two different domains to see the effects of volume thickness in the depth of focus direction and different particle image densities. For full-thick volume case with 0.043 ppp particle image density, it is possible to track about $50,000$ particles. This value is about $40,000$ particles with 0.05 ppp for half-thick volume case. Seven particles/ mm^3 spatial concentration is obtained for tracked particles which is noticeably higher compared to the previous implementations of STB method in water.

Lastly, by decreasing volume thickness in depth of focus direction and maintaining the same levels of particle image density, it would be possible to get satisfying STB results with a significantly higher spatial resolution of tracked particles but with slightly more noise in the position of the particles. On the other hand, it is essential to be capable of capturing relatively large structures in the measurement volume. Consequently, one should make a compromise between spatial resolution of tracked particles and the thickness of the measurement domain.

Further experiments will be conducted in a bigger Von Karman Experiment facility (nearly five times) providing larger Kolmogorov length scales that could be resolved by the feasible spatial concentration of tracked particles.

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