3D Fluid Flow Estimation with Integrated Particle Reconstruction

Supplementary material

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1 Experimental Data

We test our approach on experimental data provided by *LaVision* (see [3] or Package 9 in http://fluid.irisa.fr/data-eng.htm). The experiment captures the wake flow behind a cylinder, which forms a so-called Karman vortex street (see Fig. 1 and 2). Data is provided in form of a tomographic reconstruction of the particle volume. In order to run our method, we backproject the particle volume to four arbitrary camera views (we take the same as for our simulated dataset) and use those backprojected images as input to our method. Since particle densities allow it and the provided reference flow is of low resolution, we downsample the input volume by a factor of 2 from $2107 \times 1434 \times 406$ to $1054 \times 717 \times 203$ and render to 2D images of dimensions 1500×1100 with particle size $\sigma = 0.6$. Note, that since those camera locations do not necessarily coincide with the original camera locations, ghost particles in the reconstructed volume may lead to wrong particles in the backprojected image. However, as results in Fig. 3 indicate, our algorithm is able to recover a detailed flow field that correponds with the reference flow despite these deflections in the data. In addition to our own result, we show results provided by LaVision. The provided reference flow field was estimated with TomoPIV, using a final interrogation volume size of 48^3 and an overlap of 75%, i.e. one flow vector at every 12 voxel locations. It can be seen in Fig. 3 that our method recovers much finer details of the flow, due to the avoidance of large interrogation volumes. In order to cope with flow magnitues up to 15.5 voxel we chose 16 pyramid levels and a pyramid downsampling factor of 0.92. Note, that in the resulting flow field the cylinder is positioned to the right of the volume and the general flow direction is towards the left. Effects of the Karman vortex street can be primarily seen in the z component of the flow (periodically alternating flow directions with decreasing magnitude from right to left). Additional visualizations are available in the attached video.

2 PIV Challenge

Since no ground truth is provided for testcase D of the 4^{th} PIV Challenge [1] and it is no longer possible to submit to the challenge, a quantitative evaluation of our approach on this dataset is infeasible. However, additional to the quantitative comparison with StB in the main paper, we show a qualitative comparison of our method with the ground truth and the best performing method StB [5] in Fig. 4. Additionally, we show a streamline visualization of our results in Fig. 5. Additional visualizations for our comparison with StB are available in the attached video.

3 Simulated Dataset

To quantitatively evaluate our method, we use the forced isotropic turbulence dataset of the Johns Hopkins Turbulence Database (JHTDB) [2, 4], which is generated using direct numerical simulations. We sample 12 non-overlapping datasets of size $1024 \times 512 \times 342$ voxels, with a discretization level of 4 voxels per DNS grid point (as done also by [1]). Datasets are sampled at $t = 0.364$ and $t = 8.364$ at 6 different spatial locations. Standard temporal difference between two consecutive timesteps is $\Delta t = 0.004$. For each dataset we sample 480.000 seeding particles at random locations within the volume and ground truth flow vectors at each DNS grid location. In Fig. 6-9 we visualize the flow fields of the 12 resulting datasets. Quantitative evaluation on these datasets for various parameter settings, as well as for different particle densities and temporal sampling rates, are provided in the main paper. Additional visualization (incl. results of our method) for one of the datasets are shown in the attached video.

References

1. Kähler, C.J., et al.: Main results of the 4th International PIV Challenge. Experiments in Fluids **57**(6) (2016)
2. Li, Y., et al.: A public turbulence database cluster and applications to study Lagrangian evolution of velocity increments in turbulence. J. of Turbulence **9** (2008)
3. Michaelis, D., Poelma, C., Scarano, F., Westerweel, J., Wieneke, B.: A 3d time-resolved cylinder wake survey by tomographic piv. In: ISFV12 (2006)
4. Perlman, E., Burns, R., Li, Y., Meneveau, C.: Data exploration of turbulence simulations using a database cluster. In: Conf. on Supercomputing (2007)
5. Schanz, D., Gesemann, S., Schröder, A.: Shake-The-Box: Lagrangian particle tracking at high particle image densities. Experiments in Fluids **57**(5) (2016)

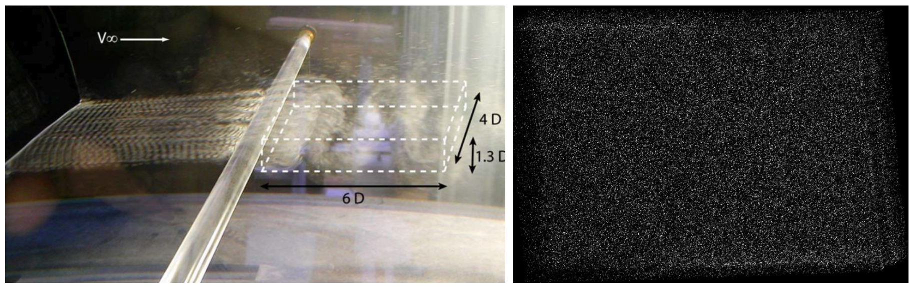

Fig. 1: *Left:* Visualization of the experimental setup for a wake flow estimation behind a cylinder (Image taken from [3]). In the measurement volume behind the cylinder the Karman street can be observed (alternating up and down flow in the z component). In the provided data the cylinder is to the right of the volume with a flow moving from right to left. *Right:* Input 2D image for one of the camera views.

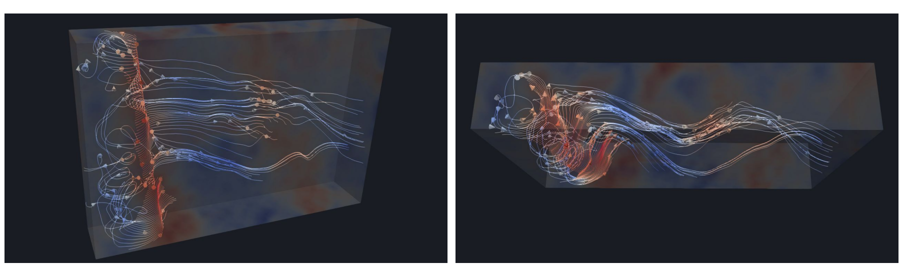

Fig. 2: Experimental data: Streamline visualizations of our results with color coding based on z component of the flow (where the Karman street can be best observed).

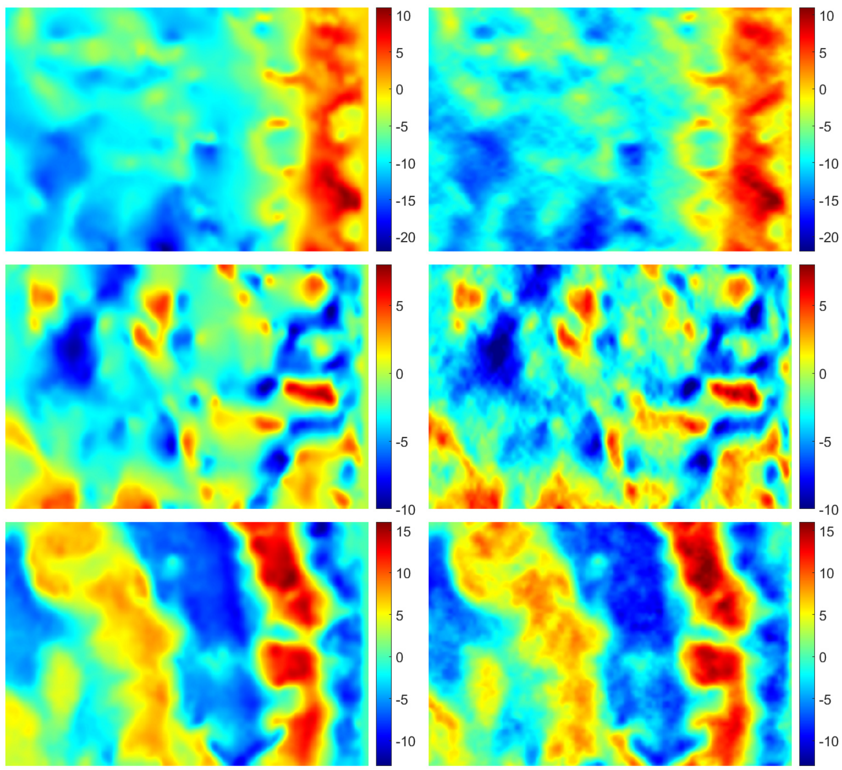

Fig. 3: Experimental data: xy-slice of the flow at $z = 203$. *Left:* Reference flow field provided by LaVision (TomoPIV). *Right:* Results with our approach. (*top* to *bottom*: flow in X, Y and Z-direction).

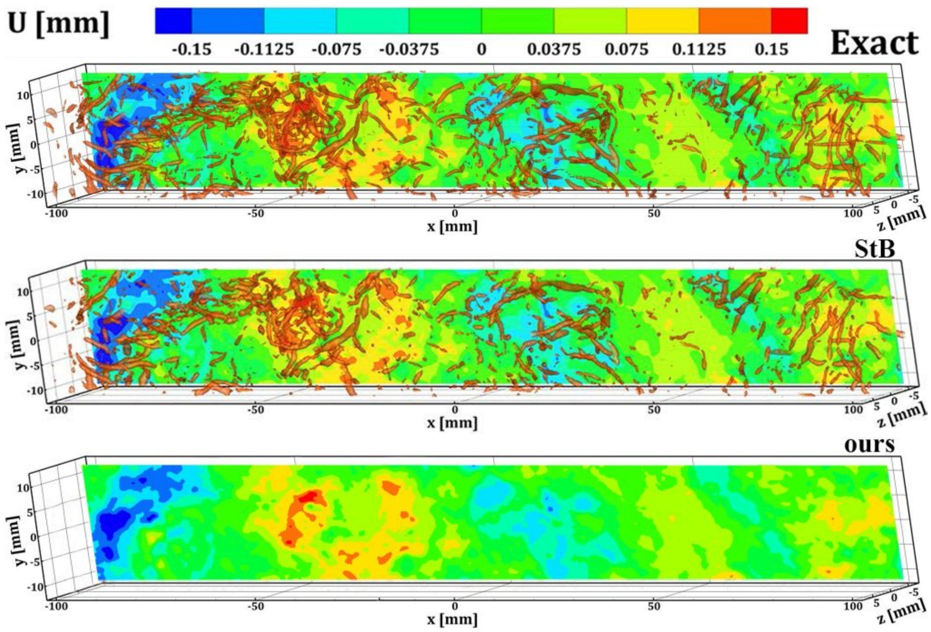

Fig. 4: PIV Challenge: xy-slice ($z = -5.2mm$) of the flow in X-direction in snapshot 23 of the 4$^{\text{th}}$ PIV Challenge [1]. *Top:* Ground truth (with additional visualization of vortices). *Middle:* StB [5], the best method on the challenge. *Bottom:* Our result. Images of ground truth and competing method adapted from [1].

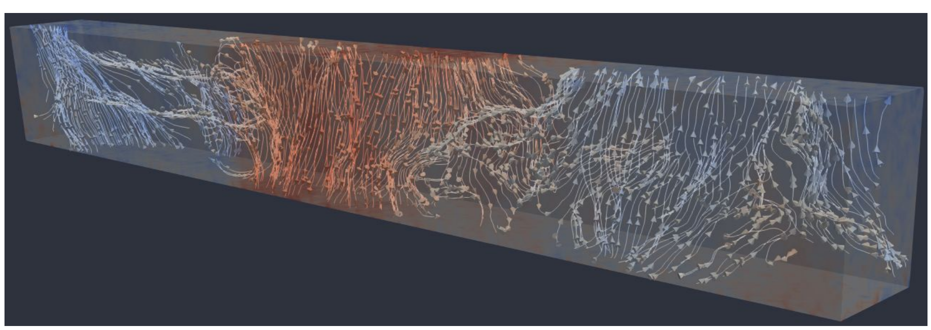

Fig. 5: PIV Challenge: Streamline visualizations of our results for snapshot 10 of the 4$^{\text{th}}$ PIV Challenge [1] with y component of the flow color coded.

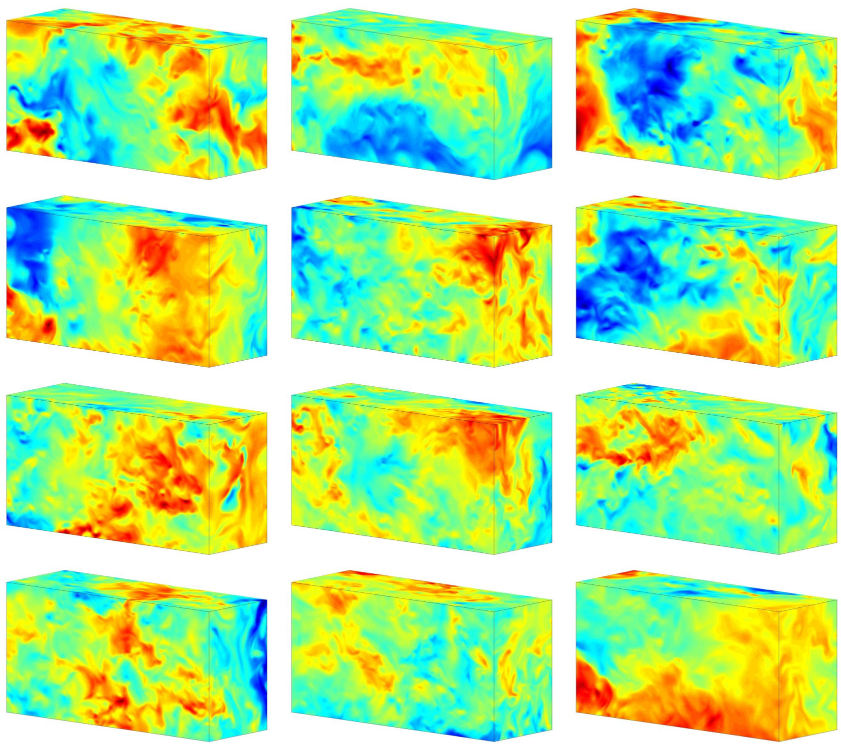

Fig. 6: 12 datasets (visualizing flow in X-direction), sampled at non-overlapping locations in the forced isotropic turbulence dataset of the JHTDB [2, 4].

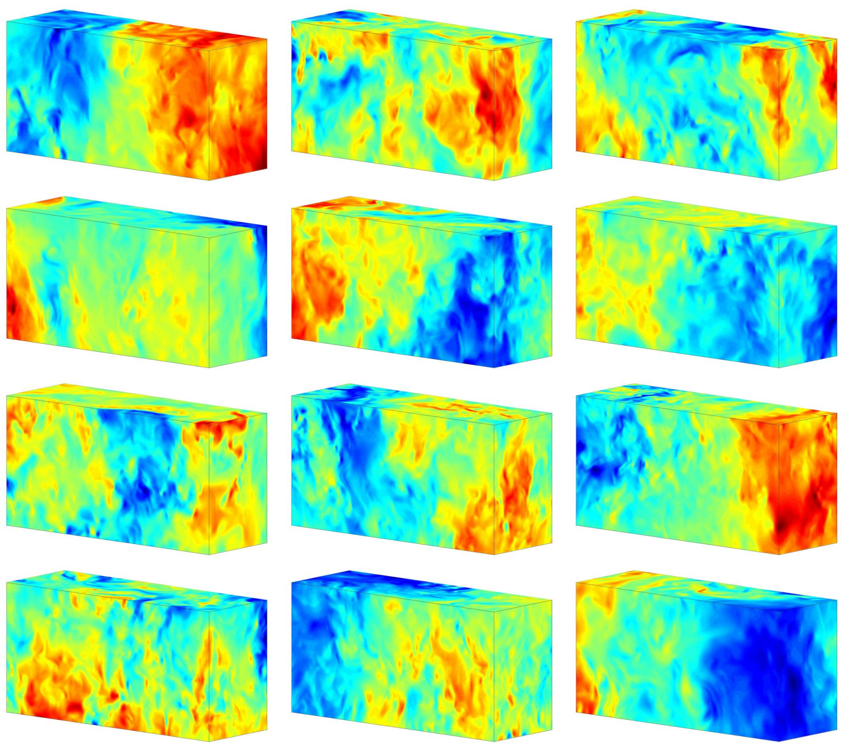

Fig. 7: 12 datasets (visualizing flow in Y-direction), sampled at non-overlapping locations in the forced isotrpic turbulence dataset of the JHTDB [2, 4].

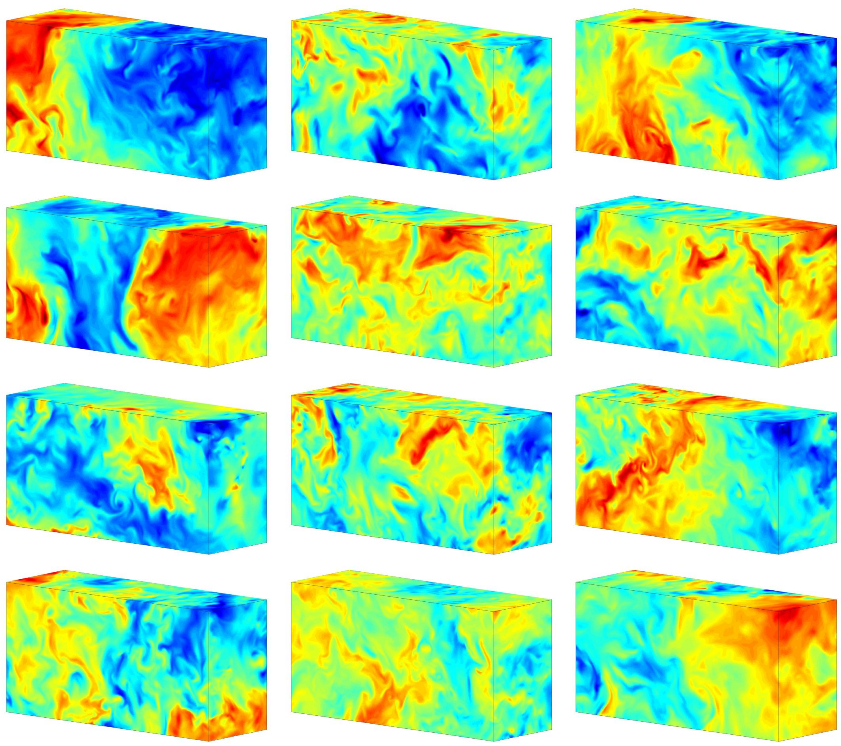

Fig. 8: 12 datasets (visualizing flow in Z-direction), sampled at non-overlapping locations in the forced isotrpic turbulence dataset of the JHTDB [2, 4].

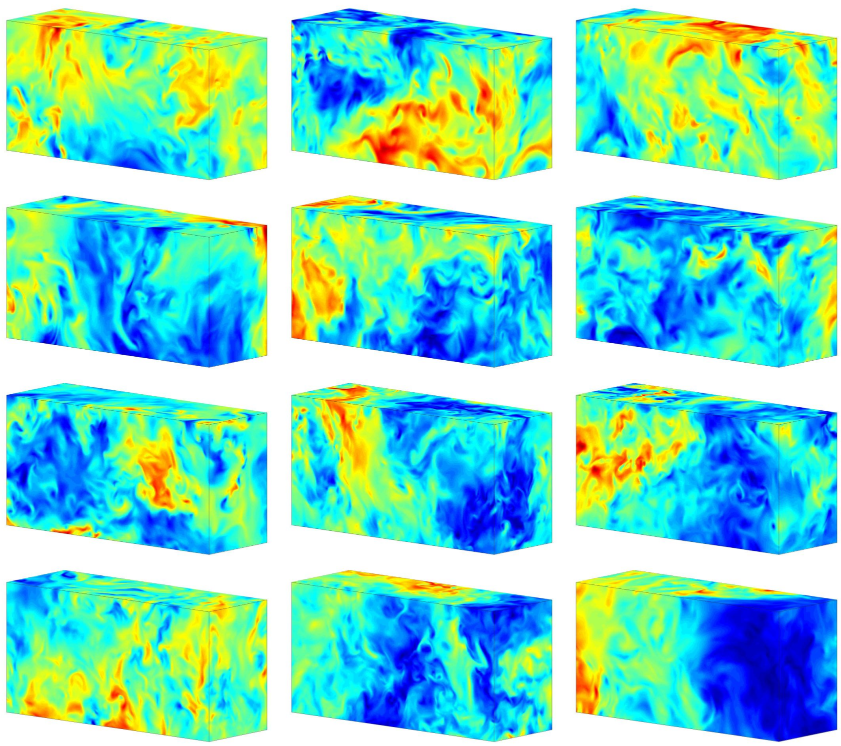

Fig. 9: 12 datasets (visualizing flow magnitudes), sampled at non-overlapping locations in the forced isotrpic turbulence dataset of the JHTDB [2, 4].