1st Spanish Fluid Mechanics Conference
Cádiz, June 19-22, 2022

Flow-field estimation of jet flow from point sensors

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Having access to the spatial description and dynamics of turbulent flows is a key enabler for a better understanding of their behaviour. In the last decades, Particle Image Velocimetry (PIV) imposed as a robust and powerful tool to achieve this goal. Time-resolved PIV discloses a full description of the flow dynamics only up to relatively low Reynolds numbers. As the Reynolds number increases, achieving time resolution becomes unfeasible due to hardware limitations. An interesting pathway to obtain time-resolved velocity fields is offered by simultaneous measurements with PIV and sparse point sensors. Time resolution is easily achievable with "point" sensors such as hot-wire anemometers or microphones, for instance. The correlation between sensor signals and field measurements can be leveraged to estimate flow fields at the same temporal resolution of the probes.

Field estimation from sensors has attracted significant interest in the recent past in the fluid dynamics community, see e.g. [1, 2]. Linear Stochastic Estimation (LSE), filtered Extended Proper Orthogonal Decomposition (EPOD) and deep learning techniques are examples of approaches to perform this task. While those methods have shown to be successful for low Reynolds number flows, 2D flows and/or in cases with a clear shedding signature, their capabilities in turbulent flows require more careful investigation. The objective of this work is to establish a computational framework in which techniques for flow estimation for turbulent flow with moderate to high Reynolds numbers can be tested in view of the final experimental application. As a prototype test case, a turbulent round jet flow is considered. A large eddy simulation of the near field has been performed. We consider a Newtonian fluid of kinematic viscosity ν steadily flowing through a nozzle of diameter D with a flat-topped velocity profile with velocity U_J. The Reynolds number of the jet is $Re_J = U_J D/\nu = 68000$. The computational domain is a cylinder of length $5D$ and outer diameter $4D$. At the inflow plane we impose a Dirichlet boundary condition with the jet velocity U_J for $r \leq D/2$ and a mild co-flow $0.03\ U_J$ for $r > D/2$, where r indicates the radial position. A free slip condition is used at the lateral boundary and a non-reflective boundary condition is employed at the outflow boundary. The simulation has been carried out with the open source spectral-element code NEK5000 [3]. The methodology is similar to that of a previous study of turbulent flow in a pipe [4].

We have performed a grid refinement study using three grids, with spectral elements of polynomial order 7. The coarsest grid had 132 elements in the cross-plane and 15 along the streamwise direction. The intermediate grid had 297 and 31 and the finest grid had 637 and 59. We have compared our results to experimental measurements [6, 8] and results from other simulations [5, 7]. Figure 1 shows profiles of the time-averaged streamwise velocity and the root-mean-square streamwise velocity fluctuations as a function of the radial coordinate at a streamwise coordinate $z = 3D$. The agreement with the data from the literature is satisfactory. The profiles also show that the results obtained with the intermediate grid are in agreement with those of the finest grid, so that the intermediate grid is used in the rest of the work. For the data analysis, we have collected 4900 snapshots of the whole velocity field and in addition we have collected time-resolved velocity signals at 144 locations. The probes are located at two radial positions ($r/D = 0.5 - 0.6$) in twelve equally-distributed angular positions. In the longitudinal directions, the probes are distributed in six planes at positions $z/D = 1, 1.5, 2, 2.5, 3, 3.5$.

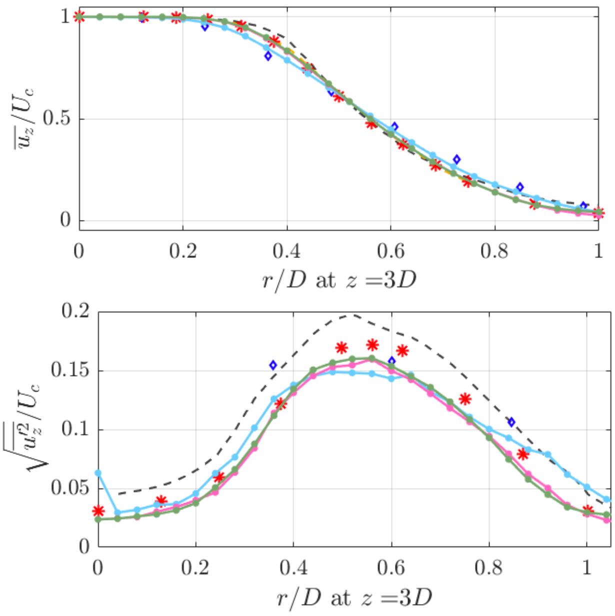

FIG. 1. Time-averaged streamwise velocity profile (top) and root-mean-square streamwise velocity fluctuations (bottom) as a function of the radial coordinate at $z = 3D$. The profiles are normalized with the jet centerline velocity U_c. Present results: coarse grid (light blue), intermediate grid (magenta), fine grid (green). Dashed black line, data from [5]. Dashed yellow line, data from [7]. Red symbols, data from [6]. Blue symbols, data from [8].

The flow estimation is performed with EPOD [9]. The correlation between velocity fields and probe data is established via the temporal mode of the corresponding snapshot matrices. Owing to the large amount of data, the POD of the velocity fields is carried out with the snapshot method based on the temporal correlation matrix. The snapshot matrix of the probe data is enriched with temporal information, in analogy with Ref. [1], and

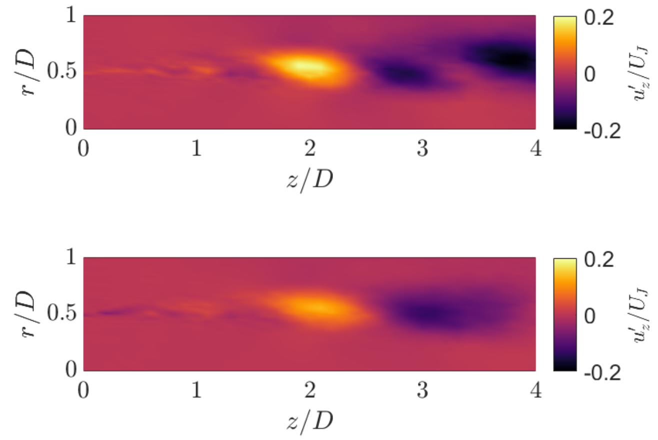

FIG. 2. Contour of the streamwise component of the velocity fluctuation field u'_z normalized with the inlet jet bulk velocity U_J, reconstructed with the 10 most energetic POD modes. Top: reference field. Bottom: reconstruction with EPOD.

following the same "virtual-probe" approach presented in Refs. [10, 11]. The main assumption is that time information collected at a certain location z_p can be incorporated as spatial information, i.e. for convective flows data recorded in time past the snapshot instant $t > t^*$ are similar to data that would have been recorded at the time t^* of the field snapshot if located upstream in the flow $z < z_p$ (assuming the convection velocity is aligned with z). In our preliminary tests, the highest reconstruction accuracy is obtained when the time span to build virtual probes is approximately equal to the convection time between one plane of probes and the following one, i.e. $0.5D/U_c$. The correlation is established in terms of temporal POD modes of the field and probe data, with the correlation matrix being filtered with the 3σ-criterion introduced by Ref. [11].

In this work, we aim to test the flow estimation procedure for time supersampling, i.e. increase the time resolution between field snapshots. We target a supersampling factor of 100, i.e. the field snapshots are separated in time by 100 time steps of the simulation (corresponding to $0.5D/U_J$, being U_J the inlet jet bulk velocity). The probe data are collected at the same time resolution of the simulation. An example of a reconstructed velocity field is reported in Figure 2. The reconstruction is limited to the 10 most energetic POD modes. The results are shown in form of contour of the streamwise component of the fluctuating velocity field. It can be shown that the main flow structures are identified, including the thin shear layer in the region upstream of the probes ($z/D < 1$), although with a degree of attenuation.

These preliminary results support the possibility of using probes to perform time supersampling also in flows with moderately high Reynolds numbers and 3D features. We aim to exploit the database in the future to investigate the effect on reconstruction accuracy of the number and position of probes, and as a benchmark to test more advanced non-linear flow estimation techniques.

ACKNOWLEDGEMENTS

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 949085).

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