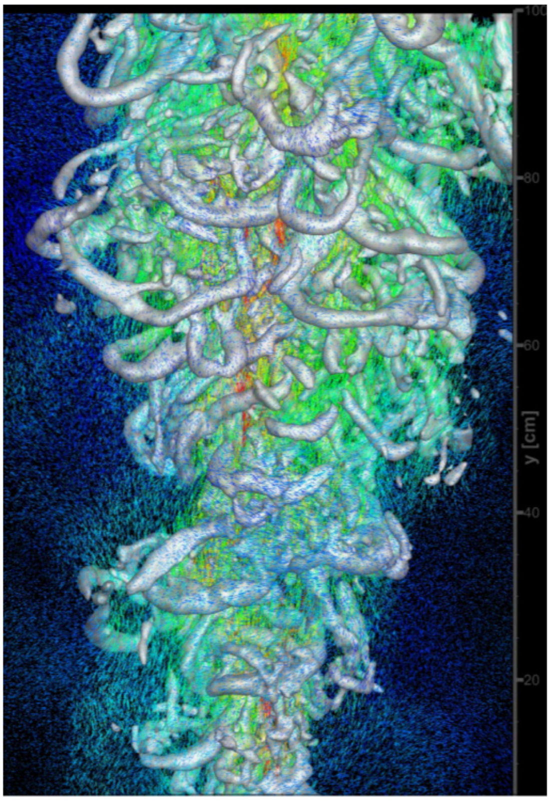
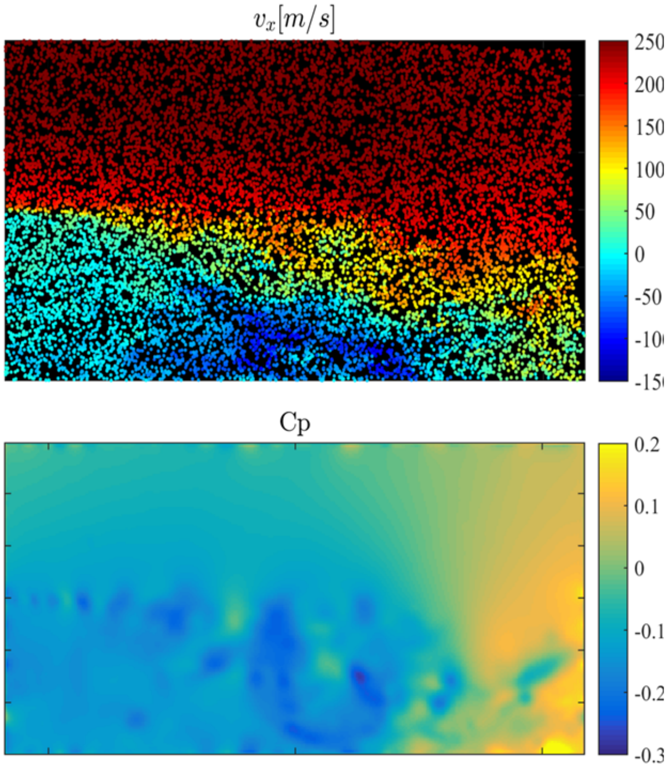
Workshop
on CFD Processing Techniques
for Particle Image and -Tracking Velocimetry

Book of Abstracts

Sunday, July 3, Lisbon, Portugal
at Hotel Real Palacio





TU Delft DLR

Final Program

18 minute presentations, after which there is time for a 5-minute discussion.

11:30 Welcome and Introduction

11:55 Compressed motion sensing in tomo PIV
R. Dalitz*, S. Petra and C. Schnörr*

12:20 Adjoint based data assimilation in compressible flow
M. Lemke *and J. Sesterhenn*

12:45 FlowFit II Implementation Details
S. Gesemann

13:10 Discussion & Coffee break

13:30 Improving on adjoint based PIV data-assimilation
R. Yegavian*, B. Leclaire, F. Champagnat and O. Marquet*

13:55 Towards PIV assimilation of large-scale wake flows: study of several sub-grid models
P. Chandramouli*, D. Heitz, E. Mémin and S. Laizet*

14:20 On variational flow reconstruction from tomographic PTV using VIC+
J.F.G. Schneiders *and F. Scarano*

14:45 Discussion & Coffee break

15:15 The effect of experimental uncertainties on the estimation of velocity based quantities
S. Scharnowski *and C.J. Kähler*

15:40 3D assimilation with PIV orthogonal-plane observations and a DNS dynamical model in a circular wake flow.
C. Robinson*, D. Heitz, A. Gronskis and E. Mémin*

16:05 How to obtain invariant Navier-Stokes solutions from time resolved 3D PIV data
J. Kühnen, *S. Altmeyer, and B. Hof*

16:30 Discussion & Coffee break

16:50 Pressure evaluation from PIV measurements by several approaches
L. David*, Y.J. Jeon, L. Chatellier, V.T. Nguyen, F. Pons, A. Beaudoin, S. Huberson and B. Tremblais*

17:15 Main results of the 4th International PIV Challenge 3D test Case D
T. Astarita

17:40 Closing

17:45 (optional) Walk to Lisbon Symposium venue for registration

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COMPRESSED MOTION SENSING IN TOMO PIV

ROBERT DALITZ, STEFANIA PETRA, AND CHRISTOPH SCHNÖRR

ABSTRACT. In previous work [PS14, PSS13] we analyzed representative ill-posed scenarios of tomographic PIV (Tomo PIV) [ESWvO07] with a focus on conditions for unique volume reconstruction. Based on sparse random seedings of a region of interest with small particles, the corresponding systems of linear projection equations were probabilistically analyzed in order to determine: (i) the ability of unique reconstruction in terms of the imaging geometry and the critical sparsity parameter, and (ii) sharpness of the transition to non-unique reconstruction with ghost particles when choosing the sparsity parameter improperly. We showed that the sparsity parameter directly relates to the seeding density used for Tomo PIV that is chosen empirically to date. Our results provide a basic mathematical characterization of the Tomo PIV volume reconstruction problem that is an essential prerequisite for any algorithm used to actually compute the reconstruction. Moreover, we have connected the sparse volume function reconstruction problem from few tomographic projections to major developments in compressed sensing (CS) and found out that the predicted critical seeding lies below the theoretical optimal threshold in CS.

In more recent work [DPS16] we complement the standard tomographic sensor, based on few projections, by additional measurements of moving objects at two subsequent points in time. Denoting by A the Tomo PIV sensor that corresponds to few projections synchronously recorded with few cameras only, the standard approach is to reconstruct an image pair (u, u_t) from $Au \approx b$, $Au_t \approx b_t$ and then - in a subsequent step - to estimate the unknown flow transport mapping $T_t(u) = u_t$ by cross-correlating (u, u_t).

Our approach is to use the available information at time step t, to consider the projections b_t as additional measurements together with b and to *jointly estimate* the images and the transformation parameters from the available multi-view measurements. Thus, we solve

$$\min_{T_t, u \geq 0} \|Au - b\|^2 + \|AT_t(u) - b_t\|^2$$

and regard $AT_t(\cdot)$ as an *additional* sensor. From the CS viewpoint this raises the key question if and how much the recovery performance of the complemented sensor

$$A_T := \begin{pmatrix} A \\ AT_t(\cdot) \end{pmatrix}, \quad A_T\, u = \begin{pmatrix} b \\ b_t \end{pmatrix}$$

improves, under the assumption that T_t is known. We call compressed sensing in connection with the correspondence information $u_t = T_t(u)$ *compressed motion sensing*. We evaluate both theoretically and numerically the recovery performance of A vs. A_T and show that our approach enables highly compressed sensing in dynamic imaging scenarios of practical relevance.

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Adjoint-Based Data Assimilation in Compressible Flow

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ABSTRACT

Data assimilation Data assimilation means the process of incorporating observations into a mathematical model of a real system. It aims to find a state among all possible states of a considered model that matches observations in an optimal sense. Thus, it enables an advanced analysis of a real system by means of a mathematical model. The 4DVar technique is the most common variational approach for data assimilation. It determines the model trajectory that fits best to observations in time by minimising the integral formulation

$$J(q) = \frac{1}{2}(q - q^b)^T B^{-1}(q - q^b) + \frac{1}{2}\int_{t_0}^{t_1} (y(t) - H(q(t)))^T R^{-1}(y(t) - H(q(t)))\mathrm{d}t,$$

usually referred to as cost or objective function, by the assimilation of parameters of the considered model. For the minimisation an adjoint model is used to compute the necessary gradient. We will present a continuous adjoint model for the compressible Navier-Stokes equations and its application for different tasks in fluid dynamics.

Pressure from PIV In the context of the NIOPLEX project the derived framework is applied to the pressure determination from PIV data [1]. A numerical simulation is modified by adaptation of artificial sources or boundary conditions in order to match the measured velocity data. Then, the pressure can be extracted from the numerical result. We will present the validation of the framework by means of synthetic data and an application to experimental data.

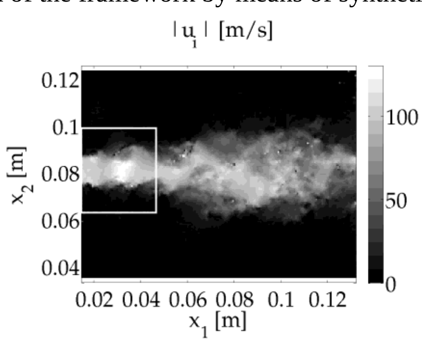

Figure 1 - Experimental absolute velocity field, determined by means of particle image velocimetry.

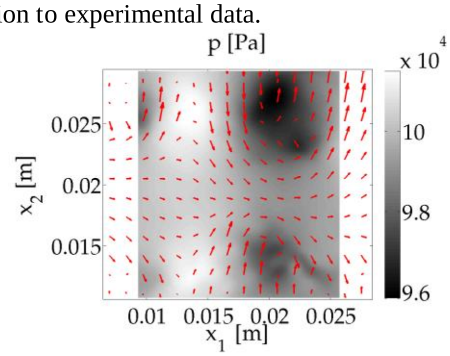

Figure 2 - Resulting pressure field in the marked region of the flow after application of the adjoint framework.

Extensions The derived framework is capable of handling multiple velocity snapshots, available for high-speed measurements, and inclusion of additional measurement quantities. Furthermore, it can be used for acoustic applications. Corresponding examples will be presented. The inclusion of a volume-penalization-method for flexible geometry implementation into the framework will be discussed as well as the extension to reactive flows [2].

Conclusion The connection between experimental and numerical analysis improves our capabilities to examine flows. The variational adjoint-based approach shows very good performance. It is found that pressure determination from PIV data in compressible flows is possible, without further assumptions beyond the Navier-Stokes equations. In particular noteworthy is the filter property of the framework. It is applicable for a model-based improvement of noisy measurement data as the assimilated solution fulfils the Navier-Stokes equations, while the PIV analysis does not.

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FlowFit II Implementation Details

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ABSTRACT

Since 2013 we have been developing methods for spatial interpolation of scattered velocity and acceleration data to complement particle tracking techniques that yield such data with a high enough spatial resolution [Scha14][Scha16]. This presentation highlights some of the properties and implementation details of the methods we termed “FlowFit” and “FlowFit 2”. Both make use of uniform 3D B-splines to represent velocity, acceleration or pressure fields and determine these fields by minimizing a cost function which possibly accounts for some physical constraints as well by penalization. The first generation FlowFit has been used in our submissions of the 4th PIV Challenge [Käh16]. It reconstructs either velocity or acceleration. The second generation FlowFit combines these two reconstruction problems into a single one to exploit more of the physical constraints we know should hold in order to improve the reconstruction quality.

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Improving on adjoint based PIV data-assimilation

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ABSTRACT

Despite continuous improvements, Particles Image Velocimetry (PIV) is often not able to capture the smallest scales of the flow. Camera and laser frequency are responsible for time filtering. Pixel sizes and interrogation-windows based algorithms are responsible for space filtering. Boundary layers also tend to be badly illuminated with low seeding densities. Such small scales and boundary layers are critical to the understanding of physical phenomena. To overcome those limitations, physical constraints are used. We search for an unsteady field, respecting the Navier-Stokes equations, as close as possible to PIV measurements, as described by Gronskis et al [1]. This is a constrained optimization problem, it is solved iteratively using the direct and adjoint discrete Navier-Stokes equations as shown in [2]. The focus of the current study will be on the effect of the optimization parameter space on the quality of the reconstructed unsteady field.
In figure 1, we apply the above approach downstream of a forced backward facing step at a low Reynolds number. Dimensionless streamwise velocities are plotted over time in the middle of the assimilation domain. The simulated ground truth is represented in black. A realistic synthetic PIV (red dots) is built upon the ground-truth with high noise and spatiotemporal filtering. Those PIV measurements are inputs for the assimilation. The resulting field at convergence without reducing the parameter space is plotted in blue on (a). With a reduced parameter space for the optimization (green line on figure (b)) the assimilation process is able to accurately recover the ground truth using only the PIV as inputs despite a low SNR.

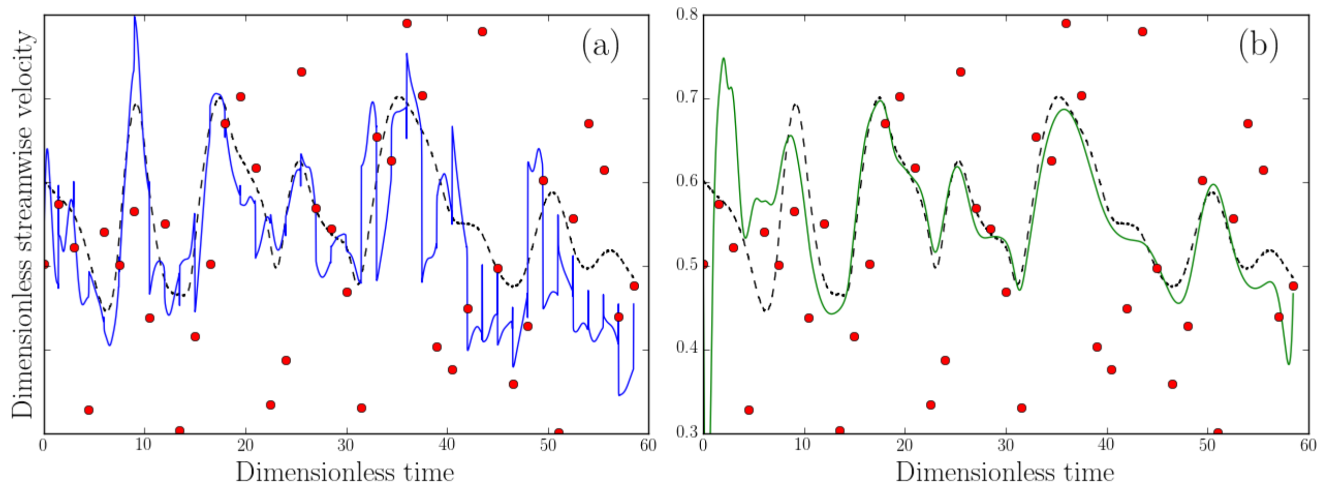

Figure 1 Dimensionless streamwise velocity with respect to time. – – Simulated ground truth; • • Synthetic PIV; (a) — Assimilated field on the full parameter space; (b) — Assimilated field on a reduced parameter space.

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Towards PIV assimilation of large-scale wake flows: study of several sub-grid models

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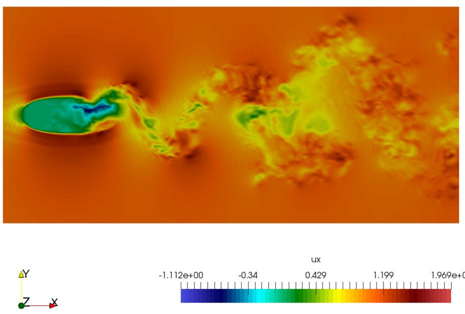
ABSTRACT

With the increasing attraction of data assimilation combined with improved computational power, the concept of using image based velocity measurements as a guiding mechanism for the numerical simulation of flow dynamics has gained a lot of interest. Previous PIV Data Assimilation study implemented on Incompact3d -a parallelised flow solver developed by [1]- has performed admirably in the case of a DNS of low Reynolds number wake flow [2]. However, performing such data assimilation on a Direct Numerical Simulation (DNS) basis remains computationally unachievable even for flows at moderate Reynolds number. Only, coarse Large Eddy Simulation (LES) is conceivable. This necessitates the identification of the best suited subgrid model for the flow under study, i.e. cylinder wake flow at a Reynolds number of 3900 corresponding to the turbulent Von-Karman vortex shedding regime (see figure 1 left). This is the focus of the present work.

Over the past decades, numerous LES sub-grid scale (SGS) models have been proposed each possessing some unique set of advantages. However, there exists no universal model providing statistically accurate results for all types of flows. Several SGS models have been compared. Models under scrutiny include the classical Smagorinsky model along with contemporary models under uncertainty developed by [2] namely Stochastic Smagorinsky (StSmag), Stochastic Spatial (StSp), and Stochastic Temporal (StTe) covariance models. The numerical simulation was performed on a very low-resolution mesh compared to a DNS as well as the LES simulations of [3]. The simulation statistics have been compared with the PIV data of [3] along with an under resolved DNS (URDNS) at the LES resolution mainly to identify the improvements in statistics (see figure 1 right). The statistics clearly show improved fit to the PIV data with the stochastic SGS models as compared to classic Smagorinsky model that over smoothens the velocity gradient– the directional dissipation associated with the stochastic models along with other factors can be attributed to this improvement. The next step will consist to perform a 4DVar PIV assimilation with such SGS models.



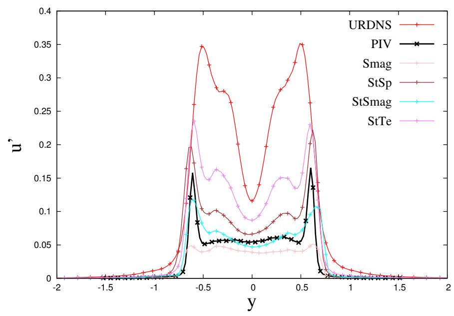


Figure 1 Cylinder wake flow LES simulations based on location uncertainty principle: (Left), Velocity norm for the LES with the StSP subgrid tensor; (Right), Streamwise velocity fluctuation profiles at 1.06D behind the cylinder axis, for different subgrid tensor models compared with PIV of [3] and an under resolved DNS.

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On Variational Flow Reconstruction from Tomographic PTV using VIC+

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ABSTRACT

The vortex-in-cell-plus (VIC+) method interpolates velocity on a dense grid from volumetric and scattered Lagrangian particle trajectory measurements. Spatial resolution achieved with such measurements is related to the seeding concentration of the tracer particles. Accurate and dense interpolation or velocity is relevant in cases where seeding concentration is limited by for example the maximum particles per pixel allowed for tomographic reconstruction or particle triangulation. The VIC+ method considers a minimization problem with the goal to minimize a cost function under the constraint of the incompressible Navier-Stokes equations in vorticity-velocity formulation. The cost function penalizes the difference between the scattered measurements and the dense reconstruction of velocity and its material derivative. The problem is solved iteratively using a gradient based optimization method, where the gradients are evaluated efficiently using the adjoint of the method.

In the presentation at the present workshop, the method is outlined with a focus on its implementation details. The presentation is concluded a summary of validation experiments in the case of time-resolved and volumetric measurements in turbulent boundary layer. The validation shows that the VIC+ technique can restore the vorticity magnitude level that is expected from DNS simulation (Fig. 1).

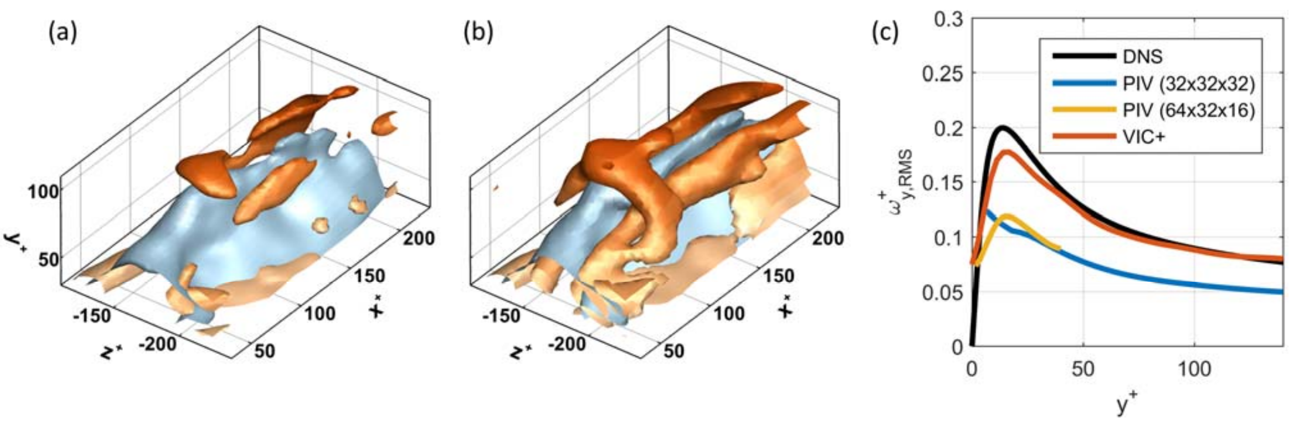

Figure 1 Close-up view of a hairpin structure from tomographic PIV (a) and VIC+ (b) at the same isosurface levels of vorticity magnitude (orange) and velocity (blue). Profile of wall-normal rms vorticity fluctuations (c). Figure reproduced from Schneiders et al. (2016).

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The effect of experimental uncertainties on the estimation of velocity based quantities

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ABSTRACT

The estimation of velocity fields with Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) became well established methods over the last years [1-4]. Due to the non-intrusive working principle of PIV/PTV, these techniques are preferred over measurements with classical intrusive sensors like hot-wires or Pitot-probes. Furthermore, the possibility to measure two or three velocity components in a two-dimensional or three-dimensional domain enables PIV/PTV users to extract spatial derivatives of the velocity components from the flow fields. In the case of low speed flows, time resolved flow field measurements are possible and also temporal derivatives can be computed. Time resolved three-dimensional PTV evaluation methods, like Shake-The-Box (STB), provide unique insights about the underlying flow physics with superior temporal and spatial resolution [5]. Spatial and temporal gradients can be determined reliably under these conditions. Thus, velocity based quantities like the Reynolds stress tensor, the vorticity or the dissipation rate can be estimated with high confidence.

However, the investigation of velocity fields with speeds relevant for aeronautical applications is often limited to planar or stereoscopic PIV/PTV measurements, because of the limited optical access of the wind tunnel test sections. Additionally, time resolved measurements are extremely challenging, because repetition rates on the order of 1 MHz would be required for high subsonic Mach numbers. Thus, only two-dimensional spatial gradients without any temporal gradients are often available for these kinds of experiments. Due to the missing knowledge about the temporal evolution of the flow, the uncertainty of the estimated velocity is usually increased, because only two PIV/PTV images with fixed time separation are used to estimate an instantaneous flow field.

The resulting noisy velocity fields cause difficulties for the estimation of velocity based quantities: Reynolds normal stresses for instance, are over estimated in the case of increased uncertainties of the velocity components, while Reynolds shear stresses are usually underestimated [6]. Also the determination of spatial gradients is strongly affected by these uncertainties. Consequently, the estimation of velocity based quantities is limited and methods known from CFD must be adapted with respect to the measurement uncertainty.

The workshop contribution discusses the possibility to reduce the measurement errors. It addresses the estimation and optimization of PIV/PTV uncertainties for planar non-time-resolved measurements. It covers the effect of different error sources, such as acceleration, velocity gradients, image noise, particle image density, out-of-plane motion and others on the uncertainty of the estimated velocity fields. Knowledge about the measurement uncertainty allows to rate the quality of deduced quantities.

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3D assimilation with PIV orthogonal-plane observations and a DNS dynamical model in a circular cylinder wake flow

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ABSTRACT

During the last decade, the fluid mechanics community witnessed the surge of techniques combining computational fluid dynamics and experimental fluid dynamics results in order to benefit from the assets and overcome the limitations of each approach. A first PIV data assimilation study had performed successfully in the two-dimensional case of a DNS of low Reynolds number wake flows [1]. The variational data assimilation technique (4DVar) was used to reconstruct the flow by modifying the initial and inflow conditions of the system. The ability of the technique to reconstruct the flow in gappy PIV data was also investigated [2].
The present study is an extension of the work of [1,2] to the reconstruction of a three-dimensional cylinder wake flow at Reynolds 300 by combining a highly accurate and parallelized code Incompact3d [3] with a sequence of two-dimensional stereo PIV observations. An important part of this application was focused on the construction and validation of the discrete adjoint parallelized code necessary to the implementation of the 4Dvar method [4]. We performed a first reconstruction of a purely synthetic flow generated by Incompact3d, using three-dimensional observations. We then performed the reconstruction of a fully three-dimensional flow from the alternated synthetic observations of orthogonal stereo PIV like observations (inflow and streamwise planes see figure 1). We investigate the possibilities of the reconstruction with the real observations obtained by orthogonal stereo PIV measurements.

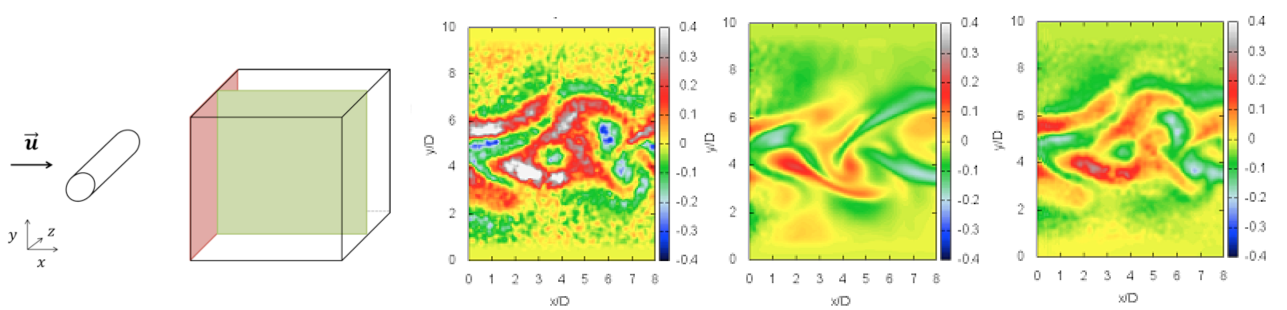

Figure 1 Data assimilation flow configuration (Lx . Ly . Lz = 8D . 10D . 6D) and snapshots of the spanwise velocity component at the beginning of the assimilation window in the streamwise plane z = 3D. From the left to the right: the PIV observation, the background and the analysis, respectively.

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How to obtain invariant Navier-Stokes solutions from time resolved 3D PIV data

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ABSTRACT

According to dynamical systems theory, turbulence is believed to be organized around unstable periodic orbit and travelling wave solutions. For short times a turbulent flow may closely resemble a particular invariant solution before approaching another one and so forth. We here test this hypothesis in pipe flow experiments. Time resolved (e.g. 200Hz at Re=2000) velocity fields are recorded using stereoscopic PIV resulting in approximately 1500 vectors in a cross-sectional plane (perpendicular to the pipe axis). Since turbulent structures are advected downstream fast (approximately at the bulk speed) we can apply Taylor's frozen turbulence hypothesis to reconstruct the 3D velocity fields for pipe segments with a length of 5 D (where D is the pipe diameter). These velocity fields are then used as initial guesses to computationally search for periodic orbits using a Newton-Krylov method. Such methods have been widely used to identify invariant solutions in direct numerical simulations of pipe and channel flows but are not commonly applied to experimental data. From experiments we are able to identify a new class of unstable periodic orbits closely resembling turbulent velocity fields. Unlike the orbits and travelling waves previously found in purely numerical studies, the orbits identified from experiments do not have any additional symmetries and are basically indistinguishable from turbulent flow (all previous discovered solutions typically included mirror or rotation symmetries). Moreover this new class of orbits features vortices of many different sizes ranging from the integral to the Kolmogorov scale. The larger vortex structures within these periodic orbit solutions include distinct sequences of hairpin vortices. It should be stressed that unlike the numerous earlier observations of such coherent structures, the hairpin vortices observed here are part of invariant solutions of the Navier Stokes equations (i.e. structures precisely repeat after one period). These solutions hence allow for an in depth study of the sustaining mechanism underlying such coherent structures.

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Pressure evaluation from PIV measurements by several approaches

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ABSTRACT

Measurement of an instantaneous pressure field around a body immersed in fluid is of great interest for purposes of both understanding flow structures in relation to local pressure fluctuations and obtaining force acting on the body. An instantaneous pressure field is generally obtained by integrating spatial pressure gradients because it is rarely possible to directly measure an instantaneous pressure field without interference in a flow [1]. Several approaches have been developed in the literature based on the resolution of the Poisson equation or coupled CFD/PIV methods. For the estimation of the pressure field from velocity fields, four approaches have been developed and tested on a 2D Direct Numerical Simulation of a flow around a Naca0012 wing and on the same kind of flow with experimental measurements.

The pressure fields are calculated from:
- A spatial integration based on the sequential Poisson solver with pre-defined subdomains [2][3].
- A polynomial approximation of the Navier-Stokes equations. An analytic expression of the pressure gradient field calculated from the projection of the velocity fields on polynomial basis is integrated [4].
- An integral formulation for the Poisson equation based on the SPH (Smoothed Particle Hydrodynamics) method [5].
- An assimilation of the PIV data for pressure and loads estimates using CFD tools.

Different Dirichlet and Neumann boundary conditions are examined and the reference pressure coefficient is given at the same location at the left-top corner of the pressure field for the different methods.
Results show the good agreement of some approaches and the influence of the boundary conditions when a profile is included inside the velocity fields.

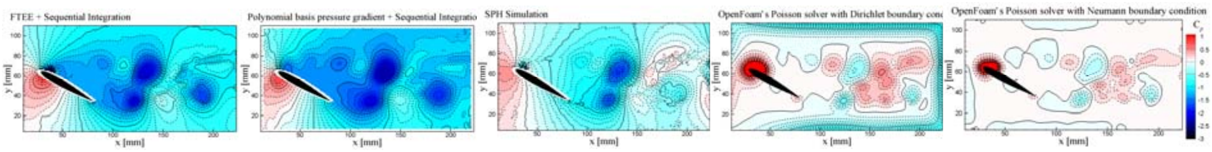

Figure 1 Comparison of different methods. (1st column) FTEE and sequential integration based on discretized subzones, (2nd column) Polynomial basis pressure gradient, (3rd column) Smoothed-particle hydrodynamics (SPH) simulation, OpenFoam's Poisson equation solver with Dirichlet (4th column) and Neumann (5th column) boundary conditions.

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Main results of the 4th International PIV Challenge 3D test Case D

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ABSTRACT

The measurement of the underlying cascade turbulence mechanism at sufficiently high Reynolds number is a challenge for both computational and experimental fluid mechanics in terms of required spatial and dynamic velocity range. The establishment of accurate three-dimensional three-components anemometric techniques is of fundamental importance to both characterize the evolution and organization of the turbulent coherent structures and to provide a benchmark for numerical codes. In the Test case D a 3D PIV experiment is simulated imposing the velocity field of a Direct Numerical Simulation of an isotropic incompressible turbulent flow.
The test case is performed on time resolved synthetic images of an isotropic turbulent flow field obtained by Direct Numerical Simulation. Projection images of 4 cameras are provided to the participants for a single value of particle concentration. The main challenge of the Test case D is to evaluate correctly the velocity gradient components and, in particular the vorticity in presence of many different length scales within the flow field.

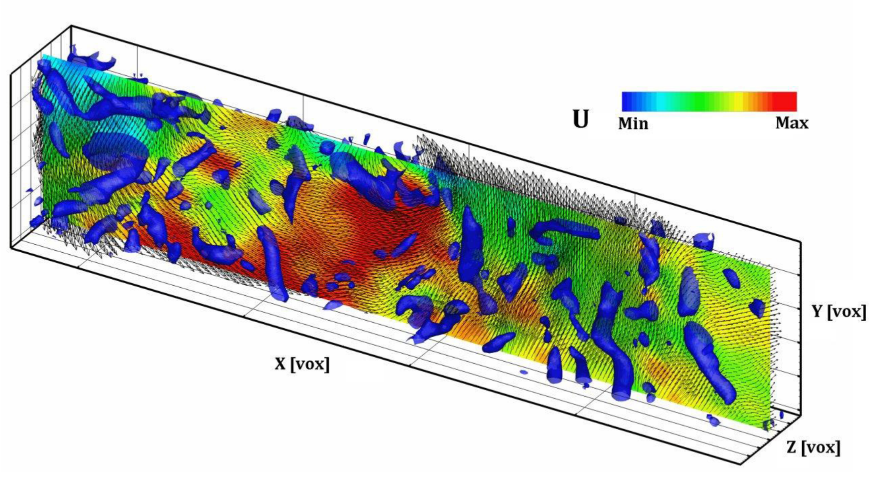

Figure 1 Case D of the 4th international PIV Challenge: Contour of the U component of the velocity field (arbitrary units) on the XY mid-plane and isosurfaces of the second invariant of the velocity gradient tensor $Q > 0$.

Main results of all 4th international PIV Challenge test cases are presented in [1].

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