Capturing coherent structures and turbulent interfaces in wake flows by means of the Organised Eddy Simulation, OES and by Tomo-PIV

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**Abstract.** The present study aims at a physical analysis of the coherent and chaotic vortex dynamics in the near wake around a flat plate at incidence, to provide new elements in respect of the flow physics turbulence modelling for high-Reynolds number flows around bodies. This constitutes nowadays a challenge in the aeronautics design. A special attention is paid to capture the thin shear layer interfaces downstream of the separation, responsible for aeroacoustics phenomena related to noise reduction and directly linked to an accurate prediction of the aerodynamic forces. The experimental investigation is carried out by means of tomographic PIV. The interaction of the most energetic coherent structures with the random turbulence is discussed. Furthermore, the POD analysis allowed evaluation of 3D phase averaged dynamics as well as the influence of higher modes associated with the finer-scale turbulence. The numerical study by means of the Organised Eddy Simulation, OES approach ensured a reduced turbulence diffusion that allowed development of the von Karman instability and of capturing of the thin shear-layer interfaces, by using appropriate criteria based on vorticity and dissipation rate of kinetic energy. A comparison between the experiments and the simulations concerning the coherent vortex pattern is carried out.

1. *Introduction*

The present flow is a generic configuration concerning trailing edge unsteady dynamics and flows arising past ailerons of micro and nano-drones among other applications. With the rise of developments in aeroacoustics and in micro and nano-air vehicles design, flat plate aerodynamics gained interest in the last decade (Pelletier and Mueller, 2000; Hsu and Huang, 2008; Beckwith and Babinsky, 2009). In this context, the French foundation Sciences et Technologies pour l’Aéronautique et l’Espace launched the EMMAV research programme (Electroactive Morphing for Micro Air Vehicles) for the period 2009-2011. This programme aims at optimising micro-air-vehicles performances in realistic environment by means of electroactive morphing concepts. The present paper concerns a first set of experiments dealing with the static configuration of a flat plate at incidence. Although it is a quite elementary configuration, a rather reduced litterature exists on the flow around a thin at plate with sharp edges. The results of the freefall tests done by Gustave Eiffel from his famous tower in 1911 are available in Rebuffet (1950). Measuring the falling time, the french engineer deduced the normal force coefficient for various aspect ratios. The ninety degrees range of angles of attack is covered with only nine points. Abernathy (1962) performed some additional measurements on the inclined at plate at various angles of attack for Reynolds numbers up to 100 000. Subsequently, some more experiments have been carried out by Perry and Steiner (1987) and Steiner and Perry (1987) for Reynolds numbers up to 37 000, by Leder (1991) and Lam (1996), both for a Reynolds number of about 30 000, and by Lam and Leung (2005) for a Reynolds number of 5 300.

A number of numerical studies appeared in the open literature in the last decade for low and high Reynolds number cases (Breuer et al., 2003; Lam and Wei, 2010; Ouvrard et al., 2010).
Even though several studies on at plates wakes exist in the open literature, none of them proposes three-dimensional velocity data that can be used further on for high Reynolds number Computational Fluid Dynamic (CFD) improvement and validation. Therefore, the present study and its data-base aims at providing a detailed 3D data-base by means of tomographic PIV and a physical analysis of a strongly detached unsteady flow useful for the CFD community, beyond the experimental goals of the EMMAV research program.

2. Methodology

The research team “InteractionFluide-Structure Sous Turbulence” IFS2T, of the group “Ecoulements Monophasiques Transitionnels et Turbulents” of IMFT developed in the last decade the Organised Eddy Simulation, OES turbulence modelling approach in the frontier beyond classic statistical approaches and hybrid ones. OES contains appropriate turbulence modelling closures to capture coherent structures unsteadiness at high-Re number (Braza et al, 2006), with economic grids.

This approach is based on splitting of the energy spectrum into two parts, the first regrouping the organised coherent motion (resolved turbulence) and the second, the chaotic random turbulence (modelled part). This part is modelled in OES by improved statistical turbulence closures, able to capture non-equilibrium turbulence and negative turbulence production regions associated to backscatter. As an example, we refer to the reconsideration of the turbulence viscosity in OES two-equation modelling, towards a tensorial eddy-viscosity concept, sensitised in capturing turbulence stress anisotropy in the strong shearing regions (Bourguet et al, 2008). This OES modelling is able to account for stress-strain three-dimensional miss-alignment, originally put in evidence by the PIV experiments of the flow past a circular cylinder (Perrin et al., 2007). This OES modelling achieves capturing of the thin shear-layers past separation by using grid refinement. Furthermore, it is worthwhile mentioning that the pure LES approach is not yet realisable at high – Re flows around bodies interesting the domains of applications.

The present article aims at capturing the thin shear layers past separation in high-Reynolds strongly detached turbulent flows, by using a reasonable grid refinement. This need is outmost important for the design, that demands an accurate prediction of the unsteady aerodynamic coefficients (up to the fourth decimal point) and especially of the pressure fluctuations in the near, intermediate and far wake regions, in respect of aeroacoustics. The present study is a collaboration between IMFT – CNRS (research team IFS2T - Dr. M. Braza) and UCL, (Prof. J. Hunt). Therefore, the present study’s target is to enhance the benefits of OES by reverse cascade modelling. This is expected to allow capturing of the highly shearing regions by using economic numerical grids. This can be achieved by introducing during the OES solution, of a stochastic forcing as a series of random modes (Turfs and Hunt 1987), or of POD modes (Bourguet and Braza, 2009) in the region located between two sheared interfaces. This forcing produces a blocking effect towards the interface by keeping it thin (Hunt et al., 2009). This mechanism produces energy transfer towards the large scales (‘upscale turbulence modelling’).

To achieve these aims, a synergy between a refined experimental and CFD study is performed. The experiments have been carried out in the S4 wind tunnel of IMFT and the simulations at the CINES and IDRIS French supercomputing centres. The flow past a flat strut with an incident angle of 10° and Reynolds numbers 200,000 and 400,000 is considered. The experiments used the standard PIV as well as the Tomo-PIV (fig.1), that is among quite rare studies in the state of the art concerning gas flows at high-Re. The simulations have been performed by means of the NSMB (Navier-Stokes Multi-Block) code. The phase-averaged Navier-Stokes equations are solved with a finite-volume implicit formulation. The OES-k-ε turbulence modelling is
employed. The structured mesh consists of $3 \times 10^5$ nodes in 2D. This unsteady flow separates at leading edge and develops a von Kármán vortex street interacting with Kelvin-Helmholtz instability at the trailing edge. Tracking of the coherent structures and of the thin interfaces is performed by 3D-POD reconstruction in the experiment and by using specific criteria to track the thin interface in the numerical approach. The capture of the irrotational/rotational interfaces is essential to correctly define the domain where stochastic perturbation must be added. The interface thickness is a point we would like to assess, but the first step in this work is to localise the limits of the irrotational zone. Different ways have been investigated to define the entrance in shear interfaces. The criteria are essentially constructed from vorticity, as well as turbulent kinetic energy and dissipation rate. Ideally these criteria have to take into account the coherent structures frequencies created at leading and trailing edges.

4. Results

The results present first the near-wake turbulence structure by means of Tomo-PIV, followed by a 3D POD analysis of the coherent patterns. Phase-averaged dynamics are presented using the first two POD modes to phase the Tomo-PIV snapshots. The numerical simulation presents phase-averaged vortex dynamics in a larger part of the wake, as well as the criteria to define the thin shear-layer interfaces and related discussion.

4.1. Reynolds averaged wake topology by means of Tomo-PIV
**Figure 3.** Reynolds averaged quantities measured by Tomo-PIV. (a) streamwise $U$ velocity component, (b) vertical $V$ velocity component.

4.2. **POD decomposition and reconstruction**

Figure 4 shows the POD decomposition of the 3D velocity fields issued from the Tomo-PIV.

![POD modes](image)

**Figure 4.** First three POD modes. The streamlines below are coloured according to the spanwise coordinate to show the 3D effects.

Figure 4 shows the first three POD modes. The two first modes can be compared to the work by Perrin et al. (2009) concerning 3CTRPIV around a circular cylinder at high Reynolds number. Their shapes illustrate the alternating vortices effect that is obtained by reconstruction, as shown in the next paragraph. Although the first and second modes display a nearly symmetric shape in reference of the middle $x$ axis as in the case of the cylinder’s wake, the third mode is strongly affected by the asymmetry in the wake pattern, due to the incidence. This mode is also the most affected by 3D effects, along $(X,Z)$ plans as shown in figure 4(c). Concerning the first and
second modes, these 3D effects are predominant in the central regions of the recirculations, Figures 4(a) and 4(b).

Figure 5 shows the POD reconstruction of an instantaneous flow field by a successively increasing number of modes. The 2-mode reconstruction clearly shows the alternating vortices effect and the formation of the saddle point (S) near the right-low part. The six-mode reconstruction shows three-dimensionality formation near the saddle point (streamlines crossing in Figure 5(b) is due to 3D prospective effects). The 3D effect in the centre of recirculation region becomes more predominant with the 9-mode reconstruction.

4.3. Phase averaged dynamics

Phase identification using POD for a wake past a plate was first proposed by Ben Chiekh et al. (2004) for an angle of attack of 90°. Following this study van Oudheusen et al. (2005) applied the method to the square cylinder, and Perrin et al. (2007) to the circular cylinder at high Reynolds number. The present study uses the same method to perform phase identification. Figure 6.1 shows the vortex shedding motion according to the eight phase instants, whose first and last illustrate practically a quasi-periodic phenomenon. The formation of the saddle point S between the vortices and the convective region are illustrated within this cycle, as well as the 3D shape of the main recirculation region. Furthermore, the formation of the lower, less strong detached vortex is also shown within this period. Both, the thin shear layers upper and lower of the alternating vortices are also clearly formed. Figure 6.2 shows the phase-averaged longitudinal $U$ velocity component, in the same period. The dynamics of the main recirculation region are clearly shown. The maximum absolute value of the $U$ velocity appears in the upper shear layer and is of order 1.20. The formation and convection of the central area of the recirculation region (white area) within the cycle of the main vortex shedding are provided.
These variations are in association with the streamlines dynamics presented in Figure 6.1.

**Figure 6.1** Phase-averaged streamlines in a period of the vortex shedding

**Figure 6.2** Phase-averaged longitudinal $U$ velocity component in a period of the vortex shedding

4.4. *Numerical simulation of the turbulent flow past the flat plate and interfaces detection*

A 2D simulation has been performed at this stage, at the same physical parameters as in the experiment, by using OES method. Furthermore, 3D - OES simulations are in progress.
Iso-contours of turbulent kinetic energy gradient (right) and vorticity gradient (left) are shown in Fig. 8. The black line corresponds to the computed interfaces. The dissipation rate gradient is quite promising in the near region than downstream. The methods developed seem to be quite relevant to capture the area of interest.

Figure 8. Numerical simulation of the flow past the flat plate, same conditions as in experiment; OES approach. Evaluation of the thin-shear-layer interface with the vorticity gradient and turbulence kinetic energy criteria.
5. Conclusions

The present study of the turbulent flow past a flat plate at incidence 10° and Reynolds number 200,000 provides the dynamics of the coherent vortex structures in the near wake by means of POD decomposition and reconstruction. The influence of turbulence on the number of modes needed to represent the coherent vortex pattern is analysed. Phase-averaged analysis performed by classification of the tomo-PIV snapshots according to the two first POD modes allowed extraction of the vortex shedding dynamics among the overall turbulent background. The numerical simulation of this flow by the OES approach provides thin-shear-layer interfaces downstream of the separation points. Criteria based on $\omega_z$ vorticity gradient vertical to the interface as well as based on turbulence kinetic energy and dissipation rate gradients are compared. The methods developed for tracking the thin shear layer interfaces are quite promising for application. They are currently compared on the experimental flow fields. The next step will be the dynamic implementation of the stochastic forcing within the area delimited by the interfaces and the comparison of the performances between OES and of ‘Upscale-OES’, with the physical experiment.

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