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# Symmetry breaking wakes of a square-back Ahmed body: LES and modes analysis using POD

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## 1. Introduction

In the current energetic and environmental context, important topics in the automobile industry are drag reduction and control of separation around bluff bodies. For trucks and SUVs most of the drag is due to the recirculation region at the rear of the vehicle, which makes studies of the wake behind square-back bodies of particular interest. In this study, Large Eddy Simulation is performed on a square-back Ahmed profile [1]. The 3D unsteady turbulent flow in the near wake is analyzed, for various ground clearances  $C$ , ranging from a zero ground clearance case (body flush with the ground) to a nearly ground-free setting (modelled with a slip condition).

Experiments performed by Grandemange *et al.* [2] have shown the presence lack of symmetry-breaking (RSB) modes, which break the reflexion symmetry of the wake over very long time scales. The deviation and key features of the wake are studied numerically by LES. In particular, POD is applied to LES data to extract information about the most energetic structures of the flow, in the full volume as well as on a plane corresponding to experimental observations [2]. This study permits a comparison to the reference experiment and an analysis of the 3D shapes of the modes. Different modified configurations are then implemented with the goal to reduce the deviation and recover the wake symmetry. Both passive and active control are investigated: the influence of flaps, aligned or not with the body, as well as the effect of blowing/suction are characterized.

## 2. Numerical method

The method uses the velocity-vorticity ( $v-\omega$ ) formulation of the incompressible Navier-Stokes equations, which allows a direct manipulation of the flow through modification of the vorticity at the boundary [3]. For turbulent modelling, LES splits the exact field into filtered variables and subgrid variables. The filtered Navier-Stokes equations are given:

$$\frac{\partial \omega}{\partial t} - \nabla \times (v \times \omega) = - \frac{1}{Re} (1 + \gamma_{sgs}) \nabla \times \nabla \times \omega \quad (1)$$

$$\omega = \nabla \times v \quad \nabla \cdot v = 0 \quad (2)$$

where  $Re$  is the Reynolds number,  $v$  the filtered velocity vector and  $\omega$  its curl, resolved on the grid. The subgrid scale model chosen is the mixed scale model, developed in LIMSI [4],  $\gamma_{sgs} = \left[ (C_s \Delta)^2 \|\omega\| \right]^\alpha \left[ C_b \Delta \sqrt{|k'|} \right]^{1-\alpha}$ , where  $k'$ , which corresponds to the subgrid kinetic energy, and  $C_b$  are linked to the TKE model and  $C_s$  is linked to the Smagorinsky model.  $\Delta$  is a characteristic length of the local cell. This model has the advantage to damp smoothly the eddy viscosity in the regions where all the scaled are well solved.

A pseudo-penalization method is used to model the solids, the Ahmed body and the ground. A special treatment is made to adapt the method to the ( $v-\omega$ ) formulation. Moreover, to force the vorticity vector to be zero inside the solid at each time step,  $\partial \omega / dt = 0$  has to be imposed. The diffusive terms of the equation (1) are cancelled, at each time step, using a penalization matrix. On a given solid

surface, tangential velocity is zero. The vorticity field at the wall (tangential components) is then calculated from velocity derivatives.

A M.A.C. staggered grid is used for the spatial discretization. Time and spatial discretizations used second order schemes. The vorticity transport equation represents a coupled Helmholtz problem which is solved with a block Jacobi iterative algorithm. The velocity field is then obtained through a projection method [3].

At the inlet of the domain, an infinite velocity  $U_\infty$  is imposed. The tangential components of the vorticity  $\omega_y$  and  $\omega_z$  are then deduced. Perturbations (white noise) are superimposed on them to produce the correct development of the turbulent flow. At the outlet surface, a convective transport hypothesis is applied (viscous effects neglected). The vorticity tangential components are calculated using an extrapolation along the characteristics. In the vertical direction  $y$ , slip conditions are imposed at the lower and upper surfaces. The lower surface condition corresponds to that of a stationary ground in the case of a moving vehicle. A periodicity condition is used for the transverse direction  $z$ .

### 3. LES results

Simulations are performed for a Reynolds number  $Re = U_\infty H / \nu_{air} = 1.7 \times 10^4$ , where  $H$  is the height of the body and  $\nu_{air}$  the viscosity of the fluid. The flow is initially at rest. The flow develops over a rather long time to obtain a turbulent unsteady state. Different ground clearances are considered to study the behavior of the flow, with a special effort to model a configuration similar to the reference experiment [2].

The figure 1 represents the spanwise component of the vorticity  $w_z$  for two clearances. The influence of the ground, with a blockage effect is evidenced. The figure 2 corresponds to a case with a slip condition at the lower surface. The flow presents structures over a large range of spatial scales and it is fully turbulent. The mixing zone is well visible. The 3D structures are complex. For instance, the shedding phenomenon here mixe the influences of the two kind of vortex shedding rolls, for infinite bodies.

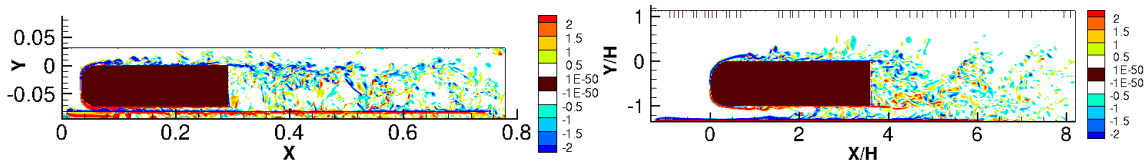


Figure 1: Unsteady flow. Spanwise component of the vorticity  $\omega_z$  in a vertical mid-plane ( $xy$ ): (left)  $C = 0.1 H$  and (right)  $C = 0.3 H$ .

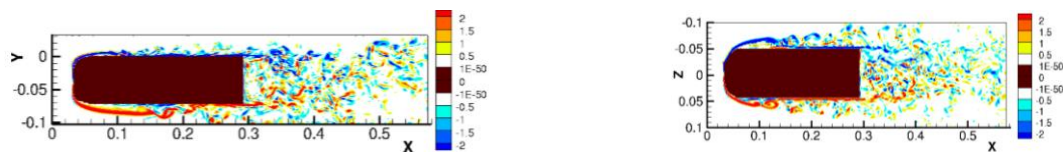


Figure 2: Unsteady flow for a slip condition: (left) spanwise component of the vorticity  $\omega_z$  in a vertical mid-plane ( $xy$ ) and (right) vertical component of the vorticity  $\omega_y$  in a horizontal plane ( $zx$ ) at mid-height of the body.

The time-averaged flow is computed and the case for a slip lower condition is represented on figure 3. In this case, for a body with a width larger than its height, we obtain a left/right deviation of the wake (top-view). The recirculation zones in the near wake are not symmetric.

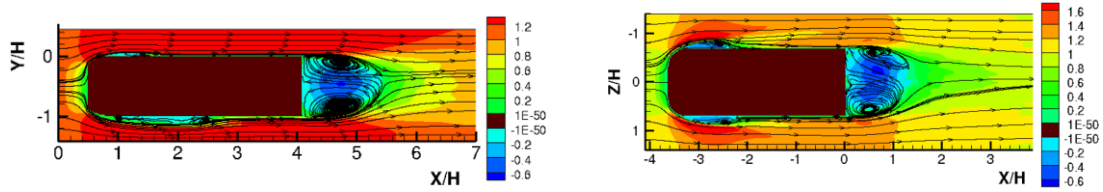


Figure 3: Mean longitudinal velocity  $\langle v_x \rangle$  (color) and stream function: (left) in a vertical mid-plane (xy) and (right) in a horizontal plane (zx) at mid-height of the body (top-view).

#### 4. POD modes

Proper Orthogonal Decomposition [5] provides a way to extract the dynamics of energetically significant patterns in the flow. The POD is based here on the velocity field, which constitute spatial POD eigenfunctions. We therefore have  $\underline{v}(\underline{x}, t) = \sum a^n(t) \underline{\phi}^n(\underline{x})$ . The amplitudes of the POD eigenfunctions vary in time and can be computed from the full vorticity field using  $a^n(t) = \int \underline{v}(\underline{x}, t) \cdot \underline{\phi}^n(\underline{x}) d\underline{x}$ .

To reduce the dimension of the problem, we use the method of snapshots, which makes it possible to recover the POD spatial modes from the temporal autocorrelation tensor (instead of the spatial autocorrelation tensor in the original method proposed by Lumley).

Using the 3D LES data, we can perform 2D-POD to allow a comparison between LES and experiments (with experimental data obtained by PIV [2] in an horizontal plane), and 3D-POD to extract and to identify the most energetic modes of the flow.

The first POD mode corresponds to the mean flow, which is evidenced by the steadiness of its temporal coefficient (RMS less than 0.2%). The figure 4 shows the comparison between LES and experiment, for the second mode, which is associated to the breaking procedure. We obtain a very good agreement.

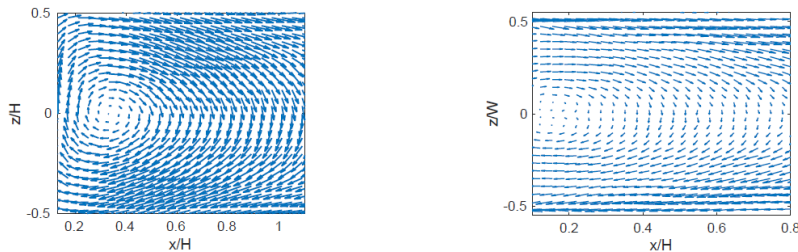


Figure 4: 2D-POD from 3D LES data and PIV experiment: (left) experiment and (right) simulation.

Using 3D-POD, we can try to understand the organization of the modes. The figure 5 presents the mean mode and the breaking mode.

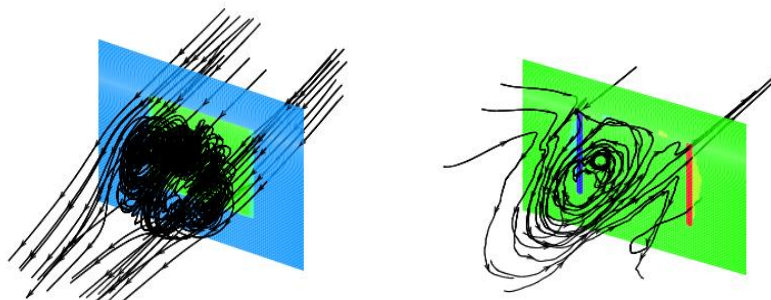


Figure 5: 3D-POD from 3D LES data: (left) mean mode and (right) mode 2 (breaking mode).

In addition, new simulations are performed using control is made on the profile using flaps (figure 6) or suction or blowing.

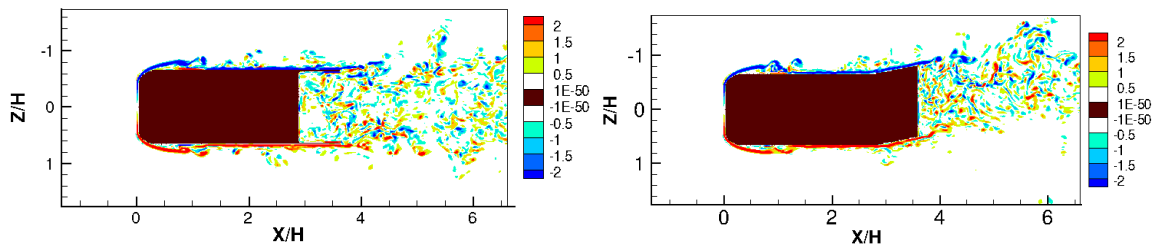


Figure 6: Top-view of vertical component of the vorticity  $\omega_y$  with control by flaps: (left) aligned flaps and (right) flaps with an angle of  $10^\circ$ .

## 5. Conclusion

The flow around an Ahmed body profile has been calculated using LES, the  $(v-\omega)$  formulation and a penalization method for solids. The deviation of the flow associated to the symmetry-breaking of the wake has been recovered numerically. POD has been applied to LES data and experimental data [2]. The modes are in good agreement in a 2D horizontal plane. The POD can also be used to understand the modes organization. Flaps have been added to control the flow and the coherent structures.

## 6. References

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