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# Characterisation of a square back Ahmed body near wake flow

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## Résumé :

*Cet article présente les résultats d'une étude expérimentale de l'écoulement autour d'un corps de Ahmed à l'échelle 0,7. Ce travail de recherche se concentre sur la zone de recirculation du sillage proche de la maquette. La caractérisation de l'écoulement est réalisée avec des capteurs de pression, des sondes anémométrique à fil chaud et de la Vélocimétrie par Image de Particules. Une décomposition en mode propre orthogonaux et une reconstruction tridimensionnelle de l'écoulement ont été réalisées à partir des acquisitions PIV.*

## Abstract :

*This article presents an experimental study of the flow around a square back Ahmed body. This work is focused on the recirculation zone that develops in the near wake of the model. Flow characterisation is done using steady flush mounted pressure taps, hot wire anemometry and Particule Image Velocimetry (PIV). PIV fields have been processed to make a three-dimensional reconstruction of the flow and a Proper Orthogonal Decomposition (POD) of the flow in the median longitudinal plane .*

**Mots clefs :** Automotive aerodynamics, Ahmed body, Square back body

## 1 Introduction

Environment standards and the rise of oil cost lead automotive manufacturers to design fuel efficient car. Up to now, the main area of research has been the improvement of the output engines thanks to downsizing. Another interesting solution is to reduce the aerodynamic drag of vehicles. Until now, the shape optimisation has been the ordinary way to decrease it but the comfort of the vehicle was impacted. In order to reduce the air resistance without diminishing the spaciousness of the car, flow control solutions have been developed. To perform efficient control, it is necessary to improve the knowledge on ground vehicle aerodynamics.

Flow around a vehicle is a complex structure that must be characterised to perform an efficient drag control. In this work a square back Ahmed body has been chosen. The square back Ahmed body is characterised by an abrupt geometry change at the rear of the model that generates the emission of vortices in all three dimensions. These vortices interact with each other and lead to the formation of a large recirculation zone. This dead air region is bounded by the shear layers emanating from the edges of the base of the model. Moreover, the boundary layer developing on the ground of the wind tunnel modifies the lower shear layer. This interaction alters the vortex emission in the wake and thus the pressure distribution on the base of the model responsible for an important part of the pressure drag. The flow of the near wake has a complex dynamic as a bi-stability [4]. Time dependent data show that two asymmetric topologies coexist in the wake of the model but time averaging leads to a symmetric flow [5]. This phenomenon is similar to the symmetry breaking found in the wake of backward facing step [6]. The present work explores the wake of the 0.7 scaled square back Ahmed body at  $40 \text{ m.s}^{-1}$ . The sensitivity of the wake to the drift angle has been tested at different sideslip angle. The topology of the near wake flow has been characterised by using Particle Image Velocimetry and flush mounted

steady pressure taps. The most energetic structures in the near wake flow have been investigated using a vectorial snapshot Proper Orthogonal Decomposition (POD) method.

## 2 Experimental set-up

The model used for this study is a 0.7 scaled square back Ahmed body [1]. His three-dimensional wake flow has a similar dynamic vorticity to the one developing at the rear part of a van. Main dimensions of the model are given in Fig. 1. The coordinate system that is used has an origin located in the middle of the upper edge of the back of the model, with the longitudinal, lateral and vertical directions given by X, Y and Z, respectively. The velocities in these directions are U, V and W. Tests were run in the subsonic wind tunnel of the PRISME laboratory at the university of Orléans. The square test section is 2 m by 2 m and 5 m long. The model is fixed above a 3 m by 2 m aluminium plate with an ellipsoidal leading edge. The rear part of the plate is equipped with a 3° incline flap in order to suppress the pressure gradient effect in the test section. All tests were run with a freestream velocity of  $40 \text{ m.s}^{-1}$  corresponding to a model length based Reynolds number of 1.5 million.

The pressure evolution at the back of the body was characterized by using 80 static pressure taps

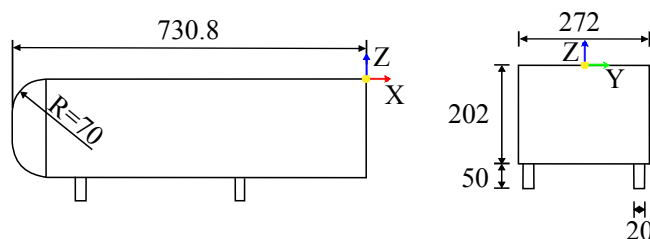


FIGURE 1 – Geometry of a 0.7 scaled square back Ahmed model

on the rear part of the Ahmed body. The measurement recording lasted 160 s with a 25 Hz sampling frequency. Only a half of the back was instrumented as the pressure distribution on the back of the body is symmetric [7, 11, 12]. The symmetry distribution has been checked with thirteen flush mounted pressure taps at mid-height of the model base.

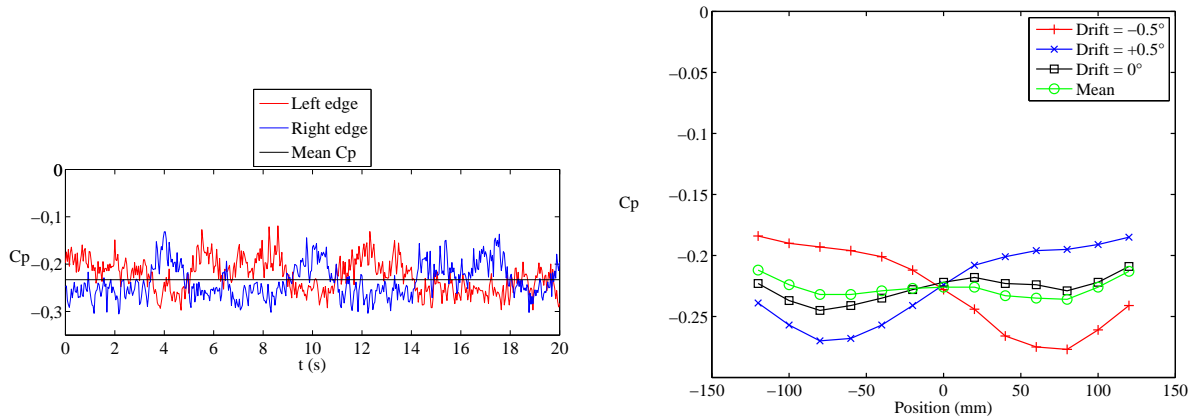
Spatial characterisation of the wake of the Ahmed body was carried out using a two-component Particule Image Velocimetry (PIV) system. The velocity fluctuations were recorded using one component hot wire probes. Measurement locations were chosen plotting the second order statistical moments of the fluctuating velocity processed from PIV data. Signals were acquired with a 20 kHz sampling frequency during 18 minutes. Most energetic frequencies are identified thanks to the Power Spectral Density of velocity fluctuations calculated with the Welch periodogram method.

## 3 Experimental results

### 3.1 Drift adjustment

Pressure fluctuations on the back of the model have been measured at  $40 \text{ m.s}^{-1}$  in order to check the value of the drift angle. Pressure coefficient ( $C_p$ ) is used. It refers to the difference between the local static pressure and the freestream static pressure, normalized by the freestream dynamic pressure. Several measurements have been performed to find a symmetrical pressure distribution on the back of the model. In this article, the results for three drift angles ( $0$ ,  $0 - \epsilon$ ,  $0 + \epsilon$  where  $\epsilon$  equals  $0.5^\circ$ ) will be presented. The zero drift angle case reveals that the  $C_p$  near the vertical edges of the back of the model oscillates around  $C_{p_{mean}}$  (Fig. 2a). These oscillations are characteristic of the bi-stability phenomenon described in [4, 5, 6]. A  $0.5^\circ$  in the drift angle breaks the symmetry of the flow (Fig. 2b) and alters the cohabitation of the two modes. In this case one state is preferred and the  $C_p$  at the edge under the wind is greater than  $C_{p_{mean}}$ . The symmetrical pressure distribution observed on the base of the model for a zero slideslip angle (see Fig. 2b) is consistent with an average of two asymmetric pressure distribution corresponding to a drift angle equal to  $-0.5^\circ$  and  $+0.5^\circ$  (see curve named Mean

on Fig. 2b). This artificial pressure distribution has the same characteristics as the measured one for a zero drift angle. The flow is then bistable and the zero drift angle seems to be a critical case where the wake shifts between two states.



(a) Evolution of the pressure at 40 mm of the rear vertical edges of the model at a drift angle of  $0^\circ$  (b) Mean pressure level on the back of the model

FIGURE 2 – Pressure measurements on the back of the model

### 3.2 Mean Flow Topology

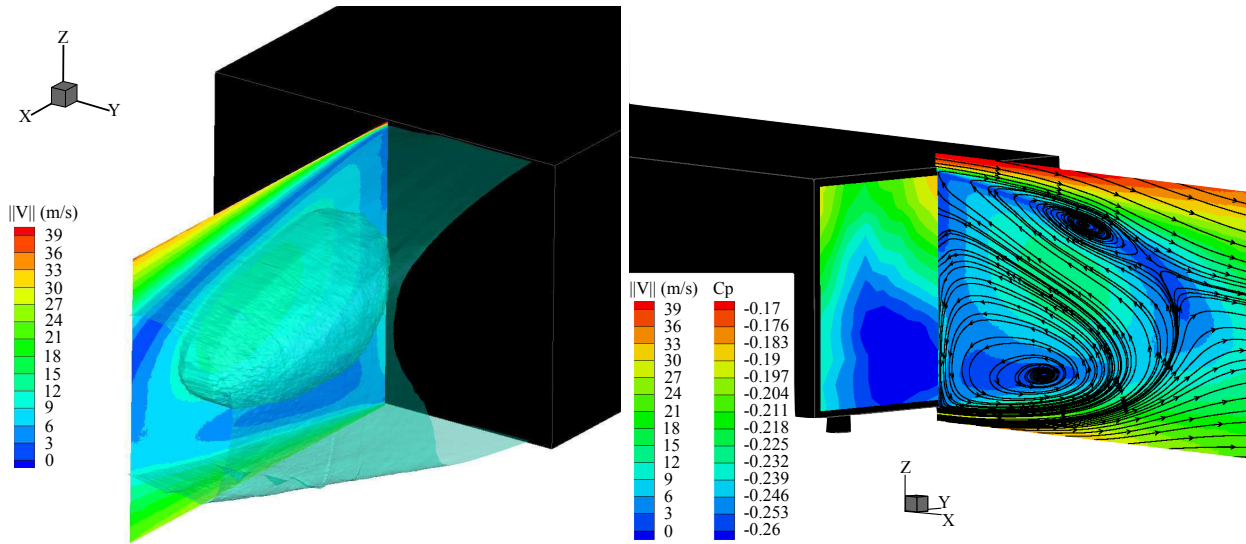
The characterization of the near wake has been done by PIV longitudinal velocity fields. The cameras and the laser source are moved crosswise by 10 mm step. A three dimensional view of the mean flow shows a circular vortex ring [9, 8] (see Fig. 3a). The mean recirculation length is equal to 293 mm. It represents 1.5 H where H is the model height. This value is approximately the same as the one found by Duell & George [3] (1.1 H) or by Khalighi [7] (1.5 H). The flow topology in the median plane is characterised by a strong skewness. The upper vortex is smaller than the lower one. The mean position of the attachment point of the flow is located at 0.2 H of the upper edge. The iso-surface of velocity allows to see the circular vortex ring that is typical of square back bluff body wake flow, as visualized for example in [8, 9].

The cartography of mean static pressure coefficient ( $C_p$ ) is plotted in Fig. 3b. It shows a strong pressure loss in the lower part of the base of the model ( $C_p = -0.26$ ). Fig. 3b shows that the lower vortex is located in the area corresponding to a lower pressure zone on the base of the model. For an inlet velocity of  $40 \text{ m.s}^{-1}$ , the mean  $C_p$  is equal to -0.235 and the drag coefficient is equal to 0.364. For this velocity the ratio of the mean  $C_p$  and of the drag coefficient is equal to 0.65. This is in agreement with Krajnovic [8] numerical study showing that the  $C_p$  is equal to -0.23 and the pressure drag of the base represents 70 % of the total drag.

### 3.3 Velocity fluctuations in the wake of the model

The unsteadinesses in the wake were characterised with spectral analysis of velocity fluctuations. The Power Spectral Densities (PSD ( $E_{uu}(f)$ )) results are associated with their respective frequency ( $f$ ). The velocity fluctuations in the wake have been measured at  $40 \text{ m.s}^{-1}$  with a one component hot wire anemometry probe. Measurements have been positioned in the shears layer. Four measurements have been done in the wake of the horizontal edges respectively (39,0,0) and (293,0,0) for the upper edge and (39,0,-202) and (293,0,-202) for the lower edge.

$E_{uu}(f)$  of the longitudinal velocity for different positions are plotted versus the frequency in Fig. 4. Spectra of the measurements at 293 mm of the base of the model have a peak at  $f_1$  is equal to 39.67 Hz.



(a) Mean PIV measurement in the median longitudinal plane and iso-surface of velocity ( $V = 10 \text{ m.s}^{-1}$ ) for an inlet velocity of  $40 \text{ m.s}^{-1}$  (b) Mean PIV measurement in the median longitudinal plane and mean pressure coefficient distribution on the base of the model for an inlet velocity of  $40 \text{ m.s}^{-1}$

FIGURE 3 – Topology of the wake

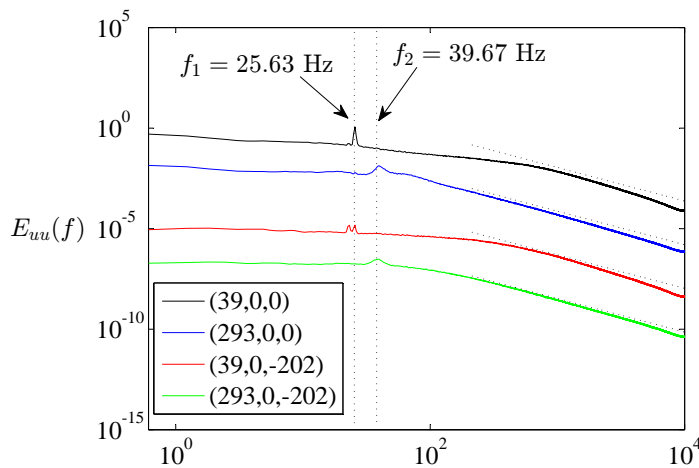


FIGURE 4 –  $E_{uu}(f)$  in the wake of the model

The corresponding Strouhal number ( $St$ ) based on the height of the model and on the free-stream velocity is equal  $St = 0.2$ . It is characteristic of a Benard-Von Karman instability in the far wake.

### 3.4 Proper Orthogonal Decomposition of PIV Fields

In order to exhibit the most energetics phenomena in the near wake flow, instantaneous velocity fields are analysed using a vectorial snapshot POD method. The contribution of the first 50 POD modes on the mean turbulent kinetic energy is plotted on Fig. 5. The curve shows that the first POD mode represents 8.% of the total kinetic energy and that the contribution of each mode rapidly decreases from the sixth mode to reach a value lower than 2%. Similar energy repartition can be found when the gap between a square cylinder and the ground of the wind tunnel is reduced [10]. The flow is modified by the interaction between the lower shear layer and the boundary layer developing on the ground wind tunnel. The flow becomes more complex and the energy is distributed over all the POD modes.

This point can be confirmed by the entropy ( $E$ ) of the flow [2] is given by :

$$E = - \lim_{N \rightarrow \infty} \left( \frac{1}{\log N} \right) \sum_{i=1}^N \frac{\lambda_i}{TE} \log \frac{\lambda_i}{TE} \quad (1)$$

where  $N$  is the number of modes,  $\lambda_i$  is the eigenvalue of order  $i$  that is equivalent to the kinetic energy associated with the  $i^{\text{th}}$  mode and  $TE$  is the total kinetic energy.  $TE$  is equal to the sum of the  $N$  eigenvalues that are the contributions of each mode to the energy present in the instantaneous flow. When  $E$  is equal to 0 all the energy is contained in the first mode. Higher value means that the flow becomes more complex and that the energy is distributed between all the modes. When this value reaches 1, the energy is equally distributed over all the POD modes. In the present study, the entropy is equal to 0.84. It means that the energy is divided between all the modes and it explains the low energy level of the first modes.

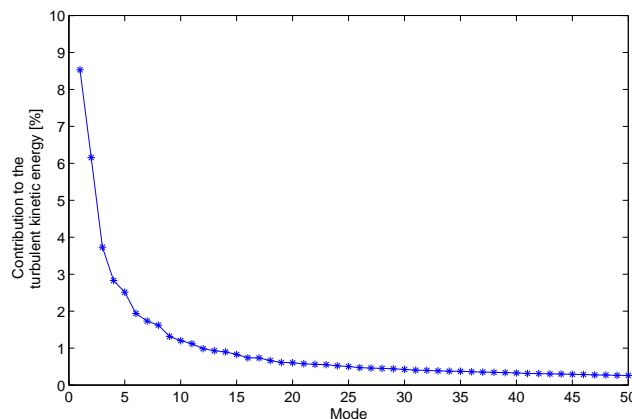


FIGURE 5 – Contribution to the mean turbulent kinetic energy of the 50 first modes

The cross plotting of the first and second mode coefficients in Fig. 6a indicates that the contributions of these two modes are not correlated contrary to the case of a vortex shedding process, for which this representation yields to a circle. It suggests that the unsteady process related with the most energetic mode can be modelled at a low order incorporating only the mean flow and the first POD mode.

Figure 6b shows the first eigenfunctions of the component  $U$  and  $W$  of the velocity. The first one is associated to the most energetic velocity mode in the flow that is the flapping of the upper shear layer. Eigenfunctions of the second and the third modes are characterised by the alternation of zones of positive and negative velocity fluctuations. This is characteristic of coherent structures convection.

## 4 Conclusions

The wake flow of a simplified road vehicle geometry was investigated experimentally. The model is a square back Ahmed body. Pressure measurements revealed a strong sensibility to the drift angle of model. The analysis of the pressure evolution at the rear edges of the model reveals two states. Those two solutions are symmetric with respect to one another and occur for respectively positive or negative slightly non zero sideslip angle. The flow is then bistable and the zero drift angle seems to be a critical case where the wake shifts between two states. Proper Orthogonal Decomposition shows no dominant coherent structures in the square back bluff body wake. The first mode represents less than ten percent of the total kinetic energy. Moreover, the contribution of the following modes decrease rapidly to reach a value lower than two percent from the sixth mode. The POD analysis shows also that the first modes are not correlated and that the flapping of the shear layer in the wake of the bluff body can be modelled by a low order model. This experimental study will be completed by a numerical survey.

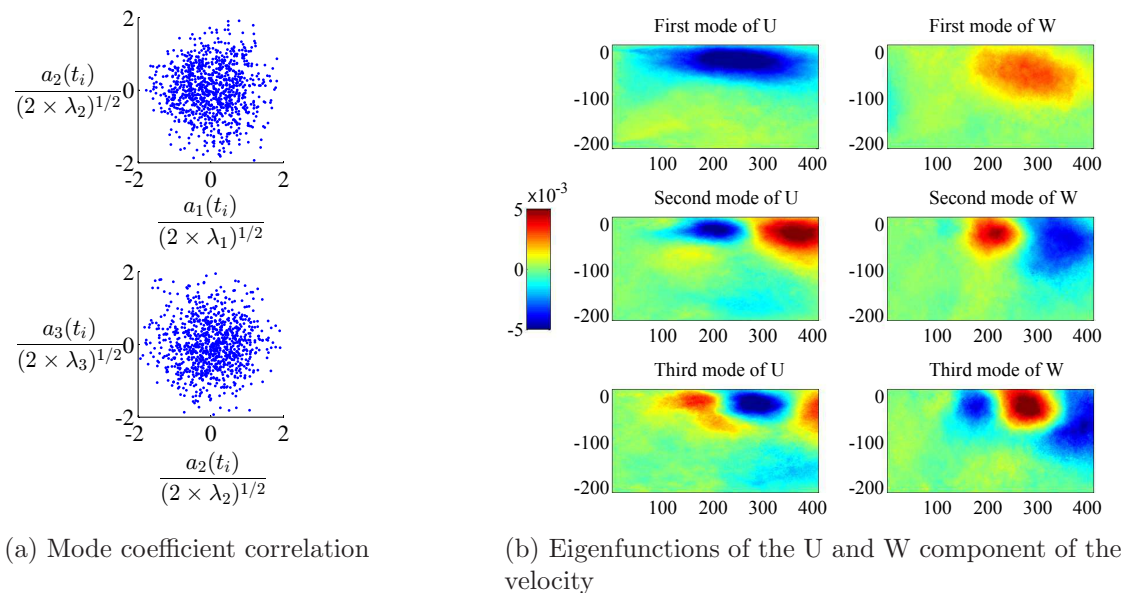


FIGURE 6 – First mode of the decomposition and their correlation

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