### **RESEARCH ARTICLE**

# Experimental characterization of flow unsteadiness in the centerline plane of an Ahmed body rear slant

A. Thacker · S. Aubrun · A. Leroy · P. Devinant

Received: 28 August 2012/Revised: 5 February 2013/Accepted: 7 February 2013/Published online: 20 February 2013 © Springer-Verlag Berlin Heidelberg 2013

Abstract This study presents the results of an experimental analysis of the unsteady features of the flow around the rear part of an Ahmed body with rear slant angle of 25°. This analysis focuses on the 3D separated and reattaching zone that develops on the rear slanted surface and provides new information, improving the understanding of the flow unsteadiness. Flow investigations were performed using particle image velocimetry, hot wire anemometry, and unsteady flush-mounted pressure transducers in the plane of symmetry above the rear slanted surface. Spectral analysis and proper orthogonal decomposition of the output signals show the emergence of low frequency unsteadiness and high frequencies activity. Characteristic timescales of both instabilities are provided and the physical effect of the low frequency unsteadiness is related to a flapping motion of the separated shear layer, while the high frequency activity is associated with a large-scale vortex emission. The results focus on the centerline plane of the rear slant and more specifically demonstrate relevant similarities with the unsteady mechanisms of 2D recirculated flow.

# 1 Introduction

Since the pioneering experimental studies by Onorato et al. (1984) and Ahmed et al. (1984), a large amount of information in relation to the complex three-dimensional topology and aerodynamic features of road vehicles has been published using the Ahmed body (Ahmed et al. 1984), enabling the identification of the main pressure drag

sources and their contribution to the overall aerodynamics. Consequently, considerable effort has been put into developing flow control devices and strategies, promising efficient drag reduction (Gilliéron 2002). Unfortunately, current knowledge of ground vehicle aerodynamics is no longer sufficient since it is often limited to time-averaged information. Apart from a few experimental (Sims-Williams and Duncan 2003; Vino et al. 2005; Gilhome et al. 2001; Duell and George 1999) or numerical (Howard and Pourquie 2002; Krajnović and Davidson 2005; Minguez et al. 2008; Serre et al. 2011) studies, the physical mechanisms related to the unsteady process involved in the flow dynamics are rarely characterized, whereas they are of significant interest especially for flow control applications (e.g., closed-loop control).

The Ahmed body simplified car geometry constitutes a reference model. It is a parallelepiped with a streamlined front part and a slanted surface at the rear that reproduces the basic flow features of the rear part of ground vehicles. Ahmed et al. (1984) pointed out that the flow is mainly controlled by the slant angle (for a given Reynolds number) and suggested a classification of the averaged flow topologies. The case of a slant angle of 25° is particularly interesting, since this configuration presents a complex organization of the flow with a high drag level and is representative of the flow topology at the rear part of common fastback cars (rear window and rear part). In that case, the flow is characterized by a complex combination of three structures: two longitudinal vortical structures, a 3D separation bubble on the rear window, and a 3D wake located at the rear base.

From an unsteady point of view, the 3D wake that develops behind the rear base is commonly related to 3D vortex shedding advected downstream in the wake (Sims-Williams and Duncan 2003; Vino et al. 2005), while the

A. Thacker · S. Aubrun (⊠) · A. Leroy · P. Devinant Laboratoire PRISME, Université d'Orléans, 8 rue Léonard de Vinci, 45072 Orléans Cedex 2, France e-mail: sandrine.aubrun@univ-orleans.fr

longitudinal vortical structures are considered to be highly stable (Krajnović and Davidson 2005; Thacker et al. 2012). Numerical studies by Krajnović and Davidson (2005), Minguez et al. (2008) and Serre et al. (2011) using large Eddy simulation provided new information about the instantaneous flow topology around the Ahmed body. Using O criterion visualization of the instantaneous flow fields (used in preference to vorticity to visualize vortex motion in sheared flows), these authors pointed out an emission of hairpin-like vortices travelling along the shear layer of the 3D separation bubble. In the same manner, another LES of the flow around the Ahmed body performed by Hinterberger et al. (2004) related that two typical instantaneous velocity fields could be found in the median plane of the slanted surface. In the first, the flow tends to reattach on the surface, and in the second, the flow is completely separated. This tendency suggests a flapping motion of the rear window separation. However, unsteady analyses of these mechanisms are still poor as no accurate spectral analyses has been provided due to the short simulated time available. In addition, these mechanisms have not yet been investigated experimentally.

In a more general context, unsteady mechanisms of 2D separated and reattaching flow configurations have been widely characterized and are of significant interest in the present application. Experimental studies by Cherry et al. (1984) and Kiya and Sasaki (1983, 1985) dealing with unsteady measurements in a 2D separated and reattaching flow formed at the leading edge of a blunt flat plate provided accurate descriptions of these mechanisms. Their studies demonstrate that the unsteadiness of 2D recirculated flows are governed by two characteristic mechanisms: the motion of large-scale vortices along the separated shear layer connected with high frequency signatures, and the vertical flapping motion of the separated flow connected with a low frequency signature. These unsteady mechanisms are also reported in more recent literature (Lee and Sung 2001; Hudy et al. 2003; Chun et al. 2004; Largeau and Moriniere 2007) and present strong similarities with the observations by Krajnović and Davidson (2005), Minguez et al. (2008), Serre et al. (2011) and Hinterberger et al. (2004) for the 3D separation bubble over the rear surface of the Ahmed body.

For these reasons, this study addresses an experimental investigation of the unsteadiness related to the development of the 3D separated and reattaching flow that develops on the slanted surface of the Ahmed body. As a preliminary characterization of these unsteady features, the study focuses on the centerline plane of the rear slant and aims to demonstrate experimentally the existence of a flapping motion of the separated shear layer and the emission of large-scale vortices as observed by Krajnović and Davidson (2005), Minguez et al. (2008), Serre et al. (2011) and Hinterberger et al. (2004). In the centerline plane of the 3D recirculated zone, the characteristic frequencies of the two are here well identified and are found to be similar to the observations of Cherry et al. (1984) and Kiya and Sasaki (1983, 1985) for 2D separated and reattaching flows. Although this study provides an accurate spectral analysis and new experimental information, complementary investigations must be carried out in order to extend the related mechanisms off the centerline plane of the 3D recirculated zone.

The flow examination is here carried out using particle image velocimetry (PIV) and hot wire anemometry in the plane of symmetry above the rear slanted surface, and unsteady flush-mounted pressure taps measuring the wall pressure fluctuations along the middle line of the separation bubble. The first part of this investigation is dedicated to the localization, identification, and characterization of the different mechanisms of unsteadiness associated with the recirculated zone and its shear layer. Spectral analyses of velocity and pressure fluctuations are then performed and the characteristic frequencies related to the flow dynamics are extracted. The second part of this investigation aims to provide physical understanding of these unsteady features by providing characteristic representations of the flow dynamics. Moreover, the proper orthogonal decomposition (POD) method applied to the instantaneous velocity fields and wall pressure distributions is shown to be efficient for this particular case.

# 2 Experimental setup

### 2.1 Model dimensions and experimental facilities

An Ahmed body model with a slant angle of  $25^{\circ}$  between the roof and the rear window was built at a geometric scale 1:1 (Ahmed et al. 1984). The main dimensions of the model and the reference frame are presented in Fig. 1a.

The experiments were run in the "Lucien Malavard" wind tunnel of the PRISME Laboratory, University of Orléans. The test section is 2 m high, 2 m wide, and 5 m long. The maximum freestream velocity in the test section is 60 m/s, the freestream turbulence intensity is below 0.3 %, and the mean flow homogeneity is 0.5 % along a transverse distance of 1,200 mm. The wind tunnel setup is shown in Fig. 1b. The model was fixed on a 2 m wide and 3 m long flat plate by means of four cylindrical feet (30 mm in diameter). This plate was located 480 mm above the floor of the wind tunnel and enabled the development of a new, thin, boundary layer upstream, and underneath the model. The flat plate had an elliptical leading edge and a controllable trailing edge flap controlling the stagnation point location at the leading edge and



Fig. 1 a Basic dimensions and reference frame of the Ahmed body model. b Wind tunnel setup

minimizing circulation around the ground board. Static pressure was measured over the ground board without the model and ensured a zero-pressure gradient of 0.5 L ahead of and behind the model area. The reference velocity  $U_0$  was measured by a pitot tube located right above the model, 300 mm from the wind tunnel roof. All tests were carried out with a reference velocity of  $U_0 = 30$  m/s which corresponds to a model length-based Reynolds number of 2.2 million. For this reference velocity, the boundary layer and displacement thickness on the ground board just upstream of the model were, respectively, 0.4 and 0.04 h. The boundary layer and displacement thickness at the edge between the roof and the slanted surface were, respectively, 0.06 and 0.006 h. At this location, the boundary layer is turbulent.

# 2.2 PIV measurements

Two-component PIV measurements were taken in the vertical plane of symmetry of the body (*XZ* sheets at Y = 0) on the rear window (Fig. 2). An Nd:Yag laser (QUANTEL ultra 200) generating 2 pulses of 200 mJ each at a wavelength of 532 nm was located above the test section. A streamwise slit in the test section roof enables the vertical laser light sheet to reach the model. The optical setup was chosen to generate a sheet as thin as possible (about 1 mm) in the proximity of the model. Images were captured with a CCD TSI Power View Plus camera



Fig. 2 PIV setup

 $(2, 048 \times 2, 048 \text{ pixels})$  located outside the test section, on one side of the wind tunnel. The camera was located in the direction normal to the laser sheet and was inclined 25°. Images were then set in the  $(X^*, Y^* = 0, Z^*)$  reference axis in order to simplify the analysis of the velocity fields of the recirculating zone. The complete tunnel circuit was seeded with micro-sized droplets of olive oil generated by a PIVTEC seeding system. The laser and the camera were synchronized by a TSI synchronizer and the image processing was performed using Insight3G software by TSI. The PIV image dimensions were 219 mm  $\times$  219 mm and interrogation windows of  $16 \times 16$  pixels were used with an overlap of 50 % to obtain velocity fields (space resolution  $\delta_x = 0.9$  mm). Five hundred pairs of independent images were captured with a sampling frequency of 5 Hz. This leads to an RMS error on the time-averaged velocity of 3.5 % for a 95 % confidence interval (Benedict and Gould 1996) in the worst case (highest turbulence intensity 40 %).

# 2.3 Velocity and wall pressure fluctuations measurements

In order to investigate the unsteadiness within and in the vicinity of the separated/reattaching flow region of the rear slanted surface, time series of the velocity and wall pressure fluctuations were recorded.

Fluctuations of velocity magnitude (i.e., Mag(U, V)) were measured by using a DANTEC miniature 1D 55P11 hot wire probe connected to the DANTEC streamline system. Time series were recorded for different vertical profiles at different streamwise locations along the rear slanted surface in order to map the different unsteady activities. The sampling frequency was fixed at 60 kHz (cutoff frequency of 30 kHz) and the sampling time was 44 s at each measurement location, allowing a sufficient resolution of high and low frequencies.

Wall static pressure fluctuations were measured simultaneously along the center line of the slanted surface by using five unsteady flush-mounted pressure taps (Fig. 3): miniature Kulite pressure transducers (model XCQ062, full range 5 psid) with a sensing diameter of 1.7 mm. The pressure accuracy of each transducer is  $\pm 1$  Pa. A comparison between pressure spectra measured with and without incoming flow showed that this accuracy is sufficient to capture properly the pressure fluctuations in our configuration, the pressure spectral density with incoming flow being three decades higher than the transducer noise in the low frequency domain and one decade higher in the high frequency domain. The samples were taken over a period of 15 min with a sampling frequency of 20 kHz (cutoff frequency of 10 kHz). The reference pressure was the static pressure  $P_0$  measured by a Pitot tube located right above the model, 300 mm from the wind tunnel roof, in the freestream flow. The dynamic pressure measured by the Pitot tube was acquired through a differential pressure transducer DRUCK 0-5,000 Pa.

## 3 Unsteadiness identification and characterization

The aim of this analysis is to provide a cartography of the different unsteady activities that could be observed in the vicinity of the recirculating zone. Although the recirculating zone over the rear window of an Ahmed body is 3D,



this investigation especially refers to unsteady mechanisms of typical 2D separated and reattaching zone (Cherry et al. 1984; Kiya and Sasaki 1983, 1985). The following results focus on the median plane of the rear window (streamwise direction) and will demonstrate strong similarities between the two cases. It will be more particularly shown that unsteady activities are governed by a low frequency activity associated with an absolute unsteadiness that corresponds to a flapping motion of the recirculating zone shear layer, and higher frequency activities associated with convective unsteadiness that corresponds to a large-scale vortex emission following the mean shear layer from the separated zone.

#### 3.1 The shear layer description

Streamlines of the mean flow and contours of  $U_{\rm rms}$  in the median plane of the rear window are presented in Fig. 4. As expected, streamlines show the development of a recirculating zone due to a flow separation at the sharp edge between the roof and the slanted surface and a flow reattachment farther down the rear slant. From a three-dimensional point of view, this recirculating zone forms a half elliptic separation region as described by Ahmed et al. (1984). The mean reattachment point at the plane of symmetry corresponds to  $X_r^*/l^* = 0.73$  in the slanted surface reference axis (where  $l^* = 222$  mm is the rear window length).

The recirculated zone is separated from the external flow region by a shear layer. The positions of the inflection points of the mean shear layer velocity profiles are also shown (white dots in Fig. 4). These positions were determined by searching for positions of the maximum of  $\partial U^*/\partial Z^*$ . Referring to the model of a turbulent 2D mixing



**Fig. 4** Streamlines of the mean flow and contours of  $U_{\rm rms}$  in the  $X^*$ ,  $Z^*$  reference axis. White dots represent the positions of the inflection points of the shear layer velocity profiles. Dashed line is a three-order polynomial least-square fitting of these positions

layer, the existence of inflection points in velocity profiles is a necessary condition for the existence of Kelvin– Helmholtz instabilities (Rayleigh criterion) which lead to large-scale vortex emission (coherent structures). By definition, the amplitude of the oscillation of the mixing layer due to KH instabilities and characteristic scales of the vortices formed are related to the vorticity thickness  $\delta_{\omega}$ . Evolution of the vorticity thickness  $\delta_{\omega}$  along the recirculating zone is presented in Fig. 5. This evolution is computed using the 2D mixing layer model :

$$\delta_{\omega} = \frac{U_{\max}^* - U_{\min}^*}{\left(\partial U^* / \partial Z^*\right)_{\max}} \tag{1}$$

where  $U^*_{\text{max}}$  and  $U^*_{\text{min}}$  are, respectively, the maximum and the minimum of the  $U^*$  profile for a given  $X^*$  location. For recirculating flow,  $U_{\min}^*$  is fixed to zero by considering that coherent structures mainly travel along the upper part of the shear layer (Aubrun 1998). Results show that the vorticity thickness linearly increases in the streamwise direction along the recirculating zone. This linear growth is consistent with observations for a 2D mixing layer (Bonnet et al. 1998) and results from the amplification of the shear layer undulations creating large-scale structures, and from the increase in the characteristic vortex scales associated with a merging process along the shear layer (Brown and Roshko 1974). In addition, the growth rate of the vorticity thickness is 0.22, of the same order of magnitude (0.2-0.3) as those found in the literature for 2D mixing layers (Brown and Roshko 1974; Papamoschou and Roshko 1988) or curved mixing layers (Tenaud et al. 2010).



Fig. 5 Vorticity thickness evolution along the recirculating zone shear layer

3.2 Spectral analysis of velocity magnitude and wall pressure fluctuations

The spectral analysis was conducted by measuring velocity magnitude fluctuations time series along vertical profiles *Z* for different locations *X* along the middle plane of the rear window, and wall pressure fluctuations along the middle line of the recirculating zone. Relevant observation zones of unsteadiness can be delimited by locating spectra where characteristic signatures are significant. These observation zones are showed in Fig. 6 with their respective characteristic frequencies from the hot wire and Kulite acquisitions. The characteristic frequencies are associated with their respective Strouhal number  $St_{X_r^*}$  based on the mean reattachment length  $X_r^*$  and the reference velocity  $U_0$ .

Spectral analysis of the velocity magnitude fluctuations shows that unsteady activities can be observed in two different zones surrounding the recirculating zone (Fig. 6). The first zone is located around the inflection points of the shear layer that corresponds to the most energetic contribution. In this zone, unsteadiness is characterized by a low frequency signature in the power spectral density. The second zone is located in the upper part of the mean shear layer and is characterized by lower levels of velocity fluctuations with higher frequency signatures in the power spectral density.

Dimensionless power spectral densities  $E_{uu}(f) \Delta f / \sigma_u^2$  of velocity magnitude fluctuations measured in the first zone are shown in Fig. 7 ( $\Delta f$  is the frequency resolution and  $\sigma_u$  is the standard deviation of velocity fluctuations). Results clearly indicate the emergence of a low frequency spectral activity. In all cases, this is characterized by a dominant frequency of  $f_{1f} = 20$  Hz that corresponds to a Strouhal



Fig. 6 Observation zones of unsteadiness around the rear window with their respective characteristic frequencies. Positions of the shear layer inflection points are shown in *dashed line* (least-square fitting)



**Fig. 7** Velocity spectrum observed in the vicinity of the mean shear layer along the recirculating zone (zone 1)



Fig. 8 Velocity spectrum observed in the *upper part* of the mean shear layer along the recirculating zone (zone 2)

number  $St_{X_r^*}^1$  of 0.11. This dominant frequency was also reported by Joseph et al. (2012) for an equivalent vehicle model and was observed and discussed by Gilhome et al. (2001) in the case of a notchback vehicle model. In both cases, this characteristic frequency have been associated with a flapping of the 3D recirculated zones. In comparison with the 2D recirculating zone, this Strouhal number is close to the one observed by Cherry et al. (1984) and Kiya and Sasaki (1983, 1985) ( $St_{X_r^*} = 0.12$ ) for a separation bubble formed at the leading edge of a blunt flat plate. According to these authors, this low frequency unsteadiness is also associated with a flapping motion of the shear layer.

Dimensionless power spectral densities of velocity magnitude fluctuations measured in the second zone are shown in Fig. 8. In some cases, the low frequency activity mainly observed in the first zone is still present but higher frequency activities can be observed. These activities are



Fig. 9 Wall pressure spectrum measured along the recirculating zone

characterized by a spectral bump for which dominant frequency is centered around  $f_{\rm hf} \approx 115$  Hz, which corresponds to a Strouhal number  $St_{X_r}^2$  of 0.63. This Strouhal number is also close to that observed for a 2D separated zone (Cherry et al. 1984; Kiya and Sasaki 1983, 1985) and associated with large-scale vortex emissions. In addition, it can be seen that the dominant frequency is weakly shifted toward the low frequency domain while moving downstream of the separation. The high frequency signatures decrease from  $St_{X_r}^2 = 0.68$  at  $X^*/X_r^* = 0.607$  to  $St_{X_r}^2 = 0.63$ at  $X^*/X_r^* = 1.599$ .

Dimensionless power spectral densities  $E_{pp}(f) \Delta f / \sigma_p^2$  of the measured wall pressure time series are presented in Fig. 9 and the locations of the observed dominant frequencies are summed up in Fig. 6. As observed with the velocity spectra, the low frequency spectral activity is well defined with a dominant Strouhal number  $St_{X_{*}}^{1}$  of 0.11. When moving downstream, this signature is encountered near the separation zone  $(X^*/X_r^* = 0.02 \text{ and } 0.11)$  and in the mean reattachment zone  $(X^*/X_r^* = 0.84)$  and totally disappears within the separation bubble  $(X^*/X_r^* = 0.35)$  and downstream of  $X^*/X^* = 1.1$ . High frequency activities are observed at each measurement position. Dominant frequencies are shifted toward the low frequency domain with the streamwise distance, as observed with velocity spectra. Close to the separation zone, at  $X^*/X_r^* = 0.02$ and  $X^*/X_r^* = 0.11$ , the dominant Strouhal numbers are, respectively,  $St_{X_{\tau}^*}^2 = 11$  and  $St_{X_{\tau}^*}^2 = 2.5$ . These very high frequency signatures can be associated with the initiation of KH instabilities in the very thin shear layer, as reported by Cherry et al. (1984) for a 2D recirculating zone. Farther

downstream at  $X^*/X_r^* = 0.35$ , 0.84 and 1.1, the dominant Strouhal numbers are, respectively,  $St_{X_r^*}^2 = 0.71$ , 0.66 and 0.63.

The decrease in the high dominant frequency observed in both velocity and pressure spectra is consistent with the development and emission of large-scale structures along the shear layer. In the context of vehicle wakes, this observation was also reported and discussed by Duell and George (1999) in the near wake shear layer of a simple square-back vehicle model. Referring to the turbulent 2D mixing layer model, the frequency signature  $f_{\rm p}$  of largescale vortices resulting from KH instabilities decreases in proportion with the increase in the vorticity thickness  $\delta_{\alpha}$ along the shear layer such that the product  $f_{\rm p}\delta_{\omega}$  remains constant. From the studies of Bonnet et al. (1998) for a 2D mixing layer and Cherry et al. (1984), Abdalla and Yang (1983), and Aubrun (1998) for a curved shear layer (recirculating zone), one can observe that the Strouhal number  $(St_{\delta_{\omega}} = f_{p}\delta_{\omega}/U_{c})$  based on the frequency signature, the vorticity thickness, and the convection velocity, has an order of magnitude of 0.2–0.3 along the shear layer. Frequency signatures of large-scale vortices that could be expected along the shear layer of the recirculating zone are presented in Fig. 10. They are computed by using measured  $\delta_{\omega}$  (see Fig. 5) and from the hypothesis that the Strouhal number  $St_{\delta_{\infty}}$  is 0.2–0.3 with a convection velocity  $U_{\rm c} = 0.5 \times U_0$  as suggested in the literature. The high frequency signatures  $f_{\rm hf}$  measured from the power spectral densities of velocity and pressure fluctuations are also presented in Fig. 10. The decrease in the observed frequencies along the shear layer is consistent with the



Fig. 10 Theoretical frequency signatures of large-scale vortices resulting from KH instabilities and measured high frequency activity along the shear layer from hot wire and Kulites measurements

expected curve. The dominant frequencies converge to a Strouhal number of  $St_{X_r^*}^2 = 0.63$ , which is typically observed in the literature for 2D recirculating zones.

### 3.3 Spatio-temporal properties of unsteadiness

An efficient method of analyzing the spatio-temporal properties of observed spectral activities is to use coherence  $\operatorname{Co}_{P_1P_2}(f)$  and phase  $\theta_{P_1P_2}(f)$  functions computed from the cross-spectral density between two pressure transducers  $P_1$  and  $P_2$ . The coherence function is defined between 0 and 1 and indicates at which frequency range the signals are the most correlated. The phase function indicates the phase shift between the two signals for each frequency. Coherence and phase functions between representative pressure signals measured along the middle line of the recirculating zone are plotted in Fig. 11.

Figure 11a presents the coherence and phase between  $P_1$ and P<sub>2</sub>, respectively, located at  $X^*/X_r^* = 0.02$  and  $X^{*}/X_{r}^{*} = 0.11$  near the separation point where the low frequency spectral activity is observed (see pressure spectra in Fig. 9). The coherence function shows that both signals are highly correlated in the low frequency domain with a maximum of coherence at  $St_{X_{*}^{*}}^{1} = 0.11$ . At higher frequencies, the coherence drops and a considerably lower correlation is observed. In addition, for the entire highly correlated low frequency range, the phase function presents a plateau with a 0° phase angle and increases for  $St_{X_{*}}^{1} > 0.11$ . These observations indicate that correlation at the near area of the separation point is strongly affected by the low frequency activity. Consequently, pressure fluctuations at the two pressure taps share the same unsteadiness with an in-phase periodicity that corresponds to the low frequency activity. In addition, the existence of a phase plateau at the highly correlated frequency range demonstrates that the low frequency activity is not a convective but an absolute unsteadiness.

These results can be further refined up by observing the correlation between the separation and the reattachment zones. Fig. 11b presents the coherence and phase function between two pressure signals measured, respectively, at  $X^*/X_r^* = 0.02$ , located near the separation point, and  $X^*/X_r^* = 0.84$ , located near the reattachment point. The low frequency activity is observed for both locations (see pressure spectrum in Fig. 9), and the coherence function in Fig. 11b indicates that the two pressure signals are well correlated in the low frequency domain with a maximum at  $St_{X_r^*}^1 = 0.11$  and that the phase function presents a plateau with a 180° phase angle in the low frequency range, which confirms that the low frequency activity is an absolute unsteadiness. Consequently, pressure fluctuations at the separation zone and the reattachment zone share the same



**Fig. 11** Coherence and phase functions from cross-spectra between two signals. **a** Between  $X^*/X_r^* = 0.02$  and  $X^*/X_r^* = 0.11$ . **b** Between  $X^*/X_r^* = 0.02$  and  $X^*/X_r^* = 0.84$ . **c** Between  $X^*/X_r^* = 0.84$  and  $X^*/X_r^* = 1.1$ 

low frequency unsteadiness with an out-of-phase periodicity. Finally, the results in Fig. 11a, b are consistent with the hypothesis of a flapping motion of the shear layer. Indeed, considering this unsteady mechanism, it can be assumed that unsteadiness is not convective since pressure fluctuations would be affected simultaneously along the entire recirculating zone. Moreover, these fluctuations can be expected to be out of phase between the separation and the reattachment zone because of the shear layer curvature change during the flapping process. This will be demonstrated in greater detail in Sect. 4.3.

Figure 11c presents coherence and phase functions between pressure signals measured, respectively, at  $X^*/X_r^* = 0.84$  and  $X^*/X_r^* = 1.1$  where the high frequency activity is observed (see pressure spectrum in Fig. 9). In that case, the maximum of coherence is observed in a wide frequency domain centered around the characteristic Strouhal number  $St_{X_{*}}^{2} \approx 0.63$  associated with the high frequency activity. For this frequency domain, the phase function increases linearly, which is representative of the convective nature of the high frequency activity (Sagaut 2008). This observation supports the hypothesis of largescale vortex convection such as can be expected from the shear layer characterization. The convection velocity  $U_{\rm c}$  of the perturbations can be assessed from the linear slope of the phase angle  $d\theta_{P_1P_2}/df$  with the relation  $d\theta_{P_1P_2}/df =$  $2\pi\Delta L/U_{\rm c}$ , where  $\Delta L$  is the distance between pressure transducers (Sagaut 2008). The convection velocity of the high frequency perturbation between the two pressure sensors is  $U_{\rm c} = 20$  m/s  $\approx 0.67 \times U_0$ , which is somewhat different from the expected value of  $0.5 \times U_0$ . Nevertheless, it leads to a Strouhal number  $St_{\delta_m}$  of 0.2 which is still in agreement with the literature for 2D mixing layers (Bonnet et al. 1998; Cherry et al. 1984; Abdalla and Yang 1983; Aubrun 1998).

# 4 Mechanisms of unsteadiness: POD and low-order modeling

In order to complete the unsteady characterization of the separation bubble that develops over the rear window, this section analyses more specifically the instantaneous velocity fields captured by PIV and the instantaneous wall pressure distribution by applying the proper orthogonal decomposition method (POD) (Lumley 1967). The objective is to associate both the high spatial resolution of PIV velocity fields with the high time resolution of wall pressure measurements in order to extract the unsteady mechanisms of the recirculated zone associated with the low and high frequency activities. This analysis will confirm the assumption of a flapping motion of the separation bubble and a large-scale vortex generation along the shear layer. The main issue is that instantaneous distributions (velocity fields and pressure profile along the recirculated zone)

contain a great amount of information especially related to the turbulent motion and significant characteristics of the flow are easily screened. For this reason, POD analysis represents an interesting way to obtain filtered information and to establish a classification of flow configurations (POD mode) in a decreasing order from the energetic point of view. Basically, POD consists in expressing each instantaneous velocity and pressure distribution  $\mathbf{v}(X^*, Z^*, t_i)$  and  $P(X^*, t_i)$  at a time  $t_i$  as the following relations:

$$\mathbf{v}(X^*, Z^*, t_i) = \langle \mathbf{v} \rangle(X^*, Z^*) + \mathbf{v}'(X^*, Z^*, t_i)$$
(2)

$$= \langle \mathbf{v} \rangle (X^*, Z^*) + \sum_{n=1}^{N_t} a_{\mathbf{v}}^{(n)}(t_i) \mathbf{\Phi}_{\mathbf{v}}^{(n)}(X^*, Z^*)$$
(3)

$$P(X^*, t_i) = \langle P \rangle(X^*) + P'(X^*, t_i)$$
(4)

$$= \langle P \rangle(X^*) + \sum_{n=1}^{N_X} a_p^{(n)}(t_i) \Phi_P^{(n)}(X^*)$$
 (5)

where  $\langle \mathbf{v} \rangle (X^*, Z^*)$  and  $\langle P \rangle (X^*)$  denote the time-averaged part of the velocity field and wall pressure distribution, respectively, and  $\mathbf{v}'(X^*, Z^*, t_i)$  and  $P'(X^*, t_i)$  their fluctuating parts.  $\Phi_{\mathbf{v}}^{(n)}(X^*, Z^*)$  and  $\Phi_{\mathbf{P}}^{(n)}(X^*)$  are the *n*th POD basis functions, and  $a_{\mathbf{v}}^{(n)}(t_i)$  and  $a_{\mathbf{p}}^{(n)}(t_i)$  are the POD mode coefficients related to the *i*th instantaneous velocity and wall pressure distributions. Since the number of instantaneous PIV velocity fields (Nt = 500 image pairs) is negligible compared to the number of measurement points  $(Nx = 255 \times 255 \text{ interrogation windows})$ , the POD is computed by using the vectorial snapshot method (Sirovich 1987). In that case, the total number of POD modes is equal to the number of instantaneous fields Nt = 500. Inversely, instantaneous wall pressure distributions are time-resolved but have a poor spatial resolution, so that the POD is computed by using the classical method (Lumley 1967). In that case, the total number of POD modes corresponds to the number of measurement locations Nx = 5. For more information about POD applications, the reader is referred to Cordier and Bergmann (2008a). Finally, note that instantaneous velocity fields and wall pressure distributions were not acquired simultaneously.

The contribution of the first thirty velocity POD modes and the five pressure POD modes to the turbulent kinetic energy (TKE) is shown in Fig. 12a, b, respectively. In the case of velocity fields (Fig. 12a), the first POD mode contributes 28 % of the TKE. This contribution decreases rapidly, reaches less than 2 % from the eighth mode. The first thirty POD modes are therefore sufficient to represent 72 % of the total energy content captured in the set of velocity fields. The large difference between the first mode and the others also seems to indicate that the physical mechanism related to the first mode is different from the others. This result will be confirmed in the following



Fig. 12 Contribution of each POD mode to the mean turbulent kinetic energy. **a** Instantaneous velocity fields (first thirty modes). **b** Instantaneous wall pressure distributions

sections and will show that the first POD mode is exclusively associated with global velocity fluctuations inside the recirculated zone that are linked with a flapping motion, while the other modes are associated with a large-scale vortex emission and the turbulent motion. This distinction between the first POD mode and the others is less visible in the case of instantaneous pressure distributions (see Fig. 12b). This is explained by the poor spatial resolution of the pressure distribution, which restricts the number of POD modes and thus the number of energy representations. Nevertheless, pressure measurements are time-resolved and the following results will finally show that the first POD mode is representative of the low frequency activity while the others are associated with the high frequency activity (and the turbulent motion).

# 4.1 POD mode analysis for instantaneous velocity fields

The velocity fields POD modes  $\Phi_{v}^{(n)}(X^*, Z^*)$  give the most energetic representations of velocity fluctuations around the recirculated zone. Consequently, the major advantage of the POD is that the first modes are often sufficient to give insight into the main mechanisms of the flow. Figure 13 presents the POD basis functions of the instantaneous velocity fields for the first three modes. The right part shows the POD basis functions  $\phi_{W^*}^{(n)}(X^*, Z^*)$  for the cross-wise component  $W^*$  while the left part presents the  $\phi_{U^*}^{(n)}(X^*, Z^*)$ functions for the streamwise component  $U^*$ . For the first POD mode, velocity fluctuations are mainly associated with fluctuations of the streamwise component  $U^*$  and include the entire recirculated zone. This indicates that the first mode of velocity fluctuations is associated with a flapping motion of the recirculated zone. This result will be demonstrated by the low-order modeling presented in the next



Fig. 13 Velocity fields POD modes  $\Phi_{\mathbf{v}}^{(n)}(X^*, Z^*)$ . a First mode n = 1. b n = 2. c n = 3

section (Sect. 4.3). From the second POD mode onward (Fig. 13b, c), the velocity fluctuations of the cross-wise component  $W^*$  become significant in comparison with  $U^*$  and different zones of extremum fluctuations alternately positive and negative are present and follow the mean shear layer. By using the periodicity of the negative and positive zones, one can define a wavelength  $\lambda$  between two positive or negative extremum zones of fluctuating velocity. This observation is classically pointed out in many studies using POD (see Cordier and Bergmann 2008b) and is representative of a large-scale vortex emission. In this configuration, the energy content of large-scale vortex emission is represented through some successive POD modes for which a parity rule is observed that describes the convective nature of the flow (Rempfer and Fasel 1994). This parity is also observed in the present study and can be illustrated with the second and the third modes (Fig. 13b, c). Indeed, it can be seen that the negative and positive alternation is shifted by a quarter wave length between the two modes. Moreover, by measuring the half wave length between a positive and a negative zone, such as illustrated in Fig. 13b, c, and by using a convection velocity of  $U_c = 20$  m/s measured from the phase function in Fig. 11c, one can assess a frequency signature of the positive/negative alternation of  $f_p =$  $U_{\rm c}/\lambda \approx 130 \,{\rm Hz}(St_{X_{\star}^*} = 0.71)$  that corresponds with the high frequency activity signature captured in this area.

# 4.2 POD mode analysis for instantaneous pressure distributions

Since the pressure measurements have a poor spatial resolution, a direct interpretation, the POD mode basis functions  $\Phi_P^{(n)}(X^*)$  would not be relevant. Nevertheless, pressure measurements are time-resolved and the determination of each POD mode basis function and coefficient  $a_p^{(n)}(t_i)$  can be used to reconstruct time series of the fluctuating pressure at each measurement location. Consequently, for each measurement location, the spectra of fluctuating pressure can be reconstructed for each POD mode independently. As a result, by comparing the original signal with each of the five mode reconstructions, the contribution of each POD mode to the low and high frequency unsteadiness can be extracted.

Spectra of fluctuating pressure for the original signal and POD reconstructions for all the measurement locations are presented in Fig. 14. Near the separation zone  $(X^*/X_r^* = 0.02 \text{ and } 0.11, \text{ see Fig. 14a, b})$ , results indicate that the first mode spectrum coincides with the original signal in the low frequency domain. The low frequency activity  $(St_{X_r^*}^1 = 0.11)$ , mostly observed near the separation point, is thus well represented by the first POD mode.

Within the separation bubble  $(X^*/X_r^* = 0.35$ , see Fig. 14c), the first POD mode is no longer predominant and the second mode mostly becomes representative. In this case, the low frequency unsteadiness is totally absent and fluctuating pressure is more specifically affected by the higher frequency activities ( $St_{X^*}^2 = 0.71$ ) reproduced by the second POD mode. Near the mean reattachment zone  $(X^*/X_r^* = 0.84$ , see Fig. 14d), the pressure spectrum shows both low frequency and high frequency activities. In this case, fluctuating pressure is dominated by the first and third POD modes. The first POD mode is again predominant in the low frequency domain and the low frequency unsteadiness is reproduced. In the high frequency domain, the first mode is no longer representative and the third mode is better suited to reproduce the high frequency activity. Finally, after the mean reattachment zone  $(X^*/X_r^* = 1.1, \text{ see Fig. 14e})$ , the low frequency unsteadiness disappears as the first POD mode becomes negligible and the fourth mode is clearly representative. In conclusion, the POD decomposition of the wall pressure spectra clearly indicates that the first mode is associated with the low frequency activity while the others are clearly linked with the higher frequency activities. The present POD analysis, by automatically sorting information by decreasing order of energy contribution, enables a decomposition of the fluctuating pressure with respect to the two unsteady mechanisms.

# 4.3 Global flapping of the recirculated zone: low-order modeling

It has been shown previously that the first POD mode of velocity fields is related to global velocity fluctuations including the entire recirculated zone while the higher modes are representative of a large-scale vortex emission. In the same way, the first POD mode of pressure distribution is exclusively associated with the low frequency unsteadiness while the higher modes are linked with the high frequency activities. The present analysis is based on low-order modeling of the instantaneous distributions (velocity and pressure) by using the first POD mode fluctuations. The objective is to separate the contribution of the first mode from the others with a view to gaining insight into its physical properties. The results presented in this section will finally show that the first POD mode of velocity and pressure distributions are the characteristic of the global flapping of the recirculated zone moving from a reduced state to an enlarged state with a periodicity that corresponds to the low frequency spectral activity.

Each low-order model of instantaneous velocity fields and pressure distributions can be obtained with the following relations :



Fig. 14 POD wall pressure spectra

 $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_i) = \langle \mathbf{v} \rangle (X^*, Z^*) + a_{\mathbf{v}}^{(1)}(t_i) \mathbf{\Phi}_{\mathbf{v}}^{(1)}(X^*, Z^*)$  (6)

$$P^{\text{LOM}}(X^*, t_i) = \langle P \rangle(X^*) + a_{\text{p}}^{(1)}(t_i) \Phi_P^{(1)}(X^*)$$
(7)

where  $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_i)$  and  $P^{\text{LOM}}(X^*, t_i)$  refer to the loworder model (LOM) of the instantaneous velocity field and pressure distribution at time  $t_i$ . The first mode coefficients  $a_v^{(1)}(t_i)$  and  $a_p^{(1)}(t_i)$  quantify the weight of the first POD mode in the *i*th instantaneous distribution. Consequently, sorting the instantaneous distributions according to the weight of these coefficients enables



**Fig. 15 a** Instantaneous velocity field  $\mathbf{v}(X^*, Z^*, t_1)$  where  $t_1$  is selected using  $a_{\mathbf{v}}^{(1)}(t_1) = \min(a_{\mathbf{v}}^{(1)}(t_i))$ . **b** Associated low-order model  $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_1)$ 

visualization of the extreme flow topologies associated with the first mode.

Particular instantaneous velocity fields  $\mathbf{v}(X^*, Z^*, t_1)$  and  $\mathbf{v}(X^*, Z^*, t_2)$  where the  $a_{\mathbf{v}}^{(1)}$  are minimum and maximum are presented in Figs. 15a and 16a, respectively, and are compared with their associated low-order model  $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_1)$  and  $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_2)$  (Figs. 15b, 16b). It can clearly be seen that the low-order model velocity fields satisfactorily represent the main feature of the flow and that the difference between the real instantaneous distributions and the filtered ones comes from higher POD modes. The comparison between the minimum and the maximum of  $a_{\mathbf{v}}^{(1)}$  (Figs. 15, 16, respectively) flow configurations indicates that the extremum features of the recirculated zone correspond to a partially attached and a totally separated configuration. More generally, one can observe that instantaneous velocity fields affected by the first POD mode coefficient between  $\min(a_{\mathbf{v}}^{(1)}(t_i))$  and 0 show that the recirculated zone is reduced compared with the mean



**Fig. 16 a** Instantaneous velocity field  $\mathbf{v}(X^*, Z^*, t_2)$  where  $t_2$  is selected using  $a_{\mathbf{v}}^{(1)}(t_2) = \max\left(a_{\mathbf{v}}^{(1)}(t_i)\right)$ . **b** Associated low-order model  $\mathbf{v}^{\text{LOM}}(X^*, Z^*, t_2)$ 

flow topology while those affected by coefficients between 0 and  $\max(a_v^{(1)}(t_i))$  show that the recirculated zone is enlarged or fully separated. Consequently, on the basis of the first POD mode, it follows that the main mechanisms that induce most of the turbulent kinetic energy corresponds to a global flapping of the recirculated zone.

Particular low-order models of instantaneous pressure coefficient distributions  $C_p^{\text{LOM}}(X^*, t_1)$  and  $C_p^{\text{LOM}}(X^*, t_2)$ , where the  $a_p^{(1)}$  are, respectively, maximum and minimum, are presented in Fig. 17, and are compared with the time-averaged distribution  $\langle C_p \rangle (X^*, t_i)$ . Note that the low-order model of pressure coefficient is computed from the following relation:

$$C_{\rm p}^{\rm LOM}(X^*, t_i) = \frac{P^{\rm LOM}(X^*, t_i) - P_0}{1/2\rho U_0^2}$$
(8)

The extremum low-order model of instantaneous pressure coefficient distributions (according to the first POD mode) has opposite distributions to that of the time-averaged



**Fig. 17** Mean pressure coefficient distribution  $\langle C_p \rangle (X^*, t_i)$  and loworder model of instantaneous pressure coefficient  $C_p^{\text{LOM}}(X^*, t_1)$  and  $C_p^{\text{LOM}}(X^*, t_2)$  for which  $a_p^{(1)}$  are, respectively, maximum and minimum

profile. The distribution  $C_p^{\text{LOM}}(X^*, t_1)$ , for which  $a_p^{(1)}$  is maximum, is lower than the time-averaged pressure coefficient in the first part of the mean recirculated zone  $(X^*/X_r^* < 0.4)$  and greater in the second part  $(X^*/X_r^* > 0.4)$ , whereas the distribution  $C_{p}^{\text{LOM}}(X^*, t_2)$ , for which  $a_p^{(1)}$  is minimum, is greater in the first part and lower in the second part. From a physical point of view, this mechanism presents strong similarities with the observations of Kiya and Sasaki (1985) explaining the influence of the global flapping of the 2D recirculated zone on the wall pressure distribution. Thus, when the shear layer moves from its mean position toward the slanted surface ("shrinkage" mechanism of the separation bubble), the longitudinal velocity near the separation point increases because of an increased curvature of the shear layer, leading to a lower static pressure compared to the mean value. Since the flow reattaches during this shrinkage mechanism, the second part of the slanted surface is characterized by a higher level of static pressure than its mean distribution. Inversely, when the shear layer moves outwards from its mean position ("enlargement" mechanism of the separation bubble), a decrease in the shear layer curvature leads to higher static pressure near the separation point. Since the flow becomes fully separated, the static pressure is lower in the second part of the slanted surface compared to the mean pressure distribution. Consequently, the distributions  $C_{p}^{\text{LOM}}(X^*, t_1)$  (maximum of  $a_p^{(1)}(t_i)$ ) and  $C_{p}^{\text{LOM}}(X^*, t_2)$  (minimum of  $a_p^{(1)}(t_i)$ ) correspond, respectively, to the reduced and the enlarged state of the recirculated zone, which indicates that the first POD mode of pressure fluctuations is associated with global flapping. Moreover, since the first POD mode of pressure fluctuations is representative of the low frequency

activity (Sect. 4.2), it can be concluded that the temporal periodicity between two reduced states or enlarged states corresponds to the Strouhal number  $St_{X_{*}}^{1} = 0.11$ .

### 5 Conclusion

An experimental characterization of the unsteady mechanisms related to the 3D separation bubble that develops on the rear slanted surface of the Ahmed model with a slant angle of 25° has been performed using PIV, 1D hot wire anemometry, and unsteady pressure transducers. The objectives of this investigation were to locate and identify the different unsteady activities that could be encountered in the near wake of the 3D recirculated zone and to provide physical understanding of these different type of unsteadiness by extracting characteristic representations of the flow dynamics. This study was more particularly based on the well-known unsteady mechanisms of 2D separated and reattaching flows with the aim to demonstrate significant similarities with the present 3D separation bubble, and to confirm experimentally previous conclusions of LES investigations of the flow around the Ahmed body performed by Howard and Pourquie (2002), Krajnović and Davidson (2005) and Minguez et al. (2008). In the interests of simplification so as to provide a preliminary physical understanding of unsteady mechanisms, all measurements and analyses were performed in the median plane of the 3D separation bubble.

The spectral analysis of velocity and wall pressure fluctuations has shown that unsteady activities of the separation bubble are governed by a low frequency activity associated with a Strouhal number based on the mean reattachment length of  $St_{X_r^*} = 0.11$ , and a high frequency activity associated with a Strouhal number of  $St_{X^*}$  = 0.6 - 0.7. These Strouhal numbers are very similar to those observed for 2D recirculating zones that are commonly associated with a flapping motion of the shear layer and a large-scale vortex emission. The analysis of cross-spectra of wall pressure fluctuations has more specifically demonstrated that the low frequency activity corresponds to an absolute unsteadiness while the high frequency activity is convective. The estimation of the convection velocity from the linear slope of the phase function showed that the high frequency unsteadiness is convected with a velocity of 0.67 times the streamwise velocity. Moreover, the Strouhal number based on this convection velocity and the measured vorticity thickness is  $St_{\delta_{\omega}} = 0.2$ , as has been pointed out in the literature for 2D mixing layers and is associated with Kelvin-Helmholtz instabilities.

The application of proper orthogonal decomposition to the instantaneous velocity fields and wall pressure

distributions has provided a preliminary physical understanding of these spectral activities. It has demonstrated that the low frequency unsteadiness can be reconstructed with only the first POD mode, which is associated with global fluctuations of the streamwise component of the velocity inside the recirculated zone. The low-order modeling of instantaneous velocity fields and wall pressure distribution by using the first POD mode has finally showed that the low frequency activity is indeed associated with a flapping motion of the separation bubble, moving from a reduced state to an enlarged state, that leads to significant velocity and static pressure fluctuations. Concerning the high frequency unsteadiness, it has been shown that it can be reconstructed from the summation of higher-order POD modes but a cutoff number must be defined to effectively separate the high frequency unsteadiness from the turbulent motion. However, POD modes of velocity fields have demonstrated that from the second POD mode on, the velocity fluctuations are mainly characterized by fluctuations of the cross-wise component. These fluctuations are alternately positive and negative, which is the characteristic of large vortex emission. Moreover, it has been shown that a parity rule is observed between successive POD modes which describes and confirms the convective nature of the unsteadiness. In addition, the characteristic frequency of the high frequency unsteadiness can be recovered from the half wave length measured between each successive alternation and the estimated convection velocity from the cross-spectral analysis.

All of these results are thus consistent with the numerical results of Howard and Pourquie (2002), Krajnović and Davidson (2005) and Minguez et al. (2008), concerning the flow around the rear part of the Ahmed body. It provides experimental confirmation of the existence of vortex emission from the shear layer and a flapping motion of the separation bubble. Although this investigation has been performed exclusively in the median plane of the separation bubble, it has provided the missing spectral information related to these mechanisms and has allowed their characteristic timescales to be assessed.

## References

- Abdalla IE, Yang Z (1983) Numerical study of the instability mechanism in transitional separating-reattaching flow. Int J Heat Fluid Flow 25:593–605
- Ahmed SR, Ramm R, Falting G (1984) Some salient features of the time averaged ground vehicle wake. SAE technical paper series 840300, pp 1–30
- Aubrun S (1998) Etude expérimentale des structures cohérentes dans un écoulement décollé et comparaison avec une couche de mélange, Thèse doctorat, Institut de Mécanique des Fluides de Toulouse, janvier

- Benedict LH, Gould RD (1996) Towards better uncertainty estimates for turbulence statistics. Exp Fluids 22:129–136
- Bonnet JP, Delville J, Glauser MN et al (1998) Collaborative testing of eddy structure identification methods in free turbulent shear flows. Exp Fluids 25:197–225
- Brown G, Roshko A (1974) The effect of density difference on the turbulent mixing layer. J Fluid Mech 64:775–816
- Cherry N, Hillier R, Latour M (1984) Unsteady measurements in a separated and reattaching flow. J Fluid Mech 144:13–46
- Chun S, Liu Y, Sung H (2004) Wall pressure fluctuations of a turbulent separated and reattaching flow affected by an unsteady wake. Exp Fluids 37:531–546
- Cordier L, Bergmann M (2008a) Proper orthogonal decomposition: an overview, Post-Processing of Numerical and Experimental Data, Von Karman Institute Lecture Series
- Cordier L, Bergmann M (2008b) Two typical applications of POD : coherent structures eduction and reduced order modelling, postprocessing of numerical and experimental data, Von Karman Institute Lecture Series
- Duell EG, George AR (1999) Experimental study of a ground vehicle body unsteady near wake, SAE paper 1999-01-0812
- Gilhome BR, Saunders JW, Sheridan J (2001) Time averaged and unsteady near-wake analysis of cars. SAE paper 2001-01-1040
- Gilliéron P (2002) Contrôle des écoulements appliqué à l'automobile. État de l'art. Flow control applied to the car. State of art. Mécanique Ind 3:515–524
- Hinterberger C, Garcia-Villalba M, Rodi W (2004) Large Eddy simulation of flow around the Ahmed body. In: McCallens R, Browand F, Ross J (eds) Lecture notes in applied and computational mechanics/the aerodynamics of heavy vehicles: trucks, buses, and trains. Springer, Berlin. ISBN 3-540-22088-7
- Howard RJA, Pourquie M (2002) Large eddy simulation of an Ahmed reference model. J Turbul 3(1):12
- Hudy L, Naguib A, Humphreys W (2003) Wall-pressure array measurements beneath a separating/reattaching flow region. Phys Fluids 15:706–717
- Joseph P, Amandolése X, Aider JL (2012) Drag reduction on the 25° slant angle Ahmed reference body using pulsed jets. Exp Fluids 52:1169–1185
- Kiya M, Sasaki K (1983) Structure of a turbulent separation bubble. J Fluid Mech 137:83–113
- Kiya M, Sasaki K (1985) Structure of large-scale vortices and unsteady reverse flow in the reattaching zone of a turbulent separation bubble. J Fluid Mech 154:463–491
- Krajnović S, Davidson L (2005) Flow around a simplified car part 1: large eddy simulation, part 2: understanding the flow. J Fluid Eng 127:907–928
- Largeau J, Moriniere V (2007) Wall pressure fluctuations and topology in separated flows over a forward-facing step. Exp Fluids 42:21–40
- Lee I, Sung H (2001) Characteristics of wall pressure fluctuations in separated and reattaching flows over a backward-facing step. Part I: time mean statistics and cross-spectral analyses. Exp Fluids 30:262–272
- Lumley JL (1967) The structure of inhomogeneous turbulent flows. In: Yaglom AM, Tatarski VI (eds) Atmospheric turbulence and radio wave propagation. Nauka, Moscow, pp 166–178
- Minguez M, Pasquetti R, Serre E (2008) High order large eddy simulation of flow over the Ahmed body car model. Phys Fluids 20:1–17
- Onorato M, Costelli AF, Garrone A (1984) Drag measurement through wake analysis. SAE technical paper series 840302, pp 85–93
- Papamoschou D, Roshko A (1988) The compressible turbulent shear layer: an experimental study. J Fluid Mech 197:453–477

- Rempfer D, Fasel HF (1994) Evolution of three-dimensional coherent structures in a flat-plate boundary layer. J Fluid Mech 260: 351–375
- Sagaut P (2008) Numerical data-processing from validation to physical understanding, post-processing of numerical and experimental data, Von Karman Institute Lecture Series
- Serre E et al (2011) On simulating the turbulent flow around the Ahmed body: a French-German collaborative evaluation of LES and DES. Comput Fluids. doi:10.1016/j.compfluid.2011.05.017
- Sims-Williams D, Duncan B (2003) The Ahmed model unsteady wake : experimental and computational analyses, SAE paper 2003-01-1315
- Sirovich L (1987) Turbulence and the dynamics of coherent structures. Q Appl Math 45:561–590

- Tenaud C, Fraigneau Y, Daru V (2010) Numerical simulation of the turbulent detached flow around a thick flate plate, 6th international conference on computational fluid dynamics, St Petersburg, July
- Thacker A, Aubrun S, Leroy A, Devinant P (2012) Effects of suppressing the 3D separation on the rear slant on the flow structures around an Ahmed body. J Wind Eng Ind Aerodyn 107-108:237–243
- Vino G, Watkins S, Mousley P, Wattmuff J, Prasad S (2005) Flow structures in the near-wake of the Ahmed model. J Fluid Struct 20:673–695