Characterizations of force and pressure fluctuations on real vehicles

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Abstract: Both the unsteady aerodynamics force and base pressure distributions are investigated for four model cars in real flow conditions. The low pass cut-off frequency of the measurements is about 5 Hz which is sufficient to consider the global fluctuations of drag, lift and side forces. The drag fluctuations are very low, they never exceed 1% of the mean drag. A clear correlation is found with the base pressure distribution fluctuations. It is found that the regions of smallest pressure fluctuations on the vehicle base are the most correlated to the drag fluctuations or in other words, the regions of largest pressure fluctuations on the base are not associated with the drag fluctuations. Sideslip effect is studied, and one of the model presented a clear bistable behavior on the lift creating huge fluctuations as investigated in the academic experiment of Grandemange, Gohlke and Cadot, *Physics of Fluids* **25** (2013) 095103.

Keywords: road vehicle aerodynamics; separated flows; three-dimensionnal wake dynamics; bistability; full-scale experiments; drag sources.

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J. Délery retired from ONERA since 2004 after a researcher director carrier in the Department of Fundamental and Experimental Aerodynamics (DAFE). He received the Aerodynamics Award by the American Institute of Aeronautics and Astronautics (AIAA). He is currently playing a major role in the French Aeronautics and Astronautics Association (AAAF) and chairing the scientific committee of the CNRT R2A association.

1 Introduction

Car aerodynamics, and more generally ground vehicle aerodynamics is of major interest for future energy saving developments. Due to severe constraints, such as functional shapes, security, and comfort, vehicles have a large aerodynamics drag. They belong to the so called bluff bodies. There is then a particular interest since the last twenty years to address this problem fundamentally. Flow control involving simplified vehicle such as the Ahmed body [1] has been studied and subjected to flow control in laboratories in order to reduce drag. One objective of the action of the CNRT R2A association [2] is to provide data from real cars [3] and to study possible strategy for drag reduction in the industrial context. It is a complementary and fruitful contribution to the fundamental research if one expects to improve efficiently the aerodynamics of our cars. Recently, Grandemange *et al.*[4] found that the Ahmed body presents multi-stable wake positions thus creating large cross flow forces and additional drag. It appears that this behaviour is much more general than the case of the geometry of the Ahmed body. Similar bistable wake was observed for a double backward facing step geometry [5]. Actually, the existence of bistability is related to the aspect ratio of the blunt trailing edge of the 3D body together with its ground clearance [6]. In car aerodynamics, Lawson *et al.* [7] observed such behaviour for a realistic car model of scale 1/4. However, all these bodies do not correspond exactly to the industrial conditions and one may wonder if such effect is still observable on real cars. Real cars are not fully symmetric, the underbody flow is complex and the air intake system modifies considerably the flow around the vehicle.

The goal of the present work is to investigate the fluctuations of drag and base pressure for four different vehicles. The simple questions we want to answer are the followings. What is the relative drag fluctuations for a car ? How do they correlate to the rear pressure distribution? Are there any global motions of the wake responsible for these fluctuations ? What are those corresponding to low drag events? And eventually, does wake bistability also exist for real cars in real flow conditions ?

2 Experiments

2.1 Facility and car models

The experiments are performed in the full scale wind-tunnel of GIE S2A at Montigny-Le Bretonneux (see [8] for a full description of the tunnel). Briefly, the test section is a 3/4 open jet with a cross-section of 24 m^2. The inlet velocity is set at $U_0 = 33.3$ m/s. The relative velocity fluctuation U_{0rms}/U_0 of the incoming flow is less than 0.05%, where "rms" denotes the classical root mean square of the quantity minus its mean. Four vehicles are tested : Kangoo, 3008, 208, 508. The heights and the widths of the vehicle bases are given in table 1. A wide moving belt is entrained at the wind speed between the four rotating wheels to mimic the road effect.

Figure 1 Rear view of the four tested vehicles with pressure measurements installation. The pressure taps location will be denoted by filled black circles in Fig. 5, 6, 7.

Table 1 Height, H and width, W of the vehicle bases.

	KANGOO	3008	208	508
H (cm)	148	120	114	129
W (cm)	165	170	160	156

2.2 Force and pressure measurements

The facility is equipped with a 6 components strain gages balance. It is generally used to give the mean quantities of forces and momentum. For the present purpose, the measured values are acquired at the sampling frequency of 10 Hz. The response frequency of the system has been roughly estimated by applying different loads (vertical, horizontal and lateral) on the car mounted on the balance. For the three components, F_x (drag), F_y (side) and F_z (lift), the response time is smaller than 0.3 s meaning that the high frequency limit is a bit larger than 3.5 Hz. This might appear low, however it has to be kept in mind that a natural frequency based on a shedding frequency at $St = 0.2$ with a separating distance given by the height of the vehicle gives $3 - 4$ Hz (see [3] for a study of the 3008 and Renault Trafic's wakes). The present time resolution gives access to the flow dynamics at the largest timescale structures of the wake which should be the major contributor to the global fluid force exerted on the car.

Each vehicle has been equipped by about 30 to 40 pressure measurements on the rear, as shown in Fig. 1 in order to obtain an estimate of the base pressure distribution. A pressure scanner ZOC from MESCAN is used. Generally, they are devoted to static pressure

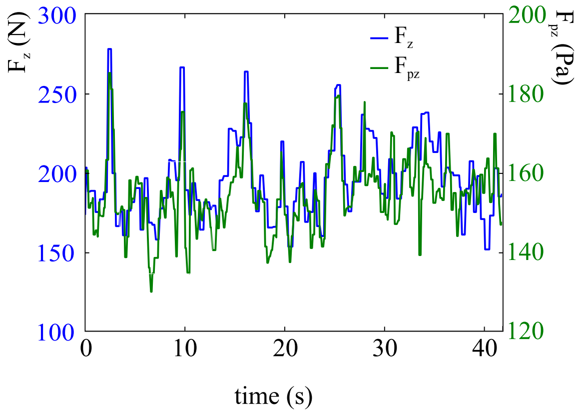

Figure 2 Comparison between the force signal (F_z) and the pressure signal for the Kangoo.

measurements at S2A, but an acquisition at the sampling frequency of 2.5 Hz is performed to obtain pressure time series. Once again, the time resolution has been roughly characterized by imposing an abrupt pressure change on one of the pressure taps mounted on the car. The response time is lower than 0.5 s, meaning that the high cut-off frequency is about 2 Hz.

Fig. 2 shows a sample of the time series of the lift force F_z measured by the balance and a quantity that is only based on the pressure measurements F_{pz}. It is simply computed from the mean pressure difference between the pressure taps located at the extreme top and those at the extreme bottom of the rear of the vehicle. From this figure, the good correlation attests that the balance captures the aerodynamics forces fluctuations in the resolved frequency domain (below few Hz). In addition, there is no observable vibrations on the balance signal due to structural effects.

Next, we present results extracted from long time acquisition (20 minutes) in order to obtain converged statistical properties of the fluctuations.

3 Results

3.1 Drag and base pressure fluctuations of the four car models

The probability density functions (pdfs) of the drag force are measured for the four cars in Fig. 3. The drag fluctuation defined as $F_{xrms}/ < F_x >$ are 1.45% for the Kangoo, 0.67% for the 3008 and 1.06% for the 208 and the 508. The squared shape of the Kangoo explains its large drag fluctuation. The small fluctuations for the monospace type 3008 is surprising. After data postprocessing, we discovered that a low pass filtering with a cut-off frequency of 1 Hz has been inadvertently applied during the test session as can be seen in Fig. 4. However we cannot attest that the reduction of the fluctuations due to the filtering can fully explain the small fluctuation rate of the 3008.

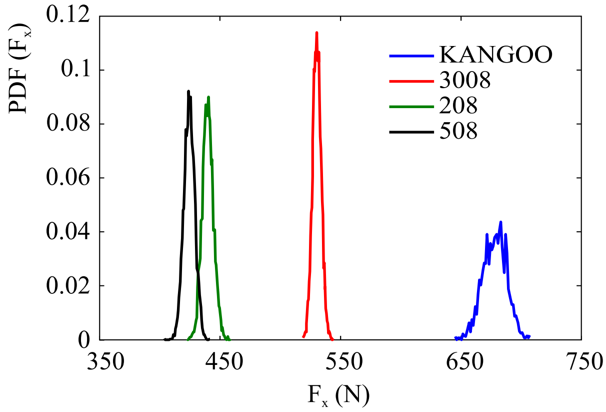

Figure 3 Pdfs of the drag force for the four car models.

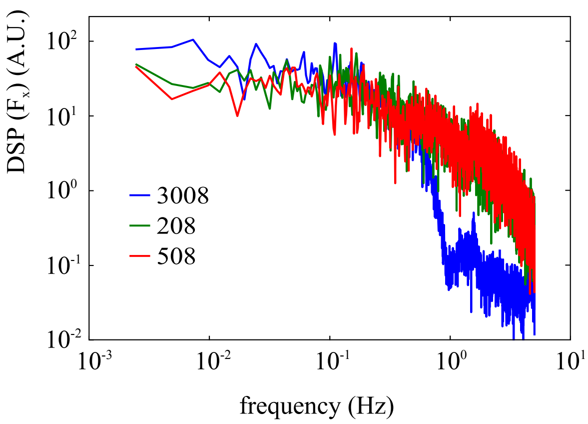

Figure 4 Density power spectra of the drag for the 3008, 208 and the 508. The spectra of the KANGOO is not shown because of a too short acquisition duration.

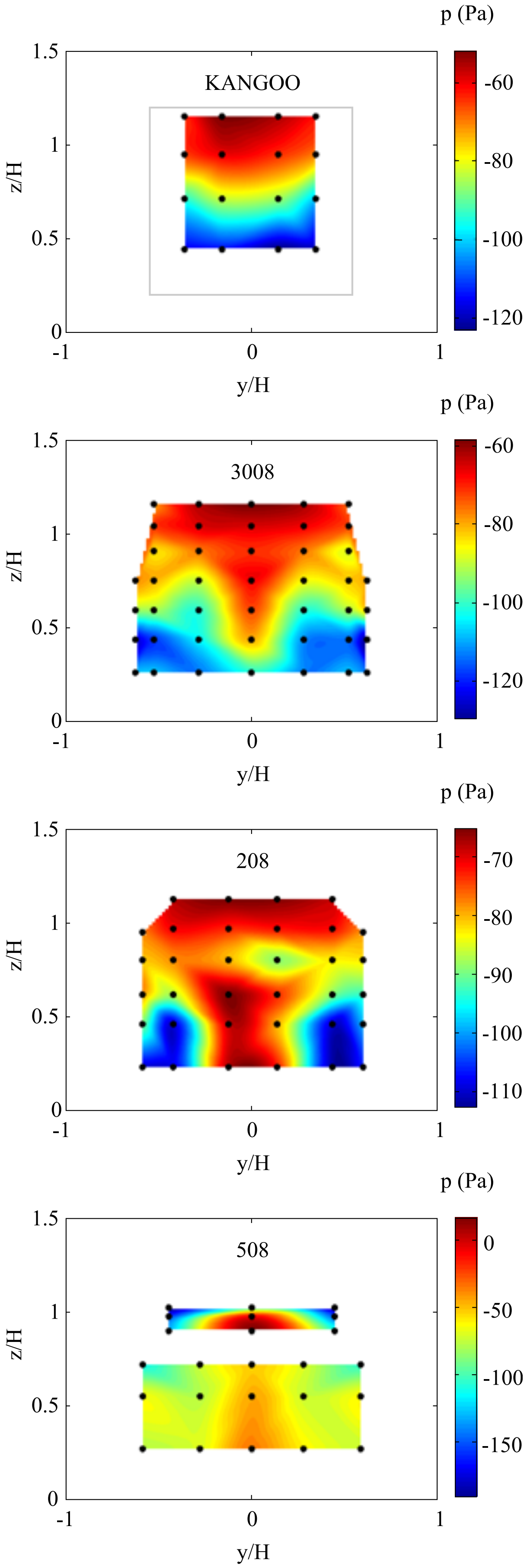

Figure 5 Base pressure measurements of the four car models.

The relevant conclusion is that the drag fluctuations of car models are small, about 1%. These fluctuations are much larger than the wind tunnel main velocity which is about 0.05%. Thus, the drag fluctuations are ascribed to the unsteadiness of the car wake, but remain very small compared to the mean drag of the car.

We turn now to the base pressure measurements. Their mean distributions are shown in Fig. 5 for the four car models. For the three blunt trailing edge models (3008, Kangoo and 208), the pressure is always negative (relatively to the free stream pressure) and the lowest is observed near the bottom. For the 508 having a very different rear shape, there is a positive pressure on the slanted rear window and two regions of very low pressure on both sides. All of these mean pressure distributions are rather symmetric.

The fluctuations of the pressure, denoted p_{rms} are plotted in Fig. 6 for the four vehicles. At first glance, they are very different from each other. The 3008 displays a fine structure associated with the sharp edge design of the back lights. A large fluctuation area is often observed in the centre for the blunt trailing edge car models. No fluctuations are observed on the slanted back window of the 508.

In order to see how these pressure fluctuations are related to the global drag fluctuations, we computed the simple correlation between each pressure taps and the drag F_x. Since low base pressure is a source of large drag, the correlation in Fig. 7 is always negative. The striking result is that the regions of large pressure fluctuations in Fig. 6 do not correspond to regions of large correlation in Fig. 7. It is an indication that some of the large local pressure fluctuations do not participate to global drag because of the averaging effect of pressure on the car. The contributing regions for the drag fluctuations are wider areas, situated at the bottom for the Kangoo, and at the top for the 3008. The asymmetric correlation observed for the 208 can be induced by the air intake system at the car front that is not symmetric. Whatever the vehicle is, the correlation never exceeds -0.3, while one would expect for a simple bluff body, for which the base pressure fluctuation is the main source of drag fluctuation, a correlation close to -1. The discrepancy is a consequence of the complexity of real vehicles, and particularly to the drag contributions that are not the body base such that the underbody roughness and the air intake system. For each of these car models, we investigated the drag fluctuations for various yaw angles. Only the Kangoo model exhibited a very specific feature that is detailed in the next section.

3.2 Force fluctuations of the Kangoo at different yaw angles

The car, the measurements balance and the moving belt are rotated by an angle β in the range $\pm 6°$ by the turntable of the S2A facility to study sideslip effects. The yaw angle β is defined as in Fig. 8.

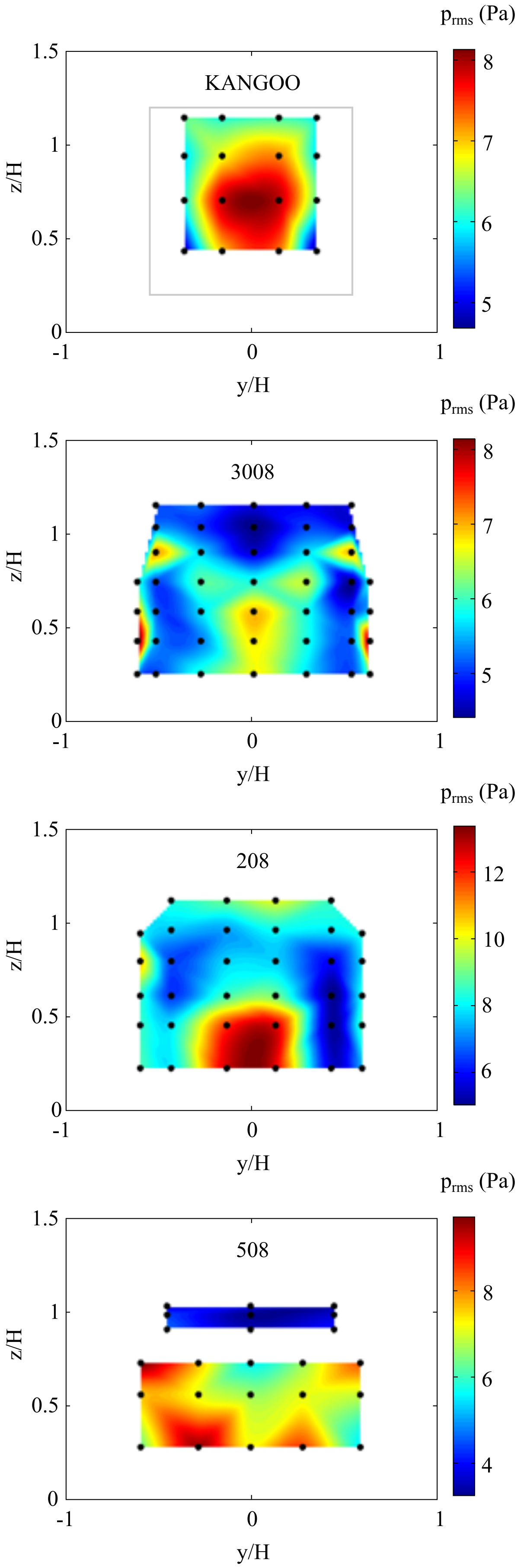

Figure 6 Pressure fluctuations distribution of the four car models.

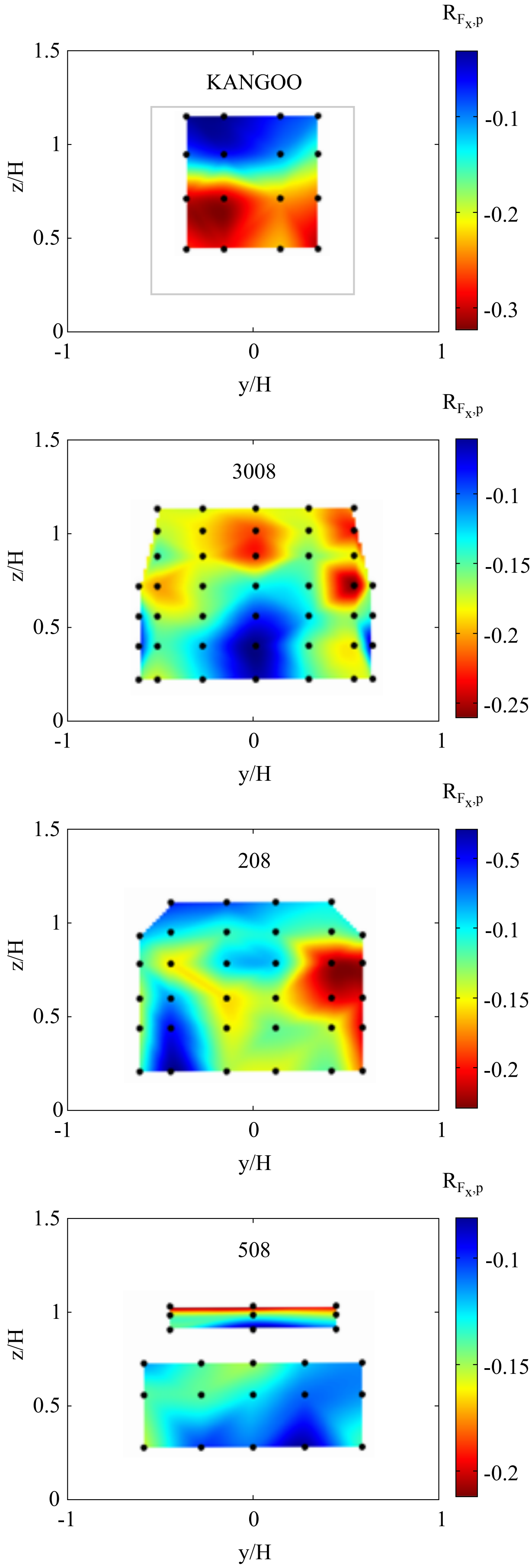

Figure 7 Correlation $R(F_x, p)$ for the four car models.

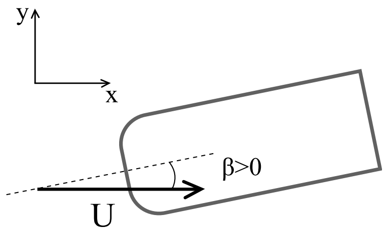

Figure 8 Definition of the yaw angle.

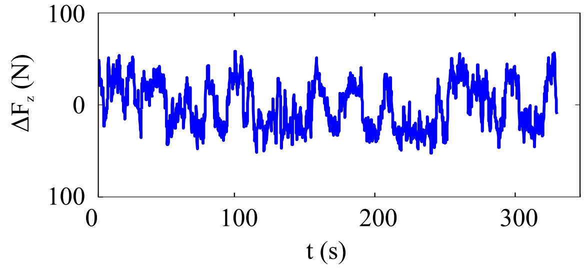

Figure 10 Lift time series for $\beta = +4°$.

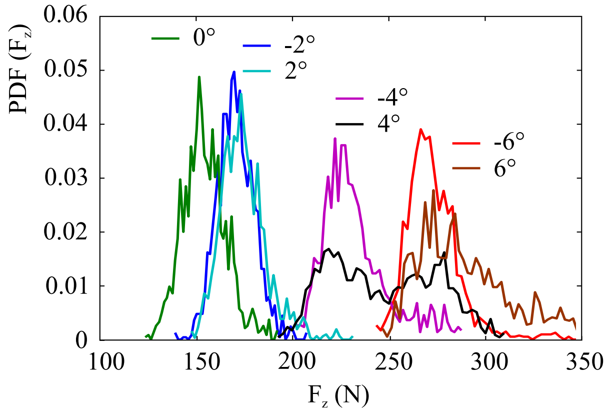

Figure 9 Pdfs of Lift of the kangoo model vs. the yaw angle.

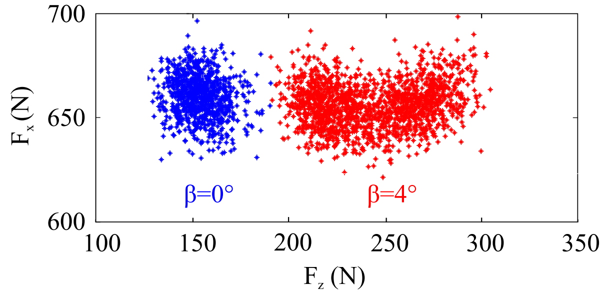

Figure 11 Scatter plot of the drag force F_x vs. the lift force F_z for (blue) the configuration at $\beta = 0°$ and (red) for the bistable case with the yaw angle $\beta = +4°$.

We can see in Fig. 9 that the probability density function of the lift component of the force becomes wider as the yaw angle is increased. At $\beta = +4°$, the distribution has two peaks meaning that there are two most probable states of the wake. When the yaw angle is increased to $\beta = +6°$, it seems that the state having the largest mean lift is selected. For negative yaw angle, the bi-modal distribution is not observed, but the corresponding Pdfs seems to be locked on one of the two preferred states.

This bistable property of the wake has been evidenced in the academic situation by Grandemange *et al.* [4] with perfectly aligned symmetric bodies. Depending on the aspect ratio of the base, the bistable behavior can be either associated to the side force or the lift force [6]. As in Fig. 10, the lift time series indicate that the wake explores randomly a high state or a low state. The typical duration of the time spent in one state is about 20 s, that represents about $350H/U$. This long time dynamics is in agreements with [4]. The yaw angle is then an important factor that contributes to the appearance of the bistability.

Fig. 11 shows the correlation of the instantaneous lift and drag. The two most probable states for the bistable case appears as the two lobes. They both display the same drag in average. However, some events between the two lobes (around $F_x \approx 245$ N) presents lower drag. Then, one can expect that if the bistability was suppressed by stabilising the wake around these mean lift, one would achieve drag reduction.

We made some experiments to test the sensitivity of the bistable wake. First, we increased the back ground clearance (height between the car floor and the road at the location of the back wheels). The back ground clearance affects the mean lift that decreases as can be seen in Fig. 12. Only one peak in the Pdf is observed for larger values of the ground clearance. It might be due to either the permanent selection of one state as a consequence of a larger angle of attack of the car or to the bistability suppression.

We investigated the sensitivity of the bistability by blocking the air intake system with cardboard. By avoiding the air to enter the car intake, the symmetry properties of the flow at the front of the vehicle is modified. In that case the bistable behaviour is suppressed in Fig. 12. Since the air intake system contributes significantly to the total drag, it remains impossible in the present experiment to estimate the drag reduction due to the wake bistability suppression.

4 Discussions and concluding remarks

Fluctuations of forces on four vehicles have been characterized in the frequency domain lower than 10 Hz. Since the resulting fluid force fluctuation on the vehicle is due to the integration (i.e. low pass filtering) of the pressure over the whole shape, its frequency domain

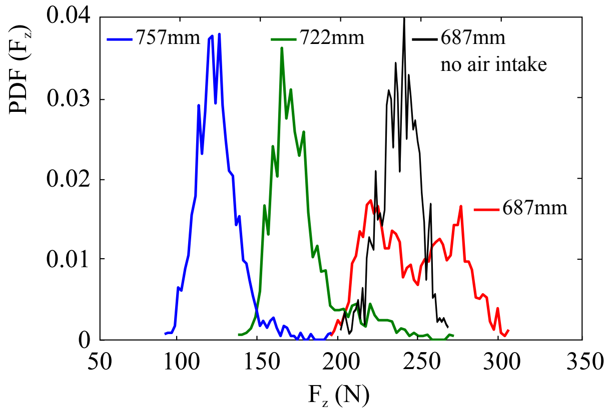

Figure 12 Pdfs of lift fluctuations at $\beta = +4°$ for different back ground clearances. The blocked air intake is only considered for the ground clearance of 687 mm.

results from an equivalent filtering. It is then expected that the force fluctuation should be dominated by the large scale structures, i.e. having lower frequencies than that of the natural shedding frequency estimated around 5 Hz for a car in real flow configuration [3]. The first result is that whatever the car tested, the drag fluctuations never exceeds 1.5% of the mean drag. One then believes that there is no much to gain by trying to control the rare event of large drag fluctuations in order to achieve a mean drag reduction, that would anyway never exceed less the percent. The second result shows the regions on the base of the body that contribute to the total drag fluctuation. There is no general tendency, although it is often observed that the largest pressure fluctuations on the base are not associated with the drag fluctuation. Eventually, bistability is observed for the Kangoo, for a yaw angle around +4°. Its existence is particularly sensitive to the air intake system opening and the ground clearance of the vehicle. The striking result is that bistability of the real car wake exists as evidenced for simplified bodies [4, 6]. In the present configuration it corresponds to a Kangoo driving at 120 km/h with a cross wind of 8 km/h, which is very likely to happen in outdoor conditions. As a consequence, the lift fluctuates over a very long time dynamics with an amplitude of about 60 N. The characteristic time of these fluctuations is two orders of magnitude larger than that of the natural shedding.

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