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Turbulent wake past a three-dimensional blunt body. Part 2. Experimental sensitivity analysis.

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The sensitivity of the flow around the three-dimensional blunt geometry is investigated experimentally at Reynolds number $9.2 \, 10^4$. Vertical and horizontal control cylinders are used to disturb the natural flow which is the superposition of two reflectional symmetry breaking states (Grandemange *et al.* 2013*b*). When the perturbation breaks the symmetry of the set-up, it can select one of the two asymmetric topologies so that a mean side force is reported. When the reflectional symmetry is preserved, some positions of horizontal and vertical control cylinders alter the natural bi-stability of the flow which may result in drag reduction. In addition, it is found that the horizontal perturbation affects the lift force especially when the top and bottom mixing layers are disturbed. The ability of the disturbances to suppress the bistable behavior is discussed and, introducing a formalism of induced drag, a quantification of the impact on the drag of the cross-flow forces observed for the natural bistable wake is suggested. Finally, a general concept for control strategy of separated flows past three-dimensional bluff bodies can be drawn from these analyses.

1. Introduction

In the transport industry, economical and environmental issues on energy consumption are motivating research activities to limit the drag of road vehicles. The objective is to develop efficient strategies of shape optimization or flow control. Due to their functional shapes, the geometries are bluff from an aerodynamic point of view and the flow is separated on the after-body. In order to achieve the drag reductions needed by industry, the comprehension of such flows should be investigated for simplified three-dimensional geometries.

An important work is devoted to the axisymmetric configurations (spheres, disks and bullet shaped bodies) for which steady and unsteady global modes are evidenced, both experimentally (Magarvey & Bishop 1961; Sakamoto & Haniu 1990; Ormières & Provansal 1999; Siegel *et al.* 2008; Szaltys *et al.* 2012) and numerically (Fabre *et al.* 2008; Pier 2008; Meliga *et al.* 2009*a*). When the Reynolds number increases in the laminar regime, a pitchfork bifurcation leads to a steady flow that breaks the axisymmetry; then, after a second bifurcation, an unsteady antisymmetric mode associated with the shedding of vortex loops appears in the wake. The numerical results of Pier (2008) highlight the impact of these symmetry breaking modes on the fluid forces: after the axisymmetry

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breaking of the sphere wake at Reynolds number 210, he reports the emergence of a side force and of an additional drag which is responsible for approximately 10% of the total drag at Re = 350.

In parallel, theoretical developments allow the structural sensitivity of global mode wakes to be obtained in the laminar regime (Hill 1992; Marquet *et al.* 2008; Luchini *et al.* 2009). This approach is able to recover qualitatively the experimental sensitivity maps of Strykowski & Sreenivasan (1990) over bi-dimensional geometries. Extending the method to the turbulent flow around a "D" shaped cylinder at Re = 1.3 10^4, Meliga *et al.* (2012) present a sensitivity map of the global mode frequency that is in good agreements with the experimental results of Parezanović & Cadot (2012), both in terms of spatial distribution and amplitude. The modifications induced by the perturbation are related to the introduction of a stagnation point in the main wake. This generates vorticity in the flow, whose interaction with the main flow vorticity is at the origin of the sensitivity (Parezanović & Cadot 2009). It appears that the particular feature of the vorticity, *i.e.* the possible presence of vortex shedding downstream of the disturbance, is not relevant; for example, Meliga *et al.* (2012) model the perturbation by a steady local forcing in the main wake. This approach appears as a useful tool in the framework of flow control since it predicts where a disturbance efficiently affects global properties such as drag or global mode frequency. Thus, for practical and industrial interests, the method should be extended to larger Reynolds number flows over more complex geometries. The identification of the sensitive regions in the flow should help to define efficient strategies of drag reduction that could be performed, in a second step, using realistic control devices such as surface mounted actuators.

Previous control experiments of axisymmetric turbulent wakes address the development of the unsteady modes, showing connections between the control parameters, the activity of the mode and the drag (Berger *et al.* 1990; Weickgenannt & Monkewitz 2000; Sevilla & Martinez-Bazan 2004; Higuchi 2005; Morrison & Qubain 2009). However, in most of these cases, the control techniques cannot be considered as perturbations. Now, by placing small control obstacles downstream of axisymmetric bodies, some experiments explore the sensitivity of the flow to steady local disturbances. First, one can refer to the work of Grandemange *et al.* (2012b) who consider the case of an axisymmetric bullet shaped body; due to the $m = 2$ azimuthal periodicity of the support, the wake presents two preferred orientations leading to a bistable flow. The results prove that the coexistence of the two asymmetric states is strongly affected by any antisymmetric perturbation. Moreover, these experiments confirm the sensitivity of the center of the recirculation bubble in which the bi-stability is suppressed together with a drag reduction. In this region, the perturbation seems to control the reminiscences of the steady axisymmetry breaking mode whose theoretical sensitivity is given in Meliga *et al.* (2009b) for a sphere and a disk.

Similar bistable wakes can equally be reported for flows past more complex geometries with only one reflectional plane of symmetry. It has been observed in the separated flows over the rear window of a notch-back vehicle (Lawson *et al.* 2007) or past a three-dimensional double backward facing step (Herry *et al.* 2011). High degrees of asymmetry have also been obtained in experiments and numerical simulations of the flow past three-dimensional geometries despite the symmetry of the set-up (Lee *et al.* 2009; Wassen *et al.* 2010); they might be the signature of a comparable instability. Analogous dynamics in the natural wake past the reference Ahmed geometry (Ahmed *et al.* 1984) are also reported in Grandemange *et al.* (2013b). In that particular case, the wake presents two different time scales.

• At short timescales $T_s \sim 5H/U_0$, weak coherent oscillations in the vertical and lateral directions are reported; they are associated with the interaction of the facing shear layers.

• At long timescales $T_l \sim 10^3 H/U_0$, the recirculation region shifts between two preferred reflectional symmetry breaking positions, the equiprobability of the two states leading to a statistical symmetric wake. The succession of these two asymmetric states is random and results in an unsteady side force that overall average is zero. This phenomenon is independent of the Reynolds number; it is ascribed to the emergence of a steady reflectional symmetry breaking mode in the laminar regime (Grandemange *et al.* 2012*a*). Indeed, at Re $= U_0 H/\nu = 340 \pm 10$, H being the height of the base, the wake undergoes a pitchfork bifurcation from a trivial steady symmetric state to a steady asymmetric regime. The generality of such cross-flow instabilities is proved by the wide domains of appearance identified in Grandemange *et al.* (2013*a*).

In this framework, the present study explores the sensitivity of the flow past the square-back model used in Ahmed *et al.* (1984). These experiments complete the analysis of the natural wake provided in Grandemange *et al.* (2013*b*). The objective is to clarify how a local disturbance affects the global properties of the flow with a particular focus on its bistable characteristic.

The article is organized as follows. In section 2, the experimental set-up and measurements are presented. Section 3 is devoted to the results: analysis of the effects of vertical and horizontal control cylinders. The ability to suppress the bi-stability as well as the link between the drag and the cross-flow forces are discussed in section 4. Finally, concluding remarks are presented in section 5.

2. Experimental set-up

The experimental facilities are identical to Grandemange *et al.* (2013*b*). The geometry and the disturbance set-up are successively presented and the measurements of pressure, force and velocity are detailed.

2.1. *Geometry*

The experimental set-up is illustrated in figure 1. A ground plate is placed in an Eiffel type wind tunnel to form a 3/4 open jet facility (open test section on the sides and on the top). The turbulent intensity is less than 0.3% and the homogeneity of the velocity over the 390 mm × 400 mm section is 0.4%. The wake is generated by the square-back geometry used in the experiments of Ahmed *et al.* (1984) at scale 1/4. The total length of the body is $L = 261.0$ mm, the height H and width W of the base are respectively 72.0 mm and 97.2 mm. The four supports are cylindrical with a diameter of 7.5 mm and the ground clearance is $C = 12.5$ mm to match the reference experiments. The blockage ratio is less than 5%. The coordinate system is defined as x in the streamwise direction, z normal to the ground and y forming a direct trihedral.

In order to have constant flow conditions, the ground plate is placed at 10 mm above the bottom side of the inlet (see figure 1a) and triggers the turbulent boundary layer, without any separation, 140 mm upstream of the fore-body. When the body is not in the test section, the thickness of the ground boundary layer based on 99% of the free-flow velocity at $x = -L$, *i.e.* 140 mm downstream of the leading edge, is $\delta_{0.99} = 6.3$ mm with a precision of 0.1 mm; the displacement and momentum thicknesses are 0.89 ± 0.05 mm and 0.60 ± 0.02 mm respectively.

FIGURE 1. Experimental set-up: side view (*a*), top view (*b*) and perspective view (*c,d*) disturbed by a vertical control cylinder (*c*) and an horizontal control cylinder (*a,b,d*); gray dots are pressure taps, they are distributed symmetrically referring to the planes $y^* = 0$ and $z^* = 0.67$ (mid-height of the body); O sets the origin of the coordinate system.

The main flow velocity is $U_0 = 20$ m s^{-1} and the Reynolds number is Re $= U_0 H/\nu = 9.2 \ 10^4$. The velocities are defined as $\vec{u} = u_x.\vec{e_x} + u_y.\vec{e_y} + u_z.\vec{e_z}$; $u_{ij} = \sqrt{u_i{}^2 + u_j{}^2}$ is the amplitude of velocity at the considered point in the plane $(\vec{e_i}, \vec{e_j})$. A (or $\langle a \rangle$) and $Std(a)$ are respectively the average value and the standard deviation of any quantity a; $a' = a - A$ is the fluctuating part of a. In the following, a_n stands for the natural value of a (characterized in Grandemange *et al.* 2013*b*). The height H of the base, density ρ and inlet velocity U_0 are used to obtain non-dimensional values marked with an asterisk.

2.2. *Disturbance apparatus for the sensitivity analysis*

The sensitivity analysis presented in the following is based on the experimental work of Parezanović & Cadot (2012) in a bi-dimensional configuration. In this previous study, the flow is found sensitive when the control cylinder disturbs the shear layers. Given the parallelepiped shape of the present geometry and the shear layer interactions reported in the natural wake (Grandemange *et al.* 2013*b*), the direct extension of the work of Parezanović & Cadot (2012) consists in disturbing the lateral mixing layers or the top and bottom ones. Hence, it appears suitable to use small vertical and horizontal control cylinders placed around the after-body as displayed in figure 1. Their lengths are logically equal to the height or the width of the body (see figures 1*c,d*).

Besides, in Parezanović & Cadot (2012), two different rod sizes are used; they correspond to $0.04D$ and $0.12D$ which should be compared to the initial thickness of the shear layer of $0.05D$, D being the main cylinder diameter. It is found that the smaller control cylinder can be considered as a disturbance while the larger one induces important modifications of the main flow features. Thus, the perturbation assumption remains relevant as soon as the control rod is smaller than the disturbed shears. In the present configuration, the diameter of the cylinders is $d = 4$ mm, *i.e.* $d/W = 4.1\%$ and $d/H = 5.5\%$. This cylinder diameter corresponds to a compromise between the perturbation assumption and the amplitude of the measurable effect on the flow. As the initial thickness of the shear is of order of $0.03H$ (Grandemange *et al.* 2013*b*), the cylinders may be too big to be considered as local disturbance in the very near wake. Nevertheless, as soon as $x > 0.2H$, the shear layers of the natural flow are larger than $0.05H$ and the perturbation assumption becomes sustainable.

The vertical rod is moved in the x and y directions whereas the horizontal one is moved in the x and z directions; their positions are denoted by (x_C, y_C) and (x_C, z_C) respectively. The disturbance location is controlled by a three-dimensional displacement system made up of three Newport (M-)MTM long travel consoles and controlled by the Newport Motion Controller ESP301; the precision of the robots is better than 0.1 mm. The disturbances are automatically displaced over a matrix by steps of $\Delta_x = 3$ mm in the streamwise direction and of $\Delta_y = \Delta_z = 1$ mm in the cross-flow directions, *i.e.* $\Delta_x{}^* = 0.042$ and $\Delta_y{}^* = \Delta_z{}^* = 0.014$. The explored domains are $(x_C{}^*, y_C{}^*) \in [0.21, 1.67] \times [-0.97, 0.97]$ and $(x_C{}^*, z_C{}^*) \in [0.21, 1.67] \times [0.15, 1.30]$. As a result, the full exploration of the wake by one disturbance typically needs more than 100 positions in the cross-flow direction and 35 in the x direction.

The cylinders are held by 0.5 mm steel wires oriented along y (one wire for the horizontal cylinder and two wires for the vertical one) in such a way that they are aligned with the base of the body. The supporting wires are sufficiently stretched to have vibra-

tion amplitudes that are negligible compared to d. Additional tests with only the 0.5 mm wires have been performed to verify that their influence is at least one order of magnitude smaller that the one of the main control cylinders.

The construction of sensitivity maps are based on global quantities of the flow. Before detailing their measurements in sections 2.3 and 2.4, it is crucial to distinguish two different approaches in this work.

• First, the construction of the sensitivity maps corresponds to a statistical approach. They are obtained after the systematic displacement of the disturbance in the wake and, for each position, the data is recorded for 60 s. This is too short to obtain converged values of mean and standard deviation, especially considering the long time dynamics of the bi-stability. These 60 s are limited by the total duration of an experiment which already lasts for two days. As a result, these sensitivity maps are only relevant as a whole and the accuracy of the associated data is visible through the dispersion of points in the scatter plots presented in the following.

• In addition, some specially control cylinder positions are studied in details in sections 3.1. They are associated with converged measurements, performed over 500 s. The accuracy of the data is identical to the natural case detailed in Grandemange *et al.* (2013*b*).

2.3. *Pressure measurements*

The pressure on the body is measured at 62 locations (see gray dots in figures 1*c*,*d*). The taps are distributed symmetrically referring to the planes $y^* = 0$ and $z^* = 0.67$, the latter plane corresponding to the mid-height of the geometry. 21 taps are located on the base of the body; 41 others give the pressure distribution on the forebody and on the sides in the planes $y^* = 0$ and $z^* = 0.67$. The pressure is obtained using a 64 port HD miniature pressure scanner and a SCANdaq 8000 interface connected to a PC with Labview software. The scanner measures the pressure at 1 Hz, as an average over the considered second, with an accuracy better than 3 Pa. Hence, these measurements only catch the long time dynamics of the signal, at time scales larger that 1 s. They are denoted c_p in opposition to the mean pressure coefficient $C_p = \langle c_p \rangle$; similarly, $Std(c_p)$ corresponds to the standard deviation of the 1 Hz measurement.

The pressure scanner is located inside the model; it is denoted "P scan" in figures 1(*a*,*b*). It is linked to each tap with less than 250 mm of vinyl tube to limit the filtering effect of the tubing. This device is connected to the measurement chain using a wire going through a front support of the model so that, apart from the supports, nothing disturbs the underbody flow.

2.4. *Force measurements*

The dimensionless coefficient c_i of the aerodynamic force f_i in the i direction is defined according to equation (2.1) using $S = 7.19 \ 10^{-3}$ m², the projected area of the geometry in a cross-flow plane.

$$c_i = \frac{f_i}{\frac{1}{2}\rho S U_0{}^2},\tag{2.1}$$

with $i \in \{x, y, z\}$.

The pressure contribution to the aerodynamic force in the i direction, denoted c_{ip}, is estimated by integration of the pressure projected in the considered direction as defined in equation (2.2).

$$c_{ip} = \frac{1}{S} \int_{body} c_p \, \vec{e_i} \cdot \vec{ds},\tag{2.2}$$

with $c_p = \frac{p-p_0}{\frac{1}{2}\rho U_0{}^2}$ and $i \in \{x, y, z\}$.

Unlike the experiments of Grandemange *et al.* (2013*b*), the balance measurements are not used. As the sensitivity analyses need a continuous blowing of the wind tunnel for two days, there is an important daily drift of the balance signal, essentially due to temperature variations. Moreover, preliminary tests have shown that the balance-based and pressure-based sensitivity maps present identical trends: they contain the same information. As a result, the forces are estimated from the pressure measurements only. Using the formalism presented in section 2.3, c_{ip} refers to the force measurement at 1 Hz, in opposition to $C_{ip} = \langle c_{ip} \rangle$ which is the time averaged pressure force.

2.5. *Particle image velocimetry*

Finally, wake analyses are made from particle image velocimetry (PIV). The system is comprised of a DANTEC dual pulse laser (Nd:YAG, 2×135 mJ, 4 ns) and a DANTEC CCD camera (FlowSense EO, 4 Mpx). The set-up acquires image pairs at a rate of 2 Hz; each acquisition records 500 image pairs. The size of the interrogation window is 32×32 pixels with an overlap of 25%. The measurements are performed in planes $y^* = 0$ and $z^* = 0.6$. The 32×32 pixels of the interrogation window correspond to physical sizes of 1.5×1.5 mm in the plane $y^* = 0$ and of 1.8×1.8 mm in the plane $z^* = 0.6$. The mean velocities are estimated from the valid vectors of the instantaneous velocity fields; these statistics are taken into account only when more than 50% of valid vectors are obtained from the 500 measurements.

From these velocity fields, the length of the recirculation region L_r is obtained as the maximal streamwise position of the dividing streamlines of the recirculation bubble. Note that the plane at $z^* = 0.6$ correspond to the z coordinate of the closure of the natural recirculation bubble (Grandemange *et al.* 2013*b*). Hence, both planes at $y^* = 0$ and $z^* = 0.6$ allow the measurement of L_r.

3. Results

As presented in Grandemange *et al.* (2013*b*), the natural wake presents two preferred reflectional symmetry breaking positions; each asymmetric state is associated with a diagonal recirculating flow and a base pressure gradient in the y direction: $\partial C_p/\partial y^* = \pm 0.17$. The states are denoted #P and #N for the positive and negative gradients respectively. The succession of the states is random and the equiprobability of the two asymmetric topologies leads to a symmetric mean flow; the bi-stability is characterized by the presence of two maxima in the probability distribution of $\partial c_p/\partial y^*$, centered on ± 0.17.

3.1. *Disturbed wake*

The disturbed flow for four typical cases of the vertical and horizontal control cylinder positions are first investigated. The analysis of these configurations is performed through PIV and pressure measurements. The corresponding velocity fields and statistics of $\partial c_p/\partial y^*$ are given in figure 2 (resp. figure 3) while the relevant quantities are listed in table 1 (resp. table 2) for the vertical control cylinder (resp. horizontal control cylinder).

The equiprobability of the states #P and #N relies on the symmetry of the set-up. As soon as the vertical control cylinder is out of the plane of symmetry, *i.e.* $y_C{}^* \neq 0$, there is no reason for the flow to be symmetric. Figures 2(*a*,*b*) present the mean velocities in the plane $z^* = 0.6$ and the base pressure statistics for the cylinder positions V_a and V_b. For the position V_a, the state #N of the flow is selected (see figure 2*a*): the wake is clearly

FIGURE 2. Velocity fields in the plane $z^* = 0.6$ (left) and probability distributions of the base pressure gradient in the y direction (right) for different positions of the vertical control cylinder: V_a for $x_C^* = 0.29$ and $y_C^* = -0.60$, (a); V_b for $x_C^* = 0.79$ and $y_C^* = -0.40$, (b); V_c for $x_C^* = 0.71$ and $y_C^* = 0$, (c); V_d for $x_C^* = 1.37$ and $y_C^* = 0$, (d). Pressure measurements are performed over 500 s to obtain converged statistics. In the PIV, the missing data correspond to cylinder shadows and laser reflections; crosses are saddle points.

Pos.	x_C^*	y_C^*	$\frac{\partial C_p}{\partial y^*}$	$Std\left(\frac{\partial c_p}{\partial y^*}\right)$	C_{xp}	C_{yp}	C_{zp}	C_{pb}	L_r^*
Natural‡			0.01	0.15	0.206	0.00	−0.08	−0.185	1.47
V_a	0.29	−0.60	−0.15	0.03	0.206	0.02	−0.08	−0.188	1.52
V_b	0.79	−0.40	0.16	0.02	0.205	−0.02	−0.09	−0.186	1.53
V_c	0.71	0	−0.02	0.08	0.194	0.00	−0.08	−0.175	1.57
V_d	1.37	0	−0.01	0.15	0.205	0.00	−0.09	−0.186	1.46
Accuracy			±0.01	±0.01	±0.005	±0.01	±0.01	±0.003	±0.01

TABLE 1. Global properties of the natural and disturbed wakes for four different positions of vertical control cylinder. ‡Data from Grandemange *et al.* (2013*b*).

FIGURE 3. Velocity fields in the plane $y^* = 0$ (left) and probability distributions of the base pressure gradient in the y direction (right) for different positions of the horizontal control cylinder: H_a for $x_C^* = 0.37$ and $z_C^* = 1.17$, (a); H_b for $x_C^* = 0.58$ and $z_C^* = 0.25$, (b); H_c for $x_C^* = 0.71$ and $z_C^* = 0.21$, (c); H_d for $x_C^* = 1.00$ and $z_C^* = 0.60$, (d). Pressure measurements are performed over 500 s to obtain converged statistics. In the PIV, the missing data correspond to cylinder shadows and laser reflections; crosses are saddle points.

oriented toward the domain $y^* < 0$; the mean diagonal recirculating flow corresponds to the presence of a single peak in the probability distribution of the base pressure gradient $\partial c_p/\partial y^*$ centered on -0.16 ± 0.01. An almost mirror image of figure 2(a) is produced in figure 2(b) which shows that the state #P is dominant for the position V_b: the wake is oriented toward the domain $y^* > 0$, the diagonal recirculating flow is associated with the maximum in the probability distribution of $\partial c_p/\partial y^*$ centered on 0.16 ± 0.01. As a result, when $y_C^* \neq 0$, the vertical disturbance can select one asymmetric state; the selected state depends not only on the sign of y_C^* but also on the streamwise position x_C^* of the disturbance. It can be seen that the base pressure and the pressure drag measured for these cylinder positions are very similar to the natural case indicating that there is no drag evolution (see table 1): the main effect of the disturbance is the selection of one asymmetric state.

The two other positions of the vertical control cylinder in figures 2(c,d) preserve the reflectional symmetry of the set-up and so, the observed flow is symmetric. For V_c, there is no clear asymmetry in the probability distribution of $\partial c_p/\partial y^*$ (see figure 2c) meaning that the bistable behavior of the flow is altered. This configuration is associated with base pressure recovery and a drag reduction of 5.8% (see table 1) while an increase in the recirculation length is observed. For the position V_d, the perturbation has no significant effect on the flow. The base pressure is equal to the natural value and the two peaks in the probability distribution of $\partial c_p/\partial y^*$ are recovered: the two states #P and #N coexist. The lift force measured for the four configurations is very close to the natural value (see table 1). Thus, the vertical control cylinder does not seem to affect the pressure distributions on the upper and lower sides of the body.

Pos.	$x_C{}^*$	$z_C{}^*$	$\frac{\partial C_p}{\partial z^*}$	$\mathcal{A} = \sqrt{\langle \frac{\partial c_p}{\partial y^*}^2 \rangle}$	C_{xp}	C_{zp}	C_{pb}	$L_r{}^*$
Natural‡			-0.02	0.15	0.206	-0.08	-0.185	1.47
H_a	0.37	1.17	-0.08	0.06	0.193	-0.06	-0.172	1.54
H_b	0.58	0.25	-0.01	0.07	0.196	-0.09	-0.175	1.54
H_c	0.71	0.21	0.16	0.01	0.234	-0.14	-0.212	0.86
H_d	1.00	0.60	0.01	0.14	0.206	-0.08	-0.188	1.45
Accuracy			±0.01	±0.01	±0.005	±0.01	±0.003	±0.01

TABLE 2. Global properties of the natural and disturbed wakes for four different configurations of horizontal control cylinder. ‡Data from Grandemange *et al.* (2013*b*).

It is now convenient to define an indicator of asymmetry that is independent of the repartition of the two asymmetric states. When the flow is symmetric in average but spontaneously asymmetric because of the bi-stability, the superposition of the two asymmetric states induces important variations of $\partial c_p/\partial y^*$: typically for equiprobable states, $Std(\partial c_p/\partial y^*) \approx 0.16$ while $\partial C_p/\partial y^* \approx 0$. In opposition, when the flow is locked in one of the asymmetric states: $Std(\partial c_p/\partial y^*) \approx 0$ while $\partial C_p/\partial y^* \approx \pm0.16$. Hence, the root mean square of the gradient, denoted $\mathcal{A}$, is used to quantify the degree of asymmetry:

$$\mathcal{A} = \sqrt{\langle \left(\frac{\partial c_p}{\partial y^*}\right)^2 \rangle} = \sqrt{\frac{\partial C_p}{\partial y^*}^2 + Std\left(\frac{\partial c_p}{\partial y^*}\right)^2}. \tag{3.1}$$

In table 1, it can be noticed that $\mathcal{A} > 0.15$ for the configurations V_a, V_b and V_d for which the asymmetric states are observed.

In contrast to the vertical cylinder, the horizontal control cylinder always preserves the reflectional symmetry of the set-up. For positions H_a and H_b in figures 3(*a,b*), the cylinder is located in the inner shear layers developing from the upper and lower side of the geometry respectively. First, for H_a, the top/bottom organization of the recirculation region is significantly modified in comparison to the natural case† which is consistent with the negative value of $\partial C_p/\partial z^*$ (see table 2). On the other hand, the flow modifications for H_b are almost undetectable and $\partial C_p/\partial z^*$ is close to the natural value. However, in both cases, there is an increase in the recirculation lengths and a suppression of the bi-stability. There is only one preferred position centered on 0 visible in the probability distribution of $\partial c_p/\partial y^*$ with $\mathcal{A} \approx 0.07$. In parallel, it is measured that these positions achieve base pressure recovery and up to 6.3% reduction of pressure drag.

At the location H_c in figure 3(*c*), the cylinder is in the outer shear layer coming from the lower side of the geometry. It generates a vertical jet by deviating flow from the mixing layer to the center of the recirculation region. The organization of the near wake is strongly modified. A curved jet develops from the control cylinder and reaches the top of the base. It is associated with the large pressure gradient in the z direction: $\partial C_p/\partial z^* = 0.16$. This control cylinder position is a high drag case ($C_{pb} = -0.212$) which is ascribed to the strong curvature of the jet and the reduced recirculation length. The probability distribution of $\partial c_p/\partial y^*$ shows that the wake is clearly stable in the centered state. For the last case presented, the control cylinder is in the middle of the recirculation

† The natural case detailed in Grandemange *et al.* (2013*b*) is not presented here; to facilitate comparison, it is worth mentioning that the natural wake has similar features to the one presented in figure 3(*d*).

FIGURE 4. Effect of the vertical control cylinder on the pressure on the body: $\partial C_p/\partial y^*$ at $y^* = 0$, (a); C_{yp}, (b); $\mathcal{A}$, (c); C_{pb}, (d). Contour intervals are 0.03 (a), 0.01 (b), 0.02 (c) and 0.005 (d); continuous and dashed line are positive and negative values respectively; contour 0 is not plotted. Thick lines are U_x contours of the natural flow: $\cdots$, $U_x{}^* = 0.1$; —, 0.5; - - -, 0.9.

FIGURE 5. Effect of the horizontal control cylinder on the pressure on the body: $\partial C_p/\partial z^*$, (a); C_{zp}, (b); $\mathcal{A}$, (c); C_{pb}, (d). Contour intervals are 0.03 (a), 0.02 (b), 0.01 (c) and 0.005 (d); continuous and dashed line are positive and negative contours respectively; contour 0 is not plotted. Thick lines are U_x contours of the natural flow: $\cdots$, $U_x{}^* = 0.1$; —, 0.5; - - -, 0.9.

region (position H_d). The bi-stability of the wake is clearly observable and all the global properties listed in table 2 are similar to the natural ones.

3.2. *Sensitivity analysis*

Figure 4 and 5 present the results of the sensitivity analyses obtained for many control cylinder positions in the wake following the methodology described in section 2.2. We first focus on the maps of figure 4 obtained with the vertical control cylinder. Figure 4(a) is the sensitivity map of the mean pressure gradient $\partial C_p/\partial y^*(x_C^*, y_C^*)$ which is a symmetry indicator of the mean recirculation bubble. For $y_C^* \neq 0$, the control cylinder almost always selects a wake orientation depending on its position in both the x and y directions. However, as soon as the symmetry of the geometry is preserved, *i.e.* $y_C^* = 0$, the flow retrieves its reflectional symmetry in average with $\partial C_p/\partial y^* \approx 0$. A second indicator of the flow symmetry is the mean side force which can be estimated from the pressure taps on the lateral sides of the geometry. From these measurements, it is observed that the asymmetric pressure distributions on the base are associated with a force in the y direction (see figure 4b). In most of the control cylinder positions where $|\partial C_p/\partial y^*| > 0.1$, a value of $C_{yp} \approx \pm 0.02$ is measured which corresponds to the side force of the asymmetric states #P and #N of the natural wake. Wherever $\partial C_p/\partial y^* \approx 0$, C_{yp} is equally measured close to 0 which confirms the symmetry of the pressure distribution around the whole geometry.

The sensitivity map $\mathcal{A}(x_C^*, y_C^*)$ is shown in figure 4(c). For most of the locations, $\mathcal{A}$ is close to 0.16. This indicates that either the flow is bistable (for $\partial C_p/\partial y^* \approx 0$) or the asymmetry in the y direction is at least equal to that of states #P and #N. The exceptions are measured in the center of the recirculation bubble, for $x_C^* \approx 0.6$ and $y_C^* \approx 0$. For such positions, the diminution of $\mathcal{A}$ indicates that the bistable behavior is suppressed and like for the configuration V_c (see figure 2c and table 1) these cylinder positions achieve base pressure recovery. The sensitivity map of $C_{pb}(x_C^*, y_C^*)$ in figure 4(d) shows that C_{pb} increases are concentrated around the center of the recirculation region where the symmetry of the flow is preserved and the bi-stability is suppressed. However, when the lateral mixing layers are disturbed, the base pressure tends to decrease. For the other control cylinder positions, C_{pb} is measured close to the natural value of $C_{pbn} = -0.185$.

The results of the sensitivity analysis obtained with the horizontal cylinder are shown in figure 5. As this perturbation preserves the reflectional symmetry of the set-up, both the mean side force and $\partial C_p/\partial y^*$ remain nil for all the disturbance positions. Thus, the considered global quantities are the mean vertical pressure gradient $\partial C_p/\partial z^*$, the degree of asymmetry $\mathcal{A}$, the mean lift coefficient C_{zp} and the base pressure C_{pb}.

The sensitivity map $\partial C_p/\partial z^*(z_C^*, y_C^*)$ in figure 5(a) shows the significant modifications of the pressure gradient when the control cylinder is in the shear layers (as

FIGURE 6. Scatter plots of C_{yp} *vs.* $\partial C_p/\partial y^*$ (a) and of $Std(\partial c_p/\partial y^*)$ *vs.* $\partial C_p/\partial y^*$ (b) for the vertical control cylinder. The dashed line is the linear fit. Crosses are natural values.

FIGURE 7. Scatter plots of $\mathcal{A}$ *vs.* C_{pb} (a) and of C_{xp} *vs.* C_{pb} (b) for the vertical control cylinder. The dashed line is the linear law $C_{xp} = -C_{pb} + 0.018$ (not a fit). Crosses are natural values.

illustrated in figures $3a, b, c$). In the lower shear layer, $\partial C_p/\partial z^* > 0$ and in the upper shear layer, $\partial C_p/\partial z^* < 0$. Elsewhere, the gradient is close to 0 like in the natural case. It is worth noting that this map strongly differs from the one presented in figure $4(a)$ due to the absence of bi-stability in the z direction. Figure $5(b)$ presents the lift modifications sensitivity map $C_{zp}(z_C{}^*, y_C{}^*) - C_{zpn}$, C_{zpn} being the natural lift coefficient. The perturbation of the top and bottom mixing layers induces significant variations: the lift is increased with the cylinder in the upper shear while it is reduced in the lower one. The degree of asymmetry $\mathcal{A}(z_C{}^*, y_C{}^*)$ is presented in figure $5(c)$. When the cylinder is located in the shear layers, $\mathcal{A} < 0.1$ so the bi-stability is suppressed as in figures $4(a,b,c)$. Everywhere else, the measurement of $\mathcal{A} \approx 0.16$ is associated with the cohabitation of the asymmetric states: as for H_d (see figure $4d$), the wake is bistable.

The base pressure in figure $5(d)$ is increased up to 6% when the control cylinder acts on the inner part of the mixing layers in the near wake. However, the lower mixing layer is particularly sensitive as illustrated by the difference observed between H_b and H_c in figure 3.

3.3. *Correlations between the modified global quantities of the wake*

Correlations between the global quantities modified by a same disturbance are informative about the flow physics. We first consider the correlation in figures $4(a,b)$ between the base pressure gradient $\partial C_p/\partial y^*$ and the mean side force C_{yp}. The relationship between these two parameters is presented in the scatter plot in figure $6(a)$: each point corresponds to one position of the vertical cylinder and the data globally follow a linear dependence. It is worth mentioning that, by definition, the evaluation of C_{yp} is performed using exclusively the pressure taps on the sides and on the fore-body whereas $\partial C_p/\partial y^*$ is defined only from the pressure measurements on the base. As a result, the two quantities rely on independent pressure data. One can conclude that the base pressure gradient in the y direction contains the information of the circulation associated with the side force on the geometry.

In equation (3.1), the degree of asymmetry $\mathcal{A}$ is the sum of two terms containing the mean asymmetry of the base pressure $\partial C_p/\partial y^*$ and its fluctuations $Std(\partial c_p/\partial y^*)$. The correlations between these mean and fluctuating contributions are presented in figure $6(b)$. Most of the data are observed on the circle centered on 0 of radius 0.16 ± 0.01, *i.e.* for $\mathcal{A} \approx 0.16$. All the configurations on that circle are wakes with different proportions of states #P and #N. This scatter plot confirms that $\mathcal{A}$ is a relevant parameter to quantify the asymmetry of the near wake. Now, some data are not located on that circle but at a reduced level of $\mathcal{A}$. These points correspond to the cylinder positions close to V_c, in the center of the recirculation region (see figures $2c$ and $4c$). As mentioned in section 3.2, these points are associated with base pressure recovery and then drag reduction (see figure $4d$).

The scatter plot of $\mathcal{A}$ *vs.* C_{pb} is given in figure $7(a)$. There is a high density of points close to the natural levels at $\mathcal{A} \approx 0.16$ and $C_{pb} \approx -0.185$. Some data report significant base pressure decrease ($C_{pb} < -0.19$) for $\mathcal{A} = 0.15 \pm 0.03$: they are associated with the disturbance of the lateral mixing layers. Nevertheless, for $C_{pb} > -0.19$, it is clear that

FIGURE 8. Scatter plots of C_{zp} *vs.* $\partial C_p / \partial z^*$ (*a*) and of C_{zp} *vs.* C_{pb} (*b*) for the horizontal cylinder: black, $\mathcal{A} < 0.1$; red (bright gray), $\mathcal{A} > 0.1$. The dashed line is the linear fit $C_{zp} = -0.083 - 0.26\,\partial C_p / \partial y^*$. Cross is natural value.

there is a correlation between the two quantities: the optimal base pressure recovery corresponds to the minimum level of asymmetry of the recirculation region.

The present experiments show that the average level of base pressure can be considered as a drag indicator. Indeed, there is a strong dependence between base pressure and pressure drag as shown in the scatter plot in figure 7(*b*). Since the evaluation of the pressure drag uses all the taps on the base so that there is, by construction, a certain correlation between these two quantities. However, the affine dependence between C_{xp} and C_{pb} with a slope -1 proves that the disturbance does not affect the pressure distribution on the fore-body: the total pressure drag is the sum of the contribution of the fore-body which is constant at first order and of the base which depends on the control cylinder position.

Similarly, an affine dependence between $\partial C_p / \partial z^*$ and C_{zp} is found in figure 8*a*. The data superimpose on the fit

$$C_{zp} = -0.083 - 0.26\,\frac{\partial C_p}{\partial z^*}. \tag{3.2}$$

In contrast to the dependence between the side force and the pressure gradient in the y direction presented in figure 6(*a*), a negative lift coefficient is obtained for $\partial C_p / \partial z^* = 0$; this point is ascribed to the ground proximity. As a consequence, the pressure gradient in the z direction reproduces the modifications of the lift but the presence of the ground introduces an offset.

The relationship between C_{xp} and C_{zp} is studied using a conditional analysis based on the value of $\mathcal{A}$. In figure 8, degrees of asymmetry with $\mathcal{A}$ larger than 0.1 in red (or bright gray) are associated with bistable flows while the data with $\mathcal{A} < 0.1$ in black correspond to flows without bi-stability. Figure 8(*b*) shows that the bistable data are concentrated around the natural point. In contrast, the stable data are measured over a wide range of base pressures ($C_{pb} \in [-0.22, -0.17]$) presenting a parabolic-like dependence towards the lift coefficient. The positions of base pressure recovery are associated with C_{zp} close to the natural value whereas the base pressure decreases are reported for significant lift modifications and then important recirculation asymmetries in the z direction (large values of $|\partial C_p / \partial z^*|$). These latter cases often correspond to the creation of a curved jet into the recirculation region as visible in figure 3(*c*). More generally, the scatter plot in figure 8(*b*) confirms that the domain of drag reduction associated with the horizontal control cylinder is limited and only correspond to few precise configurations.

4. Discussion

After presenting the probable mechanisms leading to the suppression of the bi-stability in section 4.1, the dependencies between the drag and the cross-flow forces are analyzed in section 4.2. Then, section 4.3 quantifies the drag ascribed to the bi-stability and discusses more generally the suppression of the symmetry breaking modes as a control strategy for drag reduction of three-dimensional bluff bodies.

4.1. *On the suppression of the bi-stability*

In section 3, it is found that the natural bistable behavior of the wake is suppressed by the control cylinders in two different cases:

FIGURE 9. (*a,b*) Domains of vertical control cylinder positioned in the sensitivity maps of C_{yp} and $\mathcal{A}$: —, D_1; - - -, D_2. (*c*) C_{yp} *vs.* C_{xp} for vertical control cylinder positions in the domains D_1 (red or bright gray) and D_2 (black); ×, natural values of the asymmetric states; - - -, 2$^{\text{nd}}$ order polynomial fit.

- for the vertical cylinder in the center of the recirculation, *i.e.* near the case V_c (figure 2*c*);
- for the horizontal cylinder in the top and bottom mixing layers like the configurations H_a, H_b and H_c (figure 3*a, b, c*).

The mechanisms responsible for the suppression of the bi-stability for these configurations may be detailed from the results of Grandemange *et al.* (2013*a*) who investigated the condition of existence of bi-stability through a parametric study of both the base body aspect ratio and the ground clearance height. Indeed, this experimental work evidences that the y instability (responsible for the bi-stability) corresponds to antisymmetric perturbations in the y directions and to symmetric ones in the z directions. From this statement, one can interpret the vertical cylinder in the plane $y^* = 0$ as a symmetric forcing of the flow, maybe due to the boundary condition imposing $u_y{}^* = 0$ on its surface. However, from figure 4(*c*), it is clear that the sensitivity of the flow is not uniform in the plane $y^* = 0$: for example, forcing the symmetry at the end of the recirculation bubble is useless (see configuration V_d in figure 2*d*).

On the other hand, the horizontal cylinder in the top and bottom shear layers is likely to introduce an asymmetry in the z direction, preventing the development of the y instability. This interpretation is confirmed by the comparison of figures 3(*a, c*) to figure 3(*d*). As a result, in these cases, the suppression of the bi-stability seems associated with a breaking of the relative top/bottom symmetry of the recirculation bubble observed in the natural wake.

4.2. *On the drag of the disturbed wakes*

The dependence between the drag and the cross-flow forces are now considered. We first discuss the lateral force and then the lift force before providing a synthesis on the drag contributions.

4.2.1. *Drag due to cross-flow forces*

In section 3.1, it is shown that the vertical disturbance generates modifications of drag and side force while the modifications of lift are negligible. Thus, the data obtained using the vertical disturbance are relevant to study the dependencies between the side force and the drag. To do so, two different domains of disturbance positions are considered:

- the domain D_1 for $(x_C{}^*, y_C{}^*) \in [1.08, 1.46] \times [-0.21, 0.21]$;
- the domain D_2 for $(x_C{}^*, y_C{}^*) \in [0.70, 0.87] \times [-0.49, 0.49]$.

These two domains are presented in figures 9(*a,b*) which are parts of the sensitivity maps of C_{yp} and $\mathcal{A}$ (extracted from figures 4*b,c*). In both domains, when the disturbance goes from the negative to the positive values of $y_C{}^*$, the body undergoes a mean side force from of about -0.025 to $+0.025$ which is imputed to state #P and #N respectively. The difference between both domains lies in the degree of asymmetry $\mathcal{A}$ for $y_C{}^* \approx 0$. In the domain D_1, $\mathcal{A}$ is constant at first order; the position $y_C{}^*$ of the cylinder selects the proportion of the states #P and #N. The equiprobability is obtained for $y_C{}^* = 0$ so that the wake is clearly bistable for $y_C{}^* \approx 0$ (like V_d in figure 2*d*). In the domain D_2, the degree of asymmetry $\mathcal{A}$ diminishes continuously as the mean lateral force tends to 0 and the wake bi-stability is suppressed for $y_C{}^* \approx 0$ (like V_c in figure 2*c*).

FIGURE 10. Scatter plot of C_{xp} *vs.* $\langle c_{yp}{}^2 \rangle$ for vertical control cylinder positions in the domains D_1 (red or bright gray) and D_2 (black); - - -, affine fit.

The correlation between C_{yp} and C_{xp} is revealed in the scatter plot in figure 9(c). Depending on the domain (D_1 or D_2), two different drag *vs.* side force behaviors are observed. First, in the domain D_1 (red or bright gray dots), the drag is measured constant at $C_{xp} = C_{xpn} \pm 0.002$ and independent of the side force in the whole range of C_{yp}. On the other hand, the drag from the domain D_2 (black dots) depends on the side force; the minimum of drag is measured for $C_{yp} \approx 0$ and progressively increases with $|C_{yp}|$ leading to a parabolic dependence. As a result, an additional drag proportional to $C_{yp}{}^2$ seems ascribed to the side force for control cylinders in the domain D_2; this drag contribution is denoted by C_{xp}^y.

The fact that such a quadratic dependence is not observed in the domain D_1 can be explained as follows. When located in the domain D_1, the disturbance gradually modifies the repartition between the states #P and #N so that all the values of the lateral force between -0.025 and 0.025 are explored. However, the side force is always close to the level of the current asymmetric states, *i.e.* $|c_{yp}| \approx 0.025$. Thus, if the presence of a side force generates an additional drag, an alternating side force even nil in average must equally produce additional drag.

The mean square of the lateral force $\langle c_{yp}{}^2 \rangle$ measures both the steady and unsteady contribution in the y direction. The scatter plot in figure 10 shows a linear correlation between C_{xp} and $\langle c_{yp}{}^2 \rangle$, confirming the previous analysis. Indeed, the data associated with both the domain D_1 and D_2 now follow the same trend that can be fitted by the affine law:

$$C_{xp} = 20 \langle c_{yp} \rangle + 0.18. \tag{4.1}$$

Consequently, the quantification of the total pressure drag C_{xp} contains an additional contribution of the side force denoted C_{xp}^y which must take into account both the mean side force and its fluctuations:

$$C_{xp} - C_{xp1} = C_{xp}^y = a_y \langle c_{yp}{}^2 \rangle = a_y \left[C_{yp}^2 + Std(c_{yp})^2 \right], \tag{4.2}$$

with $a_y \approx 20$. C_{xp1} is the pressure drag that can be achieved for a steady nil side force.

At this stage, it is important to mention that the measurement of $\langle c_{yp}{}^2 \rangle$ suffers from a lack of accuracy partially because the statistics are not fully converged. This is visible through the dispersion of the data along the vertical axis in figure 10. The value of $\langle c_{yp}{}^2 \rangle$ tends to be overestimated, independently of C_{xp}. Thus, a non-negligible part of $\langle c_{yp}{}^2 \rangle$ is not responsible for induced drag; in other words, C_{xp1} in equation (4.2) can not be evaluated at 0.18 as it would be expected from the fit (4.1). However, this does not affect the following analyses since only the slope of the affine fit (4.1) is used.

The drag *vs.* lift dependence is now considered when the wake is disturbed by the horizontal control cylinder (data plotted in figure 8). However, there are not only evolutions of lift but also of side force since there are stable and bistable cases. To get rid of the additional drag introduced by the fluctuations of side force and to obtain the drag evolutions ascribed to the lift only, one may subtract the term $C_{xp}^y = 20 \langle c_{yp}{}^2 \rangle$. Even if this term certainly overestimates the drag ascribed to the side force, it should not alter the drag *vs.* lift dependence: the important point is that the overestimation is independent of C_{zp}.

In figure 11 are plotted the dependence between $(C_{xp} - C_{xp}^y)$ and C_{zp}. Unlike the scatter plot in figure 8(b), the data now present a global coherence: both the stable and bistable data superimpose on the same master curve. The dependence can be approximated by

FIGURE 11. Dependence between $C_{xp} - C_{xp}^y$ and c_{zp} for horizontal control cylinder positions $(x_C^*, z_C^*) \in [0.21, 1.67] \times [0.15, 1.30]$ sorted on the value of $\mathcal{A}$: red (bright gray), $\mathcal{A} > 0.10$; black, $\mathcal{A} < 0.10$; ---, 2nd order polynomial fit.

the 2nd order polynomial fit

$$C_{xp} - C_{xp}^y = C_{xp0} + C_{xp}^z, \tag{4.3}$$

with

$$C_{xp}^z = a_z(C_{zp} - C_{zp0})^2 \tag{4.4}$$

and $a_z = 9.9$, $C_{zp0} = -0.079$. As a result, C_{xp0} corresponds to the minimal value of drag that can be achieved for a stable wake with optimal cross-flow forces but its accurate evaluation is impossible using the fit (4.3) due to the overestimation of C_{xp}^y. In parallel, it is observed that $C_{zp0} \neq 0$: the optimal drag point does not correspond to the minimum of C_{zp}^2 contrary to what is found for the force in the y direction. It seems rather to be related to the best homogeneity of the base pressure distribution: $\partial C_p/\partial z^* \approx 0$ for $C_{zp0} \approx -0.08$.

Now that the influence of each of the cross-flow forces on pressure drag are characterized, a synthesis is presented next with a confrontation to notions of induced drag for lifting airfoils.

4.2.2. *Synthesis on the drag contributions*

The quadratic dependencies between drag and side forces presented above are reminiscent of the notions of induced drag commonly used in aeronautics (Batchelor 2002). For an airfoil of lift coefficient C_L, the total drag coefficient C_D is usually separated into a parasitic drag and an induced drag (which is part of the pressure drag) that relies on three-dimensional effects. This term of induced drag is associated with the lift which can also be ascribed to the pair of counter-rotating vortices downstream of the wingtips. Denoting C_{D0} and C_{Di} the coefficients associated with the parasitic and induced drag respectively, the total drag coefficient verifies:

$$C_D = C_{D0} + C_{Di}, \tag{4.5}$$

with

$$C_{Di} = \alpha_L C_L^2 \tag{4.6}$$

and α_L depending on the geometry of the wing and more precisely, on the force distribution along the span.

In the framework of car aerodynamics, the results of Ahmed *et al.* (1984) demonstrates the critical impact of the three-dimensional flow structures on the drag. For after-body slant angles $\phi \in [13°, 25°]$, an increase of drag associated with the development of an intense pair of counter-rotating vortices is reported. Exploring the effect of flaps mounted on the after-body in the 25° case, Beaudoin & Aider (2008) prove the strong correlation between the drag, the lift and the pair of counter-rotating vortices. Moreover, extending the use of flaps at the trailing edge of a square-back configuration, Grandemange *et al.* (2013c) confirm that induced drag phenomena are relevant to interpret the drag evolutions ascribed to the modification of the flap angles.

The theory of induced drag in relation (4.6) can be extended to the analysis of the aerodynamic forces in a road vehicle configuration considering the lift force but also the side force. Moreover, both the steady and unsteady side forces must be taken into account due to the bistable behavior. Now, there is no apparent reason for considering the fluctuations of forces from bi-stability only. Even if it could not be evidenced in

this work, the fluctuations of cross-flow forces related to oscillating global modes and to turbulent activity (at least at large scales) may logically be added, in both the y and z directions. As a consequence, the following expression for the pressure drag is suggested:

$$C_{xp} = C_{xp0} + C_{xpi}, \qquad (4.7)$$

with

$$C_{xpi} = \alpha_y \langle c_{yp}{}^2 \rangle + \alpha_z \langle (c_{zp} - C_{zp0})^2 \rangle. \qquad (4.8)$$

This expression (4.8) relies on three parameters: α_y, α_z and C_{zp0}. As previously mentioned, C_{zp0} is certainly an offset due to the presence of the ground and hence it is likely to rely on the precise configuration of the vehicle such as the ground clearance. However, this optimal lift correspond to the best homogeneity of the base pressure in the z direction (see figure 8a) which may be a general rule. By extending the interpretation of α_L in aeronautics, one would expect the coefficients α_y and α_z to depend on the force distribution in the y and z directions. In the present experiment, α_y is thought to be close to a_y because $a_y = 20$ is obtained in equation (4.1) from the sensitivity analysis in the domains D_1 and D_2 only. There, the cylinder is out of the lateral shear layers and it only controls the natural circulation around the geometry. So $C_{xp}^y = 20\langle c_{yp}{}^2 \rangle$ is the drag induced by the natural lateral fluctuations of the wake, including bi-stability, independently of the control cylinder. Differently, it is clear that the horizontal cylinder produces a lift on the body, especially when it is located in the mixing layers. Consequently, the measurement of a_z in equation (4.4) is associated with the system comprised of the main geometry and the disturbance while α_z is related to the main geometry only. In other words, one expects $\alpha_z \neq a_z$.

4.3. *On the stabilization of the symmetric state as a control strategy for drag reduction*

An estimation of the additional drag due to the bi-stability of the natural wake can be provided by the sensitivity analysis. $\langle c_{yp}{}^2 \rangle$ is measured at 9.0 10^{-4}, 8.8 10^{-4} and 8.9 10^{-4} for the states #P, #N and the mean symmetric flow respectively; these values give an average of $C_{xp}^y = 0.018$. However, the direct application of equation (4.1) with $C_{xp}^y = 20\langle c_{yp}{}^2 \rangle$ may over-estimate the contribution of the bi-stability so $C_{xp}^y < 0.018$. Now, an inferior limit can be obtained from the natural flow. Using a conditional averaging technique (Grandemange *et al.* 2013b), the side force is measured at $|C_{yp}| = 0.021$ for both mirror states. Hence, it is obtained that $C_{xp}^y > 20C_{yp}{}^2 \approx 0.008$ and this inferior bound is free from the over-estimation of $\langle c_{yp}{}^2 \rangle$. As a conclusion, the drag related to the bi-stability is estimated between 0.008 and 0.018, *i.e.* between 4% and 9% of the total pressure drag.

In Grandemange *et al.* (2012a), it is found that the origin of the bi-stability is ascribed to a pitchfork bifurcation of the laminar wake. For Re > 340, the steady symmetric flow disappears and the wake solutions are two mirror steady asymmetric states. At large Reynolds numbers, turbulent fluctuations allow the exploration of the two solutions but the symmetric flow is never observable in a strict sense, at least up to Re $\sim 10^7$ (Grandemange *et al.* 2013b). The effect of the vertical cylinder placed at the center of the recirculating bubble (see figure 2c) might be interpreted as a control of the reminiscences of the steady reflectional symmetry breaking mode, which renders the symmetry of the wake.

Now, steady pitchfork bifurcations are common feature of three-dimensional flows; for instance Pier (2008) evidences that for a sphere, the loss of axisymmetry is a source of additional drag. Hence, the stabilization of this steady symmetric regime offers a

relevant control strategy for drag reduction of three-dimensional bluff bodies, even at large Reynolds numbers.

5. Concluding remarks

Using horizontal and vertical control cylinders as perturbations, the sensitivity analyses of the separated flow past a simplified ground vehicle reveal the receptive zones of the wake. First, a disturbance that breaks the reflectional symmetry of the set-up selects one of the two asymmetric states depending on both the streamwise and lateral positions of the perturbation. Besides, the receptive region of the bi-stability to a steady symmetric forcing is found in the center of the recirculation region. These positions of vertical cylinder lead to a stable centered wake with an increased recirculation length and a base pressure recovery. Moreover, the sensitivity maps obtained with a vertical control cylinder show strong similitude with the ones presented in Grandemange *et al.* (2012*b*) for the separated flow past an axisymmetric trailing edge. Thus, the bi-stability of these two geometries is very likely to result from the same physics. Given the generality of these bistable phenomena, the high receptivity of the center of the recirculation to a symmetric forcing may be a widespread characteristic of three-dimensional separated flows.

The sensitivity maps obtained with the horizontal control cylinder indicate that the receptivity is concentrated in the upper and lower shear layers. Significant lift modification are reported, especially when the control cylinder generates a jet from the high momentum flow to the recirculation region. Such a wake asymmetry in the z direction is likely to prevent the development of the y instability responsible for the bi-stability which results, in some cases, in drag reduction.

From these complementary sensitivity analyses, correlations between the drag and the cross-flow forces are identified. Extending the formalism induced drag in aeronautics, a quantification of the impact of the cross-flow forces on the pressure drag is suggested. It is found that both the steady and unsteady cross-flow forces must be taken into account. The optimal point in terms of induced drag is obtained for a steady force at $C_{yp} = 0$ and $C_{zp} = -0.08$. The fact that the optimal lift is negative should be ascribed to the ground proximity and may differ from one experiment to another; however, these forces correspond to the best uniformity in the base pressure distribution which is very likely to be a general result.

As a consequence, it is confirmed that the bi-stability of the natural flow is responsible for part of the drag, estimated between 4% to 9% of the total pressure drag. This evaluation quantifies the potential of drag reduction on the Ahmed geometry by using control devices able to force a centered wake that is steady at long time-scales.

More generally, one can wonder if the drag dependence on the fluctuations of cross-flow forces stands for non-bistable wakes at high Reynolds number. This question may motivate future studies which could lead to the definition of new strategies of drag reduction.

Acknowledgments

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