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Effect of the vortex dynamics on the drag coefficient of a square back Ahmed body: Application to the flow control

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ABSTRACT

A vortex generated behind a simplified vehicle induces a pressure force at the back wall that contributes to a significant part of the drag coefficient. This pressure force depends on two parameters: the distance of the vortex to the wall and its amplitude or its circulation. Therefore there are two ways to reduce the drag coefficient: pushing the vortices away from the wall and changing their amplitude or their dynamics. Both analytical studies and numerical simulations show that these two actions decrease the pressure force and consequently reduce the drag coefficient. The first action is achieved by an active control procedure using pulsed jets and the second action is achieved by a passive control procedure using porous layers that change the vortex shedding. The best drag coefficient reduction is obtained by coupling the two procedures.

1. Introduction

A simplified ground vehicle can be represented, as it is often the case both for experiments and numerical simulations by the Ahmed body [1]. It is a three-dimensional bluff body moving in the vicinity of the ground generating a turbulent flow. Several separations appear along the body from the front to the back. The flow behavior is strongly related to the angle of the rear window α. For instance when $\alpha = 25^\circ$ the flow on the rear window is dominated by two strong longitudinal vortices [2,3]. On the contrary when $\alpha = 90^\circ$ the geometry corresponds to a square back Ahmed body, the flow separates at the back and the base flow is no more dominated by longitudinal structures. Experimental and numerical studies confirm this behavior of the detached near-wall flow at the base of the square back Ahmed body geometry [4–7]. Indeed, the vortex shedding generates four mean recirculation zones behind the back wall that are symmetrical with respect to the center of the wall. These recirculation zones contribute to a significant part of the drag coefficient as the vortical structures induce strong pressure forces at the back [8–10]. Thus to get a drag reduction, it is necessary to modify locally the flow, in order to reduce or to push away the strong pressure wells in the near wake [11].

This can be mainly obtained by controlling the flow near the back wall with or without additional energy using active or passive devices [12,13]. On the one hand, an active control consists of adding uniform, pulsed or synthetic jets on the back wall to push away or to split the vortical structures [8,14]. On the other hand a passive control uses fixed devices like rough surfaces, vortex generators or porous layers to change the size and the dynamics of the vortical structures and consequently to reduce the pressure forces [15–19].

However, implementing an efficient control needs to better master the vortex behavior in the very near wake of the obstacle and thus to better understand the relationship between the vortices evolution and the drag forces. An important issue of this relationship is based on the pressure forces generated by the wake vortices on the back wall of the body. It depends on the strength, the size and the trajectory of the vortices in the wake as well as on the speed they are moving away from the back wall.

Some theoretical approaches have been developed considering different simplified kinematic motions in order to better understand the flow behavior [20–22]. From these works, it is possible to calculate the pressure force on the back wall and its evolution with respect to the distance of the vortices from the wall.

However, the viscous vortex dynamics in the wake is much more complex than an ideal vortex convection. Near the wall, the dissipative forces are predominant and the vortices are not directly subject to the inlet velocity. Nevertheless, such a theoretical approach is still helpful showing a general trend related to the

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modification of the vortex dynamics. Then the control processes can be directly inspired by the results of the theoretical study as they show the ideal kinematics to get.

In this work, direct numerical simulations of the two-dimensional flow around the square back Ahmed body, corresponding to simplified mono space cars or trucks, are considered. The incompressible Navier–Stokes system is solved in a computational domain including the square back Ahmed body on top of a road at medium Reynolds number. Although the Reynolds number is much lower than the real Reynolds number around ground vehicles, it is possible to study the vortex dynamics and to quantify the effects of the control. First of all, some theoretical results on ideal convective vortex motions are analyzed to compute the resulting pressure force on the wall that depends on two parameters: the distance and the circulation of the vortex. Then, the evolution of a toy vortex added in a background stationary flow is carefully studied without or with an active control by a steady jet. This first study permits to better understand the effect of the control procedure on the kinematics of one vortex and to show the resulting pressure force behaves like the theoretical force computed above.

Finally the vortex shedding of the real flow computed around the body is analyzed as we study the mean trajectory of the top and bottom vortices at the back. Two actions are then implemented to control the flow. The first one involves a closed-loop active control using blowing jets to remove the vortices as fast as possible from the wall. It appears that the control can improve significantly the trajectories and the removal speeds of some vortices to reach almost the ideal motion. The second one involves a passive control using porous layers [19,8,7] in order to change the vortex dynamics in the immediate vicinity of the back wall. The big shedded vortices are replaced by smaller ones with their own dynamics. Consequently the pressure force on the back wall is reduced and finally the drag coefficient is decreased.

This paper is organized as follows. Section two is a recall of the analytical approach showing the link between the removal of vortices from the back wall and the corresponding pressure forces for three different functions. Section three presents briefly the modeling and the numerical simulation. Section four illustrates what is given by the theory with the numerical simulation of a toy vortex added to a steady background flow. In section five a careful analysis of the results obtained by the direct numerical simulation without or with active control is provided. Section six is devoted to the dynamics of smaller shedded vortices and to the passive control procedure that yields a significant drag reduction. Section seven shows that better results can be achieved by coupling active and passive control procedures. At the end some conclusions are deduced.

2. Analytical approach

With non-viscous hypothesis, the two-dimensional vortex model is based on two theories: the circular vortex theory [21,22] and the mirror image vortex theory [20]. The first one considers the vortex as a disk. The velocity is infinite in the center and decreases when the radius increases. To avoid the infinite velocities on the wall, the vortex position is considered to be at least as far as a classical viscous radius value ϵ from the body. The second theory allows to model the vortex sliding actions to the wall. In fact, the sliding force at the wall is the amount of the forces generated by the studied vortex and its wall mirror image vortex. Let us recall here the basis of such an approach and its extension to the force evaluation on the wall.

Let H be the height of the back wall of the obstacle characterized by the coordinates set $x = 0$ and $-H/2 \le z \le H/2$ (see Fig. 1). Let us consider $M(0, z)$ a point on the back wall and a vortex whose center is located at point $P(x_1, z_1), x_1 > 0$. The distance between

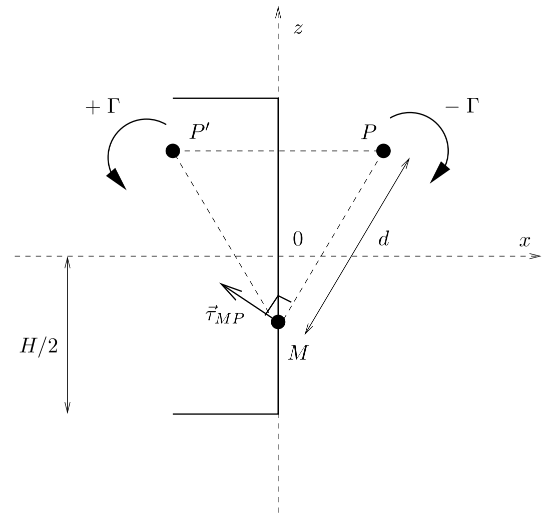

Fig. 1. Location of the vortex center P respecting to the wall.

M and P is denoted d, and $\vec{\tau}_{MP}$ is the unit vector orthogonal to $\overrightarrow{MP}$ given by $\vec{\tau}_{MP} = \overrightarrow{MP}^{\perp} / \|\overrightarrow{MP}\|$. In that case, according to [21], the wall velocity induced at point M by the vortex is given by

$$\vec{V}(M) = \frac{\Gamma}{2\pi d}\, \vec{\tau}_{MP}, \tag{1}$$

where $-\Gamma \in \mathbb{R}$ corresponds to the (negative) vortex circulation. Near the wall, the longitudinal component of the velocity is negligible so the velocity is parallel to the wall. To nullify the normal component of the velocity near the wall, a mirror image vortex has to be located at point $P'(-x_1, z_1)$ with the circulation $+\Gamma$ [20]. The velocity $\vec{W}(M)$ at point M due to this mirror image vortex can be defined in the same way, and a simple calculation shows that the modulus of the resulting velocity $\vec{V}_R(M) = \vec{V}(M) + \vec{W}(M)$ is given by

$$V_R(M) = \|\vec{V}_R(M)\| = \frac{\Gamma\, x_1}{\pi\,(x_1^2 + (z - z_1)^2)}. \tag{2}$$

According to Bernoulli, the local pressure p with respect to the pressure at rest p_0 is given by

$$p(M) - p_0 = -\frac{\rho}{2} V_R^2(M) = -\frac{\rho}{2} \frac{\Gamma^2\, x_1^2}{\pi^2 (x_1^2 + (z - z_1)^2)^2}, \tag{3}$$

where ρ is the density of the fluid. Consequently, integrating on the back wall, we get the horizontal pressure force F_p induced by the vortex on the whole back of the body:

$$\begin{aligned} F_p &= \int_{-\frac{H}{2}}^{+\frac{H}{2}} -(p(M) - p_0)\, dz \\ &= \frac{\rho}{2} \frac{\Gamma^2}{\pi^2} \int_{-\frac{H}{2}}^{+\frac{H}{2}} \frac{x_1^2}{(x_1^2 + (z - z_1)^2)^2} dz. \end{aligned} \tag{4}$$

Now, if we consider that the vortex is moving, the instantaneous pressure force $F_p(t)$ induced by the vortex on the wall at time t can of course be evaluated by:

$$F_p(t) = \frac{\rho}{2} \frac{\Gamma^2}{\pi^2} \int_{-\frac{H}{2}}^{+\frac{H}{2}} \frac{x_1^2(t)}{(x_1^2(t) + (z - z_1(t))^2)^2} dz. \tag{5}$$

This pressure force depends of course strongly on the circulation Γ but also on the functions $x_1(t)$ and $z_1(t)$. Taking $x_1(t) = \epsilon + t^r$ with $1/2 \le r \le 2$ and $\epsilon = \sqrt{\Gamma^2 \rho / p_0}$ (see [21]), and considering in a first approach an horizontal evolution ($z_1(t) \equiv 0$), some