Drag reduction of a blunt body by unsteady shear layer forcing and Coanda blowing

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Résumé

Nous étudions les effets d'un forçage périodique du sillage sur la traînée d'un corps non-profilé au culot droit. Avec la combinaison des jets pulsés et d'une surface courbée, le contrôle augmente de 30% la pression au culot grâce à l'effet Coanda et à la periodicité des jets. La fréquence d'actuation est un ordre de grandeur plus élevé que les instabilités du sillage. Avec la vélocimétrie par image de particules, nous observons que l'actuation diminue la section verticale du sillage et modifie l'evolution de la vorticité des couches cisaillées. Toutefois, la dynamique du sillage proche ne semble pas être modifiée qualitativement.

Abstract

We analyze the effects of periodic forcing on the wake and drag of a square back bluff body. In combination with a Coanda effect, shear-layer forcing by periodic blowing allows to recover over 30% of the base pressure. The actuation frequency is an order of magnitude higher than the natural shear-layer instabilities. Velocity measurements indicate that the forced wake is thinner and that the vorticity along the shear layer development is modified. However, the wake dynamics further downstream remains very similar to the unforced vortex shedding mode.

Mots clefs : Wakes, Drag Reduction, Flow Control

1 Introduction

Drag reduction of bluff bodies has become a major challenge for transport vehicles due to increasing need for reducing fuel consumption and carbon pollution. The aerodynamic drag of cars is principally due to their shape, causing significant pressure differences between their front and rear surfaces. The wake flow of simplified square back road vehicles was extensively studied in the past [1] and complemented, more recently, by other studies [2]. The wake contains low energy recirculating flow surrounded by free shear layers. These shear layers are convectively unstable and act as a noise amplifier while the absolute instability of the recirculating flow produces self-sustained large-scale oscillations.

In recent years flow control turned out to be an efficient way to modify bluff body wakes with the aim to increase the baseline pressure [3]. For fully 3D flows past rectangular bluff bodies , pressure recovery

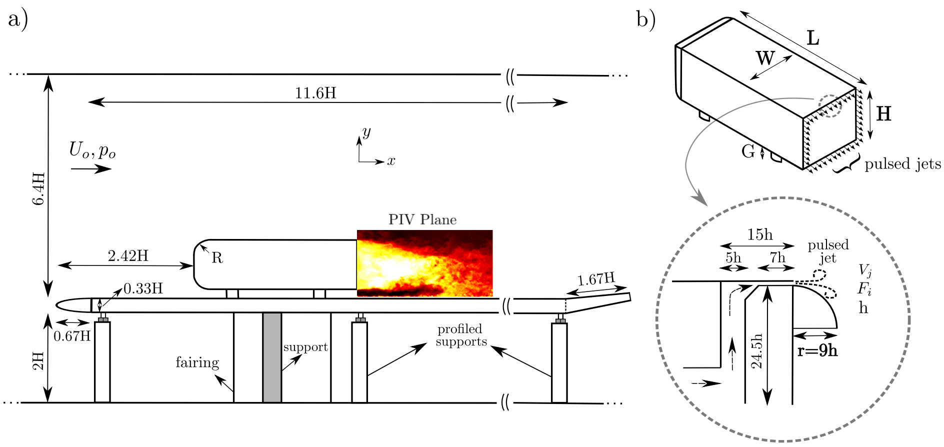

FIGURE 1 – Experimental set-up details. a) Wind-tunnel, flat plate dimensions and model positioning. The PIV field of view is illustrated in the symmetry plane of the configuration. b) Model geometry and description of the pulsed jet system with the Coanda surface.

at the base can be obtained by boat-tailing of the body shape or by producing a flow deflection through steady jets associated or not with a Coanda effect. For practical applications, all so far tested control techniques show limitations related to power cost and geometrical constraints. In this study we explore the possibility to decrease both constraints by deviating the flow through unsteady pulsed jets combined with a Coanda effect. Recent studies applied periodic pulsed jets to manipulate the base pressure of blunt bodies [4,5]. The unsteady jets were released along the border of the back side in the direction of the main flow. The time-averaged flow appeared virtually shaped with reduced cross section of the wake associated with a decrease of the pressure drag. In the present work, we combine the straight high frequency jet actuation in [4,5] with an unsteady Coanda effect to further reduce the pressure drag.

2 Experimental setup

The experiments were performed in a low-speed wind tunnel with $2.6 \times 2.4\ m^2$ cross-sectional area. Figure 1 shows the details of the test configuration. The blunt body model with height $H = 0.297\,m$, width $W = 0.350\,m$ and length $L = 0.893\,m$ is the same as used in [4]. The leading edges of the model were rounded with radius $R = 0.085\,m$. The model was mounted on a false floor to control the upstream boundary layer thickness. Four profiled supports fixed the geometric ground clearance G to 0.05 m. The upstream velocity U_o was kept constant at 15 m/s throughout the experiments which gives a Reynolds number based on H of $Re_H = 3 \times 10^5$.

In order to evaluate the pressure drag changes obtained by control, 17 pressure taps were installed on its rear surface. The pressure measurements are normalized as $C_p = \frac{p-p_o}{q_o}$, where p_o and q_o are the upstream static and dynamic pressure. Particle Image Velocimetry (PIV) was performed in the wake of the model to capture the essential modifications of the forced wake. Sequences of 1000-1500 velocity fields were used to compute first and second order statistics of the streamwise and transverse (respectively x and y directions) velocity components with a resulting spatial resolution of 0.3% of the model's height.

The periodic wake forcing is performed by pulsed jets along the four trailing edges of the model, as shown in figure 1(b). The jet velocity V_j and frequency F_i are driven periodically by the use of solenoid valves

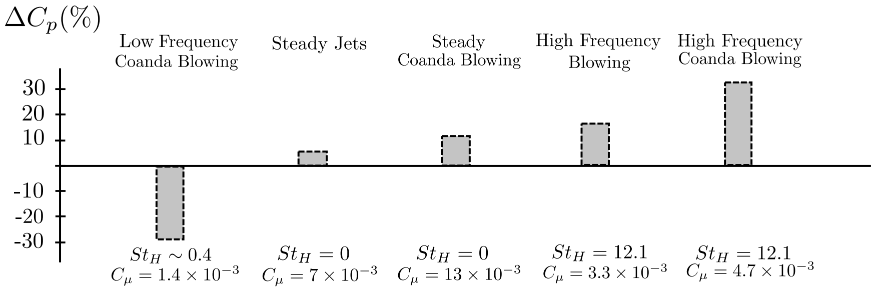

FIGURE 2 – A hierarchy of base pressure for different forcing parameters. Low-frequency forcing considerably decreases the base pressure of the model, while high-frequency actuation increases the rear pressure by about 30% using the Coanda surface.

located inside the model. The width of the exit cross-section of the jet slit is $h \sim 1\,mm$. A Coanda surface composed of a quarter of a disk with radius $r = 9\,mm$ can be fixed just bellow the jet exit . Measurements performed with and without this small appendice will be analyzed in what follows. We define the momentum coefficient of the jet as $C_\mu = \frac{s_j \overline{V_j}^2}{S U_o{}^2}$, where s_j and S are the jet slit cross-sectional area and the frontal area of the model, respectively. For spectral analysis, the actuation frequencies is considered in dimensionless form by defining Strouhal number $St_H = \frac{HF_i}{U_o}$.

3 Results and discussions

The effects of the actuation frequency St_H on the base pressure are summarized in figure 2. A hierarchy of the forced wakes is established by the variations of the base pressure promoted by the pulsed jets. First, low-frequency forcing at $St_H \sim 0.4$ decreases considerably the pressure of the rear surface, indicating important increase of the model's pressure drag. Steady blowing increases base pressure very slightly (about 2%) when no Coanda surface is added. A significant improvement of base pressure recovery is obtained by adding a curved surface (increase of about 10% of C_p). Actuation at higher frequencies improves the base pressure recovery further even without the Coanda surface at $St_H \sim 12$. This frequency corresponds to about 60 times the discrete oscillatory frequency of the wake (see the next paragraph) and about 11 times the most amplified estimated frequency of the upper shear layer [6]. Hence, actuation at this frequency is decoupled from the natural flow instabilities and is denominated high frequency (HF) actuation. Base pressure increase over 30% is achieved by HF Coanda blowing.

PIV measurements of the mean streamwise velocity component $\overline{u}$ shed light into the spatial evolution of the wake. In figure 3(a, left) far from the bluff body the contours $\overline{u} = 0.25$ indicate that HF Coanda forcing decreases the wake width , while the length of the recirculation zone remains rather unchanged. Close to the model figure 3(a, right) shows for the forced case a rapid convergence of the maximum mean vorticity inside the shear layers towards the horizontal symmetry line , which points to important modifications of the near wake structure. At the same time, the thickness of the shear layers becomes larger while the peak value of vorticity decreases over more than 15% between $x/H = 0.08$ and $x/H = 0.16$.

The changes in flow curvature are particularly visible in a zoomed view near the upper trailing edge of the model in figure 3(b). We compare the natural Coanda flow (i.e. no blowing) to HF Coanda blowing. The picture shows the mean transverse velocity contours and velocity vectors near the flow separation at the upper shear layer. The deflection of the actuated flow is clearly visible. The streamline originating

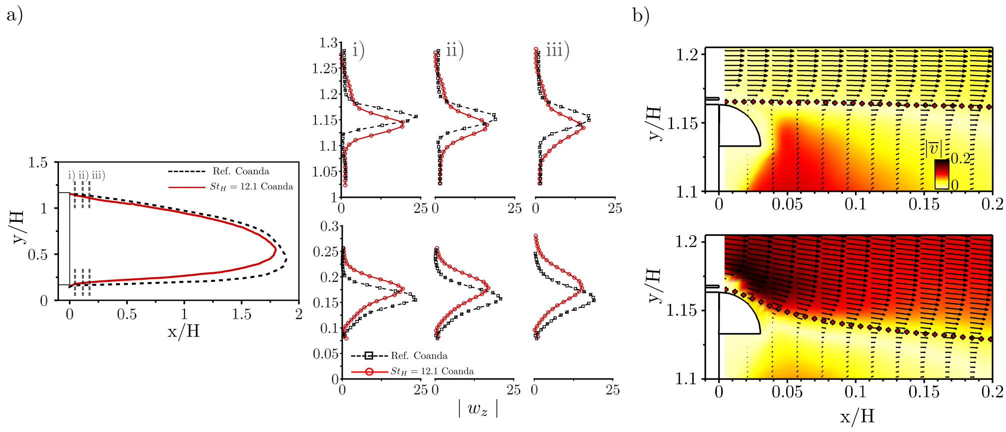

FIGURE 3 – a) Left : streamwise velocity iso-contour $\overline{u} = 0.25$ for the unforced flow and for HF Coanda blowing ($St_H = 12.1$). Right : evolution of the time-averaged vorticity along x. b) Upper shear layer zoom and transverse velocity field for the unforced flow (top) and HF Coanda blowing (bottom). Dotted points represent the streamlines originated from the exit slit.

from the middle of the blowing slit (dotted points) indicates that HF frequency forcing leads to a much higher flow deflection. The resulting increase of convex streamline curvature is accompanied by an increase of the pressure gradients across the separating shear layer. This implies a higher base pressure recovery for the HF Coanda blowing in accordance to the measured pressure increase presented in the last paragraph. Additionally, we observe a considerable reduction of the upward velocity near the rear surface of the model, indicating that the intensity of the recirculating flow has been modified.

The velocity fluctuations and spectral content of both wakes are now described. Figure 4(a) presents contour maps of the transverse velocity fluctuations $\overline{v'^2}$ in the wake. Generally, we note that these fluctuations are damped for $x/H > 0.2$. At $x/H = 0.2$, $\overline{v'^2}_{\max}$ reduced by 16% and at $x/H = 0.5$ the reduction is even increased to 26% in both shear layers, suggesting a modified development of shear flow instabilities. The distribution of $\overline{v'^2}$ remains, however, quite similar along the wake for both natural and forced cases, indicating that the dynamics of the near wake flow is not strongly affected spatially. This is also confirmed by the power spectral density (PSD) of a velocity signal taken at ($x/H = 2.1$, $y/H = 0.9$) by a single hot-wire probe. In figure 4(b), the reference flow exhibits a discrete peak at the normalized frequency $f_H = \frac{Hf}{U_o} \sim 0.2$, which is the vortex shedding mode commonly observed for this square back geometry [2]. Interestingly, the high frequency forced wake exhibits the same mode, indicating similar global oscillatory shedding for both flows at the same frequency.

4 Concluding remarks

In the present work, we combined periodic shear-layer forcing and flow deflection by the Coanda effect to increase the base pressure of a square back bluff body. Base pressure increases of more than 30% can be achieved by this combination. The unsteady Coanda effect produces flow deflections near the base of the blunt body as well as a decrease of the velocity fluctuations in the wake. The deflections are responsible for the formation of convex curved mean streamlines with strong transverse pressure gradients, which finally lead to a significant increase of base pressure. Hence, the HF Coanda actuation works like aerodynamic form shaping but needs minimal geometrical modifications to achieve substantial pressure recovery. The dynamics leading to the aforementioned mean flow modifications are presently under investigation.

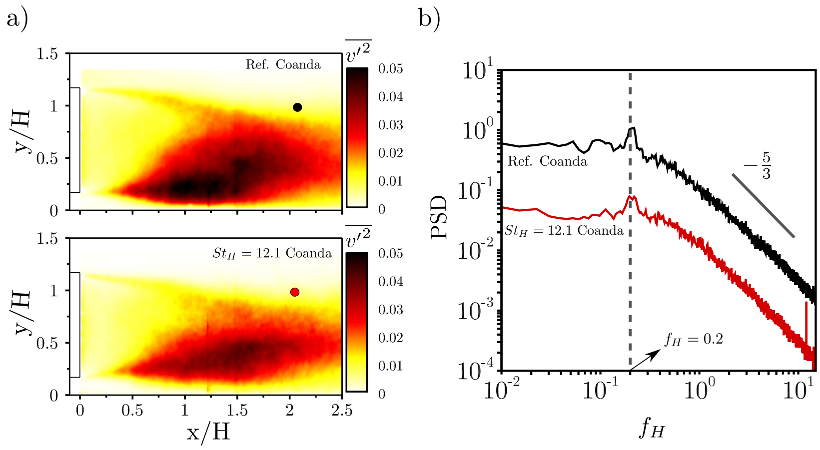

FIGURE 4 – Velocity fluctuations and oscillatory mode. a) Transverse velocity fluctuations for unforced flow (top) and HF Coanda blowing (bottom). b) Effects of actuation on the global vortex shedding frequency.

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