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Fluid force and symmetry breaking modes of a 3D bluff body with a base cavity

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ABSTRACT

A cavity at the base of the squareback Ahmed model at $Re \simeq 4 \times 10^5$ is able to reduce the base suction by 18% and the drag coefficient by 9%, while the flow at the separation remains unaffected. Instantaneous pressure measurements at the body base, fluid force measurements and wake velocity measurements are investigated varying the cavity depth from 0% to 35% of the base height. Due to the reflectional symmetry of the rectangular base, there are two Reflectional Symmetry Breaking (RSB) mirror modes present in the natural wake that switch from one to the other randomly in accordance with the recent findings of Grandemange et al. (2013b). It is shown that these modes exhibit an energetic 3D static vortex system close to the base of the body. A sufficiently deep cavity is able to stabilize the wake toward a symmetry preserved wake, thus suppressing the RSB modes and leading to a weaker elliptical toric recirculation. The stabilization can be modelled with a Langevin equation. The plausible mechanism for drag reduction with the base cavity is based on the interaction of the static 3D vortex system of the RSB modes with the base and their suppression by stabilization. There are some strong evidences that this mechanism may be generalized to axisymmetric bodies with base cavity.

1. Introduction

Bluff bodies in uniform streams are known to experience substantial form drag due to the full flow separation at their base (Schlichting and Gersten, 2000). Since they are very common in our surrounding industrial environment, such as transportation industries (ground vehicles and submerged part of ships), civil engineering (buildings and bridges) or off-shore industries (risers and platforms) it is of a major interest to investigate the possible fluid force reduction that can be achieved under the constraint of conserving their functional shapes. In that context, it is useful to address the issue of reducing drag without changing the location of separation (separation control is then out of the focus of this work). Bodies with blunt trailing edge have the advantage to fix the separation and one may wonder what is possible to realize within this constraint. The response lies in the dynamics of the separated area and the low pressure therein, called the base pressure. Drag reduction mechanisms are always intimately associated with the increase of base pressure (Roshko, 1993) and their physical comprehension often points on the identification of the different contributions of the base pressure. A relevant

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quantity that quantifies the base pressure effect in the drag is the base suction coefficient defined as $C_b = -C_{pb}$, where the pressure coefficient $C_{pb} = \frac{1}{\Sigma}\iint_{\Sigma} \frac{p_b - p_0}{\frac{1}{2}\rho U_0^2} dS$ is averaged over the surface Σ of the blunt base. Here, U_0 and p_0 are respectively the velocity and the pressure of the uniform upstream flow.

There are several drag reduction techniques (see for instance reviews by Viswanath, 1996; Choi et al., 2008), and not all of them are yet elucidated. The passive technique that consists in producing a body cavity at the base is particularly interesting because, in addition to the fact that it leads to a substantial base drag reduction (Morel, 1979; Viswanath, 1996) in the range 10–20% for both the 2D and 3D generic axisymetric bluff bodies, it keeps unchanged the location of the separation. The effect is found to saturate for cavity depth larger than about 25% the body height. The mechanism was revealed by Kruiswyk and Dutton (1990) and Molezzi and Dutton (1995) for 2D bluff bodies. The drag reduction is related to the global Bènard von Kàrmàn instability leading to the periodic vortex shedding. The reason for drag reduction is not an alteration of this global dynamics, but simply because of the increased distance between the body base and the zone of vortex formation. However, this explanation is not completely satisfactory, and the mechanism is more subtle. Actually, the pressure increase on the base reduces the drag force and then the external force necessary to hold the body. Hence the flow has to be modified. Indeed, when the drag is reduced, the vortices are found to be weakened (Molezzi and Dutton, 1995), and their pressure higher as can be clearly seen in the numerical simulation of Martin-Alcantara et al. (2014). In addition, it has to be acknowledged that at large Reynolds number flows (modeled as inviscid flow), the interaction of a flat wall with a vortex source produces an increased velocity on the wall associated with a low pressure.

Cavity effects on axisymmetric bodies are reported to give similar amounts of base drag reduction to those obtain with two dimensional bodies. On the contrary to two dimensional bodies, the reduction is observed even in the absence of wake periodicity (Viswanath, 1996). The periodic vortex shedding is then not the cause for the cavity effect. Instead, mean flow modifications are generally evoked (Viswanath, 1996) but they might be a simple consequence of the external force reduction as discussed just above. So, there is no clear interpretation of the cavity effect in this case.

The wake dynamics and topology of axisymmetric bodies are drastically different from cylinders. For instance, the first bifurcation at low Reynolds number is a steady breaking of the axial symmetry (Fabre et al., 2008; Pier, 2008; Bohorquez et al., 2011) leading to a static mode having a planar symmetry (Mittal et al., 2002), that we will refer for the remainder of the paper as symmetry breaking (SB) mode. As the Reynolds number increases, Berger et al. (1990) showed that the wake recovers the axisymmetry in average but presents instantaneously a large scale spatial structure that does not preserve the axisymmetry. Recent studies of Rigas et al. (2014) and Grandemange et al. (2014a) demonstrate that the planar symmetry is persistent at least for Reynolds numbers up to 2×10^5, but that the azimuthal position of the symmetry plane undergoes a fully random long time dynamics. The static SB modes are then present in the turbulent axisymmetric wake.

In cases of bodies with rectangular blunt base, such as the squareback Ahmed body (Ahmed et al., 1984) a similar wake dynamics has been recently evidenced. The work of Grandemange et al. (2013b) shows the permanent existence of Reflectional Symmetry Breaking (RSB) modes at least for Reynolds number up to 2.5×10^6. The main difference with axisymmetric bodies is that the basic symmetry of the rectangular base allows only two opposite azimuthal positions for the RSB modes. Consequently the wake dynamics is governed by a random switching between these two RSB modes leading to a bistable behavior. As for the SB modes of the axisymmetric bodies, the characteristic time associated with the RSB mode switching is 2–3 orders of magnitude larger than the time for periodic shedding with a Strouhal number St=0.2 (Rigas et al., 2014; Grandemange et al., 2013b). The study of the squareback Ahmed body at low Reynolds numbers (Grandemange et al., 2012) indicates that the RSB modes are reminiscent of the two stable solutions obtained after a pitchfork bifurcation in the laminar regime. However, the closer the Ahmed body to the wall (to simulate a road effect), the larger the critical Reynolds number of the bifurcation threshold which eventually occurs in the turbulent regime (Cadot et al., 2015).

One may wonder whether the presence of the symmetry breaking modes is related to the cavity effect of 3D bodies, such as the periodic Kàrmàn shedding is for cavity effect of 2D bodies. Sanmiguel-Rojas et al. (2011) studied the cavity effect on the stability properties of the SB modes in the laminar regime of a blunt based axisymmetric body. They found a stabilization effect, the threshold for the symmetry breaking which is obtained for Re=400 with no cavity is postpone to an asymptotic value of about 600 for body cavities deeper than 60% of the body diameter. So, a question is how does the cavity interact with the SB modes in the turbulent regime ?

The aim of the paper is to address this fundamental issue in the geometry of the squareback Ahmed body. We are aware of two studies in an industrial context from Irving Brown et al. (2010) and Grandemange et al. (2015) showing that a body cavity at the rectangular base reduces significantly the drag.

The paper is organized as follows. Section 2 describes the geometry and the measurements. The sensitivity of the wake dynamics to the body alignment in the wind tunnel is presented in Section 3. Results in Section 4 are presented in four parts. Section 4.1 characterizes the reference case (no cavity). Cavity effects are first studied on fluid forces and base pressure in Section 4.2 and then on the wake in Section 4.3. In Section 4.4, the cavity effect is investigated again but when a vertical control cylinder is placed in the near wake, known as a technique to stabilize the bistable behavior of the reference case (Grandemange et al., 2014b; Cadot et al., 2015). Discussions in Section 5 are separated in two parts. A first discussion in Section 5.1 aims at describing the observed stabilization within the framework of the bifurcation theory and a second discussion in Section 5.2 interprets the physical mechanism of drag reduction using a body cavity. Section 6 concludes the paper.