Journal of Fluids and Structures 55 (2015) 191–203

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Connection between base drag, separating boundary layer characteristics and wake mean recirculation length of an axisymmetric blunt-based body

A. Mariotti *, G. Buresti, M.V. Salvetti

Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Via G. Caruso 8, 56122 Pisa, Italy

ARTICLE INFO

Article history:
Received 29 July 2014
Accepted 24 February 2015
Available online 21 April 2015

Keywords:
Axisymmetric bodies
Drag reduction
Base drag
Base pressure
Wake recirculation

ABSTRACT

The variation of the base drag of an axisymmetric bluff body caused by modifications of the boundary-layer separating at the sharp-edged contour of its base is analysed through different numerical simulations, and the results are compared with those of a previous experimental investigation. Variational MultiScale Large-Eddy Simulations (VMS-LES) are first carried out on the same nominal geometry and at the same Reynolds number of the experiments. Subsequently, Direct Numerical Simulations (DNS) are performed at Reynolds numbers that are roughly two orders of magnitude lower, in order to investigate on the sensitivity of the main findings to the Reynolds number. The results of experiments, VMS-LES and DNS simulations show that an increase of the base pressure – and thus a decrease of the base drag – may be obtained by increasing the boundary layer thickness before separation, which causes a proportional increase of the length of the mean recirculation region behind the body. In spite of the different setups, Reynolds numbers and turbulence levels in the experiments and numerical simulations, in all cases the base pressure is found to be directly proportional to the length of the mean recirculation region, which is thus a key index of the base drag value. In turn, the recirculation length seems to be connected with the location of the incipient instability of the detaching shear layers, which can be moved downstream by an increase of the thickness of the separating boundary layer and upstream by an increase of the turbulence level.

1. Introduction

The main contribution to the aerodynamic drag of a bluff body is normally given by the low pressures acting on its base, which is the part of the body surface lying within the separated wake. Decreasing the base drag would then have a considerable importance in many engineering applications, such as the design of low-consumption road vehicles. However, the present knowledge on the physical mechanisms influencing the base drag is still far from satisfactory; considerable research work is thus needed to reach a deep understanding of the physical mechanisms that influence the value of the pressures acting on the base of a bluff body and, consequently, to be able to devise methods to control it.

* Corresponding author.
E-mail addresses: alessandro.mariotti@for.unipi.it (A. Mariotti), g.buresti@ing.unipi.it (G. Buresti), mv.salvetti@ing.unipi.it (M.V. Salvetti).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.02.012
0889-9746/

As a preliminary objective, it is of significant scientific interest to characterize the relationship between the base pressure and the parameters defining a particular flow configuration, and, especially, to identify the physical origin of this relationship. The present paper aims at giving a contribution in this direction, focusing, in particular, on the influence of the thickness of the boundary layer separating at the contour of the blunt base of an axisymmetric bluff body and trying to provide an explanation for the observed results. Indeed, some indications exist in the literature that the characteristics of the boundary layer developing over the lateral surface of a bluff body before its separation may influence the base pressure. This effect is particularly significant for bodies whose base is a sharp-edged flat surface perpendicular to the free stream. For instance, in the two-dimensional case the base drag of a thick plate with elliptic leading edge and flat base was found to decrease when the boundary-layer thickness was increased (see, e.g., Rowe et al., 2001). As for axisymmetric bodies in free air, some experimental data on the connection between separating boundary layer and base drag are available in the literature (see, e.g., Porteiro et al., 1983). However, to our knowledge the first experimental systematic investigation on this subject is documented in Mariotti and Buresti (2013), where the few relevant results available in the literature are also described in detail and an introductory discussion on the connection between base pressure and near wake flow features is reported. In the experiments of Mariotti and Buresti (2013) different thicknesses of the boundary layer developing over the lateral surface of an axisymmetric blunt-based body were obtained by adding small strips of emery cloth in various positions. The results showed that increasing the thickness of the boundary layer at separation – which was always turbulent – produced a reduction of the base suctions. Furthermore, a deeper analysis of the mean and fluctuating near wake flow suggested that this effect may be connected with an increase of the length of the mean recirculation region present behind the body, which, in turn, is caused by a downstream movement of the incipient instability in the detaching shear layers.

In order to obtain further confirmation to the above experimental evidence, in the present paper we describe the results of numerical simulations carried out to widen the analysed flow conditions and to try to attain a deeper understanding of the parameters and flow features that are responsible for the ascertained connection between base pressure, boundary layer characteristics and near-wake flow features. Furthermore, considering that numerical simulations can also provide the complete flow dynamics, the obtained information is complementary to that given by the outputs of the experimental measurements, which were limited to hot-wire anemometry and pressure measurements over the body surface. A better description of the flow field is indeed important because it is known that the base pressure drag of bluff bodies is closely connected with the flow dynamics in the wake. For axisymmetric bodies this dynamics is more complex than the one characterizing two-dimensional bodies, which is dominated by the von-Karman vortex street. In particular, as the Reynolds number increases the wake undergoes several transitions associated with different wake regimes (see, e.g., Sevilla and Martinez-Bazan, 2004; Barkley, 2006; Bohorquez and Parras, 2011; Bohorquez et al., 2011; Bury and Jardin, 2012 for elongated axisymmetric bodies and Miau et al., 1997; Johnson and Patel, 1999; Mittal and Najjar, 1999; Kiya et al., 2001 for spheres and disks). Another advantage of numerical simulation is that the flow conditions are easier to be controlled than in experiments, and the effects of a given parameter may thus be singled out. However, to our knowledge no previous numerical investigations are available concerning the effect of the boundary layer thickness on the base drag and on the near-wake flow features of axisymmetric bodies. Some clues on the effect of the characteristics of the separating boundary layer on the near-wake velocity field and, in particular, on the length of the mean-flow recirculation region, may only be obtained from results on axisymmetric backward-facing steps (see, e.g., Hudy et al., 2005; Rajasekaran, 2011).

In this paper the variations of the base pressure obtained through boundary-layer and near-wake modifications are analysed by using two sets of numerical simulations, and the results are compared with the ones of the experimental investigation described in Mariotti and Buresti (2013). The objective of the simulations was not to exactly replicate the experiments but, rather, to ascertain whether the general trends found in the experimental campaign could be confirmed and explained also in significantly different flow conditions. First, Variational MultiScale Large-Eddy Simulations (VMS-LES) are carried out on the same nominal body geometry and at the same Reynolds number of the experiments. However, neither the wind tunnel free-stream turbulence nor the model support are present in the numerical simulations, and the variation of the boundary layer thickness is produced by using a free-slip boundary condition over different initial portions of the body surface. Subsequently, Direct Numerical Simulations (DNS) are performed at Reynolds numbers roughly two orders of magnitude lower than in the experiments and in the VMS-LES simulations, in order to investigate on the sensitivity of the relevant phenomena to the Reynolds number. In this case, only the flow over and downstream of the final portion of the axisymmetric body is simulated and a self-similar laminar boundary-layer velocity profile with different thicknesses is imposed at the inlet of the computational domain. The comparison between all the various cases is carried out through the analysis of the mean base pressure and of the mean and fluctuating near-wake velocity field.

2. Problem definition and methodology

2.1. Experimental setup

The main features of the experimental setup of Mariotti and Buresti (2013) are now briefly recalled in order to highlight the differences with the numerical simulations. The tests were carried out in a closed-return, subsonic wind tunnel with a circular open test section 1.1 m in diameter and 1.42 m in length. The considered model is axisymmetric, has a forebody