FLOW BEHIND A TWO-DIMENSIONAL BLUNT-TRAILING-EDGED BODY; PART I: OVERALL ANALYSIS

Marcos A. Ortega
ITA - Technological Institute of Aeronautics
ortega@ita.br

Roberto M. Girardi
ITA - Technological Institute of Aeronautics
girardi@ita.br

Jorge H. Silvestrini
PUC/RS - Pontifical Catholic University
jorgehs@pucrs.br

Abstract. *Some initial results of a numerical investigation of the flow about a two-dimensional blunt-trailing-edged body are presented. The ultimate objective of this research is to undertake a systematic study of the geometry in question, considering attached and detached splitter plates aligned with the undisturbed flow, detached splitter plates normal to the direction of the undisturbed flow, base bleed, among other influences. We shall try to investigate and compare many aspects that are, in a way, scattered in the literature. A DNS (Direct Numerical Simulation) code, a modern computing tool that incorporates most of the state-of-the-art strategies, is applied in the calculations. A series of experiments were performed in order to assess the many interesting fluid-mechanical phenomena that happen to be present in this kind of physical situation. The Reynolds number,* Re*, based on the body base height, ranges from subcritical values up to about* 1000*, but most of the data here presented corresponds to a value of* 200*. A large assortment of parameter distributions is obtained and compared with classical experiments. The aim of this paper is to present an overall analysis of the data, and, therefore, mean values of parameters are used. The focus in this article is on the formation region, and distributions of pressure and velocity fluctuation will be used in its analysis and definition.*

Keywords: *Blunt body, Formation region, DNS*

1. Introduction

The study of the flow in the wake of a blunt body is one of the main topics of research in fluid mechanics. And the reason is directly connected to the attempt of undestanding and controlling the lift and drag mechanisms. The periodicity of the normal force might shorten the structure's life, and the vortex shedding increases the mixing action behind the body. Many authors have dedicated their efforts in the undestanding of this topic. A classical work is that of Roshko (1954, 1955) who measured, among other characteristics, the vortex shedding frequency behind bluff bodies. After that much has been done in the area, with some discrepancies appearing in the measurements. Some of these were due to differences in experiments conditions, but there were also a difficulty related to the three-dimensional character of the wake behind two-dimensional circular cylinders. This was clarified after the studies of Williamson (1989) about the existence of a discontinuity near $Re = 70$ in the Strouhal versus Reynolds curve. Spanwise parallelization of the wake flow, by means of end plates, for example, was sufficient to resolve the discontinuity. These experiments have also triggered a renewed interest on flows at low Reynolds numbers.

Recently, particular emphasis are being placed on matters of flow instability phenomena (Huerre and Monkevitz, 1990) as well as on the control of vortex shedding (Schumm et al., 1994). Schumm et al. divide the several techniques into two classes. The open loop techniques that correspond to some physical modification in the obstacle, such as, for example, the use of splitter plates, periodic rotation of the cylinder, etc. and the closed loop techniques that consist of acting upon the flow itself by way of base suction, base bleed, wake heating, to name a few. The splitter plate, also classified in the literature as one of a kind of passive control, has been widely and successfully used as a controlling mechanism of vortex shedding behind a bluff body. Roshko (1954) has experimented with splitter plates attached to and detached from the cylinder. In the former case shedding disappeared completely when the splitter length reached five times the diameter ($Re = 1.45 \times 10^4$). Gerrard (1966) also studied experimentally the wake behind the cylinder fitted with attached splitter plates and showed the dependence of Strouhal number upon the length of the plate. Many other works could be cited and some can be found in the paper of Kwon and Choi (1996).

There are also numerous numerical simulations of the flow behind a circular cylinder (example, Braza et al., 1986), but not many considering splitter plates, and especially in the transient range ($100 < Re < 300$). Kwon and Choi (1996) investigated the laminar vortex shedding behind a circular cylinder and its control by means of splitter plates mounted at the rear of the cylinder. The Reynolds number was varied in the range $80 < Re < 160$, and the numerical code integrates

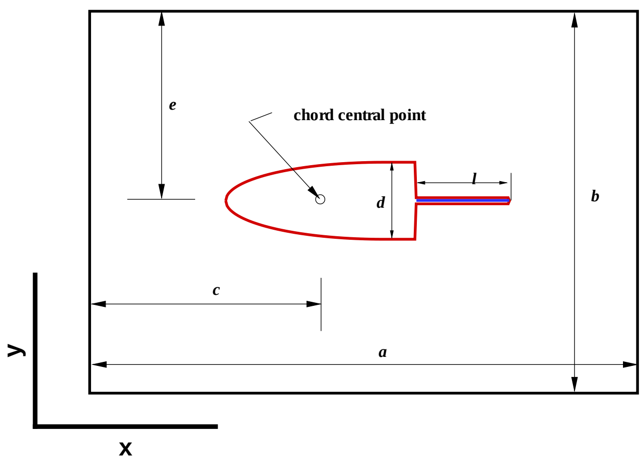

Figure 1. Geometry of flow with main dimensions of the calculation domain.

the two-dimensional unsteady Navier-Stokes equations in conservation law form and generalized coordinates.

The aim of the present study is the numerical investigation of the flow behind a two-dimensional model with a blunt trailing edge. The numerical tool is a DNS code, whose main characteristics shall be presented in the sequel. The majority of the cases to be encountered in the literature corresponds to the flow about a circular cylinder. Few of these focus on a blunt-trailing-edged body. Among these stem the works of Berman (1965, 1967) who studied extensively the shedding mechanism considering as control devices splitter plates and base bleed. The same case will be considered here and results relative to the body fitted with splitter plates will be presented in this paper. The ultimate objective of this research is to undertake a systematic study of the geometry in question (see Fig. 1), considering attached and detached splitter plates aligned with the undisturbed flow, detached splitter plates normal to the direction of the undisturbed flow, base bleed, among other influences. We shall try to investigate and compare many aspects that are, in a way, scattered in the literature. For example, Bearman (1965) has attempted to correlate the vortexes formation region to the longitudinal distribution of velocity fluctuation, while Roshko (1954) did the same but considered the longitudinal pressure distribution. We shall try to consolidate studies like these, and others, in only one situation corresponding to a unique geometry. On the other hand, numerical studies have the advantage of providing the researcher with a complete set of data along all the flow domain, what guarantees the possibility of a complete analysis. This is not always possible in experimental studies that are most of the time limited by the size of models and probes, influence of the probes or measurement techniques upon the flow topology, and so on.

This paper is organized as follows. Initially the body and flow geometry are presented, followed by the main characteristics of the numerical code. Results are then presented and discussed for the case of the body fitted with attached splitter plates. In this particular paper we shall concentrate mainly on mean distributions of parameters, such as pressure and velocity fluctuations. The idea is to keep a grossly overview and a more general analysis of the situation. In a companion paper (Ortega et al., 2005) we will dedicate attention to the details of the physical mechanisms at the wake.

2. Numerical method

Details of the model and computational domain are shown in Fig. 1. The model cross-section consists of an ellliptic nose section, with semi-major and minor axes of $5/6$ and $1/12$ respectivelly, followed by a parallel-sided section of length $1/6$. The base height, d, is equal to $1/6$. All of these are dimensionless figures and the reference length is the chord of the body. Observe that l indicates the splitter length. The body is fixed to the Cartesian system of coordinates, with x denoting the streamwise and y the crosswise directions, respectively. Most of the cases were run considering the following main dimensions: $a = 36d$, $b = 14.4d$, $c = 12d$, and $e = 7.2d$, where c and e mark the position of the chord central point. In general, each grid unit was divided in 150 equal intervals.

The direct numerical simulation of the flow in figure 1 was performed by a multi-purpose code named Incompact3d. This code has been already verified and validated, and results corresponding to complex flows simulations and forces calculations have been extensively published (Lamballais and Silvestrini, 2002, Lardau and Lamballais, 2002, Silvestrini and Lamballais, 2004, Ortega and Silvestrini, 2004). The main characteristics of Incompact3d are as follows. (i) Solves the two- and three-dimensional incompressible Navier-Stokes equations, and uses a “pressure-based type" strategy, what means that a Poisson equation is associated to the calculation; (ii) Advancement in time. Realized by means of an hybrid Adams-Bashforth/Runge-Kutta strategy; (iii) Space discretization. Spatial derivatives are approximated by compact finite-difference schemes (Lele, 1992); (iv) Poisson equation. If the longitudinal flow direction — the main direction of flow — is periodic the equation is completely resolved in spectral space, otherwise, a mixed method is applied where part of the equation is discretized in physical space and part in spectral space (Lamballais, 1996); (v) Strategies of solution: DNS and LES; (vi) Boundary conditions at solid surfaces. Simulated by means of the so called “virtual wall" (sometimes also called “immersed boundary") technique (Goldstein et al., 1993). Enforcing no-slip boundary conditions in such way permits the discretization on an uniform Cartesian grid, an outstanding advantage.

3. Results and discussion

3.1 Base pressure

Pressure is one of the main physical factors affecting the flow at the body base region. Roshko in his basic work of 1954 had already pointed out that the mechanisms of the wake are mostly affected by the events happening at the region close to the body base, in contrast to the momentum diffusion across the shear layers that emanate from the separation points. If this is the case the installation of splitter plates should interfere strongly on the vortexes dynamics. We begin by illustrating this effect through figures 2 and 3. Fig. 2 shows distributions of mean pressure accross the base, for the cases of the body without splitter plate and for an attatched splitter plate of length $l/d = 3$. Fig. 3 displays values of the mean pressure along a line that borns at the center of the body base and stretches downstream parallel to the x-axis. In both cases we observe an increase of the base pressure due to the presence of the plate.

Further, on Fig. 4, a plot of $-C_p$ at the base against splitter plate length is presented. By "$-C_p$ at the base" we mean the value of the coefficient at the base height mid-point. C_p, the pressure coefficient, is defined standardly as $(p - p_\infty)/(\rho {V_\infty}^2/2)$, where symbols have their usual meaning and the subscript "∞" refers to the undisturbed flow condition. At first there is a sharp increase in base pressure, and therefore a reduction in drag, for splitter-plate lenghts up to $l/d = 2$. After that, there is a mild increase with a maximum corresponding to $l/d = 3$, and afterwards, for lengths beyond $l/d = 4.0$, the value of the pressure coefficient falls to a basic constant value of about -0.56. This same qualitative result had been already obtained experimentally by Bearman (1965), who worked with Reynolds numbers of 1.4×10^5 and 2.45×10^5. We have also calculated the mean drag as a function of the splitter plate length and its distribution is given in Fig. 5; these information in a way complement the data in Fig. 4. It is very interesting to note that the drag has a minimum for l/d about 3. The time-averaged drag agrees qualitatively very well with the results of Kwon and Choi (1996) who investigated the flow about the circular cylinder with and without splitter plates for a Reynolds number in the range $80 - 160$.

3.2 The Formation Region

The “formation region" is referred to as the region between the base of the body and the start of the fully developed vortex street. The start of the fully developed street is considered as coincident with the position of maximum velocity fluctuation (Schaeffer and Eskinazi, 1959). This region is instrumental for the development of the wake, and we shall try to illustrate and discuss some important points. It is pertinent to observe that the discussion about shedding frequency and related matters is being presented in a companion paper (Ortega et al., 2005). Anyway, we inform that shedding is completely inhibited for a splitter plate length somewhere between 1.5 and 2, for a Reynolds number equal to 200, and that the critical Reynolds number for the present geometry is about 90. Pressure and velocity fluctuations seem to be the most important influences on the definition of the formation region. Initially, by observing Fig. 3, and for the case of the plain body (the body without splitter plate), we see that there is a region of low pressure whose distance to the base of the body is about $1.15d$. How does this region relates to the formation region? Before trying to answer this question let us examine the distributions of root mean square velocity fluctuation.

The “measurement" of the velocity fluctuations is made at a distance of a quarter of the base height from the base centerline. These kind of information are plotted in Fig. 6. These graphs have many interesting features. First of all there is really a peak of fluctuation in front of the base. The introduction of the splitter plate, as expected, moves the peak forward and decreases the peak value. It is important to note that our solution reproduces very well the experimental curves (see Bearman, 1965). There are some discrepancies however that are certainly due to the difference in the values of the Reynolds numbers. The principal is the fact that our peaks are shifted farther relative to the base. For example, in the case of the body without splitter plate, we found the peak at $x/d = 2$, while the experimental value of Bearman, for $Re = 1.4 \times 10^5$, is equal to 1. The formation region tends to be larger for smaller values of Re.

Besides these “measurements" of velocity fluctuations along lines parallel to the centerline we have also calculated

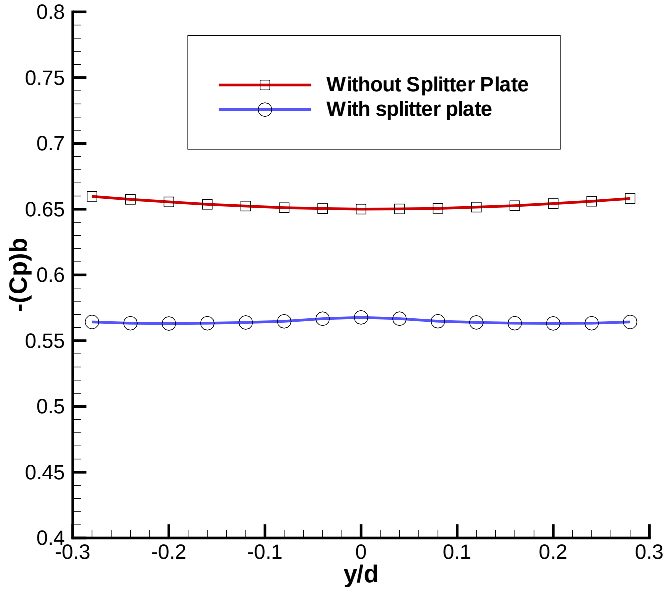

Figure 2. Mean-pressure distribution accross the base. $Re = 200$, and the splitter plate length is equal to $3d$.

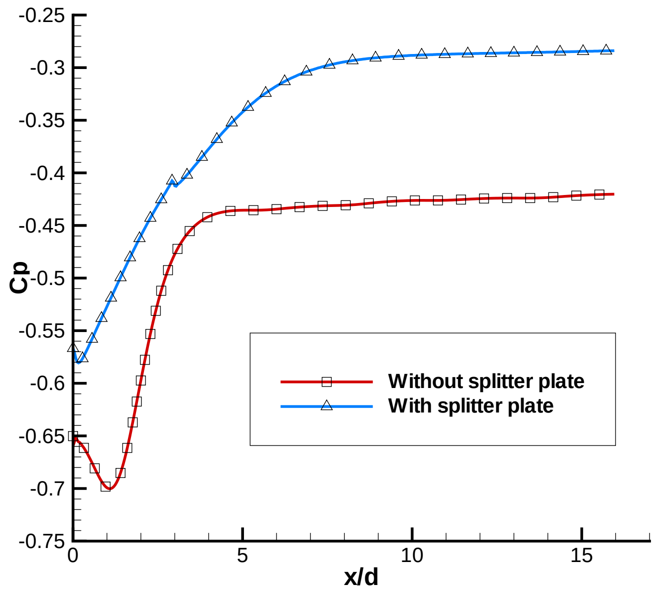

Figure 3. Mean pressure distribution along wake center line. $Re = 200$, and the splitter plate length is equal to $3d$.

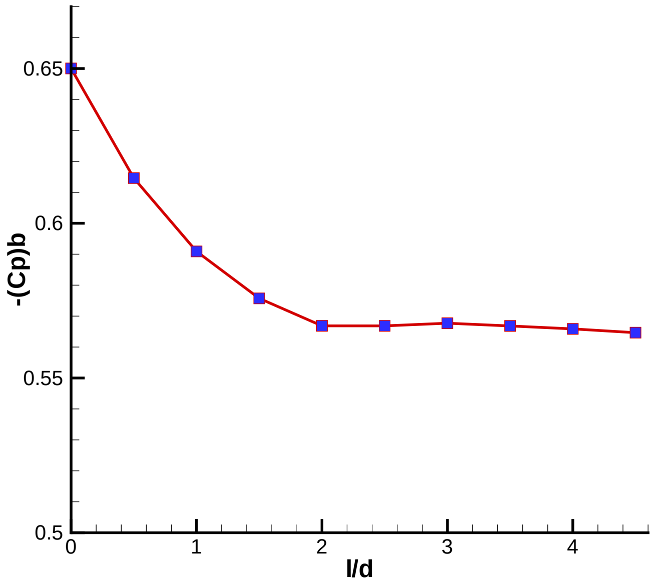

Figure 4. Distribution of base-pressure coefficient as a function of splitter plate length. $Re = 200$.

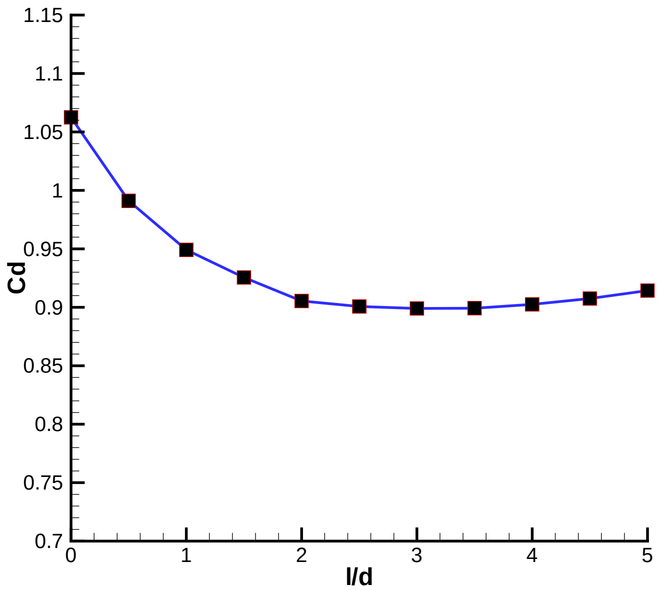

Figure 5. Drag as a function of splitter plate length. $Re = 200$.

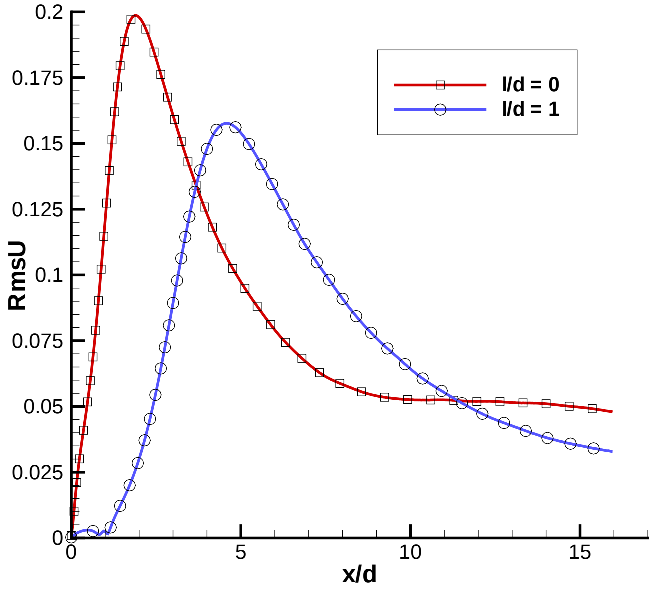

Figure 6. Root mean square of the horizontal velocity fluctuation as function of the distance from the body base.

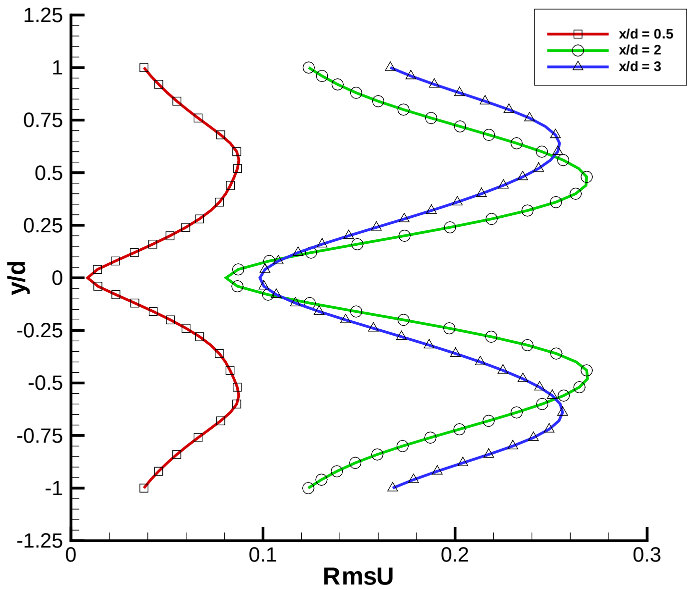

Figure 7. Velocity-fluctuation traverses accross the wake for the plain body. $Re = 200$.

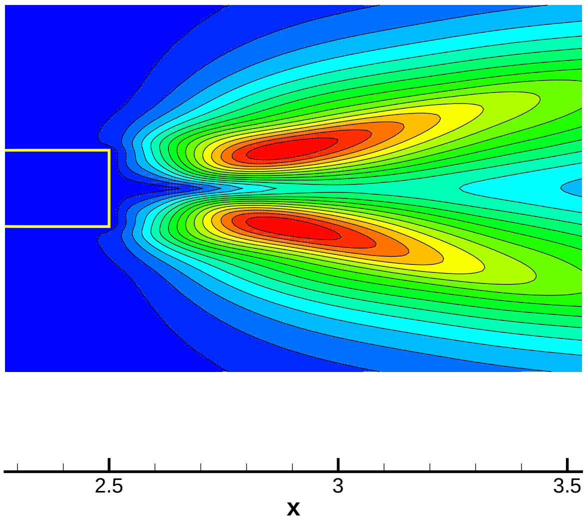

Figure 8. Distribution of the horizontal velocity fluctuation at the base region.

the root mean square values throughout the whole field of flow. This permits the obtention of other kind of distributions like the ones appearing in Fig. 7. In this figure, distances are measured in terms of d and are referred to the mid-height base point. Here we represent traverses accross the wake in the y-direction. Near the base these traverses reproduce sharp peaks produced by passing through the free shear layers emanating from the corners of the model. The maximum of the peaks forms at a distance about $2d$ from the base of the body (Fig. 6). But, by observing Fig. 7, another very interesting feature gets apparent. Initially, that is, closer to the body, the peak to peak distance is larger, then it gets smaller — the peaks move in towards the center of the wake —, and then they diverge. In other words, there is a necking effect, which had already been pointed out by Schaefer and Eskinazi (1959) (see also Bearman, 1965).

Moreover, many authors (Kovasznay, 1949, Schaefer and Eskinazi, 1959, Berman, 1965) after examination of the wakes of circular cylinders at low Reynolds numbers, have stated that vortexes centers are practically coincident with positions of maximum velocity fluctuations. That is, the distance between the related peaks constitute a very good aproximation of the lateral spacing of the vortices. The extent of the formation region can then be established according to Bearman (1965), as the region between the body producing the vortices and the point of minimum spread of vortices. Therefore, for $Re = 200$, and from Fig. 7 we conclude that, for the geometry of Fig. 1, the extent of the formation region in this case is about $2d$. How does this relate to the pressure distribution? From Fig. 3 we see that the region of lowest pressure is located about $1d$ from the body base. But this lowest pressure is associated with the low-pressure region at the center of the vortex that is being formed. Therefore, one can argue that the formation region is mostly associated with the velocity fluctuation by means of its peaks path, than to the pressure distribution. The region of lowest pressure is in fact immersed in the formation region. Fig. 8 shows the field of root mean square velocity fluctuation for the wake region. From the figure, the reader can clearly observe the necking effect referred above. The scale that is shown in this figure indicates x-distances in terms of the plain body chord, and the reader should remember that the body chord is equal to $6d$.

4. Conclusion

The present authors have started a systematic study of the flow about a blunt trailing-edged body, using a DNS code as the numerical predictive tool. The first results were discussed above, and had the main purpose of confronting some established literature concepts and data (see Bearman, 1965). In general, predictions of the main aspects of the flow are in excellent agreement with the data, in spite of the difference in the value of the Reynolds numbers. It is interesting to observe that the body drag presents a minimum value for a splitter plate length about 3. Besides, a very important assertion about the necking effect at the formation region was verified and confirmed. The formation region extent seems to be consistently related to the velocity fluctuation and not much related to the mean pressure low in front of the body base.

5. Acknowledgements

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