# FLOW BEHIND A TWO-DIMENSIONAL BLUNT-TRAILING-EDGED BODY; PART II: PHYSICS OF THE WAKE

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***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* $200$*. The contents of this article are related only to the initial case of the body fitted with attached splitter plates, and we begin the process of physical analysis of the flow, especially in the wake region. Particular attention is payed to some aspects of the shedding mechanism as well as to the dynamics of the vortices. In this later case we shall deal with the mean and the instantaneous fields of flow, in a trial to understand some of the main physical mechanisms that are involved.*

***Keywords:*** *Blunt body, Wake physics, 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. There is a miriad of studies in the literature, both experimental and theoretical, and we shall not attempt to list them here. There are lists of works that can be accessed by the reader — see, for example, a good sample of articles in the paper by Kwon and Choi (1996) (see also Ortega et al., 2005). Most of the time the geometry of the body is a circular cylinder of constant radius, mounted such that the direction of its axis is located normal to the undisturbed velocity vector.

The aim of the present study is the numerical investigation of the flow behind a two-dimensional model with a blunt-trailing edge. An example of a treatment of this geometry is represented by the classical experimental 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 some results relative to the body fitted with splitter plates will be presented in this paper. A blunt-trailing edge is very important because it is representative, in practice, of many cases, as, for example, buses, trucks, cars, and so on. It is true that in real life the three-dimensionality of the flow is decisive, but we shall start with the two-dimensional configuration in order to gain insight and experience. Besides, two-dimensional studies of other geometries can be easily found in the literature and they will, sometimes, serve the important purpose of comparison references.

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. The numerical tool is a DNS code, whose main characteristics will be presented in the sequel. Numerical studies have the advantage of providing the researcher with a complete set of data along all the flow

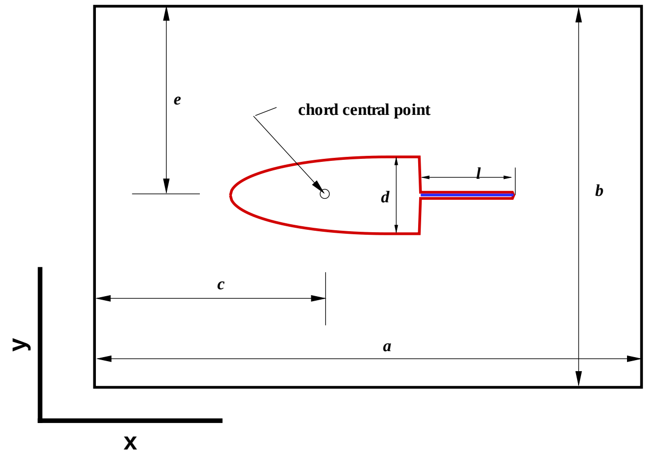


Figure 1. Geometry of flow with main dimensions of the calculation domain.

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 the shedding mechanism as well as on the dynamics of the vortices. In this later case we shall deal with the mean and the instantaneous fields of flow, in a trial to understand some of the main physical mechanisms that are involved.

## 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.

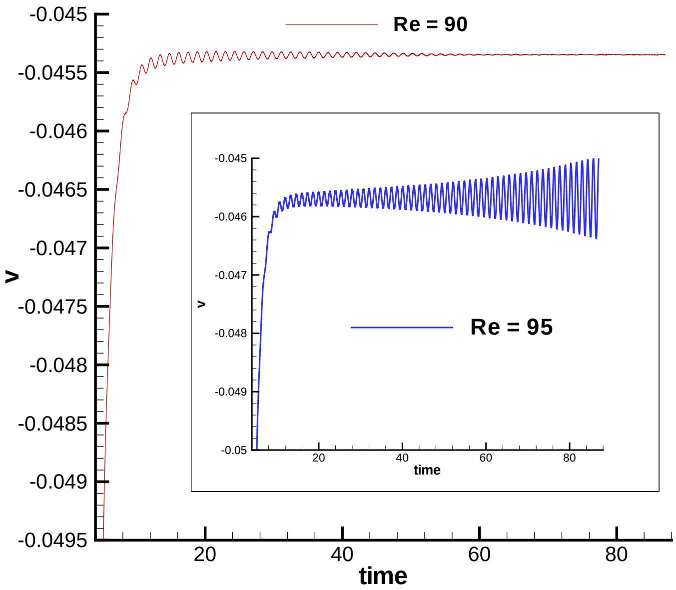


Figure 2. The time history of the y-component of velocity at the transitional Reynolds number.

## 3. Results and discussion

### 3.1 The Shedding Mechanism

In this section we will examine some aspects of the shedding mechanism, considering as the leading parameter the shedding frequency in its nondimensional form, i.e., the Strouhal number, $St = fd/U$ ($f$ is frequency and $U$ is the undisturbed velocity). It is instructive to discuss the positions of the "numerical anemometers". Here we have profited from the experimental trials made by Bearman (1965). Based on his experiments he proposes two rules: "first, the wire should be placed just outside the wake, and, secondly, the best streamwise position was downstream of the splitter plate but not more than one base height beyond the end". Therefore, we have done the following. The crosswise position of the anemometer(s) was always taken as $y = 0.75d$ relative to the base centerline. In the streamwise direction we have "installed" a certain number of anemometers, depending on the size of the splitter plate. For $l/d = 0$ and $0.5$, one anemometer was positioned such that $x/d = 1$, where $x$ is considered here as the distance to the body base. For splitter plates whose lengths were longer than $0.5$ at least two anemometers were installed, one such that $x/d = l/d$ and the other with $x/d = (l/d + 1)$. For longer splitter plates other anemometers were placed in positions between the body base and the plate tip. From these "measurements" it was an easy task to obtain the frequency, considering that the velocity oscilations (after an initial transient process) were virtually sine waves of constant frequency and practically constant amplitude

First of all, it is necessary to discuss the question of the critical value of the Reynolds number for the present geometry — here we speak of the plain body, that is, the body without splitter plate. Until now we have run cases ranging from $Re = 60$ up to $Re = 500$, where $Re$ is calculated taking as reference length the body base height. A refinement was undertaken at the lowest end of this interval and the transition was verified for $Re = 95$, or at least for a value between 90 and 95. This can be verified by inspecting Fig. 2 where the time evolution of the y-component of the velocity is shown for Reynolds numbers equal to 90 and 95. The first 5 units of dimensionless time (the transient régime) were cut from both graphics in order to enhance the (small) variation of the parameter. But, it is obvious that the initial perturbation, which is due to the fact that the body is set in motion instantaneouly at $t = 0$, is being damped for $Re = 90$ and amplified for $Re = 95$.

Before leaving this topic an observation is due. For other classical shapes, circular cylinders and flat plates, for example, the transition from steady flow to a shedding pattern is realized for lower values of the Reynolds number. The interval of Reynolds number is basically $35 - 50$ (Roshko, 1954, Schlichting, 1979). For the present case we have found the transition at $Re = 95$. Two factors might explain this difference. The first is what we could recognize as the "degree of bluntness", that can be defined as the ratio between the wake width and the base height of the body. The plain body of Fig. 1 has a much less degree of bluntness when compared to the other shapes, what might eventually stabilize further the twin vortices at the base of the body. The other factor is the history of the boundary layer and its thickness at the

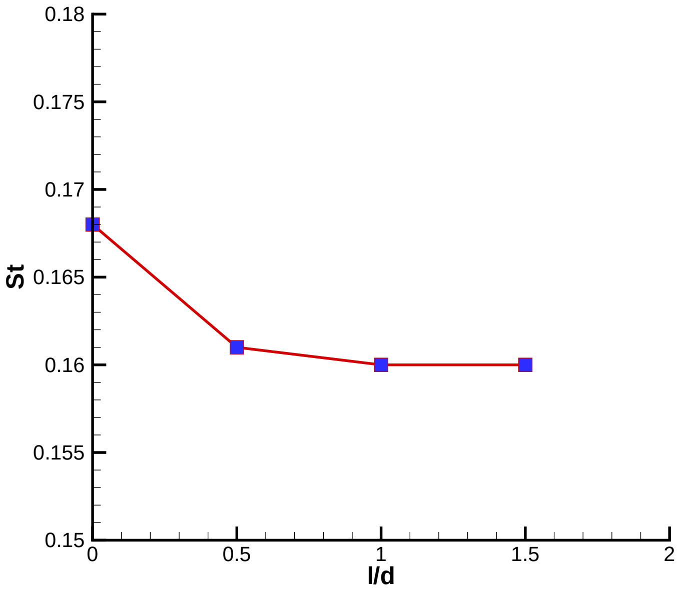


Figure 3. Strouhal number as a function of the splitter plate length.

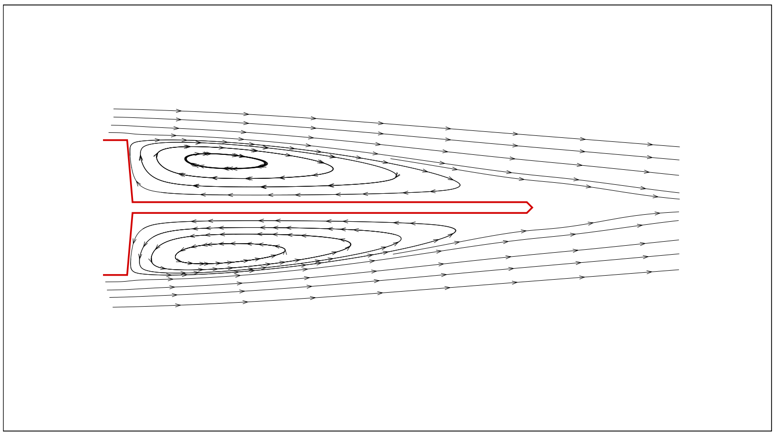

Figure 4. Mean field of flow. Splitter plate length $l/d = 3$.

separation station. But further studies are necessary in order to fix the point, especially other experiments with bodies of different aspect ratios.

Splitter plates with lengths ranging from $0.5d$ to $5d$ were “installed" and the flow calculated for a Reynolds number of 200. Fig. 3 shows the distribution of $St$ as function of $l/d$. One can see that the wake with the greatest frequency is generated by the body without splitter plate, and the application of the plates acts in the sense of slightly decreasing the frequency. This is in contrast to the results obtained by Bearman (1965). The experimental distribution presents a maximum for $l/d$ about 1.4, and, besides, the values of $St$ are in general greater than those of Fig. 3 (mean experimental values are about $0.27$). These discrepancies are certainly related to the values of the Reynolds number. Bearman experimented with two different Reynolds numbers, $Re = 1.45 \times 10^5$ and $Re = 2.45 \times 10^5$ while we have worked with $Re = 200$. On the other hand, our results are consistent with those 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 $80 - 160$. These authors recognized two regimes: for $Re = 80$ and 100 the Strouhal number decreases systematically as the length of the splitter plates increases, while for a Reynolds number larger than 120 the Strouhal number passes by a maximum.

In our studies we have found that shedding ceased completely for a splitter plate length somewhere between $1.5d$ and $2.0d$. The experimental range is $2.0 - 2.5$ (for $Re = 1.45 \times 10^5$ and $Re = 2.45 \times 10^5$, Bearman, 1965). But most interesting is the point made by Bearman about the shedding being inhibited for $l/d = 2.5$, considering that reattachment of the flow had ocurred at $2.9d$ with the $3.0d$ splitter plate (experimental values). At the time, the author wrote: “One has to postulate, therefore, the flow forming a closed bubble beyond the end of the plate". We have tried to clarify this

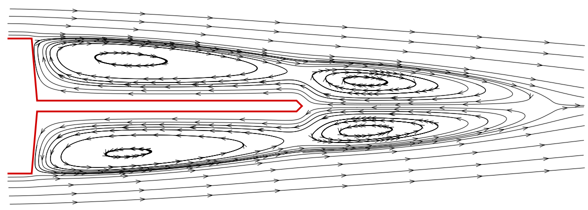

Figure 5. Mean field of flow. Splitter plate length $l/d = 2$.

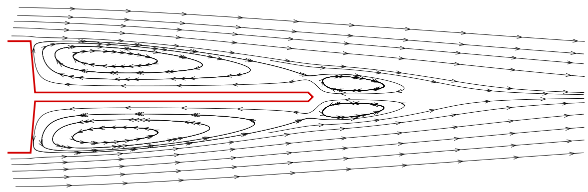

Figure 6. Mean field of flow. Splitter plate length $l/d = 2.5$.

point. Fig. 4 shows the mean flow about the body for a $3d$ splitter plate. There is no shedding and the reattachment length is equal to $2.5d$ ($Re = 200$), and therefore the plate has sufficient length to accomodate the standing vortexes. This is not the case for the $2.5d$ and $2d$ plates, as can be seen in figures 6 and 5. In these instances the front of both the great structures plus the room occupied by the plate tip form a kind of virtual step, what induces the appearance of other smaller vortexes in front of the plate in order to accomodate the flow topology. Due to the sign of the vorticity on both sides of the plates, the two structures on each side ultimately form a great bubble. Therefore, the “postulate" advanced by Bearman is absolutely justified by the numerical prediction. There are in fact two bubbles stretching beyond the plate, but inside each bubble there are two structures and not a single one, what might have been the intuition of that author at that time. But what seems to be the most important physical aspect here is the anchoring effect provided by the plates. This is clear by observing the sequences of figures 4, 6, and 5. It is apparent that the big bubble that encapsulates the two vortical structures (on each side) is being anchored by the plates, and, with the shortening of the plate length, there will be a time when this anchoring effect will not be sufficient to stabilize the bubbles, and then, the structures get “liberated" and shedding is established.

Another strategy to destabilize the vortexes pattern of Fig. 5 is to raise the Reynolds number. We have run the same case but with $Re = 500$. The result is shown on Fig. 7 for a dimensionless time of $84.11$ units. At exactly this same instant of time, but for $Re = 200$, the flow topology corresponds to that of Fig. 5. Another very important point that can be observed in Fig. 7 is the appearance of a secondary vortex at the tip of the splitter plate. This structure, albeit being secondary, has the same level of vorticity as the primary ones. Therefore, it will interact with them and the result will be an increase in the Strouhal number (see also Kwon and Choi, 1996). We are now, at the moment of writing this article, repeating all the calculations but with a Reynolds number of $500$. This will allow the possibility of drawing a broader perspective of the problem as a whole.

## 4. Conclusion

The flow about a blunt-trailing-edged body fitted with splitter plates has been numerically investigated. The transition Reynolds number for the plain geometry in question was found to be between $90$ and $95$. The shedding mechanism and its control by means of splitter plates was investigated at a Reynolds number of $200$. The overall results agreed qualitatively

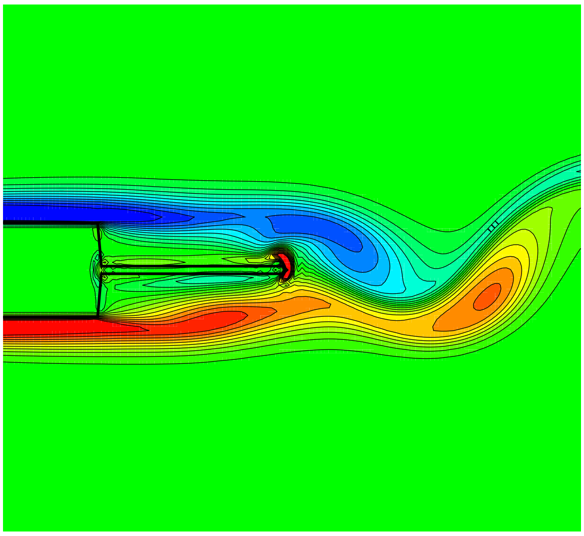

Figure 7. Instantaneous vorticity field. Splitter plate length $l/d = 2$. $Re = 500$.

well with the literature, and the main discrepancies are certainly due to differences in the value of the Reynolds number and the geometry investigated. Shedding was completely inhibited for a length of the plate somewehre between 1.5 and 2. Besides, and most importantly, we have verified an important assertion made by Bearman (1965) about the topology of the flow for lengths of the splitter plate close to, but less than, the reattachment length. This paper represents the initial efforts of a research program whose main aim is to investigate the flow about the present geometry when subjected to a variety of influences.

## 5. Acknowledgements

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