FLOW CONTROL DOWNSTREAM OF A BACKWARD FACING STEP: A DPIV STUDY

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Abstract

In the present paper a control method for separated flows will be analyzed through the DPIV technique. The method consists in substituting the solid wall downstream the step, in the separation region, by a porous wall under which lays a closed cavity. The specific advantages of the measurement technique allow to provide an explanation for the controlled flow behavior, which experiences a remarkable stabilization. A better understanding is expected to provide the ability to design control devices specifically tailored for practical applications.

1 Introduction

The back facing step (BFS) flow is an appropriate test case for real-life separated flows because of several reasons. It shows essentially all the flow features of practical engineering applications where separation and reattachment occur; moreover, the geometry is very simple and easily reproducible. Furthermore, the separation point is *fixed*, which reduces greatly the experimental difficulties and the measurement uncertainties. A schematic of the flow topology and the reference system employed throughout the paper is presented in Fig. 1.

Most of the engineering problems that are posed by separating flow are associated with the high increase in dissipation and thus in aerodynamic drag and with the consequences of the stress fluctuations caused by the high level of unsteadiness that characterizes this class of flows. The latter effect, in particular, can bring to various undesirable phenomena like fatigue ruptures or collapses due to excitation at some resonant frequencies of the structures bounding the separated region.

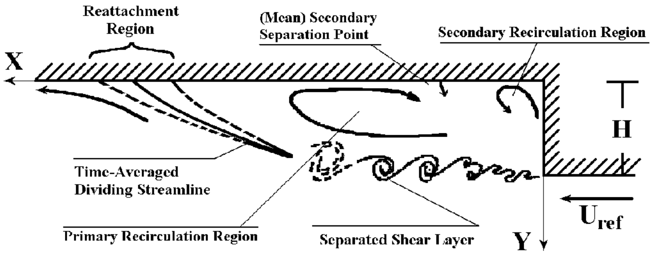

Fig. 1 Schematic of BFS flow topology and reference system used in the present work.

An important technological outcome of the basic research on separated flows is thus related with studies about methods aimed at controlling the unsteadiness around the separated region.

Several authors (see e.g. [4, 8, 13]) have worked on the separated flow downstream a step, evidencing several aspects of the problem related with the mean flow structure and with the unsteadiness of this kind of flow. About this last point, investigations indicate the contemporary presence of at least two instability sources, namely the vortex shedding from

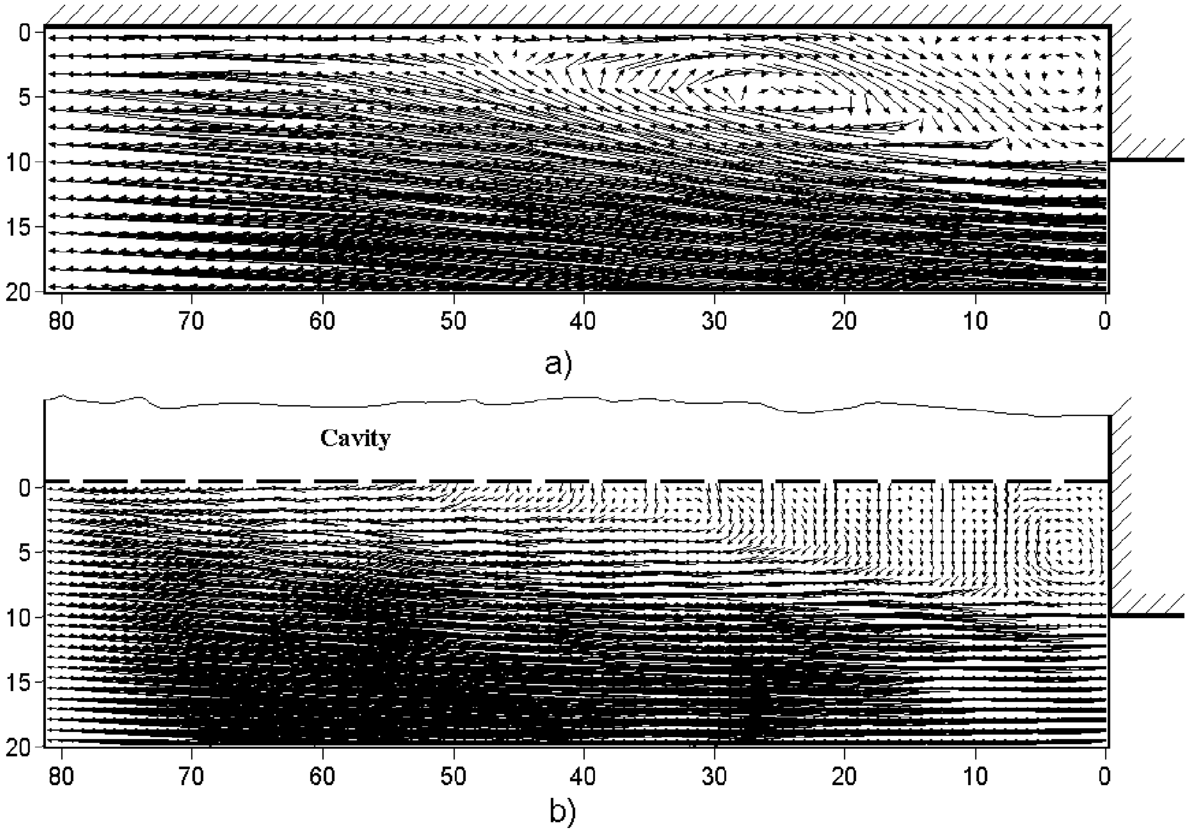

Fig. 2 Typical whole-field averaged maps of separated region. a) Natural case; b) controlled case. Dimensions in mm; the walls' locations are indicated by slanted lines.

the primary separation point and a low frequency motion of the whole separated region, called 'flapping'. These phenomena produce unsteadiness on two frequency ranges, separated by roughly one order of magnitude. Despite the important difference in frequencies, there are also indications of an interaction between the two phenomena.

A control method that was reported to be of satisfactory success in bibliography is the porous wall method [10, 11], that allows to stabilize the flow by reducing the unsteadiness. Other ways of controlling the separated region are an acoustic control focused on the separation point [3, 5] or modulated fluid jets exiting the separation point [9]. The latter method produces a regularization of the vortex shedding and thus a flattening of the whole field unsteadiness. Finally, another passive control method was recently explored [17], which consists of a LEBU-like device placed in front of the step edge. It was shown that careful placement of the device allows to greatly reduce the fluctuation, whilst deeply modifying the average stress values.

Within the research project going on at CNR-CSDF in cooperation with DIASP-Politecnico di Torino and aimed at reaching a better understanding of the origins of separated regions unsteadinesses and to the control of these phenomena, [7, 14, 15, 17], the porous wall control method was analyzed by using the DPIV technique.

2 Experimental Apparatus

Experiments were carried out in the Hydra water tunnel. This facility is a closed loop, open surface channel with 350 × 500 × 1800 mm^3 test section. The test model was constituted

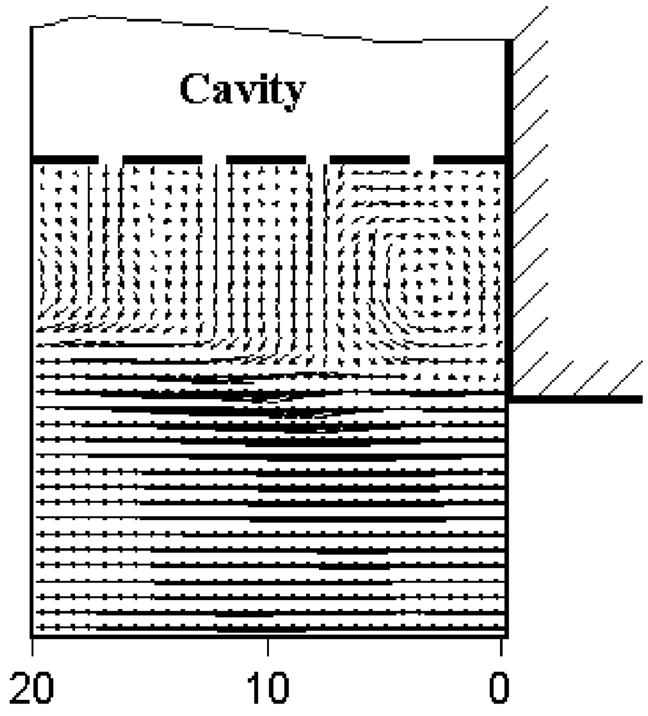

Fig. 3 Zoom of the controlled velocity field in the near step region.

by two plexiglass plates. The two blocks, when joined, constituted a plate 1800 mm long and spanning the whole width of the test chamber, and with a step 10 mm high at a distance of 1180 mm from the leading edge. The modular construction allowed to move one plate relative to the other, hence producing under the step foot a cavity 125 mm (i.e. 12.5 step heights, H) long and 20 mm deep, over which a porous panel could be positioned; this panel was a steel plate 1 mm thick through which 1 mm diameter holes were drilled in an hexagonal pattern with a spacing such to provide a porosity of 26.4%.

The water of the tunnel was seeded with spherical solid particles, 2μm nominal diameter. A Nd-YAG laser source with 200 mJ of energy per pulse and a duration of 8 ns provided double-pulsed light sheets (approximately 0.5 mm thick) with a repetition rate of 10 Hz. Images were recorded using a 1008 × 1012 pixels CCD videocamera (Kodak Megaplus ES 1.0). The local particle-image displacement was determined by using a cross correlation based algorithm [2, 18], structured as an iterative multigrid method [12] whose last iteration was performed on 32 × 32 pixels interrogation windows with 50% overlap (see [6] for details); each of the vector hence obtained represents a locally filtered value of the velocity in a physical dimension of $\Delta x =$ 0.625 mm, $\Delta y = 0.625$ mm in the plane (x, y). Statistical analysis was performed by averaging over 450 PIV images for both the natural and the controlled case.

PIV measurements were taken in a plane (x, y) normal to the wall; x is the streamwise coordinate. The (x, y) images were situated in the test chamber central plane; analysis was performed in the area 0 mm $< x <$ 80 mm, 0 mm $< y <$ 20 mm. In order to fully encompass the separation region with a definition sufficient for analysis, the field had to be divided into four subregions where PIV images were subsequently recorded. Hence, it is not possible to obtain an instantaneous picture of the whole field, but only of each separate subregions. It has to be remarked, on the other hand, that the averaged values show an excellent degree of matching, as will be shown later (see, e. g., Fig. 5, where only a slight misalignment of the isolines at the connection locations are present).

The upstream turbulent boundary layer flow was characterized by $Re_\vartheta = 1160$, $H =$ 1.32, $u_\tau/U_e = 0.044$, $\delta = 43$ mm and an external free-stream turbulence of 1.2%.

3 Low-Frequency Unsteadiness

As discussed in 1, the back-facing step flow is characterized by a large-scale fluctuation of relatively long period (flapping motion). The origin of this motion is a current subject of research; in [16], working on flow visualization and time-resolved measurements, the following scenario was proposed in order to explain the flapping motion. In the cited paper, it was postulated that there exists a cyclic be-

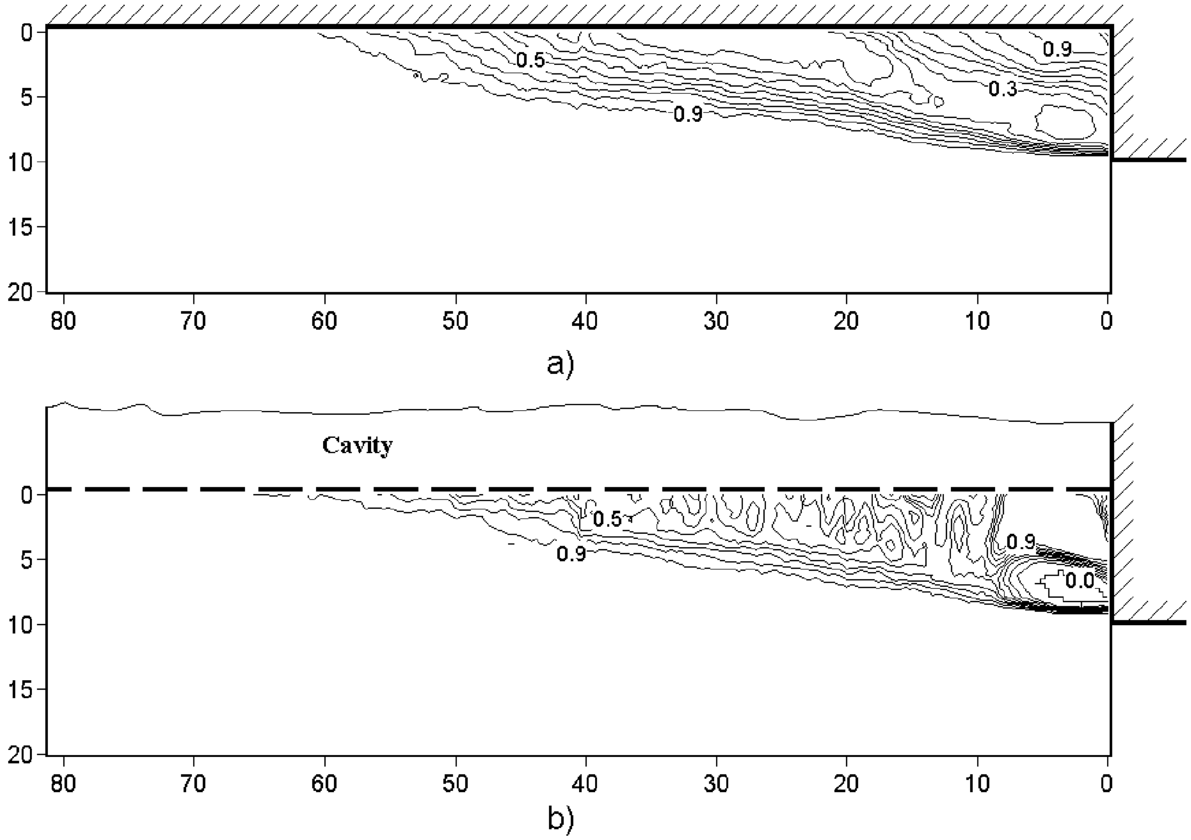

Fig. 4 Forward-Flow Probability maps of separated region. a) Natural case; b) controlled case. Dimensions in mm; the walls' locations are indicated by slanted lines.

havior originating in the reattachment region, where the flow is observed to travel along the wall towards the step; this back directed near wall flow passes along the underside of the primary bubble and, after lifting from the wall, is partly entrained around the primary bubble and reaches again the free shear layer. Another part of the back flow (in some instances, most of it) intermittently reaches the step wall in the form of a jet flow. This jet flow forms a stagnation point (secondary reattachment) at a position fluctuating between 0.7 and 0.9 H from the step foot. At this stagnation point, the jet divides into a part turning toward the inner corner of the step and another one entrained by the separated flow at the step. The relative importance of these two parts fluctuates: the majority of the flow from the jet is sometimes directed towards the step foot and sometimes towards the shear layer. The former fraction, turning back downstream, originates a vortex bounded by the step walls and with a rotation opposite to the one of the primary bubble.

The interaction of the back flow jet and of this vortex causes an increase in the velocity difference between the shear layer and the separated region, increasing thus the formation frequency of the vortices shed from the step, hence their growth rate. This effect raises the amount of fluid traveling up the wall, strengthening in turn the jet and the corner secondary bubble. The growth of the secondary bubble strength, accompanied by a clearly visible growth in size, continues until its dimension becomes of the same order as the step height. Soon after this, a bursting of the organized flow is observed, concluding the cycle that later is repeated. In [16] it is shown that the average frequency of this cycle corresponds

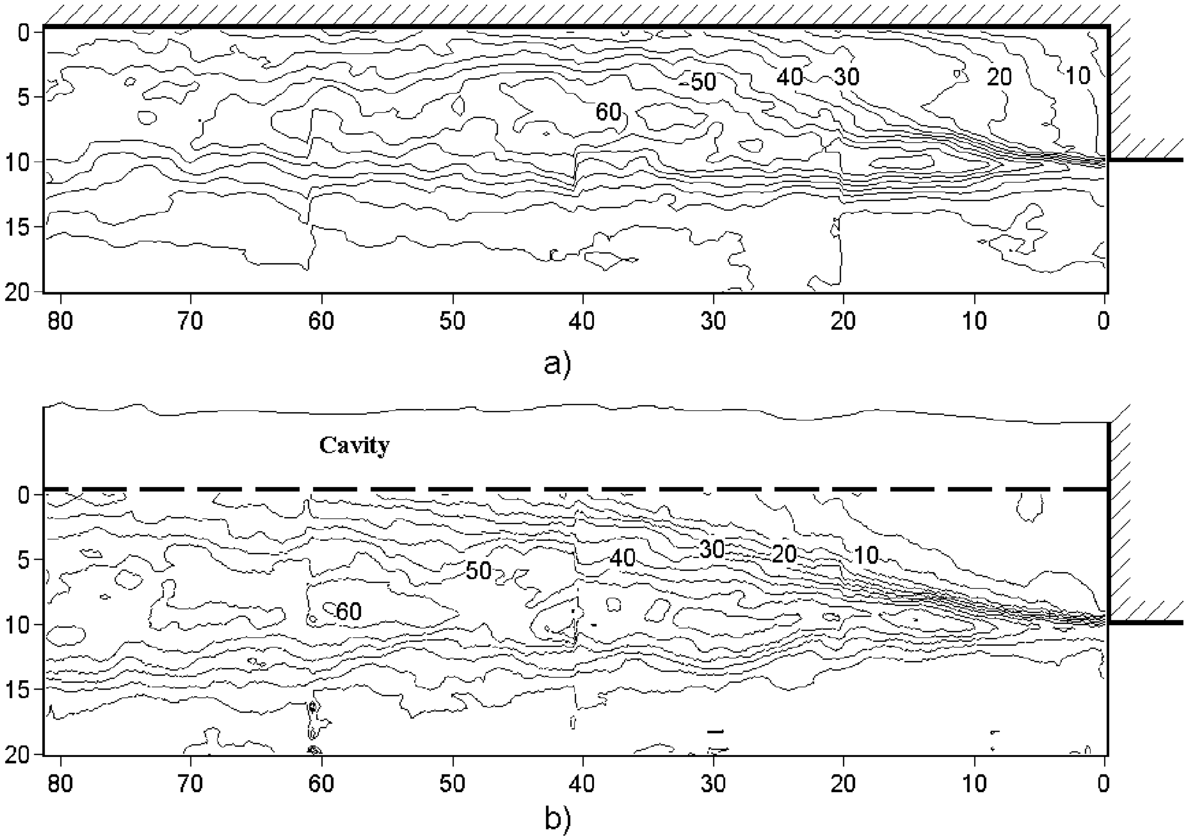

Fig. 5 u_{RMS} field. a) Natural case; b) controlled case. Distances in mm; isolines values in mm/s.

to the typical frequencies reported in the literature for the flapping motion.

4 Experimental Results

First of all, whole field average velocity maps of the natural and controlled steps are presented in Fig.2. It is clear from this figure that the control produces great modifications in the flow topology. Specifically, in the controlled case separated region it is no more possible to identify a primary bubble, but a cell structure is clearly present. Remark that the cell borders abscissae are in correspondence to the porosity holes in the control plate. This observation is of paramount importance to the aim of the phenomenon explanation. Indeed, it is well known that the static pressure in the separated region is lower than in the main flow, while in the reattachment and in the relaxation regions it increases again (see. e.g. [1, 11]). Now this pressure distribution implies that the quiet chamber under the porous wall is subject to a nonuniform pressure distribution so that an upstream flow is naturally generated within it; moreover, part of the fluid in this flow will be broached by the holes as the pressure over the plate decreases, hence generating a series of jets in the y direction. Notice furthermore that the momentum of these jets should be increasing as x decreases because the pressure difference generating them is expected to increase in this direction; pressure measurements within the cavity are forecast in order to check this statement. This configuration is confirmed by the zoom of the controlled case in the near step region presented in Fig. 3. In this figure three vertical jets are very evident. Their strength is reduced while going towards larger x, because the pressure

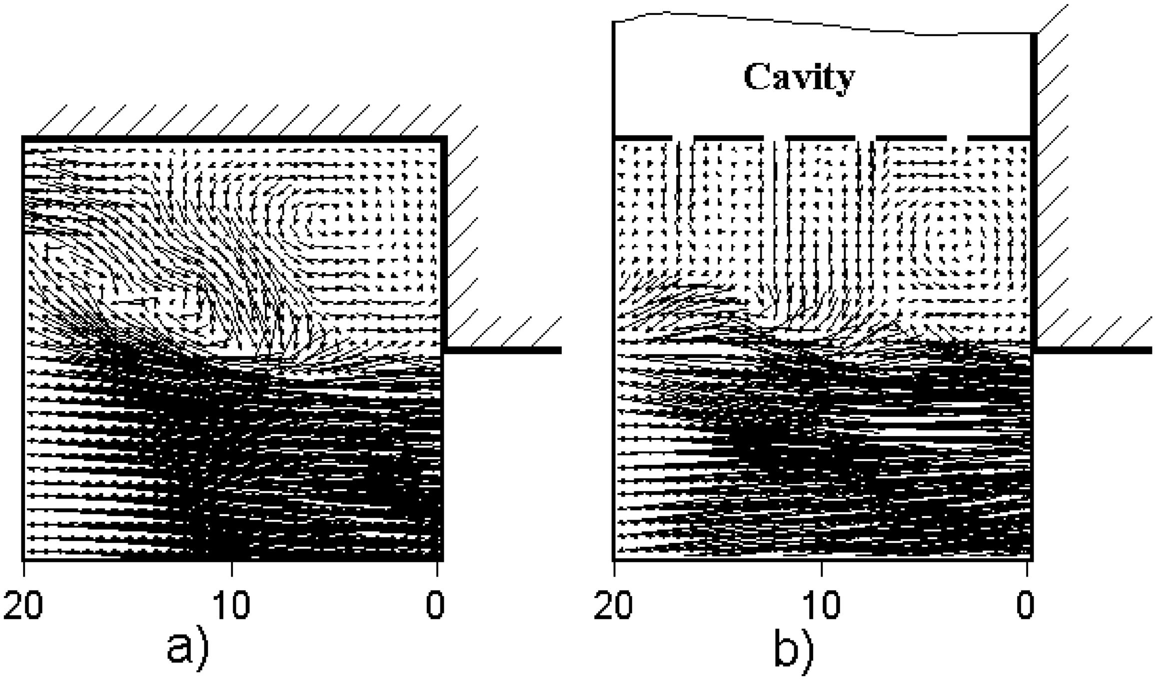

Fig. 6 Instantaneous velocity fields in the near step region; a) natural case; b) controlled case.

difference generating them also reduces in that direction. Remark that a fourth jet can be identified under the corner bubble axis, but is much weaker than the others and is soon smoothed down because of the strong circulation in that region.

Separated flows average behavior can fruitfully be studied through a statistical parameter, the so-called FFP (Forward Flow Probability), which is the probability of finding flow directed downstream at a given location. The FFP maps for the natural and controlled cases are presented in Fig.4. It can readily be observed that the flow topology is strongly influenced by the manipulation. The first quantitative information that can be extracted from these maps is the mean reattachment point location. This is defined as the point on the wall where the probability of having flow directed upstream or downstream are equal, or FFP$=0.5$. In the natural case the mean reattachment location is at approximately 48 mm from the step (4.8 H), while in the controlled case it has moved to 40 mm (4 H), i.e. a movement of about 16%. It can also be observed that the external isoline at 0.9 reaches the wall much more smoothly in the controlled case. Observing now the separation region, the change in the step corner is very evident. Looking at the controlled case, a large region with FFP almost 1 is present in the corner, and coincides with the lower part of the circulation cell; over it, a zone with very low (essentially 0.0) FFP is also clearly present. The very sharp probability gradients hence created between the two parts of the cell and between the upper part and the external flow indicate a likewise sharp separation between these three flow regions. The irregular pattern of the isolines close to the wall for 15 mm $\lesssim x \lesssim$ 40 mm is due to the presence of the vertical jets discussed above.

Fig. 5 presents the field of the fluctuating velocity component in the $x$direction, u_{RMS}, in the separation region for the natural and controlled cases; the maps of v_{RMS} provide essentially the same information and will not be presented. It can be observed that the fluctuation intensity is strongly damped in the manipulated case, especially in the region close to the walls; the shear layer fluctuation on the other hand is unaltered in its general topology; remark though that the maximum fluctuation, albeit having approximately the same value in the two cases, is located more downstream and farther from the wall than in the natural case. This is reasonable as the shear layer fluctuation is due essentially to the vortices shed from the step, which are expected to be only slightly affected by the control technique presented here. Remark that other control methods, like e.g. fluid injection at the corner, are conversely expected to produce their main effects on the vortex shedding. The u_{RMS} maps show that the control technique discussed here has a remarkable potential for application. Indeed, the strong reduction of fluctuation in the regions close to the walls implies that the unsteady solicitation to which the structures in the separated region are subject is also greatly alleviated. The stabilization due to the control can be demonstrated also in another way. Consider the velocity fields displayed in Fig. 6. Each of them refer to a DPIV image couple, i.e. is an instantaneous picture of the velocity field. Now it is evident that, while a single velocity field in the natural case bears very little resemblance to the corresponding averaged plot, the controlled instantaneous field is essentially coincident to the average (see Fig. 3), especially in the regions bounded by a jet couple.

These observations allow to explain the fluctuation reduction as follows. Consider the natural flow; as said in 3, in this case the separation region growth causes an instability that ends up in a collapse of the structure. In the controlled case, on the other hand, the vertical jets exiting the plate holes act as fences splitting the separated region into several cells (see Fig. 2 where this phenomenon is clearly visible). Now the pressure difference generating the jets decreases while going downstream so that the 'fences' are lower and lower, hence the cells show a smoothly decreasing height. Also, it is important to observe that the jets effect has a substantial difference from the one that would be provided by solid fences insowhat the jets do not provide the flow inside the cells with a no-slip condition but with a prescribed boundary velocity; as the direction of this imposed velocity is the same on the whole boundary of the cell, no recirculation is possible within the cells (except the one located at the step foot, for which one of the y-directed boundaries is a solid wall). Because of these boundary conditions, the flow within the cells appears to be essentially stationary; this is quite evident in the vectorial map presented in Fig. 2. Such a flow field therefore looks essentially stable and has a very low fluctuation intensity.

It is interesting to observe that the plate porosity and the ensuing jets, discussed earlier, provide an essentially 3-D interference to the natural, nominally 2-D separated flow. In order to better understand the interaction between the baseline flow and the control method, it would be useful to repeat this experiment using a wall plate with the same open area ratio used in the present work, but in which the open area is formed by two-dimensional slots: this would provide a purely two-dimensional control.

5 Conclusions

A method for the control of separated flows was analyzed through the DPIV technique, which allowed to highlight some of the advantages it brings and to clarify the underlying fluid dynamical mechanisms. An explanation of the flow behavior was attempted and discussed, based on the measurement results, whose quality was found to be sufficient for a quantitative and in-depth analysis. It was concluded that the working mechanism of this control method involves a complex interaction of the flow fields in the separation region and within the external cavity. A general idea of this interaction was discussed, but more work and specifically tailored experiments will be needed in order to reach a full understanding of the phenomenon.

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