INFLUENCE OF A SYNTHETIC JET EXCITATION ON THE DEVELOPMENT OF A TURBULENT MIXING LAYER

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ABSTRACT

The paper presents an experimental study of a flow control of a turbulent plane mixing layer by normal synthetic jets deployed through an array of circular orifices. The experimental configuration represents a flow control strategy for deflecting a mixing layer which has application in the control of separated flows. The mean and turbulent fields have been investigated. The control jet interacts with the mixing layer and modifies its turbulent energy behaviour. It is observed that the more important effect is the enhancement of the mixing properties of the mixing layer when controlled. This effect creates a deflection of the mixing layer toward the wall.

INTRODUCTION

In most of flow separation control strategies, the actuators are placed upstream of the location of the separation. The actuators are then acting on the boundary layer structure, introducing extra vorticity that enhances the momentum transfer towards the wall, making the boundary layer more resistance towards an adverse pressure gradient. A different strategy has been used by Viswanath *et al.* (2000). They introduced tangential jets via pneumatic means within the separated bubble and demonstrated its effectiveness. In this case the physics of the interaction between the control jets and the separated layer is quite different from the upstream actuation. Such *downstream* control can be a unique tool for partial attachment of massively separated flows. This has application in cases when separation occurs due to geometrical effects (often called inertial separation). It is encountered, for example, in afterbody separation of bluff bodies such as rear panels of cars or high lift devices.

In order to mimic the main characteristics of this control method, we define a simple, fundamental flow configuration composed of a turbulent mixing layer developing in non symmetric external conditions. This means that one wall of the wind tunnel is closer than the other from the mixing layer axis. It mimics, partially, a separation bubble (or an open separation) that occurs over a solid surface. The dissymmetry of the external field has an effect on the behaviour of the mixing layer: the side which is nearer to the wall will be modified by the entrainment effects of the mixing layer. On the contrary, the other side corresponding to the wall which is furthest from the mixing layer, will be minimally affected. Then it is expected that, any action on the mixing process of the mixing layer will be amplified by the dissymmetry in external conditions.

Currently, a plane turbulent mixing layer modified by synthetic jets is used to infer the physics of the control of separated boundary layer on wings or inertial separations. Previous experiments (Bourgois 2007) lead to the conclusion that it was possible to reattach a separated boundary layer over a NACA 0015 airfoil by introducing a synthetic jet normal to the wall within the separated region. The same actuator was installed on a flat plate to test its effect on a mixing layer. The aim of this approach is directed towards better understanding of the mechanisms which drives the boundary layer reattachment in such a configuration.

EXPERIMENTAL FACILITY AND FLOW ARRANGEMENT

The flat plate model is mounted into the test section (1.25 x 1.25 m^2) of an open loop wind tunnel. The chord of the model is 1m and its span is 1.25m. A splitter plate is used to generate the mixing layer as described in Fig. 1. The distance from the upper wall is 400 mm when the lower wall is 80 mm away from the axis of the mixing layer (in terms of the vorticity thickness at the location of the control, these distances are respectively 11 and 2.3). This dissymmetry provides a realistic representation of the mixing layer in a separated flow over a solid surface. Fig. 1 shows the experimental arrangement. The characteristics of the mixing layer are described in Table.2. The parameters used to characterize the mixing layer are the velocity ratio r, the mean velocity U_m, the velocity difference ΔU and the velocity parameter λ which are defined as follows:

$$r=U_2/U_1 \qquad U_m = (U_1+U_2)/2$$
$$\Delta U = U_1-U_2 \qquad \lambda= \Delta U/2U_m$$

The jets are generated by small loudspeakers installed inside the flat plate. Such methods were used by Seifert and Pack (1998); Amitay *et al.* (1983). The jet axis is orientated normal to the wall; the diameter of the circular orifices (d_j) is 3 mm and the spacing between them is 10mm. The frequency of the actuator can be adjusted between 20 and 100Hz. The corresponding velocities measured by hotwire anemometry are tabulated in Table.1.

Frequency (Hz)	Peak velocity (m/s)	RMS Velocity (m/s)
20	27	4.16
40	20	5.20
60	27	7.05
80	25	6.74
100	17	3.19

Table 1 – Characteristics of the synthetic jet actuator

The results presented in this paper are obtained by PIV. The origin of the streamwise (X=0mm) coordinate is located at the actuator location, the vertical origin being at the splitter plate trailing edge. The trailing edge of the splitter plate is located upstream of the actuator (at X=-317mm and Y=0mm) such that the mixing layer is developed and reaches a quasi-asymptotic state where it is controlled. The end of the flat plate (in which the loud speakers are installed) is a bevel of 15°. It is used to simulate the trailing edge of an airfoil. Position X=184 mm corresponds to the beginning of the bevel (the plates ends at X= 407).

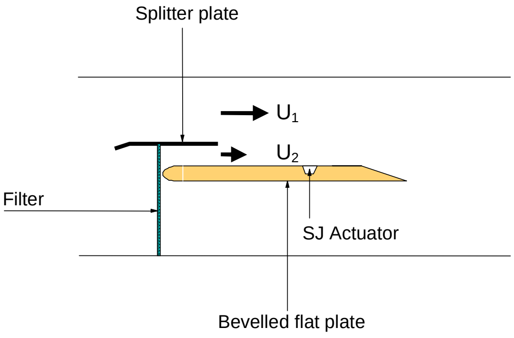

Fig. 1. Experimental setup.

RESULTS

The first part of the study consists in qualifying the flow without actuation. With reference to the work of Bourgois (2007), three velocities were tested. In the present paper, we focus on the parameters of the flow presented in Table.2.

U_1 (m/s)	R	U_m	ΔU	Λ
2.35	0.60	1.87	0.95	0.25

Table 2 – Characteristics of the mixing layer for the different configurations

The mean velocity field obtained by PIV is as shown in Fig. 2(top). It can be observed that, in the natural situation the flow is slightly displaced towards the lower wall. This is due to asymmetric location of the splitter plate. On the mean velocity profiles (Fig. 3) a wake effect is observed near the splitter plate trailing edge. This effect rapidly disappears and the mixing layer behaves in a self similar way at the location of the control jet (X=0mm). Due to the wall proximity, the vorticity thickness follows approximately the conventional evolution as plotted in Fig. 4. The values of the vertical velocity component plotted shown in Fig.5(left) indicated a small deflexion effect.

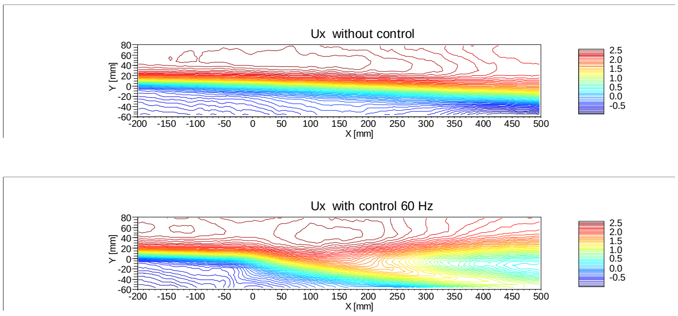

Fig.2 – Mean velocity fields and distributions of kinetic energy without actuation (top) and with control jets deployed (bottom).

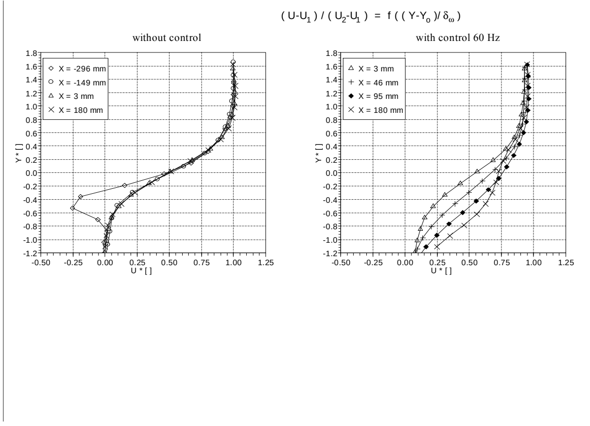

Fig. 3. Mean longitudinal velocity profiles. Natural flow (left), controlled fow (left)

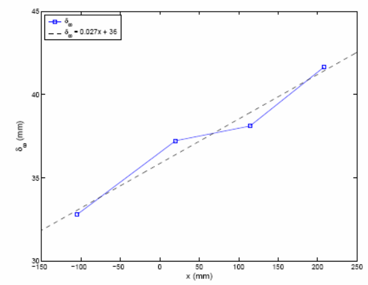

Fig. 4. Vorticity thickness of the natural boundary layer.

When the control jets are deployed, a stronger deflexion of the mixing layer is observed, see Fig. 2 (bottom). The mean shear is displaced toward the wall. In Fig.5 (right), the large negative value of the mean vertical velocity corresponds to this deviation. This effect is what one should seek in various attachment configurations.

The actual velocity of the control jet (peak velocity ~ 27m/s) is large compared with the main stream velocity. The trajectory of the control jet is somewhat difficult to identify from the data. However, it is possible to estimate this trajectory by using the model developed by Hasselbrink and Mungal (2001) and Favier (2007) :

$y/r_d = (2/ C_{ej} . x/ r_d)^{1/2}$ (where $r_d = U_j/U_{ext}.d_j$, U_{ext} is the local velocity at y, and $C_{ej} = 0.32$). This trajectory is plotted on Fig. 6. In this configuration, it is clear that the control jet passes through the mixing layer, its trace being visible in the upper part of the flow.

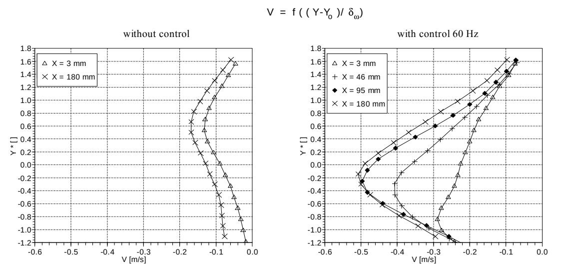

Fig. 5. Mean transverse velocity profiles. Natural flow (left), controlled flow (right)

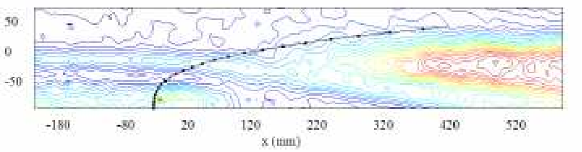

Fig. 6. Model of control jet trajectory.

As far as the turbulent activity is concerned, a strong impact is observed from the contours of turbulent kinetic energy in Fig. 7(bottom). In the controlled case, a large increase of the levels is observed downstream of the interacting region (Note that the iso-levels have not the same color scales on the two figures). After X = 180 mm, very large level of turbulence are observed. These levels correspond to the high velocity gradients generated at the interface of the control jet and the deviated mixing layer. As a consequence of the streamwise reattachment, a high shear and turbulence activity is generated. This could be due to excess augmentation in jet velocity that induces intense shear after the attachment. The profiles of the streamwise velocity fluctuation, in the interaction region (up to the beginning of the bevel), are plotted in Fig. 8. Before jet deployment, see Fig 8(left), we observe that a maximum occurs at Y=0mm which corresponds to a profile of a conventional mixing layer. This maximum corresponds to a value of 0.015 in the iso contour plot of Fig.7 (top). After jet deployment, this contour level (0.015) has been split into two distinct parts. The first occurs at around Y=-0.2, see Fig.8 (right), and is attributed to the control jet having penetrated the mixing layer. The second maximum is closer to the wall (Y~-0.1) and is attributed to the actual position of the deviated mixing layer.

The behaviour of the main production term, $u'v'\ \partial U/\partial y$ is plotted on Fig. 10. The production is drastically reduced in the upper part of the flow. This is mainly due to lower velocity gradient in the regions less affected by the mixing layer. The production is more spread-out when the flow is controlled. An increase is observed in the part closer to the wall corresponding to the increase of the turbulence level.

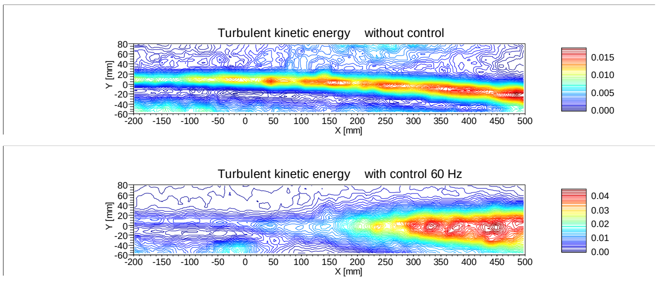

Fig. 7 – Turbulent energy ($\langle u'^2 \rangle + \langle v'^2 \rangle$) without actuation (top) and with control jets deployed (bottom).

The same behaviour is observed on the turbulent shear stress as seen in Fig. 9; the upper maximum is lower in the outer part when the control is applied and the region closer to the wall has a significant turbulent stress activity. Once again, from a different point of view, as shown in Fig. 7 at X = 180mm, the flow is separated into two distinct regions: the upper one which is the turbulent activity generated by the control jet; the lower one, closer to the lower wall, corresponds to the deviated mixing layer. It should be noticed that the mixing layer has a lower turbulent energy when it approaches the lower wall.

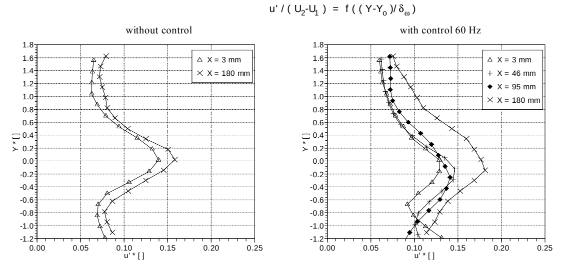

Fig. 8. Energy of streamwise fluctuations. Natural flow (left), controlled flow (right).

The increase of the mixing is associated to an increase of the entrainment process. Providing the upper part of the mixing layer can be considered as an infinite medium, the effect of this increase has no particular effect. This is not the case for the lower part, which comprises between the mixing layer and the main wall. In this part of the flow, the extra entrainment should correspond to a need for extra debit that has to be extracted from the equivalent channel flow. This explains qualitatively the deviation of the mixing layer.

The activation of the synthetic jet results in an acceleration of the flow in the low velocity side of the mixing layer, with a more distributed turbulent activity. Farther downstream, after the attachment, the turbulence level strongly increases (as seen on Fig.7), this maximum occurred between the actual location of the control jet (upper part) and the deviated mixing layer.

In order to visualize and extract information concerning the large eddies in the mixing layer, the technique of snapshot POD (Lumley (1967), Delville *et al* (1999)) is applied to the

400 realizations of the PIV. The first three spatial modes of the natural flow (Fig. 11, left) reveal a series of eddies (actually, the primary structures of the mixing layer) in the mixing layer region.

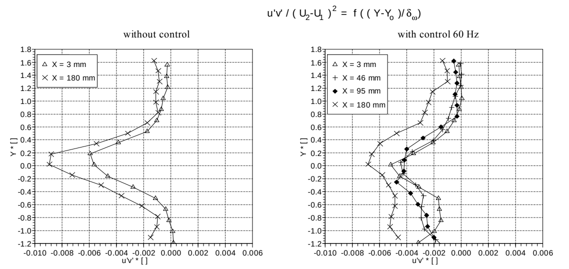

Fig. 9. Turbulent shear stress profiles. Natural flow (left), controlled flow (right).

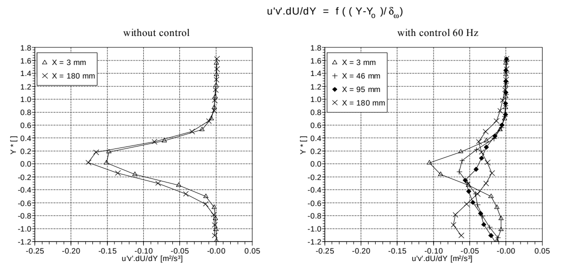

Fig. 10. Turbulent production. Natural flow (left), controlled flow (right).

In the actuated configuration, POD revealed a series of contra-rotating vortices generated by the interaction occurring further downstream, see Fig.11 (right). This correlates to the high value of the turbulent kinetic energy observed downstream of the interaction region (X>180 mm) as depicted in Fig. 7 (bottom). The flow structure has been drastically modified by the control. The major modifications of the organization and of the turbulent energy of the flow occur downstream of the interaction and attachment region.

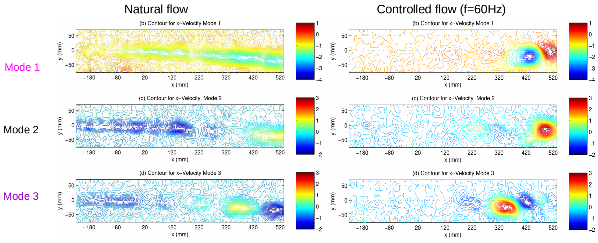

Fig. 11. Three first POD modes. Natural flow (left), controlled flow (right).

CONCLUSION

A mixing layer adjacent to a solid wall has been controlled in order to simulate a control strategy acting inside a separation bubble. Such a control has been used with success on a NACA 0015 airfoil (Bourgois 2007). The control is performed with synthetic jets impacting the mixing layer in its developed region.

It has been shown that the deployment of the control jets results in a deviation of the mixing layer that could approach the lower wall. In the present configuration, each jet crosses the mixing layer and its effect can be identified in the upper part of the flow further downstream. The resulting turbulent field is complex. In the controlled case, the production and turbulent energy are separated into two distinct regions. This indicates that some wasted energy. Preliminary experiments show that the jet velocity and its relative distance (from the mixing layer) for penetration are required for a significant deviation of the mixing layer. This would be the penalty for such a control method. As far as the interaction region is concerned, the displaced mixing layer has lower turbulence energy. The POD analysis shows a strong reorganisation of the flow downstream of the interaction.

The proposed mechanism of the mixing layer deviation is the increase of the mixing due to the control jet effects. This effect has a dramatic effect on the flow deviation due to the proximity of the wall on one side of the mixing layer. Future work will involved the quantification of the impact of the mixing enhancement on the deviation. In addition, parametric studies will be performed for the optimization of the method. These can lead to further improvements in terms of attachment of the mixing layer by using an actuation frequency adapted to the frequencies within the flow. After which, application to practical situations like flow separations on wings will follow.

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AKNOWLEDGEMENTS

The authors gratefully thank M. Jean-Marc Breux for his help in experiments and data processing.

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