# MODIFICATIONS OF THE SHEAR LAYER DOWNSTREAM A BACKWARD FACING STEP BY DIELECTRIC BARRIER DISCHARGE PLASMA ACTUATOR

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## ABSTRACT

The present article deals with a free shear layer induced by the separation of a turbulent boundary layer due to wall divergence. The investigated flow configuration is produced by a 30-mm-height backward-facing-step mounted in a closed-loop wind tunnel. The experimental measurements are performed at 15 m/s , corresponding to a Reynolds number (based on this velocity and the step height) around $3x10^4$.

The modifications of the shear layer are achieved with a surface plasma actuator based on a single Dielectric Barrier Discharge (DBD). This actuator produces an electrohydrodynamic force, resulting in a flow called electric wind just upstream the flow separation.

The plasma discharge is able to manipulate the first stages of the formation of the free shear layer and consequently to modify the flow dynamics, highlighting the control authority of plasma discharge.

Time-averaged and time-resolved measurements techniques are used to investigate the influence of plasma device in two ways. The first one considers the modification of mean reattachment length whereas the second one studies the effect over large-scale structures.

## INTRODUCTION

Free and bounded turbulent shear flows are intensively studied. The turbulent energy balance splits these flows in two generic configurations: wall-bounded and free shear layers. These two types of flow are usually found in the nature and also in a variety of engineering applications. Knowledge of the flow and the ability to control it are fundamental topics in turbulence.

This paper is devoted to the characterization of a free shear layer produced by turbulent boundary layer separation and manipulated by a plasma actuator. The massively separated flow is yield by a sudden wall expansion. The sharp step corner is the fixed location where separation occurs and the location where Kelvin-Helmholtz instability mechanism begins. The whole process is dominated by the structures arising from this instability (Ho & Huerre, 1984). The effects presented here influence not only the mean flow but also these organized large-scale flow structures.

In some extend, the particular 'step' flow can be compared with the canonical plane mixing layer case. Their characteristics are very similar in the initial region of the free shear layer but further downstream, the growth and evolution of the free shear layer are affected by the presence of the wall downstream in the case of the BFS. A recirculating region forms and feeds continuously the shear layer producing an increase on the overall turbulence (Adams & Johnston, 1988). Another important feature of a backward facing step flow is the unsteady and highly three-dimensional location of the reattachment point. The dynamic of the separated flow is directly linked with this unsteadiness (Driver *et al.*, 1987).

The objective of this study is to investigate the ability of plasma actuators as an effective device for modifying (manipulating) the shear layer, with the final objective of being able to control/reduce the parasitic effects such as unsteadiness, noise, etc. A surface non-thermal plasma discharge is used as flow control device which is now recognized for being effective in different aerodynamic configurations (Benard & Moreau, 2012). This device adds a volume force resulting in a secondary flow, usually called electric wind. Its amplitude and frequency are directly linked to the electrical input signal, this being of primary interest for studying the influence of localized periodic or non-periodic flow perturbations.

After the details of the experimental configuration used and the inlet parameters, two main analyses are presented: a parametric study to determine the most effective actuation and a dynamic study of the natural step flow organization. The last part corresponds to a detailed analysis of the particular effective actuation.

## EXPERIMENTAL SET-UP

The configuration, shown in figure 1, corresponds to an initial ramp guiding the flow from the inlet of the test section (1.2:1) to a plate where the turbulent boundary layer develops. A laminar-to-turbulent boundary layer transition is forced by a zig-zag tripper installed upstream the separation (x/h=-10). The turbulent boundary layer evolves into a free shear layer by a backward-facing step with a height of 30 mm. The ratio of incoming boundary layer thickness to step height remains small enough (δ/h=0.4) in order to not be considered as a roughness element (Bradshaw & Wong, 1972).

The model is mounted inside a recirculating closed-loop wind tunnel with a turbulent intensity, for the measured velocity, of approximately 1%. The dimension of the test section is 300x300 mm² and the model covers the full span. The expansion ratio, corresponding to the relation between test section and step height, is equal to 1.1 and the aspect ratio, span/step height, is 10. This latter value is the minimum suggested by Brederode and Bradshaw to assure a two-dimensional flow in the centre of the wind tunnel.

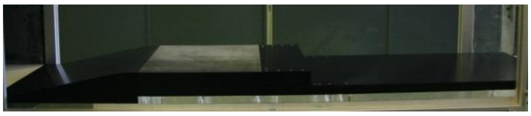

Figure 1. Configuration model of the step.

### Reference flow parameters

The measurements are performed for a freestream velocity of 15 m/s for which the Reynolds number, based on the height step h ($Re_h$), is 30000.

The boundary layer parameters are calculated from two measurement techniques: stereoscopic PIV and LDV. The thickness boundary layer is estimated to approximately 12 mm. The shape factor ($H=\delta/\theta$) remains equal to 1.38.

The growth of the shear layer is calculated to confirm the similarity to a classical mixing layer (or jet). Local vorticity thickness ($\delta_\omega$) shows a longitudinal gradient equal to 0.11, being near to the typical experimental values of a mixing layer in the case of two identical fluids: $d\delta_w(x)/dx = 0.16\lambda$ (Fiedler, 1987) where in our case $\lambda=1$ with one side at rest.

### Surface plasma actuator: DBD

The surface plasma actuator is flush-mounted just usptream separation, as shown in figure 2. The Dielectric Barrier Discharge (DBD) device is composed of two conductive electrodes: one is exposed to the free stream flow and connected to the high voltage supply, and the other one is grounded and placed below the 3-mm PMMA plate that plays the role of the dielectric barrier. The electrode thickness is equal to 70 µm. Different tests have been made with and without actuator to verify that the electrode does not modify the shear layer development. The boundary layer parameters given in the previous section consider the electrode in place.

The electric field between electrodes separated by the dielectric produces a surface discharge due to air ionization. The collisions between neutral and charged species produce an electrohydrodynamic volume force resulting in a tangent flow to the wall and restricted to the boundary layer region. This force is driven by the plasma parameters. In particular, the resulting flow is an out-of-phase mirror of the electric input signal. Here, the used signal is a sinusoidal wave form of some kV of amplitude (E) and driven at a frequency of 1 to 6 kHz ($f_{AC}$). This type of signal results in flow oscillations at $f_{AC}$.

The AC signal can be modulated by a square form producing burst modulation whose frequency ($f_{BM}$) varies from 25 to 500 Hz while the duty-cycle can vary.

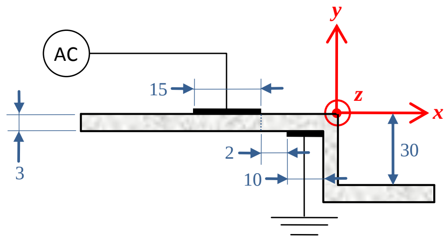


Figure 2. Sketch of the DBD actuator on the step, units in mm.

## PARAMETRIC STUDY

The electric parameters that control the discharge and which are transmitted to the flow by the body force have a wide range of actuation, as seen before. The effectiveness of the control device is firstly evaluated through the modifications of the mean reattachment point of the free shear layer.

In a first experiment, a stereoscopic PIV system is used in order to access to the complete Reynolds stress tensor. The measurements are recorded in a thin plane at the centre of the model thanks to a pulsed laser (Big Sky Twins ultra, 30mJ) and two CCD cameras (CCD Pulnix 4M pixel resolution). The measurement region is 300x200 mm² and, after multi-passes adaptive correlations for computing the velocity field, the final spatial resolution is one vector per 1.5 mm. To guarantee convergences of first and second order moments, 1000 pairs of images are recorded for each flow control configuration. The total number of images is taken in independent series of 250 pairs.

The investigated parameters include the voltage amplitude, the driving AC frequency, the burst modulation frequency and its duty-cycle. The reference conditions are $f_{AC}$=1 kHz and E=20 kV. For forcing by steady actuation mode, the voltage varies from 12 to 24 kV and the frequency from 1 to 6 kHz. For excitation by unsteady forcing mode, a sine voltage at 1 kHz is modulated at frequencies $f_{BM}$ from 25 to 500 Hz. This type of excitation results in periodic flow oscillations largely dominated by the $f_{BM}$ frequency.

For all the measurements, the actuation results in a reduction of the distance of mean reattachment point from the step. The best performance, in terms of separation length reduction is observed with the burst modulation at 125 Hz. As shown in figure 3, such an excitation allows us to reduce the mean reattachment length by 17% when steady forcing produces a recirculating region reduction of only 3%.

All the results are not presented in the present paper, but they can be found in Sujar-Garrido *et al.*, 2012. As indicated previously, the most effective actuation, from the $X_R$ point of view, consists on burst modulation of a sinusoidal wave ($f_{AC}$=1 kHz, E=20 kV) at 125 Hz and duty-cycle of 50%, for which the reduction of mean reattachment length attains approximately 17%.

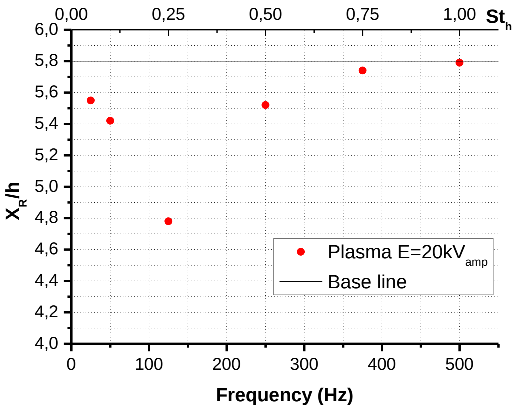


Figure 3. Evolution of $X_R$ for a range of $f_{BM}$.

In figure 4, the average of each Reynolds stress component calculated in time and in space over a limited area downstream separation is presented (in case of burst modulation actuation). The same frequency excitation that produces the maximum length reduction also produces the maximum modification on $u'^2_i$ components. The increase in turbulent level due to the periodic excitation results in a reduction of the mean flow region.

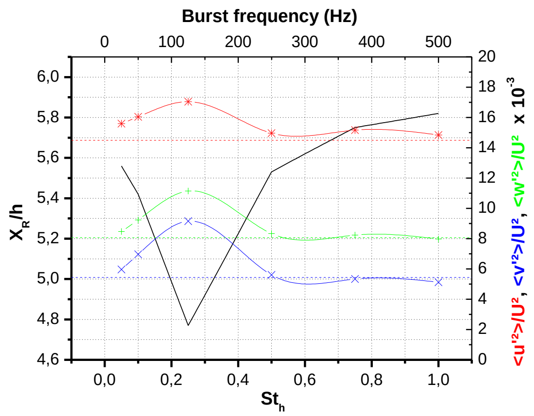


Figure 4. Normal Reynolds Stress component for unforced (dash lines) and forced case at severals $f_{BM}$ (solid lines).

This optimal modulation frequency of 125 Hz ($f_{BM}$) corresponds to a Strouhal number, based on this forcing frequency $f_{BM}$ and the height of the step h, of $St_{BM\text{-}h}$=0.25. In literature (Yoshioka *et al.*, 2001), it can be found an optimal Strouhal number of control over a backward facing step between 0.2 and 0.3 which is consistent with the present results. Furthermore, this Strouhal number near 0.2 is supposed to correspond to the natural flow instability driven by the vortex formation in the free shear layer (Bhattacharjee *et al.*, 1986).

## TIME-RESOLVED INVESTIGATIONS

In a second experiment, a time-resolved investigation is carried out with time-resolved PIV and LDV measurement. The flow dynamics of the shear layer can then be investigated from a spectral point of view.

Firstly, the LDV system used was an argon-ion laser of 10 W with two wavelengths giving access to the two velocity components. The sampling rate usually varies from 10 to 20 kHz. The system is used to obtain the turbulent power spectra with enough accuracy at different positions in the free stream direction ($x$) as well as several points in the normal direction ($y$). The final area of measurement had a maximum size of 2 mm².

The case without actuation is firstly studied by estimations of the power density spectra measured along the shear layer.

Considering a downstream position, i.e. x/h=3, the transverse evolution ($y$ direction) of the spectrum for fluctuating velocities v' shows the transformation from a typical turbulent spectrum – within the shear layer– to hump spectra –over the interface– at low frequencies, suggesting the periodic passage of a structure (Figure 5). The vertical position where the maximum amplitude of the bump is observed is approximately 5 mm (i.e., y/h=0.17).

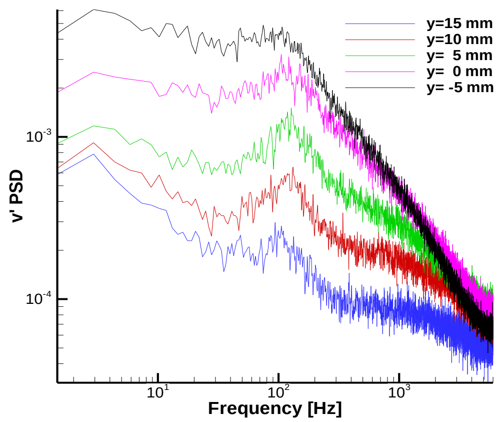


Figure 5. Local spectrum through the shear layer calculated by LDV for several positions in $y$ (x/h=3).

To analyze the evolution of these bumps along the shear layer, figure 6 represents the spectrum at different $x$ locations (y/h=0.17 where the hump get its maximum amplitude). The results show that the periodic signature in the spectra moves to lower frequency as the measurement position moves downstream. This is due to the interactions and amalgamations among vortex and increase of the mixing layer thickness.

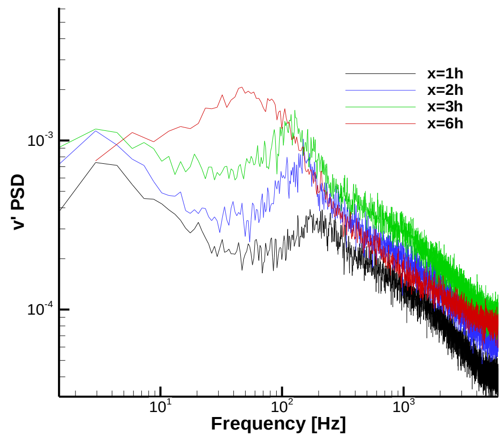


Figure 6. Local spectrum along the shear layer calculated for several positions x/h by LDV (y=5 mm).

To obtain information over the whole spatial field, the previous results are completed with the TR-PIV system, composed by a dual pulse laser (Darwin-Duo Nd:YLF) and a high speed camera type CMOS (LaVision) 1024x1024 pixel². The spatial field covers the separation and the reattachment region (-1<x/h<7) and after multi-pass adaptive correlation, the final spatial resolution is about 4 mm². The repetition rate at 1 kHz is applied to catch events occurring around 100 and 200 Hz.

The PIV gives the possibility to produce a spatial distribution of the frequencies that represents the structures and the turbulence. At each spatial point of the measurement PIV grid, the spectrum is computed. The Kelvin-Helmholtz instability starts after separation and a distance downstream, the shedding of structures reaches a frequency between 150 and 120 Hz. This corresponds to a Strouhal number based on the step height h of 0.3-0.2. The structures formed at this point are affected by the presence of the wall and they have to modify their organization; the passage frequency over this reattachment region is about 60 Hz, which is in the order of the value found in literature in the past decades (Driver *et al.*, 1987).

Both experimental measurement techniques, LDV and PIV, provide similar frequency values. The main values along the shear layer are given in table 1.

Table 1. Frequencies values for the shear layer.

| Dimensionless *x* position | Frequency (Hz) |
|---|---|
| 1h | ≈200 |
| 2h | ≈150 |
| 3h | ≈120 |
| 6h | ≈60 |

Finally, the preferred mode of actuation appears when the excitation is in the range of occurrence of the dominant structures of the natural flow. This actuation corresponds to a burst modulation at the frequency of the structures passing through approximately 3 times the step height. More detailed results are exposed in the next section.

## MOST EFFECTIVE ACTUATION

Once the most effective actuation and the natural flow dynamics have been identified, a deeper analysis is discussed in this section in order to better understand the origins of the sensitivity of the flow to a periodic excitation at St=0.25 (with, duty-cycle=50%, $f_{AC}$=1 kHz and E=20 kV). From here to the end, this is referred as the forced case. The both PIV methods, stereoscopic and time-resolved, allow to applied different identification methods.

Different methodologies have been applied in order to extract the large scale flow structures embedded in the free shear layer. The primarily goal is to reveal the changes produced in the vortex formation due to the actuation.

The Q-criterion represents locations in the flow where the rotation dominates the strain. Through the analysis of different flow sequences, it is concluded that actuation reinforces the shear layer in the first stages of the Kelvin Helmholtz formation (x/h<1), as illustrated by figure 7. The increase close to the step suggests that the created perturbation forms a more stable first vortex that evolutes further downstream.

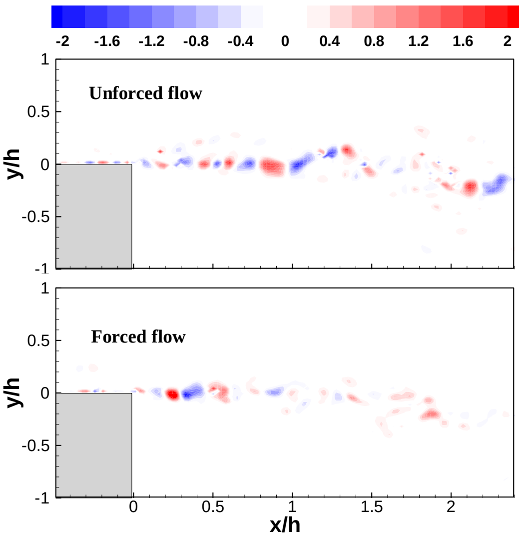


Figure 7. Image instantaneous Q criterion

To go further with this vortex analysis, the complete field has to be considered. First, identification by $\Gamma_2$ criterion is computed (Graftieaux *et al.*, 2001). This method permits to localize geometrically the centre of the vortex structure. It is basically based on the flow topology rather than on the computation of velocity gradients such as vorticity method or previous Q-criterion. This detection needs a threshold value which has to be carefully chosen, because it plays a key role in the number of detected vortex. However if the same threshold is used for unforced and forced case the main difference can be represented as in figure 8.

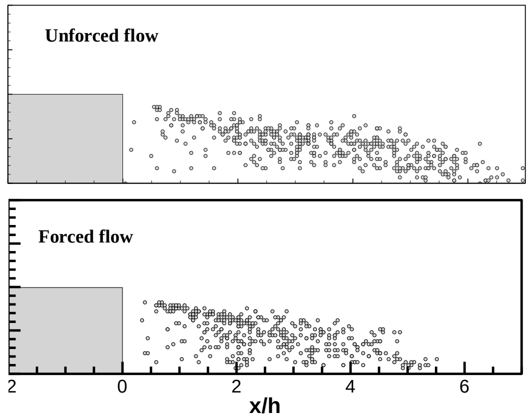


Figure 8. Vortex centres obtained by $\Gamma_2$ criterion for 250 instantaneous fields.

In the present case, the number of vortices distributed over the whole domain is not significantly affected by the actuation (figure 8); however, the actuator produces a change in the distribution of the vortex centres with a bended path line and a noticeable reduction of their life time in the measurement plane.

To evaluate the change caused over the shear layer and to extend the analysis of modifications produced over the Reynolds stress, the production term of turbulent kinetic energy equation is assessed in the unforced and optimal forced case (Figure 9). In the natural case the TKE is produced by the shear layer just downstream of the separation. For the forced case at $St_{BM}$=0.25, the production term distribution resembles to the unforced one but the production region is slightly delayed in space and an increase is observed all along the large-scale flow structure pathway. This amplified and new distribution of the TKE is due to the external force on eddies at low-frequency scale produced by the DBD actuation.

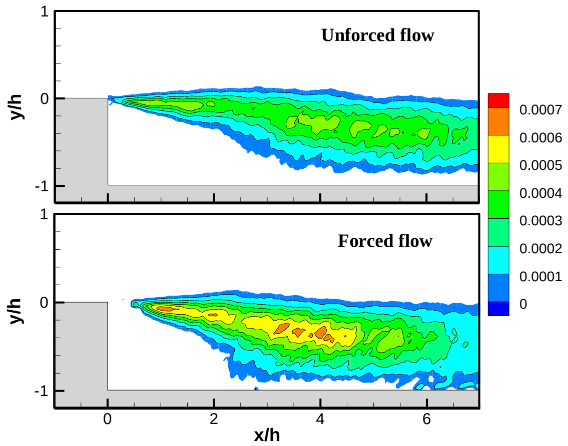


Figure 9. Production of TKE for unforced and forced flow.

Following with the evaluation of the optimal forced case, a spectral analysis is conducted. It has been shown previously that the characteristic frequencies exhibited by the coherent quasi-deterministic structures are approximately equal to 150 Hz at a distance of 2h from separation ($St_h$=0.3). For the particular case of burst modulation at 125 Hz ($St_{BM}$=0.25), the flow positively reacts to the forcing, not only with a large reduction in mean reattachment length but also with a new organization of the vortex street embedded in the background turbulence. The actuation reinforces the shear layer, as it is suggested by figure 7. A similar effect is observed from vortex identification criterion (figure 8) and turbulent production term (figure 9). When the actuator is turned on, the original bump at low frequency reported in figure 6 is modified with a new high amplitude peak at the actuation frequency (see figure 10).

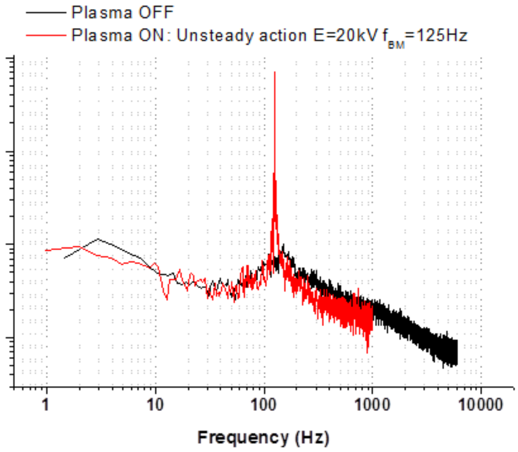


Figure 70. Spectre from LDV data (x/h=2 y=5mm).

Figure 10 depicts an example of a local bump modification, but, as it will be demonstrated later in the paper, the modification is obtained over the entire shear layer. As shown in this figure, the actuation forces the flow to form vortex at the forcing frequency (a frequency shift from 130 Hz to 125 Hz can be observed in figure 10), this resulting in a lock-on phenomenon. Local measurement points proved that effect. However, larger scale effect can be evidenced using the TR-PIV data to study the effect over the whole spatial domain.

A mean (over time slots of 512 samples) FFT is used to obtain the power density spectra; afterwards a moving average filter is used to filter the signal and to better localize the maximum amplitude in each computed spectrum at each spatial point of the measurement PIV grid (Figure 11). This figure represents the evolution of the organized structures which produces a bump in the spectrum at their passage frequency. For the natural flow, these structures evolve in size that tends to reach a self-similar region, as in a jet or mixing layer, so their frequency passage varies. The TR-PIV measurements done for the burst action confirm that the local maximum peak frequency over the downstream flow region is substantially changed compared with the unforced flow. Indeed, these results suggest that the actuation promotes a quasi-constant frequency excitation over the entire shear layer corresponding to the burst frequency (in this case 125 Hz).

The local representation of maximum amplitude peaks for unforced and forced cases exhibits the important modifications produced by the plasma actuator. As an example, the evolution of the local frequency for y≈5 mm is depicted in figure 12. The oscillating flow at the wall surface upstream of the separation results in a change in the shear layer from linear decreasing evolution to a constant frequency over the entire shear layer. One more time, this shows that the plasma actuation results in a "regularisation" of the vortex street.

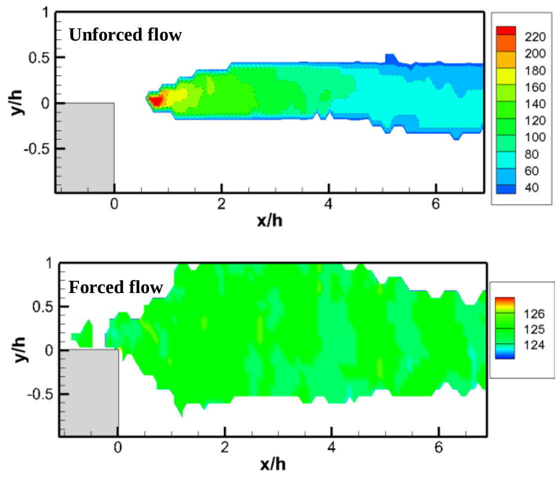


Figure 8. Spectrum map by TR-PIV

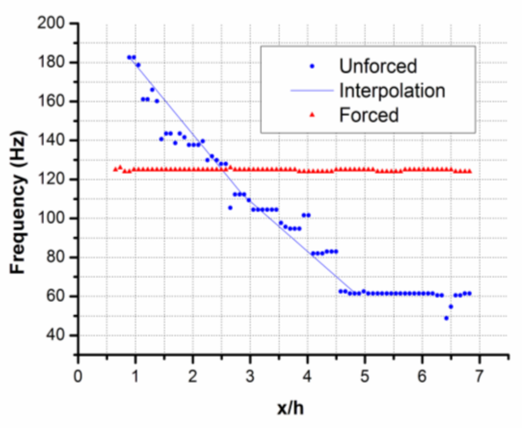


Figure 9. Evolution of the frequency with the distance downstream x/h

The different experimental techniques and diverse analysis methods confirm this result. The induced perturbation is able to modify the formation of the large-scale flow structures. This effect over the unsteady structures belonging to the shear layer affects the mean reattachment region.

The coherent structures play a key role in the shear flow and they produce a known feedback upstream, principally caused by the impingement of the shear layer. These two linked features make that the perturbation within the initial free shear flow affect the mean reattachment point.

The present study demonstrates that the manipulation of this type of flow is enhanced by a forcing at a preferred mode, this mode being the frequency of vortical flow structures in the axis of the shear layer.

## CONCLUSION

An active plasma actuator (DBD) is tested to manipulate the separated shear layer over a backward facing step.

The different results demonstrate the authority of plasma discharge in the present case. A perturbation imposed at an appropriate frequency promotes the production of Reynolds stress and consequently enhances the momentum transfer. Therefore, the effects over the large-scale eddies existing within the shear layer are proved by different time-resolved techniques. The global flow characteristics have been affected from the manipulation of the large-scale structures. A more detailed analysis by decomposition of the coherent structures according to their turbulent energies is currently conducted to identify the influence of the actuation on the periodic and stochastic turbulent contributions.

## ACKNOWLEDGMENTS

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