FLOW CONTROL BY PERIODIC EXCITATIONS

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Abstract. *The periodic excitation can be used to delay boundary layer separation, and, by doing so, enhance the lift coefficient and reduce the drag of a wing. This project seeks studying the transient response of this system when applied to a diffuser, by periodic excitation with zero net mass flux. This project is fundamentally experimental. A small wind tunnel was made, with a diffuser in the end, and the synthetic jet excitations, generated by a sub-woofer, were applied parallel to the flow, at the joint of the diffuser. The disturbed velocity profiles, result of the interaction of the main flow and the excitations, were measured by hot-wire anemometry, connected to a data acquisition system of high frequencies.*

Keywords: *flow control, synthetic jets, periodic excitation*

1. INTRODUCTION

The boundary layer separation is generally associated to the flow detachment of a solid surface, caused by some factors, for example, a high adverse-pressure gradient, studied by Simpson (1996), or a geometric aberration, as related by Bradshaw and Wong (1972). The boundary layer separation is almost always related to the degradation of some aerodynamic parameters, including lift reduction and drag augmentation.

The separation control by periodic excitation shows significant importance in areas related to engineering, and that is why it has been studied extensively in the last decades. For example, the boundary layer separation control of an external flow was studied by Béra et al (2000) for cylinders, and by Seifert et al (1993) and MacManus and Magill (1997) for wings. In the latter, the control applied near the wall produced a delay of the boundary layer separation and increased the lift of the wing.

To control the flow using periodic excitations, we can use bi-dimensional slots where acoustic/speaker equipments (Béra et al, 2003), pistons or piezoelectric actuators (Pack and Seifert, 1999 and Smith and Glezer, 2002) are linked to diaphragms to generate the excitations. In addition, flow perturbations can be achieved by actuators positioned on the surface analyzed, such as fliperons (Gleenblatt and Wygnanski, 2000).

The periodic excitations accelerate and control the formation of coherent structures. This effect is more accentuated when the main flow is instable, transferring linear momentum across the mixing layer, as observed by Oster et al (1978) and Browand and Ho (1983).

In specific applications to airfoils, some experiments showed that the periodic excitations can delay the boundary layer separation, increasing by 120% the variation of maximum lift coefficient (ΔC_{Lmax}) and by 240% the lift coefficient (ΔC_L) after stall, as can be observed in the results of Smith et al (1998) and Amitay et al (1998).

This work has the objective of analyzing the introduction of periodic excitations in a flow, more precisely the study of the flow's behavior when submitted to an adverse pressure gradient, taking into account the interference of a wide-angle bi-dimensional diffuser. The actuators do not introduce mass in the system, otherwise a mechanism similar to a suction/blow system would be produced, and that is not the objective of this work.

The methodology of this project is mainly experimental. A mini-wind tunnel with an exit diffuser was built, and a slot located at the junction mini-wind tunnel/diffuser allowed one to introduce periodic excitations parallel to the main flow. The effects of the synthetic jets were measured by hot wire anemometry.

Among the innumerous advantages of the control by periodic excitation one can cite: efficient delay of the boundary layer separation, allowing higher lift coefficients and lower drag coefficients; important reduction of weight when compared to conventional methods; possibility of load modifications without production of additional efforts to the airplane structure; possibility of switching off the system and better efficiency when compared to uniform suction/blow systems.

2. EXPERIMENTAL SETUP

2.1 Mini wind-tunnel

To execute this project, a MDF duct of a length of 1450mm and rectangular cross section of a height of 190mm and a width of 25mm was constructed. A contraction was attached to the admission section of the duct. It has an exhaust section with the same dimensions that the interior of the duct, and a square section of 120mmX120mm in the admission section. To this point of the tunnel was installed an 110V alternating current engine, that spins an air-screw, responsible for the production of the main flow.

A diffuser of variable angle was assembled in the exit of the duct, as shown in Fig.1. The components fixed to the rotation shafts (Fig.1) can spin according to these axes, changing the diffuser angle. All the others structures in the Fig.1 are fixed to the upper and lower walls of the duct.

The walls, presented in gray in Fig.1, have the same height of the internal section of the duct, 190mm, and a total length of 53mm, which includes a circumference of 7,5mm radius.

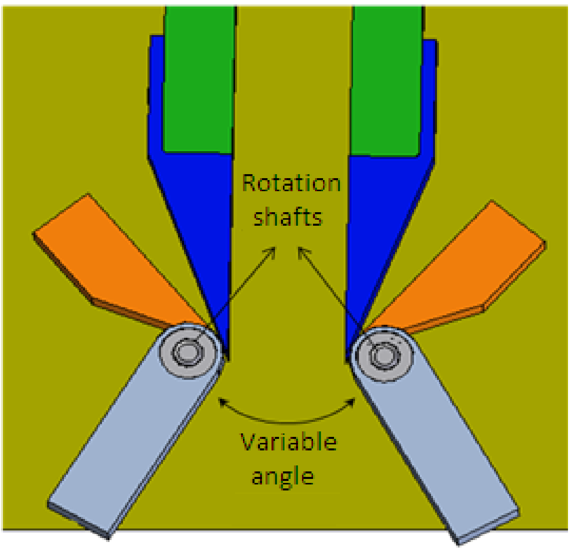

Figure 1. Variable angle diffuser (upper view without the upper wall)

To measure the angle of the diffuser, two protractors connected to the rotation shafts were installed on the top of the upper wall of the duct, as shown in Fig.2.

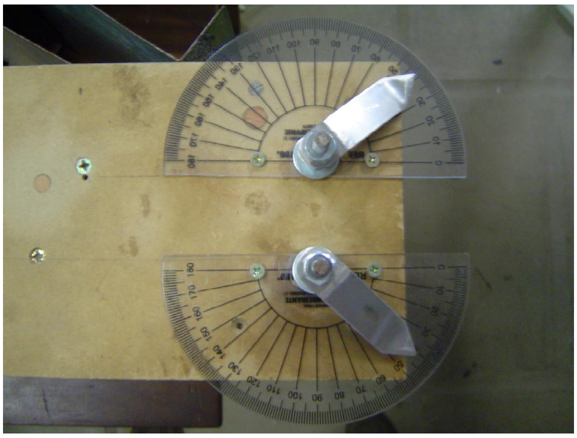

Figure 2. Protractors used to measure the diffuser's angle

In both sides of the exhaust part of the duct there is an all height side wall slot, by where sinusoidal periodic excitations, generated by a sub-woofer, were introduced to the main flow (in fact just one slot was used). The synthetic jets were introduced parallel to the main flow, because studies have shown that this configuration increases the efficiency of the process (Pack and Seifert, 1999).

During the calibration, the velocity profiles were measured by an $8705DP - Calc^{TM}$ digital micro-manometer, in different points of the exit of the diffuser. During the actual measurements a hot wire anemometer was used. The accurate position of the points of measurement was assured by positioning equipment, constructed specifically to this experiment.

2.2 Data acquisition system

Several programs were developed according to the channels that each one controls. The objective was to allow the easy development of routines to data acquisition to the different inputs of the physical system.

The Data Acquisition System (DAS) has internal timebase and memory. It has a maximal sampling rate of 40kHz in its 2 input channels (resolution of 0.3mV) and 1 output channel (resolution of 4mV), both of which were controlled by the timebase. In the same system there were also two anti-alias filters, with resolution of 200Hz, which were set to cut by the Nyquist frequency.

The system works quite independently, but was still controlled by a computer, which also controlled the position of the sensor set on a positioner built on a printer. The set up of the system is shown in Fig.3.

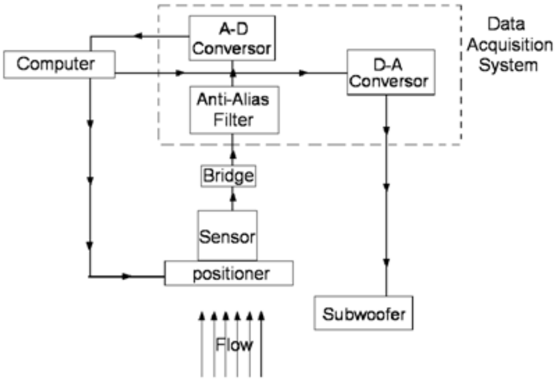

Figure 3. Data Acquisition System Setup

The bridge referred to in the image is the Wheatstone Bridge which reads for us the result of the anemometer.

The sub-woofer was chosen because we believe that the best excitation frequencies will be around 50Hz (Béra et al, 2003).

It has a curve of efficiency, as have all the loudspeakers. We have studied its efficiency and have concluded that it has a sufficiently constant efficiency between 10 and 60Hz. For frequencies greater than that the excitation starts to lose amplitude.

We have measured the signal in the excitation exit, and compared it to the signal sent by the computer for 10Hz in Fig.4.

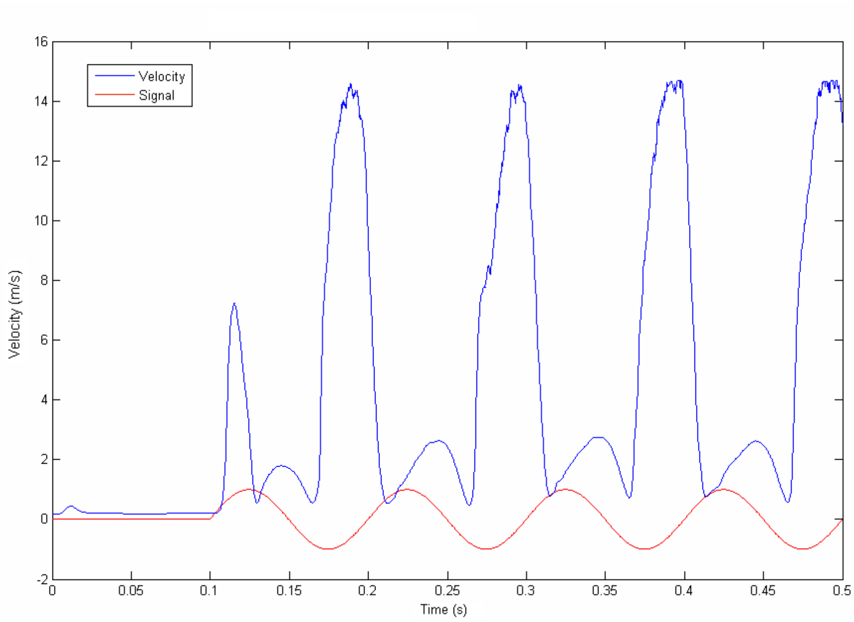

Figure 4. Velocity and signal of the 10Hz excitation

There is a very small lag between the signal and the actual movement of the air (<0,1s). It is also clear that the first impulse of the loudspeaker is weaker because it is only half the movement. The suction also appears as a positive signal weaker than the blow, because the anemometer can not distinguish between the directions of the flow.

3. METHODOLOGY

3.1 Calibration

Before starting the velocity profiles measurements, it was necessary to calibrate the anemometer. To do so, the King's law, described by the Eq.(1), was used.

$$E^2 = A + BU^n \tag{1}$$

where E is the difference of tension generated in the anemometer circuit due to the main flow, A and B are two constants experimentally obtained, and the n is a number chosen between 0,4 and 0,5. To execute the calibration, n was chosen equal to 0,45, as suggested by Collins and Williams (1959). The velocities were measured using a Pitot tube, connected to a digital micro-manometer.

To change the alternating current motor rotation velocity, an inverter was used. The output tension was kept equal to 110V and the frequency was varied. This method was chosen because the constant tension produces a constant torque, even with the changing of frequency.

A way of optimize the calibration constants of Eq.(1) is use a method of minimum squares sum, for example, the method of the Sum of Errors Squared (SES) applied to the difference of tension $E_R - E_C$, as showed by Eq.(2).

$$SES = \sum_{I=1}^{N} (E_{R_I} - E_{C_I})^2 \tag{2}$$

where N is the number of measured points, E_{R_I} is the calibration voltage experimentally obtained and E_{C_I} is the calculated voltage obtained by the Eq.(1).

Alternatively the SES may be evaluated from

$$SES = \sum_{I=1}^{N} (E_{R_I}^2 - E_{C_I}^2)^2 \tag{3}$$

According to Pitts and McCaffrey (1986), the Eq.(3) simplifies a curve approximation when the Eq.(4) is used. The SES method can be applied to analytical functions, and it determines the optimal values of the calibration constants. The approximation accuracy of the selected hot-wire response relationship can by described by the related normalized standard deviation, ε_u, described by the Eq.(4).

$$\varepsilon_u = \left[\frac{1}{N} \sum_{I=1}^{N} \left(1 - \frac{U_{R_I}}{U_{C_I}} \right)^2 \right]^{\frac{1}{2}} \tag{4}$$

where U_{R_I} is the measured velocity during the calibration (using Pitot) and U_{C_I} is the velocity obtained by inverting the Eq.(1), when the constants are already known.

3.2 Measurements

The data obtained from the measurements allowed us to build complex images such as shown in Fig.(4). These images where built by the measuring of the flow at a distance of 35mm from the duct exit through a line perpendicular to the main flow (velocity equal to 10m/s and Re $\simeq$ 34000).

The data was taken in 32 positions separated by 0,5mm, with a frequency of 5120Hz (in each position), in the 0,4s of the experiment. These images show us the deflection of the flow after the excitation starts at 0,2s. The contour plots are, therefore, graphs of the velocity of the flow passing through a line. In the horizontal axis we have the time, in the vertical axis we have the position perpendicular to the flow, and the velocity of the flow in each coordinate time/space is represented by a color.

4. RESULTS

It is clear that the response of the system is not immediate (Fig.5, where the velocities are shown in m/s). It takes approximately 0,01s to the system to show some reaction to the excitation. This is more evident in the response to higher frequencies signals. The reason for this delay is between the response of the sub-woofer to the electric signal, which is not immediate (considering the precision of the system), but is quite fast (<0,01s) and the flow. It is likely that this happens because of the first excitation being half one (as the sub-woofer starts its course in the middle of the way). The system is obviously effective nevertheless, as it indeed changes the direction of the flow that comes out from the duct. It is also noticeable that the flow will still be excited to the frequency of the synthetic jet. The answer of the system to the excitations is quite fast, and the small time of 0,2s is more than enough for the system to stabilize.

By comparing the reactions of the flow, it becomes quite clear that the frequency of 10Hz is not high enough to stabilize the response of the system, instead it generates a flow that changes direction all the time. This was to be expected, as the frequency is very low, and can not form the coherent structures which are the basis for the system of control by synthetic jets.

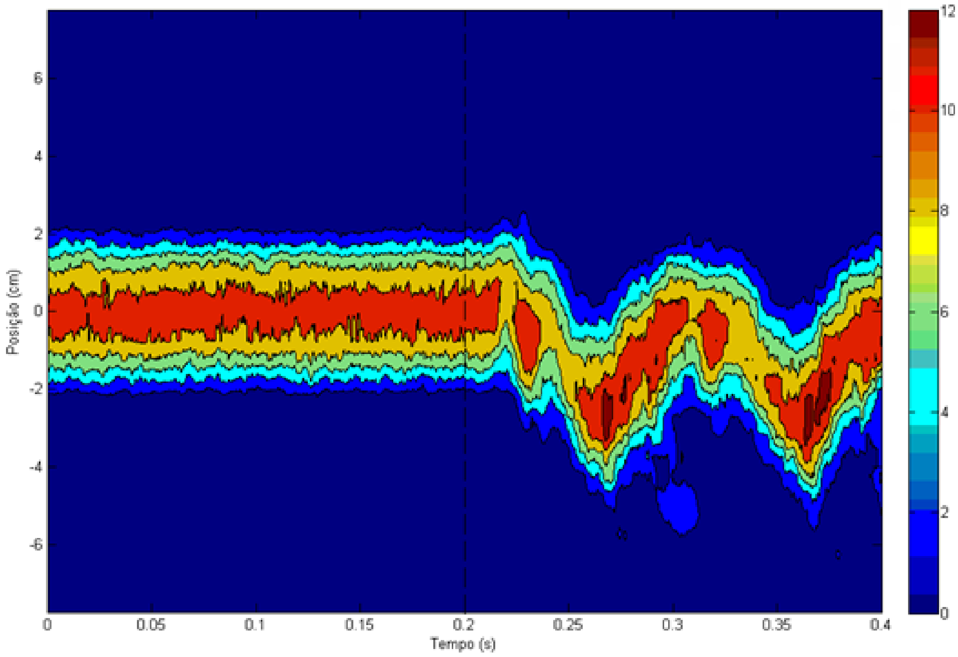

Figure 5. Response to a 10Hz step signal

By raising the frequency to 20Hz the response of the system changes dramatically, as shown in Fig.6. The flow is not unstable anymore: it is quite constant, even though one can not forget that the exciting frequency will always interfere with it.

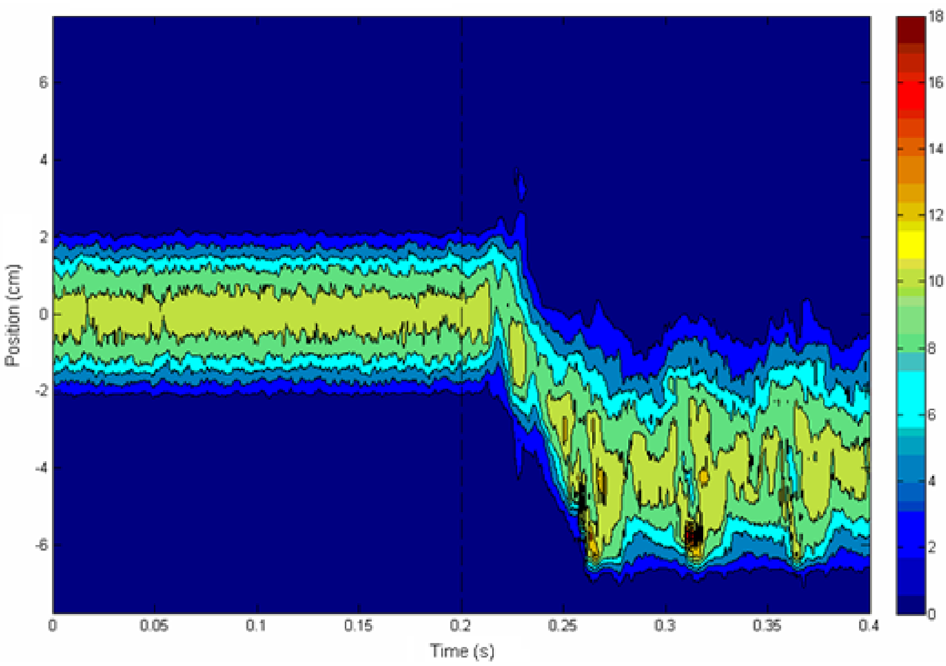

Figure 6. Response to a 20Hz step signal

Raising the frequency to 40Hz shows us a even more stable flow, still with the interference of the excitation frequency, but quite similar to the response to the flow excited at 20Hz otherwise. It is plotted in Fig.7.

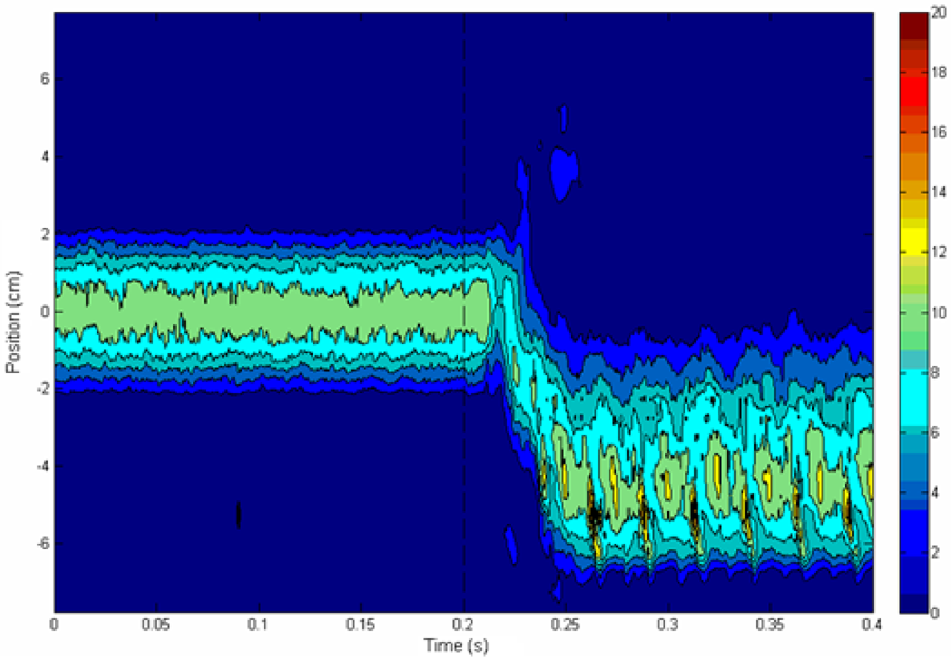

Figure 7. Response to a 40Hz step signal

Studies for higher frequencies have also been made, but as the sub-woofer loses its efficiency over 60Hz, it is only for qualitative analysis. Figure 9 shows us the response of the flow to a jet of 100Hz (the velocity of the main flow is reduced to 6m/s, to compensate for the velocity of the jet). There is still the presence of the excitation frequency in the response, but not the structures in the outer part of the flow excited to lower frequencies.

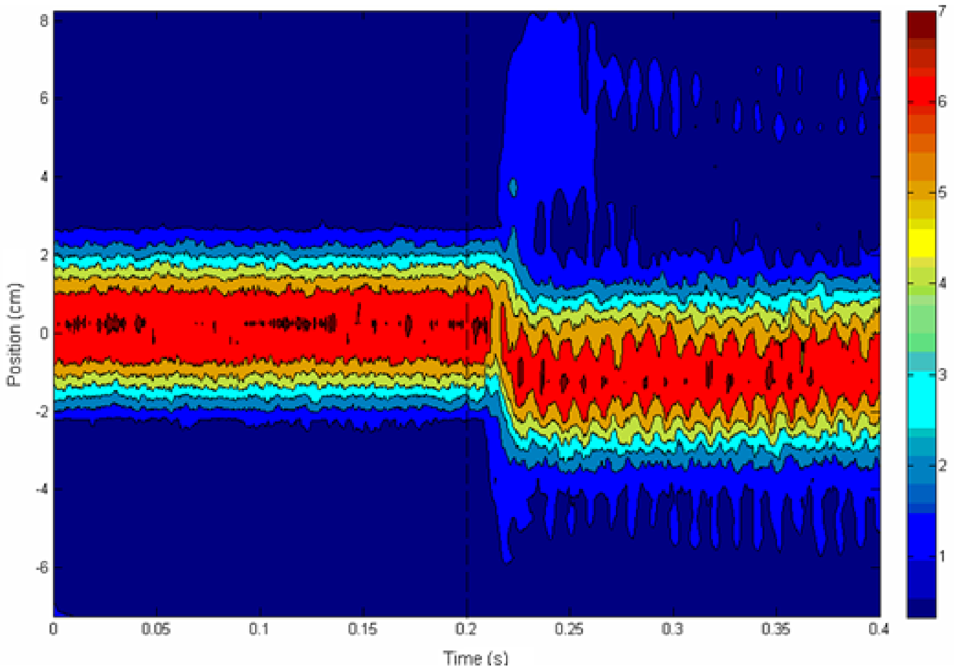

Figure 8. Response to the 100Hz step signal

There are lots of differences between the system excited at different frequencies. However it is difficult to compare such complex images. To do so more effectively, it was calculated the mean position proportional to the velocity, using Eq.(5).

$$Pos = \frac{\sum_{i=1}^{M} P_i V_i}{\sum_{i=1}^{M} V_i} \tag{5}$$

where M is the number of measured points, P_i is the position and V_i is the measured velocity (using hot-wire anemometry).

In Fig.9 it is plotted the result of the application of Eq.(5) on an equivalent contour plot.

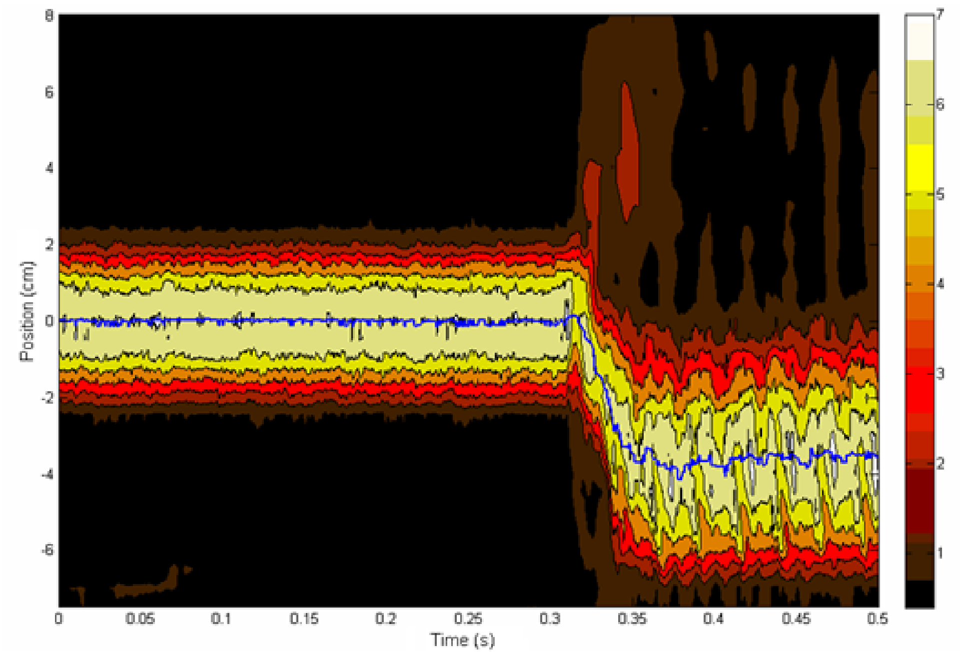

Figure 9. Mean position over counter plot

Now it is possible to compare different responses in the same image. Fig.10 shows the responses to 10, 20 and 40Hz. It is clear that 10Hz is too low to be used to deflect the flow, and only succeeds in modulating it. The frequencies of 20 and 40Hz, even though showing the same deflection of the flow, have different delays of response (i.e. the time it takes to the jet to stabilize in the deflected position). The higher frequency shows a faster response.

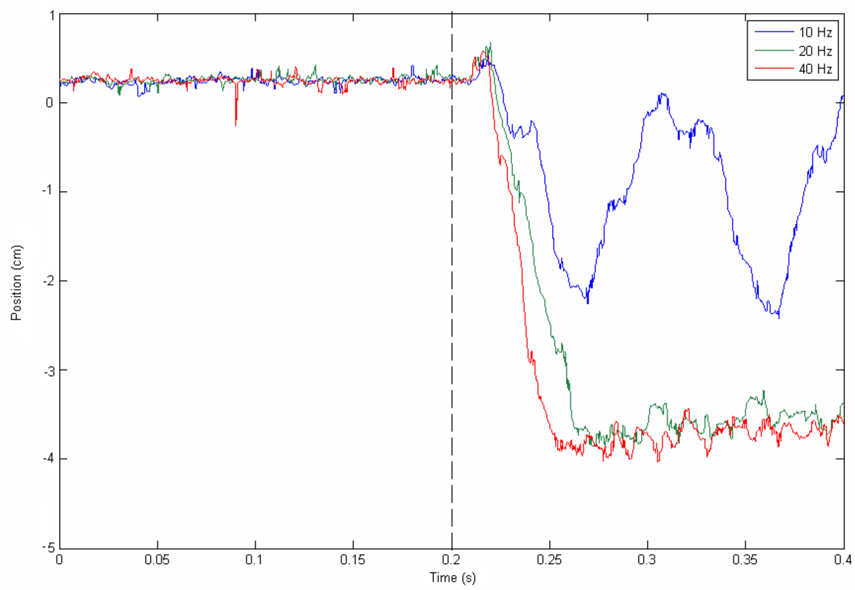

Figure 10. Response to step signals (10Hz, 20Hz, 30Hz)

When the frequencies of 20, 40 and 60Hz are plotted in the same figure (Fig.11), it shows quite clearly that the jet at 60Hz starts to lose its efficiency, deflecting the flow less than the two other lower frequencies. More interestingly, the delay of response is greater for the higher frequency. It seems that the fastest response frequency is also the more effective one. The existence of a more effective frequency was to be expected, since most of the works related to this field have shown one (Béra et al, 2003).

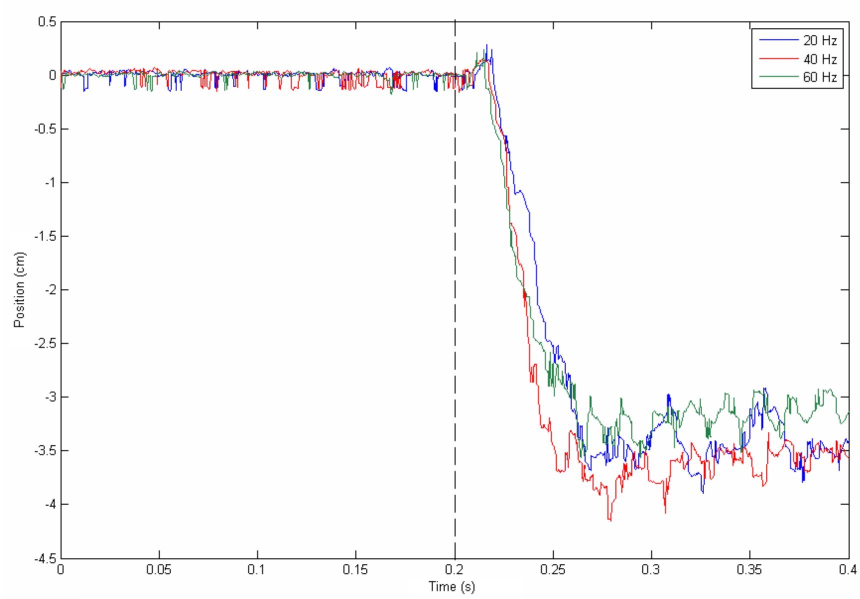

Figure 11. Response to step signals (20Hz, 40Hz, 60Hz)

In Fig.12 it is shown the response of the 10Hz step signal and the corresponding excitation. During the suction the jet is deflected, whilst it returns to the center when the sub-woofer blows. It could be assumed that the suction causes an area of low pressure that is filled by the jet, thus deflecting it. The opposite happens when the sub-woofer is blowing.

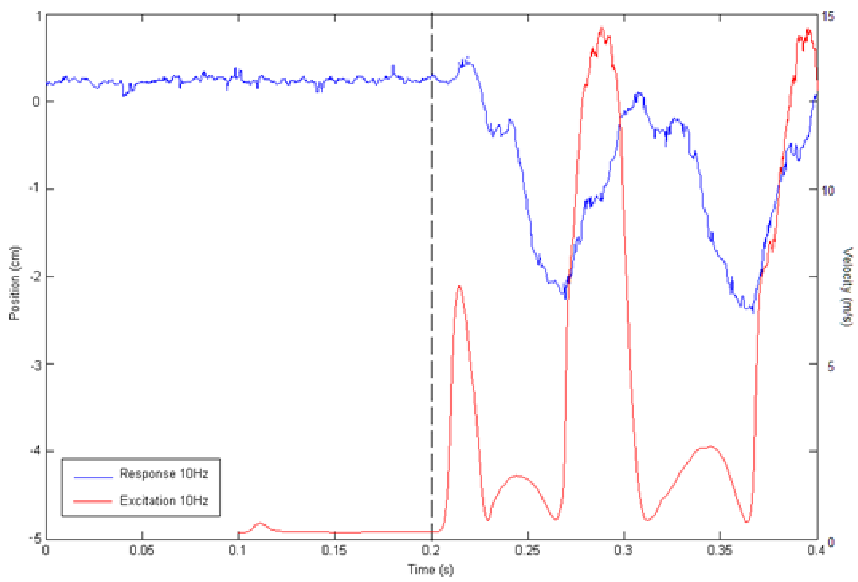

Figure 12. Excitation and response at 10Hz

5. CONCLUSION

We can see that the system is effective in changing the direction of the flow. The contour plots have shown us the presence of periodic structures in the excited flow, especially near the diffuser wall. We saw that the speed of the response of the system is very fast, and that it does not take more than 0.1s to the system to stabilize from the start of the signal. By comparing different frequencies of excitation, we found the range of frequencies optimal for our system, and discovered that the delay is also determined by the frequency, and there is also a best frequency for the minimum delay, and, for our system at least, it is the same as the optimal frequency. However, one should remember that our data is based on a sole system, the simplest there is, and requires further investigation so that we can confirm these conclusions.

6. ACKNOWLEDGEMENTS

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