

## Aspects of the influence of an oscillating mini-flap upon the near wake of an airfoil NACA 4412

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**Abstract.** A NACA 4412 airfoil was tested, in a boundary layer wind tunnel, with the aim to study the effect of a Gurney mini-flap, as an active and passive flow control device submitted to a turbulent flow field. The main objective was the experimental determination of flow pattern characteristics downstream the airfoil in the near wake. The untwisted wing model used for the experiments had 80cm wingspan and 50cm chord, with airfoil NACA 4412. The mini-flap was located on the lower surface at a distance, from the trailing edge, of  $8\%c$  ( $c$  airfoil chord). The Reynolds number, based upon the wing chord and the mean free stream velocity was 326,000 and 489,000. The turbulence intensity was 1.8%. The model was located into the wind tunnel between two panels, in order to assure a close approximation to two-dimensional flow over the model. As an active control device a rotating mini-flaps, geared by an electro-mechanical system (which rotate to a  $30^\circ$ ) was constructed. The wake pattern and pressure values near the trailing edge were measured. The results obtained, for this mechanism, show us that the oscillating mini-flap change the wake flow pattern, alleviating the near wake turbulence and enhancing the vortex pair near the trailing edge at the mini-flap level and below that level, magnifying the effect described first by Liebeck [1]. That effect grows with the oscillating frequency. Additionally, the wake alleviation probably affects also the far wake. All of these facts suggest us to continue with the experiments, trying to measure the pressure distribution around the airfoil in all the cases, obtaining the lift and drag characteristics.

### 1. Introduction

The trailing edge camber and its geometry together with its influence upon Kutta condition could be used to the lift, pressure drag and wake management. Researchers analyzed various passive and active flow control mechanisms in order to enhance lift coefficient, in particular, during landing approach and also take off. One of those mechanisms is the mini-flap Gurney, which is a small width plate located on the lower surface of the airfoil, as close as possible to the trailing edge, along wingspan. The goal is to achieve a drift of the rear stagnation point (Kutta condition) with the subsequent circulation enhance and, so, achieving a lift enhance. One of the pioneer researchers was Liebeck [1], whom worked with a symmetrical Newman airfoil with a  $1.25\%c$  height Gurney flap, being  $c$  the airfoil chord. He founded an important lift increase, associated to circulation enhance due to the

downwash increment in the near wake. Further, other researchers performed several studies [2,14], which corroborated that, as other trailing edge passive flow control devices, Gurney flaps (see Figure 2) enhanced the lift, the maximum lift coefficient and the  $C_l$  versus angle of attack slope, with little drag and stall angle changes. Moreover, they found that the best height of such devices was the local boundary layer thickness on the lower surface near the trailing edge. Also they found that the near wake was a von Kármán type wake [11]. There weren't observed coherent structures in the wake of an airfoil without Gurney flap.

Vortex shedding increment suction on the upper surface near the trailing edge and, at the same time, decelerate the flow on the lower surface with the subsequent pressure increment on that side, near the trailing edge. These pressure differences near the trailing edge enhance the overall circulation around the airfoil and, hence, the lift. A Gurney flap on the lower surface near the trailing edge will delay the stall, promoting grows of the maximum lift coefficient. For that reason many designers considered the use of those mini-flaps Gurney type combined with other flow control devices in order to achieve less complex high lift devices than the classical ones, without performance loss during takeoff and landing. If we observe the wake, in particular, the near wake, we could conclude that a circulation grow is associated with a downwash increment. This requires more asymmetry of the near wake.

From our point of view, it's not realistic the conception of a classical physical model of the wake flow, as a symmetrical one like a von Kármán street, because due its symmetry there will not be a net downwash associated with a lift enhance. Moreover, in the near wake region of an airfoil with a mini-flap on the lower surface, under lift conditions, the intensity of vortex shed from the upper surface will be different than the one shed from the lower surface. This asymmetry will be responsible of the net extra downwash and, hence, of the lift enhance. Experiments performed by the authors in a previous work [15], showed that in the near wake region, where the vortex system begins its formation, there are an important frequency peak in the instantaneous velocities spectra, generating the so called *wake instability*. Nevertheless, the major part of the works referring the study of flaps Gurney, as passive flow control devices, was made in conditions of laminar or almost laminar free stream flow.

Another authors [10, 15] proposed the use of micro tabs capable to move, to make active flow control upon wind turbines rotor blades. Another author [16], suggested the use of active mini-flaps Gurney type to diminish the wake development and intensity. Tang et al [17] analyzed the aerodynamic behavior of a NACA 0012 with an oscillating Gurney flap, reaching maximum lift and pitching-moment coefficients enhancing, which increase with the oscillating frequency. But all of the cited authors and, in general, the research in such fields are made under a laminar or almost laminar free stream.

So, we were motivated to analyze the use of mini-flaps as active flow control devices, in order to modulate shear layers which generate a circulation grow and, subsequently, a lift enhancement, in the field of turbulent low Reynolds aerodynamics that is, for Reynolds numbers below  $10^6$ , based the number upon the mean free upstream velocity and the airfoil chord, being turbulent the free stream. This is because an important number of aerodynamics problems occur in the low atmospheric boundary layer, which is essentially turbulent under windy conditions (airplanes during takeoff and landings; small size unmanned aerial vehicles; wind turbines; etc).

In this first work, the authors proceed to study in the boundary layer wind tunnel, the near wake of a wing model with a NACA 4412 airfoil, located horizontally inside the test section, between parallel plates in order to have 2D flow over it. The model had a mini-flap of  $1.5\%c$  (being "c" the model chord), located along wingspan at  $8\%c$  from the trailing edge on the lower surface, capable to oscillate around its axis with variable frequency. The model, also, have 35 pressure taps around its mid-span, one on the leading edge and the other per pairs at the same streamwise position along chord, over the upper and lower surfaces respectively.

Under such circumstances we carried out the experiments with the model inside the wind tunnel test section, looking to qualify and quantify the near wake characteristics and, simultaneously, taking pressure data.

We look forward to finding a relation between the near wake characteristics and the flow circulation which - in fact - will be influenced by the wake.

## 2. Experimental procedure

The experiments were carried out in the closed circuit boundary layer wind tunnel at the Boundary Layer & Environmental Fluid Dynamics Laboratory, Aeronautical Department, Engineering Faculty, National University of La Plata (Argentina). Test section is 1.4m width, 1m height and 7.5m length. The untwisted wing model, with a NACA 4412 airfoil, had 80cm wingspan, 50cm chord ("c") and a 1.6%c (8 mm) height mini-flap located at 8%c from the trailing edge at the lower surface, along wingspan. The mini-flap was capable to oscillate around its axis, being possible to vary the oscillating frequency.

The wing model was mounted between two double lateral plates, which trailing edges were capable to manually adjust along each axis, in order to have a favorable (or almost zero) pressure gradient along the test section, with the thinnest possible boundary layer (see Figure 1). The aim is to have not only 2D flow over the model, but also little difference between the geometric and the aerodynamic chords.



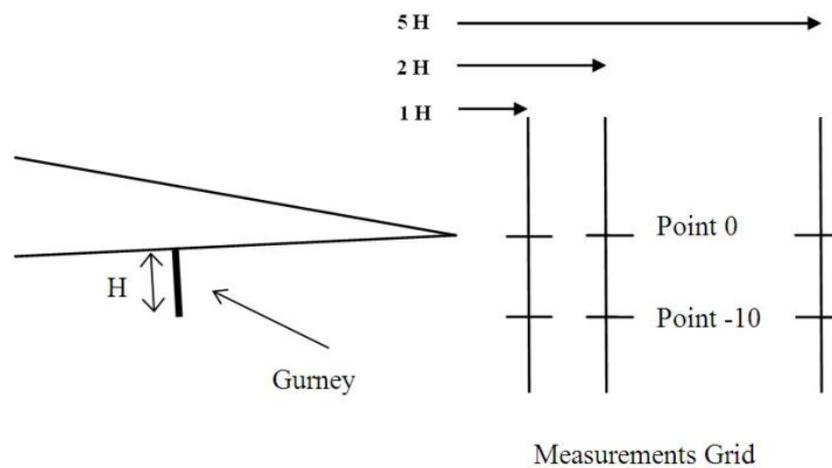
**Figure 1.** Front view of the wing model at the test section. We could see the anemometer's probe to check the mean free stream velocity and the wall panels at each side of the model.

In the experiments we measure the instantaneous velocity in the near wake region, in three "x" positions, 1h, 2h and 5h (Positions 1, 2 and 3 respectively, being h the mini-flap height) and, at each "x" position, the data were measured in 20 vertical points, which upper limit was 1.5%c and lower limit 2%c, separated each 0.04%c. Turbulence intensity was 1.8%. Experiments were performed for two Reynolds numbers, 326000 and 489000, based upon the mean free stream velocity (at 1.5m ahead the model at its height) and the model chord, corresponding to values of 10m/s and 15m/s respectively.

Experiments were carried out in three steps, for each Reynolds number: 1<sup>st</sup> step with the clean model; 2<sup>nd</sup> step with the mini-flap deployed but fixed (as a passive flow control device); 3<sup>rd</sup> step with the mini-flap oscillating at three frequencies each time (22Hz, 38Hz and 44Hz). In all steps, for four values of the angle of attack:  $-3^{\circ}$ ,  $0^{\circ}$ ,  $5^{\circ}$  and  $11^{\circ}$  (this last near stall angle). We measured instantaneous velocities in the points cited above, by means of a constant temperature hot wire anemometer Dantec Streamline, with X-wire sensor probes. The acquisition frequency was 4000 Hz, filtered at 1000Hz, taken 8192 samples per channel in each measuring point. The mini-flaps frequencies were measured with a laser tachometer. The wing model had two pressure taps at the same "x" position (0.88c), one

on the upper surface and the other on the lower surface. The connection between the pressure taps and the Pressure System (NetScanner, equipped with piezoelectric sensors) was by tubes of 1.8mm inside diameter, each of the same length. Such pressure taps were located upstream of the perturbation zone (mini-flap position), with the aim to obtain instantaneous pressure data not perturbed, directly, by the mini-flap position itself.

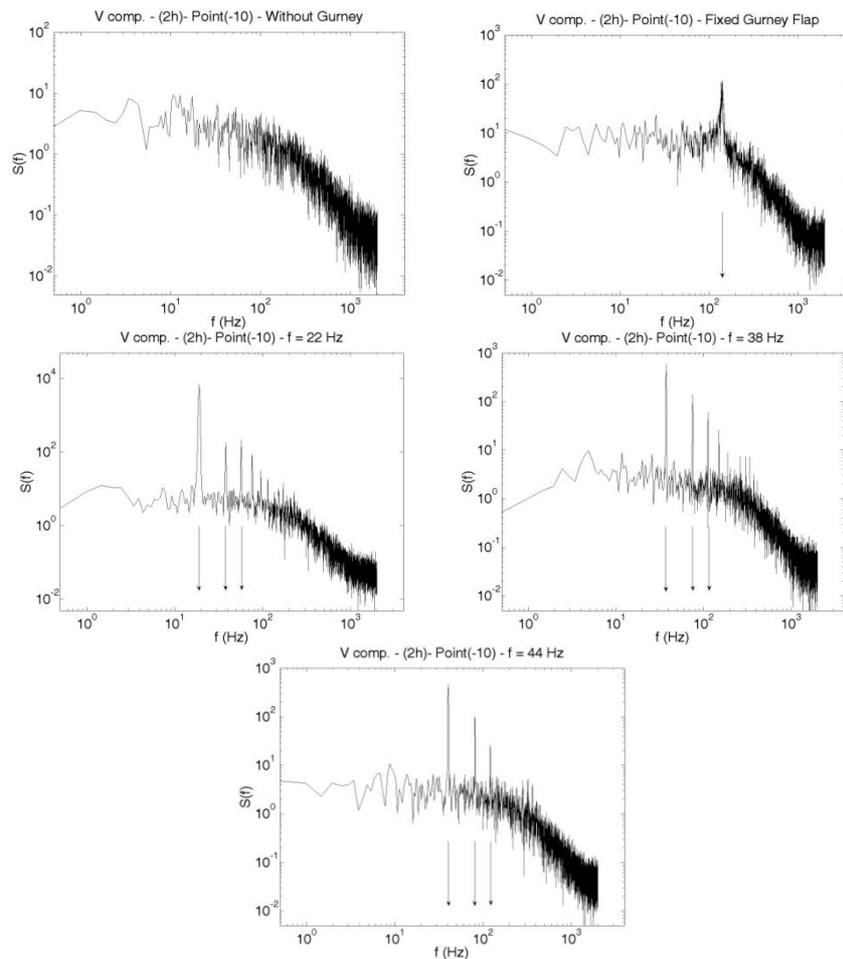
Figure 2 shows a schema of the wake measuring positions, along “x” axis and the corresponding vertical points, indicating in this Figure only the 0 and -10 points the separation between vertical adjacent points is  $0.25H$  (2 mm).



**Figure 1.** Wake measurement schema.

### 3. Experimental results

Below we show up some of the experimental results with the aim to explore qualitatively and quantitatively the particular fluid dynamic pattern, promoted by the mini-flap oscillations, in the near wake region, as a consequence of the active flow control of such device upon the airfoil's aerodynamic characteristics. We observed the almost perfect matching between the mini-flap oscillating frequencies and the special wake structure, with a peak at the same frequency than the oscillating one and other peaks which are other structures, not harmonics because they aren't multiples of the first (fundamental). In order to support such assumptions, we also showed the corresponding velocities spectra at some selected vertical points (Figure 3) and the horizontal ( $U$ ) and vertical ( $V$ ) velocities components on each “x” position ( $1h$ ,  $2h$  and  $5h$ ) for all the vertical points (mean free stream of  $10\text{m/s}$  and  $0^\circ$  angle of attack):

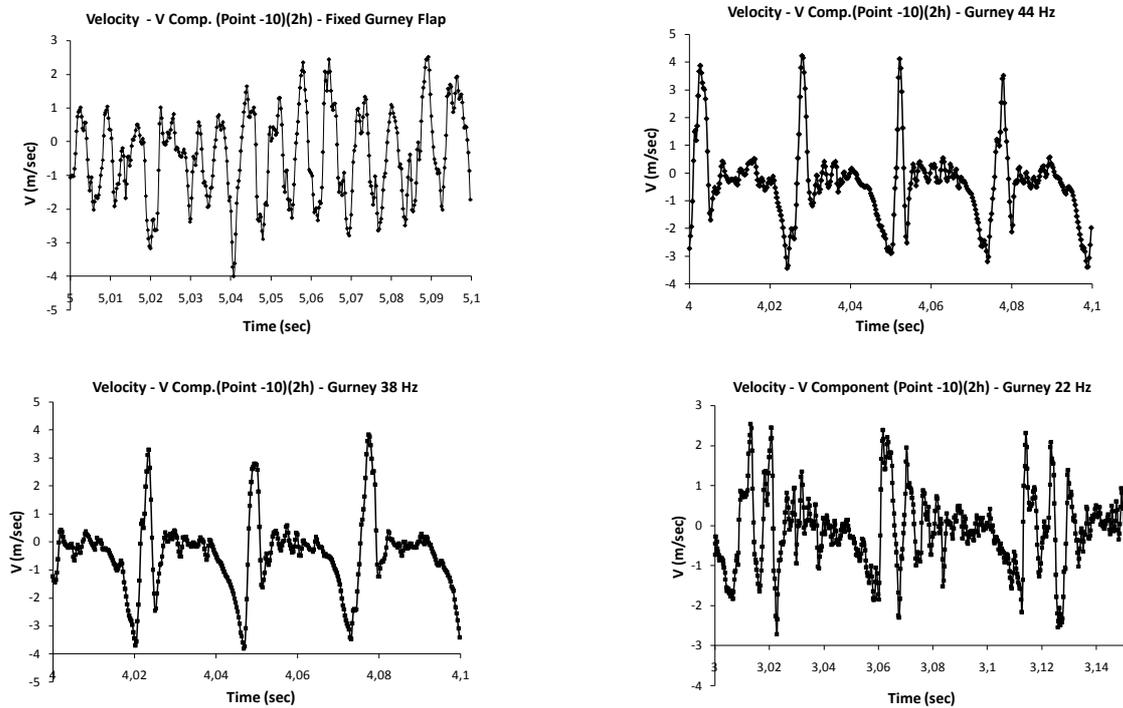


**Figure 2.** V component velocities spectra for the clean airfoil, fixed Gurney and moving one (three frequencies), 2h “x” position and vertical point -10.

We observe, above, the power density spectra evolution of the downstream vertical velocities, at the 2h “x” position in a vertical point located at the same horizontal level of the mini-flap’s trailing edge (point -10), for the clean airfoil (PS), the mini-flap deployed fixed (GF) and for the mini-flap oscillating at 22; 38 and 44 Hz. In all cases, the free stream upstream velocity was 10 m/s.

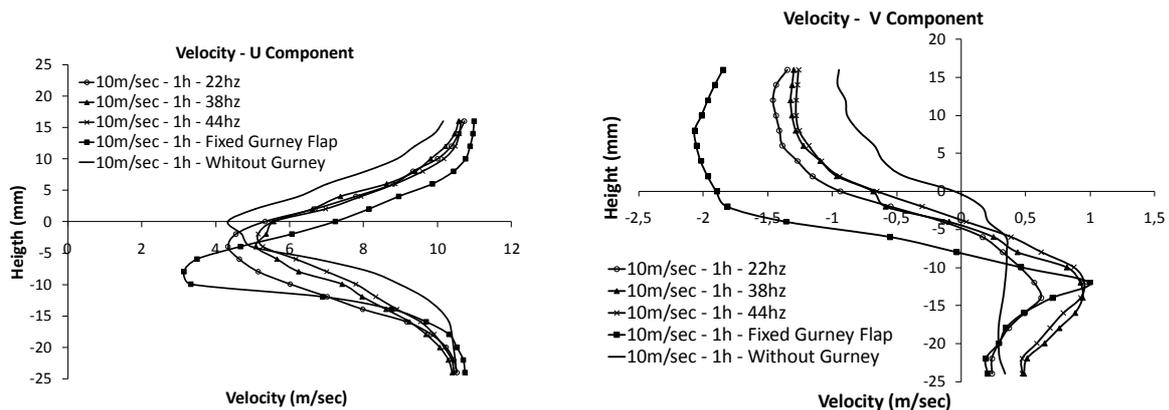
The spectra peaks were as follows. For 22 Hz (oscillating frequency), first peak at 22 Hz and successively (approximate) 39 Hz, 58 Hz, 74 Hz, 92 Hz and 110 Hz; for 38 Hz (oscillating frequency), the peaks were at 30 Hz, 78 Hz, 110 Hz, 124 Hz, 190 Hz; for 44 Hz (oscillating frequency), the peaks were 44 Hz, 82 Hz, 108 Hz. For the fixed GF condition, the peak was at 142 Hz. One could see how the oscillation of the mini-flap made important changes on the wake characteristics. The periodic (coherent) vortex street, generated by the oscillating mini-flap, had enough strength to overlap and diminish the intensity of the turbulent structures typical of the airfoil with the fixed mini-flap. This behavior is more significant as the oscillating frequency grows. In that way, the important changes in the wake, promoted by the oscillating mini-flap, will affect directly the general circulation around the airfoil. Thus, our main concern is to measure the near wake with detail.

Figure 4 shows the instantaneous velocities at those -10 points. The curves exhibit peaks, of course, in accordance with those power density spectra (Figure 3). We could see how the turbulent intervals between peaks, are reduced as the oscillating frequency grows. This is due, probably, to the fact that once we overcome some frequency step, the characteristics of the periodic structures, shed by the oscillating mini-flap, become almost independent of the frequency and, so, the near wake structure will be similar for frequencies above such step.



**Figure 4.** Instantaneous vertical velocities curves at -10 points for the wing with GF fixed and wing for the three mini-flap frequencies oscillation

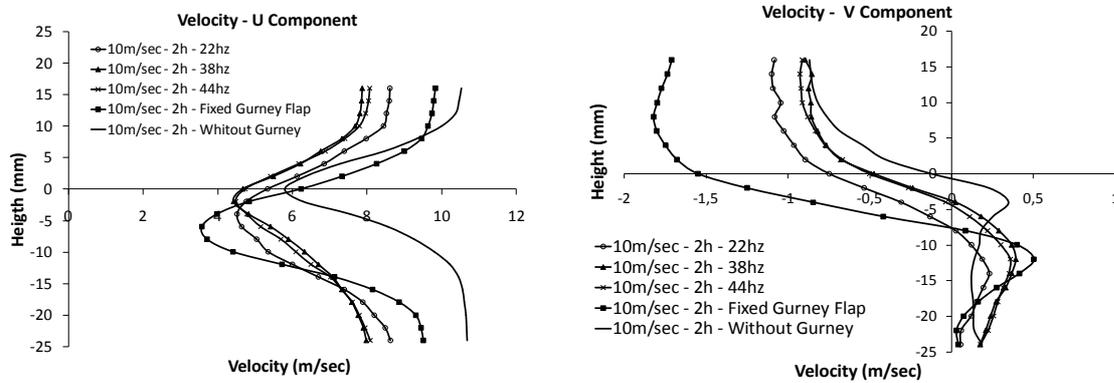
Figure 5, 6 and 7 shows the horizontal and vertical velocities, for a free stream of 10m/s and  $0^0$  angle of attack, for all vertical points in each “x” position (1h, 2h and 5h), for the clean airfoil, the fixed deployed mini-flap and the oscillating condition for the three frequencies.



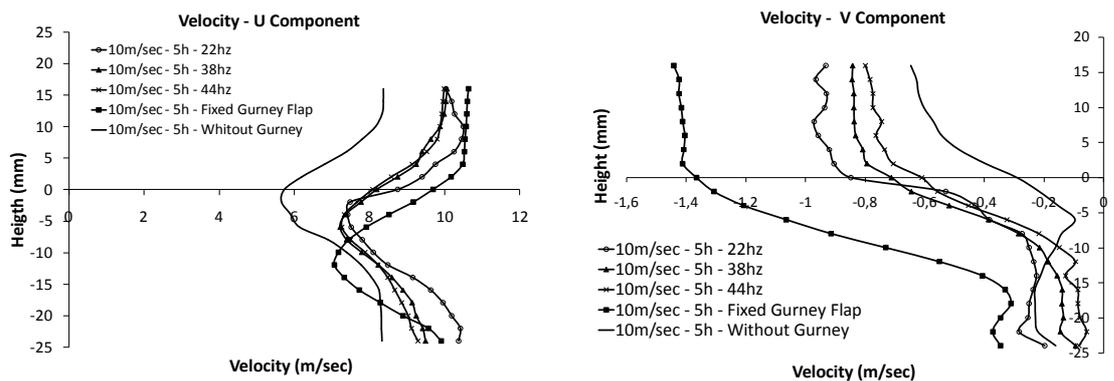
**Figure 5.** U and V component velocity distributions in the wake at 1h.

Regarding the Figure 5, we could conclude that the U-component has small variations between the different conditions (clean airfoil; fixed flap; etc), being always positive above and below the trailing edge, but with a reduction of its magnitude from the trailing edge level to the end of mini-flap level. The vertical velocities exhibit important differences, above the trailing edge, between the clean airfoil and the fixed mini-flap case. Respect the oscillating mini-flap, there are small differences between the vertical velocities for the three frequencies but, if we look close the vertical velocities at the mini-flap level and lower, their values are greater than the corresponding to clean airfoil or even the fixed mini-

flap case. Qualitatively, the situation is similar for the 2h “x” position (Figure 6). Analyzing both Figures, it’s clear that we have an anticlockwise vortex behind the mini-flap. This is consistent with the results founded by other authors [1, 3, 4, 5, 8, 9, 10, 14, 15 and 17].

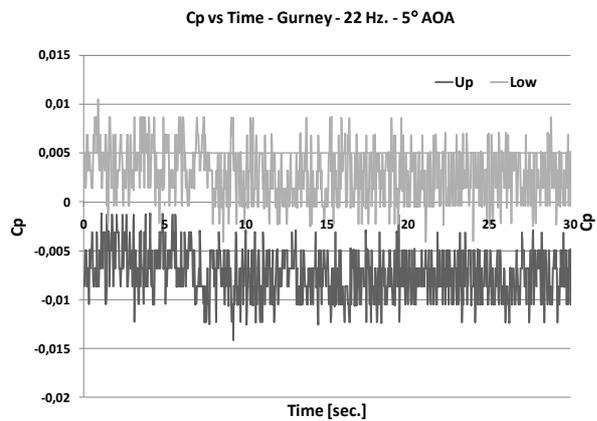


**Figure 6.** U and V component velocity distributions in the wake at 2h.

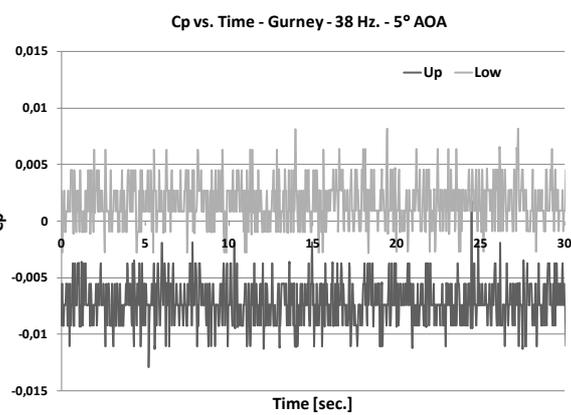


**Figure 7.** U and V component velocity distributions in the wake at 5h.

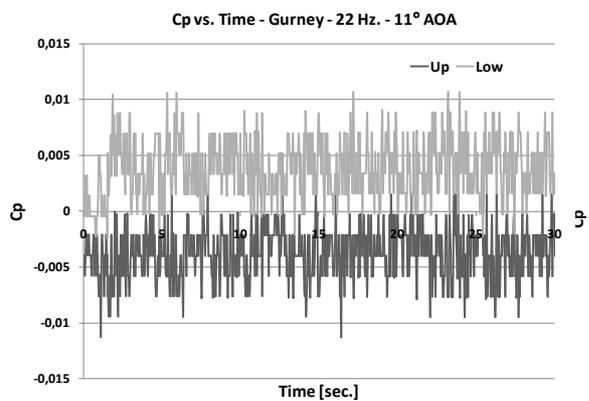
Following some of the ideas exposed by Tang et al [17], we selected two upstream points, one on the upper surface and the other on the lower surface (see Experimental procedure), to analyze the pressure time history. Our pressure taps were located at the “x” position  $0.88c$  being the mini-flap location at  $0.96c$ . Such pressure taps were designated Up (for upper surface) and Low (for lower surface). The main difference, regarding the procedure followed by Tang et al [17], was our election of the pressure taps location, upstream the perturbation device (mini-flap) location. Figures 8a and 8d show the  $C_p$  time history for  $5^\circ$  angle of attack (AOA) and 22Hz and 38Hz oscillating frequencies, respectively. Figures 8c and 8d are for those two frequencies but for  $11^\circ$  of angle of attack.



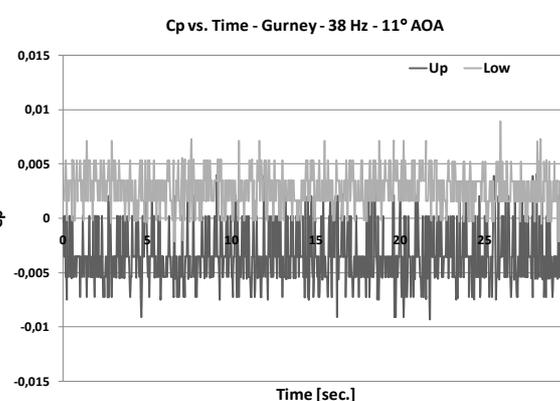
**Figure 8a.** Cp vs. time (22 Hz – 5° AOA)



**Figure 8b.** Cp vs. time (38 Hz – 5° AOA)



**Figure 8c.** Cp vs. time (22 Hz – 11° AOA)



**Figure 8d.** Cp vs. time (38 Hz – 11° AOA)

Figure 8a show some irregularities in the pressure fluctuations, than Figure 8b. It seems that as frequency grows, the pressure fluctuations become similar in amplitude, both in the upper and lower surfaces. The difference between those times histories could be associated with the changes in the near wake as the frequency grows (see Figure 4). Although velocities spectra showed in Figure 4 corresponds to 0° of angle of attack, we could made a comparison between such results and the pressure time histories for 5° angle of attack, bearing in mind the similar qualitative behavior of the airfoil for 0° and 5° angles of attack. Moreover, such times history behavior is also associated with the pair of vortex structures in the near wake (described above, regarding Figures 5 and 6). If we observe carefully, for the same angle of attack and far away from the stall, as frequency grow, the upper  $C_p$  becomes more negative whereas the lower  $C_p$  becomes a bit less positive as the frequency grow. From an overall point of view we could conclude that as frequency grows the lift will enhance. Figures 8c and 8d show us the situation for 11° of angle of attack, exhibiting an overall increase of the pressure fluctuations, in comparison with the case for 5° of angle of attack, but with they seems to diminish the difference between the upper and lower  $C_p$ 's. So, that could imply an small lift lowering, in comparison with the 5° angle of attack. Such behavior, on the upper surface, could be a result of the interaction of the external turbulent flow and the boundary layer near to stall and, in the lower surface, the interaction of the external flow and the fluctuations induced by the oscillating mini-flap.

Finally, looking to achieve an overall understanding of the whole phenomena, we prepared the Table 1 in order to compare the upper and lower  $C_p$ 's, for the airfoil with the fixed mini-flap and the airfoil with the oscillating mini-flap, for the three frequencies. The first conclusion is that the  $C_p$  differences between the lower and upper surfaces, for three reference angles of attack (0°, 5° and 11°),

are greater for the fixed mini-flap than the oscillating one. The second conclusion is that the corresponding  $C_p$  differences between the lower and upper surfaces diminish as the oscillating frequency grows, but in all cases (even for the minor frequency) the values are lesser than the fixed mini-flap case.

**Table 1.**  $C_p$  values at the trailing edge.

Device		Position		
		Cp Up	Cp Low	
Deployed Gurney Flap	0°	-0.1673516	0.2247924	
	5°	-0.413925	0.2588836	
	11°	-0.2374264	0.2957263	
Movable Gurney Flap	22 Hz.	0°	-0.1477534	0.1360552
		5°	-0.3680741	0.142911
		11°	-0.1969174	0.1875045
	38 Hz.	0°	-0.0647598	0.1507643
		5°	-0.3591227	0.0808359
		11°	-0.1732171	0.1346238
44 Hz.	0°	-0.0308086	0.1724985	
	5°	-0.3501714	0.0187608	
	11°	-0.2016496	0.1066335	

#### 4. Conclusions

From the analysis of the power density spectra, vertical velocities spectra, horizontal and vertical velocities in the near wake and pressures time history, we could say that the oscillating mini-flap change the wake flow pattern, alleviating the near wake turbulence and enhancing the vortex pair near the trailing edge at the mini-flap level and below that level, magnifying the effect described first by Liebeck [1]. That effect is more evident as the oscillating frequency grows. Additionally, the wake alleviation probably affects also the far wake. All of these facts suggest us to continue with the experiments, trying to measure the pressure distribution around the airfoil, with an enough number of taps around it to find relations between the special near wake characteristics and the overall pressure behaviour around the airfoil.

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