TRAILING EDGE TREATMENT TO ENHANCE HIGH LIFT SYSTEM PERFORMANCE

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Abstract

A quasi two-dimensional experimental and numerical investigation was performed to determine the effect of different trailing edge treatment on the performance of a two-element high lift wing. Two trailing edge treatments were used in both main element and flap: a saw-tooth trailing edge and Gurney Flap and a combination of both. The saw-tooth trailing edge consisted of triangles, wishbone and trapezoidal formats applied to the trailing edge of the wing main element of in order to promote mixing between the higher-pressure flow from the lower surface with the flow on the upper surface. The Gurney flap was a flat plate on the order of 1 to 4% of the airfoil chord in length, oriented perpendicular to the chord line and located on the airfoil windward side at the trailing edge. The flow field around the airfoil was numerically predicted using CFX, with non-linear RANS turbulence model. The results from both numerical and experimental work show that the serrated trailing edge can improve the flow over the flap by delaying turbulent separation consequently decreasing pressure drag. Also, Gurney flaps increase the airfoil lift coefficient with an increase in drag coefficient. The combination of both serrated trailing edge and Gurney flap can lead to a higher performance high lift wing especially for the take-off configuration.

1 Introduction

One of the most effective devices to increase wing lift is the trailing edge flap. With the flap it is possible to produce more lift for the same incidence angle and at a lower velocity, enhancing take-off and landing performance. For take-off it is also important to increase the maximum wing CL that is not always achieved with a flap. Therefore, sometimes a slat or leading edge flap is also necessary. Single flaps have difficulty producing a considerable increase on CLmax mainly due to the turbulent separation on the suction surface. Higher performance can be achieved by using multi-element fowler flaps but their mechanisms are complex and heavy. The ideal flap would be a single element fowler flap, which could produce high maximum CL with a low boundary layer pressure drag penalty. With this kind of flap, in some cases, the leading edge high lift devices would be not necessary. The use of vortex generators is widely employed in aeronautical engineering to reduce turbulent separation on the wing and reduce pressure drag. The effect of vortex generators on wing performance was first studied by Taylor [1] in 1945. However, in general, vortex generators are not practical at cruise speeds and also produce parasite drag [2.3]. Also, it is not easy to locate vortex generators at the flap upper surface in order to inject enough turbulence into the boundary layer due to the lack of space between main element and flap in the stowed position. Novel trailing edges have been proposed by Werle et al [4] in order to alleviate separation on airfoils and wings. This consists on waving the trailing edge in order to promote mixing between the higher-pressure flows from the lower surface with the flow on the upper surface. This mixing reduces wing trailing edge separation increasing maximum lift values. For the case of a wing main element and flap waving the main element trailing edge would make flap stowing impossible. This work proposes to use a similar method of mixing flow at the trailing edge by adopting a saw tooth trailing edge rather than using waves. There have been quite a number of works on the Gurney flap since the race driver Dan Gurney used this flap on the inverted wing of his car, increasing down force, in the 60's. Despite this fact, the use of Gurney flaps still almost restricted to race cars with little use in aircraft design mainly due to the increase in drag that may occur especially in cruise conditions. However, the demands for a high lift system that could be at same time highly efficient and with a minimum complexity, has brought attention back for the use of Gurney flap on multi elements wings. Numerous wind tunnel tests on Gurney flaps have been conducted in both single and multi-element airfoils of 2-D and 3-D wings. Giguerre et al [6] presents an extensive list of these works. The first work concerning Gurney flaps was carried out by Liebeck [5] who found that lift is increased with the attachment of a Gurney flap at the trailing edge of airfoils. Liebeck also found that drag increases but for Gurney flaps with a height below 2% of the chord a slight decrease in drag can occur. For Gurney flap heights beyond 2% drag penalty may be prohibitive even if overall L/D increases. A parametric study of the application of Gurney flaps on a single and multi-element three-dimensional wing was carried out by Moyse and Heron [7]. Moyse and Heron found that the Gurney flap increased lift for the majority of the configurations tested with a drag penalty dependent of the Gurney flap height. They also founded that placing a Gurney flap at the trailing edge of the main element; in general there is no significant improvement in the wing performance mainly due to the change in the gap of the slotted flap. On the other hand, Ross et all [8] demonstrated experimentally and computationally that placing a Gurney flap on both flap and near the trailing edge of the main element can achieve an increase in lift of 12% and 40% on the lift to drag ratio. The range of Gurney flap heights tested was from 0.125 to 1.25% of the airfoil reference chord. Ross et al [8] positioned the Gurney flap at 0.5% chord upstream of the trailing edge of the main element rather than right at the trailing edge. This allowed the Gurney flap to be retracted when the high lift system is stowed. Intensive computation analysis was performed by Jang et al [9] and Carrannanto [10] in order to investigate the effect of the Gurney flap on an airfoil by using an incompressible Navier-Stokes solver with the one-equation turbulence model of Baldwin and Barth. The numerical data was compared with experimental data available in order to validate the computational flow visualization in the Gurney flap region. The general conclusion on the effect of the Gurney flap on the local flow is the production of a pair of counter rotating vortices downstream of the trailing edge. These vortices act like an airfoil extension, increasing the effective chord and camber. In this sense, it is expected that the Gurney flap at the main element trailing edge region will change the flow inclination in order to alleviate flap adverse pressure gradient and thus delaying separation. Delaying flap separation is good news for the high lift system in the climb configuration but is not necessarily welcome for landing when drag is also necessary. Unless the Gurney flap is of the retracted type as suggested by Ross et al [8] the use of this device will not be directly applicable in aircraft design before a trade-off analysis. An alternative to solve this problem is to use a different device at the main element trailing edge that would delay flap separation in the climb configuration but would be less effective at high flap angles such as in landing configuration. Lemes and Catalano [11] proposed a serrated trailing edge that promotes mixing between the higher-pressure flow from the lower surface with the flow on the upper surface to produce vortices. These vortices feed high momentum and low turbulent kinetic energy flow into the flap boundary layer delaying separation. A serrated main element in conjunction with a flap with Gurney flap could create a high lift system that would bring benefits to both take-off/climb and approach/landing. In this work, application of the Gurney flap at the trailing edge of a slotted flap in a quasi-two-dimensional two element wing is analyzed experimentally and numerically. Also, a serrated main element trailing edge of the same wing is analyzed in order to find the potential benefit of applying both systems in a high lift wing.

2 Experimental Set-up

The experiment was conducted in the Wind tunnel of Aerodynamic Laboratory of Sao Carlos Engineering School, University of Sao Paulo. The Wind tunnel is closed circuit and closed working section, the height dimensions of which are: 1.75m width, 1.30m height and 4m length. Turbulence level and maximum velocity are 0.20% and 50m/s respectively. The wing model has two elements with a flap and main element as showing in Fig. 1. The flap and main element are made of fiberglass with steel spars fixed to circular end plates to simulate a two-dimensional wing. The main dimensions of the wing are in Table 1. Using end plates does not assure two-dimensional flow, especially in high lift wings such as this model. However, at the center of the wing, where chordwise pressure measurements are performed the three-dimensional flow induced by the secondary vortices at the end plate is minimal. Also, the comparative analysis of this work assumes that any secondary vortex effect at the center of the wing will be present in both configurations: with and without the trailing edge treatment. The flap incidence angle can be changed but within a small range due to the subsequent change in the wing/flap gap and overlap. A total of 90 chordwise pressure taps were used to measure pressure coefficient distribution on both surfaces of the wing main element and flap. The pressure coefficient distributions were measured by two mechanical D48 scanivalves fitted with ± 1.0-psia setra transducer. The wing was positioned in a vertical position attached to the aerodynamic balance below the tunnel floor (Fig.. 2). The aerodynamic balance has only two components so that drag and side force (lift) were measured for a range of incidence angle of –4o to 20o. The two-component balance used is of the strain gage type and has a measurement accuracy of ± 0.7% for maximum loading. Therefore, accuracy for Lift and Drag are ±1.0N and ±0.19N respectively. Incidence angle was measured with an accuracy of ±0.1 deg.

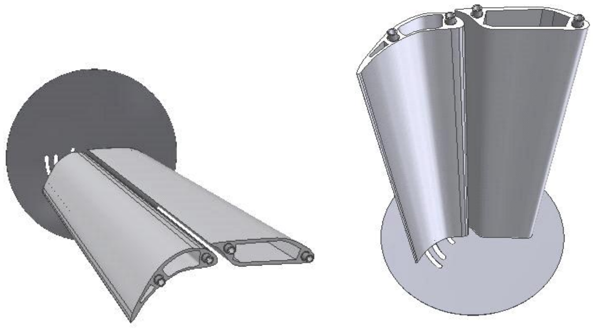

Fig.. 1 Wing model.

Tab 1: Model wing Main dimensions.

	Main Element	Flap
Reference area	0.399 m^2	0.396 m^2
Span	1.00 m	1.00 m
Chord	0.186 m	0.170 m

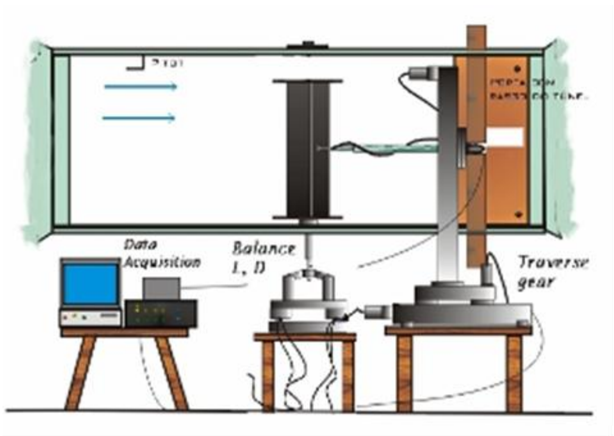

Fig. 2 Experimental set-up.

A series of saw-tooth plywood strips were glued to the trailing edge of the main element. The saw tooth geometry was defined by the size of the tooth and the distance between each of them. Fig. 3 shows the dimensions of trailing edge serrations. The saw tooth trailing edge changes the gap and overlap between main element and flap in comparison with the clean wing. Therefore, the clean wing case was tested with an increase of the longitudinal trailing edge dimension of 2% and 3% of the main element chord in order to assure the same gap and overlap of the wing with the saw tooth trailing edge. Previous results [5,6 and 7] suggest that

Gurney flap with heights of less than 5% of airfoil chord may produce less drag penalty. Therefore, in this work only the Gurney flaps of heights of 1%, 2% and 4% of reference chord were used in the tests. The experiments were conducted at an average Reynolds number of 400.000 and no trip wire or roughness strip was attached on the leading edge so that transition was free and laminar bubbles were expected to occur.

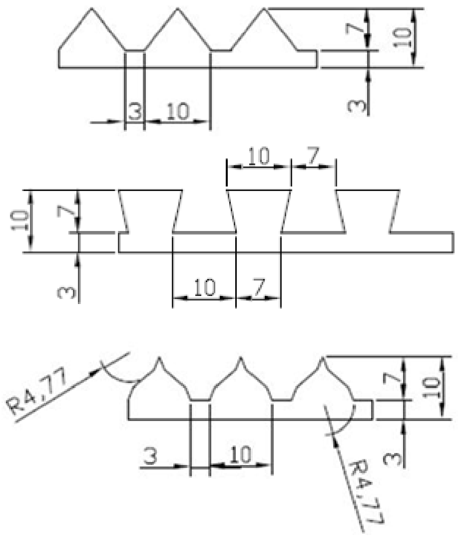

Fig. 3 Trailing edge serration dimensions.

The confluent boundary layer and shear layer between main element and flap was measured using a single hot wire probe positioned in 465 points in a plane at 0.25% downstream of the flap leading edge as shown in Fig. 4. Boundary Layer transition was also investigated through flow visualization with the sublimation technique.

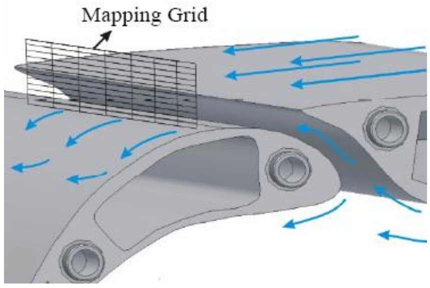

Fig. 4 Mapping grid of the hot wire anemometry measurements.

2.1 Numerical Set-up

The computer program used was the Ansys CFX with its auxiliary software for grid generation the ICEM CFD 5.0, and CFX-Pre/Pos 5.7 for pre-processing and pos-processing. The computational domain adopted has exactly the wind tunnel working section dimensions: 1.3m x 1.75m with a length sufficiently long in order to not be affected by the presence of the wing model and simulate the working section flow. Also, the computational domain length was the shortest for the least computational cost. The non-structured mesh of the computational domain and model are shown in Fig. 5. Details of the wing and end-plate non-structured mesh can be seen in Fig. 6. One of the main objectives of the numerical work was to analyze the region of the Gurney flap and the effect that this element imposes on the whole model. In the above mentioned region, flow separation is likely to occur thus, it was decided to apply the k-ε turbulence model which is a non-linear Reynolds Averaged Navier-Stokes model (RANS). The main advantage of this formulation is that it simulates with more accuracy the phenomena and has less computational cost compared with LES (Large Eddy Simulation) and DNS (Direct Numerical Simulation).

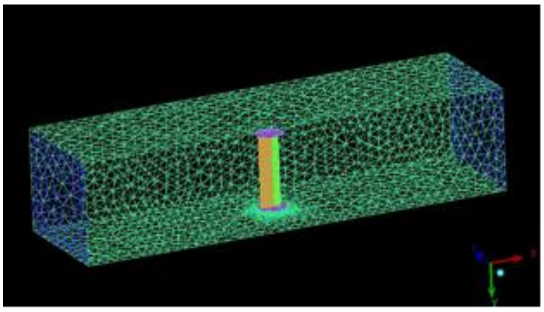

Fig. 5 Computational domain and model.

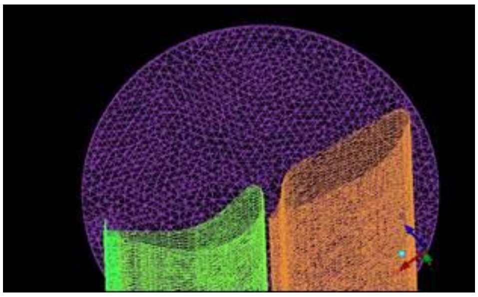

Fig. 6 Unstructured grid for the two element wing with Gurney flap and end-plate.

3 Results and Discussion

The results are presented and discussed separately for serrated trailing edge and Gurney flap set-ups. The numerical investigation was carried out for the Gurney flap in order to understand the flow at that part of the wing, as well as, the flow mapping was carried out only for the main element and flap slot flow.

3.1 Serrated trailing edge

During the tests was decided to use two different sizes for the triangular serrations. The Tri 3% and Tri 5% the triangle high is 3% and 5% of the main element chord respectively. Figures 07 and 08 show the effect of the saw-tooth trailing edge mixing on the flap separation as well as on its suction peak. The increase of attached flow was approximately 20% and 46% for the Tri3% and Tri5% respectively for the range of wing incidence angles higher than 8deg. For low incidence the effect is more intense only for the Tri5% and there is also an increase on the flap suction peak as shown in Fig. 7. However, for the entire range of incidence angles tested there was an increase in suction on the downstream end of the wing main element, showing that there was an improvement on tangential velocity in that region. This effect combined with the injection of turbulence on the flap boundary layer may improve flap aerodynamic performance. These effects did not affect the laminar separation bubble located at the wing main element upper surface. The laminar separation bubble is shown in Figs. 8 and 9 by the letters LS (laminar separation), T (transition) e TR (turbulent reattachment). For low incidence angles and flap at 4deg the effect of the saw-tooth trailing edge also appears as a global increase of circulation. This effect can be confirmed in Fig. 10 by the increase of suction and pressure on the upper and lower surface of the front part of the wing main element respectively. From the analysis of the previous results it is clear that the effect of the saw-toothed trailing edge depends on the wing geometry, gap and overlap and saw-tooth geometry and that a proper saw-toothed trailing edge must thus be designed for each new wing. The hot wire mapping measurements showed very interesting results in both the confluent boundary layer and at the flap surface. Comparing the cases with and without the saw-toothed trailing edge in Figures 11 to 15 it can be seen that there is an intermittent vortex formation on the saw-tooth that injects turbulence and energy into the flap boundary layer as the tangential speed at the flap surface also increases. The tendency is for downstream mixing-up of this stratification to occur which affects beneficially the turbulent separation. Figures 16 and 17 show the velocity profile at the serration vertex and between two serration teeth (y=0 is not at the wall). It is clear from Fig. 16 that the vortices pair formed at the serration induces a downwash to the main element wake increasing the near the flap surface velocity. Fig. 17 shows the same increase of the velocity near the flap surface as a turbulent boundary layer profile. This effects discussed above can explain the improvement of the flap aerodynamics although, the optimization between gap, overlap and serration geometry must be carried out in order to get best results. The sublimation technique is used to detect the transition front as the naphthalene sublimes under turbulence, in this way the results of Fig. 18 shows that laminar flow has increased but this effect occurs due to the stratified flow pattern generated by the saw-toothed trailing edge where there are transition spots and laminar flow forming a “zigzag” transition front. The results from mapping the flow just behind the saw-tooth trailing edge showed that there remains a field for the of study different geometries for the saw-tooth in order to produce a better interaction between the vortices generated and the flow from the wing/flap gap of any other format. Fig. 19 shows the pattern of oil flow visualization for the trapezoidal serration. The quite complex flow created between the vortices and the laminar separation bubble at the flap surface may be the key for the downstream movement of the separation front.

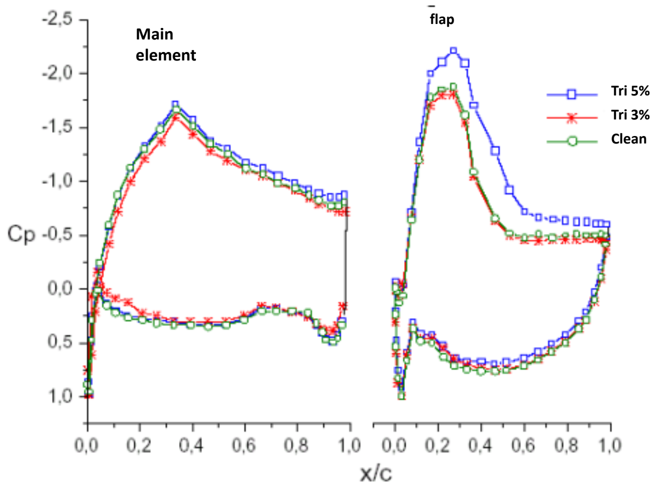

Fig. 7 Cp vs. x/c for α=0° and flap angle at 8°.

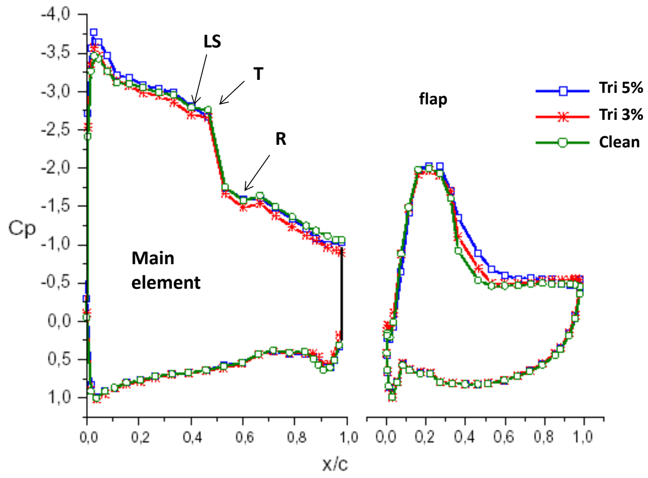

Fig. 8 Cp vs. x/c for α= 10° and flap at 8°.

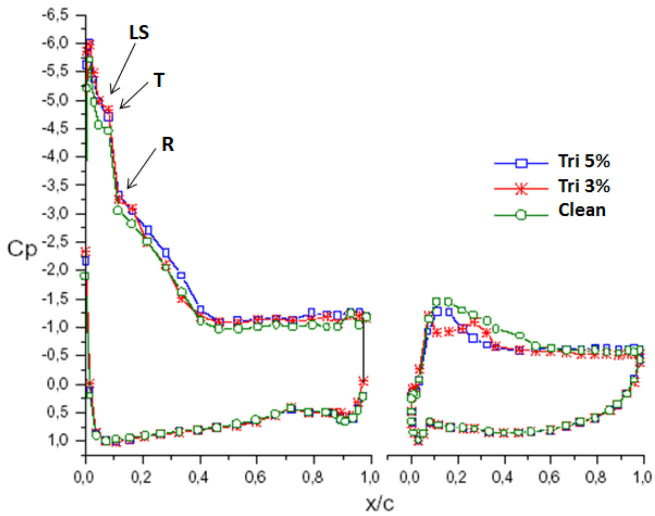

Fig. 9 Cp vs. x/c at α=20° and flap at 8°.

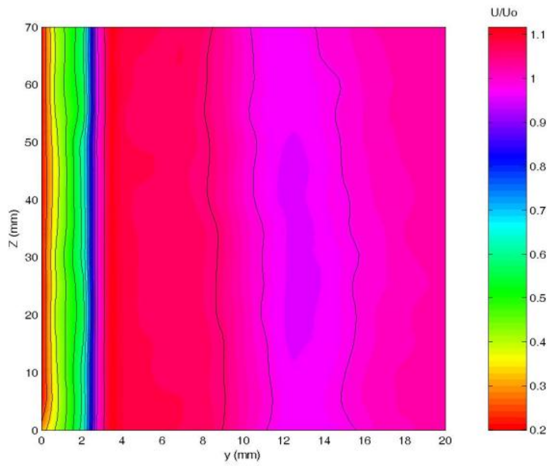

Fig. 10 Velocity topography of clean wing α = 10° flap at 12°.

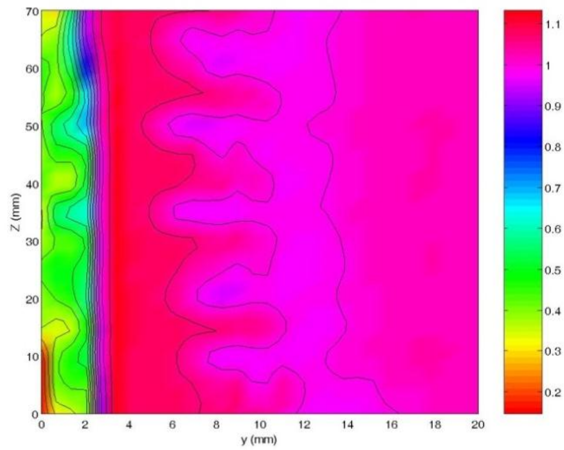

Fig. 11 Velocity topography for Tri3% for α = 10° flap at 12°.

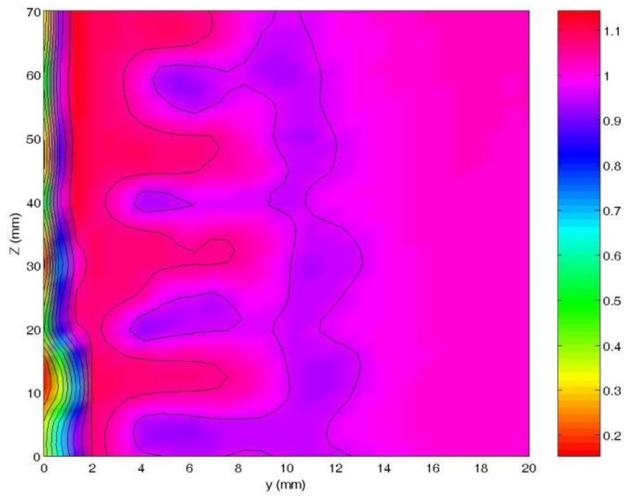

Fig. 12 Velocity topography for Tri5% α = 10° flap 12°

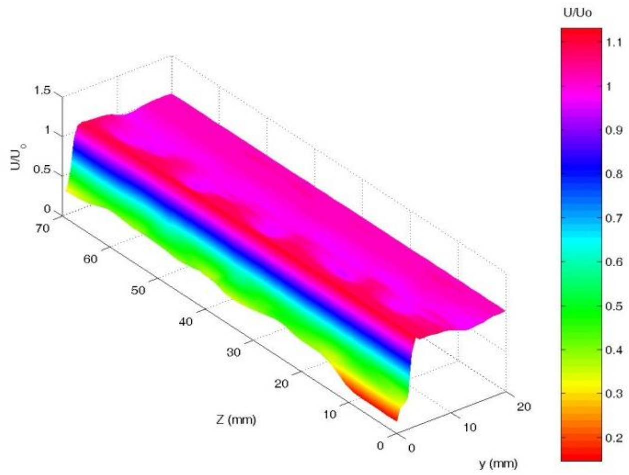

Fig. 13 3-D velocity distribution of airfoil with Tri3% at α = 10^o and flap at 12^o.

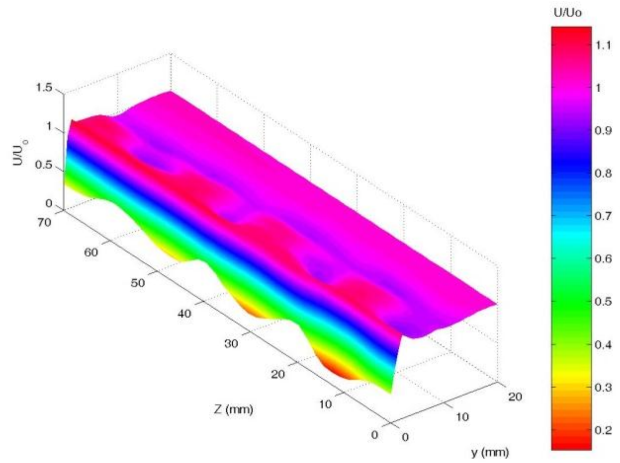

Fig. 14 3-D velocity distribution of airfoil with Tri5% at α = 10^o and flap at 12^o.

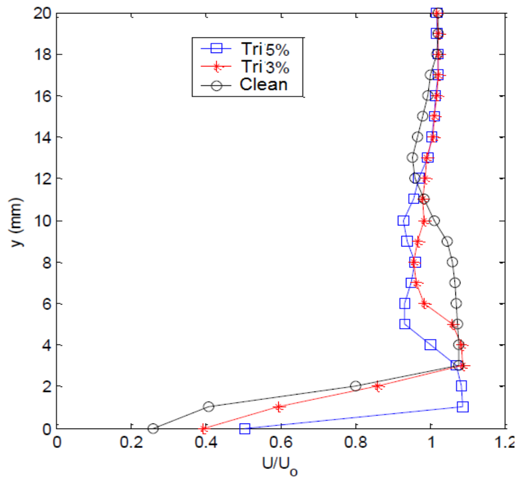

Fig. 15 Velocity profiles at serration vertex, α=10^o, flap at 12^o.

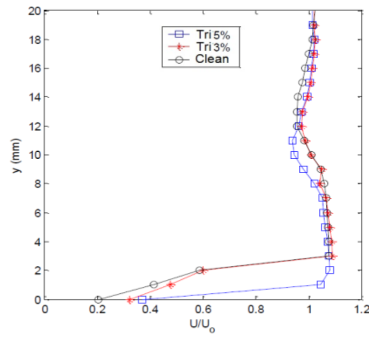

Fig. 16 Velocity profile between serrations, α=10^o flap at 12^o.

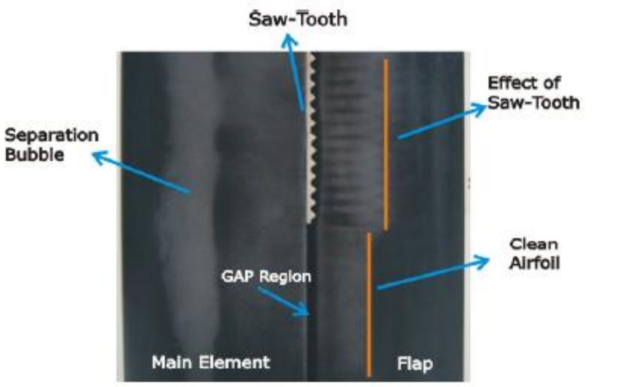

Fig. 17 Visualization using naphthalene over flap upper surface α = 10^o, flap at 12^o.

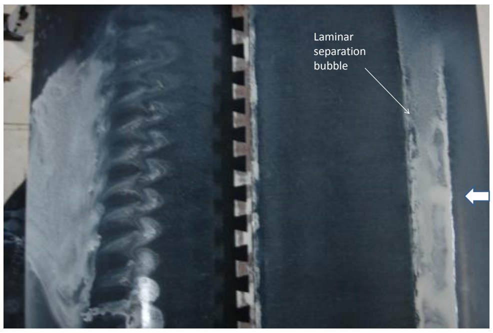

Fig. 18 Oil flow visualization α=4^o flap at 12^o.

3.2 Gurney Flap

The results for pressure coefficient are presented always in comparison between the three Gurney flaps and the wing without Gurney flap. Figures 19 to 22 presents the results for incidence angles of: 0^o, 8^o and 16^o with the Gurney flap installed at the trailing edge of the flap set at a flap angle of zero degrees. For this wing the flap at zero degree means that the flap is in the design position. For all the experimental results it is clear that the Gurney flap increases effective camber as can be seen in Figs 20 to 22, in which the suction peak becomes bigger as Gurney flap height increases. Also it is clear that at the bottom surface near the flap trailing edge the pressure increases with the Gurney flaps. These two effects combined can result in an increase in lift of up to 10%.

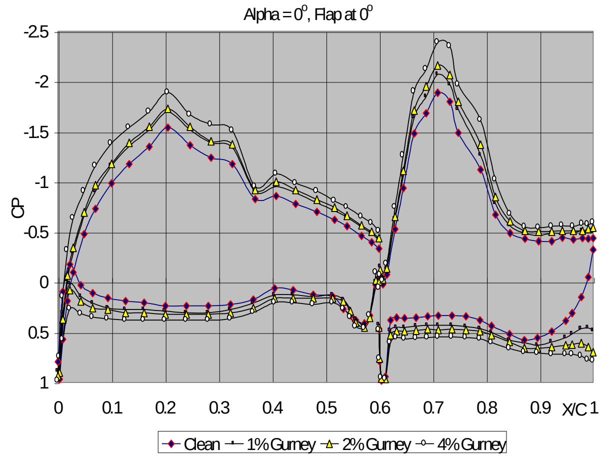

Fig. 19 Pressure Coefficient for alpha=0° and flap at 0°

From Fig. 22 is clear that even with the flap fully separated the pressure increase at the bottom surface near the flap trailing edge still to occur, but it does not affect the main element flow. Fig. 22 shows the curve of CL x α from integration of pressure distribution. Despite the fact there are a small number of points, it can be seen the Gurney flap effect on CL by shifting the curves to the right.

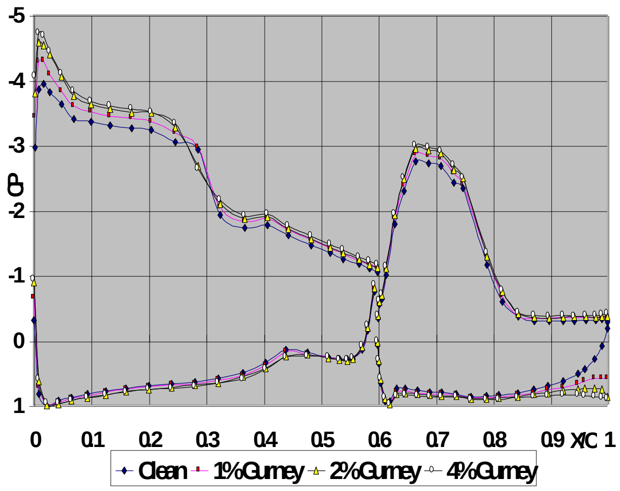

Fig. 20 Pressure coefficient for alpha=8° and flap at 8°.

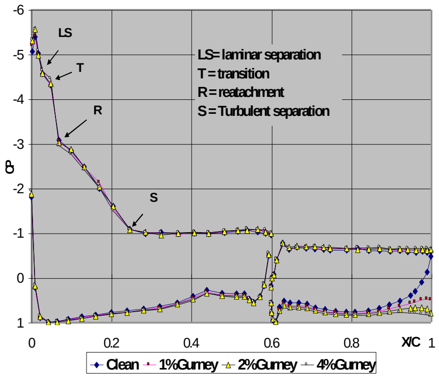

Fig. 21 Pressure coefficient for alpha=20° and flap at 8°.

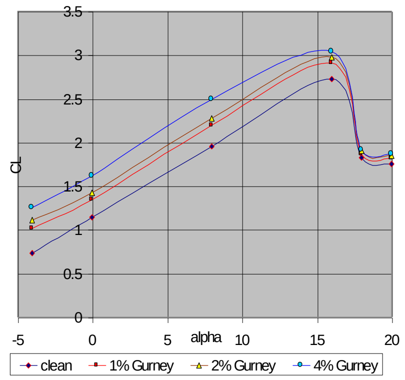

Fig. 22 Lift coefficient from pressure distribution integration, flap at 0°.

Figures 24 and 25 show the pressure distribution for the case with a 2% Gurney flap at the main element trailing edge for the flap set at zero. Fig.25 shows that the rise in pressure at the main element trailing edge is in accordance with previous results [7]. However, the presence of the Gurney flap at the slot changed the gap between flap and main element affecting the flap performance. These results show that the gap and overlap should be changed in order to establish the best performance for the flap.

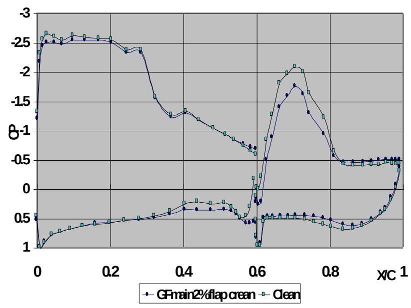

Fig. 23 CP for alpha=8°, flap 0° no GF. 2% GF at the main element trailing edge.

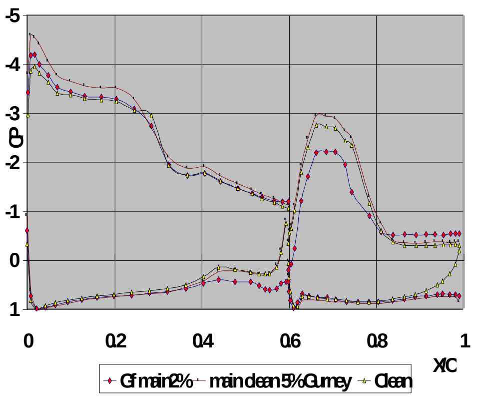

Fig. 24 Cp for α=8°, flap at 8° 2% Gurney flap at the main element and flap.

3.3 Numerical Results

The numerical results are presented in Fig. 25 with respect to the comparison with experimental pressure distribution. Computational results have failed to reproduce with accuracy the complex flow exiting in this particularly wing. Although suction peaks are at same level, the numerical calculation did not predicted well the large laminar separation bubble existing at all incidence angle mainly due to the low Reynolds number of the experiment (0.4x106) and the airfoil leading edge geometry which would induce laminar separation bubble. At the flap there was another problem with the position of the suction peak and the separation point, probably due to the numerical solution of the confluent boundary layer created by the main element wake. However, computation results were used to identify points of interest in the flow around the wing such the Gurney flap area. Figs 26 to 29 show results by using the computational flow visualization. The area of interest shown in Fig. 26 is that at the flap trailing edge with the 4% Gurney flap. The incidence angle is 8deg with the flap at zero deg. Fig. 27 shows the two counter rotating vortices and these results are in agreement with previous works [8, 9 and 10]. It is clear from Fig 27 the different scale of the two vortices making a downward movement of the flow that is leaving the upper surface at the trailing edge. This downward movement in conjunction with the existence of a vortex wake body displaces the stagnation point (or effective Kutta point) as it can be seen in Fig. 27 thus increasing effective camber and chord. The same computational procedure was applied to the case of serrated trailing edge in order to visualize the flow at the flap gap. Figure 27 shows the results for the Tri5% serration. It can be seen from these results the vortices and the effect on the flap surface in a similar pattern of the mapping experimental results at that region.

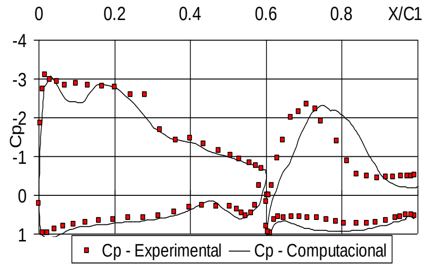

Fig. 25 Comparison with numerical results, alpha = 8o flap at 0o, 1% Gurney flap.

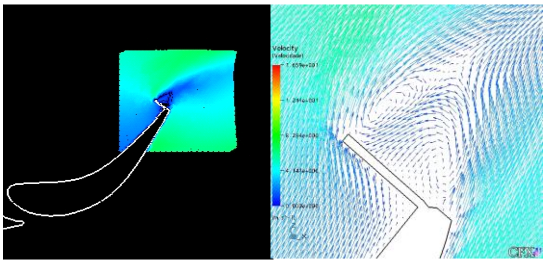

Fig. 26 Definition of the area of investigation at the Gurney flap region.

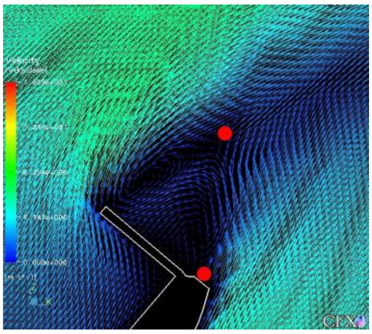

Fig. 27 Downstream and downward displacement of the Kutta point.

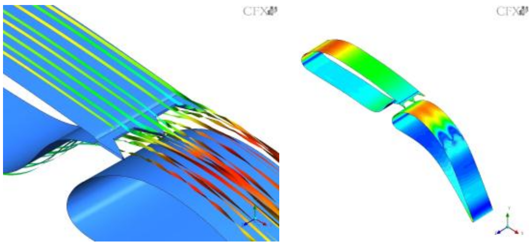

Fig. 28 Flow at the serration flap at 0°.

4 Conclusions

An experimental and numerical study was carried out in order to evaluate the potential benefit of trailing edge treatment on the aerodynamic characteristics of a high lift wing with a single slotted flap. It were evaluated the effect of a saw-toothed trailing edge of a main wing on the aerodynamic performance of a single flap and the application of Gurney Flaps of different height at the trailing edge of the flap. The results showed that vortices is formed at the saw-toothed trailing edge through the mixing between the flow from the pressure side to the suction side at the main wing and flap gap. This vorticity is injected inside the flap boundary layer delaying separation. However, the generalization of these results depends on new experimental tests with a wing/flap model that could change gap and overlap. Performing such tests, the relationship between saw-toothed trailing edge geometry and the gap and overlap could be optimized. It was used three Gurney flap heights 1%, 2% and 4% of the reference chord. The results showed that the Gurney flap positioned at the flap trailing edge can increase lift for most of the incidence tested. The Gurney flap is less effective when large turbulent separation occur at the flap and main element. The use of Gurney flap at the trailing edge of the main element is highly dependent on the gap and overlap optimization. The numerical simulation using k-ϵ turbulence model which is a non-linear Reynolds Averaged Navier-Stokes model (RANS) did not predicted accurately the pressure distribution. However, with more grid adjustment and refinement good results could be achieved. Numerical simulation of the flow at the region where the Gurney flap was installed was qualitatively very important to explain the effect of the Gurney flaps. The low cost and mechanical installation simplicity allied with its significant impact on aerodynamic performance make the Gurney flap a very attractive device to be used in subsonic aviation.

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