EXPERIMENTAL AND NUMERICAL STUDY OF A TWO-ELEMENT WING WITH GURNEY FLAP

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Abstract

A quasi two-dimensional experimental and numerical investigation was performed to determine the effect of a Gurney flap on a two-element wing. A Gurney flap is a flat plate of 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 effects of various tabs were studied at a constant Reynolds number on a two-element airfoil with a slotted flap. The experiments were conducted in a low speed wind tunnel for the wing with Gurney flap sizes of 1.0%, 2%, and 4.0% of the airfoil chord, located at the flap trailing edge and also at the main element trailing edge. The flowfield around the airfoil was numerically predicted using CFX, with the non-linear RANS turbulence model. Computational results were compared with the experimental results. The results from both numerical and experimental work show that the Gurney flaps can increase the airfoil lift coefficient with only a slight increase in drag coefficient. Although these effects with a Gurney flap positioned at the main element trailing edge are highly dependent on the gap and overlap adjustments for maximum performance, Use of a Gurney flap increases the airfoil lift coefficient decreasing the angle of attack required to obtain a given lift coefficient. The numerical solutions show details of the flow structure at the trailing edge and provide a possible explanation for the increased aerodynamic performance.

1 Introduction

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 [2] presents an extensive list of these works. The first work concerning Gurney flaps was carried out by Liebeck [1] 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 [3]. 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 [4] 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 [4] 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 [5] and Carrannanto [6] 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 [4] 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 [7] 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 in a quasi two-dimensional two element wing is analysed experimentally and numerically in order to produce more information of its effect on the wing aerodynamic characteristics.

2 Experimental set-up

The experiment was conducted in the Wind tunnel of the Aerodynamic Laboratory of Sao Carlos Engineering School, University of Sao Paulo. The Wind tunnel is closed circuit and closed working section, with dimensions of 1.75m width, 1.30m high and 4m length. Turbulence level and maximum velocity are 0.25% and 50m/s respectively. The wing model has two elements with a flap and main element and the experiment is shown in Fig. 1 and Fig 2. 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 Gurney flap installed at the trailing edges. 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. The aerodynamic balance has only two components so that drag and side force (lift) were measured for a range of incidence angle of -4^{o} to 20^{o}. 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.

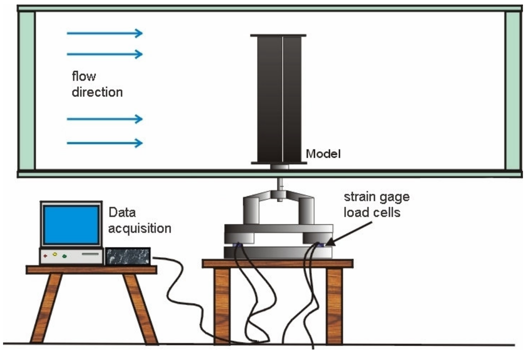

Fig. 1 Experimental set-up

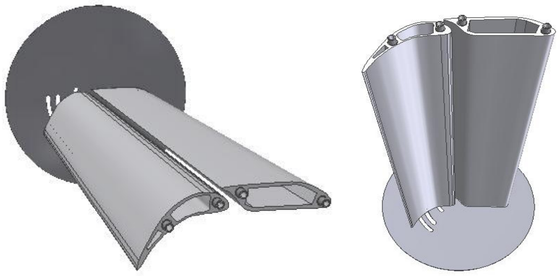

Fig. 2 Wing model lay-out.

Table 1 Model dimensions

	Main Element	Flap	**Flap incidence**	**0º**	**8º**
Reference area	0.399 m^2	0.396 m^2	**Gap (mm)**	8,80	10,15
Span	1.00 m	1.00 m	**Overlap (mm)**	12,00	13,00
Chord	0.186 m	0.170 m			

2.2 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. 3. Details of the wing and end-plate non-structured mesh can be seen in Fig. 4. 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).

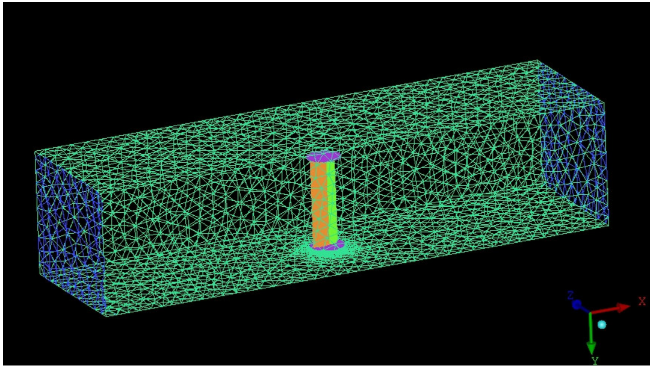

Fig. 3 Computational domain and model

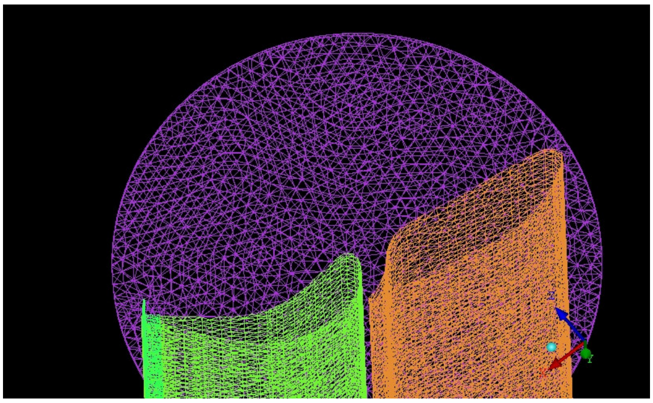

Fig 4 Unstructured grid for the two element wing with Gurney flap and end-plate.

3 Results and Discussion

Experimental results: Previous results [1,2 and 3] 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. Because the model wing was not fitted with a mechanism for changing flap gap and overlap, the Gurney flap used for the main element trailing edge was the 1% chord height. The results for pressure coefficient are presented always in comparison between the three Gurney flaps and the wing without Gurney flap. Figures 6 to 9 presents the results for incidence angles of: 0^o, 8^o, 16^o and $18^o$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, see Fig 5 for reference. For all the experimental results it is clear that the Gurney flap increases effective camber as can be seen in Figs 6 to 10, 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%.

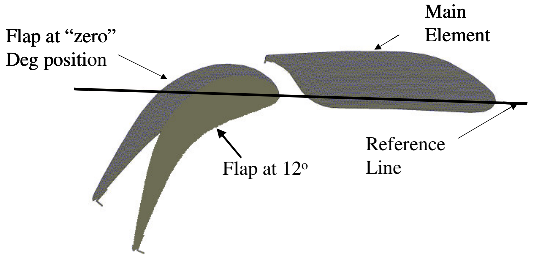

Fig. 5 Wing reference angles.

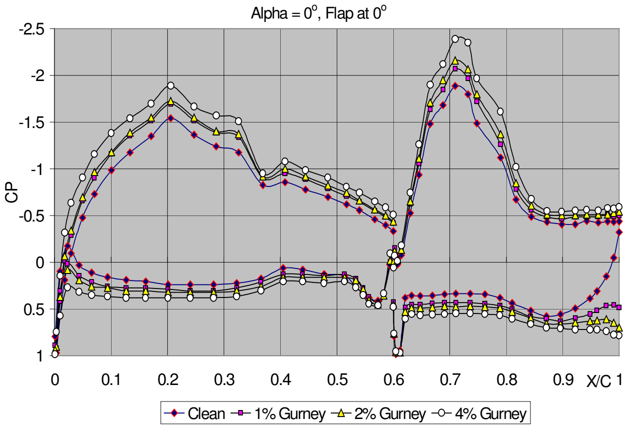

Fig. 6 Pressure Coeficient for alpha=0^o and flap at 0^o

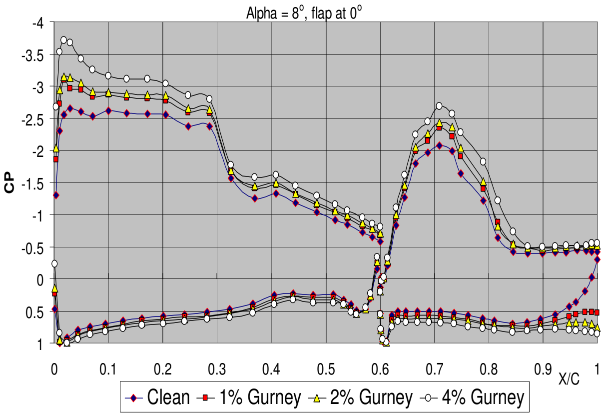

Fig. 7 Pressure coefficient for alpha=8^o and flap at 0^o.

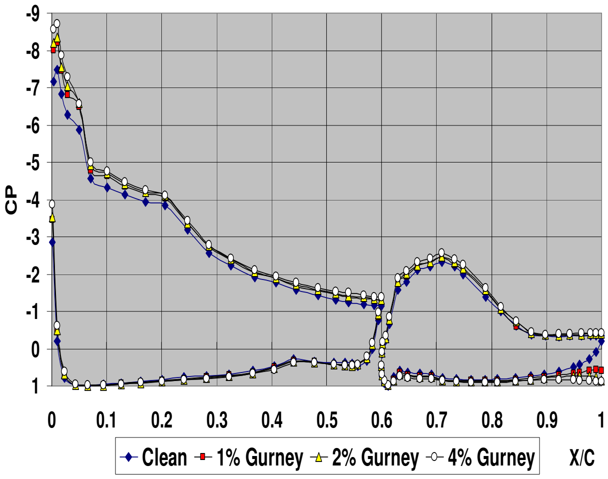

Fig. 8 Pressure coefficient for alpha=16^o and flap at 0^o.

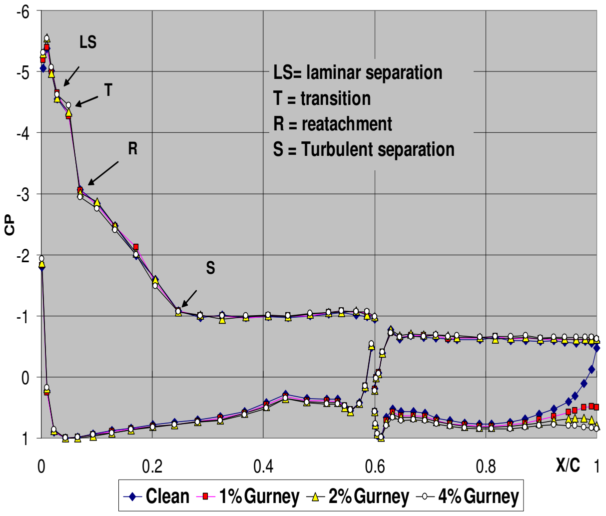

Figure 9 Pressure coefficient for alpha=20^o and flap at 0^o.

It can be seen from Fig. 7 that the turbulent separation point has been slightly delayed for the 4% Gurney flap installed. This effect could be related with the higher suction peak at the flap imposed by the Gurney flap. From Fig. 9 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. 10 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.

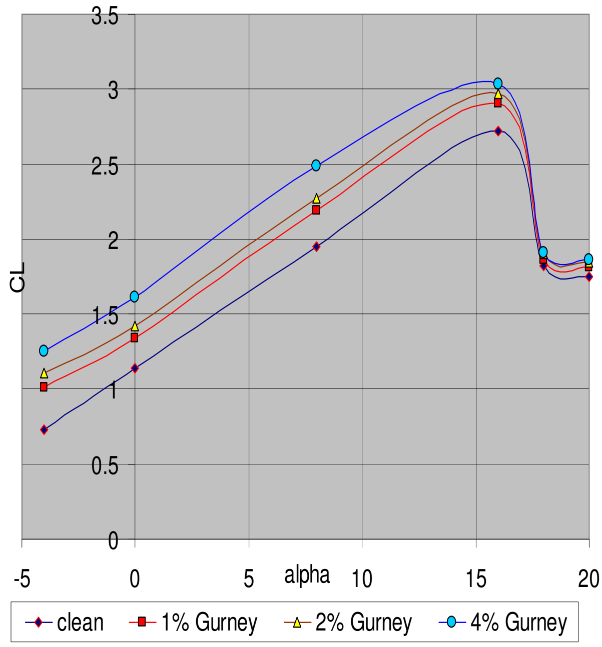

Fig. 10 Lift coefficient from pressure distribution integration, flap at incidence zero.

The Figs 11 and 12 show the pressure coefficient distribution for alpha 8^{o} and 16^{o} with the flap at 8^{o} of incidence. Similar effect of the Gurney flaps still occurring, although with less intensity at the flap. For alpha=16^{o} the Gurney flap effect delayed turbulent separation at the flap as it can be seen in more details in Fig. 13. A combination of two effects: the increase of velocity through the slot and the high pressure at the bottom rear end due the Gurney flap may explain the decrease of the adverse pressure gradient at the flap upper surface.

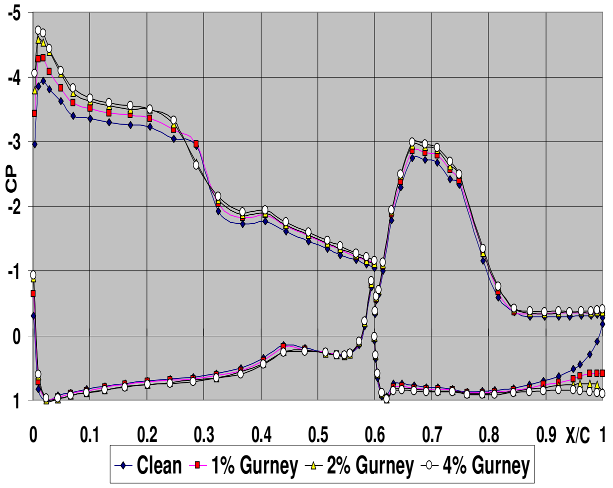

Fig. 11 Pressure coefficient for alpha=8^{o} and flap at 8^{o}.

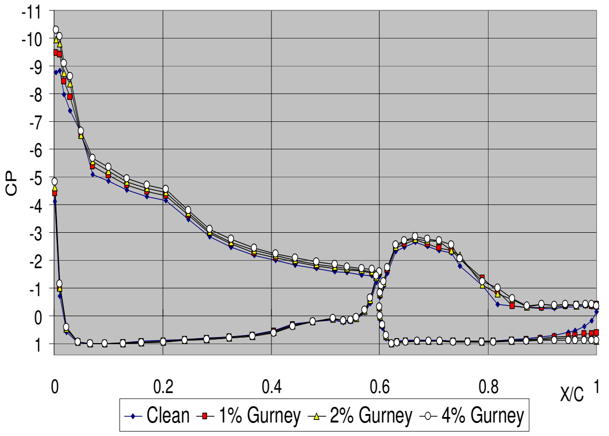

Fig. 12 Pressure coefficient for alpha=16^{o} and flap at 8^{o}.

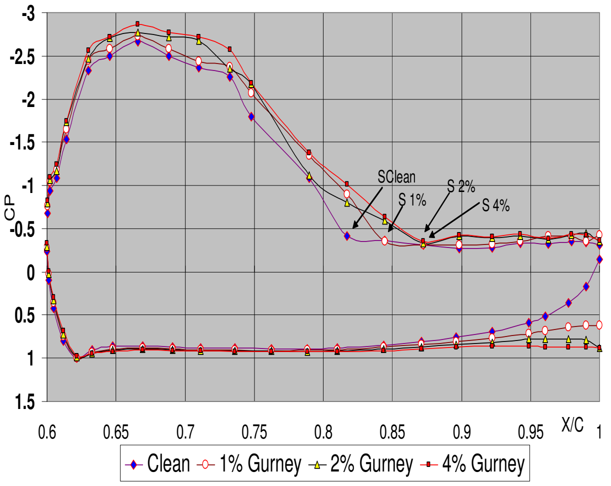

Fig. 13 Pressure distribution at the flap for alpha=16^{o} and flap at 8^{o}.

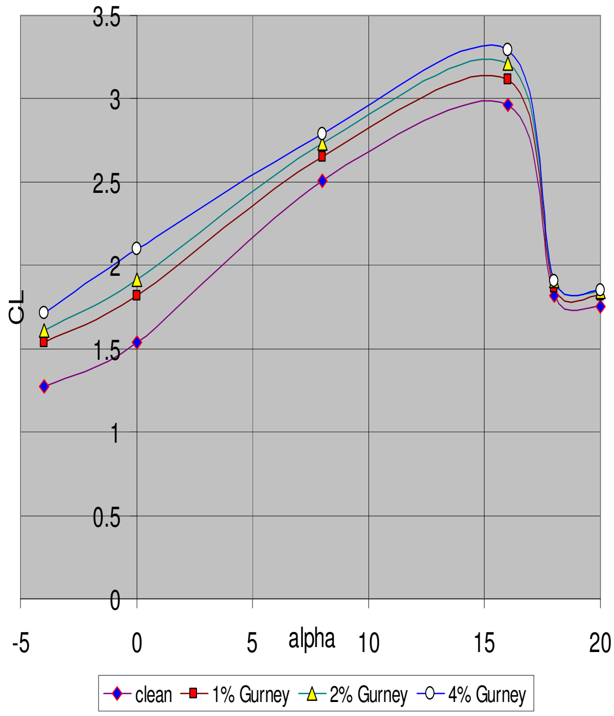

Fig. 14 Lift coefficient for flap at 8°.

The Gurney flap effect is less effective for the flap at high angles due to the turbulent separation at the flap is more intense as it can be seen in Fig.14. Figs. 15 and 16 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.14 shows that the rise in pressure at the main element trailing edge is in accordance with previous results [3]. 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 16 shows the gap change due to the presence of the Gurney flap. Different positions of positioning the Gurney flap inside the main element and flap slot probably as suggested in [4] could bring better results, although still the need to optimize the gap and overlap.

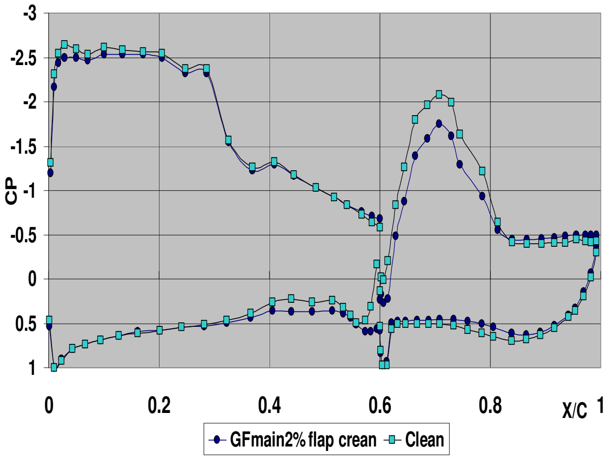

Fig. 15 Pressure distribution for alpha=8o, flap at zero without Gurney flap. 2% Gurney flap at the main element trailing edge.

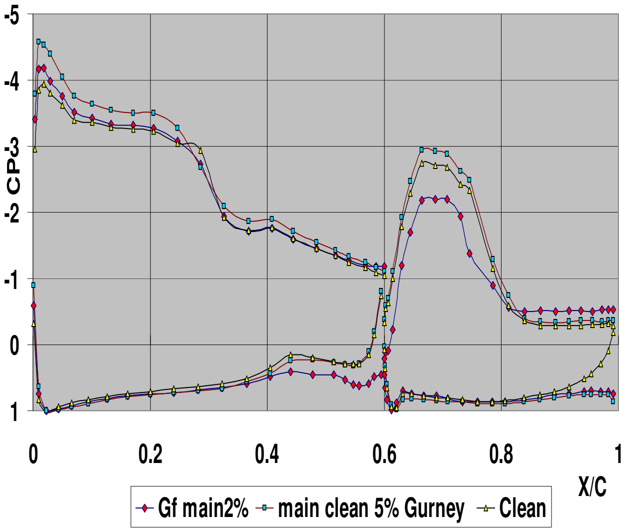

Fig 16 Pressure distribution for alpha=8°, flap at 8°. 2% Gurney flap at the main element trailing edge.

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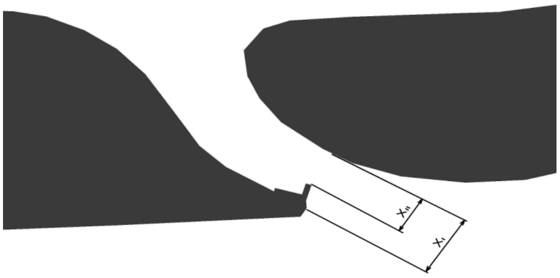

Fig. 17 Gap change due to the Gurney flap.

Numerical Results: The numerical results are presented in Figs. 18 to 20 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 (see Fig. 9) existing at all incidence angle mainly due to the low Reynolds number of the experiment ($1.3x10^6$) 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 21 to 24 show results by using the computational flow visualization. The area of interest shown in Fig. 21 is that at the flap trailing edge with the 4% Gurney flap. The incidence angle is 8deg with the flap at zero deg. Fig. 22 shows the two counter rotating vortices and these results are in agreement with previous works [4, 5 and 6]. It is clear from Fig 22 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. 23 thus increasing effective camber and chord. The development of the wake from a wing with the Gurney flaps can also be visualized as shown in Fig 24. Wake studies are an important issue in the application of the Gurney flaps in aviation as they can create a stronger vortex shedding due to the von Karman structure of the two counter rotating vortices.

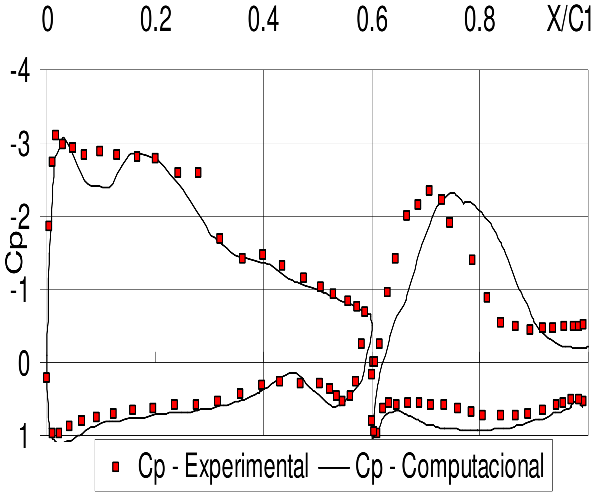

Fig. 18 Comparison with numerical results, alpha = 8^o flap at 0^o, 1% Gurney flap.

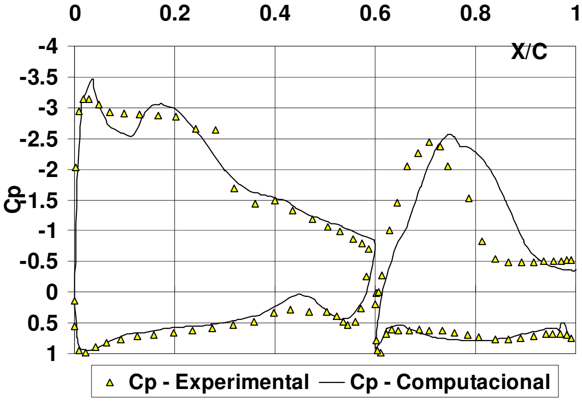

Fig. 19 Comparison with numerical results, alpha = 8^o flap at 0^o, 2% Gurney flap.

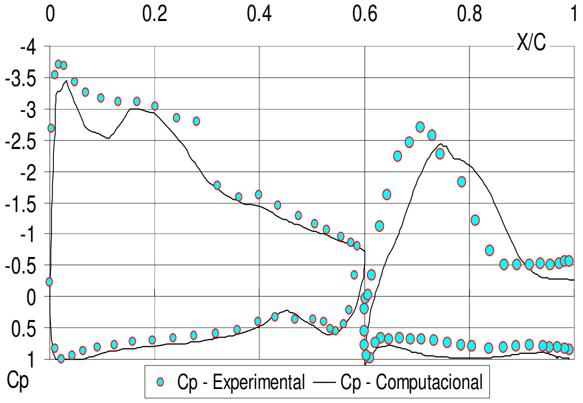

Fig. 20 Comparison with numerical results, alpha = 8^o flap at 0^o, 4% Gurney flap.

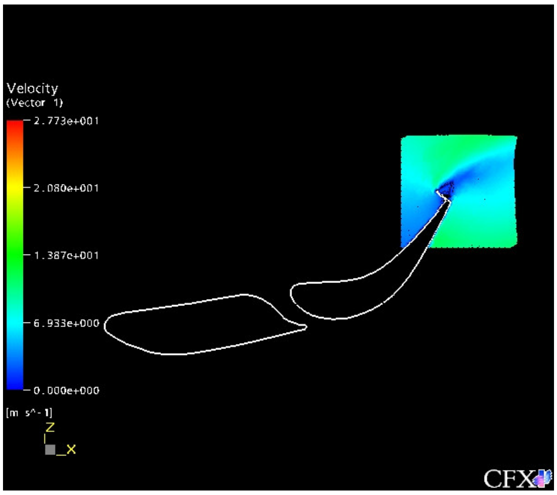

Fig. 21 Definition of the area of investigation at the Gurney flap region.

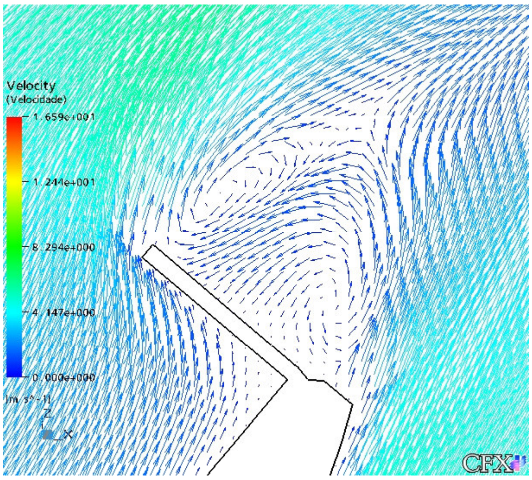

Fig. 22 Counter rotation vortices at Gurney flap

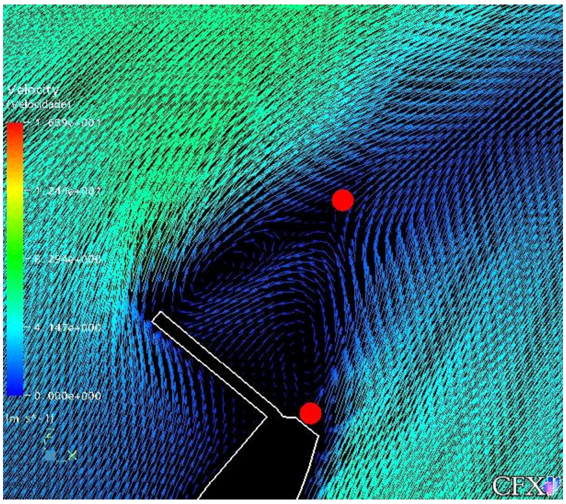

Fig. 23 Downstream and downward displacement of the Kutta point.

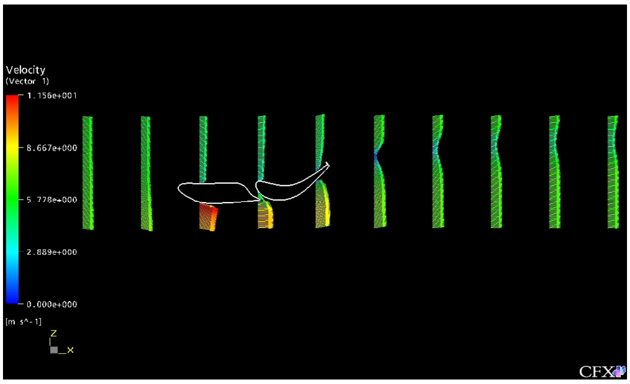

Fig. 24 Boundary layer and wake development, 4% Gurney flap installed

3 Conclusions

An experimental and numerical analysis of the application of the Gurney flaps in a two element wing was performed. The quasi two-dimensional wing had a non-conventional configuration as the flap dimensions was of 45% of the total chord. 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 when compared with the experimental results, mainly due to the difficulties in simulating of the large laminar separation bubble at the main element. 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 in the entire flow around the wing. 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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