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Aerodynamics of Gurney Flaps on a Wing in Ground Effect

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1. Description of independent study

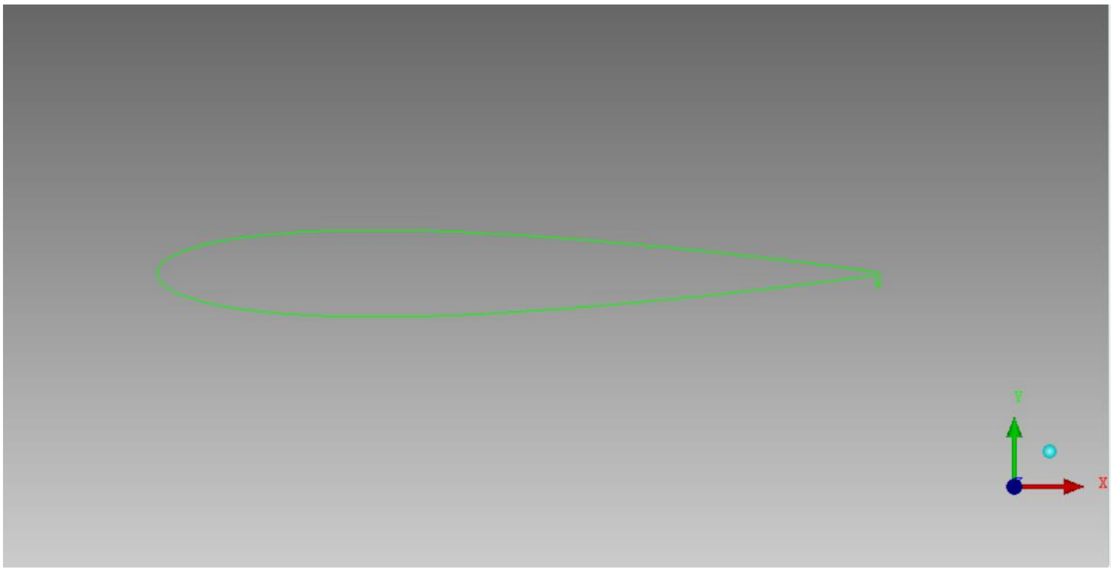
My independent study will focus on the Computational Fluid Dynamics (CFD) simulation of the ground effect of a Gurney flap on its lift enhancement. The commercial flow solver ANSYS ICEM will be used for generating the mesh and ANSYS FLUENT will be employed to solve the airfoil lift and drag coefficient under low speed turbulent flow conditions. The boundary conditions for the CFD models will be implemented such that they correspond to the experimental conditions. The CFD simulation results will be compared to the experimental data. It is expected that the successful simulation results should compare well with the experimental data provided by the NF-3 wind tunnel.

2.Methodology to be used in conducting independent study

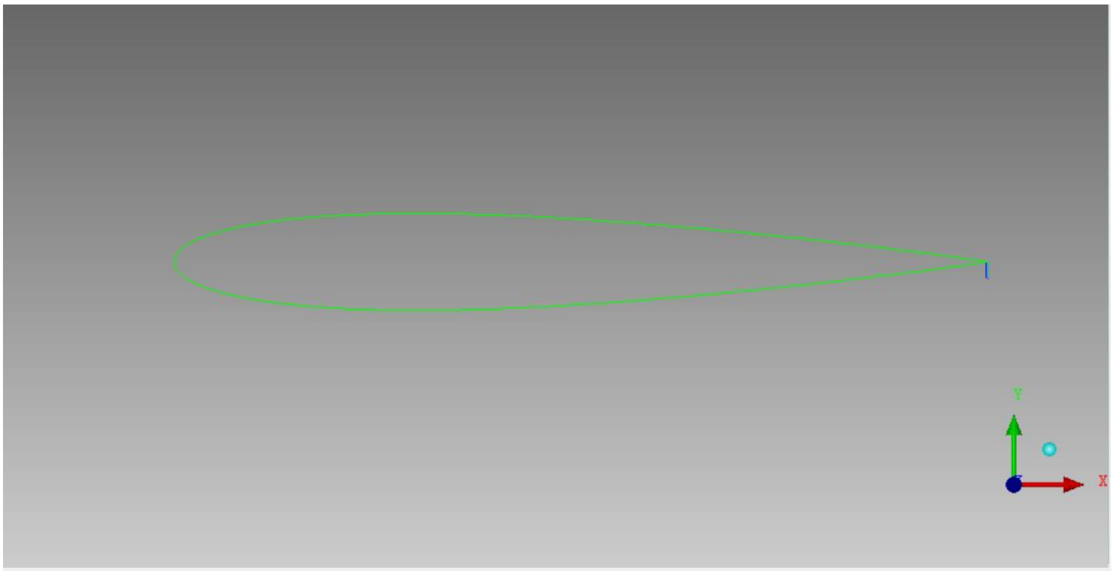
The geometry will be defined by the CAD software and will be imported into ANSYS ICEM. A two dimensional rectangular mesh will be created around the body. Flow field calculations will be performed for the experimental conditions using the CFD solver ANSYS FLUENT. The simulation results will be compared with the experimental data. All the software to be used is available in the CFD lab.

3. Geometry verification and mesh independence.

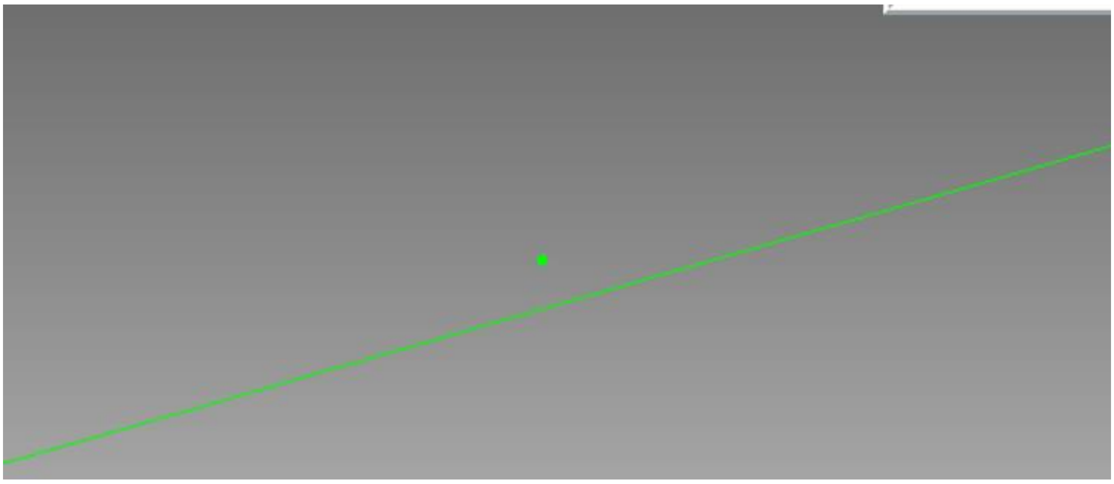
Formatted point data form UIUC airfoil database:



Geometry from NASA NACA0012 airfoil verification:



At leading edge, the airfoil drawn by formatted point data form UIUC airfoil database have some curves deviate from its points at the leading edge:



These makes the airfoil coarse at the leading edge and result in an inaccurate calculation. Accordingly, airfoil model from NASA NACA0012 verification is used.
Using NACA0012 airfoil at angle of attack $\alpha = 2°$ to test the mesh independence:

Table 1 Assessment of mesh independence

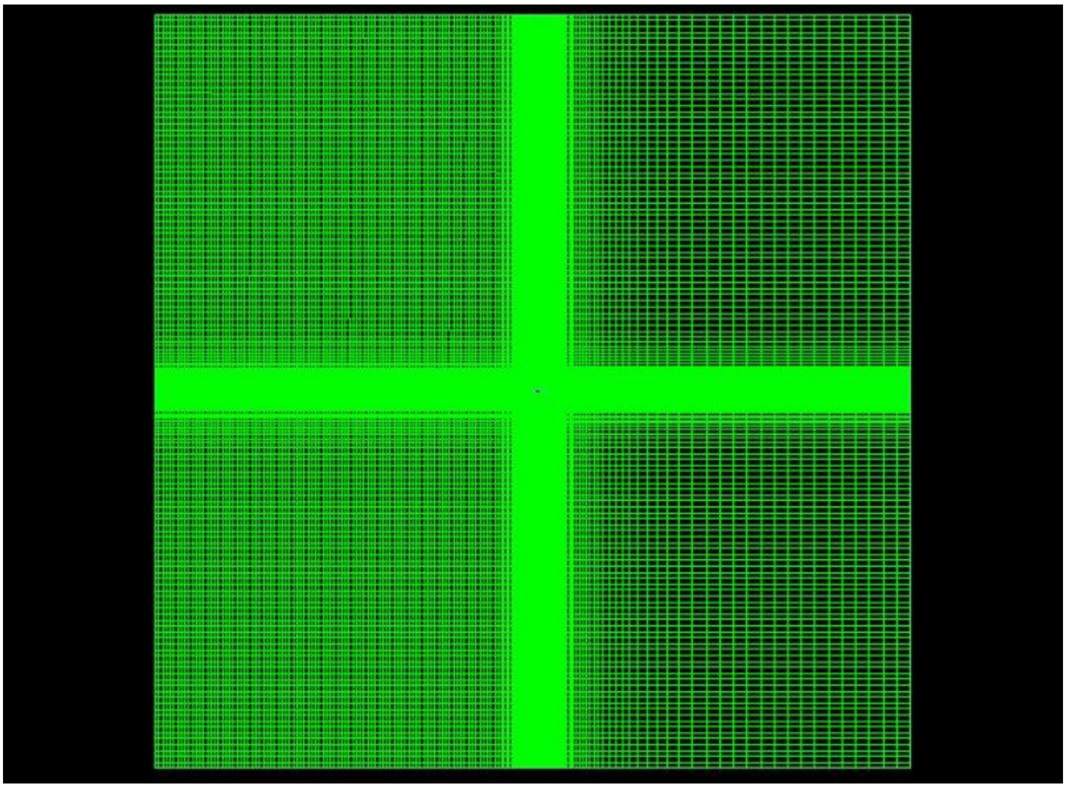
Mesh	Cell numbers	C_l	C_d
Coarse	120000	0.1254	0.01174
Standard	170000	0.1127	0.01127
Fine	400000	0.1123	0.01088

In order to have an efficient calculation, standard mesh is used in calculation.

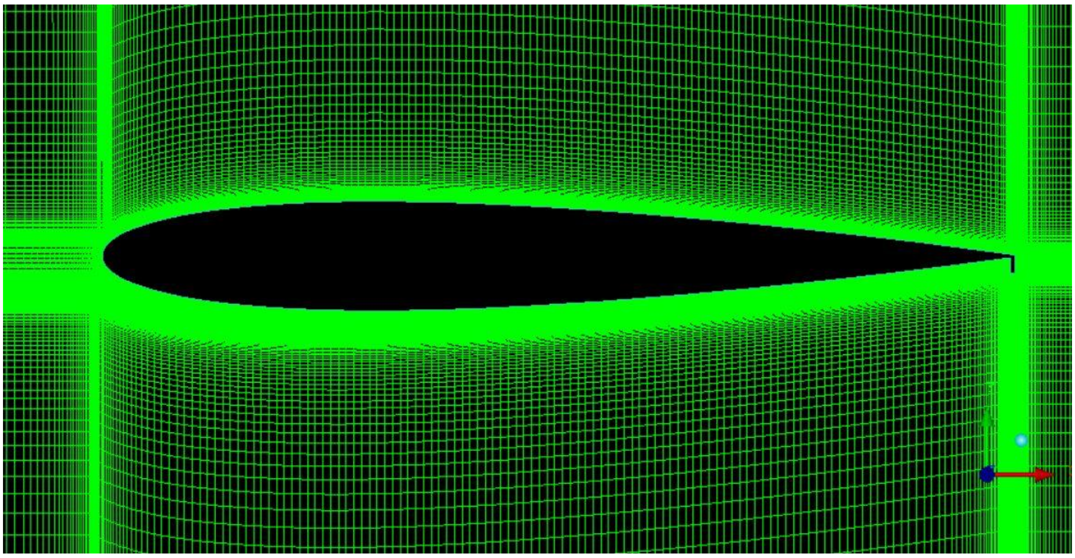
In CFD analysis, two dimensional mesh was created with a rectangular far field which can be modified for further study on the ground effect of the gurney flap. The case was set at a pressure based steady condition.

The number of grids around the boundary of airfoil is 8000. The value of y+ is of the order of 1 for the first grid point above the airfoil surface.

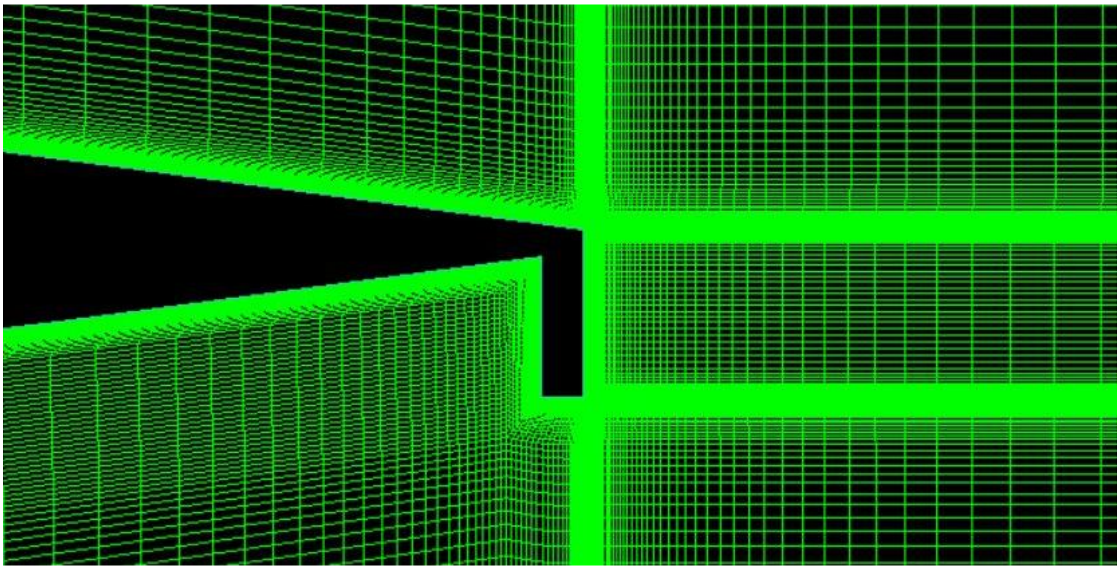
The height of rectangular gurney flap is 1.5% and 2% of chord length and width is 5mm. Both 45º and 90º of the mounting angle were tested. Lift coefficient(C_l) and drag coefficient(C_d) were calculated to compare with the experimental data[1]. The angle of attack(α) varies from 2ºto 6º.



a) Computational domain



b) Grids around NACA0012 airfoil with gurney flap (h=2%C $\theta = 45°$)



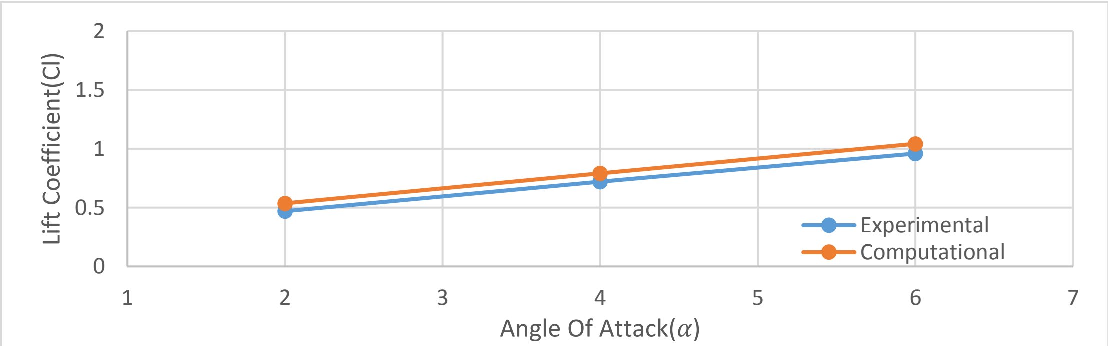
c) Detailed grids around gurney flap (h=2%C)

Fig1. Computational domain and NACA0012 airfoil with gurney flap

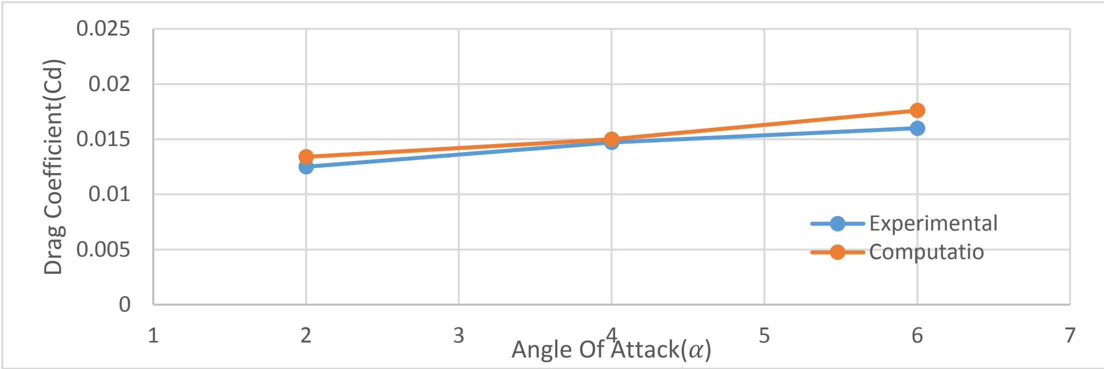
4.Data comparison

In the wind tunnel test, height of gurney flap on a 1m chord NACA 0012 airfoil have kept between 0.5%C and 3%C with a 0.5%C gradient increase. The wind velocity is set to 130m/s and turbulence viscosity is less than 0.045%. Reynolds number of the flow is 2.1×10^6.

Among several turbulence models, k-omega SST viscous model was used because of its high correlation with experimental data. In order to have result precise and efficiently, Couple scheme was used to resolve the pressure-velocity coupling with second order upwind discretization for all equations.

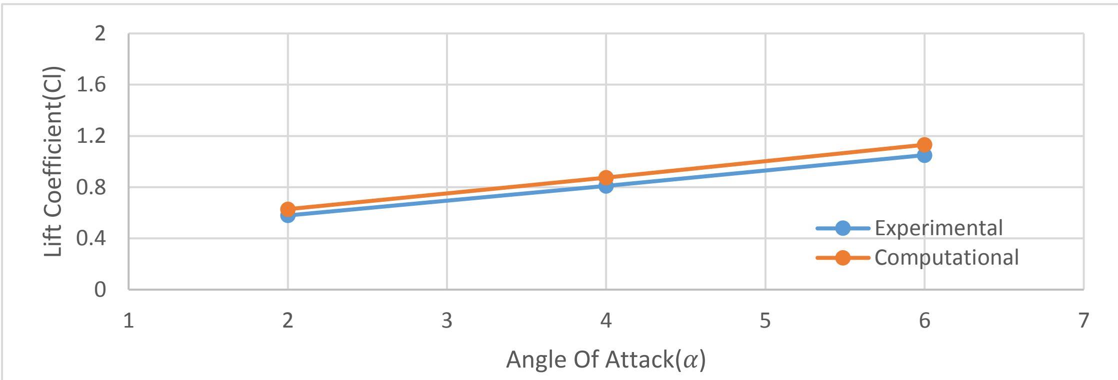


a) lift coefficient versus angle of attack

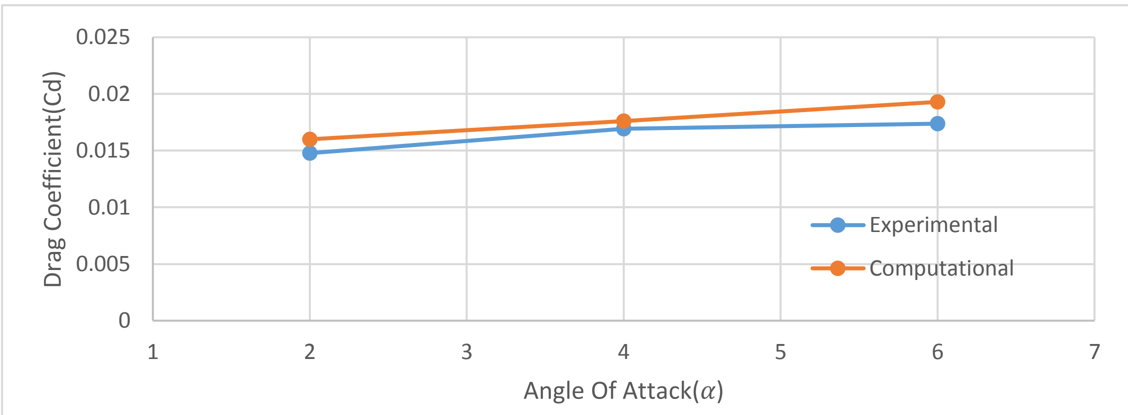


b) drag coefficient versus angle of attack

Fig.2 Comparison of experimental and computational data for NACA0012 airfol with h=1.5%C gurney flap



a) lift coefficient versus angle of attack



b) drag coefficient versus angle of attack

Fig.3 Comparison of experimental and computational data for NACA0012 airfoil with h=2%C gurney flap

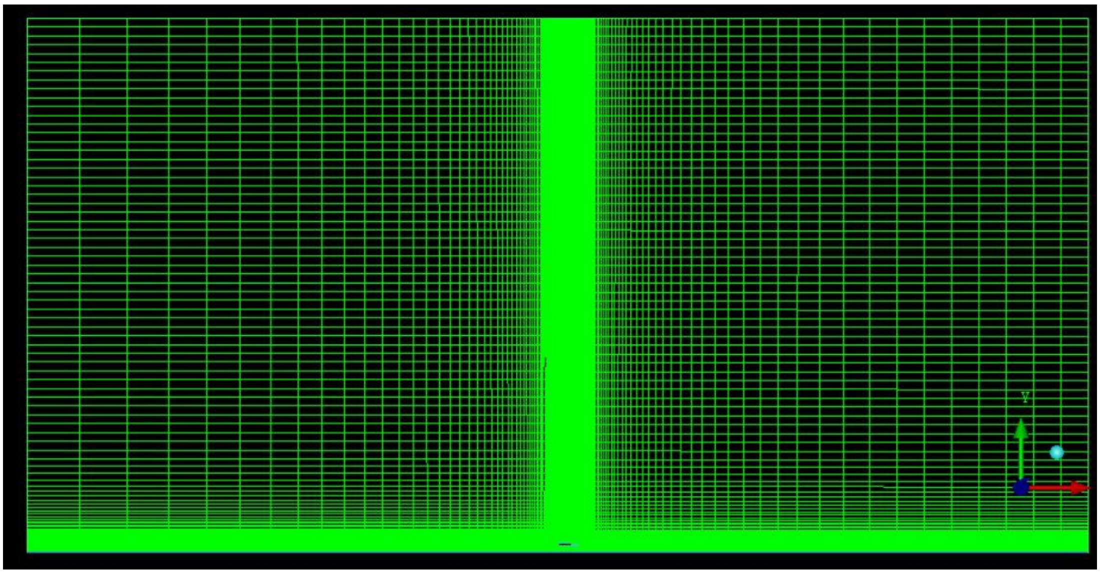
Computations were performed for NACA0012 airfoils with 3 different types of gurney flaps in Fig.2. The comparison between experimental and computational results focused on the lift and drag coefficient of the airfoil. All calculated results are within 12% error comparing with experimental data [3]. For higher angle of attack, the flow becomes unsteady and particularly beyond the stall while steady flow case was used in Fluent analysis. This can explain how percentage of error for lift coefficient increases with angle of attack in computation. Also the flow in computation is assumed as fully turbulent while in experiment the flow-field is not fully turbulent. This maybe result in a larger drag coefficient in Fluent is higher than wind tunnel test. [4]

For small angle of attack, higher height (h) of gurney flap can create larger lift force but also brings more drag force to the aircraft. When the mounting angle is higher ($0^\circ<\theta<90^\circ$), the lift force will increase but the airfoil will have larger drag coefficient. These result agrees with the conclusion in wind tunnel test. [3]

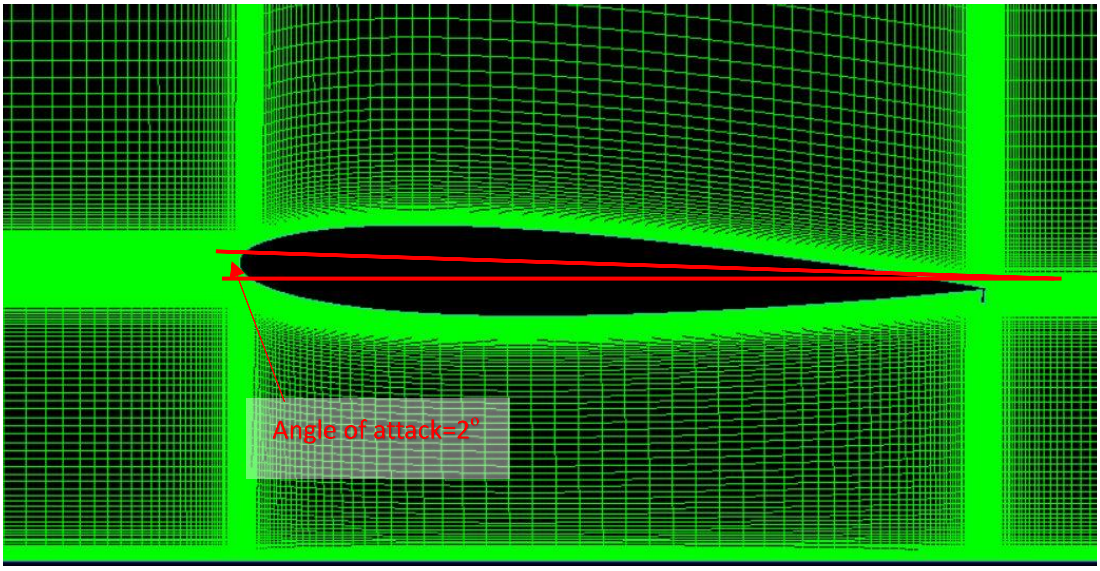
The flat plate flow is a basic verification/validation case for any turbulence model. A cross section of the computational setup is shown in Fig.2 [5]. The plate was extended one meter from the inflow boundary to reduce its influence. Periodic boundary condition in z-direction is used for LES simulation.

5. Ground Effect Model And Simulation

In order to keep consistent with the previous test, the model was based on a 1-meter-long NACA0012 airfoil with rectangular gurney flap. The height of gurney flap is 0.2%C and the mounting angle is 90º. The bottom point of airfoil is 0.2meters above the ground. (H=20%C) The flow speed is 130m/s and turbulence viscosity is less than 0.045%. The total number of grids around the airfoil is 33,000 and the mesh contains around 140,000 elements. Different from mesh for cruising airfoil, mesh of airfoil at ground effect have to rotate about z-axis to reach its angle of attack. K-omega SST viscous model was used to keep consistent with cruising airfoil computation. Coupled solution methods was used and all special discretization are all set to be second order equation. The valve of y+ is of the order of 1 for sthe first grid point above the airfoil surface. Also a mesh of NACA0012 clean airfoil was used to compare and analyze the gournd effect. In order to control variables, all solution method are set the same as the fluent case of NACA0012 with h=0.2%C gurney flap.



a) Computational Domain

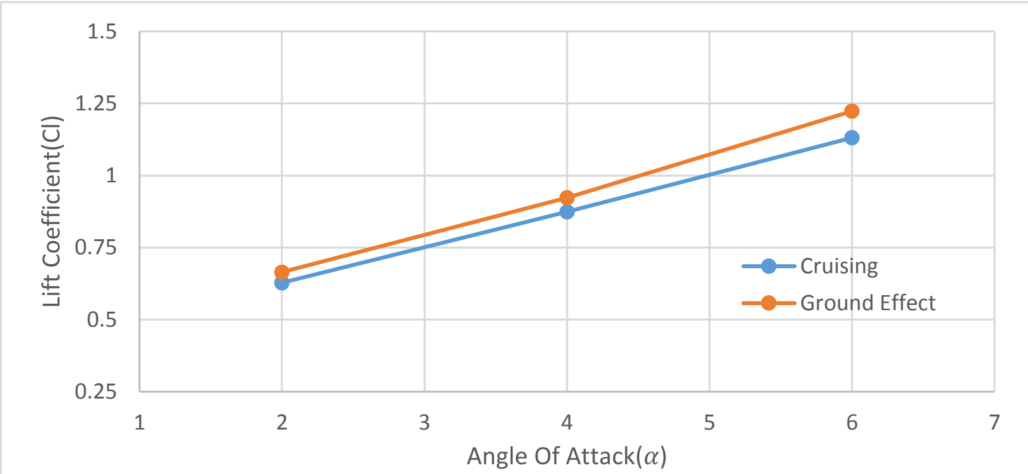


b) Boundary layer of NACA0012 airfoil with gurney flap

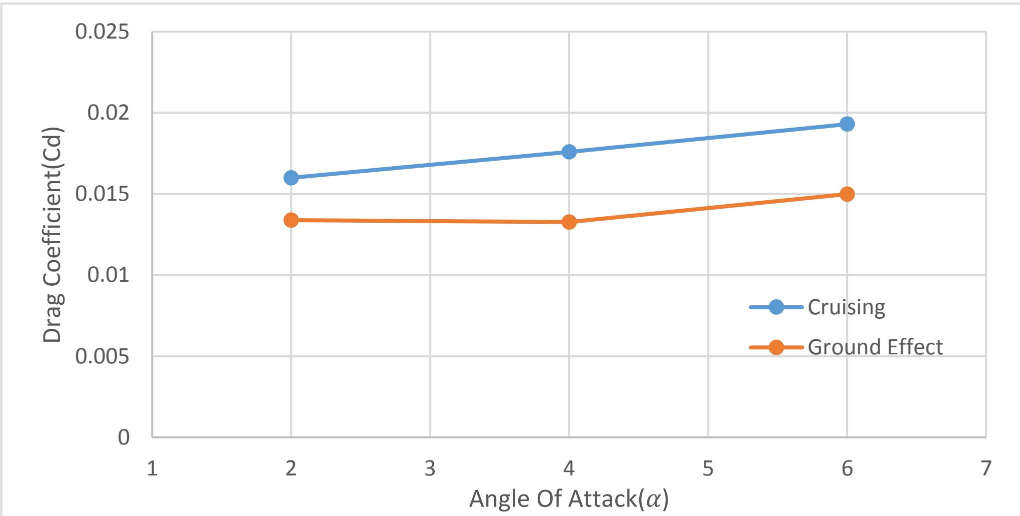
Fig.4 Computational domain and NACA0012 with gurney flap (Ground Effect)

6.Result And Discussion

Result shows that while landing or takeoff, NACA0012 airfoil provides more lift coefficient and less drag coefficient than high altitude cruising, leading to a better lift-to-drag ratio.



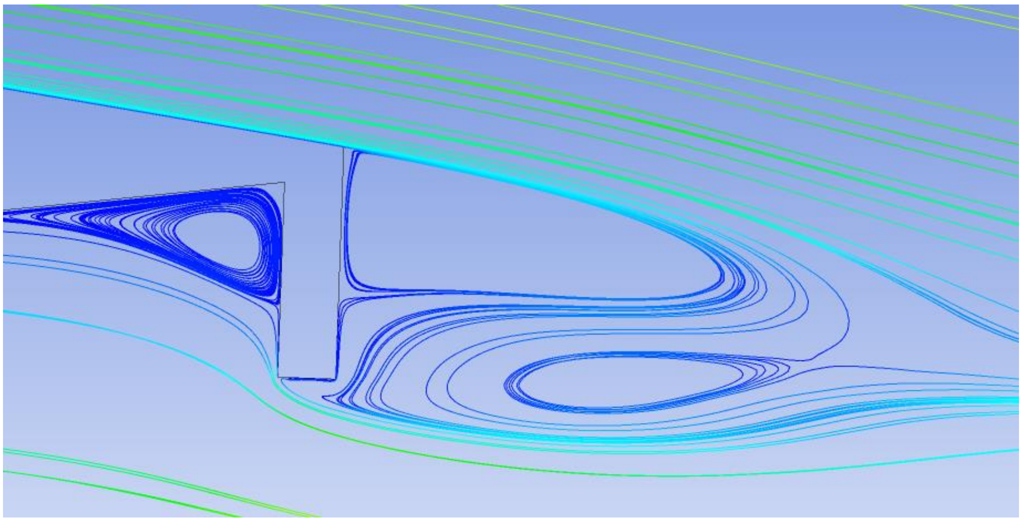
a) lift coefficient versus angle of attack



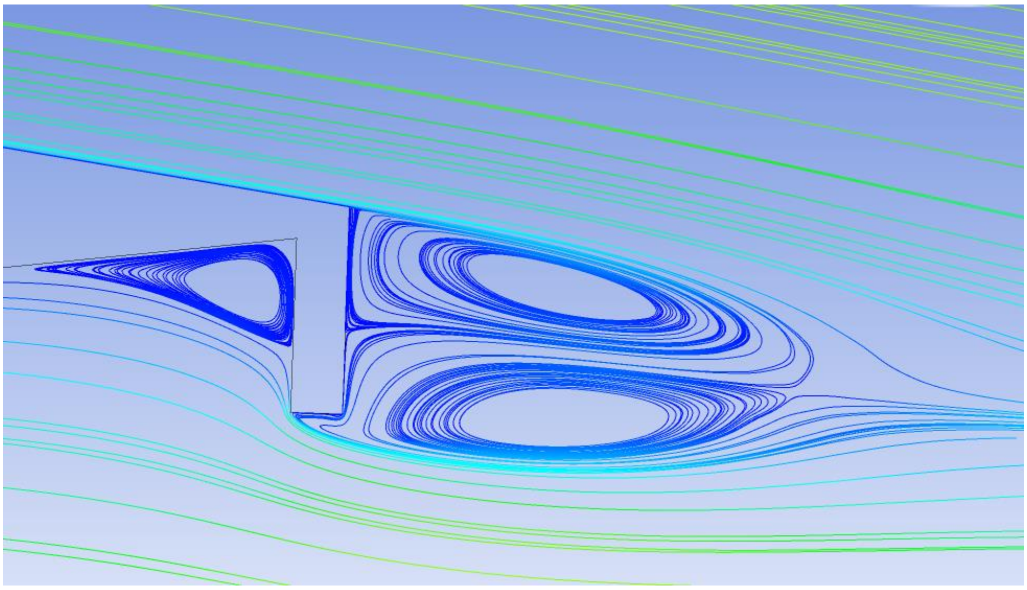
b) drag coefficient versus angle of attack

Fig.5 Comparison between unbounded and ground effect of NACA 0012 airfoil with h=2%C gurney flap

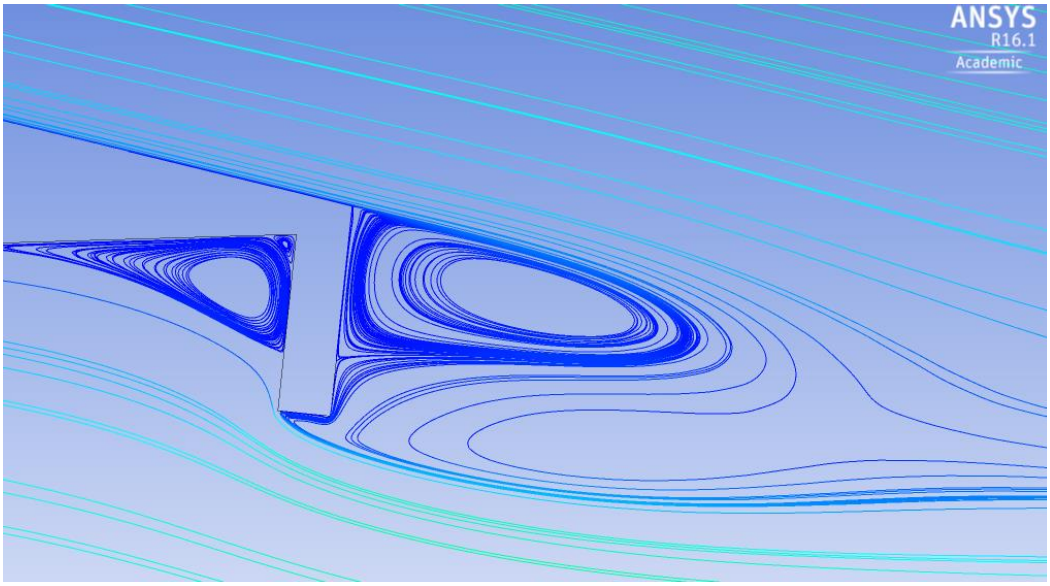
In Fig.*, the streamline can be sketched by using CFD POST. Taking 2ºangle of attack of a NACA0012 airfoil with h=2%C gurney flap as an example to analyze the impact to tip vortices by ground effect. In both cruising and ground conditions, max points in CFD POST were set to 150 for a clear streamline. The perpendicular gurney flap creates separation bubbles at trailing edge. Different from clean NACA0012 airfoil while the fixcd wing aircraft with gueney flaps is landing or taking off, not only flow under pressure surface of the airfoil will be compressed but also the vortices at trailing edge created by gurney flaps will be squeezed into a smaller size so that drag will be reduced. The compressed vortices can provide more pressure than ground deflection of dowmwash stream formed at a clean airfoil traling edge. When the angle of attack increases, the vortices at trailing edge will have larger include angle with streamline direction and vortices will be squeezed more intensively. This may be the reason for higher angle attack have larger lift-to drag ration in ground effect.



a) vortices at trailing edge for a NACA 0012 airfoil at high altitude crusing



b) vortices at trailing edge for a NACA 0012 airfoil close to ground($\alpha = 2°$)



c) vortices at trailing edge for a NACA 0012 airfoil close to ground($\alpha = 6°$)

Fig.5 vorticies at the trailing edge

In order to analyze the effect from gurney flap and ground effect separately, the case of clean NACA0012 airfoil have taken into comparison. Assume that:

$$(\Delta C_l)_1 = [C_l(clean, h = \infty) - C_l(clean, h = 0.2\%C)] + [C_l(gurney, h = \infty) - C_l(clean, h = \infty)]$$

The first term is the C_l enhancement from ground effect and the second term is the enhancement of gurney flap and also assume that:

$$(\Delta C_l)_2 = C_l(gurney, h = 0.2\%C) - C_l(clean, h = \infty)$$

which means the the coupling enhancement of both ground effect and gurney flap.

If the ground effect and effect of gurney flap have a linear influence on lift coefficient of airfoil, $(\Delta C_l)_1 = (\Delta C_l)_2$. However, according to computation result, the coupling effect of gurney flap and ground effect is smaller than calculating each effect independently.

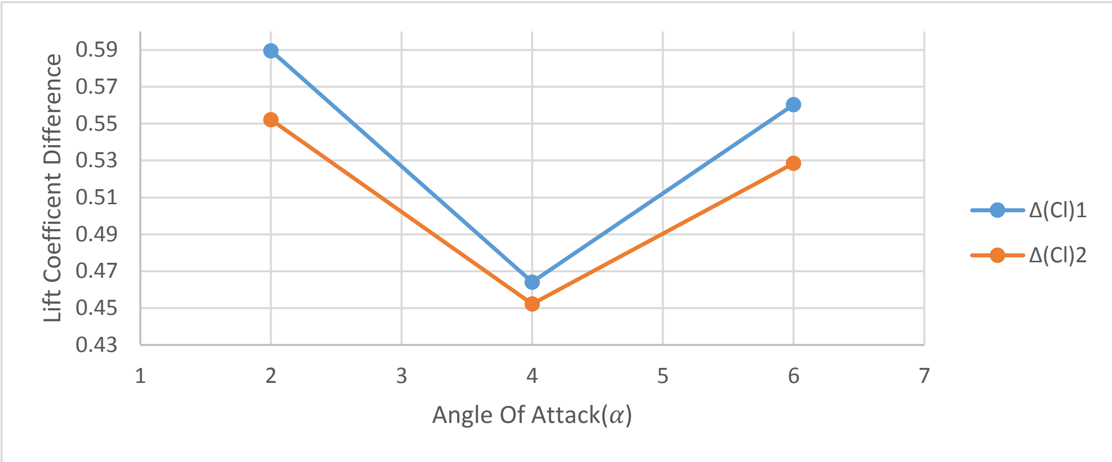
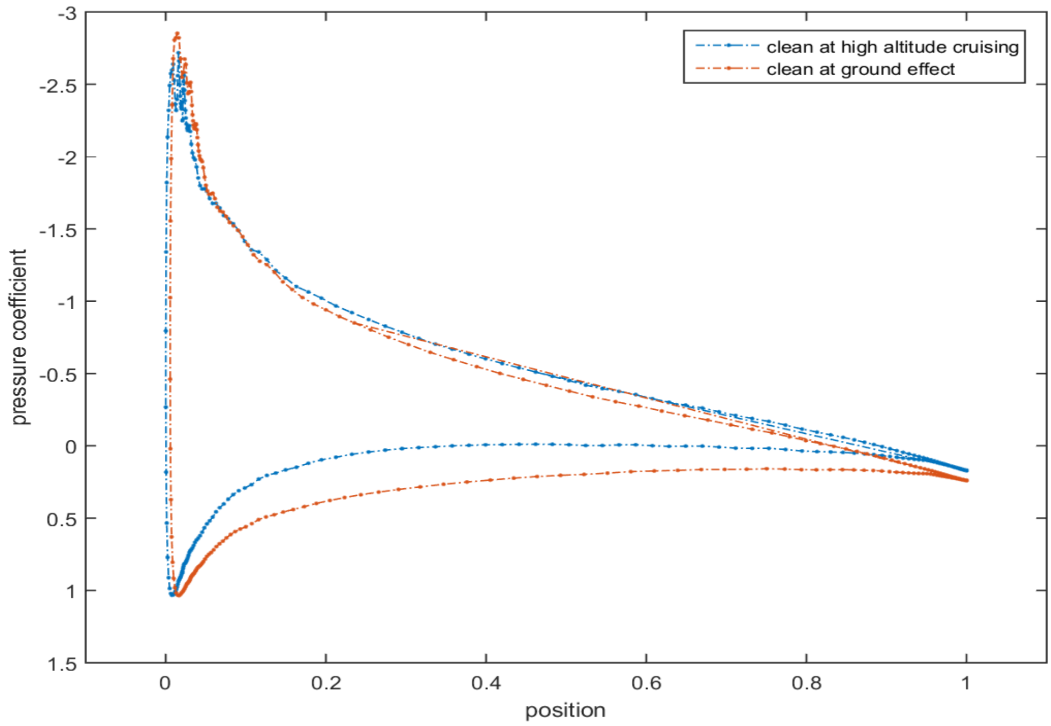
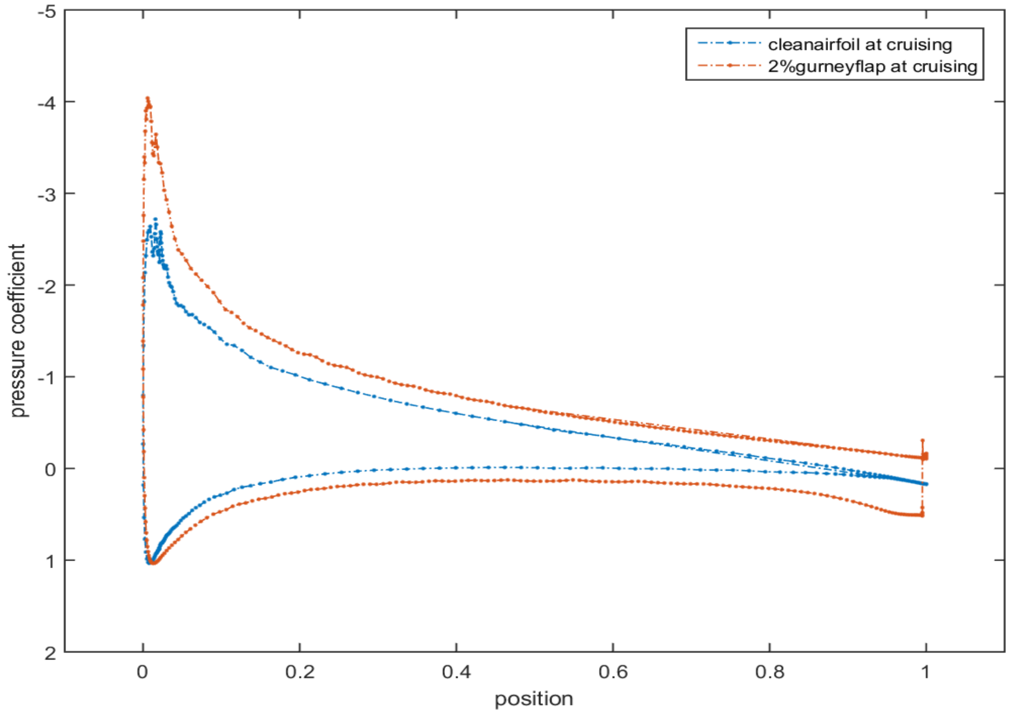


Fig.6 Difference between two lift coefficient enhancement

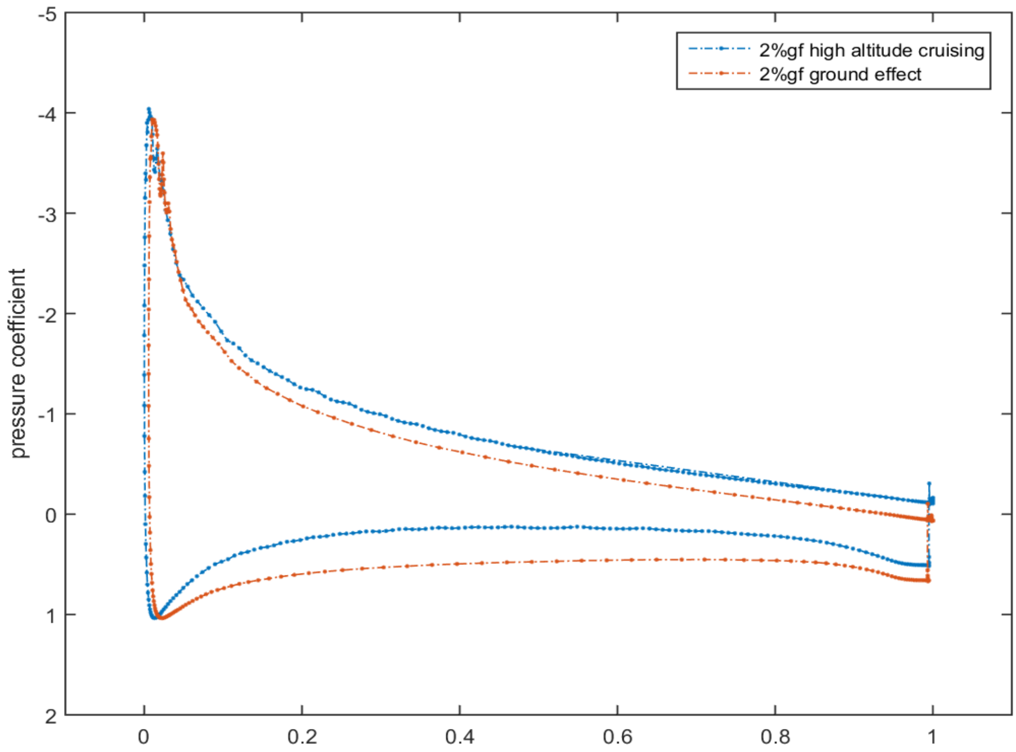
Plotting the pressure coefficient of NACA0012 clean airfoil and NACA0012 airfoil with gurney flap for both ground effect and high altitude cruising.



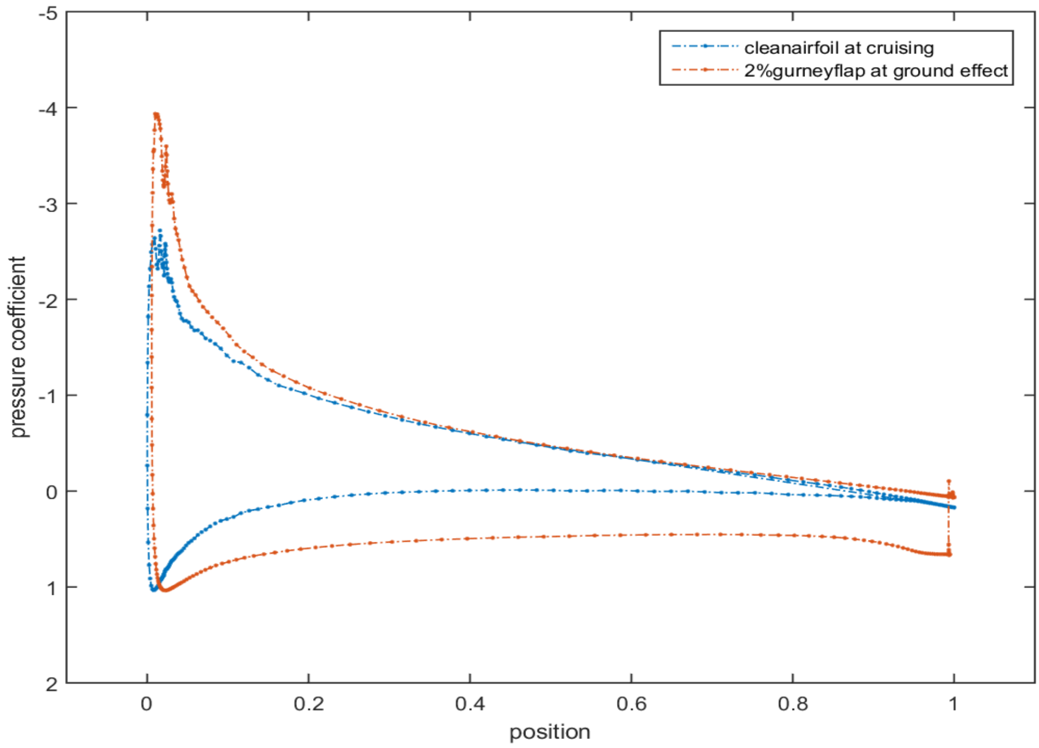
a) ground effect of clean NACA0012 airfoil



b) effect from gurney flap



c) ground effect on airfoil with gurney flap



d) the coupling of ground effect and gurney flap

Fig 7. The pressure coefficient comparison

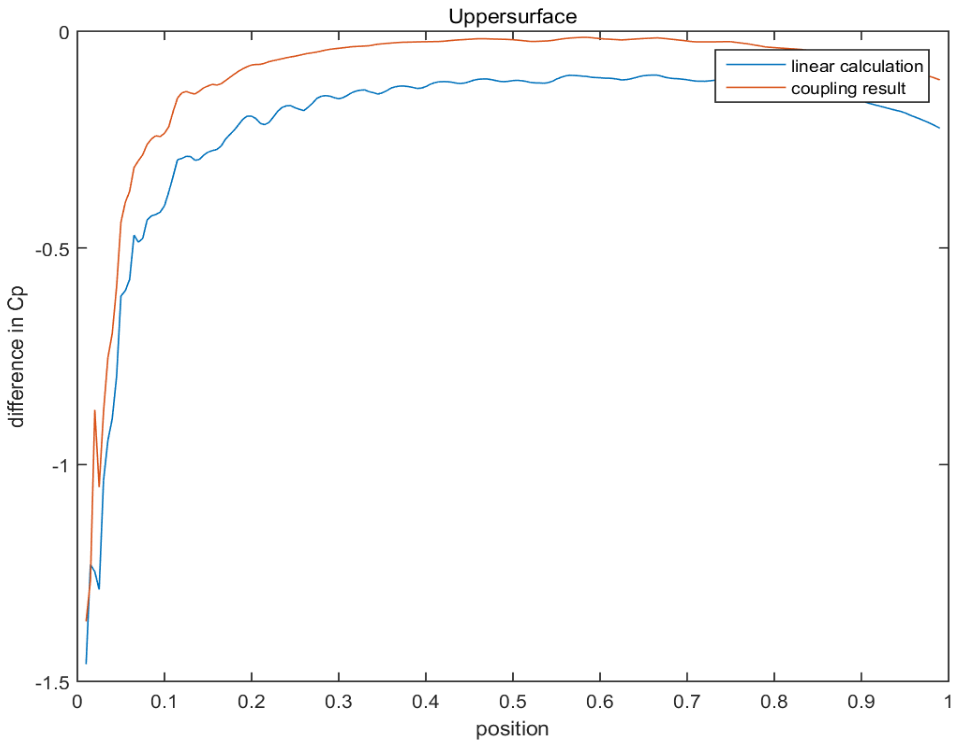
For a simply ground effect situation (Fig.7a), the pressure around upper surface will remain the same while the lower surface has larger pressure. While the airfoil deflects the wind downward, the ground effect provides more pressure on the lower surface as the flow was compressed in a low altitude. The gurney flap decreases the pressure on upper surface and increase the pressure on lower surface simultaneously (Fig.7b). Comparing with gurney flap at cruising state, gurney flap at ground effect lose some suction force on the upper surface but gain more pressure on lower surface which caused a better lift-to-drag ratio. (Fig.7c) The gurney flap sets up a downward turning wake at the trailing edge which increase the effective camber of the airfoil and provide more lift force. Taking both ground effect and gurney flap into consideration, the pressure at the mid part of upper surface is similar to a cruising clean NACA airfoil which reduce the lift enhancement brought by gurney flap.(Fig.7d) Using matlab code to calculate the pressure coefficient numerically and plot the upper surface and lower surface separately where linear calculation stands for:

$$(\Delta C_p)_1 = \left[C_p(clean, h = \infty) - C_p(clean, h = 0.2\%C)\right] + \left[C_p(gurney, h = \infty) - C_p(clean, h = \infty)\right]$$

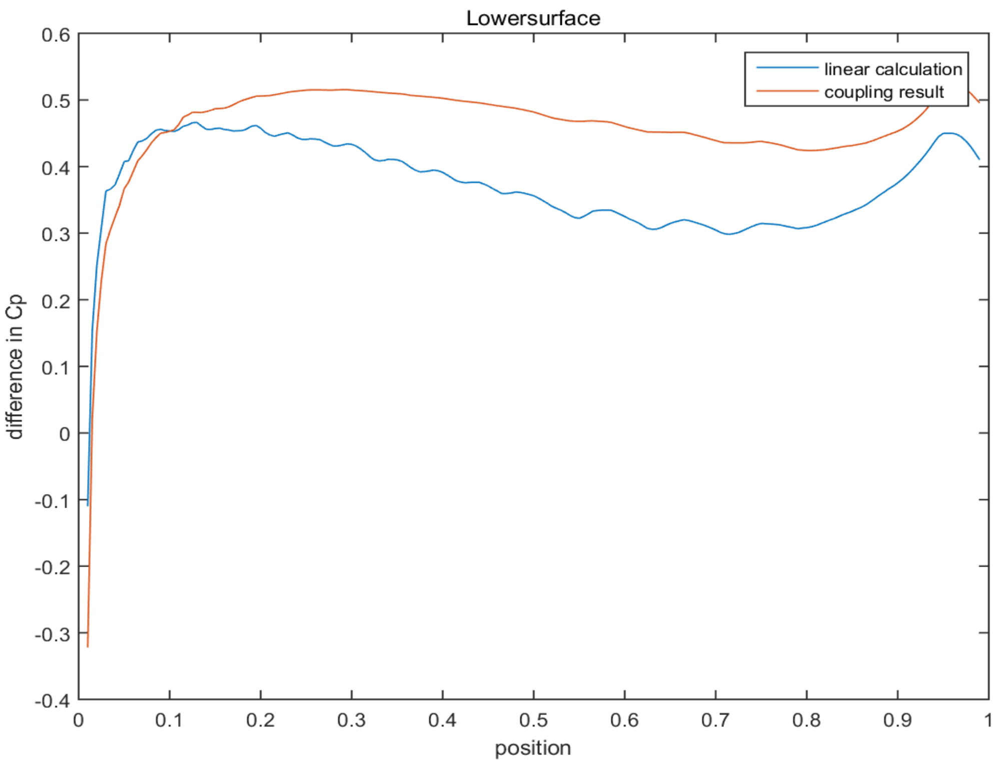
and coupling results stands for

$$(\Delta C_p)_2 = C_p(gurney, h = 0.2\%C) - C_p(clean, h = \infty)$$

The result shows that there is merely difference between clean airfoil at cruising and airfoil with h=2%C gurney flap in ground effect, also the actual pressure on lower surface is smaller than linear calculation.



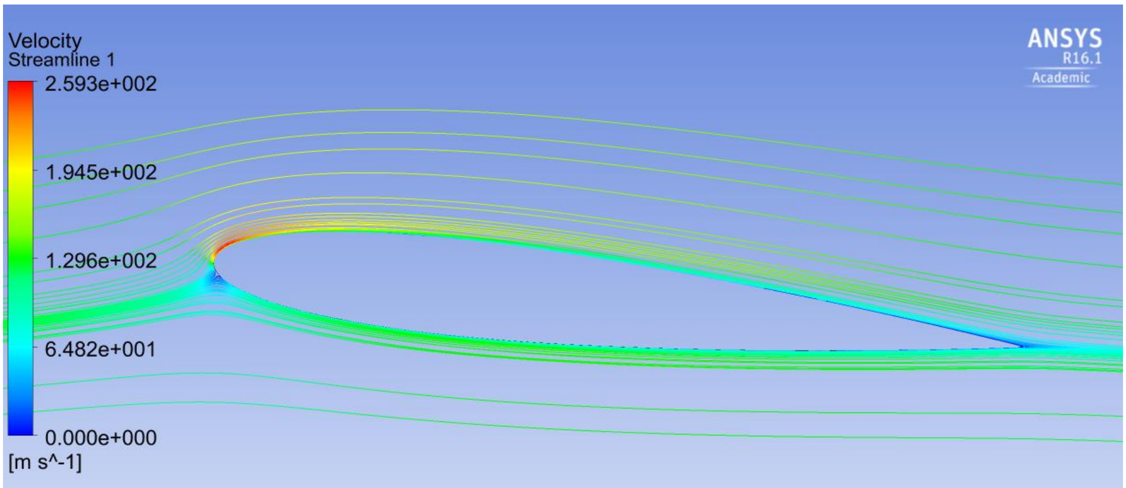
a) comparison of Cp on upper surface



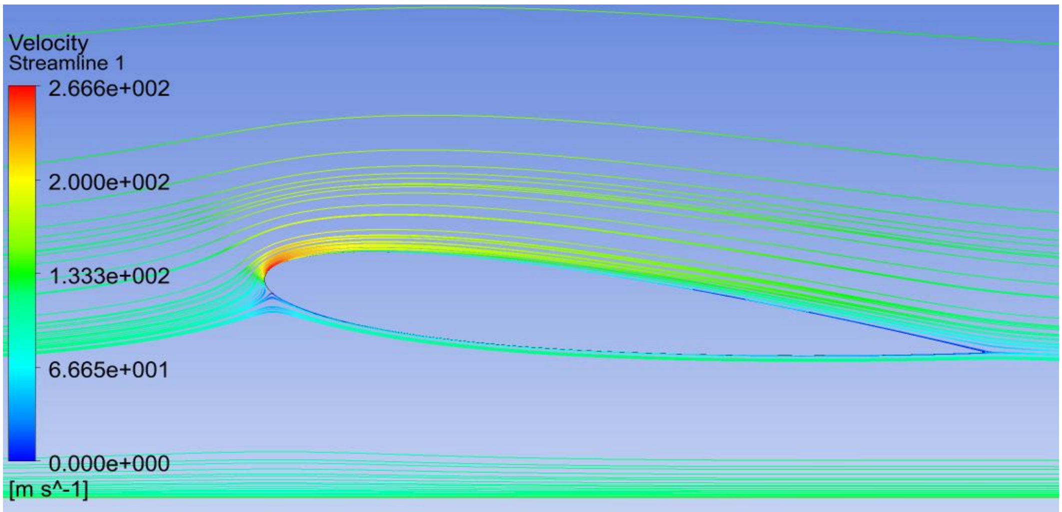
b) comparison of Cp on upper surface

Fig8. Comparison of Pressure Coefficient calculation

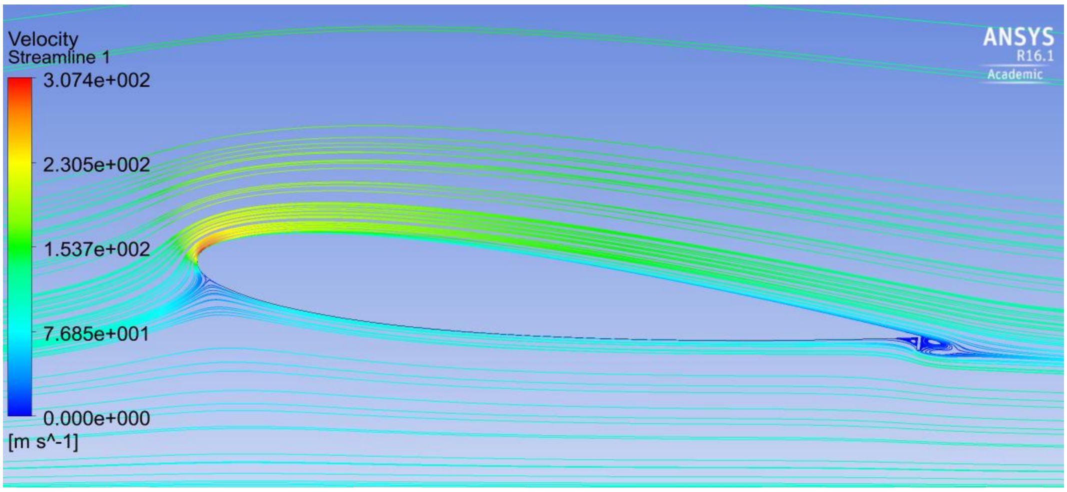
It shows that at middle part of the upper surface, the stream velocity of a clean airfoil at crusing is similar to a airfoil with gurney flap at ground effect. The velocity is smaller than a clean airfoil at ground effect. So the linear calculation leads to a larger result of the ground effect term and have deviation with the coupled effect.



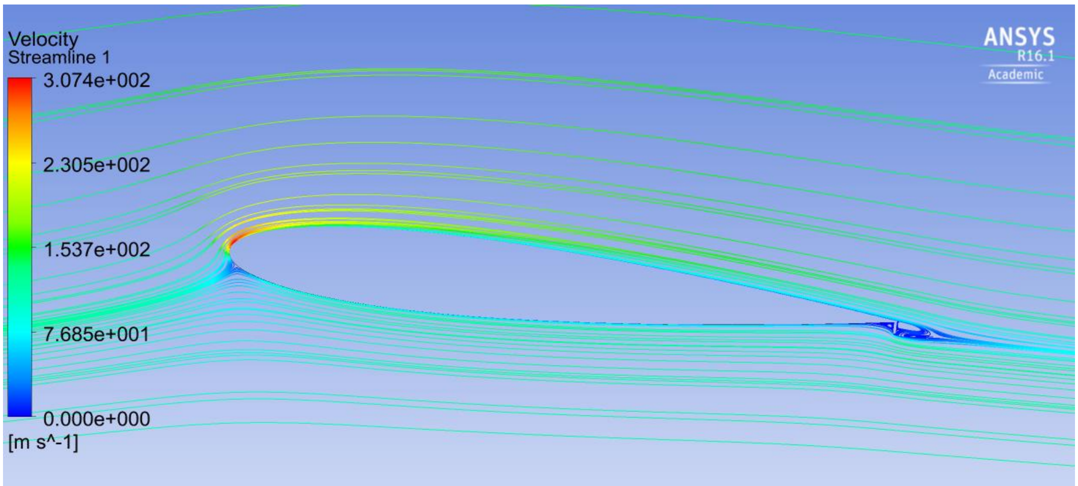
a) streamline of clean airfoil at cruising



b) streamline of clean airfoil at ground effect



c) streamline of airfoil with gurney flap at cruising



d) streamline of airfoil with gurney flap at ground effect

Fig.8 streamline comparison (h=2%C , $\theta = 90°$ and $\alpha = 6°$)

I. Conclusions

Gurney flap have been tested in 3 angle of attack for a ground effect situation. The simulation and computational result shows that airfoil with gurney flap have a more evident lift enhancement than clean airfoil. At the trailing edge, vortices were generated because of wing separation flow. Pressure brought by ground effect will squeeze vortices into a more flat one which reduce the drag of airfoil. When angle of attack increase, the lift to drag ratio will increase evidently because bubbles are compressed more intensively. Some vortices will be even compressed into flow uniform to streamline direction which can greatly reduce the drag force.

The resultant effect of both ground effect and gurney flap are not independent. When takeoff or landing, gurney flap provides a lower speed wind flow on the upper surface which decrease the pressure(suction) on upper surface and make lift force less than a clean airfoil. Meanwhile, the pressure coefficient on lower surface increased greatly pushing the airfoil upward, the coupling effect from both surfaces leads to a larger lift force than crusing, making a better lift-to-drag ratio.