CFD analysis of the performance of different airfoils in ground effect

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Abstract. Ground effect is a phenomenon caused by the presence of a fixed boundary layer below the wing when it moves close to a fixed surface. This results in an effective increase in lift to drag ratio of the airfoil. In this paper, the performance of three airfoils used in general aviation is analysed in ground effect using ANSYS FLUENT at different operating conditions namely, the angle of attack and the height above the fixed surface. The main objectives are to evaluate the performance of these airfoils in ground effect at different ground clearances and angles of attack and find the most suitable airfoil which can be used to exploit the advantages of ground effect. It was found that all the airfoils experienced an increase in lift and decrease in drag as distance from the ground reduced thus validating ground effect. The aerodynamic efficiency increases, reaches a maximum, and then decreased as the angle of attack increased due to the onset of flow separation at the top surface of the airfoil. It was also noted that the symmetric airfoil experienced negative lift at very low ground clearances which was attributed to the formation of a venturi effect between the airfoil and ground

1. Introduction
Ground effect is the phenomena when a fixed wing aircraft flies at close proximity (at or below the wingspan in case of a fixed wing aircraft or the rotor diameter in case of a helicopter) with a fixed surface such as the ground. Favourable aerodynamic conditions such as increased lift and decreased drag is observed when an aircraft flies in the ground effect region. This is attributed to the disruption of wind tip vortices which causes leakage from the high pressure bottom part of the airfoil to the top. Hence a high pressure “ram” effect is formed below the airfoil. Ground effect can be made use of to significantly reduce fuel costs, shorten the take-off distance and lower the stall speed.

2. Background

2.1 Literature Survey
The study of the influence of the ground on airplanes began as early as the 1920s by Raymond [1]. It was found out that the air trapped between the airfoil and the ground acts as cushion thus increasing the lift coefficient and causing the aircraft to skim over the runway for an abnormally long time before
finally touching down. Over the years many aircrafts were developed to make use of ground effect called WIG (Wing in ground effect) crafts. They were developed both for civilian as well as military use. The most famous of these was the soviet “Ekranoplane”. Ando [2] conducted a review of the WIG crafts used over the years. Sharma [3] conducted a comparative study between NACA airfoils and a new class of DHMTU airfoils which were specially designed for use in WIG aircrafts and obtained good results. In the research conducted by Razenbach and Barlow [4-6], it was found out that lift reaches a maximum at 0.08c (c denotes the chord length of the airfoil) and as the ground clearance reduces to zero, the boundary layers were seen to merge which explains the reduced lift force very close to the ground. Ahmed [7] studied the flow characteristics of symmetrical airfoils in ground effect at different angles of attack and found out significant high values of pressure coefficient at low ground clearances and this high-pressure coefficient extended over almost the full bottom section at high angles of attack. In further wind tunnel tests, Ahmed [8] found out that the airfoil geometry also played a role in the behaviour in ground effect. A strong suction effect was noticed at very small ground clearances of 0.05 h/c (h denotes the height of the airfoil from the ground) which was attributed to the formation of a convergent divergent passage between the airfoil and ground. Lot of research work is also ongoing for inverted WIG airfoils which are used as front wings and spoilers of race cars [9-10].

2.2 Airfoil Nomenclature
The following are the terms related to airfoil nomenclature.
   a) The suction (or upper) surface is usually associated with low static pressure and high velocity.
   b) The pressure (or lower) surface has a higher value of static pressure when compared to that of the suction surface.

The geometry of an airfoil is described using the following terms.
   a) The point at the front of the airfoil with maximum curvature, called the leading edge.
   b) The point at the rear of the airfoil with minimum curvature, called the trailing edge.
   c) The straight line connecting the leading and the trailing edge, called the chord line. The length of the chord line is called the chord length.

The shape of the airfoil is defined by the locus of points, midway between the upper and lower surfaces of the airfoil, called the camber line.

2.3 NACA Series
The airfoil shapes developed by the National Advisory Committee for Aeronautics (NACA) are called NACA airfoils. The shape of the NACA airfoils is described using a series of digits following the word "NACA". The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

   In Four-digit NACA series, the
   a) First digit expresses camber in percent chord.
   b) Second digit gives location of maximum camber located in tenth of chord.
   c) Last two digits give thickness in percent chord.

For example, the NACA 2412 airfoil has a maximum camber of 2% located 40% (0.4 chords) from the leading edge with a maximum thickness of 12% of the chord. The NACA 0015 airfoil is symmetrical, the 00 indicating that it has no camber. The 15 indicates that the airfoil has a 15% thickness to chord length ratio: it is 15% as thick as it is long.

3. Objectives
A survey of the literature yields that ground effect is still not completely understood and more research is required at varied operating conditions and on different airfoil sections. This paper aims to
   a) study the performance of three airfoil sections operating in ground effect during take-off and landing conditions.
   b) compare and study the performance of the three airfoils at varying h/c ratios and varying angles of attack.
c) To obtain the aerodynamic coefficients at different ground clearances and angles of attack.

d) To find the most suitable wing airfoil section for WIG crafts from the three airfoils considered.

Here three different NACA airfoils are taken namely the NACA 4412, NACA 6412 and the NACA 0012. The NACA 0012 is a symmetrical airfoil whereas the other two are unsymmetrical.

4. Methodology

4.1. Airfoil and domain modelling

The airfoil coordinates are obtained by giving the particular NACA series number, angle of attack and the chord length from airfoiltools.com. The chord length was set as 1m and the airfoils were generated for AOA (Angle of Attack) 0, 4 and 8 degrees. The 2D models of the airfoils were then developed using the coordinate points in the Ansys design modeller.

A rectangular flow domain was created with distance of the airfoil from top surface of the domain wall taken as 6.6c [13] and the inlet and outlet distances set as 15c from the leading and trailing edges respectively as it was observed that this dimension does not affect the simulation. The airfoil boundary was then subtracted using Boolean and the rectangular flow domain is obtained.

4.2. Meshing

After naming the domain boundaries and the airfoil, the named edges and surface were selected and mesh controls were applied. Edge sizing is given to the ground, top, inlet, outlet and the airfoil. Inflation was given with the ground and airfoil as boundaries. Mesh independent study was also conducted and the grid sizes employed were 36782, 52343, 70502 and 172670 elements. The parameters monitored for convergence were $C_L$ (Coefficient of Lift) and $C_D$ (Coefficient of Drag). It was found that the mesh with 70502 elements provided sufficient convergence and this grid size was used for the simulation.

![Figure1. A sample mesh shown](image)

4.3 Solver settings

Ansys Fluent was used for the simulations. The double precision solver is selected and the solver type is set to pressure based. The standard k-epsilon viscous model is selected and air is chosen as the flow material. Boundary conditions are given to make the airfoil stationary and the ground is considered as a moving wall and given a velocity of 30 m/s in the X- direction [13] to simulate ground effect. Slip wall boundary condition is given at the top boundary [13]. An inlet velocity of 30 m/s was applied
[13]. All the reference values were computed from inlet. The Simplec scheme is selected for the analysis and monitors were set up to monitor the values of $C_L$ and $C_D$. The convergence criteria selected for continuity was set at $1 \times 10^{-6}$. The initialization method is chosen as standard and the inlet values were chosen for initialization. Iterations were performed till convergence is obtained and pressure and velocity contours were plotted.

5. Results and discussion

Results are obtained for the three airfoils with a flow velocity of 30 m/s and at h/c ratios 0.2, 0.5 and 1 and taking different values of angles of attack ($\alpha$) 0°, 4° and 8°. The values of $C_L$, $C_D$ and the aerodynamic efficiency $C_l/C_d$ are obtained. The pressure and velocity contours are also plotted.

It is observed in all cases that the $C_L$ value decreases as the height from the ground increases due to the decrease in the ground effect. The drag is also observed to increase as the height from the ground increases due to the reduced ground effect.

5.1 NACA 6412

| $\alpha$° | h/c | $C_L$ | $C_D$ | $C_l/C_d$ |
|----------|-----|-------|-------|-----------|
| 0        | 0.2 | 0.67112 | 0.012566 | 53.41     |
| 0        | 0.5 | 0.65475 | 0.012614 | 51.66     |
| 0        | 1.0 | 0.65437 | 0.013279 | 49.28     |
| 4        | 0.2 | 1.1841  | 0.015862 | 74.65     |
| 4        | 0.5 | 1.0658  | 0.019398 | 54.94     |
| 4        | 1.0 | 1.0397  | 0.020825 | 49.93     |
| 8        | 0.2 | 1.5217  | 0.031304 | 48.61     |
| 8        | 0.5 | 1.3245  | 0.034725 | 38.14     |
| 8        | 1.0 | 1.3183  | 0.034992 | 37.67     |

The NACA 6412 airfoil has the maximum camber of all the three airfoils considered here. Hence at 0° angle of attack, the lift generated will be solely due to its curvature. At 4° angle of attack a substantial increase in $C_L$ is observed[14]. This is primarily due to the increased lift as the angle of attack increases and also due to the wing shape. At 8°, it is seen that the lift increases due to increase in angle of attack but the drag almost doubles from that at 4°, leading to a decrease in aerodynamic efficiency. This increase in drag is due to the higher values of pressure drag forces which is because the flow over the airfoil surface is at the verge of separation.
Figure 2. Velocity plot of NACA6412 at 8° AOA. Drag increases drastically at 8° AOA due to the onset of flow separation at the trailing edge on the upper surface as seen in the figure.

5.2 NACA 4412

Compared to the NACA 6412 airfoil, the value of maximum camber decreases from 6% to 4% for NACA 4412. Hence comparable results were obtained for both airfoils. Similar to NACA 6412, value of lift decreases and the value of drag increases as the height of the airfoil from the ground increases. At 4° angle of attack, an increase in the value of Cl is observed as expected. Its value decreases as h/c ratio increases. At 8° angle of attack too, the trend of lift and drag variation are similar to that of NACA 6412.

| \(\alpha^\circ\) | h/c | \(C_l\) | \(C_d\) | \(C_l/C_d\) |
|---|---|---|---|---|
| 0 | 0.2 | 0.447 | 0.0126 | 35.42 |
| 0 | 0.5 | 0.443 | 0.0136 | 32.57 |
| 0 | 1.0 | 0.442 | 0.0142 | 31.12 |
| 4 | 0.2 | 0.97783 | 0.01734 | 56.39 |
| 4 | 0.5 | 0.83693 | 0.018293 | 45.75 |
| 4 | 1.0 | 0.84758 | 0.0194439 | 43.60 |
| 8 | 0.2 | 1.2442 | 0.027928 | 44.55 |
| 8 | 0.5 | 1.1533 | 0.032597 | 35.38 |
| 8 | 1.0 | 0.65771 | 0.051955 | 12.66 |

5.3 NACA0012

The NACA0012 is a symmetric airfoil. Hence the lift will be generated solely due to the angle of attack. At 0° angle of attack, it produces no lift [14]. A suction effect is observed on the lower surface at 0° angle of attack. This phenomenon is due to the formation of a convergent–divergent passage between the airfoil and the ground, the velocity of flow increases between the ground and he lower surface leading to a decrease in pressure causing a local drop in lift force.
Table 3. Showing $C_l$ and $C_d$ values of NACA 0012 airfoil at various angles of attack ($\alpha$) and $h/c$ ratio

| $\alpha^\circ$ | $h/c$ | $C_l$     | $C_d$       | $C_l/C_d$ |
|---------------|-------|-----------|-------------|-----------|
| 0             | 0.2   | -0.27124  | 0.014698    | -18.45    |
| 0             | 0.5   | -0.06215  | 0.01223     | -5.08     |
| 0             | 1.0   | -0.0047938| 0.011781    | -0.4      |
| 4             | 0.2   | 0.45471   | 0.021619    | 21.03     |
| 4             | 0.5   | 0.42817   | 0.021712    | 19.75     |
| 4             | 1.0   | 0.39020   | 0.021493    | 18.15     |
| 8             | 0.2   | 1.0757    | 0.031047    | 34.65     |
| 8             | 0.5   | 0.85732   | 0.030974    | 27.68     |
| 8             | 1.0   | 0.79180   | 0.033440    | 23.68     |

6. Conclusions

A CFD Analysis of three airfoils were undertaken in ground effect. The effects at various operating conditions such as the height above the ground ‘$h$’, the angle of attack and also the effect of the airfoil geometry were studied and the following conclusions can be made.

1. All the three airfoils experience increased lift as the distance from the ground decreases. This increase in lift is due increased static pressure at the lower surface of the wing and due to the disruption of the formation of wind tip vortices by the ground.

2. The values of $C_l$ and $C_l/C_d$ are maximum at 4$^0$ AOA for NACA 4412 and NACA 6412. These values decrease when $\alpha$ is increased to 8 deg. This is due to the starting of flow separation on the upper surface at the trailing edge at high angles of attack. For NACA 0012, $C_l/C_d$ increases till 8$^0$ AOA. This is because NACA 0012 has no camber and has less curvature of upper surface. Hence the flow separation at the trailing edge is delayed.
3. In the NACA 0012 airfoil, a suction effect is observed at 0° at all clearance ratios. This is due to the formation of a convergent-divergent section between the bottom surface of the airfoil and the ground. This creates a venturi flow below the wing leading to the formation of a low-pressure section, and hence results in negative lift.

4. NACA 6412 shows the highest aerodynamic efficiency of 74.65. This is seen at an angle of attack of 4° and at a h/c ratio of 0.2.

5. NACA 6412 shows the best performance of the three airfoils considered in ground effect. Compared to NACA 4412, NACA 6412 has more camber and hence more curvature of the top surface which can generate higher pressure drop. It also has a flatter bottom surface compared to NACA 0012 and hence the venturi effect which reduces lift is not observed at 0° angle of attack. Hence the best suited airfoil for WIG crafts from the three airfoils considered is NACA 6412.

7. References
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