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EFFECT OF GROUND PROXIMITY ON AERODYNAMIC CHARACTERISTICS OF NACA 4412 AIRFOIL

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Abstract:

Ground effect plays a vital role in modulating the flow behavior over any streamlined body. The most widely used wing-in ground effect (WIG) aircrafts and seaplanes utilize this phenomenon in order to enhance the aerodynamic performance during the landing and take-off phases of flight. This paper investigates the aerodynamics of ground effect on a NACA 4412 rectangular wing without end plates. The experiment was conducted in a low-speed wind tunnel at $Re=2\times10^5$ for the ground clearance of 1 and 0.5 of the chord, measured from the maximum thickness position on the airfoil. The pressure distribution over the chord length was recorded for $\alpha=3°$ and 6° to verify the effect of ground clearance during takeoffs. The results have shown to be in good accordance with the literature, as the coefficient of lift augmented with increase in ground proximity and the induced drag was minimized.

Keywords: Ground Effect; Aerodynamic characteristics; Pressure distribution; Lift argumentation; Induced Drag; Wind tunnel.

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1 INTRODUCTION:

Induced drag reduction is one of the major challenges faced in aircraft design as it instigates about 50% of the total drag acting on any lifting surface. It is produced as a consequence of the wing tip vortices formed over the pressure surfaces of the aircraft. They are originated from the accelerated air flow over the wing tips developed due to the greater pressure difference between the upper and lower surfaces of the wing (Green Sheldon, 1995). In attempts to avoid the adverse effects of drag over a body, the effect of ground proximity is taken advantage of.

Ground effect is constituted when the wing tip vortices interact with the surface of the ground. This is followed by a significant reduction in induced drag and higher aerodynamic efficiency of an aircraft. The effect of downwash deteriorates gradually as we move closer to the ground and hence the lift vector tilts back diminishing the induced drag component. The takeoff and landing phases are most impacted by this effect as the aircraft is prone to stalling due to loss of incidence and floating effect respectively. (Green Sheldon, 1995).

1.1 HISTORICAL BACKGROUND:

The ground effect was first observed in 1920s when an inverted wing's aerodynamics was studied by positioning it closer to the wall. The era of open-wheeled race cars began in mid-1940s (post the Second World War) and the idea of utilizing the downward lift force produced by an inverted wing helped balance the cornering forces and subsequently increase the mechanical load on the tires without raising the structural weight of the vehicles. Another remarkable revolution in the history was the advent of side skirts, which redirect the flow around the car and develop swift accelerations underneath it improving the aerodynamic performance, is a great epitome of ground effect. (Cui, E. and Zhang, X. 2010).

Early studies have concluded that when the aircraft flies at a height of one wingspan from the ground, the wing tip vortices are curtailed leading to a declined downwash effect. Also, when the wing is approaches the ground i.e., at 1/4 the of the wing span or lower, it experiences a cushioning effect which prolongs the fleet of the aircraft on runways (Cui, E. and Zhang, X. 2010).

Another revolutionary technology-Aero train, introduced in 1970s hovers on an air cushion developed due to the ground effect, reduced the friction problems of wheeled trains promising higher efficiency and much higher speeds. Chenguang Lai et.al demonstrated the influence of angle and attack and relative position on the aerodynamics of an aero train model tested in closed circuit wind tunnel at 35m/s. The position of the wing had a greater dominance in affecting the L/D ratio than the variation in angle of attack (Lai, Chenguang & Ren, Boqi & Zhou, Yuting, 2017).

1.2 **THEORETICAL EXPLANATION:**

The ground effect on an aircraft depends upon various parameters such as wingspan, angle of attack, chord length, airspeed and wing loading. A computational study conducted to find the prominence of wingspan in improving the aerodynamics of an inverted wing, observed that a reduced span size could make it move closer to the ground avoiding the down force losses. It was also recorded that the separation was delayed for shorter spans with the vortex size remaining constant (Diasinos, Sammy & Barber, Tracie & Doig, Graham ,2012)

An experimental study carried out to examine the effect of angle of attack and ground clearance on the flow characteristics of a symmetrical airfoil in ground effect observed a suction effect beneath the wing up to 5° angle of attack due to the venturi-effect impacting the lift. The coefficient of pressure on the lower surface increased with the increase in angle of attack at lower h/c ratios ($h<0.5$) (M. R. Ahmed & S.D. Sharma,2005). Lance W.Traub showed an upsurge in the lift curve but there weren't any trials of drag reduction as the ground neared to the 2D airfoil. Nevertheless, a considerable decrement in vortex drag accompanied by lift enhancement was found in the case of a three-dimensional wing, resulting in better aerodynamic efficiency. The effect of ground was perceived by means of skin friction lines on the surface, apprehended with the aid of a special flow visualization technique typically adopting titanium dioxide and paraffin oil (Lance W. Traub,2013).

Most of the WIG aircrafts employ end plates in an effort to produce the edge vortices, formed as a consequence of flow separation around the lower edge of the plate. These edge vortices promote the force performance as opposed to the wing tip vortices which lower the performance. Many studies on WIG crafts are done by adopting end plates of various lengths. The ground effect on the aerodynamic characteristics of an airfoil with and without end plates was researched and had a good agreement with the previous studies regarding lift augmentation and induced-drag reduction. The end plates have shown a positive effect in increasing the lift-curve slope. The wing was shown to possess greater longitudinal stability with creasing h/c ratio at positive angles of attack. (Carter, A,1961)

Ahmed et al. documented a detailed study on aerodynamics of a NACA 4412 airfoil whose results revealed the significance of suction effect on the lower surface on affecting the aerodynamic behavior of the wing. The wake characteristics displayed that the suction effect was accompanied by laminar separation which promoted drag enhancement and lift reduction at low ground clearances. The ram pressure developed due to the stagnation of air under the airfoil helps increase the lift coefficient (Ahmed, M. Rafiuddin & Takasaki, T. & Kohama, Y,2007**)**. According to Justin Gross et.al, the lift increases and also does the minimum drag in the ground proximity. However, the lift augmentation was found maximum only up to an *h/c*=0.2 and an effective increase in minimum drag was observed at *h/c*<0.4 at lower incidence angles. The stall angle didn't pronounce a significant change with increase in ground proximity. Theoretical methods were developed so as to evaluate the lift, drag and velocity parameters in the presence of ground effect using various approaches (Lance W. Traub,2012)

Several experimental and computational works were done on the analysis of ground effect on UAVs. Although the ground effect plays a major role increasing the lift and reducing the drag, the reverted flow of air from the ground makes the rotor unstable and adds to thrust requirements or heavy battery consumption. However, trade-offs have been made to optimize the UAV's structure and control ability to improve the aerodynamic efficiency (Timms, W. P. (2021) (Sanchez Cuevas & Pedro Jesus 2017) (Guillermo & Ollero, Anibal, 2018).

This paper discusses the influence of angle of attack and ground clearance on the aerodynamic response of a cambered wing in ground effect. Owing to prior experimental and numerical studies in this genre, the lift augmentation and the induced-drag reduction are evident with increasing ground proximity. However, this study validates the pressure distribution over the airfoil about the chord locations and presents an explicit conceptualization on wing in and without ground effect. The results of the wind tunnel tests conducted at two different *h/c* ratios are recorded and the implicated plots are illustrated.

2 **MATERIALS AND METHODS**:

The nearly flat-bottomed airfoil NACA 4412, is chosen for this research as it produces positive ground effect in contrast to the highly cambered airfoil and desists the Venturi flow under the airfoil. It is a cambered airfoil (stimulates positive lift at $\alpha = 0°$) with maximum thickness of 12% located at 30% chord and maximum camber at 40% chord location. The height *h* was measured from the maximum thickness location of the airfoil to the ground as a function of chord.

The model wing has been fabricated through 3D printing as it enables rapid prototyping and easy handling. The material used in this construction was Polylactic acid (PLA) which is the most default choice opted as it retains higher strength and stiffness values and also can be printed at low or room temperatures. The wing holds a span of 450mm and a 168mm chord length; therefore, it is characterized to behave like a three-dimensional wing capable of producing the wing tip vortices leading to the induced drag.

2.1 **PRACTICAL APPROACH:**

The ground effect could be simulated in the wind tunnel using the four basic methods:

a) Mirror image model method

b) The ground plate method

c) Moving belt method

d) Towing model method

Out of these methods, the ground plate method was adopted as it is a simple yet direct approach to make a pretense of the ground effect. Thereby, a wooden plank functioning like a fixed ground plate was placed on the tunnel floor by adjusting its distance for the two selected *h/c* ratios from the chord line.

2.2 **EXPERIMENTAL SETUP:**

Wind tunnel investigations were conducted at Institute of aeronautical Engineering's test facility. An open type low speed wind tunnel bearing a test section of 2000mm ×600mm × 600mm driven by a 22kW AC motor was used to perform the experiment. The tunnel's operational speed is 3m/s to 45m/s and the maximum velocity at which it can be calibrated is 50m/s, mostly feasible for Low Reynolds number flows. It consists of a multi-tube manometer and an inclined tube manometer whose limbs are connected to the static pressure holes.

Fig 1.1. Wing mounted in test section

Fig 1.2. Pressure probes connected to the multitube manometer

Fig 1.3. Wing fixed at unit ground clearance

The wing embodies 13 pressure tapings in the chord wise direction to obtain the pressure data (Fig 1.2). Thence, the model was mounted to a plug in the test section of the wind tunnel by a rod as shown in the Fig 1.1. The 1mm internal diameter silicon tubes were connected to the 30-tube manometer. The angle of attack was adjusted by rotating the wall fitting; initially the chord of the wing being parallel to the floor at 0 degrees. The flow velocity was maintained at 18m/s. The test trials were conducted at a Reynolds number of $2x10^5$. The experimental model was tested at 3° and 6° angles of attack in order to visualize the consequences of ground effect during take-off and landing. Our fundamental motto is to authenticate the conclusions obtained from the historical survey by carrying out real time wind tunnel investigations and comparing the aerodynamic characteristics of the wing with and without the ground effect at two height to chord ratios. The experimental results will significantly rely on the data collected from the manometer. The pressure data obtained from the wind tunnel was then utilized to evaluate the axial and normal components of the resultant aerodynamic force which is acquired as a function of angle of attack as presented in the analytical data and compared with the result obtained from theoretical formulae or lift and drag.

3 **CALCULATION:**

The pressure distribution over the wing was found out using the below equation at various locations over the airfoil using multitube manometer.

$$C_{p,x/c} = \frac{h_i - h_{static}}{h_{total} - h_{static}} \qquad \text{---------------[3.1]}$$

h_i=manometer reading at ith port.

h_{static}=manometer reading at static pressure port.

h_{total}=manometer reading at total pressure port.

4 **RESULTS:**

The effect of ground proximity on the aerodynamic characteristics is apprehended by the experimental data recorded through the pressure measurements. The plots of the lift and drag curves varying with α and *h/c* in the presence of ground effect are shown in Fig 2. The experiment was also performed for the wing without ground effect to compare the ground impact made on the flow behavior.

The pressure distribution for the two distinct angles of attack is evaluated by determining the values of Coefficient of pressure (Cp) at the respective port locations, solved by using [3.1]. The Cp vs x/c plots are depicted for corresponding *h/c* ratios.

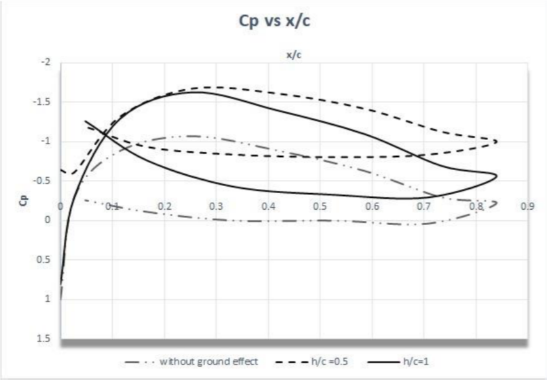

Fig 2.1. Pressure distribution at α= 3°

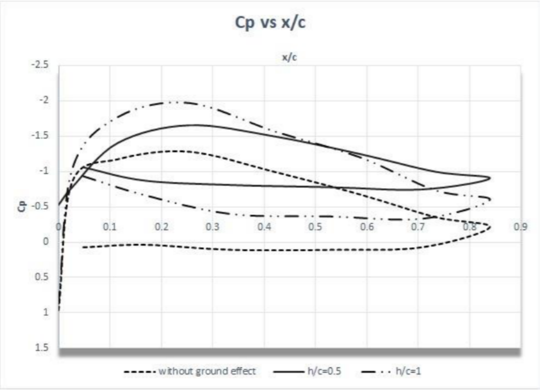

Fig 2.2. Pressure distribution at α= 6˚

The negative values of Cp indicate the low pressure over the airfoil's surface. However, most of the Cp values at the lower side of the airfoil also indicated negative pressures; there was a significant difference in the pressure differences observed for both the surfaces. For the first case where no ground proximity was effective, the Cp distribution for both the angles of attack looked no different from the conventional pre-existing data obtained for the same NACA 4412 airfoil. At α =3°, there was a greater pressure difference recorded at the maximum thickness location for the ground clearances. Consequently, at 6° angle of attack, the curves were oriented towards the negative Cp values showing an increase in lift caused due to the suction pressure underneath the wing.

The coefficient of lift (C_L) and the coefficient of drag (C_D) are generally derived from the pressure distribution, as the components of axial and normal forces acting over the airfoil surface. Although in this case, the values were deduced by calculating the area under the curves obtained from pressure distribution.

The difference between the areas covered by the upper and the lower curve using MATLAB R2021b; yielded the values of coefficient of lift and drag. It is well established that the area under Cp vs x/c plot gives the measure of lift. The coefficient of drag was also found employing the similar procedure.

The below graphs illustrate the significance of ground clearance on the lift and drag quantities with and without the influence of ground effect. At angles of 3° and 6° from the chord line, the coefficient of lift is seen to vary considerably for the three cases shown in Fig. 3.1. It is clearly displayed in the graph that the C_L value increased as the *h/c* ratio decreased. It is clearly pictured that at half the value of *h/c* the lift coefficient almost increased by 35% for α =3°.Similarly, it was noted that the C_L value for α =6° amplified by 26%. This data when compared with the case when there isn't any ground plate in the vicinity of the wing showed a notable difference in the C_L vs α graph. Likewise, the coefficient of drag did show some variation with increase in *h/c* ratio. At 3° angle of attack, the total drag value increased with increasing *h/c* ratio. The value of C_D reduced by 11.4% when the ground clearance was halved. The drag at α =6° almost showed an identical decline when neared to the ground. For no ground effect case, as shown in Fig.3.2, the drag recorded was lower than the that of the above two cases at respective angles of attack.

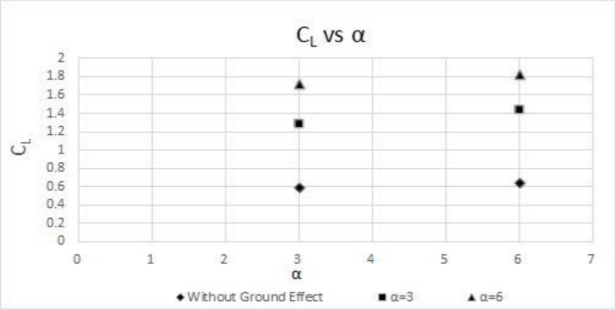

Fig 3.1. Variation of coefficient of lift with angle of attack

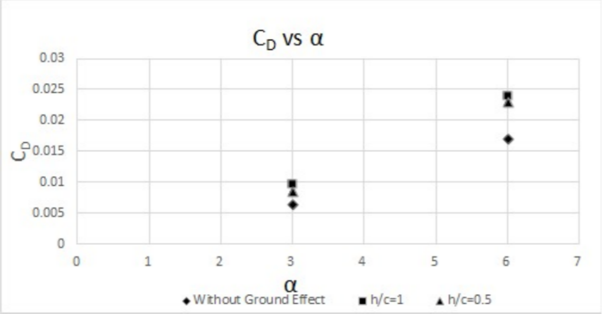

Fig 3.2. Variation of coefficient of drag with angle of attack

This graph depicts the influence of the angle of attack on the variation of the lift and drag measure sat various *h/c* ratios. The angle of attack didn't markedly alter the lift coefficient as shown in the Fig 4. At a ground clearance of 0.5 of the chord, the lift increased by 5.27% and when *h/c*=1, there was a 12% increase in lift. The minor increase in the percentage of lift was due to the increase in angle of attack by 3°. The plot of the drag coefficient with respect to *h/c* presents the increase in drag with increasing angle of attack. At *h/c*=0.5, the drag coefficient raised by a factor of 1.7 and a similar trend was observed for *h/c*=1.

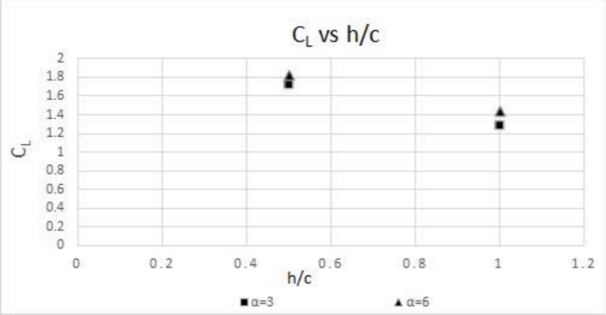

Fig 4.1. Variation of coefficient of lift with ground clearance.

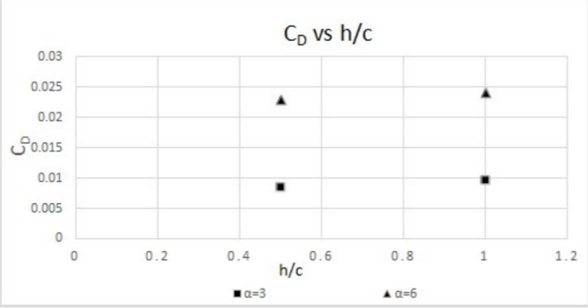

Fig 4.2. Variation of coefficient of drag with ground clearance

For a constant ground clearance i.e., when the aircraft is hovering at a constant altitude, the angle of attack also contributes to the lift enhancement but plays a role in increasing the drag component. This is due to the increased profile drag with increase in the incidence angle. Therefore, it is suggested to maintain a steady angle of attack while varying the ground clearance accordingly in an effort to obtain the best aerodynamic efficiency when in ground proximity.

5. **CONCLUSION:**

As the influence of ground effect is being greatly addressed in recent times, there is a need to reconsider its costs and benefits in an effort to develop the aerodynamics of future aircrafts and UAVs. This research presented a brief outline highlighting the effects of the ground clearance and angle of attack on NACA 4412 airfoil in ground effect. An experimental analysis was done in a low-speed wind tunnel at low Reynolds number and the difference between the lift and drag characteristics with and without ground effect was compared. The lift was augmented and the total drag decreased at a lower h/c ratio. The performance of the wing was enhanced as the induced drag minimized correspondently. This flow behavior has a wide scope of applications viz the Aero train and levitation of WIG planes which could pave the outgrowth of commuting. However, this study could be further extended for investigating the consequences of ground effect in landing and take-off phases of aircraft's flight through a computational approach.

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