RESEARCH NOTE

# EFFECT OF CAMBER AND THICKNESS ON THE AERODYNAMIC PROPERTIES OF AN AIRFOIL IN GROUND PROXIMITY

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**Abstract** A linear vortex panel method is extended to include the effect of ground proximity on the aerodynamic properties of two dimensional airfoils. The image method is used to model the ground effect . According to the results, lift coefficient of an airfoil may increase or decrease in ground effect based on a combinative effect of its camber, thickness, angle of attack and ground clearance. Airfoils with different section parameters are analysed and their relative effectiveness are compared.

**Key Words** Ground Effect, Panel Method, Vortex Method, Lift, Airfoil

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## INTRODUCTION

The favorable characteristics that are obtained when a wing flies close to a surface has been the basis of many practical applications. Examples are, wing in ground (surface) effect vehicles, aerodynamic surfaces of racing cars, guide way trains and take-off and landing phases of an aircraft.

There has been some theoretical as well as experimental studies on the influence of ground on the aerodynamic properties of wing sections. The earliest analytical solution was developed by Wieselsberger [1] who utilized the principle of reflection(image) method. For the case of two dimensional steady potential flow past a thin airfoil in the presence of ground, conformal mapping was used to obtain exact solutions [2,3,4]. The same method has been extended to include the effect of thickness, [6,7]. These methods are complex and their applicability is limited. Pistolesi [8] was among the first who solved the ground effect problem of a thin airfoil by the single vortex method. His method was extended to discrete vortex method by Coulliette and Plotkin [9] to calculate the effect of camber, and by the present authors [10] to calculate the effects of camber, and flap and also the variation of pressure center in ground effect. The effect of thickness has been considerd by Plotkin and Kennel [11], using a simplified matched asymptotic expansion method, Dragos [12] by the method of fundamental solution and Coulliette and Plotkin [9], by panel method. Euler solution of the problem has been performed by Agrawal and Deese [13].

The experimental investigation of ground effect has two main difficulties.One of them is the correct modeling of the ground and the other is the large number of test runs required due to the new additional parameter which is the ground height. Some experimental results are presented by Sowdon and Hari [14] and Steinbach [15].

According to the previous results, ground proximity could lead to an increase or decrease in lift coefficient, but there has been no investigation to represent the effect of the complete set of parameters affecting this variation.

The reason is that in most of the above studies selection of wing profiles was intuitive and a direct comparison of different practical wing sections have not been performed.

In this study we investigate the effect of camber, thickness and angle of attack on the aerodynamic properties of two-dimensional airfoils near the ground. The aim of this study is to find the best combination of the above parameters which lead to the most lift increase in ground proximity. The results are intented to be used in optimizing the lifting properties of a new wing in surface craft [16]. As in the proposed application there is no large increase in angle of attack (due to ground clearance limitation), we use a potential based panel method, which is well justified in these ranges of angle of attack [9,17].

## PROBLEM FORMULATION

The incompressible, irrotational flow around a body can be calculated by using the potential flow theory. The governing equation for this flow is the Laplace equation:

$$\nabla^2 \phi = 0 \qquad (1)$$

where $\phi$ is the total velocity potential. The appropriate boundary condition on the solid surfaces is:

$$\nabla \phi . n = 0 \qquad (2)$$

which is the flow tangency condition on these surfaces. The other boundary condition is that, the influence of an airfoil on the flow field around it vanishes far from the body. This condition is automatically satisfied through appropriate selection of the singular solutions.

## SOLUTION METHOD

The ground plane is substituted by an image of the real airfoil as shown in Figure 1.

In this way the equal and opposite flow velocities induced by real and image wings, cancel at the plane designated as the ground and the tangency condition 2 is automatically satisfied there. So it suffices only to apply the flow tangency condition on the real wing.

Among the central issues in solving a problem by panel method, are the choice of singularity elements and the type of boundary condition. The method used here is an extension of Coulliete and Plotkin analysis [9]. They applied the linear vortex panel method to a symmetric Joukowski airfoil. We extended the method to include both symmetric and non-symmetric airfoils in and out of ground effect.

The geometry of the real airfoil and its image are discretized into N equal or non-equal elements (panels). The discretization generally

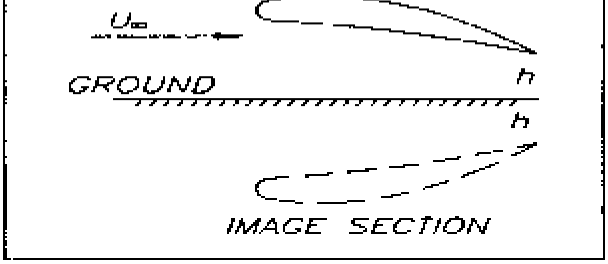


**Figure 1.** Principle of image method.

starts at the lower surface of the trailing edge. Two coordinate systems are used in the problem. One is a globally fixed and the other is a panel based coordinate system. The strength of the vortex distribution varies linearly along the elements. The collocation point of each panel, where the tangency boundary condition applies, is placed at the middle of each panel. The velocity induced at each collocation point is produced by the contribution from linear vortex distribution on the real and image airfoil, and the free stream velocity. Substituting the appropriate forms of these velocities into Equation 2 yields:

$$[\sum_{j=1}^{N}[(u,w)_{i,j} + (u,w)_{i,j}^{image}] + (U_\infty, o)].n_i = o \qquad (3)$$

where the summation is on the total number of elements. In the above equation $i$ accounts for the collocation points. If the strength of the vortex distribution at the beginning of each panel is set equal to the strength of the vortex at the end point of the previous panel, there will be an equation with N+1 unknowns, which are the panel edge values of the vortex distribution ($\gamma_j$, $\gamma_{j+1}$, ...), in the from of:

$$\sum_{j=1}^{N} A_{i,j}\gamma_{lj} + A_{i,N+1}\gamma_{tN} = -(U_\infty, o).n_i \qquad (4)$$

where $\gamma_{lj}$ is the vortex strength at the leading edge of each panel and $\gamma_{tN}$ is the vortex strength at the trailing edge of the last panel.

The value of the influence coefficient $A_{i,j}$, can be found by minor modifications of the procedure developed and described in detail by Katz and Plotkin [17]. It is not reproduced here due to space limitation.

The above equation leads to a system of N equations with N+1 unknowns. The Kutta condition is applied at the trailing edge to enforce the uniqueness of the solution. The Kutta condition at the trailing edge for the two-dimensional case, considered here, is in the form of:

$$\gamma_{TE} = 0 \quad \text{or} \quad \gamma_U - \gamma_L = 0 \qquad (5)$$

where $\gamma_U$ and $\gamma_L$ are the corresponding upper and lower surface vortex strengths at the trailing edge, respectively. In this way, Equation 4 can be solved by any standard matrix solver. Once the strength of vortices at the panel edges were found, one can obtain the tangential panel velocities from which the pressure coefficient on each panel can be calculated as:

$$C_p = 1-(u_t / U_\infty)^2 \qquad (6)$$

The lift coefficient is obtained by integrating the pressure coefficient around the airfoil in the from of:

$$C_L = \frac{1}{C}\oint_l C_p(x,z)\, n_z(x,z)\, dl \qquad (7)$$

where the integration is over the length $l$ of the airfoil section. The center of pressure of the airfoil can be found by the following equation:

$$X_{cp} = -\frac{1}{C_L}\oint_l x.C_p(x,z)\, n_z\, dl \qquad (8)$$

## RESULTS

The validity of the present solution method is established through application to two test cases. The first is a comparison between the exact solution of a symmetric Joukowski airfoil with the present results. It was found that by selecting 90 panels the error between the two results reduced to 1.3%. Therefore, the same number of panels with a half cosine spacing near the leading edge is used in comparisons made hereafter. The other test case is a comparison between the experimental results obtained by Steinbach [14] and the present results in ground effect. The results in the form of pressure coefficient distribution for a CLARK-Y 11.4% airfoil for $h/C=0.1$, is shown in Figure 2.

In order to find the effects of thickness and camber, we applied the method to five wing sections, having $h/C=0.05$ to 1, and three angles of attack of 0, 3 and 6 degrees. The wing

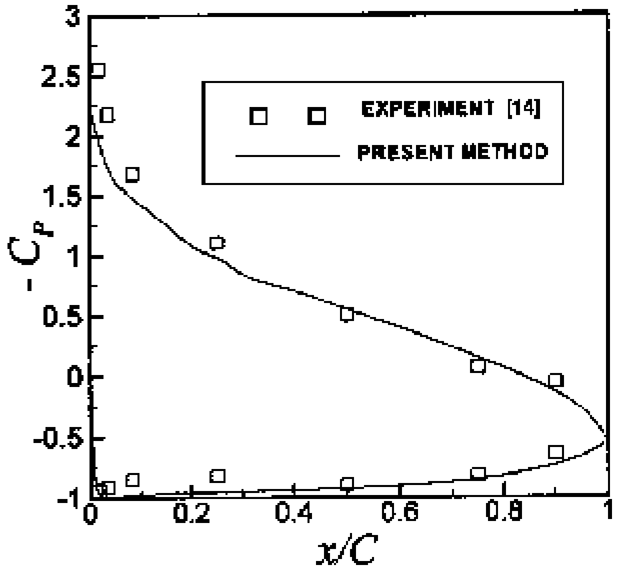


**Figure 2.** A Comparison of the data calculated with the experimental results.

sections analysed at $h/C = 0.10$ and zero angle of attack are shown in Figure 3. Comparisons have been made in two cases, one is based on the variation of thickness in a fixed camber, and the other is based on the variation of camber, in a fixed thickness. Results of these two cases for lift coefficient $(C_L)$, and normalized lift coefficient $(C_L/C_{L\infty})$, are shown in Figures 4 and 5. In Figure 4 three airfoil sections, namely NACA 4406, NACA 4409 and NACA 4412, with equivalent camber and different thickness are compared . As seen from the figure, increasing the thickness may lead to a sudden decrease in the lift coefficients in ground proximity, at low angles of attack.

The situation is reversed by a slight increase in angle of attack, where, decreasing the ground clearance leads to a favorable ground effect. In ground proximity the lift of lower thickness airfoils, becomes more than the higher thickness ones, in contrary to the out of ground case.

A similar comparison is made in Figure 5 for three airfoils of constant thickness and different cambers, namely, NACA6409, NACA4409, and NACA0009. At a first glance it can be seen that variation of camber has a more pronounced effect in comparison to thickness variation, in

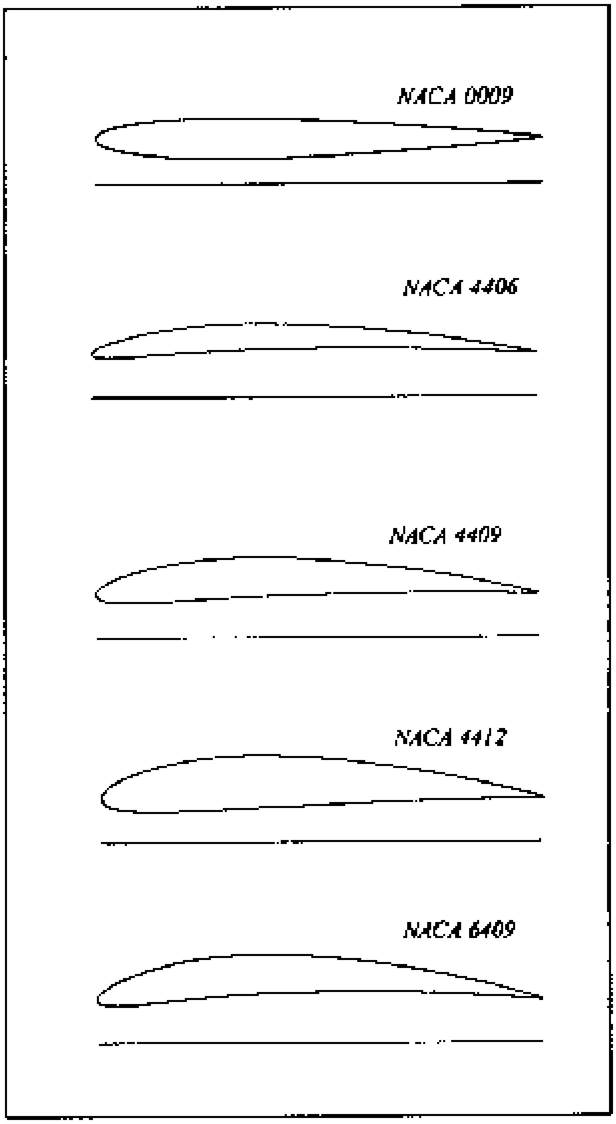


**Figure 3.** Position of airfoils relative to the ground.

agreement with the out of ground case. It can be seen that while a symmetric section produces no lift in free air, decreasing its height from a supporting surface produces a large downward force. The same effect can be seen in low cambered airfoils at low angles of attack, when their thickness is more than a certain value. This is mainly due to the venturi shaped channel formed between the lower surface of the airfoil and the ground. The channel shape can clearly be compared in Figure 3, among the airfoils considered. It is concluded that in applications such as race cars, where a

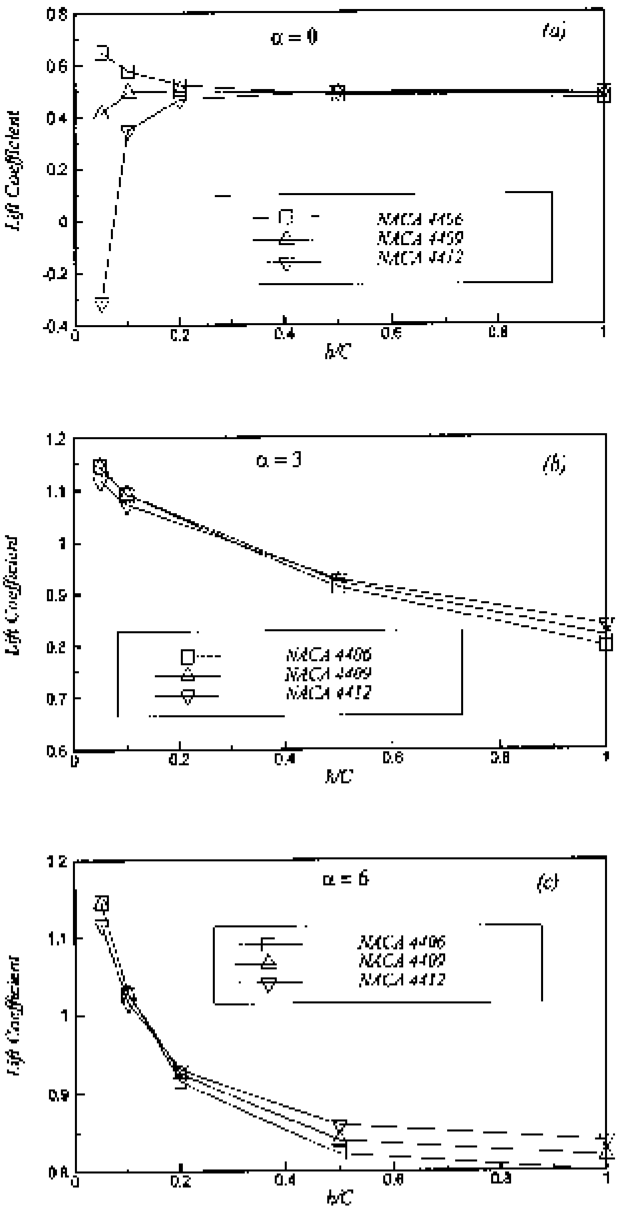


**Figure 4.** Effect of angle of attack on lift coefficient.

downward force is required for better stability at high velocities, a symmetric or even a reversed cambered thick wing section must be used.

Other results shown in Figure 5 indicate that increasing the camber, increases the absolute value of lift coefficient in ground effect and decreases the normalized lift coefficient. This is clearly shown in Figure 5-e and Figure 5-f, where the lift increase for a symmetric airfoil is about 40 percent more than the lift increase for a relatively high cambered airfoil, namely, NACA 6409, at *h/C=0.05*.

Yet another result seen in these figures is that the normalized lift coefficient of a non-symmetric airfoil in large ground height is always less than the free stream value. The reason for this change is illustrated in our previous paper [10], and is mainly due to the bound vortex of the image airfoil. By increasing the height above the ground the normalized lift coefficient approaches to one in the limit.

Excluding NACA0009 due to its unfavorable behavior as a lift augmenting section near the ground, a comparison between other remaining airfoils are shown in Figures 6 and 7 for $\alpha$=3$^3$. It can be seen that while the largest lift coefficient of the airfoils analysed in ground effect belongs to NACA6409, but the most increase in the normalized lift coefficient is obtained for the airfoil with the least camber and thickness, namely, NACA 4406.

The variation of center of pressure for the same airfoils are shown in Figure 8. It is seen that by decreasing the ground clearance the center of pressure is moved toward the trailing edge. The reason for this could be found from Figure 9. This figure shows the pressure coefficient on the upper and lower surface of NACA4406 airfoil for three different heights from the ground. It can be seen that, ground effect, mainly influences the pressure distribution on the lower surface of the airfoil.

As the height decreases, the pressure coefficient *Cp* on the lower surface of the airfoil approaches to 1, which is the stagnation condition. This flattening of pressure distribution leads to a backward (toward trailing edge) movement of the center of pressure which must be considered, when the stability criteria of ground effect vehicles are analysed.

## CONCLUSION

Aerodynamic properties of two dimensional airfoils in ground effect was investigated by a linear vortex panel method. According to the results, the combined effects of angle of attack,

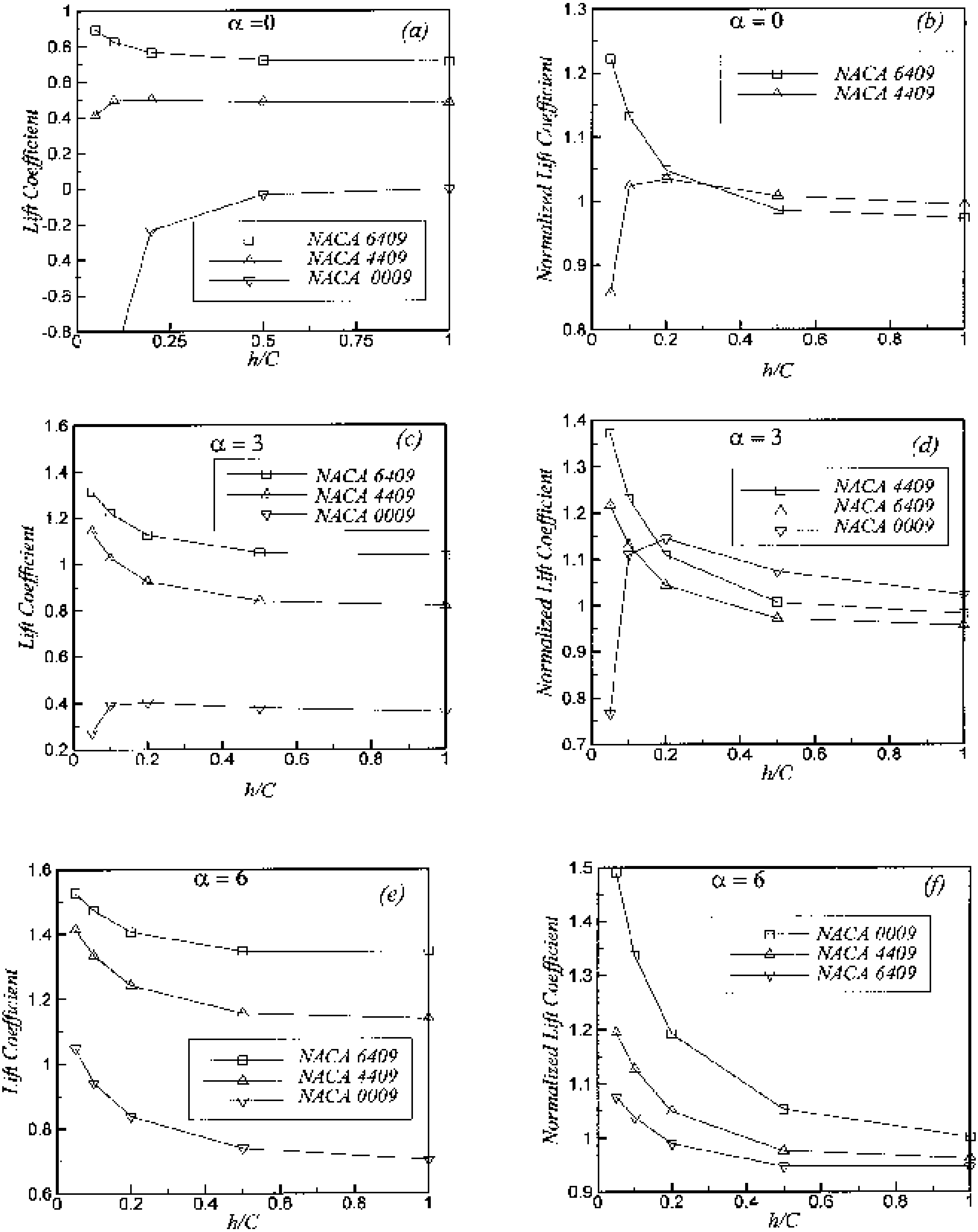


**Figure 5.** Effect of angle of attack on lift coefficient and normalized lift coefficient.

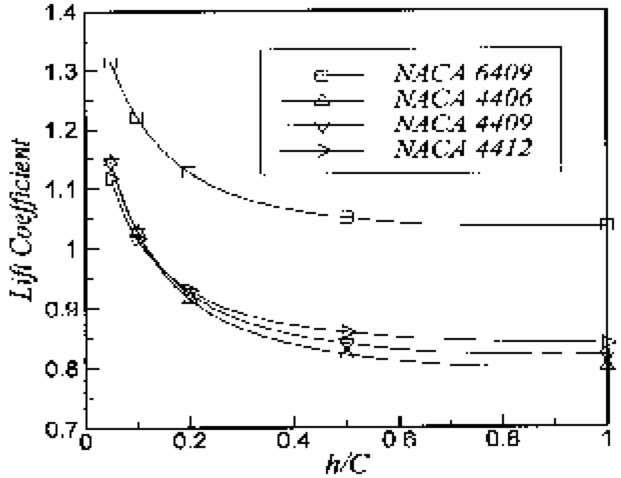


**Figure 6.** Lift coefficient at a= 3 deg.

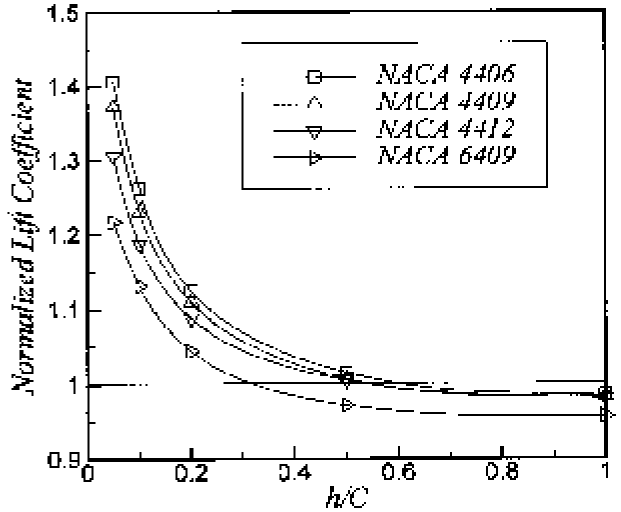


**Figure 7.** Normalized lift coefficient at a= 3 deg.

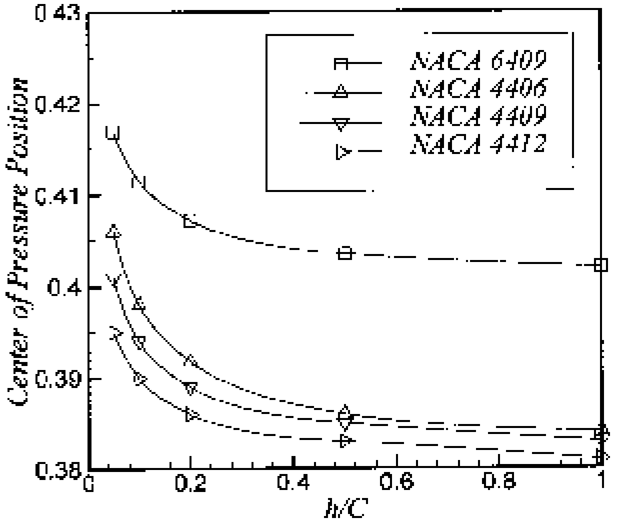


**Figure 8.** Center of pressure at a= 3 deg.

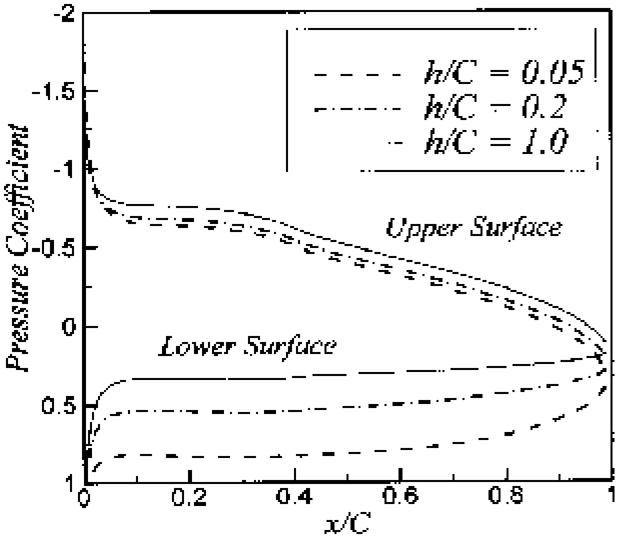


**Figure 9.** Pressure coefficient for NACA 4406 at a= 3 deg.

camber and thickness in ground proximity leads to the following results:

-In ground effect, symmetric airfoils produce a negative (downward) lift which its absolute value increases with reducing ground height. Increasing the thickness for these airfoils, increases the downward force.

- For low cambered or high thickness airfoils,in ground effect, the same lift reduction may occur below a certain height, when the angle of attack is relatively low.

- The combined effect of low thickness and average or large camber leads to a continuous increase in the lift coefficient in ground proximity .

- The normalized lift coefficient decreases by increasing both camber and thickness.

- The normalized lift coefficient reduces by increasing the angle of attack for those airfoils which have a positive lift increase in ground effect.

- The two previous mentioned results show that while increasing the thickness, camber and angle of attack in general can lead to an increase in $C_L$, but the normalized lift coefficient in ground effect behaves in reverse.

- The lift coefficient, increases or decreases more sharply as the ground height approaches its smallest value.

- As a rule of thumb it can be said that, for an airfoil section to be a lift augmenting device, no part of its lower surface must be below the trailing edge. This prevents the venturi effect on the airfoil which sucks it down.

## NOMENCLATURE

| | |
|---|---|
| $A$ | Influence coefficient |
| $C$ | Chord length |
| $C_L$ | Lift coefficient |
| $C_P$ | Pressure coefficient |
| $h$ | height of trailing edge from ground |
| $l$ | Length along the airfoil section |
| $n$ | Unit vector normal to the airfoil surface |
| $N$ | Number of vortex panels |
| u | Horizontal component of induced velocity |
| $u_t$ | Tangential velocity along the airfoil surface |
| $U_\infty$ | Free stream velocity |
| $w$ | Vertical component of induced velocity |
| $x$ | Horizontal axis |
| $X_{cp}$ | Position of pressure center relative to the leading edge |
| $z$ | Vertical axis |

## Greek Symbols

| | |
|---|---|
| $\alpha$ | Angle of attack |
| $\gamma$ | Vortex strength |
| $\phi$ | Total velocity potential |

## Subscripts

| | |
|---|---|
| $i$ | Collocation point index |
| $j$ | Vortex location index |
| $l$ | Panel leading edge |
| $t$ | Panel trailing edge |

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