Aerodynamic analysis of the boundary layer region of symmetric airfoils at ground proximity

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Abstract

In this paper, effects of flight distance from ground surface and the thickness of the airfoils moving at ground proximity on the inception point of the transition phenomenon, the start of flow separation, and the boundary layer thickness have been analyzed. The amounts of drag force as well as the lift of the airfoil in viscous flows are influenced by these parameters. Included in this study are the effects of change in Reynolds number and angle of attack on the symmetric airfoils which are carefully investigated. Results of this aerodynamic analysis indicate that the motion at ground proximity is the cause of some changes in boundary layer properties. By close scrutiny of these changes; justifications are found for the behavior of the lift and drag forces at ground proximity.

1. Introduction

Airfoils are recognized as lifting surface objects and a particular criterion called performance parameter is defined for them. This parameter is the ratio of lift to drag of the airfoil. Since these objects move in viscous fluid, a particular flow regime with low thickness and larger velocity gradient is formed around them which is identified as boundary layer. This flow regime causes several changes in behavior of the airfoils such as the inception point of the transition phenomenon, the starting point of flow separation, and the boundary layer thickness. The amounts of drag force as well as the lift of the airfoil in viscous flows are influenced by these parameters.

Wings in ground effect possess many aerodynamic features of both practical and fundamental importance. In general, the lift and drag forces of a wing will considerably change near the ground. When an airfoil moves near the ground, flow around the airfoil is viscous and has many viscous interactions with the ground. In the analysis of ground effect on the aerodynamic properties of the airfoils, the boundary layer on the airfoil must be considered. On the other hand, prediction of location of the onset of the transition phenomenon, as an example of boundary layer characteristics, is also necessary in order to predict the drag because the skin friction related to a laminar boundary layer is lower than that of a turbulent one[1].

Generally, in the analysis of the ground surface effect on airfoils, the three-dimensional effect has special importance and this can be attributed to the flow penetration from the lower surface to the upper surface of the airfoils. On the other hand, due to the higher pressure at the lower surface, the three-dimensional effect of the flow considerably increases near the ground surface. In the meantime, by adding two auxiliary elements called “end plate” to the two ends of the wing along the span, it becomes possible to substantially reduce the three dimensional effect of the flow. Under these circumstances, the flow becomes two-dimensional and the prevailing condition can be considered analogous to infiniteness of the length of span [12]. Accordingly, all airfoils in the current studies are considered to be two-dimensional meaning that the length of the airfoil span is exceedingly high and that the airfoil has very high aspect ratio.

Silverstein and becker [1], in 1939, experimented three symmetrical airfoils in wind tunnel and the effects of variation in lift coefficient, Reynolds number and airfoil thickness on transition were investigated. Von Doenhoff [2] investigated boundary layer around the symmetrical NACA airfoil in zero lift condition. His surveys were made considering different Reynolds number based on airfoil's chord. In that work, drag of airfoil, distribution of skin friction over the surface of the airfoil and onset of the transition point were found. Lian and Shyy [3] investigated performance of a rigid airfoil and a flexible airfoil by numerical method. They coupled Navier-Stokes solver by the e^N transition model to study flow characteristics with the laminar separation and transition in low Reynolds number.

All the cited works were focused on the investigations of airfoils at distance far from the ground surface, but limited work has been performed or reported for the airfoil that moves near the ground. However, one particular related research that can be reported is the work done by Takahashi and et al. [4]. Takahashi and et al. numerically investigated aerodynamic characteristics of cambered airfoils near the ground. Their study were limited only to investigation of location of turbulent separation of a cambered (non-symmetric) airfoil in ground proximity which indicated that, moving near the ground, would cause the flow separation to move toward the leading edge.

Therefore, it can be stated that, in the previous related works, very limited studies were devoted to airfoils at ground proximity in which case only a particular airfoil has been analyzed with no parametric studies done on the subject of discussion. However, in the current article, several types of airfoils have been examined and various parametric studies have been performed on the Reynolds number, airfoil thickness, altitude from the ground surface, and different angles of attack. Furthermore, the impacts of these parameters have been investigated locally on the inception of separation, transition phenomenon, and the thickness of the boundary layer, and globally on the lift and drag that the airfoils exhibit.

2. Solution Method

A computer code named WIGPMBL is written to combine the vortex panel and boundary layer methods in order to examine the ground effect on the aerodynamic properties of the airfoils. WIGPMBL models the interactions of the viscous-inviscid fluids. Vortex panel method models the inviscid part while boundary layer method deals with the viscous fluid. By finding the velocity distribution, the obtained data is fed into the boundary layer scheme. As a result, wall friction coefficient as well as displacement thickness were calculated. Subsequently, by adding the newly found local displacement thickness to the original value of geometry surface, second iteration is performed and so on and so forth. These iterations are continued until the convergence criterion is satisfied and a converged solution is achieved. Significant parameters which are calculated in the process of these iterations include pressure distribution, boundary layer characteristics such as onset of the transition phenomenon, starting point of flow separation, boundary layer thickness, distribution of the skin friction coefficient, and more importantly the aerodynamic properties of lift and drag forces.

2.1. Vortex panel method

The vortex panel method is a powerful numerical tool for determining the circulation density for a thin airfoil that belongs to more general scheme known as panel method. The first assumption of all panel methods is that the flow must be incompressible and irrotational. For the incompressible and irrotational flow, continuity equation in terms of the total potential Φ will be Laplace equation that is written as:

$$\nabla^2 \Phi = 0 \quad . \quad (1)$$

Free stream potential is $\phi_\infty = U_\infty x$ and thus the total potential can be written as:

$$\Phi = \frac{1}{2\pi} \iint [Ln(r) \nabla \phi - \phi \nabla (Ln(r))] n ds - U_\infty x \quad . \quad (2)$$

In every panel method, the airfoil is comprised of panels, boundary points and control points. The control points are the midpoints of the panels.

2.2 Boundary conditions

2.2.1 Body of the Airfoil

A zero normal velocity component is imposed upon the control points. This condition is necessary because the airfoil is a solid body and streamlines do not penetrate into the solid bodies.

$$\nabla(\phi_p + \phi_\infty) \cdot \vec{n} = 0 \quad \text{on} \quad S_F \quad (3)$$

2.2.2. On the ground

In this case, similar to the case of airfoil body, normal velocity on the ground surface should be zero that is satisfied by Neumann boundary condition.

$$\nabla(\varphi_p + \varphi_\infty) \cdot \vec{n} = 0 \quad \text{on} \quad S_G \quad (4)$$

2.2.3 Kutta condition

For a body with a cusped trailing edge where the upper and lower surfaces meet tangentially, a smooth flow at the trailing edge requires equal velocities on both sides of the edge in the tangential direction.

$$\nabla\Phi \cdot \vec{t} \Big|_L = -\nabla\Phi \cdot \vec{t} \Big|_U \quad (5)$$

2.3 Physical model

In figure 1, physical parameters are illustrated. Parameter h is the flight distance from ground measured from nearest (lowest) point of airfoil to the ground surface. α is the angle of attack and its positive direction is considered clockwise. U_∞ is the free stream velocity.

Fig.1. Illustration of physical parameters.

2.4 Boundary layer method

Solution obtained by the WIGPMBL for the viscous part of the flow is based on the concept of Boundary Layer Theory. The two-dimensional steady incompressible integral boundary layer is described by the following two equations, obtained by integration of the boundary-layer momentum and continuity equations in the direction normal to the wall [5]:

$$\frac{\partial \theta_{ss}}{\partial s} + \frac{\theta_{ss}}{U_{s_e}} \left(2 + \frac{\delta_s^*}{\theta_{ss}} \right) \frac{\partial U_{s_e}}{\partial s} = \frac{1}{2} C_{f_s} \quad (6)$$

$$H_1 \frac{\partial \theta_{ss}}{\partial s} + H_1 \frac{\theta_{ss}}{U_{s_e}} \frac{\partial U_{s_e}}{\partial s} + \theta_{ss} \frac{\partial H_1}{\partial s} = C_E \quad (7)$$

where δ_s^* and θ_{ss} are the displacement and momentum thicknesses, respectively. The shape factor H_1 is defined as $(\delta - \delta_s^*)/\theta_{ss}$ where δ is the boundary layer thickness. The coefficients C_{fs} and C_E are the skin-friction and entrainment coefficient.

2.3.1 Laminar boundary Layer

For the calculation of the steady two-dimensional incompressible boundary layer in the laminar region, up to the transition, it is much easier to use Thawites' method. This simple model relies on the integral momentum equation [5]:

$$\text{Re} \frac{\partial}{\partial x} (\theta_{ss}^2 U_{s_e}^6) = 0.45 U_{s_e}^5 \cdot \quad (8)$$

Knowing the value of U_{s_e} , momentum thickness (θ_{ss}) can be calculated, and subsequently shape factor (H) as well λ will be obtained.

$$(9) \quad \lambda = \text{Re} \theta_{ss}^2 \frac{\partial U_{s_e}}{\partial s}$$

$$(10) \quad \begin{aligned} H(\lambda) &= 2.61 - 3.75\lambda + 5.24\lambda^2 \quad \text{for } 0 < \lambda < 0.1 \\ &= 2.088 + \frac{0.0731}{\lambda + 0.14} \quad \text{for } -0.1 < \lambda < 0 \end{aligned}$$

Thawite method indicates that separation will occur only when $0.1 < \lambda < -0.1$ [7]. Under low Reynolds number conditions, the boundary layer at the onset of pressure rise may still be laminar and thus unable to resist substantial adverse pressure gradients and flow separates [8]. Under certain circumstances, the separated flow experiences laminar-turbulent transition and later reattaches to the airfoil to form a laminar separation bubble. Depending on parameters such as the local Reynolds number, pressure gradient, surface roughness and free stream turbulence intensity, the turbulent free shear layer may entrain enough high momentum fluid to reattach as a turbulent boundary layer behind a laminar separation bubble [3].

Izumida [6] has reported that the length of laminar separation bubble is approximately 150 times the momentum thickness at the laminar separation point and he started the turbulent boundary layer calculation from the end of laminar separation bubble.

2.3.2 Transition Boundary Layer

Transition to turbulence is to be included in the various boundary layer prediction methods. In this work, Cebeci and Smith relation [8] is used for estimated location of natural transition. This criterion is based on the idea that the transition starts at a specific Reynolds number based on the distance 's' from the start of the boundary layer [8], i.e. when

$$Re_{\theta_{ss}} > Re_{\theta_{ss \max}} = 1.174 \left(1 + \frac{22400}{Re_s} \right) (Re_s)^{0.46}. \quad (11)$$

where $Re_{\theta_{ss}} = Re \cdot U_{se} \cdot \theta_{ss}$ and $Re_s = Re \cdot U_{se} \cdot s$ and Re is the free stream flow Reynolds number while $Re_{\theta_{ss}}$ and Re_s are Reynolds number based on momentum and distance from stagnation point, respectively. Since the flow transition happens when $Re_{\theta_{ss}} > Re_{\theta_{ss \max}}$, then $Re_{\theta_{ss \max}}$ can indeed be considered as the **transition critical** Reynolds number.

2.3.3 Turbulent Boundary Layer

For a large enough Reynolds number, the boundary layer can become turbulent. Turbulent flow is unsteady and three dimensional. For solution of turbulent boundary layer, Head's method is used. Head's method is a typical integral method and it is a reasonably accurate and especially fast method [7]. By simultaneous solution of equations 12 and 13, the shape factor (H) and the momentum thickness (θ) in turbulent boundary layer can be obtained.

$$(12) \quad \frac{1}{U_e} \frac{d}{dx} (U_e \theta_{ss} H_1) = 0.0306 (H_1 - 3)^{-0.6169}$$

$$(13) \quad \begin{aligned} H_1 &= f(H) = 3.3 + 0.8234(H - 1.1)^{-1.287} \quad \text{for } H \leq 1.6 \\ &= 3.3 + 1.5501(H - 0.6778)^{-3.064} \quad \text{for } H > 1.6 \end{aligned}$$

Separation occurs when $H > 2.4$ or $H_1 > 3.3$ [7]. In separation regime, shape factor and momentum thickness will not be developed and are assumed diminished (zero)[8], but boundary layer thickness will be developed with slope of panel in separation point to trailing edge. Drag coefficient can be calculated by Young-Squire formula that included both pressure drag and friction drag. In this formula, boundary layer characteristics (H and θ_{ss}) are taken into account at the trailing edge [7].

$$C_D = \left[2\theta_{ssTE} \cdot \left(U_e \right)_{TE}^{\frac{H_{TE}+5}{2}} \right]_{UP} + \left[2\theta_{ssTE} \cdot \left(U_e \right)_{TE}^{\frac{H_{TE}+5}{2}} \right]_{LOW} \quad (14)$$

3. Discussion and Analysis

This article focuses on the effect of ground surface on the boundary layer characteristics. Boundary layer characteristics include the thickness of boundary layer displacement, the location of flow separation from the airfoil surface, the location of the occurrence of the transition phenomenon. For this purpose, WIGPMBL has been developed in which the basis of computations is Vortex Panel Method. By using this method, the inviscid part of

the flow is analyzed. In order to determine the viscous effects of the fluid, the boundary layer theory is utilized. In this part of the analysis, all the necessary information (velocity distribution and exerted pressure on the airfoil surface) is available from computations performed in the inviscid part.

In this work, symmetric airfoils have been examined. Using four different airfoils NACA 0009, NACA 0012, NACA 0015, and NACA 0018, the effects of flight distance from the ground surface and change of airfoil thickness, on the boundary layer characteristics are analyzed. In order to explore the ground effect phenomenon, airfoils have been considered at several different flight distance from ground which also includes the motion of an airfoil in an infinite environment and away from the ground surface that is indicated by $H/C=\infty$.

In order to validate the performance of the written computer code, the results of airfoil NACA 0012 [9] has been compared against the experimental data as well as the results produced by the Xfoil software. These comparisons are for the situations when the airfoil is moving in the infinite environment. In figures 2 and 3, graphs of lift force and polar diagram of this airfoil are respectively sketched. It can be seen quite clearly how agreeable the results of WIGPMBL code are compared to the experimental data as well as the numerical results of the Xfoil software.

In order to examine the results of the WIGPMBL code in vicinity of surface, another comparison is made. In it, the results of the developed code is compared with another numerical result which has utilized finite volume method in the analyses [10].

Fig.2. Comparison of the numerical and experimental results of lift force for NACA 0012 being out of ground effect, at $Re=1.44 \times 10^6$.

Fig.3. Comparison of polar diagram of computed airfoil NACA 0012 being out of ground effect with related experimental results.

In figure 4, plot of lift force for airfoil NACA 0012 in the neighborhood of surface is illustrated. As observed, the WIGPMBL results match the numerical results by Hsiun-Chen [10] very well. The slight discrepancy that exists may be attributed to the coarse mesh, the difference in defining the boundary conditions or the method by which the corresponding boundary layer is solved.

Fig.4. lift force of the NACA 0012 near the ground surface effect at $Re=1.0 \times 10^5$.

Fig.5. Demonstration of sufficiency of mesh density on drag coefficients for three different panel numbers for NACA0012 at $\alpha = 9^\circ$, $Re = 3,430,000$, (Nf: Number of panel on the foil, Ng: Number of panel on the ground)

In Fig.5, the plots of drag coefficients corresponding to four different numbers of panels (i.e. 60 panels on the ground and 100,140, 170, and 200 panels on the foil) are illustrated. As evidenced in the graph, variation of number of panels has minimal effect on the computations and the calculations can be considered independent of the number of panels (i.e. at this range of panel numbers).

Since one of the focal points of studies in this article is the location of transition phenomenon, it becomes imperative to show the validity of the method used for this purpose. Accordingly, numerical results of the WIGPMBL code as well as data produced by XFOIL software in the current study for to the position of the transition phenomenon are compared against an available experimental data [1]. As mentioned previously, method of Cebeci and Smith is used in the WIGPMBL software to determine the position of transition point. However, XFOIL software utilizes e^N method to determine where the change of regime between laminar and turbulent flows occurs. In the experimental data demonstrated in figures 6 to 9 as a reference, the location of the onset of transition phenomenon and the ending of this phenomenon is demonstrated by the dark lines. Therefore, computational results for the transition point are expected to lie somewhere between these lines. Considering the comparisons made in figures 6, 7, 8, and 9, accuracy of WIGPMBL performance is verified, and as a result, motions of airfoils can, with certainty, be analyzed using this code. The boundary layer equations used in this code is

valid in the fluid incompressibility limit. Accordingly, the conditions are also considered on this basis. Three different Reynolds numbers 18×10^5 , 25.7×10^5 , and 34.3×10^5 have been designated for performing these analyses and the corresponding Mach numbers are $M=0.08$, $M=0.11$, and $M=0.15$. These Mach and Reynolds numbers are chosen in a way that they fall within the performance limit of flying boats (or WIG) and that the fluid, with certainty, can be claimed to be incompressible.

Fig. 6. Comparison of numerical and experimental findings of position of transition phenomenon at $C_L = 0.00$ for NACA 0012.

Fig. 7. Comparison of numerical and experimental findings of position of transition phenomenon at $C_L = 0.00$ for NACA 0018.

Fig. 8. Comparison of numerical and experimental findings of position of transition phenomenon at $C_L = 0.33$ for NACA 0012.

Fig. 9. Comparison of numerical and experimental findings of position of transition phenomenon at $C_L = 0.33$ for NACA 0018.

3.1. Investigation of altitude from surface

For investigation of the effect of flight distance from ground relative to the ground surface (H/C) on the boundary layer characteristics, airfoil NACA 0012 was analyzed. In figure 10, plot of the location of the occurrence of the transition phenomenon based on the airfoil lift coefficient at infinite flight distance from ground is presented. In this plot, the results corresponding to the three Reynolds number are illustrated. With an increase in the Reynolds numbers, the length of the turbulent boundary layer on the airfoil would become approximately larger. This means that the occurrence of the transition phenomenon leans toward the leading edge.

Fig.10. variation of location of transition phenomenon in terms of lift coefficient at $H/C=\infty$ for NACA0012.

Fig.11. Variation of location of turbulent separation at the upper surface of airfoil NACA 0012 with change in angle of attack.

In figure 11, the location of inception of separation phenomenon is shown. The boundary layer equations used in WIGPMBL are able to determine the location of start of separation phenomenon, but they cannot analyze the separation itself. In this plot, it is quite clear that, with an increase in the angle of attack, separation surface at the upper surface of the airfoil increases. In other words, the separation point moves toward the leading edge. An increase in separation surface will mean an increase in the drag. At the lower surface of the airfoil, Separation point is very close to the trailing edge. At high angles of attack, because of the desirable changes of pressure at the lower surface of the airfoil, separation does not easily occur.

One of the boundary layer characteristics is its displacement thickness. If the entire flow is assumed as non-viscous, then the displacement thickness is defined to be the distance by which the boundary would have to be displaced such that if the same mass flows rate maintained at each cross section [11]. In figure 12, the displacement thickness of airfoil NACA 0012 at angle of attack of 8 degrees and at three different Reynolds numbers are illustrated. Based on this plot, we can conclude that, with an increase in Reynolds number which is equivalent to an increase in velocity and thus implicitly implying an increase in fluid momentum, the boundary layer thickness decreases.

Fig.12. Displacement thickness of Boundary Layer at 8 degrees angle of attack and three Reynolds number of NACA 0012.

In the analysis of the airfoil motion near the ground surface, the boundary layer characteristics are compared at four different flight distances from the ground (H/C) of 0.1, 0.5, 1, and ∞ . In table 1, the location of transition points at the upper surface of the airfoil are compared for five angles of attack and two Reynolds numbers. In table 2, the location of transition point at the lower surface of the airfoil is also compared for the same indicated angles of attack and Reynolds numbers.

Table 1- Location of the inception of transition phenomenon at the upper surface of airfoil NACA 0012 (quantities are non-dimensional w.r.t. the chord length of airfoil).

H/C \ AOA	Re=2570000				Re=3430000			
	0.1	0.5	1	∞	0.1	0.5	1	∞
0	0.2	0.338	0.353	0.353	0.187	0.309	0.323	0.323
3	0.11	0.152	0.152	0.164	0.1	0.13	0.141	0.141
6	0.116	0.121	0.074	0.074	0.07	0.066	0.066	0.066
9	0.066	0.065	0.068	0.069	0.072	0.064	0.066	0.067
12	0.075	0.069	0.064	0.064	0.08	0.068	0.069	0.063

Table 2- Location of the occurrence of transition phenomenon at the lower surface of airfoil NACA 0012 (quantities are non-dimensional with respect to the chord length of airfoil).

H/C \ AOA	Re=2570000				Re=3430000			
	0.1	0.5	1	∞	0.1	0.5	1	∞
0	0.2	0.338	0.353	0.353	0.187	0.309	0.323	0.323
3	0.11	0.152	0.152	0.164	0.1	0.13	0.141	0.141
6	0.116	0.121	0.074	0.074	0.07	0.066	0.066	0.066
9	0.066	0.065	0.068	0.069	0.072	0.064	0.066	0.067
12	0.075	0.069	0.064	0.064	0.08	0.068	0.069	0.063

0	0.546	0.383	0.353	0.353	0.546	0.353	0.338	0.323
3	0.629	0.647	0.617	0.601	0.63	0.601	0.586	0.57
6	0.91	0.871	0.852	0.843	0.886	0.872	0.848	0.825
9	0.976	0.938	0.918	0.905	0.958	0.939	0.913	0.901
12	0.956	0.954	0.962	0.951	0.936	0.955	0.95	0.952

Considering the data given in table 1, when approaching the ground surface, the location of the transition point at the upper surface of the airfoil, at low angles of attack, gets closer to the leading edge. As a result of this, larger part of airfoil surface will be exposed to the turbulent flow. However, at high angle of attack the ground proximity moves the transition point towards the trailing edge and the turbulent boundary layer will decrease. At the lower surface of the airfoil, when approaching the ground surface, the transition point approaches the trailing edge.

In figures 13 and 14, velocity distributions at upper as well as lower surface of the airfoil NACA 0012 at angles of attack of 3 and 9 degrees have been presented for various flight distances from the ground. Observation of these figures indicates that the difference in velocities on the upper surface of the airfoil is not significant, as the airfoil approaches the ground surface. Upon careful consideration of Eq. 11, one can justify the variation of the location of transition point and reach the conclusion that the transition point depends on two factors: 1) Reynolds number based on momentum thickness ($Re_{\theta_{ss}}$) and 2) Local Reynolds number based on distance from the stagnation point (Re_s). Definitions of these Reynolds numbers indicate that the values of $(U_{se}.\theta_{ss})$ and $(s.U_{se})$ play important roles in determination of the location of transition phenomenon. However, since the velocity distribution on the upper surface of the airfoil does not vary considerably with flight distances from the ground, the only factor that remains to be effective on the location of the transition point is the momentum thickness (θ_{ss}). Figures 15 and 16 illustrate the momentum thickness over the airfoil NACA 0012 at two angles of attack for several flight altitudes. In each of these figures, the location of the transition point on the upper surface of the airfoil has been captured and denoted by an ellipse. It is clear that the momentum thickness in the elliptic zone has significantly larger variation near the ground surface compared to higher flight altitudes. Accordingly, with any change in Reynolds number associated with the momentum thickness, i.e. $Re_{\theta_{ss}}$, the location of the transition point changes as such that an increase in momentum thickness causes the transition point to move closer to the leading edge of the airfoil.

On the other hand, at the lower surface of the airfoil, the location of transition point is seen to depend only on velocity distribution and, as shown in figures 14 and 15, is not affected by the momentum thickness.

In table 3, the starting point of separation at the upper surface of the airfoil is presented at different flight distances from the ground. Based on these results, with a decrease in flight distance from the ground, a larger portion of the airfoil will be under the separated flow. This is so, because at surface proximity, the Reynolds number based on the

momentum thickness over the airfoil surface increases which will indicate a decrease in fluid momentum. A decline in fluid momentum accelerates the separation phenomenon, albeit this doesn't happen at low angles of attack.

Table 3- Location of the starting point of separation phenomenon at the upper surface of airfoil NACA 0012 (quantities are non-dimensional w.r.t. the chord length of airfoil).

H/C \ AOA	Re=2570000				Re=3430000			
	0.1	0.5	1	∞	0.1	0.5	1	∞
0	1	1	1	1	1	1	1	1
3	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
6	0.997	0.997	0.997	0.998	0.997	0.997	0.998	0.998
9	0.986	0.99	0.992	0.992	0.986	0.992	0.992	0.994
12	0.942	0.962	0.967	0.968	0.929	0.968	0.973	0.973

Fig.13. Velocity distribution on the surface of airfoil NACA 0012 at $\alpha = 3^\circ$, $Re = 3,430,000$, and different flight distances from ground.

Fig.14. Velocity distribution on the surface of airfoil NACA 0012 at $\alpha = 9^\circ$, $Re = 3,430,000$, and different flight distances from ground.

Fig.15. Momentum thickness distribution on the surface of airfoil NACA 0012 at $\alpha = 3^\circ$, $Re = 3,430,000$, and different flight distances from ground.

Fig.16. Momentum thickness distribution on the surface of airfoil NACA 0012 at $\alpha = 9^\circ$,
and different flight distances from ground. $Re = 3,430,000$,

Generally speaking, an increase in the surface of separated flow causes the drag to increase and the lift force to drop. Therefore, in order to benefit from the ground effect phenomenon, it is more suitable that the airfoil angle of attack be low.

Analysis of the effect of Reynolds number on aerodynamic coefficients of the airfoil is presented in figures 17 and 18. As evidenced in these graphs, change in Reynolds number does not affect the lift coefficient considerably while an increase in Reynolds number would bring about a decrease in drag coefficient.

Fig.17. Effect of Reynolds number on the lift coefficient at different flight distances from ground (angle of attack is 8 degrees).

Fig.18. Effect of Reynolds number on the drag coefficient at different flight distances from ground (angle of attack is 8 degrees).

3.2. Effect of maximum thickness

Another parameter which has been considered in this paper is the airfoil thickness. In 4 digits NACA airfoil (i.e. NACA 4-DIGIT), the two digits on the right indicate the ratio of maximum thickness to the chord length of the airfoil (i.e. t/c). Four symmetric airfoils with thickness percentages of 9, 12, 15, and 18 are considered for computational purpose.

In table 4, location of the transition from laminar regime to turbulent regime at the upper surface of the airfoil is categorized based on the airfoil thickness. These quantities have been computed at three angles of attack and four flight altitudes, and the Reynolds number of the flow is 34.3×10^5 .

Table 4- Location of the occurrence of transition phenomenon at the upper surface of the airfoil based on the airfoil thickness at $Re=34.3 \times 10^5$ (quantities are shown as a percentage of the chord length of airfoil).

AOA	t/c	H/C			
		0.1	0.5	1	∞
6.00	9	0.037	0.037	0.038	0.039
	12	0.112	0.066	0.066	0.066
	15	0.127	0.09	0.101	0.100
	18	0.182	0.134	0.147	0.128
9.00	9	0.037	0.037	0.038	0.039
	12	.064	0.064	0.066	0.067
	15	0.098	0.106	0.112	0.110
	18	0.137	0.16	0.165	0.160
12.00	9	0.058	0.052	0.052	0.052
	12	0.068	0.068	0.069	0.063
	15	0.109	0.093	0.093	0.09
	18	0.131	0.13	0.126	0.147

In table 5, location of the transition point at the lower surface is non-dimensionally presented as (x/c) , where c is the chord length of airfoil. In this table, the presented data is also categorized based on different airfoil thicknesses at one angle of attack with various flight distances from ground. The corresponding Reynolds number of the flow is 34.3×10^5 .

By studying tables 4 and 5, we can state that with an increase in airfoil thickness, the length of turbulent regime over upper surface of the airfoil decreases and the transition point moves toward the trailing edge. In the meantime, at the lower surface of the airfoil, the length of turbulent regime of the boundary layer will increase and the transition point will tend toward the leading edge.

Table 5- Location of the occurrence of transition phenomenon at the lower surface of the airfoil based on the airfoil thickness at $Re=34.3 \times 10^5$ (quantities are shown as a percentage of the chord length of airfoil).

AOA	t/c	H/C			
		0.1	0.5	1	∞
6.00	9	0.976	0.901	0.903	0.88
	12	0.91	0.872	0.848	0.825
	15	0.7	0.787	0.757	0.734
	18	0.592	0.711	0.679	0.663
9.00	9	0.978	0.972	0.957	0.941
	12	0.976	0.939	0.913	0.901
	15	0.937	0.889	0.866	0.859
	18	0.844	0.841	0.825	0.809
12.00	9	0.956	0.962	0.96	0.96
	12	0.936	0.955	0.952	0.952
	15	0.935	0.923	0.930	0.899
	18	0.932	0.896	0.871	0.855

The starting points of the separation in turbulent boundary layer are given in table 6, in terms of airfoil thickness. Data provided in this table corresponds to the Reynolds number 34.3×10^5 . Considering these results, we can state that, an increase in airfoil thickness causes the separation point to move toward the leading edge. This implies that the surface of separated flow expands and causes the drag to increase.

Table 6- Location of the occurrence of separation phenomenon at the upper surface of the airfoil based on the airfoil thickness at $Re=34.3 \times 10^5$ (quantities are shown as a percentage of the chord length of airfoil).

AOA	t/c	H/C			
		0.1	0.5	1	∞
6.00	9	1	1	1	1
	12	0.997	0.997	0.998	0.998
	15	0.994	0.994	0.996	0.995
	18	0.987	0.987	0.99	0.991
9.00	9	0.992	0.997	0.997	0.997
	12	0.986	0.992	0.992	0.994
	15	0.973	0.983	0.987	0.986
	18	0.953	0.967	0.968	0.973
12.00	9	0.956	0.934	0.986	0.99
	12	0.929	0.968	0.973	0.973
	15	0.91	0.945	0.953	0.956
	18	0.877	0.919	0.93	0.937

In order to study the effect of thickness on aerodynamic properties, plots of lift and drag forces at angles of attack 3 and 6 degrees and Reynolds number 34.3×10^5 are shown in figures 19 and 20. Lift force of the airfoil increases as thickness increases, but

at ground proximity, an increase in thickness causes a drop in lift. However, drag force increases as thickness increases.

Fig.19. lift coefficient based on the airfoil thickness at different flight distances from ground.

Fig.20. drag coefficient based on the airfoil thickness at different flight distances from ground.

Based on the analysis performed, it seems like the shape of geometry as well as operation conditions such as angle of attack, altitude from ground surface, and the velocity of airfoil motion can have profound effect on the motion near the ground. Considering all the cases analyzed in this article, we can indicate that, it is more suitable that airfoils with minimum thickness be used at low angle of attack for motion near the ground surface.

4. Conclusion

This paper has focused mainly on the effects of altitude from ground surface and the thickness of the airfoils moving near the ground, on the characteristics of the airfoil boundary layer. Topics analyzed, as properties of the boundary layer, included the location of the inception of transition phenomenon, the phenomenon of flow separation, and the boundary layer thickness.

Characteristics of boundary layer around the airfoil depend on the flow velocity. Decreasing the altitude and approaching the ground surface will be the cause of some changes in velocity distribution around the airfoil. Therefore, motion at ground proximity strongly affects the boundary layer characteristics. This topic has been the main subject of study in the current paper. In this work, by investigating the changes of boundary layer characteristics, behavior of lift and drag forces and thus the performance of the airfoil near the ground are predicted and justified.

The effects of the discussed parameters in this article on the characteristics of the boundary layer and the aerodynamic properties of the airfoil are summarized in table 7. In first column of this table, boundary layer characteristics (transition phenomenon, location of separation, boundary layer thickness) and aerodynamic properties (lift and drag) are listed. These properties were found to be functions of the four parameters of increasing Reynolds number, increasing angle of attack, decreasing flight distance from ground, and increasing thickness of airfoil, which are listed in columns two thru five, respectively.

Table 7- Effects of various parameters on boundary layer characteristics and aerodynamic properties of the airfoil near the ground surface.

Parameters/boundary layer characteristics	Increasing Reynolds number	Increasing angle of attack	Decreasing flight distance from ground	Increase in thickness of airfoil
Location of inception of the transition phenomenon	moves toward the leading edge and the length of turbulent flow increases.	toward the leading edge at the upper surface of the airfoil, but approaches the trailing edge at the lower surface.	approaches the leading edge at the upper surface of the airfoil, and departs from the leading edge at the lower surface.	approaches the trailing edge at the upper surface of the airfoil, and approaches the leading edge at the lower surface.
Location of occurrence of separation point at the airfoil Upper	Occurrence of this phenomenon is delayed and	approaches the leading edge.	approaches toward the leading edge.	approaches the leading edge and larger surface

surface	separation moves to toward the trailing edge.			experiences this phenomenon.
Thickness of boundary layer	decreases.	increases at the upper surface while decreases at the lower surface.	decreases even with a small change.	
Lift coefficient	does not change substantially.	increases linearly up to stalling angle	increases.	Generally increases
Drag coefficient	decreases.	increases nonlinearly.	decreases.	increases(in low angle of attack) and decreases(in high angle of attack).

These results have been achieved by examining a wide range of Reynolds numbers, angles of attack, flight distances from ground, and airfoil thicknesses. In this table, the general behavior of boundary layer characteristics and aerodynamic properties under the influence of the mentioned parameters are presented. In some cases, it is possible that there are considerable behavioral differences. For instance, for symmetric airfoils at very low flight altitude, in the event the angle of attack is low, the lift force decreases while drag increases. In this situation, a decrease in thickness of the airfoil causes a decrease in the lift. The reason for this is the establishment of a converging-diverging passage at the airfoil lower surface. Among other important observations, would be the case of large angle of attack in which case, when approaching the ground surface, the transition phenomenon moves near the trailing edge.

Having considered all the findings in this work, it is fair to conclude that, approaching the ground surface would cause the local Reynolds number at the surface of the airfoil to drop, which in turn causes the occurrence of the transition phenomenon to be delayed, increase in momentum thickness would cause the flow separation to be accelerated, and the thickness of the boundary layer to be increased. Consequently, lift was shown to have no significant alteration, while drag affected considerably, showed a tendency to increase. Readers are reminded again that the results presented in this paper are only related to the case of symmetric airfoils.

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