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Aerodynamic Performance Assessment of various NACA Airfoils on a Low Aspect Ratio Wing-in-Ground-Effect (WIGE)

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Abstract

The “ground-effect” is a phenomenon that occurs while aerial vehicles perform flights close to the ground. In case of wing-in-ground-effect (WIGE) aircraft, flight completely consist of operations subjecting to the ground-effect and require special aerodynamic considerations during the design of the vehicle. WIGE aircraft practically bases on the idea of benefiting this effect, therefore the wing, and correspondingly airfoil is the most important geometry to be precisely designed or selected from the beginning of the conceptual design. The objective of this study is to obtain, assess and compare the aerodynamic characteristics of various NACA airfoils in ground-effect with a conceptual design perspective. To this end, a low aspect ratio wing (*AR*=1.5) was selected as the baseline model and aerodynamic investigation of the design carried out using a Vortex Lattice Method (VLM) solver, comparing and validating with experimental wind tunnel data at Reynold number of $3.4x10^5$. A gird independence study was also carried out to ensure the results were independent from number of panel elements. Subsequently, the airfoils that have been previously known to be used on aerial vehicles (NACA 6409, NACA 4412, NACA 23015, NACA 63-415 and NACA 65(2)-215) were applied on the same wing model and analyzed at various ground clearances (*h/c*) employing the same numerical methodology. The aerodynamic performances of the airfoils were compared in terms of their lift coefficient, drag coefficient and lift-to-drag ratio characteristics.

Keywords: Aerodynamics, NACA, Airfoil, Low aspect ratio, Wing, Ground effect.

1. Introduction

Aerial vehicles have subject to the aerodynamic phenomenon known as the “ground effect” when operating close to the ground at flight phases such as take-off and landing [1]. The effect is mainly based on limitation of vertical movement of the air by ground, resulting in a more favorable pressure gradient around the wing, providing an increase in lift with a reduction in drag, consequently an improved lift-to-drag ratio (*L/D*) during flight.

In case of fixed-wing aerial vehicles, some specific designs, known as wing-in-ground-effect (WIGE) aircraft, are specifically designed to take the advantage of this phenomenon by flying at an altitude close to the ground, and have superior flight performance in terms of range or endurance [2, 3]. In the history, the first attempts on WIGE aircraft design dates back to 1930s while the most popular Russian Ekranoplans and the German Lippisch X114 craft were started to develop at the beginning of 1960s [4]. These vehicles have a distinctive appearance than conventional aircraft with their small aspect ratio wings, endplates, large tail area and special landing gears, as an up-to-date example presented in Figure 1.

Figure 1. The AirFish 8 WIGE aircraft [5].

The WIGE aircraft perform their flight completely in ground-effect, except for obstacle avoidance, and necessitates designers to consider special issues, different than conventional concepts. From the aerodynamic point of view, performance of these vehicles extremely depends on wing geometries, airfoil geometries and the ground clearance (*h/c*), which is the ratio between the flight altitude (*h*) and the chord length of the wing (*c*). These variables should be designed or selected precisely to obtain optimal benefit from ground-effect. Previous studies shown that the most efficient ground clearance value in flight vary between 0.1 to 0.5 [6].

The airfoils are two-dimensional section geometries, which are strongly determinative on aerodynamic characteristics of the wing. The shape of the airfoils specifically designed for ground-effect commonly thicker, has flat or slightly concave lower surface, and maximum camber is located close to the leading edge. For designers, during the airfoil selection process, it is important that the profile has aerodynamic performance that meet the design requirements. In most cases, designers select among the existing airfoils rather than effort for developing a new one. The unitless aerodynamic coefficients of airfoils are useful metrics for comparing their performances. The low-fidelity computational methods come to the fore particularly in conceptual design phase to obtain such data fast and adequate accuracy. In preliminary design phase, this could be extended to more advanced tools such as Computational Fluid Dynamics (CFD). In the literature, there are various studies using computational methods for aerodynamic investigation of airfoils (in 2-dimension) or wings (in 3-dimension) in ground effect. For instance, Mohammadhossein Nirooei [7] focused on both aerodynamic and stability characteristics of the original and a modified version of NACA 4412 airfoil with S-shaped camber in case of extreme ground effect. The aerodynamic analyses of the airfoils were performed using a Reynolds-averaged Navier–Stokes (RANS) solver, and concluded that the modified design has a smaller effective angle of attack, while being more height stable. Gao et al. [8] investigated transonic RAE2822 airfoil at various ground clearances from 0.5 to 0.8 Mach number airspeed using CFD with a commercial RANS solver. The study shown the existence of a steady shock on the lower surface of the airfoil in ground effect for low angles of attack and a new coupling between the shock buffets on the lower and the upper surface of the airfoil was observed. The tandem configuration NACA 0012 airfoils were numerically investigated in ground effect by Yin et al. [9] at ultra-low Reynolds numbers (10^2-10^3) in a perspective of pico-aerial vehicles (PAVs). The configuration found to be aerodynamically more efficient than isolated airfoils especially when the fore airfoil is higher than the aft airfoil. Mongkol Thianwiboon [10] compared aerodynamic characteristics and center of pressure movement of three airfoils (NACA 6409, NACA 4412 and Clark-Y) at ground clearances varying from 0.05 to 1 at 3×10^6 Reynolds number. The CFD analyses using SST *k-ω* turbulence model involved wide range of angles of attack in ground-effect. Hu et al. [11] studied on NACA 4412 wings with various aspect ratios to investigate the aerodynamic and longitudinal stability effects of wingspan on ground-effect using CFD method at the ground-clearances between 0.05 to 0.3. They obtained that the increased wing span leads lift coefficient to become more sensitive to pitch angle and altitude, and increased downwash angle. In another study, Ye Wang [12] proposed anti-S airfoil named NACAM27 and compared performance with well-known airfoil NACA 4412 using STAR-CCM+ CFD software. The study also considered geostatic stability of the airfoils and shown that the proposed airfoil has higher lift-to-drag ratio and the static stability margin was simply predictable.

The literature survey shown that there are numerous studies covering the numerical or experimental aerodynamic investigation of various NACA airfoils in the presence of ground effect. Nonetheless, the majority of studies have been concerned with the evaluation of only a particular airfoil or with a comparison with an another. In the context of conceptual aircraft design, usually a more comprehensive comparison among a high number of candidates is necessitated for designers within the specific design requirements. In this regard, the objective of this study is to make a comparison on a number of NACA airfoils applied on a low-aspect ratio WIGE wing, with a conceptual design perspective in terms of ground clearance and angles of attack, and contribute to the existing literature by providing a useful, practical and accessible data set for aircraft designers to benefit. The aerodynamic investigations of airfoils were carried out using a Vortex Lattice Method (VLM) solver on a low aspect ratio (*AR*=1.5) wing, which is the typical value for a WIGE aircraft. The computational methodology compared and validated on a NACA6409 model at a Reynolds number of 3.4×10^5 with experimental wind tunnel data, and a grid independence analysis was conducted. Later on, the selected airfoils (NACA 4412, NACA 23015, NACA 63-415 and NACA 65(2)-215) applied and investigated on the same wing design to be compared in terms of lift-to-drag ratio, minimum drag coefficient and lift curve slope.

2. Material and Numerical Method

2.1. Airfoil Geometries and Wing Design

The NACA airfoils to be investigated have been selected as NACA 6409, NACA 4412, NACA 23015, NACA 63-415 and NACA 65(2)-215 relying on historical trends used on aerial vehicles in the literature, and illustrated in Figure 2. The selection criteria for these airfoils are principally based on mainly their geometrical characteristics such as thickness and camber, in addition to the historical prevalence in existing aerial vehicles. For instance, with the exception of the validation case airfoil NACA 6409, the airfoils selected are thicker that generate stronger pressure gradients that is useful to interact more with the ground. Furthermore, thicker

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airfoils also delay flow separation and serve as structural support for wings. In terms of camber, the selected airfoils have moderate level that is desirable for high lift potential and preventing extreme nose-down pitching moment tendency. Prementioned geometrical properties of these airfoils make them come to the fore as a candidate airfoil applied in WIGE aircraft designs.

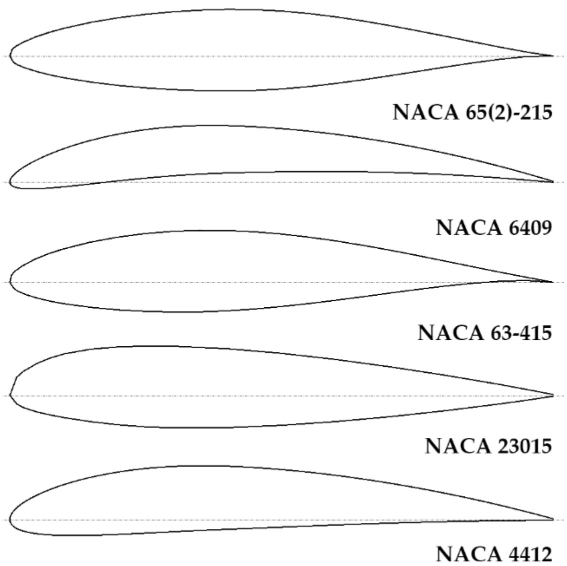
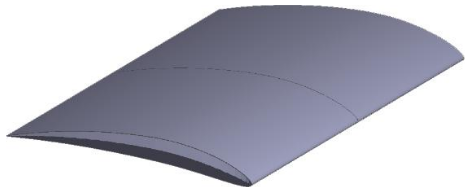
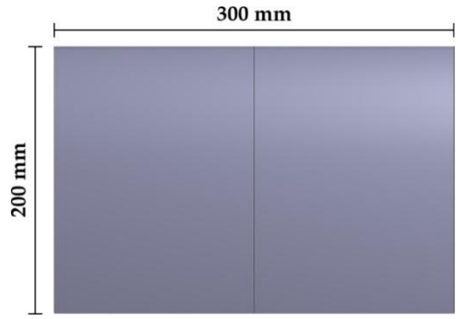


Figure 2. The selected NACA airfoil geometries with neutral lines dashed.

NACA 65(2)-215, NACA 63-415 and NACA 23015 were the thickest geometries among the selected airfoils with a maximum thickness value of 15% of their chord lengths, while the maximum cambered airfoil was NACA 4412 with a maximum camber value of 40% of its chord length.
In aircraft conceptual design, low-fidelity tools come to the fore in obtaining fast and reasonably accurate results in predicting aerodynamic performance parameters. In this context, XFLR5 is a useful public licensed software capable of performing aerodynamic analysis using both Vortex Lattice Method (VLM), 3D Panel Method (PM) or Lifting Line Theory (LLT) on three-dimensional wing geometries [13]. The software is also capable of simulating flows in-ground-effect (IGE) using mirror image method and modeling the influence of the proximity to the surface on the aerodynamic performance by placing an inverted duplicate of the lifting surface beneath the ground plane.
In a previous study, the wind tunnel experiments of a low-aspect-ratio (*AR*=1.5) NACA 6409 wing geometry was performed in ground-effect by Jung et al. [14]. In order to validate and ensure the accuracy of the numerical methodology to be used in this article, the similar wing model was designed on XFLR5 software, as illustrated in Figure 3.



(a)



(b)

Figure 3. The wing model and its dimensions; a) isometric-view b) top-view.

2.2. Vortex Lattice Method

The Vortex Lattice Method (VLM) is a panel-based linear potential flow modeling methodology assuming the flow incompressible, irrotational, and inviscid [15]. However, the viscous variables could be optionally interpolated from lift coefficients obtained previously for airfoil geometries.
The method constructs a grid consisting of quadrilateral panels on the wing geometry, where a bound vortex filament allocated along each panel's quarter chord line. In principle, the VLM considers the perturbation generated by the wing as a sum of vortices disturbed over the wing planform grids. Correspondingly, the strength of each vortex is calculated to meet proper boundary conditions. The lift force acting on each panel could be defined as given in Equation 2.1, where Γ is vortex strength times its length, ρ is the air density and V is the airspeed.

$$F = \rho V \times \Gamma \quad \textbf{(2.1)}$$

The lift coefficient could be obtained from Equation 2.2, where S is the planform area, F_{wz} is the projection on the vertical wind axis.

$$C_L = \frac{1}{\rho S V^2} \sum_{panels} F_{wz} \quad \textbf{(2.2)}$$

From drag force and coefficient point of view, XFLR5 estimates induced drag using the downwash generated by the vortex system for obtaining the induced angle of attack. The total drag estimation necessitates combining this output with two-dimensional aerodynamic data from airfoil analysis.

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In case of ground effect, VLM employs the theoretical methodology known as "mirror image" for modelling a solid boundary like the ground altering the flow field around a wing or lifting body. A mirror image of the wing is located beneath the ground plane at a distance equivalent to the actual wing with its orientation mirrored. This facilitates the modelling of the effect of ground on the airflow without an explicit solid surface definition.

2.2.1. Grid Independence Analysis

In VLM analysis, the number of panels on a wing geometry should be precisely determined to ensure that the results are independent from the quantity, similar with finite element methods. To this end, the NACA 6409 wing geometry was analyzed at 0° angle of attack, Reynolds number of 3.4×10^5, at an altitude referring to ground clearance (*h/c*) of 0.15 and using sea-level conditions with the number of panels varying from 200 to 12800.

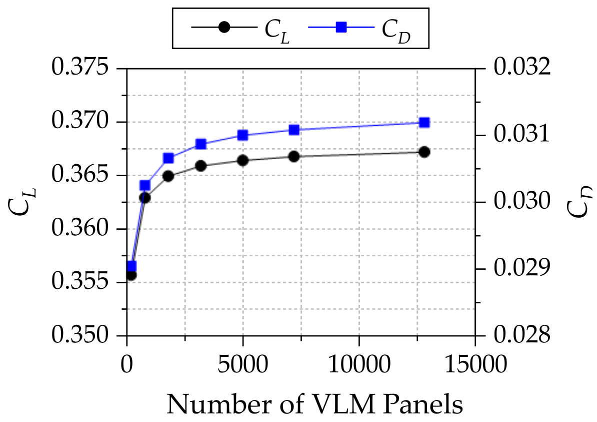

Figure 4. Grid independence results for lift and drag coefficients for NACA 6409 wing model.

The results for lift and drag coefficients were presented in Figure 4, which indicates that approximately 4000 panels are adequate to obtain results with a reasonable accuracy for further analyses. The VLM model with adequate number of panel elements illustrated in Figure 5.

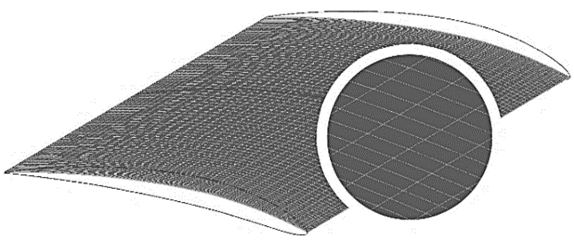

Figure 5. The VLM model and closer view of the NACA 6409 wing model surface with 4050 panel elements.

2.2.2. Method Validation

The VLM analyses of generated NACA 6409 wing model was carried out for ground-clearances of 0.025, 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3 to validate the accuracy of the methodology comparing with previously mentioned wind tunnel experiments by Jung et al. [14]. Analyses were performed at 0° angle of attack, Reynolds number of 3.4×10^5 similar with grid independence analyses and results were presented in Figure 6. A comparison for the same wing at 0 to 8 *degrees* angle of attack for specifically *h/c*=0.2 could be achieved from another validation study by the author [16].

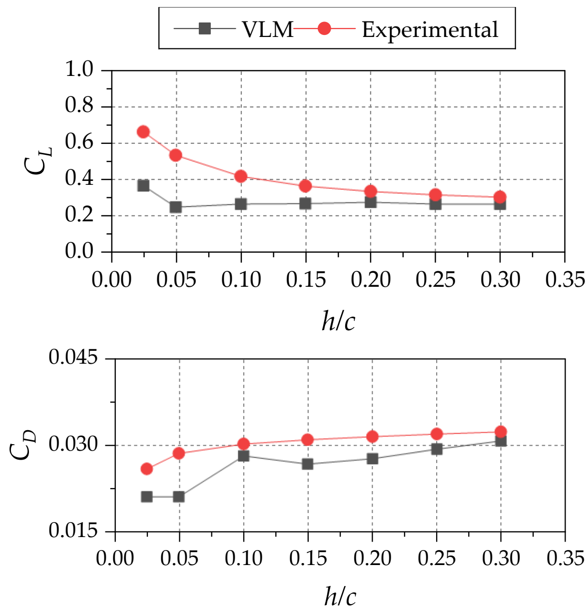

Figure 6. Numerical (VLM) and experimental results for lift and drag coefficients of NACA 6409 wing model varying with ground clearance at 0° angle of attack.

The results shown that the experimental and numerical analyses were in the similar tendency with variation in ground clearance, while the VLM incapable of modeling extreme ground-effect conditions especially in terms of lift characteristics. The reason behind this incapability can be attributed to the utilization of the mirror image methodology, which becomes less accurate at low ground clearances. The closer distance of the wing to the ground results in growing ground boundary layer and interaction with the main wing's flow field. Furthermore, the viscous effects become dominant, adverse pressure gradients and local separations are potentially arise, which VLM is not able to successfully model. The lift and drag predictions were acceptable for a conceptual design perspective especially up to *h/c*=0.15, while lower ground clearances necessitate more precise analyses using advanced tools such as CFD. In CFD methodology, the ground is modelled as a wall boundary and the limitations in VLM is disappeared. Furthermore, the employment of sophisticated mathematical approaches such as Navier-

Stokes equations coupled with turbulence models are able to physically model the flow realistically even at extreme ground effect conditions. Therefore, this study has been focusing on discussions regarding with ground clearances higher than 0.15. The visual results of streamlines at various ground clearances were illustrated in Figure 7, including the out-of-ground-effect flight. The constraining effect of ground, the change in the wingtip vortices with ground clearance and reduced downwash angle are clearly visible. The findings demonstrate that the employed numerical method have generated results in close proximity to the experimental data, with an adequate accuracy for such a comparative conceptual study.

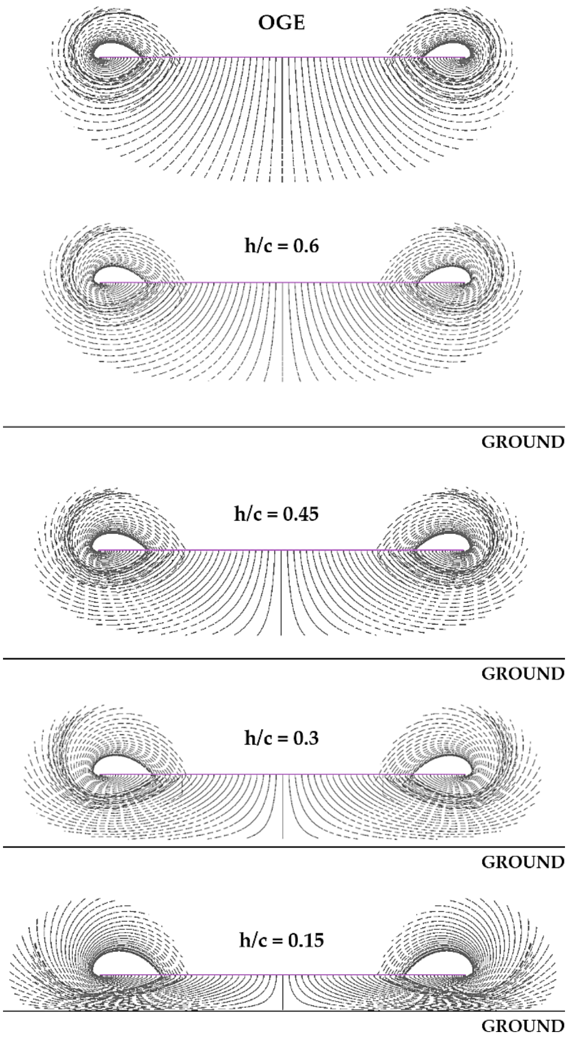

Figure 7. Front view of the streamlines flowing over NACA 6409 wing model at various ground clearances and out-of-ground-effect (OGE).

3. Results and Discussion

The selected airfoils were analyzed using the validated VLM methodology at 3.4x10^5 Reynolds number, a wide range of angles of attack from -5 to 20 *degrees* and at various ground clearances including OGE. The lift coefficients at 0° angle of attack, lift-curve slope values, minimum drag coefficients, lift-to-drag ratio values at 0° angle of attack and maximum lift-to-drag ratios and related angles of attack for OGE and *h/c*=0.15 were presented in Table 1, Table 2, Table 3, Table 4 and Table 5 respectively. Lift and drag coefficients at various ground clearances were presented in Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12 for wing models with NACA 6409, NACA 23015, NACA 4412, NACA 63-415 and NACA 65(2)-215 airfoils, respectively. The results for NACA 4412 and NACA 6409 shown a great agreement with the up-to-date studies in the literature [17,18].

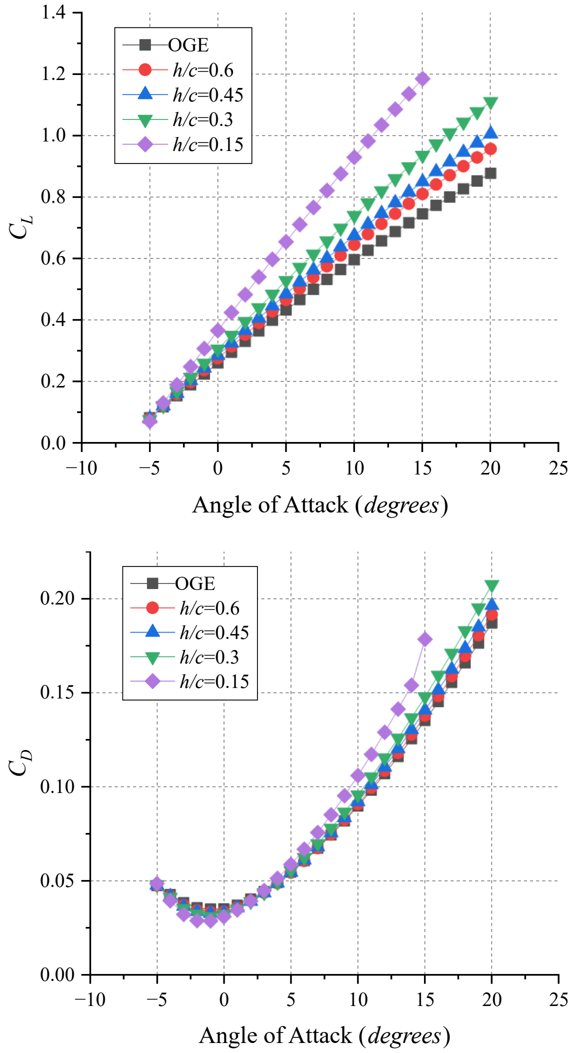

Figure 8. Lift and drag coefficients of NACA 6409 wing model at various ground clearances

From the lift coefficient point of view, at 0° angle of attack, all of the wing models were increased with lower values of ground clearance. Besides this favorable tendency, the NACA23015 wing model has demonstrated an extreme increase almost twice that of the others, as given in Table 1. The dramatical lift increment with respect to ground clearance variation in

NACA23015 may be considered originated from the rearward camber, which has maximum camber of 1.8% located at 15% chord among all other airfoils investigated.

The lift-curve slopes of wings with all airfoil sections were clearly found to be increased regarding to decreasing ground clearance, which was due to the increased effective angle of attack and reduced wingtip vortices. However, as demonstrated in Table 2, NACA 23015 and NACA 65(2)-215 wings were found to be more sensitive to altitude alteration in ground effect and exhibit steeper increments in comparison to other models. This could be a beneficial characteristic during the conceptual design of a WIGE aircraft, due to the fact that providing opportunities to designer on various amount of twist and angle of incidence applications to the wing. Furthermore, it could be useful for obstacle avoidance capabilities that is an important issue for such aerial vehicles.

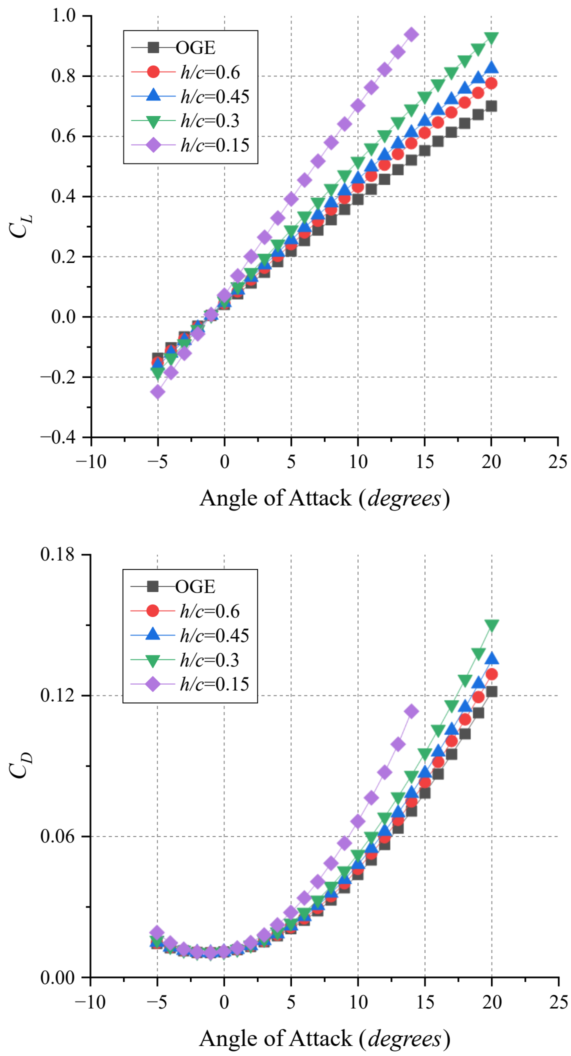

Figure 9. Lift and drag coefficients of NACA 23015 wing model at various ground clearances

Table 1. Lift coefficient results at 0° angle of attack for OGE and h/c=0.15.

Airfoil	OGE	h/c=0.15	diff.
NACA 6409	0.2601	0.3661	40.72%
NACA 23015	0.0421	0.0735	74.39%
NACA 4412	0.1741	0.2543	46.00%
NACA 63-415	0.1349	0.1936	43.56%
NACA 65(2)-215	0.0677	0.0998	47.32%

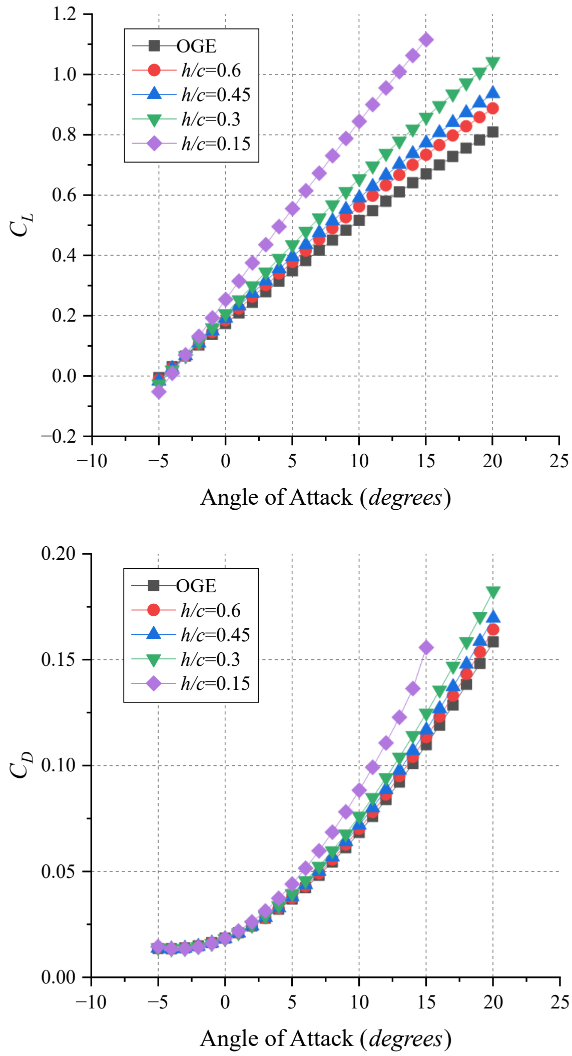

Figure 10. Lift and drag coefficients of NACA 4412 wing model at various ground clearances

The lift-curve slope has a significant effect on stability and control issues of the aerial vehicles. For instance, the increment in the slope improves roll damping and lateral control power in lateral stability perspective [19]. Static stability point of view, the increased slope results in aerodynamic center of the wing to generate larger moments, and, the tail required to provide a higher stabilizing moment. This could be possible by a larger tail or higher tail arm distance that leads to longer aerial vehicle. Control point of view, the higher the lift-curve slope, higher the effectiveness of the control surfaces and vehicle becomes sensitive to control inputs from pilot.

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The drag coefficient variations of all wing models were become steeper with the decreased ground clearance, especially effecting the values at higher angles of attack. From the minimum drag coefficient point of view, a noteworthy decrease was observed only for the NACA 6409 wing model, while others almost remained constant. This was an expected tendency in accordance with the experimental data and previous studies in the literature [8, 9] . In vast majority of the airfoils, a notable drag reduction could be obtained at the extreme ground effect region (i.e. *h/c* lower than 0.1), which is out of the scope of this study.

Table 2. Lift curve slope results (*1/deg*) for OGE and *h/c*=0.15.

Airfoil	OGE	*h/c*=0.15	diff.
NACA 6409	0.0336	0.0563	67.72%
NACA 23015	0.0348	0.0628	80.17%
NACA 4412	0.0341	0.0589	72.49%
NACA 63-415	0.0343	0.0607	76.60%
NACA 65(2)-215	0.0347	0.0629	81.16%

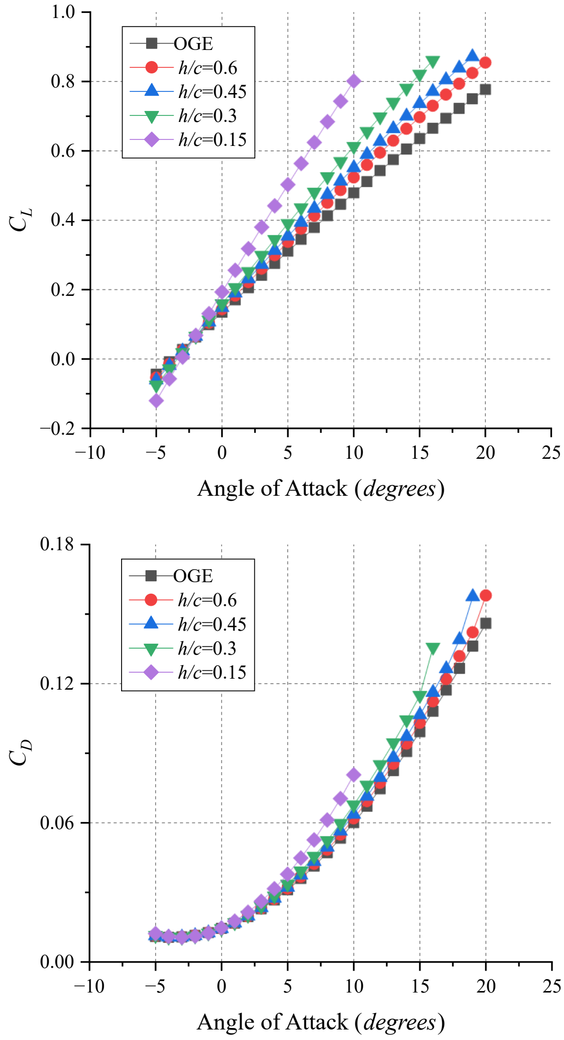

Figure 11. Lift and drag coefficients of NACA 63-415 wing model at various ground clearances

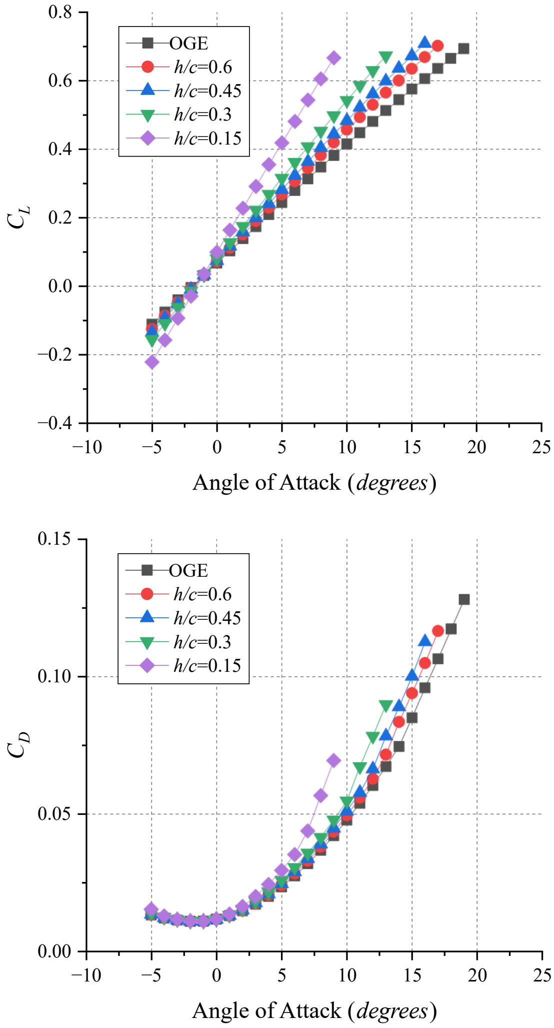

Figure 12. Lift and drag coefficients of NACA 65(2)-215 wing model at various ground clearances

Table 3. Minimum drag coefficient results for OGE and *h/c*=0.15.

Airfoil	OGE	*h/c*=0.15	diff. %
NACA 6409	0.035007	0.028697	-18.02
NACA 23015	0.010633	0.010633	0.00
NACA 4412	0.013577	0.013567	-0.07
NACA 63-415	0.010707	0.010719	0.11
NACA 65(2)-215	0.011028	0.01104	0.1

While all the wing models exhibited substantial improvement in lift-to-drag ratio at 0° angle of attack, the NACA 6409 and NACA 23015 models exhibited a significantly enhancement by 60.17% and 71.19%, respectively, as demonstrated in Table 4.
Furthermore, it is evident that the maximum lift-to-drag ratios of the models are highly comparable, with the exception of NACA 6409, which exhibits a lower ratio, as given in Table 5. The increments with respect to the ground clearance alteration were found to be similar for all models, where the NACA 6409 has slightly steeper tendency.

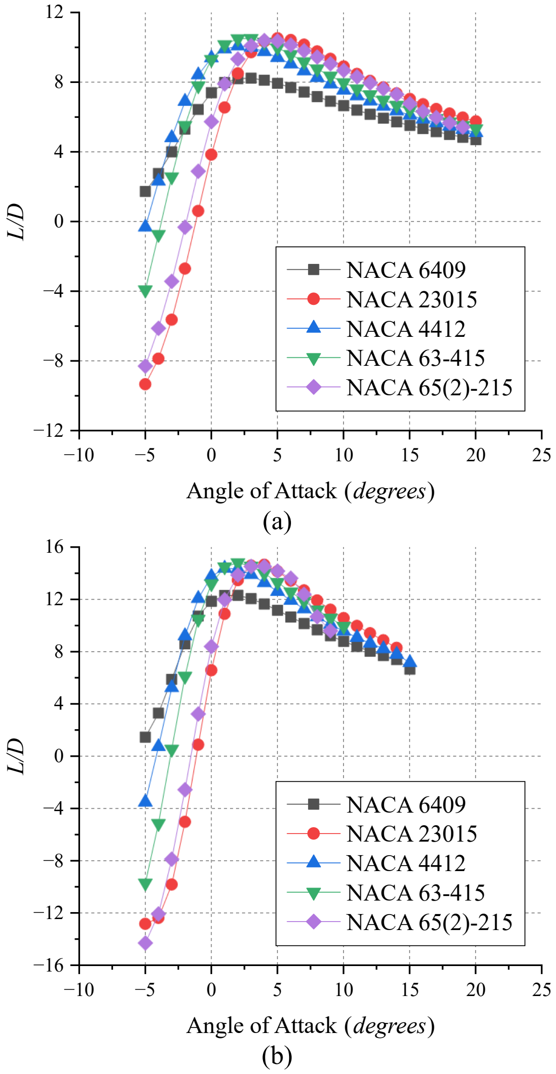

Figure 13. Lift-to-drag ratio of airfoils at; a) OGE, b) *h/c*=0.15.

Table 4. Lift-to-drag ratio results at 0° angle of attack for OGE and *h/c*=0.15.

Airfoil	OGE	*h/c*=0.15	diff.
NACA 6409	7.38	11.83	60.17%
NACA 23015	3.83	6.56	71.19%
NACA 4412	9.38	13.73	46.33%
NACA 63-415	9.30	13.18	41.66%
NACA 65(2)-215	5.73	8.38	46.23%

Table 5. Maximum lift-to-drag ratio and related angle of attack for OGE and *h/c*=0.15.

Airfoil	OGE	*h/c*=0.15
NACA 6409	8.22 (3°)	12.28 (2°)
NACA 23015	10.51 (5°)	14.62 (4°)
NACA 4412	10.06 (2°)	14.36 (1°)
NACA 63-415	10.49 (3°)	14.78 (2°)
NACA 65(2)-215	10.38 (4°)	14.49 (4°)

As demonstrated in Figure 13, it is clear that there is a steeper change in the lift-to-drag ratio with variation in angle of attack at lower ground clearances. This results in a narrow angle of attack region where peak values are achieved. The lowest angle of attack for the maximum lift-to-drag ratio was provided by the NACA 4412 and NACA 63-415 models, which are desirable for WIGE aircraft designs. The lift-to-drag ratio is directly proportional to range and endurance, which are the main flight performance parameters for an aerial vehicle. The dramatical decrement in lift-to-drag ratio indicates NACA 23015 and NACA 6409 airfoils to be not suitable for OGE flights. These airfoils shown a characteristic mainly proper for permanent IGE flights to have high range or endurance. Other airfoils had shown similar tendency with each other with a moderate variation; therefore, they were found to be more suitable for operations including both IGE and OGE flights.

4. Conclusion

The present study was aimed to provide an extension to the existing data in the literature concerning the aerodynamic characteristics of airfoils in ground-effect for aircraft conceptual design purposes. Accordingly, aerodynamic performances of various NACA airfoils were assessed on a low aspect ratio wing-in-ground-effect using VLM. The numerical methodology was initially validated on the basis of the experimental data for the wing model with NACA 6409 airfoil and the further analyses carried out using NACA 4412, NACA 23015, NACA 63-415 and NACA 65(2)-215 airfoils on the same wing model to be compared. Methodologically, the study shown that the VLM is a valuable and accurate tool for aircraft conceptual design purposes even in case of ground-effect, except for the extreme-ground-effect that proved unable to be simulated correctly especially in terms of lift coefficient. The results of the analyses demonstrated the alterations in lift and drag characteristics of each model compared with out-of-ground-effect, and flights at various ground clearances, which has a key role on stability and control issues during an aircraft design.

Ethics

There are no ethical issues after the publication of this manuscript.

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