Ground proximity effect on the flow over NACA 4412 multi-element airfoil in clean configuration

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Abstract. The paper presents the influence of ground distance on aerodynamic characteristics of the flow over NACA 4412 multi-element airfoil in clean configuration. The angle of deflection was kept constant throughout the computations. Finite volume method was used for the grid generation and the numerical calculation. Further investigation suggests the best range of angle of attack where the aerodynamic performance of the airfoil increases in the presence of ground. Furthermore, the condition of flow separation jeopardizing the airfoil performance appeared. It was found that at certain range of angle of attack, the cushion of high pressure at the pressure side of the airfoil is insufficient to compensate the influence of the separation. This work shed insight on the important parameters that need to be taken into account in the operational of an airplane.

1. Introduction
The phenomenon of ground effect becomes apparent in the proximity of the runway, and is beneficial in the control of fixed wing aircrafts during take-off and landing. When an aircraft is flown at approximately one wing span above the runway, the interaction between the airflow around the airfoil and the ground surface modifies the fluid velocity’s vertical component and changes its normal pattern which results in change of the lift-to-drag ratio $L/D$ [1,2,3]. In particular, the corresponding rotation of the resultant force vector gives change to the component of lift and drag forces [4,5]. A well trained pilot takes the phenomena into account in order to enhance the safety prior to airborne and touchdown [6].

This paper evaluates the influence of ground on the multi-element airfoil during landing. The problem is analysed with regard to the aerodynamic characteristics of the flow over NACA 4412 airfoils. We take STOL CH750 light sport aircraft (LSA) as a reference for the practical selection of study parameters. In fact, the NACA 4412 airfoils form the constant cross sections of the aircraft wing [7,8]. The main airfoil is equipped with a Junkers flap with constant angle of deflection (AoD). The Junkers flap is slotted below the trailing edge of the main airfoil. The design allows the airflow to pass between the main airfoil and the flap, even when the latter is retracted. Because of the increase in airflow, a significant increase in lift is added to the airfoils, even at low speeds. The flap is employed nowadays in many modern ultralights [9].

The evaluation focuses on various angles of attack $\alpha$, namely 3°, 7°, 11°, 14°, which is crucial in achieving touchdown point accuracy and preventing stalling of aircraft especially when it is close to the runway during flare; the recovery from such problem would require emergency procedures.
The distance between the airfoil and the ground is also taken into account. A steady-state RANS investigation was performed using the commercial CFD code ANSYS. The relationship between \( \alpha \) and the nature of ground effect at constant landing speed was observed. The effect was also considered for different distances between the airfoil and the ground.

2. Governing equations and modelling assumptions

A finite volume numerical method based on solving RANS equations describing the case under consideration was used for calculating the flow around the airfoil. In the case of incompressible, steady, 2-D viscous flow, the equations are given by

\[
\rho \left( u_1 \frac{\partial u_1}{\partial x_1} + u_2 \frac{\partial u_1}{\partial x_2} \right) = F_1 - \frac{\partial P}{\partial x_1} + \mu \left( \frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_1}{\partial x_2^2} \right) - \rho \left( \frac{\partial u_1'}{\partial x_1} + \frac{\partial u_1'}{\partial x_2} \right), \tag{3.1}
\]

and

\[
\rho \left( u_1 \frac{\partial u_2}{\partial x_1} + u_2 \frac{\partial u_2}{\partial x_2} \right) = F_2 - \frac{\partial P}{\partial x_2} + \mu \left( \frac{\partial^2 u_2}{\partial x_1^2} + \frac{\partial^2 u_2}{\partial x_2^2} \right) - \rho \left( \frac{\partial u_2'}{\partial x_1} + \frac{\partial u_2'}{\partial x_2} \right), \tag{3.2}
\]

where \( u_1, u_2 \) are time-averaged velocity vectors, \( P \) is the pressure, \( \mu \) is the dynamic viscosity, \( u_1', u_2' \) are fluctuating velocity vectors, and \( F_1, F_2 \) are body forces. It is necessary that the continuity equation,

\[
\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} = 0, \tag{3.3}
\]

is satisfied by (3.1) and (3.2).

Since the Reynolds averaging is involved in the derivation of (3.1) and (3.2), then a set of new unknowns called the Reynolds stresses need to be modeled to ensure that the equations can be closed. In particular, standard \( k-\epsilon \) turbulence model which gives a general description of turbulence by means of two transport equations was applied. In addition, standard wall functions were used for near-wall treatment.

The method was applied with second-order upwind discretization schemes. The algorithm called SIMPLE was employed for the velocity-pressure coupling. The airfoil velocity and the Reynolds number are 25 m/s and \( 1.7 \times 10^6 \), respectively. The values are within the range of CH750 landing and take-off conditions. The Mach number of flow is equal to 0.07, so then the compressibility effects could be neglected since they should be taken into account for a Mach number greater than 0.3. The investigated \( \alpha \) and heights of airfoil flights represented by the relative ratio of the height-to-airfoil chord length \( (h/c) \) were introduced.

3. Geometry, grid and computational domain

The flow was studied for the NACA 4412 for both the main airfoil and the Junkers flap. The airfoil has a flat shape of the pressing (bottom) side. The geometry of the airfoil is given in Fig. 1.
For discretization of the computational domain, an unstructured type of grid with quad elements was selected. The airfoil model moving above the ground and the grid used for calculations are given in Fig. 2.

Inlet and outlet boundary conditions were specified on the outer sides of computational domain with necessary turbulence and flow parameters. The boundary condition on the airfoil is a no-slip condition with zero relative speed enforced. This should produce better representation of the reversing flow assumption.

![Grid applied for multi-element airfoil moving close to the ground surface](image)

**Figure 2.** Grid applied for multi-element airfoil moving close to the ground surface

**4. Results of calculations**

The preliminary result of the velocity field around the NACA 4412 airfoil at zero angle of attack is shown in Fig. 3. Note that the airfoil is in ground proximity. It is obvious that the velocity is relatively low in particular at the pressure side when the airfoil approaches the ground, and thus gives direct influence to $L/D$ a moment after the roundout. This indicates that the airfoil floats on a cushion of high-pressure air region above the ground surface. Furthermore, the stagnation point shifts to the lower side of the airfoil due to the ground effect.
The ground effect on the velocity field around the airfoil at 5\% of the chord length from the ground (i.e. h/c = 0.05) is shown in Fig. 4 and Fig. 5. Clearly the velocity drop is acute at the pressure side when \( \alpha \) changes from 3\(^\circ\) to 7\(^\circ\), 11\(^\circ\), and consequently 14\(^\circ\), giving therefore great influence to \( L/D \) during the roundout and flare. Apart from the shift of the stagnation point to the lower airfoil side with the increase of \( \alpha \), the onset of flow separation occurs near the trailing edge of the main airfoil at \( \alpha = 7\(^\circ\) \). The flow separation point then shifts further upstream and finally reaches the leading edge at \( \alpha = 11\(^\circ\) \) and 14\(^\circ\), respectively. This reveals
that the basic aerodynamic characteristics deviate from those for unbounded airflow. Apparently the ground effect advances the flow separation. Note that for unbounded airflow the separation begins at $\alpha = 17^\circ$.

Figure 4. Velocity contour at $h/c = 0.05$

(a) $\alpha = 3^\circ$  (b) $\alpha = 7^\circ$  (c) $\alpha = 11^\circ$
Figure 5. Velocity contour at $h/c = 0.05$, $\alpha = 14^\circ$

The early flow separation causes the degradation of the lift-to-drag ratio $L/D$ whose percentage of reduction in the presence of the ground is shown in table 1 for $h/c = 0.05$. The next question is whether the overall aircraft performance can be achieved for $0.05 \leq h/c \leq 0.25$ at a given $\alpha$.

Table 1. Influence of $\alpha$ on $L/D$ at $h/c = 0.05$

| $\alpha$ (deg) | $L/D$ | $\Delta L/D$ (%) |
|----------------|-------|------------------|
| $3^\circ$ (ref.) | 60.58 | -- |
| $7^\circ$ | 29.53 | -51 |
| $11^\circ$ | 11.83 | -80 |
| $14^\circ$ | 6.00 | -90 |

The computation results based on different settings of the distance between the airfoil and the ground are tabulated in table 2 and table 3. Lift and drag are the forces which act on the geometry of main airfoil and flap as a whole. The tabulated data reveals that at $\alpha = (7^\circ, 11^\circ, 14^\circ)$, the average lift-to-drag ratio increment ($\Delta L/D)_a$ with respect to $h/c$ is given by a negative value which indicates that the aircraft would sink to the runway relatively faster before the touchdown. Such low overall performance is due to the flow separation which compromises the main airfoil lift (see Fig. 4 and Fig. 5). The airfoil however best performs at $\alpha = 3^\circ$ where $(\Delta L/D)_a$ is approximately 3%.

Table 2. Influence of $h/c$ on $L/D$ at $\alpha = 3^\circ$ and $\alpha = 7^\circ$

| $\alpha$ (deg) | $h/c$ | $L/D$ | $\Delta L/D$ (%) |
|----------------|-------|-------|------------------|
| $0.25$ (ref.) | 0.25 | 57.14 | -- |
| $0.20$ | 59.27 | 3.73 |
| $3^\circ$ | 0.15 | 56.69 | -0.78 |
| $0.10$ | 58.66 | 2.66 |
| $0.05$ | 60.58 | 6.03 |

| $\alpha$ (deg) | $h/c$ | $L/D$ | $\Delta L/D$ (%) |
|----------------|-------|-------|------------------|
| $0.25$ (ref.) | 0.25 | 36.17 | -- |
| $0.20$ | 33.12 | -8.42 |
| $7^\circ$ | 0.15 | 32.45 | -10.27 |
| $0.10$ | 32.46 | -10.26 |
| $0.05$ | 29.53 | -18.35 |
Table 3. Influence of h/c on L/D at α = 11° and α = 14°

| α (°) | h/c | L/D  | ΔL/D (%) | α (°) | h/c | L/D  | ΔL/D (%) |
|-------|-----|------|----------|-------|-----|------|----------|
|       | 0.25 (ref.) | 16.19 | --       | 0.25 (ref.) | 8.05 | --   |          |
| 11°   | 0.15 | 12.96 | -6.51    | 0.15  | 6.65 | -17.45 |          |
| 0.10  | 12.39 | -23.47 |          | 0.10  | 6.83 | -15.14 |          |
| 0.05  | 11.83 | -26.90 |          | 0.05  | 6.00 | -25.43 |          |

5. Final remarks
The study focused on the ground proximity effect on the flow over NACA 4412 multi-element airfoil. In the absence of flow separation (i.e. at $\alpha = 3°$), the ground influence prevails, causing higher pressure at the pressure side of the airfoil, and thus slowing down the touch down of the airplane. Higher $\alpha$ (i.e. $7° \leq \alpha \leq 14°$) will result in sinking of the aircraft at relatively high rate; the cushion of high pressure at the pressure side of the airfoil is insufficient to neutralize the effect of flow separation. It is therefore important to take $\alpha$ and h/c into consideration in the operational of an airplane during landing. Further relevant investigation would involve both $\alpha < 3°$ and $3° < \alpha < 7°$.

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