ANALYSIS OF THE EFFECT OF GROUND PROXIMITY ON THE UNSTEADY FLOWS PAST OSCILLATING AIRFOILS AT LOW REYNOLDS NUMBERS

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Summary This paper presents solutions for the unsteady flows at low Reynolds numbers past oscillating airfoils in the proximity of the ground, analyzing the effect of the distance to the ground on the unsteady aerodynamic coefficients (pressure distribution, lift and drag) and on the flow separation appearing on the airfoil at low Reynolds numbers. These solutions are obtained with an efficient numerical method developed by the authors for the solution of the Navier-Stokes equations at low Reynolds numbers, which is second-order-accurate in time and space. The effect of ground proximity on the unsteady lift and drag coefficients and on the flow separation on the upper side of the airfoil has been studied for several Reynolds numbers and for several symmetric and cambered NACA airfoils of various relative thickness and camber. The flow separation region, which is formed on the upper side of the airfoil at relatively low incidences, was found to increase with the closer proximity to the ground.

GENERAL CONSIDERATIONS AND METHOD OF SOLUTION

The flows past airfoils and wings at low Reynolds number recently received a special interest due to the development of the unmanned micro-air-vehicles (MAV), which can operate in various indoors or outdoors environments including tunnels, deserts and jungles {1, 2]. Various flight evolutions of the micro-air-vehicles, especially indoor or in tunnels, take place in the proximity of the ground, ceiling or a wall, which require the steady and unsteady aerodynamic solutions at the low Reynolds numbers.

Previous studies on airfoil aerodynamics at low Reynolds numbers (without ground effect) include those published by Kunz & Kroo [1] and Mateescu and Abdo [2, 3] for steady flows and, more recently, by Mateescu *et al.* [4] for unsteady flows. The effect of the ground proximity in steady flows has been studied recently by Mateescu *et al.* [5].

This paper presents the analysis of unsteady subsonic flows past oscillating airfoils at low Reynolds numbers in the proximity of the ground. Solutions are obtained for the unsteady aerodynamic coefficients at low Reynolds numbers between 500 and 3000, analyzing the effect of the distance to the ground (no previous solutions are known for this problem). The unsteady incompressible flow problem is solved in a rectangular computational domain obtained from the physical domain by time-dependent coordinate transformations defined for six sub-domains, in which the moving boundary conditions are efficiently and rigorously implemented.

Unsteady flow solutions for airfoils in the proximity of the ground are obtained with an efficient numerical method developed by the authors for the time-accurate solution of the Navier-Stokes equations at low Reynolds numbers, which is second-order accurate in both time and space. This method uses a pseudo-time relaxation procedure based on artificial compressibility and a factored Alternate Direction Implicit (ADI) scheme for integration in pseudo-time. A second-order central finite differencing formulation is used on a stretched staggered grid (which avoids the odd-and-even points decoupling). A key feature of this numerical method is a special decoupling procedure that eliminates the pressure from the momentum equations by using the continuity equation, which reduces the problem to the solution of scalar tridiagonal systems of equations, enhancing thus substantially the computational efficiency of the method (details of the numerical methods are included in the presentation, but not given here due to space limitation).

SOLUTIONS FOR UNSTEADY FLOWS PAST OSCILLATING AIRFOILS IN THE GROUND PROXIMITY EXAMPLES OF RESULTS

Solutions are obtained for the unsteady flows past various symmetric and cambered NACA airfoils executing pitching oscillations defined as $\alpha(t) = \alpha_0 + \alpha_A \cos(\omega t)$, where α_0 is the mean angle of attack, α_A is the amplitude of pitching oscillations (with respect to α_0), $\omega = 2\pi f\, c/U_\infty$ is the nondimensional frequency of the oscillations and $t = t^* U_\infty / c$ is a nondimensional time, in which U_∞ is the uniform stream velocity and c is the airfoil chord.

The unsteady lift and drag coefficients, C_L and C_D, and the lift-to-drag ratio, C_L/C_D, are calculated for various nondimensional (with respect to c) distances to the ground, H, for various Reynolds numbers (between 500 and 3000) and for several values of the mean incidence α_0, and of the amplitude α_A and the oscillation frequency ω.

The influence of various parameters (Reynolds number, oscillation amplitude and frequency, relative thickness and camber) on the ground proximity effect on these unsteady aerodynamic characteristics is especially studied.

The paper also presents a detailed analysis of the flow separation on the upper side of the oscillating airfoils in the proximity of the ground, which appears at relatively small incidences at these low Reynolds numbers. The influence on the flow separation length of various geometric and flow parameters, such as the distance to the ground, Reynolds number, amplitude and frequency of oscillations and relative thickness and camber, is thoroughly analyzed.

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Typical variations of the unsteady lift and drag coefficients and of the lift-to-drag ratio are shown in Figures 1 and 2 for various geometric and flow parameters (H , Re, α_0 , α_A , ω).

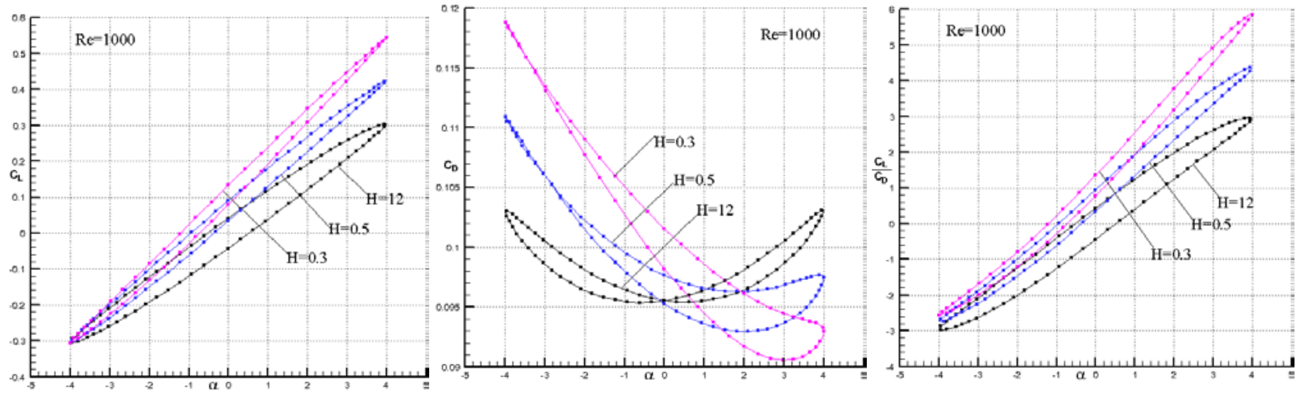

Figure 1. *Typical effect of the nondimensional distance to the ground* H : Solutions for the unsteady lift and drag coefficients, C_L , C_D , and C_L/C_D for a NACA 0002 airfoil executing pitching oscillations, with $\alpha_0 = 0^o$, $\alpha_A = 4^o$ and $\omega = 0.05$, at Re= 1000 for three distances to the ground: $H = 0.3$, 0.5 and 12 (no ground effect) .

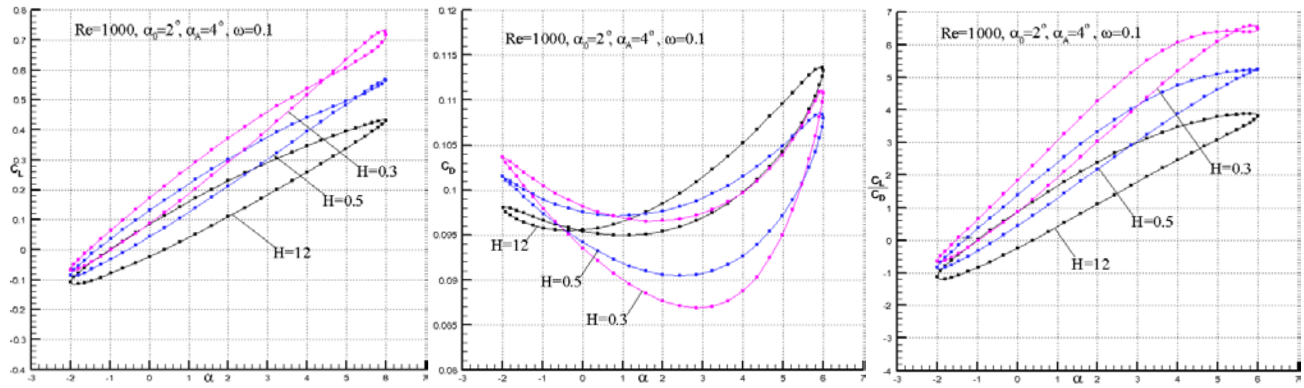

Figure 2. Solutions for the unsteady lift and drag coefficients, C_L , C_D , and C_L/C_D for a NACA 0002 airfoil executing pitching oscillations $\alpha(t) = \alpha_0 + \alpha_A \cos(\omega t)$, with $\alpha_0 = 2^o$, $\alpha_A = 4^o$ and $\omega = 0.05$, at Re=1000 for three distances to the ground: $H = 0.3$, 0.5 and 12 (no ground effect) .

The change in shape of the hysteresis curve of C_L versus α in Figure 2 for $H = 0.3$ indicates the presence of the flow separation on the airfoil upper side at $\alpha > 4.5^o$, which is absent for $H = 12$ when the airfoil is far from the ground.

CONCLUSIONS

Solutions are obtained for the unsteady lift, drag and lift-to-drag ratio for airfoils executing pitching oscillations at low Reynolds numbers in the proximity of the ground by using an efficient numerical method developed by the authors.

The effect of the distance to the ground on these unsteady coefficients and the influence of the Reynolds number, and of the oscillation amplitude and frequency on the ground effect have been thoroughly studied.

The analysis of the unsteady flow separation revealed that the flow separation region developed on the upper side of the oscillating airfoil increases with the closer proximity to the ground and with the increase in the Reynolds number and in the amplitude of oscillations, as well as with the increase in the relative thickness of the airfoil and its mean incidence.

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