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Technical Comments

Comment on "Aerodynamic Characteristics of a Two-Dimensional Airfoil with Ground Effect"

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THE authors of Ref. 1 applied the steady, incompressible Navier–Stokes equations to treat the aerodynamic problem of an airfoil in ground proximity. The standard k-ε two-equation model was used to account for turbulent flow at high Reynolds numbers. The system of equations was solved numerically by flowfield discretization and application of the finite volume technique. The angle of attack of the airfoil was small to moderate ($\alpha \leq 10$ deg) and the ground clearance varied between $H/c = 0.05$ and infinity (Fig. 1a).

Unfortunately, the paper presented in Ref. 1 contains some errors and some results concerned do not correspond to the physical experience of experimental and theoretical wing in ground aerodynamics.

First of all, the transformation of the physical problem is not correct. Since in reality the ground is not model fixed, but flow fixed, the boundary condition (3) after Eq. (6) in Ref. 1 for the Navier–Stokes equations, that is the no-slip condition ($u = 0$, $v = 0$), must not be applied to the ground plane. Thus, the correct boundary condition for the ground plane is the slip condition ($u = 1$, $v = 0$).

As a direct consequence of the correct formulated boundary condition, there does not exist a boundary layer along the ground in steady flow, and additionally, the recirculation bubble below the leading edge of the airfoil (shown in Fig. 16b of Ref. 1) will disappear. Hence, the undesired boundary layer on the ground affects the subsequent results in Ref. 1, in particular for the smallest ground distance $H/c = 0.05$.

Indeed, in the wind-tunnel practice much effort is needed to avoid the development of a boundary layer on the ground (tunnel floor) by use, for instance, of suction systems or moving belts.

The dramatic loss of lift for the airfoil very close to the ground with $H/c = 0.05$ (Figs. 5 and 6 in Ref. 1) is in contrast to the experimental experience. Generally, the airfoil with moderate thickness ($t/c = 12\%$) and moderate camber at small to moderate angles of attack (e.g., the NACA 4412 airfoil, which was investigated in Ref. 1), shows a positive ground effect with respect to the lift when approaching the ground, i.e., the lift increases progressively with decreasing ground height.[2–4] This holds for medium to high (supercritical) Reynolds numbers, at least. Because of the near ground, the pressure on the lower side of the airfoil nearly reaches stagnation pressure, in contrast to the result in Ref. 1, i.e., Figs. 14 and 15 for $H/c = 0.05$.

For comparison, Figs. 1 and 2 show some results for an airfoil (Clark-Y, $t/c = 11.7\%$), which was tested in plane wind-tunnel flow with a fixed ground board, equipped with a suction system.[3] The ground distance was $h/c = 0.1$, which corresponded about the value $H/c = 0.05$ in Ref. 1 for $\alpha = 5$ deg. The Reynolds number was 1.3×10^6.

For $\alpha = 3.95$ deg (Fig. 1), the pressure coefficient on the lower side of the airfoil was already rather high; with $\alpha = 5.87$ deg (Fig. 2), stagnation pressure was nearly achieved. The calculations in Ref. 3, based on a surface singularity method, confirmed essentially the experimental result.

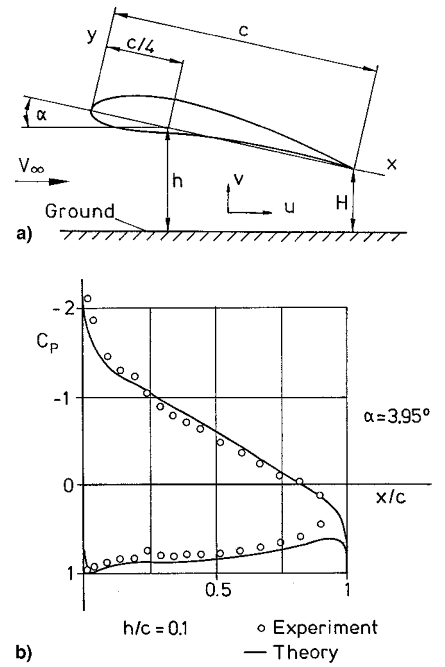

Fig. 1 a) Geometric definitions for the airfoil with ground and b) measured and calculated pressure distribution for the airfoil Clark-Y 11.7% with ground effect, α = 3.95 deg and Re = 1.3 × 10^6.

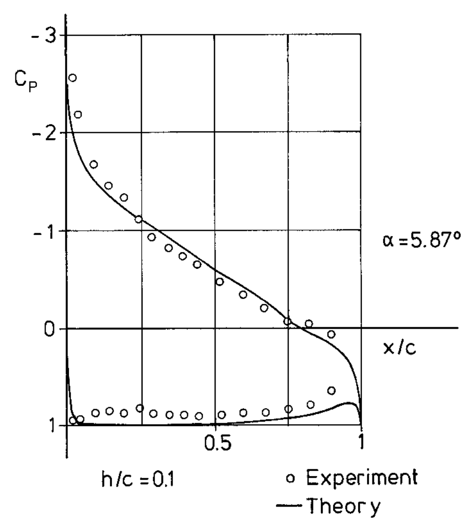

Fig. 2 Measured and calculated pressure distribution for the airfoil Clark-Y 11.7% with ground effect, α = 5.87 deg and Re = 1.3 × 10^6.

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The physical reason for the high-pressure field under the airfoil because of the ground effect is that the circulation of the reflected, fictitious airfoil induces upstream-directed velocities, which diminish or even compensate the oncoming freestream, in particular in the region beneath the airfoil. There, the induced velocities of both airfoil circulations are directed primarily upstream. It follows that for ground distances small enough, there is practically no mass flow between airfoil and ground and the oncoming freestream passes completely over the suction side of the airfoil, in contrast to Figs. 9 and 16b for $H/c = 0.05$ in Ref. 1 (see also Ref. 2 and Fig. 2 there).

The dynamic generation of the air cushion under the airfoil near ground is often called the ram-wing effect and this effect is utilized, among others, by the known wing-in-ground vehicles.

The pressure drag coefficient does not reduce naturally with decreasing negative pressure on the upper surface of the airfoil, as stated in Ref. 1 (see the definition of the pressure drag coefficient). If flow separation does not occur there the pressure drag coefficient is not much affected by ground influence. However, because of the lower local flow velocities on the airfoil, the boundary-layer parameters (δ_1, δ_2, . . .) are generally increased by decreasing ground heights and the pressure drag may also be increased.[4] This holds in particular if partial flow separation takes place on the upper side of the airfoil.

It should be pointed out that the primary reason for the marked reduction of the drag for a (finite) wing near ground can be attributed to the decrease of the induced drag. The downwash field of the trailing vortices of the wing is diminished by the interference of the upwash field of the reflected (image) wing, leading to a smaller induced angle of attack and to a higher effective aspect ratio.

The author believes that the problem could be treated more suitably by applying the Navier–Stokes calculations for both the primary and the reflected airfoil in the flow, and also to avoid possible mass flow losses through the ground boundary because of the numerical procedure. This can easily be carried out by applying the computational grid of Fig. 2 in Ref. 1, together with the corresponding image grid, obtained by reflecting the first grid at the ground plane.

References

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