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NUMERICAL INVESTIGATION OF AIRFOIL IN GROUND PROXIMITY

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The paper presents numerical investigation of the ground effect which affects an air flow when a craft's wing approaches the ground or sea surface. The effect has crucial significance for the wing-in-ground craft operation and decides about the purpose of building one at all. The two-dimensional viscous flow problem is solved and the results of calculations are presented. Furthermore, some most important issues related to the basics of an ekranoplan application are very briefly discussed. On the basis of numerical calculations, an empirical formula has been proposed for quantitative assessment of the chord dominated ground effect.

Key words: wing-in-ground effect, ekranoplan, numerical computations, fast transport

1. Introduction

Wing-in-ground (WIG) boat is a promising mean of transport for the near future or at least one worth to be considered. Recently, people have been traveling at increasing speeds. New means of transport are usually faster than the ones they replace. In marine transport, conventional displacement hulls reach their limits of performance and hardly can keep up with the speed. It is very unlikely that any conventional boat would be able to operate at speeds higher than 100 km/h with an acceptable fuel efficiency. Speeds of WIGs are much higher than ship speeds, and overall operational expenses are lower than those of planes. Higher speeds can be achieved with hydrofoil boats or so called surface effect ships. Definitely, a marine vehicle without any water contact would be the solution for a very low drag induced only by air.

A WIG craft is a boat with wings that sails just above the water surface, floating on a cushion of high-pressure air region between its wing and the water surface. This cushion is created by the aerodynamic interaction between the wing and the surface, called the ground effect. A WIG boat is different from an aircraft because it cannot operate without the ground effect.

There are many papers related to WIG's construction or operation. Some of them are Afremov *et al.* (1996), Chawla (1988), who present wind tunnel results, also Kornev and Matveev (2003) who give details of their research on flight modelling problems. The problems with implementation of WIG crafts are presented by Taylor (2000). Experiments on aerodynamics of an airfoil subject to the ground effect have been recently carried out by Ahmeda and Sharmab (2004), who tested a symmetrical NACA 0015 in a low speed wind tunnel. The results of their investigations were lift and drag forces and detailed characteristics of the flow. Another work is the paper of Rafiuddin (2005) who also presents experimental studies of the NACA 4415 airfoil in ground proximity. A numerical approach to the solution of the considered problem is presented by Park and Chun (1995).

Fig. 1. A WIG craft recently introduced to operation by *Pacific Seaflight* on Alaska

2. Overview of the ground effect

When a wing approaches the ground two phenomena are actually involved in the increase of the lift force and reduction of the drag. The ground effect is a common name for both effects, which is sometimes confusing. These two phenomena are sometimes referred to as span dominated and chord dominated ground effect. The former results mainly in the reduction of the induced drag (D) and the latter in the increase of the lift (L). The designations span dominated and chord dominated are related to the the fact that the main parameter in the span dominated ground effect is the height-to-span ratio, whereas in the chord dominated ground effect it is the height-to-chord ratio.

As it was in the mentioned above, the span dominated effect reduces drag. The drag of an aircraft can be split up into different contributions. The two main sources of drag are called the friction drag and induced drag. The friction drag is caused by friction between the air and the surface of the craft, and is therefore dependent on its wetted area. The induced drag is sometimes called the lift induced drag because it is the drag due to generation of lift. When a wing generates positive lift, the static pressure on the lower side of the wing is higher than that on the upper side. At the wingtip, there is a complication: the high pressure area on the lower side meets the low pressure area on the upper side, therefore the air will flow from the lower side to the upper side around the wingtip. This is called the wingtip vortex. The energy that is stored in those vortices is lost and is experienced by the aircraft as drag. In free air, the vortices around the wing tips have more space to develop than when they are bounded by the ground. The amount of induced drag is dependent on the spanwise lift distribution and the aspect ratio of the wing. A high aspect ratio wing has a lower induced drag than a low aspect ratio wing since its wingtip vortices are weaker. There is not enough space for the vortices to fully develop when a wing is approaching the ground. The vortices are also pushed outward by the ground, apparently the effective aspect ratio of the wing becomes higher than the geometric aspect ratio, Fig. 2.

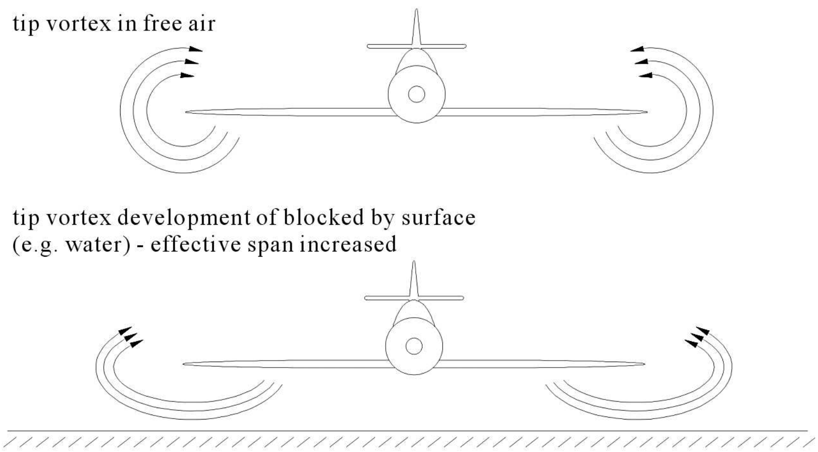

Fig. 2. Span dominated ground effect

The chord dominated ground effect increases lift. The air cushion is created by high pressure that builds up under the wing when the ground is approached. This is sometimes referred to as ram effect or ram pressure. When the ground distance becomes very small the air can even stagnate under the wing, giving the highest possible pressure, pressure coefficient unity. The chord dominated ground effect not always increases lift. It is possible, under certain conditions, that the lift reduces when an airfoil approaches the ground. This is the case when the bottom of the foil is convex and the angle of incidence is very low or negative, and in that case a venturi nozzle is created between the foil and the ground where high-speed low-pressure air sucks the airfoil down. This effect is used by race car designers to make it stick to the road at high speeds. To avoid this effect, the pressing side of the airfoil should be as flat as possible and the angle of attack should be positive.

In the next part of the paper, only the chord dominated effect is studied in details. The *Fluent Inc.* numerical software was applied for calculations of viscous flow around a NACA airfoil. The results show significant influence of the flight height on the lift of the airfoil.

3. Governing equations and modelling assumptions

For calculation of viscous flow around an airfoil, a numerical method based on solving equations describing the case under consideration, i.e. *RANS* equations, is used. These equations have the following form for the incompressible, steady, two-dimensional flow

$$\begin{aligned}\rho\Big(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\Big)\rho &= F_1-\frac{\partial P}{\partial x}+\mu\Big(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\Big)-\rho\Big(\frac{\partial\overline{u'u'}}{\partial x}+\frac{\partial\overline{u'v'}}{\partial y}\Big)\\ \rho\Big(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\Big)\rho &= F_2-\frac{\partial P}{\partial y}+\mu\Big(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\Big)-\rho\Big(\frac{\partial\overline{u'v'}}{\partial x}+\frac{\partial\overline{v'v'}}{\partial y}\Big)\end{aligned} \tag{3.1}$$

In the above equations, u, v are components of the mean velocity vector, P is the pressure, μ is the viscosity, u', v' are fluctuation parts of the velocity vector, F_1, F_2 are volumetric forces. Furthermore, the model must satisfy the continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3.2}$$

The Spalart-Allmaras turbulence model has been applied for the modelling of the Reynolds stresses. This is a single transport equation model solving directly for a modified turbulent viscosity, especially developed for aerospace applications. The overall of the applied technique is based on the finite volume method with segregated formulation and second-order upwind discretization schemes. The SIMPLE algorithm is employed for the coupling of velocity and pressure.

The placement of the first grid point was established on the basis of a non-dimensional distance parameter y^+, describing the local Reynolds number.

For the first estimation, y^+ may be determined according to the theory of flat-plate flow, e.g. Schlichting (1968)

$$y^+ = 0.172\Big(\frac{y}{L}\Big)R_n^{0.9} \tag{3.3}$$

where y is the distance from the wall, L – body length. The grid was constructed in such a way that the parameter was maintained at $y^+ = 100$.

The considered flow velocity (airfoil velocity) was assumed 30 m/s, the Reynolds number of the flow was 2 100 000. This was close to the expected cruising velocity of a small WIG boat. The Mach number of flow was equal to 0.1, so then the compressibility effects could be neglected since they should be taken into account for a Mach number greater than 0.3. The flow was at first studied for the airfoil moving in unbounded air and then the results were compared against the calculations for the cases with the ground effect. The investigated heights of airfoil flights were introduced by relative ratios of the height-to-airfoil chord length (h/c).

4. Geometry, grid and computational domain

The flow was studied for the NACA/Munk M15 airfoil with a flat shape of the pressing (bottom) side. This combined with the assumed angle of attack which was equal to 3°, should result in the clearly visible chord dominated ground effect. The geometry of the airfoil is given in Fig. 3.

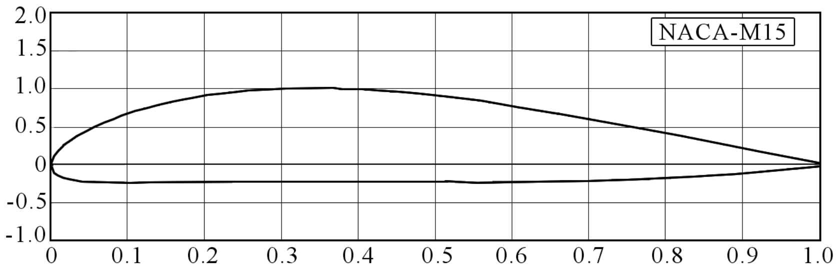

Fig. 3. Geometry of NACA/Munk M15 airfoil

For discretization of the computational domain, an unstructured type of grid with quad elements was selected. The grid for the airfoil moving in free air is presented in Fig. 4, while the grid used for calculations in the ground effect case is given in Fig. 5.

Inlet and outlet boundary conditions were specified on the outer sides of computational domain with necessary turbulence and flow parameters. The

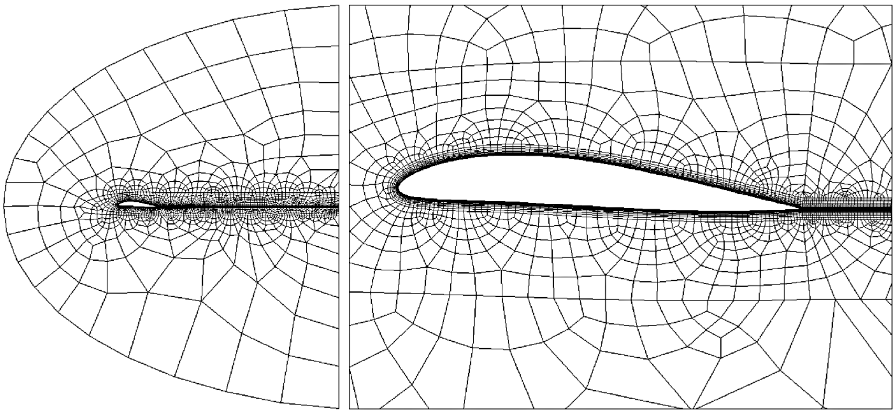

Fig. 4. Grid applied for airfoil moving in free air

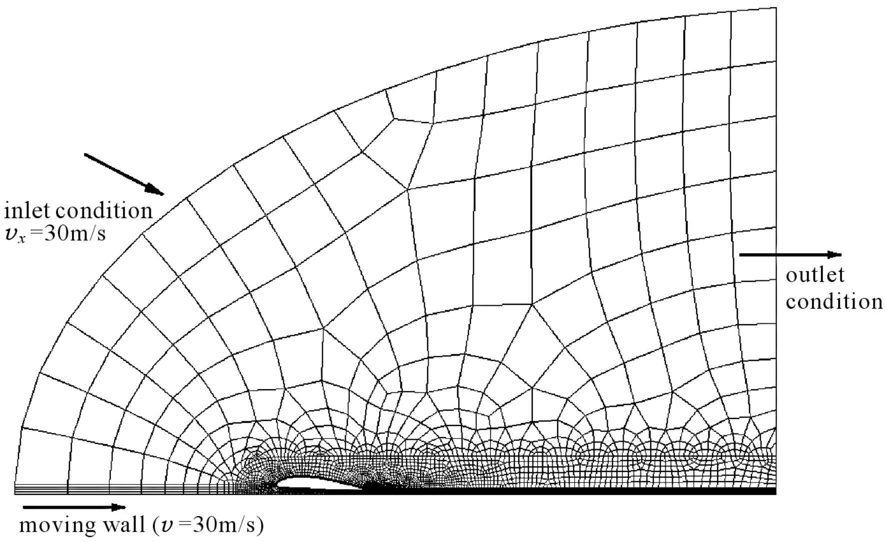

Fig. 5. Grid applied for airfoil moving close to surface

boundary condition on the airfoil is a no-slip condition with zero relative speed enforced. Just below the airfoil moving wall condition has been applied for better representation of ground modeling when the ground effect was investigated, Fig. 5. This should produce better representation of the reversing flow assumption. The velocity of the moving wall is the same as for the inlet condition, $v = 30\,\mathrm{m/s}$.

5. Results of calculations

All applied physical models described above and grid topologies presented in Fig. 5 and Fig. 6 produced results which are presented in this Section. Computed pressure coefficients C_P contours are given in Fig. 6-Fig. 9. The results of calculated distributions of C_P values were compared to the potential flow solver, and the comparison is demonstrated in Fig. 10. Due to restricted capabilities of available potential flow solver, the comparison was carried out only for the case of a flight in open air. The comparison of presented results with the potential flow solver in terms of the lift coefficient has given reasonable conformity. The lift coefficient for the unbounded air case was found to be 0.6, while the one calculated with the help of potential solver 0.66.

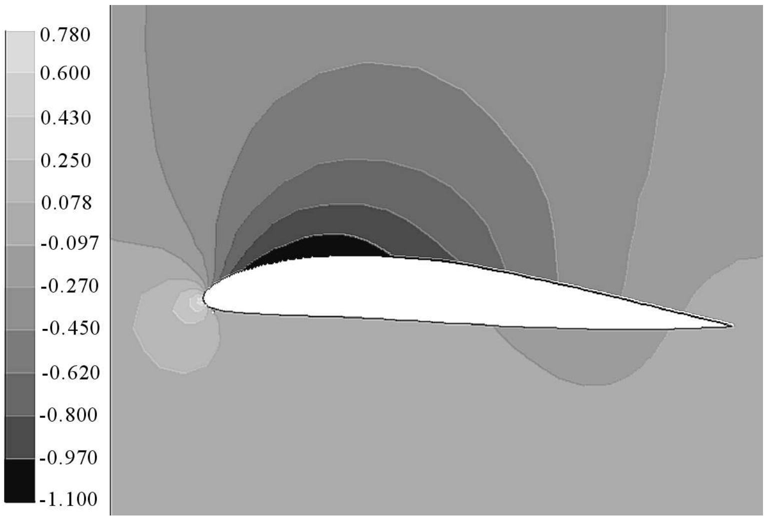

Fig. 6. Pressure coefficient contours C_P. Airfoil moving in unbounded air

The convergence history of the iteration process was investigated on the basis of scaled residuals of continuity, velocity and turbulence quantities. Usually, it is also worth to study the quantity being the subject of interest, i.e. the lift force coefficient in the presented case. These values are shown in Fig. 11, where the convergence history for the airfoil moving in unbounded air is presented, while the history for the airfoil in the ground effect $(c/h = 0.05)$ is given in Fig. 12. The sufficient convergence was archived after about 900 iterations.

On the basis of the function presented in Fig. 12, an empirical formula has been derived for practical and preliminary calculations of the chord-dominated ground effect. It has the following form

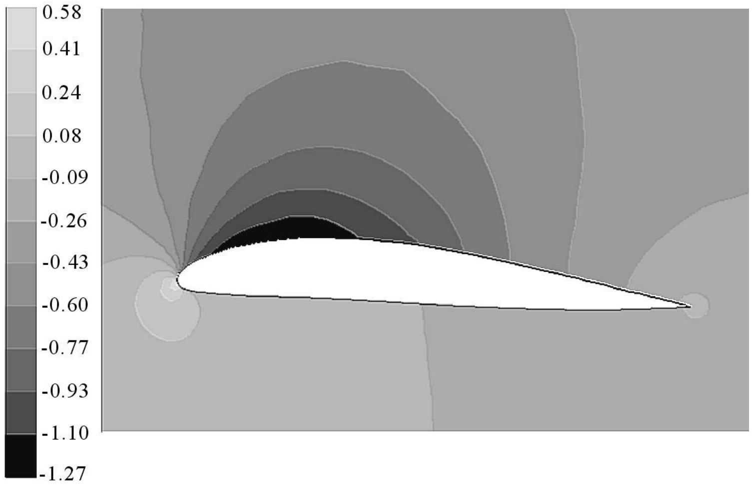

Fig. 7. Pressure coefficient contours C_P. Airfoil moving in 0.25 h/c

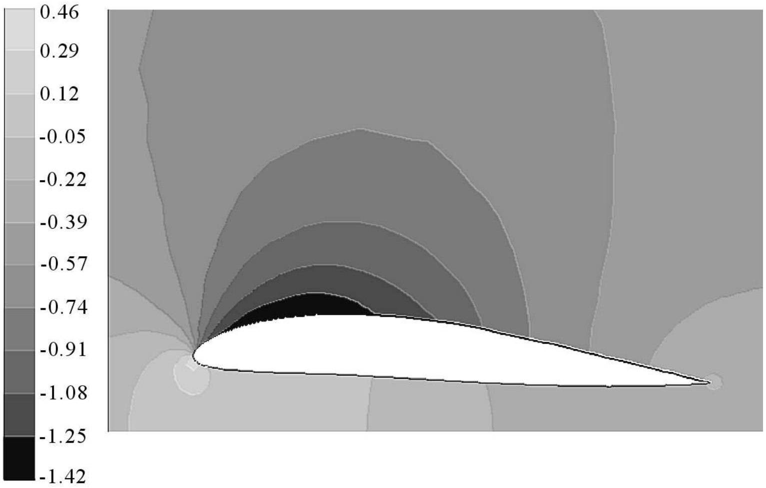

Fig. 8. Pressure coefficient contours C_P. Airfoil moving in 0.1 h/c

$$C_{L\,ground} = C_L\Big(\frac{h}{c}\Big)^{-0.11} \tag{5.1}$$

where $C_{L\,ground}$ represents the wing lift coefficient in the ground effect mode, C_L – lift coefficient in open air, h indicates height of the wing and c is the chord length.

The above presented formula should be used with care, having in mind that it is based on numerical calculations. However, in terms of safety, we are on the safer side due to taking into account only one component of the overall

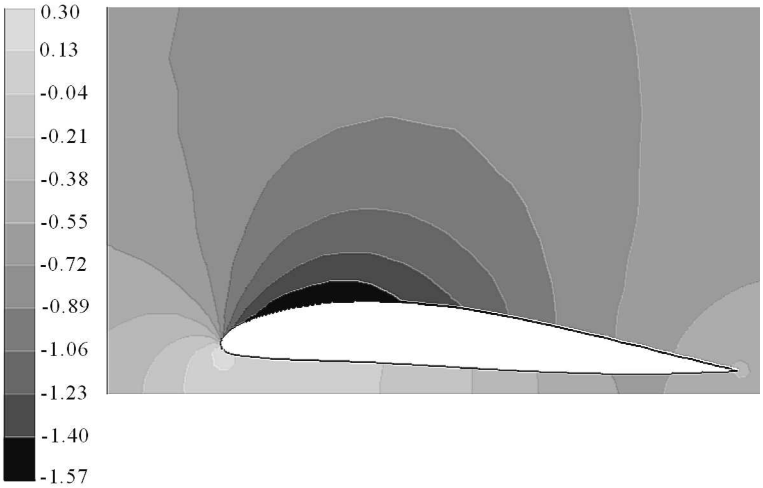

Fig. 9. Pressure coefficient contours C_P. Airfoil moving in 0.05 h/c

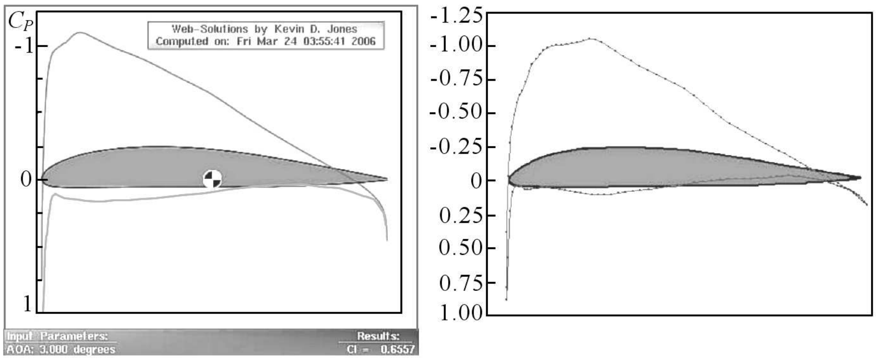

Fig. 10. Calculated pressure coefficients C_P – own calculations (right), compared with java-based, potential flow solver (left) available on-line at: http://www.aa.nps.navy.mil/~jones/

ground effect, the chord dominated one. In a real WIG's journey, the span dominated effect will occur as well, which should produce some safety margin.

6. Final remarks

The increase of the numerically calculated lift coefficient in the ground mode was 40% when compared to the lift coefficient in unbounded air. The effect shows that wider application of WIG crafts has a great potential. Obviously, anyone who considers a small and fast mean of transport in such areas as rivers,

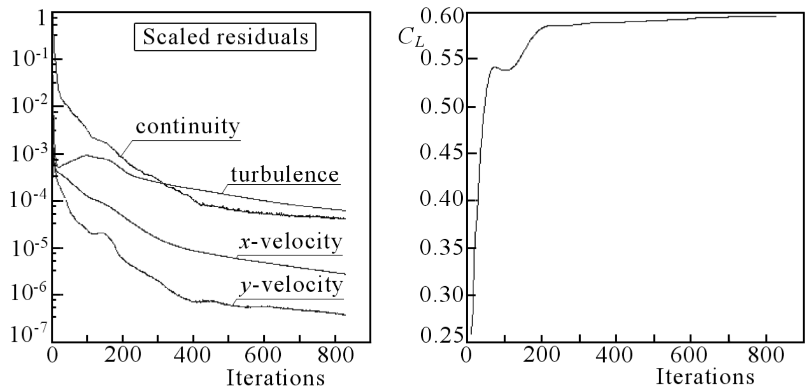

Fig. 11. Convergence history of flow quantities for unbounded air case

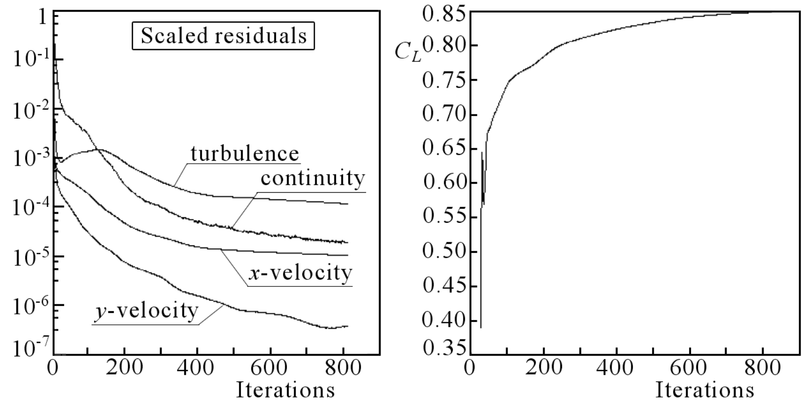

Fig. 12. Convergence history of flow quantities for ground effect case, $h/c = 0.05$

lakes or gulfs should seriously have the WIG potential in mind. A company which is going to find a big, long range oceanic vehicle can also consider an ekranoplan. Cole (2002) presented a notable example of such a design idea.

The results presented here can be applied at the preliminary design stage for the initial analysis of a WIG craft moving in the ground effect mode. The further work will deal with analysis of the second effect which affects total ground effect phenomena. This is the span dominated effect, and because it requires three dimensional calculations such analysis would take into account both effects and cumulative gains are expected to occur. For building a real WIG craft or at least a model of it, one should also study the problem of flight stability and control.

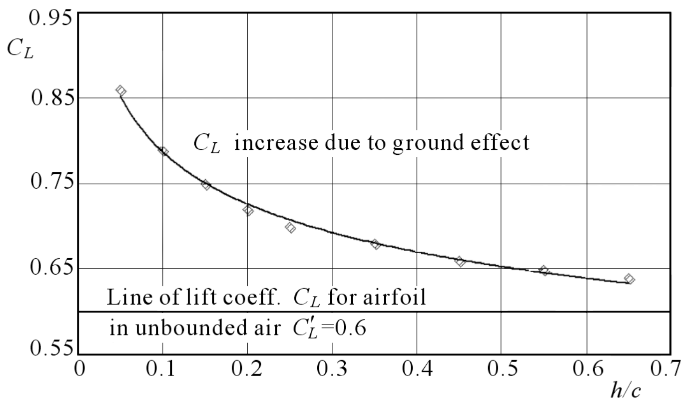

Fig. 13. Lift coefficient for different values of h/c. Line of constant $C_L = 0.6$ is for airfoil in unbounded air

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Numeryczne badanie efektu przypowierzchniowego profilu aerodynamicznego

Streszczenie

Artykuł prezentuje wyniki badań numerycznych jednego z dwóch zjawisk zmieniających opływ skrzydła zbliżającego się do powierzchni gruntu lub morza. Efekt ten ma podstawowe znaczenie dla eksploatacji obiektu typu WIG, a przede wszystkim stanowi o sensie budowania takiej jednostki w ogóle. Uzyskano rozwiązanie dla przepływu dwuwymiarowego i zaprezentowano wyniki. Bardzo ogólnie zaprezentowano również podstawowe problemy związane z zastosowaniem ekranoplanu jako środka transportu. W oparciu o wyniki badań numerycznych zaproponowano wzór empiryczny do oceny ilościowej efektu przypowierzchniowego związanego ze zbliżaniem się profilu aerodynamicznego do powierzchni gruntu lub morza. Zależność tą można wykorzystać w praktyce, jeżeli tylko efekt związany z wirem wierzchołkowym skrzydła będzie miał pomijalny wpływ na cały efekt przypowierzchniowy.

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