Study on Wake Roll-Up Behavior Behind Wings In Close Proximity to the Ground

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Abstract

A numerical simulation of wake behavior behind three-dimensional wings in ground effect is done using an indirect boundary element method (Panel Method). An integral equation is obtained by applying Green's 2nd Identity on all surfaces of the flow domain. The AIC is constructed by imposing the no penetration condition on solid surfaces, and the Kutta at the wing's trailing edge. The ground effect is included using an image method. At each time step, a row of wake panels from wings' trailing edge are convected downstream following the force-free condition. The roll-up of wake vortices behind wings in close proximity is simulated.

Key Word : Numerical Simulation, Indirect Boundary Element Method. Ground Effect, Wake Roll-up.

Introduction

When a wing is flying in close proximity to the ground, it is known to experience significant changes in aerodynamic forces, characterized by the increase in lift and the decrease in drag. This phenomenon is called as Wing-In-Ground (WIG) effect. It has been a well-known phenomenon from the commencements of the manned flight. Recently, there have been worldwide efforts to develop WIG vehicles, focused on increasing efficiency and economy of shipping operation by increasing the speed of vehicles. Some of these vehicles have been built or are under consideration. Basic research on the WIG aerodynamics is crucial for the reliable prediction of the WIG vehicles' performance and their stability.

Naoki, M. and Kazuo, S. [1] investigated the wave making phenomena caused by the pressure distributions on the water surfaces by using a boundary element method (panel method). They analyzed the air-flow field around WIG vehicles and the interaction between the wing and the free surface by considering the pressure distributions acting on the free surface. They showed that the free surface deformation effects on the aerodynamic characteristics of WIG vehicles were negligible. Chun, H.H. and Park. I.R. [2] studied the steady and unsteady performance of 3-dimensional wings in the vicinity of free surface with prescribed wave elevations. They solved the problem by using the panel method, by distributing dipoles and sources on the wing and the free surface. They concluded that the free surface effects affected the aerodynamic characteristics of a wing less than in the case of ground effects, when the wave length is over a chord length.

The problem of the interaction between vortex wakes and wings is very common in aircraft analysis and design. Examples include wing-vortex interaction due to short interval airport takeoff, canard-wing interference, rotor analysis, and propeller-wing interference [3]. The accurate simulation of the behavior of wake vortices behind the trailing edge of a wing is important

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because of the induced drag on the generating vehicle cruising in close proximity to the ground. For high Reynolds number flow past a wing at moderate angles of attack, the methods based on the potential flow theory are useful within the initial stage of the wake rollup before the breakup of the trailing vortex system [4]. Thus, rapid computational approaches for the accurate descriptions of vortex wakes with close interactions between lifting surfaces have been developed using the vortex-lattice method and the panel methods.

Though the studies on the WIG effect on the aerodynamic analysis of wings in ground effect are extremely rich [See Ref. 5 for a wide review for the computational efforts to develop the WIG vehicles], not much is known on the effects of wing's trailing wake behavior on the aerodynamic characteristics of wings in close proximity to the ground. Hackett and Evans [6] studied the problem using the two-dimensional, time-dependent analogy. However, their procedure failed because vortices could penetrate the ground. Goez et al. [7] predicted aerodynamic characteristics of wings in ground effect using a higher-order panel method without wake roll-up. They concluded that proper modeling of the wing wake would be required to improve accuracy. Zhu, K. and Takami, H. [8] investigated the effect of ground on vortex wake roll-up behind a lifting surface using a three-dimensional vortex-lattice method. However, the solution was divergent below h=0.2.

Panel methods represent the viscous shear layer behind the trailing edge of a wing as the vortex sheet surface. This is reasonable when the Reynolds number is infinite and the viscous shear layer is confined to the thin region. Many free-wake analysis techniques have been developed to successfully obtain an accurate analysis and reliable prediction of vortex flows in dealing with modern designs of fighter aircrafts, missiles and helicopters.

Thus, in this paper, an aerodynamic analysis of wings using a free-wake scheme will be described in this paper for the case of wings flying in close proximity to the ground. The three-dimensional wing moving with a constant speed over a ground is modeled by using the indirect boundary element method (potential-based panel method). The aerodynamic coefficients of the wings are calculated after the convergence of the wake shapes have been evaluated. The effects of the wake roll-up on the aerodynamic forces are investigated for various wing heights.

Panel Method

To treat the steady motion of a wing moving through the air, it is assumed that the air is blowing over the wing. The flow is assumed to be inviscid, incompressible and irrotational over the entire flow field, excluding the wing's solid boundaries and its wake. Therefore a velocity potential Φ can be defined and the continuity equation becomes Laplace equation.

$$\nabla^2\Phi = 0 \tag{1}$$

Consider a body with known boundaries S_B(wing surface), S_W (wake surface) and S_∞ (outer boundary). The general solution to eq. (1) based on Green's identity can be constructed by a sum of source σ and dipole μ distributions on the boundaries.

$$\Phi(x,y,z) = \frac{1}{4\pi}\int_{S_B+S_W} \mu\vec{n}\cdot\nabla\left(\frac{1}{r_A}\right)dS - \frac{1}{4\pi}\int_{S_B}\sigma\frac{1}{r_A}dS + \Phi_\infty \tag{2}$$

where r_A is the distance from the point over the surface to the calculation point in space.

To impose the Dirichlet boundary condition on the surface, the perturbation potential has to be specified everywhere on S_B. If for an enclosed body $\frac{\partial\Phi}{\partial n}=0$, then potential inside the body will not change. Thus, eq. (2) becomes as follows.

$$\frac{1}{4\pi}\int_{S_B+S_W} \mu\vec{n}\cdot\nabla\left(\frac{1}{r}+\frac{1}{r'}\right)dS - \frac{1}{4\pi}\int_{S_B}\sigma\left(\frac{1}{r}+\frac{1}{r'}\right)dS = 0 \tag{3}$$

The ground effect is included using an image method. Thus, $1/r_A$ in eq. (2) is the sum of $1/r$ and $1/r'$, where r is the distance from the point over the surface and r' the distance from the point over the image surface. The contribution of an additional control surface enclosing the wing and it's wake to the integral (2) can be estimated from the expansion of a general three-dimensional velocity potential in spherical harmonics, and it vanishes in the limit where this surface is an infinite distance from the body. The Dirichlet formulation requires that the source strength should be given as follows.

$$\sigma = -\vec{n} \cdot (\vec{V}_0 + \vec{v}_{rel} + \vec{\Omega} \times \vec{r}) \tag{4}$$

The geometry of the body is divided into surface panel elements. The panel corner points, collocation points and the outward normal vectors are identified. The the aerodynamic influence coefficient matrix can be constructed by specifying the no penetration boundary condition at each collocation point.

$$\sum_{k=1}^{N} C_{ik}\mu_k + \sum_{l=1}^{Nw} C_{il}\mu_l + \sum_{k=1}^{N} B_{ik}\sigma_k = 0 \tag{5}$$

where k is the counter for each panel on wing's surface and l is the counter for each panel on wing's wake surface.

The additional physical conditions, required for a unique solution, can be established by applying the two-dimensional Kutta condition along the three-dimensional trailing edge.

Wake Roll-Up Procedure

Since the vortex wake is force-free, each vortex must move with the local stream velocity. The local velocity can be computed at any point in the flow field summing over all surface and wake panels. Then, the velocity is computed at each wake corner points. The wake shape calculation proceeds from the first station to the last section downstream of the trailing edge as follows.

- The total velocities at the corner points in the first station are computed. The velocities are used to find the new location of corner points in the next station.
- The panels downstream of the current row are moved by the same amount as those at the current row.
- The modified AIC considering the change in wake shape is solved for the next solution.
- The computation is repeated until the last row of panels.
- The total velocities at all corner points of all the wake panels are evaluated. All the panels are aligned and repaneled. Repeat this step until the geometry of the wake is converged.

The step from one wake grid plane to the nest is performed using the Euler convection scheme with a pseudo time step Δt.

$$(\Delta x, \Delta y, \Delta z) = (u, v, w)_i \Delta t \tag{6}$$

To have more accurate solution, predictor/corrector cycle can be employed. For a point, W, in the Mth wake grid plane, the point in the next wake grid plane is [9]:

$$W_{M+1}^{j} = W_M + \left(\frac{\vec{V}^j}{V_X^j} \right) * DX \tag{7}$$

where $\vec{V}^j$ is the mean velocity across the interval for the Jth predictor/corrector cycle.

$$\vec{V}^j = \frac{(V_M + V_{M+1}^j)}{2} \tag{8}$$

V_M is the velocity at the upstream end, W_M, of the wake filament. V^j_{M+1} is computed at the point, W^{j-1}_{M+1}. $\vec{V}_X$ is not allowed to fall below a lower limit.

Results and Discussions

Fig. 1 shows the lift coefficient variations due to the change in the ground height. The ground height is defined as the distance from the wing's trailing edge to the ground. In the figure, the present results show good agreement with the computed results of Ref. 2. It can be deduced from the figure that, if the position of the maximum camber is placed toward the trailing edge, it has the effect of increasing the lift for the NACA wings.

Fig. 2 shows the lift coefficient variations due to the change in the angle of attack. In the figure, the present results show good agreement with the computed results of Ref. 2. When a wing is flying in close proximity to the ground, the aerodynamic characteristics of the wing become slightly nonlinear for the change in angle of attack [10].

In Fig.3, wake shapes behind wings in and out of ground effect is represented. Fig. 3(a) is the side view of wake shapes behind a wing at h/c=1.0 and another wing at h/c=0.05. The wing tip vortices behind wings in free flight are usually moving down due to the downwash induced by the generating wings. However, for wings flying in close proximity to the ground, the wake vortices are not developed fully because they are bounded by the ground. In Fig. 3(b), the rear view of the wake vortices developing behind wings in and out of ground effect

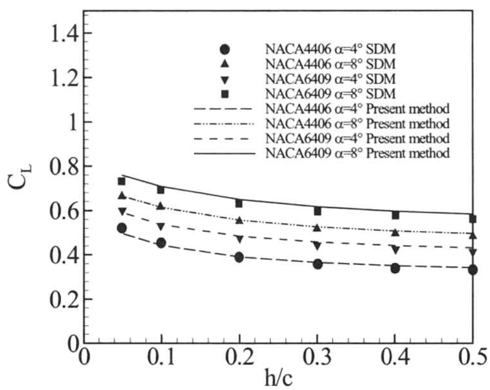


Fig. 1. The lift coefficients variations due the change in ground height.

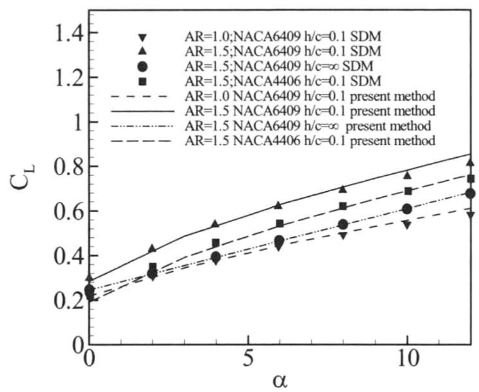
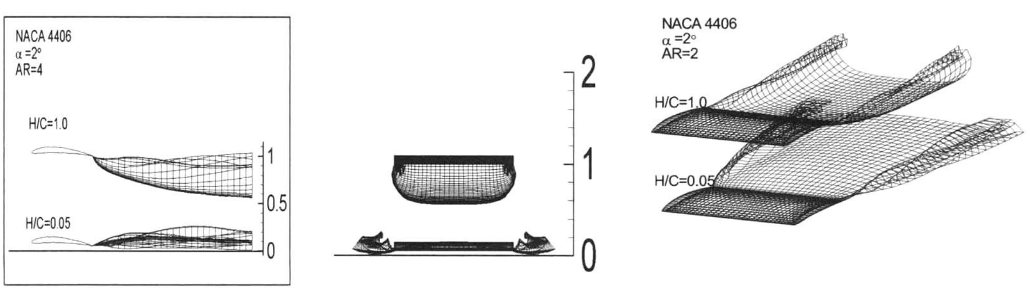
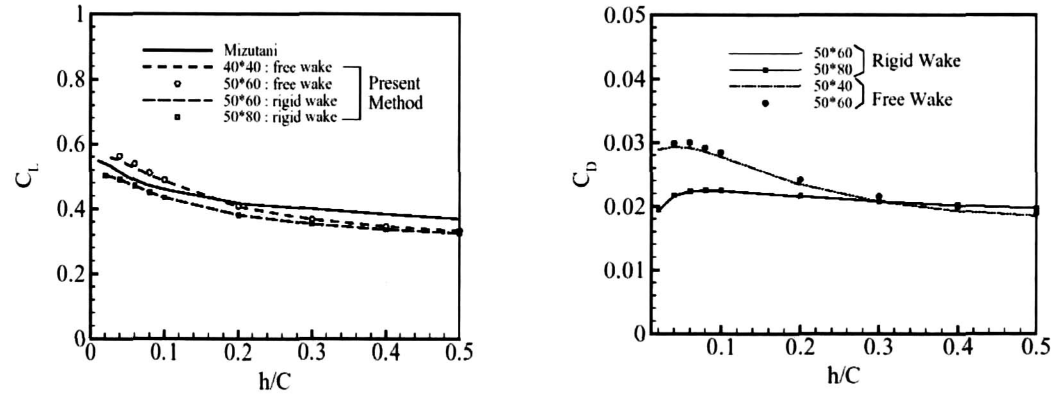


Fig. 2 The lift coefficients variations due the change in the angle of attack



(a) Side view (b) Rear view (c) Cabinet View

Fig. 3. Comparison of the wake shapes between wings in and out of ground effect.



(a) Lift coefficient (b) Drag coefficient

Fig. 4. Convergence Test: the variations of the aerodynamic coefficients of a NACA 4406 wing due to the change in the ground proximity.

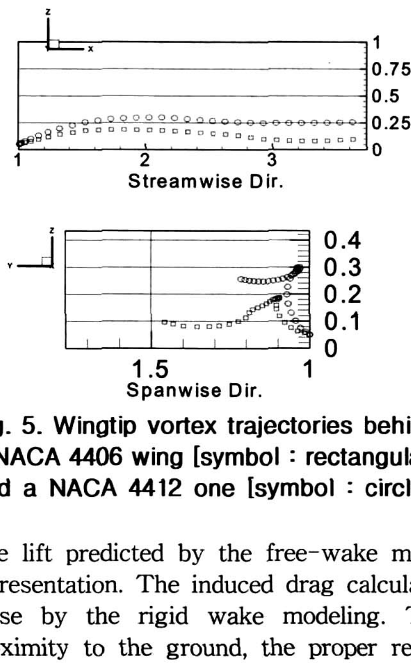


Fig. 5. Wingtip vortex trajectories behind a NACA 4406 wing [symbol : rectangular] and a NACA 4412 one [symbol : circle].

is shown. The tip vortices from the wing in ground effect move more outward in the spanwise direction than those from the wing out of ground effect. In Fig. 3(c), the cabinet view of the wake shapes for a NACA 4406 wing in ground effect is plotted compared to those for the same wing out of ground effect. In the figure, the wake behind the midspan firstly moves upward, then, keeps its altitude behind several chord lengths away from the wing's trailing edge.

Fig. 4 shows the convergence test results of the present method. When a wing is flying at high altitude from the ground, predicted values of the lift are independent of the wake modeling. However, for a wing in close proximity to the ground, the wake modeling has a significant effect on the aerodynamic characteristics of the wing. The lift predicted by the free-wake modeling has a larger value than that by the rigid-wake representation. The induced drag calculated by the freewake modeling are larger compared with those by the rigid wake modeling. Thus, it can be concluded that, for a wing in close proximity to the ground, the proper representation of the wing's wake is required to improve the numerical accuracy.

Fig. 5 shows the wingtip vortex trajectories behind NACA 4406 and NACA 4412 wings, respectively. In the figure, the trajectory of a NACA 4412 wing moves greater distances in the upward direction than that of a NACA 4406 wing. It is because the air trapped between the NACA 4412 wing at low angles of attack and its underlying surface form a venturi tube near the trailing edge and the accelerated flow there pushes the shear layer in the upward direction.

Conclusions

The effect of wake modeling on the aerodynamic characteristics of wings flying in close proximity to the ground is investigated. The accurate calculation of the induced drag coefficient is important in the vehicle's performance in take-off and landing, where the viscous effect is not so great. For the wings near the ground, the proper modeling of the wing wake using a freewake scheme improves the accuracy in predicting the aerodynamic characteristics of the wings. When the wings are flying in close proximity to the ground ($h/c<0.3$), induced drag force calculation is dependent on the wake modeling. The wingtip vortex trajectories of thick wings are shown to move upward farther than those of thin wings. The strong wingtip vortices from the symmetric thick wing induced more drag forces at low angles of attack comparing to those from the thin wings.

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