A Numerical Analysis of the Thickness-Induced Effect on the Aerodynamic Characteristics of Wings Moving Near Ground

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Abstract

A numerical method to simulate Wing-In-Ground(WIG) effects for the wings moving near ground is developed. The aerodynamic analysis scheme for the wings is based on a compressible non-planar lifting surface panel method and the WIG effect is included by images. The thickness-induced effect is implemented into the lifting surface panel method by using the teardrop theory. The numerical simulation is done for the rectangular wings by varying the ground proximity. The present method is validated by comparing the calculated aerodynamic coefficients with other numerical results and measured data, showing good agreements.

Key Word : Ground effect, Panel, Thickness

Introduction

Wing-In-Ground(WIG) effect is characterized by the increase in lift and the decrease in drag. The study on this phenomenon was firstly initiated since the beginning of the 20th century, relating to the take-off and landing of aircraft. Recent research on the ground effect has been motivated mainly by the introduction of a new concept for sea transporters called "WIG Vehicles" which cruise at speeds beyond the limit of conventional sea transporters or land vehicles.

Early studies on WIG effect were analytical or semi analytic. Wieselsberger[1] was the first who tried to solve this phenomena by using the image method, thus satisfying the no penetration boundary condition on the ground. Tomotika et al.[2], Havelock[3] and Green[4] used the conformal mapping method and found exact solutions for the flow around an airfoil near ground. Especially, Green[4] showed that camber tends to increase the lift, while the thickness tend to decrease it.

Panel methods have also been applied to the calculation of Wing-In-Ground effects for a wing moving near the surface. John and Scott[5] studied the ground effect on a spanloader by using experiments and Source-Doublet Method(SDM). Chun and Park[6] performed steady and unsteady panel method calculations. Their results showed that the ground effect for a wing above the waves is lower than above the flat ground. Mizutani and Kazuo[7] also calculated the aerodynamic characteristics of a wing moving near ground changing the thickness distributions. Goez et al.[8] used the PANAIR panel method for the aerodynamic analysis of a low aspect ratio rectangular wing with end plates and trailing edge flap deflections.

Katz[9] used a vortex-lattice method(VLM) that included a freely deforming wake to investigate the ground effect on the lift of wings used for a racing car. Nuhait and Mook[10] developed a general model of finite lifting surfaces in steady and unsteady ground effect.

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With the continuing development and application of Navier-Stokes codes, the number of researches using Navier-Stokes codes are increasing. One of these efforts is the results of Hirata and Kodama[11]. They applied a Navier-Stokes solver for calculations on a three-dimensional wing with end plates in ground effect.

To the author's knowledge, there are very few studies in the literature conducted on the ground effect of wings using the lifting surface panel method. In the present study, a numerical method based on a compressible non-planar lifting surface panel method developed by Han and Cho[12] is extended to investigate the thickness-induced effect on the aerodynamic characteristics of a wing moving in ground proximity. The WIG effect is included by the image method. The thickness-induced effect is implemented by using tear drop theory[13]. The object of the present study is to demonstrate the potential of the lifting surface panel method for the investigation of the thickness-induced ground effect on a wing moving in ground proximity.

Lifting Surface Panel Method

1. Formulation

Consider an initial value problem for linearized compressible flow in which the initial disturbances vanish away from the lifting surfaces. Taking a Laplace transform gives the usual form of the equations that one gets for simple harmonic motion, but with $i\omega$ replaced by the Laplace variable s[14]. Since the aerodynamic response(for bounded motion) should have no more than algebraic growth at larger time, the Laplace integrals will be well-defined for Re(s)>o. We shall define the transform in Re(s)<0 by analytic continuation so that the usual rules for analytic functions hold and the resolutions will be meaningful in the entire s plane.

A point on a lifting surface $\vec{x_0}$ with unit normal $\vec{n_0}$ is assigned a transformed pressure differential $\triangle p = \rho_\infty U_\infty P$. The lifting surface induces a transformed velocity at an arbitrary point $\vec{x}$, in an arbitrary direction $\vec{n}$, which is given by an integral over the lifting surface.

$$w(\vec{x}) = \int\int K(\vec{x}, \vec{x_0})\ P(\vec{x_0})\, dS \tag{1}$$

The kernel is the fundamental solution of the reduced wave equation corresponding to the velocity w induced at $\vec{x}$ by a point load applied at $\vec{x_0}$. In the standard problem, w is specified on the surface and we solve for the load P. The integral is discretized, for simplicity, by a piecewise constant approximation.

$$[w] = [C][P] \tag{2}$$

,where C is the integral of K over each panel, and P is to be thought of as a vector of loads on all panels. The problem then is to develop efficient methods for evaluating the coefficients C, with accuracy consistent with the discretization errors in Eq.(2)[14].

2. The WIG effect

Following Wieselsberger[1], the ground effect is included by the image method. The ground is simulated by placing the image of a wing below the ground plane at an equal distance of h from the ground as shown in Fig. 1. Two symmetrically positioned lifting surfaces are considered to create a straight streamline along the ground plane. In Fig. 1, γ is the dihedral angle, α is the angle of attack, c is the chord length and h is the height of a wing at a quarter chord from the leading edge of a wing to the ground.

3. The implementation of thickness induced effect

Consider a symmetric wing with a thickness distribution of $f_t(x, y)$ at zero angle of attack. The equation to be solved is the Laplace equation for the velocity potential. Then the approximate boundary condition to be fulfilled at the z=0 plane is

$$\frac{\partial \Phi}{\partial z}(x, y, 0\pm) = \pm \frac{\partial f_t}{\partial x} Q_\infty \tag{3}$$

The solution of this problem can be obtained by distributing basic solution elements of Laplaces equation. Because of the symmetry, a source/sink distribution can be used to model the flow, and should be placed at the wing section centerline. If point sources are distributed over the wings projected area on the x-y plane, the velocity potential at an arbitrary point(x,y,z) will be

$$\Phi(x, y, z) = -\frac{1}{4\pi} \int_{wing} \frac{\sigma(x_0, y_0) dx_0 dy_0}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + z^2}} \tag{4}$$

where $\sigma(x_0, y_0)$ is the strength of source elements on the area of $dx_0 dy_0$. (x_0, y_0) is the point at which a point source is located. The integration is done over the wing only(no wake). The normal velocity component at an arbitrary point can be obtained by differentiating Eq. (4) with respect to z.

By using a limit process,

$$w(x, y, 0\pm) = \pm \frac{\sigma(x, y)}{2} \tag{5}$$

Substituting Eq.(5) into the boundary condition results in

$$\sigma(x, y) = 2Q_\infty \frac{df_t}{dx}(x, y) \tag{6}$$

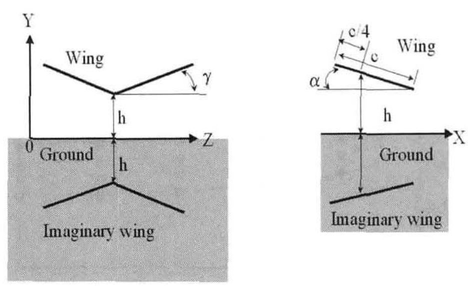

Fig. 1. Representation of a ground-plane image system for a lifting surface panel method.

So in this case the solution for the source distribution is easily obtained after substituting Eq.(6) into (4) for the velocity potential and differentiating to obtain the velocity field.

RESULT

The present results by using the numerical implementation of the thickness-induced effect to a previously developed lifting surface method[12] are validated by comparing them with those by other numerical methods and measured data.

In Fig. 2, the section lift coefficient for a NACA2415 airfoil is compared to the measured data[15]. To compare the present results with the 2-dimensional data, the calculation is done for a wing with an aspect ratio 100 and the result is obtained at the midspan. The number of panels used in this calculation are 300 in spanwise and 20 in chordwise direction, respectively. Fig. 2 shows that the present results show good agreement with the measured data.

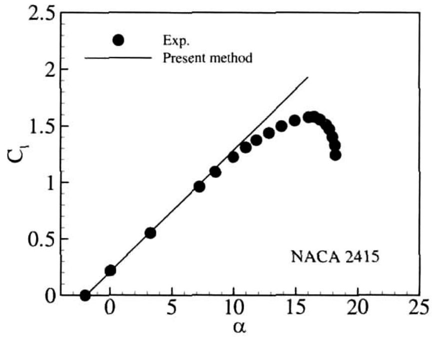

Fig. 2. The section lift coefficient as a function of the angle of attack for a NACA2415 airfoil.

In Fig. 3, the large increase in the wing's lift is shown when wings are close to the ground. Wings used for the calculation have an aspect ratio 1.5. In the figure, the present results show good agreement with those by SDM[6]. The wing with NACA4406 airfoil section has the same maximum camber with the wing with a NACA6409 airfoil section. It can be easily deduced from the results of Fig. 3 that the rearward maximum camber position for wings with the same maximum camber increases the lift.

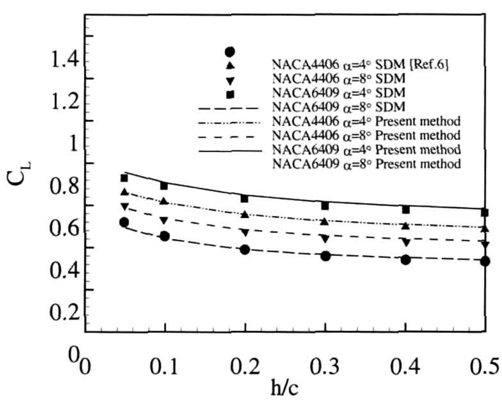

Fig. 3. The lift coefficients for rectangular wings with different airfoil sections in ground effect.

In Fig. 4, the lift coefficients for wings with aspect ratio 1.0 and 1.5 are plotted as a function of an angle of attack. In the figure, the present method is also validated by comparing the results with those by SDM[6]. The present results agree well with those of SDM calculations. In Fig. 4, the lift curve slope for a wing in close proximity to the ground(h/c=0.1) are steep at small angles of attack(α<3 degrees). For wings out of ground effect(for example, a wing with AR=1.5 and a NACA6409 airfoil section in the figure), this trend is invisible. This phenomenon shows the thickness-induced effect on a wing moving in close proximity to the ground, which will be shown more clearly later. In the thin wing calculations of the VLM(Vortex Lattice Method)[9] and the Lifting Surface Method of Han and Cho[12], the thickness-induced effect is neglected, thus the computed results deviate slightly from the measured data at small h[12].

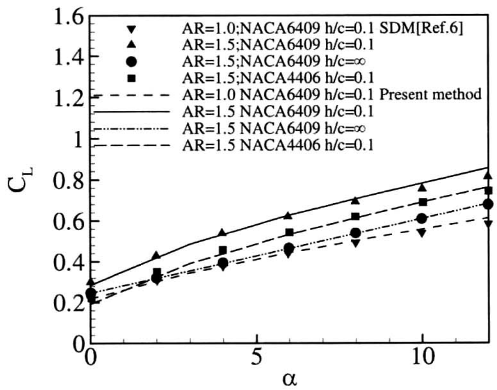

Fig. 4. The lift coefficients for rectangular wings as a function of the angle of attack.

In Fig. 5, the results for wings with various symmetric airfoil sections are presented and compared with the results of Mizutani[7]. A result for a flat wing in ground effect is also plotted for comparison. The increase in the thickness of an airfoil section decrease the lift, when the wing is flying in very close proximity to the ground. Especially, the wing with a NACA0012 airfoil section shows rapid decrease in the lift at h/c<0.1.

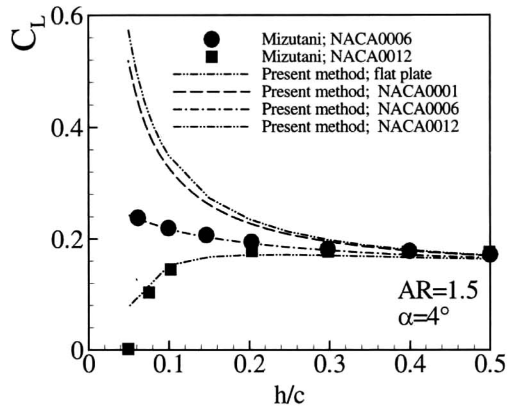

Fig. 5. The thickness effect for wings with the symmetric airfoil sections.

In Fig. 6, the lift coefficients for NACA wings with a 4-series airfoil section are plotted with the ground proximity. For a wing with NACA4406 airfoil section, the computational result by SDM of Mizutani[7] is included for comparison purpose. In the figure, the present results agree well with those of Mizutani[7]. Even for a thick wing with a nonsymmetric airfoil section(NACA4412), the lift decreases at small angles of attack as the wing is flying very near ground.

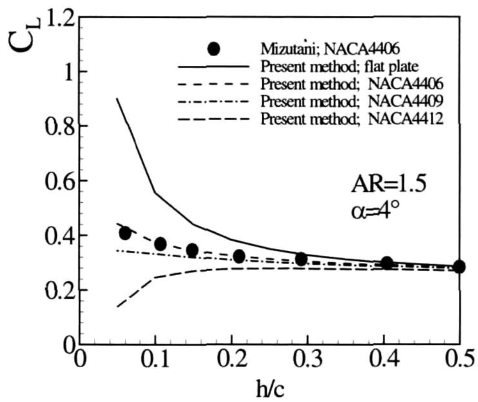

Fig. 6. The thickness effect for wings with the nonsymmetric airfoil sections.

The phenomena shown in Fig. 5 and Fig. 6 can be explained by the venturi effect. The bounded channel formed by the lower surface of the wing and the upper surface of the image wing has the shape of a venturi tube. The flow would accelerate between these two surfaces and reduce the pressures on those surfaces. The upper-surface pressure is almost unchanged, whereas the lower-surface pressure is markedly decreased. The venturi effect on the lower surface can completely negate the upwash effect of the ground plane and actually reduce the lift drastically very near the ground. For WIG vehicles that are proposed to operate at low h/c ratios, the reduction in lift(if present on the real configuration) would lead to hard handlings, instead of the cushioned landings that are anticipated due to favorable ground effect.

Conclusions

A numerical method to simulate Wing- In-Ground(WIG) effect for wings moving near ground is developed. The present method has been validated by showing that it produces results that are in good agreement with published results of other numerical methods and measured data.

The comparisons made with other numerical results and measured data show that the venturi effect occurs for thick wings and this venturi effect can actually reduce the lift drastically very near the ground.

The aerodynamic results show that the present method is useful in the calculation of the thickness-induced effect which is one of the crucial design parameters for WIG vehicles moving in close proximity to the ground.

Acknowledgement

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