Study on the Aerodynamic Characteristics of Wings Flying Over the Nonplanar Ground Surface

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Abstract

Aerodynamic analysis of NACA wings moving with a constant speed over guideways are performed using an indirect boundary element method (potential-based panel method). An integral equation is obtained by applying Green's theorem on all surfaces of the fluid domain. The surfaces over the wing and the guideways are discretized as rectangular panel elements. Constant strength singularities are distributed over the panel elements. The viscous shear layer behind the wing is represented by constant strength dipoles. The unknown strengths of potentials are determined by inverting the aerodynamic influence coefficient matrices constructed by using the no penetration conditions on the surfaces and the Kutta condition at the trailing edge of the wing. The aerodynamic characteristics for the wings flying over nonplanar ground surfaces are investigated for several ground heights.

Key Word : Wing-In-Ground Effect, Nonplanar Ground, Boundary Element Method

Introduction

The environmental problems such as the green house effect and the production of teratogenic constituents to human genetic damages become a serious issue all over the world. Those problems have their origin in the consumption of a huge amount of energy (fossil and atomic energy) to sustain a convenient way of life. The new human-friendly pollution-free vehicles may be a key solution to the environmental problems[1]. In recent years, a high speed guide way train (Aero-Train) has been proposed in Japan. The concept of Aero-Train[1] is created to establish the "Zero-Emission Vehicle". The drastic drag reduction is obtained by introducing the wing-in-ground (WIG) effect, so that the minimum fuel consumption ratio could be attained.

In Korea, an Aero-levitation electric vehicle (AEV)[2] was proposed as a novel form of the ground transport. The proposed Aero-levitation Electric Vehicle is another form of the over-the-ground-surface tracked WIG vehicle (TWIG)[3], propelled by counter rotating propellers using the electricity as the power resource. The TWIG is a tracked overland vehicle that flies in close proximity to the ground in a track (or guideway), achieving its guidance and levitation from aerodynamic forces. It is free from the surface conditions due to the ground rigidity. Thus, it can fly faster at a very low altitude compared with the over-the-water-surface type WIG vehicles.

To develop transporters such as an AEV flying over the channel, a numerical method is required for the reliable prediction of the aerodynamic characteristics of a wing in the guideway.

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Early studies on WIG effect were analytic. Wieselsberger[4] was the first who tried to solve this phenomenon by using the image method, thus satisfying the no penetration boundary condition on the ground. Tomotika et al.[5], Havelock[6] and Green[7] used the conformal mapping method and found exact solutions for the flow around an airfoil near ground.

Panel methods have also been applied to the calculation of Wing-In-Ground effects for a wing moving near the surface. John and Scott[8] studied the ground effect on a spanloader by using experiments and Source-Doublet Method(SDM). Chun and Park[9] 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[10] also calculated the aerodynamic characteristics of a wing moving near ground changing the thickness distributions. Goez et al.[11] used the PANAIR panel method for the aerodynamic analysis of a low aspect ratio rectangular wing with end plates and trailing edge flap deflections. A numerical method based on a compressible non-planar lifting surface panel method is developed by Han and Cho[12]. The thickness-induced effect on the aerodynamic characteristics of a wing moving near the ground is investigated.

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[13]. They applied a Navier-Stokes solver for calculations on a three-dimensional wing with end plates in ground effect. However, to the author's knowledge, there are very few studies in the literature conducted on the ground effect of wings flying over the nonplanar ground.

The aim of this study is to develop a numerical method using a boundary element method. The aerodynamic coefficients of NACA wings are investigated for variable distances from the ground surface to the trailing edge of the wings' root chord. The aerodynamic characteristics of wings flying over the rail are compared with those of wings flying inside the channel.

Formulations

Flow is assumed to be inviscid, incompressible and irrotational over entire flow fields, excluding a wing, its wake and the solid ground. Then, a velocity potential can be defined in the flow domain and the continuity equation becomes Laplace equation of the velocity potential.

$$\nabla^2\phi=0, \quad V=\nabla\phi \tag{1}$$

Consider a body with known boundaries S_B (wing surface), S_W(wake surface), S_G(ground surface) and S_∞(outer boundary) as shown in Fig. 1. The general solution to eq. (1) can be constructed by applying Green's identity to the fluid domain.

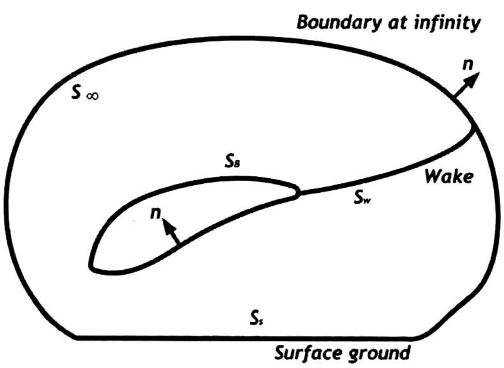


Fig. 1. Flow domain and boundary surfaces

Thus, eq. (1) becomes

$$\phi(P)=-\frac{1}{4\pi}\int\int_S\left[\frac{1}{r}\frac{\partial\phi_Q}{\partial n}-\phi_Q\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right]dS \tag{2}$$

where P represents an arbitrary point in space and Q is a point on the boundary. A source and a dipole can be represented as potential derivatives and potential differentials.

$$\sigma=\frac{\partial\phi_Q}{\partial n}=\frac{\partial\phi_{in}-\partial\phi_{out}}{\partial n} \tag{3}$$

$$\mu=\phi_Q=\phi_{in}-\phi_{out} \tag{4}$$

To find the unique solutions of eq. (1), several following conditions should be satisfied.

A. The flow disturbance, due to the wing's motion through the fluid, should vanish far from the wing. This boundary condition can be satisfied automatically by specifying sources and dipoles as the singularity distributions.

$$\vec{V}_\infty = \nabla \phi = 0, \quad at \ S_\infty \tag{5}$$

B. Zero normal flow across the solid boundaries.

$$V_n = \frac{\partial \phi}{\partial n} = \vec{n} \cdot \vec{V} = 0 \tag{6}$$

where V_n is the normal to the body's surface. If $\frac{\partial \Phi}{\partial n} = 0$ for a enclosed body, then the potential inside the body will not change[15].

$$\Phi_i = const. \tag{7}$$

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 specification of Dirichlet boundary condition on a wing and the ground surface will have the form as follows,

$$\int\int_{wing} \sigma \frac{1}{r} dS + \int\int_{surface} \sigma \frac{1}{r} dS + \int\int_{wing+wake} \mu \frac{\partial}{\partial n}\left(\frac{1}{r}\right) dS + \int\int_{surface} \mu \frac{\partial}{\partial n}\left(\frac{1}{r}\right) dS = 0 \tag{8}$$

C. The Kutta condition. This condition at the trailing edge of the wing is satisfied by specifying the strengths of doublets as zero

$$\phi_{wake} = \phi_{upper} - \phi_{lower} \tag{9}$$

From eq.(6) and(7), the source strength is given as follows.

$$\sigma = -\vec{n} \cdot \vec{V_\infty} \tag{10}$$

The unknown strengths of the potentials are determined by inverting the aerodynamic influence coefficient matrices.

$$\sum_{k=1}^{N} C_k \mu_k + \sum_{l=1}^{M} C_l \mu_l + \sum_{k=1}^{N} B_k \mu_k = 0 \tag{11}$$

$$\sum_{k=1}^{N} A_k \mu_k = -\sum_{k=1}^{N} B_k \sigma_k \tag{12}$$

The surface velocities over the wing surfaces are obtained using the potential strengths and the surface static pressures are calculated from Bernouilli's equation. Then, the aerodynamic forces on the wings are calculated by integrating the pressure values over the wing's surface.

Results and Discussions

The calculated pressure coefficients over a NACA 65A010 wing with an aspect ratio of 1 are shown in Fig. 2. Present results are compared with other numerical ones by Kikuchi [14]. In Fig. 2, the pressure coefficients are plotted at the mid span of the wing. It is shown in the figure that the present results are in good agreement with other numerical ones.

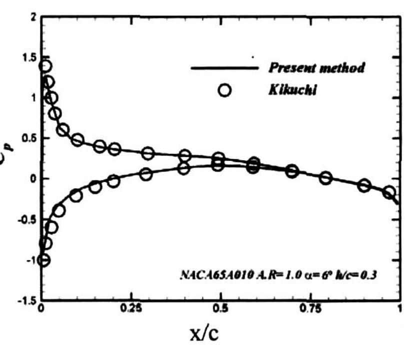
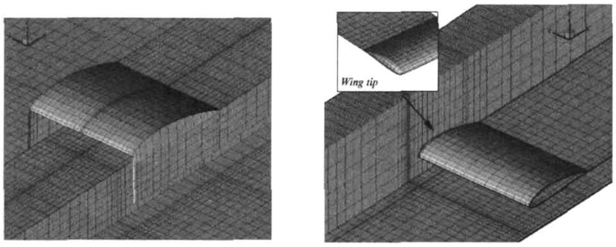


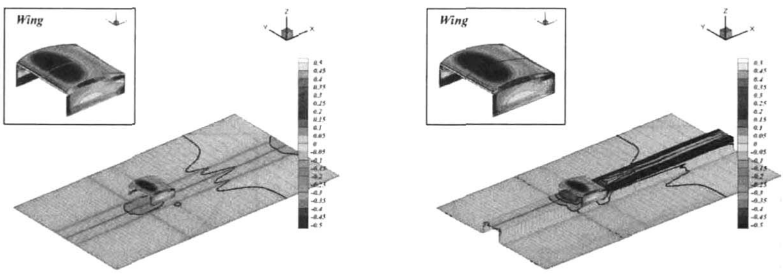
Fig. 2. Pressure coefficient values over a NACA wing at an angle of attack of 6 and h/c=0.3

Fig. 3 shows computational models used for the aerodynamic analysis of wings flying over the nonplanar ground surfaces. Fig. 3(a) shows a



(a)Rectangular rail (b) Rectangular channel

Fig. 3. Computational model for the non-planar ground surface modeling



(a) planar ground (b) nonplanar rail

Fig. 4. Static pressure contour: AR=1.0, =4, h/c=0.5, endplate thickness=0.015c, endplate height=0.3c

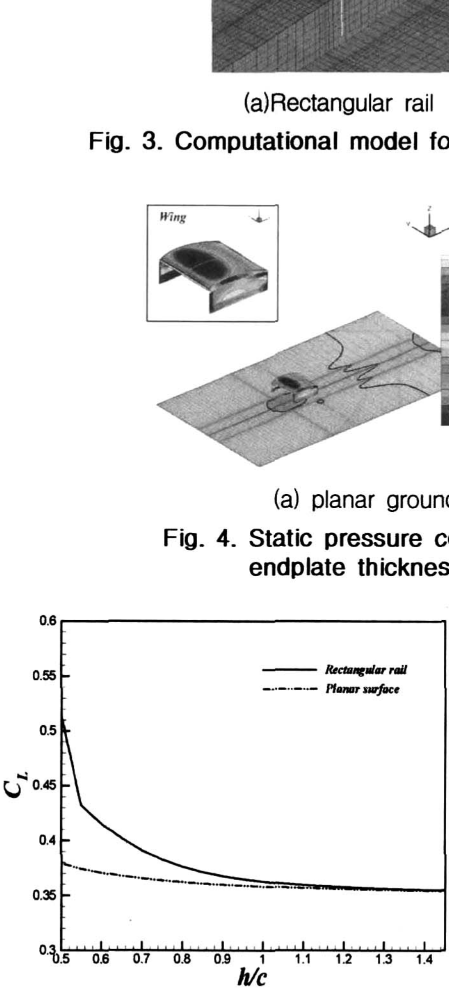


Fig. 5. Ground effect on the lift coefficient of a wing flying over the rectangular rail

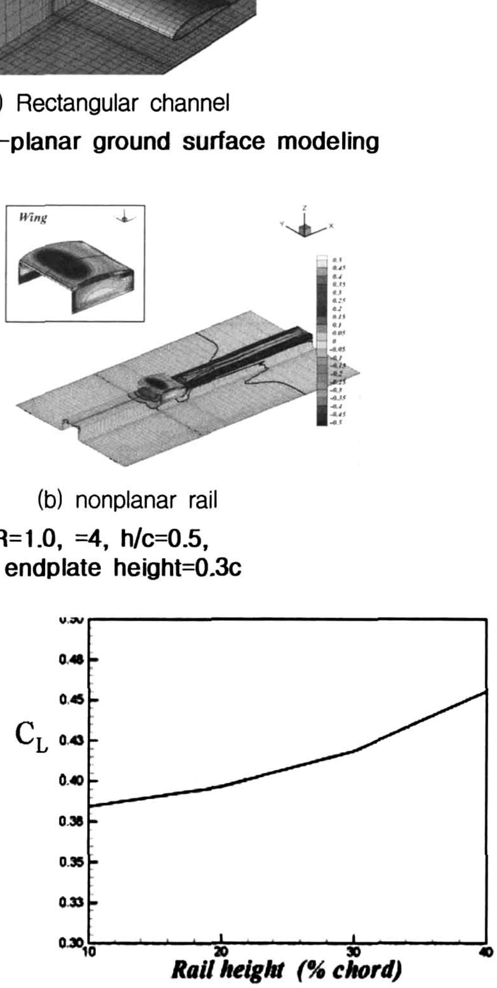
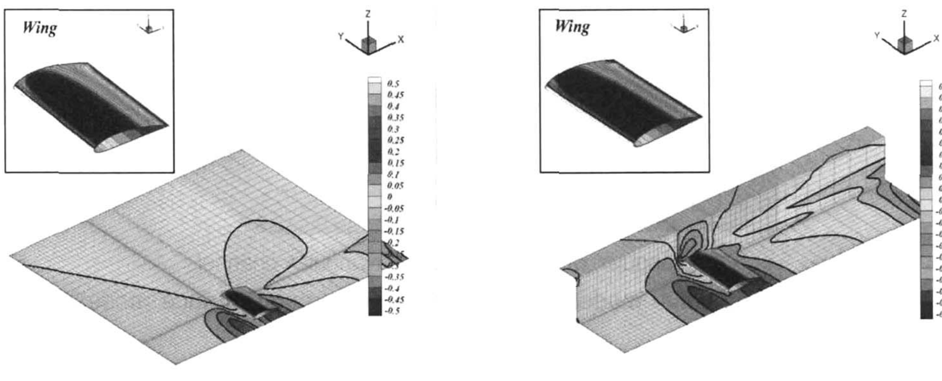


Fig. 6. Rail height effect on the lift coefficient of a wing flying over the rectangular rail

rail-type ground surface. Fig. 3(b) shows another channel-type ground surface.

Fig. 4 shows static pressure contours for a NACA6409 wing with AR=1.0 at α=4° and h/c=0.5. Endplates have the maximum thickness of 0.015c, and the endplate height is 0.3c. Static pressure contours for the wing flying over the flat ground is shown in Fig. 4(a), whereas the static pressure contours for the wing flying over the rail is shown in Fig. 4(b). From the figures in Fig. 4(a) and (b), it can be deduced that the ground effect increase the static pressure between the wings and their underlying surfaces.

Fig. 5 shows that, at the same ground proximity, the lift of a NACA 6409 wing with AR=1.0 at α=5° flying over the rail is larger than that of the wing flying over the flat ground. It can be concluded that the rail-type nonplanar ground surface has an effect of increasing the lift coefficient of the wing.



(a) planar ground (b) nonplanar channel

Fig. 7. Static pressure contours(a NACA4415 wing with AR=3.1 at α=2° and h/c=0.3)

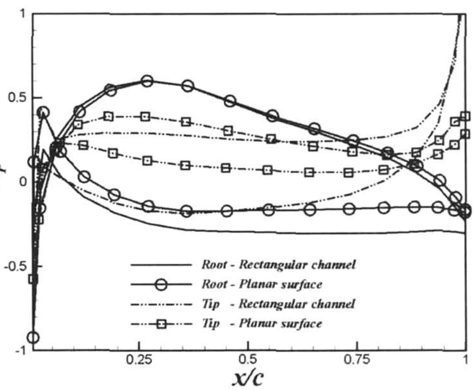


Fig. 8. Pressure coefficients with planar and non-planar ground effects ; NACA4415, AR=3.1, α=2°

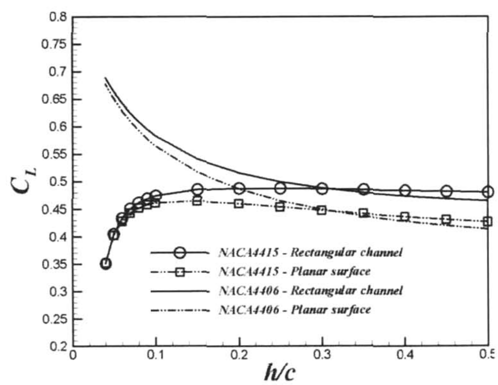


Fig. 9. Thickness effect on lift coefficients with planar and non-planar ground effects(wings with AR=3.1 at α=2°)

Fig. 6 shows the rail height effect on the lift coefficient of the same wing in Fig.5 at a fixed ground height. In the figure, the rail height is represented as the percentage of the chord. It can be deduced from the figure that the close proximity of the wing to the top surface of the rail increase the lift coefficient of the wing.

Fig. 7 shows the static pressure contours for a NACA4415 wing with AR=3.1 at α=2° and h/c=0.3. The static pressure contours for wings flying over the flat ground and the channel are shown in Fig. 7(a)and Fig. 7(b), respectively. At each case, the ground effect increase the pressure between the wings and their underlying ground surfaces. It can be deduced that the nonplanar ground surface traps much air than the planar ground, and this has an effect of producing additional lift increments.

In Fig. 8, the pressure coefficients at the root and tip of a NACA 4415 wing with AR=3.1 at α=2° are plotted along the airfoil's surface. From the pressure coefficient distributions over the sidewall of the channel, it can be concluded that the air is enclosed by the sidewall, the wing and the ground and thus the trapped air increase further the ground effect compared to the wing flying over the flat ground.

In Fig. 9, the lift coefficients of a NACA 4415 wing is shown to be decreased at small ground proximity. In contrast to this, the lift coefficient of the NACA 4406 wing is increased for the same ground height. For thick wings placed near the ground at a small angle of attack, the ground has the effect on producing the negative lift (down force)[8]. The phenomena shown in Fig. 9 can be explained by the venturi effect. The bounded channel formed by the lower surface of the wing and the ground surface 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.

Conclusions

The usefulness of the present method for the aerodynamic analysis of wings flying over the nonplanar ground surface is shown. The wing's lift is increased when the wing is flying over the ground. The nonplanar ground surfaces, rail and channel, have the effect of blocking the trapped air between the wing and its underlying surface. Thus, wings flying over the nonplanar ground experience more increments in the lift force comparing to those flying over the flat ground surface.

The effect of the rail height for the wing positioned at a fixed ground height is to reduce the ground height, thus to increase the lift. Thick wings at a small incidence angle experience the negative lift (down force).

Acknowledgement

This work was supported by grant No. (R01-1999-000-00265-0) from the Basic Research Program of the Korean Science and Engineering Foundation.

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