Steady Aerodynamic Characteristics of a Wing Flying Over a Nonplanar Ground Surface Part II : Channel

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The steady aerodynamic characteristics of a wing flying over a channel are investigated using a boundary-element method. The present method is validated by comparing the computed results with the measured data. Compared with a flat ground surface, the channel fence augmented the lift increase and induced drag reduction. When the fence is lower than the wing height, the gap between the wingtip and the fence does not affect the aerodynamic characteristics of the wing much. When the fence is higher than the wing height, the close gap increased the lift. The induced drag is reduced when the wing is placed near the ground or at the same height as the fence. It is believed that present results can be used in the conceptual design of the high-speed ground transporters flying over the channel.

Key Words : Wing In Ground Effect, Channel-type Guideway, Boundary Element Method, High Speed Ground Transporter

Nomenclature

Roman Symbols

AR : Aspect ratio, S/b^2
b : Wing span, m
c : Chord length, m
C_L : Lift coefficient
C_{Di} : Induced drag coefficient
C_p : Pressure coefficient
f : Fence height, m
h : Distance between the wing's trailing edge and the channel ground surface, m
S : Wing area
t : Gap between the wingtip and the fence, m

Greek Symbols

α : Angle of attack (A.O.A.), degree
Φ : Velocity potential

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1. Introduction

Recently, there have been worldwide efforts to develop new conceptual vehicles, focused on increasing efficiency and economy of shipping operation by using the wing in ground effect (WIG). Some of them have been built or are under consideration. For sea transporters, the wings in ground effect vehicles (WIGVs) are flying on a cushion of relatively high-pressure air between a wing and its underlying water surface. The developments of these high-speed ground transporters have a long history. Ollia (1980) and Hooker (1989) published historical reviews of WIGVs and technological knowledge necessary to develop these vehicles. Rozhdestvensky (2000) presented an extensive literature review on the WIGV development. Most of the WIGVs are water based or amphibious. The water based WIG vehicles have water contact during take-off and landing. Thus there occurs a power mismatch between take-off and cruise.

Several conceptual land-based WIGVs have also been proposed. Himcke (1997) proposed an over-the-ground-surface type WIGV which is called as AeroLev. In recent years, a high-speed guide way train (Aero-Train) has been proposed in Japan (Kono and Kohama, 1994; Kohama et al., 2000). The drastic drag reduction is obtained by introducing the WIG so that the minimum fuel consumption ratio could be attained. An Aero-levitation Electric Vehicle (AEV) has been proposed as a novel form of ground transportation (Han et al., 2005). It is worth noting that in the cruising mode of operation in close proximity to the ground, the qualities of a transport in terms of lift-to-drag ratio, static and dynamic stability, controllability, and ride comfort are extremely sensitive to design decisions adopted (aerodynamic configuration, geometry of lifting surfaces, takeoff and landing devices, cruise engines, automatic control system) (Han, 2003). In case of the design of such unconventional vehicles for which restricted prototype data exist, a rational approach should reflect the essential features of the vehicle under consideration.

Even though the phenomenon related to the aerodynamic characteristics of wings in ground effect has been revealed for last three decades with the development of WIGVs, only a very limited amount of research has been done so far on Tracked Wing-In-Ground effect vehicles (TWIGs) (Sankrithi, 1983). The mathematical model employed for the purpose of conceptual and preliminary design should meet certain requirements, in particular be sufficiently similar to a real and include most essential factors; secure the possibility of fast, inexpensive, and interactive evaluation of the quality of the system; be tailored for the application of optimization procedures concerning the economic viability of a transportation system, reserves of stability, etc. Han et al. (2006) investigated the steady aerodynamic characteristics of NACA wings flying over the rail. The channel-type guideway is also promising that it can be used to augment the ground effect by trapping the air between the underneath of the wing and the ground, and the fence.

The objective of this paper is to develop a boundary element method (panel methods) that can predict the aerodynamic characteristics of a wing flying inside the channel type nonplanar ground surface and to investigate the effect of the basic configuration parameters such as channel width, fence height, and wing height on the aerodynamic characteristics of flying wings inside the channel.

2. Boundary-Element Method

The assumptions and limitations of the boundary-element method (BEM) are discussed in detail (Han et al., 2006). Using the BEM, the aerodynamic characteristics of the three-dimensional arbitrary-shape bodies can be obtained with less computing time than the other computational fluid dynamics. Only the discretization of the body surfaces is required without setting up any further grid systems. The computed results do not depend much on the grid quality. Discretizing the surfaces with a large number of small plane quadrilateral elements (N body surface panels, N_W additional wake panels and N_G ground surface panels) and imposing the Dirichlet boundary condition on each of the N collocation points will have the following form:

$$\sum_{K=1}^{N}\frac{1}{4\pi}\int_{bodypanel}\mu n\cdot\nabla\left(\frac{1}{r}\right)dS+\sum_{K=1}^{N}\frac{1}{4\pi}\int_{wakepanel}\mu n\cdot\nabla\left(\frac{1}{r}\right)dS$$
$$+\sum_{K=1}^{N_G}\frac{1}{4\pi}\int_{surfacpanel}\mu n\cdot\nabla\left(\frac{1}{r}\right)dS-\sum_{K=1}^{N_G}\frac{1}{4\pi}\int_{surfacpanel}\sigma\left(\frac{1}{r}\right)dS \quad (1)$$
$$-\sum_{K=1}^{N_G}\frac{1}{4\pi}\int_{surfacpanel}\sigma\left(\frac{1}{r}\right)dS=0$$

The integration in (1) is limited now to each individual panel element representing the influence of this panel on point P. After computing the influence of each panel on each other panel, Eq. (1) for each point P inside the body becomes

$$\sum_{K=1}^{N} C_{ik}\mu_k + \sum_{l=1}^{N_W} C_{il}\mu_l + \sum_{m=1}^{N_G} C_{im}\mu_m + \sum_{k=1}^{N} B_{ik}\mu_k + \sum_{m=1}^{N_G} B_{im}\sigma_m = 0 \tag{2}$$

Here, the source strength is defined as

$$\sigma = \vec{n} \cdot \vec{V}_\infty \tag{3}$$

where $\vec{n}$ is the unit normal and $\vec{V}_\infty$ is the total kinematic velocity due to the motion of the arbitrary bodies. To fix the amount of the circulation of the wing, the two-dimensional Kutta condition is specified at the wing's trailing edge. Consequently, for each collocation point P, a linear algebraic equation containing N unknown singularity variables μ_k can be derived :

$$\sum_{K=1}^{N} A_k\mu_k + \sum_{m=1}^{N_G} A_m\mu_m = -\left(\sum_{K=1}^{N} B_k\sigma_k + \sum_{m=1}^{N_G} B_m\sigma_m\right) \tag{4}$$

The unknown strengths of the potentials are determined by inverting the aerodynamic influence coefficient matrices. The surface velocities over the wing surfaces are obtained using the potential strengths. Using the central differencing scheme, tangential components of the perturbation velocity are as follows.

$$\begin{aligned} v_l &= \frac{\partial \mu}{\partial l} = \frac{1}{2\Delta l}(\mu_{l+1} - \mu_{l-1}) \\ v_m &= \frac{\partial \mu}{\partial m} = \frac{1}{2\Delta m}(\mu_{m+1} - \mu_{m-1}) \\ v_l &= -\sigma \end{aligned} \tag{5}$$

where l, m, n represent the local coordinate systems (see Figs. 1 and 2). If the strength of the doublet is assumed as the polynomials of 2nd order (VSAERO),

$$\mu = as^2 + bs + c \tag{6}$$

then, the tangential components of the perturbation velocity along the body surface are determined from simple algebraic derivations.

$$\begin{aligned} v_l &= (SP \cdot \Delta P - TM \cdot \Delta Q)/TL \\ v_m &= \Delta Q \end{aligned} \tag{7a}$$

$$\begin{aligned} \overrightarrow{\Delta Q} &= (D1 \times S3 - D3 \times S1)/(S3 - S1) \\ \overrightarrow{\Delta P} &= (D4 \times S2 - D2 \times S4)/(S2 - S4) \end{aligned} \tag{7b}$$

where $S1 = -(SQ_{N1} + SQ_K)$, $S2 = (SQ_K + SQ_{N2})$,

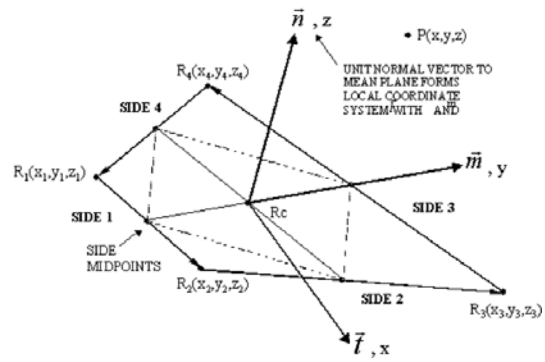


Fig. 1 The nomenclature for the velocity components on the surface

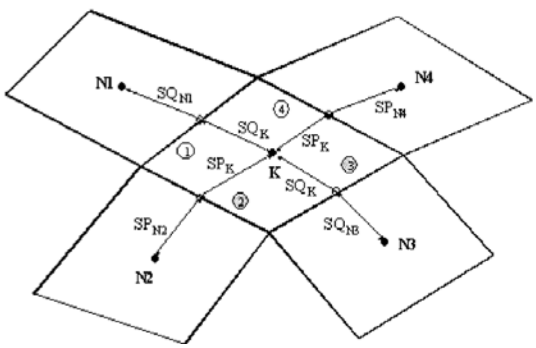


Fig. 2 The nomenclature for Eq. (9)

$S3 = (SQ_K + SQ_{N3})$, $S4 = -(SQ_K + SQ_{N4})$, $D1 = (\mu_{N1} - \mu_K)/S_1$, $D2 = (\mu_{N2} - \mu_K)/S2$, $D3 = (\mu_{N3} - \mu_K)/S3$, and $D4 = (\mu_{N4} - \mu_K)/S4$. The total velocity at the control point P is

$$\overrightarrow{Q_P} = \overrightarrow{V_{kine}} \cdot (l, m, n)_P + (v_l, v_m, v_n)_P \tag{8}$$

where $\overrightarrow{V_{kine}}$ is the kinematic velocity. The surface static pressures are calculated from Bernouilli's equation.

$$C_p = 1 - |\overrightarrow{Q}|^2 / |\overrightarrow{V_{kine}}|^2 \tag{9}$$

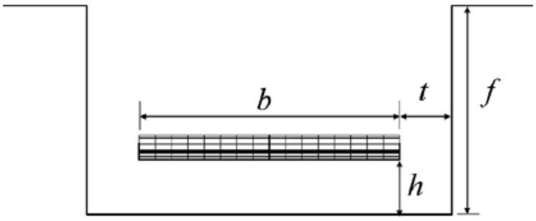
The aerodynamic force on the panel element P is

$$\Delta\overrightarrow{F_P} = -C_p(P)\Delta S_p \overrightarrow{n_p}\left(\frac{1}{\rho}|\overrightarrow{V_{kine}}|^2\right) \tag{10}$$

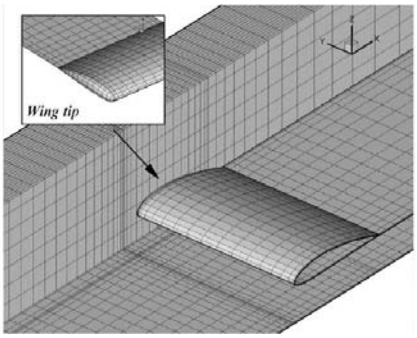
The net aerodynamic forces on the wing are calculated by integrating the pressure values over the wing's surface.

3. Results and Discussion

Figure 3 shows the nomenclature and computa-

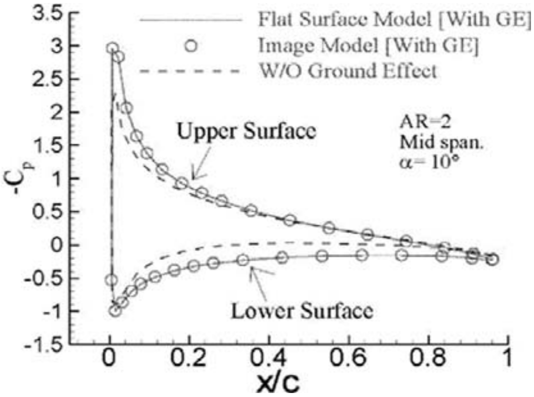


(a) Nomenclature

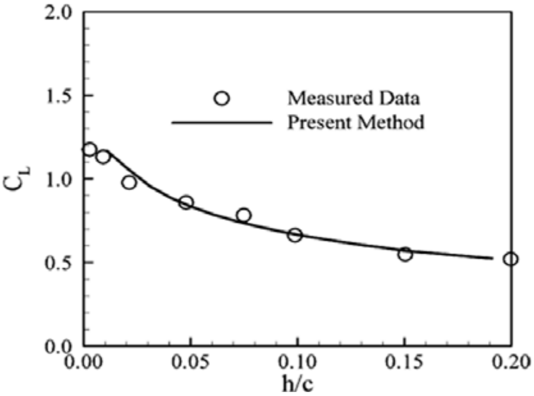


(b) Computational model

Fig. 3 The nomenclature and computational model for a wing flying over a channel



(a) Pressure coefficient values over a NACA wing at h/c=0.3



(b) Lift coefficient of a body in a channel (William and William, 1976)

Fig. 4 Validation of the present method

tional model of a wing flying inside a channel. The channel is composed of a channel ground surface, two side walls (fences). The wing is assumed to cruise at the wing height of h that is the distance between the wing's trailing edge and the channel ground surface. The fence height is represented as f whereas the gap between the wingtip and the fence is defined as t.

In Fig. 4, present method is validated using self-consistency test and comparing computed results with measured data. Figure 4(a) shows that the present results using the flat surface ground model agree well with the results from image method. Figure 4(b) shows the lift coefficient values of a body flying in a channel (William and William, 1976). As shown in Fig. 4(b), the present results are in good agreement with the measured data. Thus, it can be deduced that present method can be applied to the simulation of the wing flying inside a channel.

In Fig. 5, the chordwise pressure coefficient distributions at the root and tip of a NACA 4415 wing are plotted along the wing surface. As shown in the figure, the pressure coefficient on the pressure side of the wing inside the channel

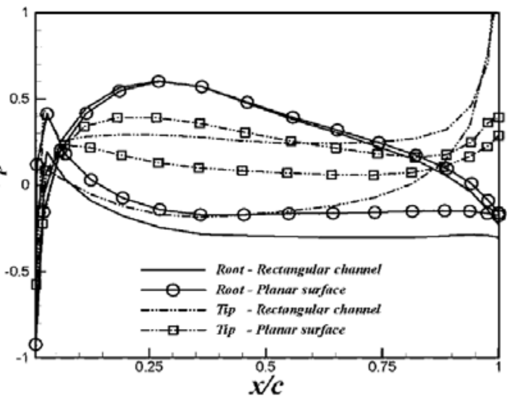
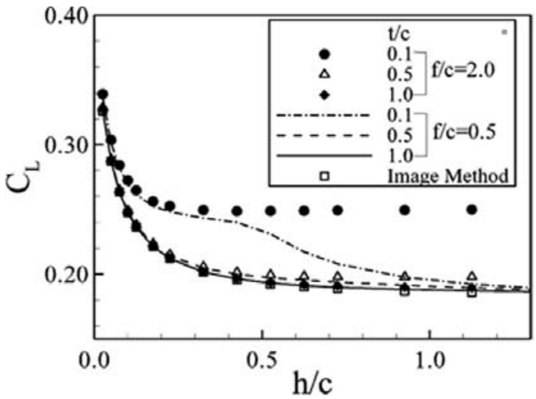


Fig. 5 Pressure coefficients with planar and non-planar ground effects; NACA4415, AR=3.1, $\alpha=2°$

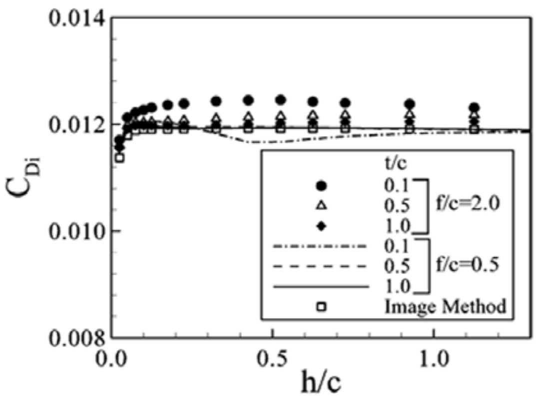
has larger values than that of a wing flying over the flat ground. It can be deduced from the figure that the trapped air under the wing enclosed by the sidewall and the ground results in the augmentation of WIG effect further compared to the case of the wing flying over the flat ground.

Figure 6 shows the aerodynamic characteristics of rectangular NACA 4406 wings flying inside the channel. The wings have an aspect ratio of 1 and moving at an angle of attack of 2 degree. The gap (t) is changing from 0.1 c to 1.0 c. The fence height effect are tested for the two cases of f/c= 0.5 and 2.0. It can be deduced from the computed results that cambered wings flying over the flat ground experiences the increase in the lift and the decrease in the induced drag. When the fence is higher than the wing and the gap between the wing and the fence is narrow (t/c=0.1), the lift is augmented more than any other cases. In case of f/c=0.5, the lift increases suddenly only if the wing is lower than the fence and the gap is narrow (t/c=0.1). Figure 6 (b) shows the variation of the induced drag for the change of the wing height. When the wing is flying higher than the fence, the induced drag is less than any other cases investigated in this study. It can be deduced from the Fig. 6 that, only if the gap is narrow (t/c= 0.1 in this study), the relative height of the wing to the fence is crucial to the aerodynamic characteristics of the wing flying over the channel.

Figure 7 shows the effects of both the fence height and the gap on the aerodynamic characteristics of a NACA 4406 wing flying inside a channel. The wing height is equal to 0.8 c. When the gap is less than 0.5 c, the fence height does not significantly affect the aerodynamic characteris-

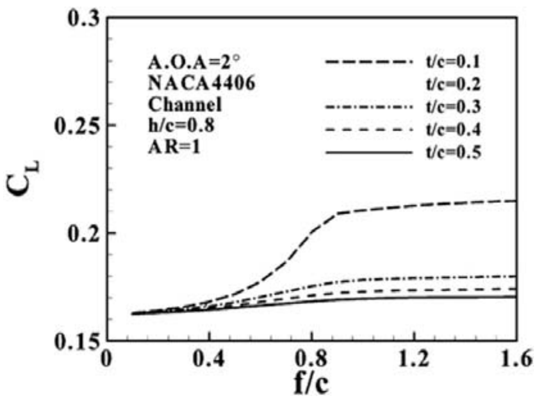


(a) Lift coefficient

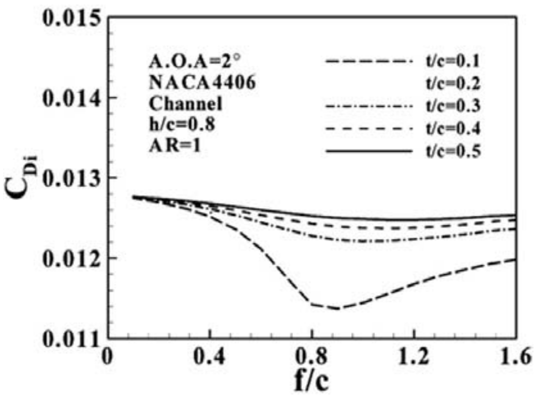


(b) Induced drag coefficient

Fig. 6 Effect of the gap on the aerodynamic characteristics of a NACA 4406 wing flying inside a channel



(a) Lift coefficient



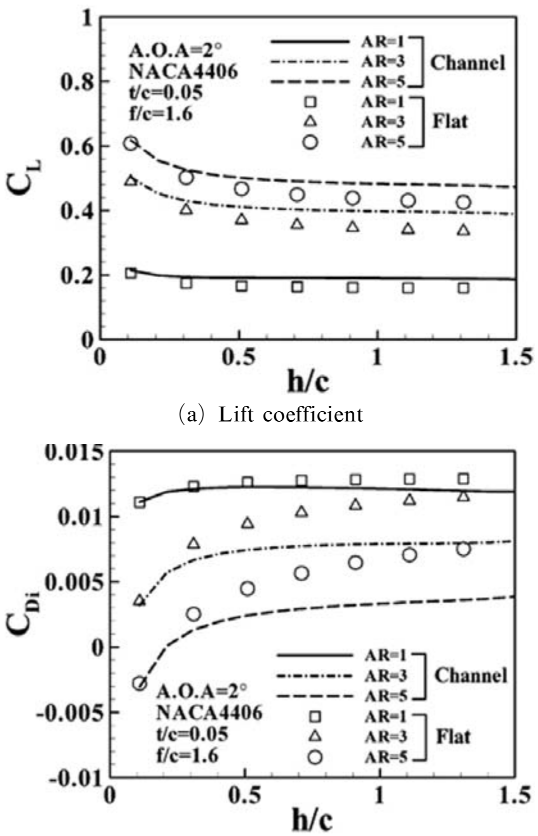
(b) Induced drag coefficient

Fig. 7 Effect of both the fence height and the gap on the aerodynamic characteristics of a NACA 4406 wing flying inside a channel tics of the wings. In case of the small gap (t/c< 0.5), the aerodynamic characteristics of the wings change much due to the variation of the fence height. The wing flying with a narrow gap produces larger lift and smaller induced drag with more nose-down pitching moment compared with the wing flying with a wide gap. When the fence is lower than the wing, the gap does not affect much the aerodynamic characteristics of the wing. When the fence is higher than the wing, the decrease in the gap has an effect of increasing the lift and the nose-down pitching moment. The minimum induced drag can be obtained when the wing height is almost the same as the fence height at the smallest gap.

Figure 8 shows that the wing aspect ratio has an effect of augmenting this ground effect. Inside the channel with the higher fence than the wing, the ground effect on the wings is larger than the case of the wings flying over the flat ground.

Figure 9 shows the thickness effect on the aerodynamic characteristics of NACA wings flying inside the channel. In the figure, it is shown that the thickness has an effect of decreasing the lift of a wing near the ground (h/c<0.5). At the same ground height, the thick wing has the larger induced drag and nose-up pitching moment than the thin wing.

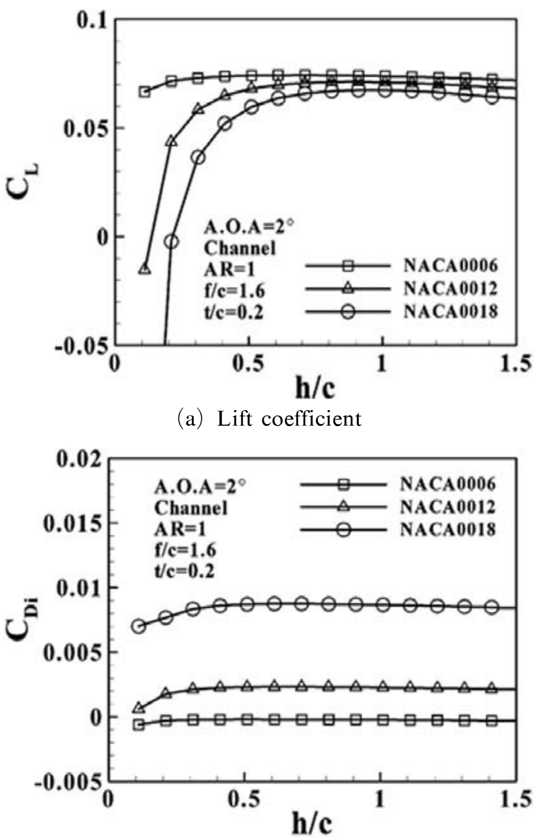
Figure 10 shows the camber effect on the aerodynamic characteristics of NACA wings flying inside the channel. Compared to a wing with a symmetric airfoil section, cambered wings have larger lift and induced drag with the augmented nose-up pitching moment. The maximum camber has an effect of increasing the lift, the induced drag, and the nose-up pitching moment.



(a) Lift coefficient

(b) Induced drag coefficient

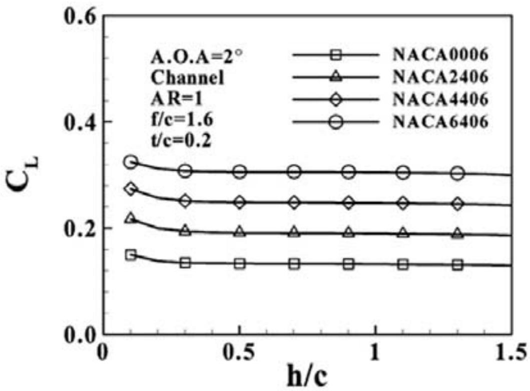
Fig. 8 Aspect ratio effect on the aerodynamic characteristics of the wing flying inside the channel



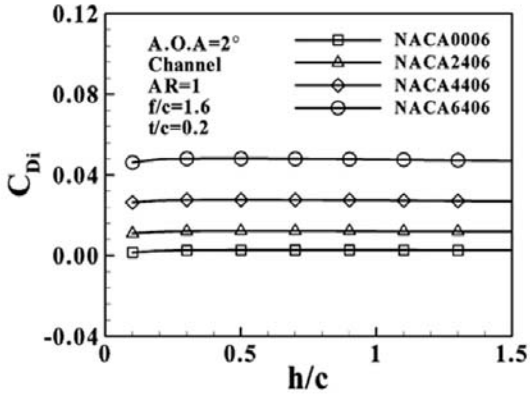
(a) Lift coefficient

(b) Induced drag coefficient

Fig. 9 Thickness effect on the aerodynamic characteristics of a wing flying inside a channel



(a) Lift coefficient



(b) Induced drag coefficient

Fig. 10 Camber effect on the aerodynamic characteristics of a wing flying inside a channel

4. Conclusions

A study of the aerodynamic characteristics of a NACA wing flying over the channel is done using a boundary element method. For the investigated cambered wings, the ground has an effect of the increase in the lift, the decrease in the induced drag, and the increase in the nose-down pitching moment. The thickness has an effect of decreasing the lift and increasing the induced drag. The maximum camber has an effect of increasing both the lift and the induced drag while stepping up the nose-down pitching moment.

The wing aspect ratio and the fence have an effect of augmenting the ground effect. When the fence is lower than the wing, the gap is shown to have not much effect on the aerodynamic characteristics of the wing. For a higher fence than the wing, the small gap augments the magnitudes of the lift and the nose-down pitching moment. The induced drag of a wing is small when the wing approaches to the ground or when the wing is as high as the fence.

Although the present result is limited to the inviscid, irrotational assumption, it is believed that the present method will be useful for the conceptual design of the high speed ground transporters moving over the nonplanar surface.

Acknowledgments

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