$c\dot{\alpha}/U_\infty = 0.02$. According to Ref. 2, $K_{a1} = 2.0$ and $K_{a2} = 4.0$. Thus, for $\xi_{CG} = 0.25$, Eq. (3) becomes

$$\Delta\alpha_s = \begin{cases} 6.0\,\dot{\alpha}_{ND} & : \dot{\alpha}_{ND} \leq 0.01 \\ 0.06 & : \dot{\alpha}_{ND} > 0.01 \end{cases} \tag{4}$$

The estimate of the dynamic stall overshoot $\Delta\alpha_{sep}$ given by Eqs. (1), (2), and (4) is in very good agreement with the experimental results of Daley and Jumper[1] (Fig. 1). The agreement is not as good for the very high pitch-up rates tested by Deekens and Kuebler[3] (Fig. 2). In addition to the very large pitch-up rate, well beyond the range for which the analysis in Ref. 2 was developed, the reason for the difference could be any existing difference between the dynamic stall angle, for which the prediction is made, and the angle of attack for which flow separation at 25% chord was observed in the dynamic test. One message that Fig. 2 gives is that at high pitch-up rates the dynamic overshoot $\Delta\alpha_{sep}$ of static stall is mainly due to $\Delta\alpha_w$, the Kármán-Sears wake effect.[4] As this is a pure time lag effect, the part $\Delta\alpha_w$ of the measured dynamic overshoot $\Delta\alpha_{sep}$ of the static stall angle does not produce any corresponding overshoot of the static lift maximum. The dynamic overshoot of static $C_{L\max}$ is generated by the combined effect of $\Delta\alpha_s$ and the "spilled" leading edge vortex.[5]

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Dynamic Ground Effects on a Two-Dimensional Flat Plate

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Introduction

CONVENTIONAL analytical models for the prediction of ground effects on the aerodynamic characteristics of wings in ground proximity have utilized the image vortex system to account for the effects due to the presence of the ground. These analytical models have assumed that the ground height of the wing is fixed in time in the formulations.[1,2] This assumption cannot model the flight conditions properly for aircraft during takeoff and landing transitions as the ground height is changing with time. When the ground height is a function of time, wing lift or circulation around the wing becomes time variant. The time derivative of the wing circulation is accompanied by continuous vortex shedding convecting downstream in the wing wake. The shed vortices in turn create an up- or downwash influence on the wing and affect the resultant lift of the wing. This effect of time-varient wing lift due to the change in ground height is referred to as the dynamic ground effect or unsteady ground effect.

In the present Note, the effect of time-variant vortex shedding is simulated by a sequence of discrete vortices convecting downstream in the wake of a two-dimensional flat plate. The lifting condition of the flat plate is modeled by using the quasivortex lattice method (QVLM).[3] The boundary condition of this problem is specified such that the tangency condition on the surface of the flat plate is satisfied. This boundary condition takes into account the effect of airfoil motion relative to the ground.

Purpose of this study is to show that significant lift changes occur due to the dynamic ground effect that are very important for aircraft during takeoff and landing transitions.

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Method of Approach

The theoretical model of the ground effects on a two-dimensional flat plate airfoil, for fixed ground height h and angle of attack α_0, can be described by the following relation for small α_0:

$$\alpha_0 \approx \sin\alpha_0 = \frac{1}{2\pi}\left[\int_0^1 \frac{g(\xi)}{x-\xi}\,d\xi - \int_0^1 \frac{g(\xi')\hat{r}\cdot\hat{n}}{|\vec{R}|}\,d\xi'\right] \tag{1}$$

where g represents the airfoil vortex density, $\hat{r}$ is perpenticular to $\vec{R}$, and $\hat{n}$ is an unit vector normal to the airfoil surface as shown in Fig. 1a. Note that the last term of Eq. (1) represents the upwash influence due to the airfoil image vortices.

When the ground height is changing, Eq. (1) must be modified to account for the effects of the shed vortices and airfoil motion on the boundary condition. These effects are given by

$$\alpha_0(t) + a(t) = \alpha(t) \approx \frac{1}{2\pi}\left[\int_0^1 \frac{g(\xi)}{x-\xi}\,d\xi - \int_0^1 \frac{g(\xi')\hat{r}\cdot\hat{n}}{|\vec{R}|}\,d\xi'\right] \text{at } t + \frac{1}{2\pi}\int_0^t \frac{dG}{d\tau}\left[\frac{\hat{q}_2\cdot\hat{n}}{|\vec{Q}_2|} - \frac{\hat{q}_1\cdot\hat{n}}{|\vec{Q}_1|}\right]d\tau \tag{2}$$

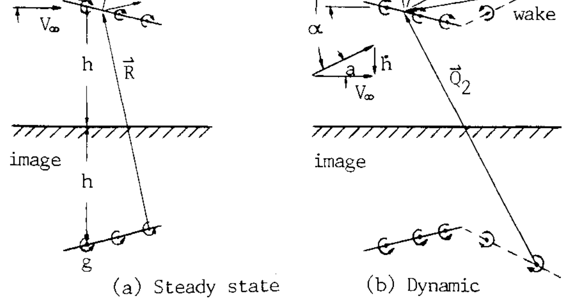

Fig. 1 Geometry and vortex systems in ground effect of a flat plate.

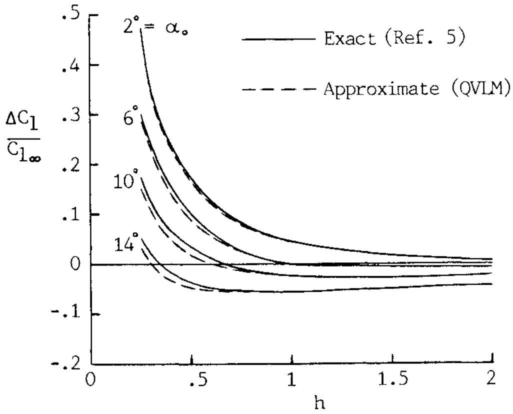

Fig. 2 Sectional lift increment due to steady-state ground effect.

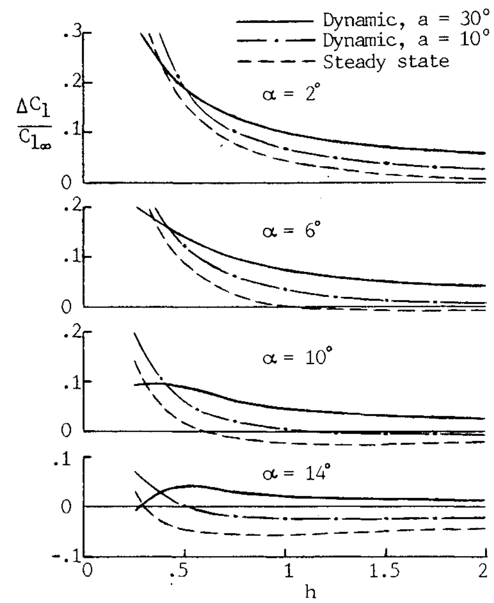

Fig. 3 Dynamic ground effect on sectional lift for constant rate of descent.

where G represents total circulation around the airfoil and

$$a(t) = \tan^{-1}\left[-\frac{\dot{h}(t)}{V_\infty}\right]$$

Geometric relationships between $\vec{Q}_1$, $\hat{q}_1$, $\vec{Q}_2$, and $\hat{q}_2$ are illustrated in Fig. 1b. Note that the additional term in Eq. (2) (the last term) is due the effect of the vortex shedding in the wake. The airfoil angle of attack is also a function of the ground height and time.

The system of integral equations (1) and (2) are solved by using the QVLM discretization technique. For Eq. (2), discretization in time is also required in order to integrate the last term of Eq. (2).

Spatial positions of the discrete shed vortices and their images are determined by

$$\Delta x' = \frac{1}{\ln(4\cdot\Delta x + 1)} - \frac{1}{4\cdot\Delta x}$$

where $\Delta x'$ is the vortex location relative to the leading edge of each wake segment with length Δx. This relation is obtained by requiring an equal downwash contribution to the ¾ chord point of the airfoil by a continuous vortex sheet and a concentrated vortex.[4] Strength of the discrete shed vortex of each time step is set equal to the difference between the total circulations of the airfoil of the current and the last time solutions. That is,

$$\int_{t_{j-1}}^{t_j} \frac{dG}{d\tau} d\tau \approx \Delta G_j = \left[\int_0^1 g(x)dx\right]_{t_j} - \left[\int_0^1 g(x)dx\right]_{t_{j-1}} \tag{3}$$

Solutions of Eq. (2) are obtained by starting from any steady-state flight condition and then marching in time for a specified time step. Upon obtaining the solution of g after each time step, sectional lift increament due to dynamic ground effect at time j can be computed from

$$\frac{C_{l_j} - C_{l_\infty}}{C_{l_\infty}} = \frac{\Delta C_{l_j}}{C_{l_\infty}} = \frac{1}{\pi\alpha_j}\left\{\int_0^1 g(x)[1+u(x)]dx\right\}_j - 1 \tag{4}$$

where $u(x)$ is the backwash velocity component produced by the image vortex system and shed vortices.

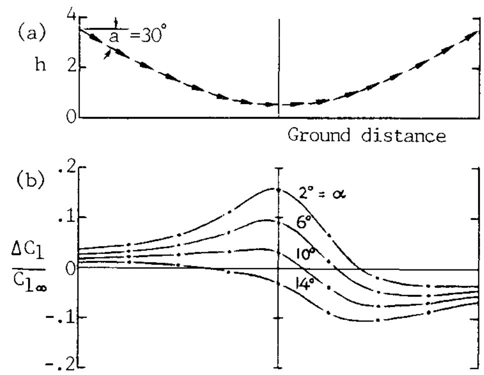

Fig. 4 Dynamic ground effect for a sine curve flight path.

Numerical Results and Discussion

Accuracy of the QVLM discretization is examined by comparing to the exact solutions for the steady-state ground effect using Eq. (1).[5] Results of this comparison are shown in Fig. 2 and clearly reveal that the sectional lift is generally underpredicted slightly for all angles of attack, especially when the airfoil is close to the ground.

For cases of dynamic ground effect, two types of flight conditions are investigated: constant rate of descent and varying rate of descent or climb. Figure 3 shows the result of the constant rate of descent using Eq. (2). In these cases, the wing wake is assumed to be straight along the flight path. It is shown in Fig. 3 that the lift increases with more negative flight path angle $-a$. This effect is reversed when the airfoil is very close to the ground where the shed vortices effects becomes prominent.

Results of the varying rate of descent or climb are examined for a given flight path, as shown in Fig. 4a, that simulates the situation of landing approach and go-around conditions. A curved wing wake is obtained in these cases. Figure 4b illustrates the results of the computations. The lift of the airfoil is increased as the airfoil is approaching the ground when the angle of attack is not too high. Significant lift loss is shown clearly when the airfoil is leaving the ground, especially at high angles of attack. These results of the trend of the lift variations are similar to those obtained in flight tests for ground effects.[6]

Accuracy of the present model cannot be assessed at this point, since there is no experimental data available for comparison. But the results do reveal significant changes in sectional lift of a two-dimensional flat plate due to the dynamic ground effect.

Conclusion

The general idea of discretization described in the present model for dynamic ground effect predictions can be extended to three-dimensional lifting surfaces. It is expected that a similar trend of lift variations is to be obtained in the case of a wing in dynamic ground effect.

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