Three-dimensional Flows around a Flapping Wing in Ground Effect

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Abstract: We investigate the ground effect for a wing flapping above a horizontal plane using three-dimensional numerical simulation. A rectangular flapping wing is considered and the Reynolds number based on the maximum translation velocity and chord length is 100. The distance (*d/c*) between the ground and wing center is varied from 1 to 20. For all the wings considered, the lift force increases at *d/c*=1, and the amount of lift increase becomes bigger with increasing *AR*. For *AR*=1, the ground effect is negligible except a small increase in the lift at *d/c*=1. On the other hand, for $AR \geq 8$, a noticeable reduction of lift is observed near *d/c*=2 and becomes more significant with increasing *AR*. At *d/c*=1, the effective velocity of the wing from the induced motion by previous leading- and trailing-edge vortices significantly increases due to the ground effect and thereby the lift force is increased. On the other hand, the wing-tip vortex for low *AR* wing modifies this induced flow by suppressing the trailing-edge vortex, causing negligible ground effect.

Keywords: Ground Effect, Flapping Wing, Wing Span, Wing-tip Vortex.

1 Introduction

Gao and Lu [1] showed from their numerical simulations that the drag and lift forces on a two-dimensional wing in hovering motion decrease and increase as it approaches the ground, which results from the modification of the evolution of leading- and trailing-edge vortices. On the other hand, for a finite wing, the wing-tip vortex induces strong three-dimensional flow motion and its effect on the aerodynamic performance is dominant especially for a low aspect ratio (*AR*) wing [2,3]. Thus, the ground effect should depend on the *AR* of the wing. Therefore, in this study, we numerically investigate the ground effect by varying the *AR* of flapping wing.

2 Numerical Details

We consider a rectangular wing having elliptic cross-section. The aspect ratio of wing (*AR*) varies from 1 to 20, where *AR* is the ratio of wing span (*b*) to the wing chord (*c*). The wing in hovering motion moves back and forth in the horizontal direction above a flat plate (ground) and its motion is modeled using a sinusoidal function [1]. The flapping amplitude is 2.5*c* and the angle of attack (AoA) at mid-stroke is 45^{o}. To investigate the ground effect, we vary the distance (*d/c*) between the ground and wing center from 1 to 20. The Reynolds number considered is 100 based on the wing chord length and maximum translational velocity *U*. The lift coefficient is defined as C_L = lift / $0.5\rho U^2 bc$, where ρ is the density. To simulate the flow around a flapping wing, we use an immersed boundary method [4]. All the far-field boundaries are located at 20*c* from the wing center, and the minimum grid size is set as $\Delta x = \Delta y = 0.025c$ and $\Delta z = 0.04c$ for all the cases simulated. For the wing of *AR*=4 and *d/c*=2, the number of grid points are $321 \times 176 \times 257$ in *x*-, *y*- and *z*-directions, respectively.

3 Results

Figure 1 shows the variation of time-averaged lift coefficient in ground effect with the wing span. For all the wings considered, the lift force increases at *d/c*=1, and the amount of lift increase becomes bigger with increasing *AR*. For *AR*=1, the ground effect is negligible except a small increase in the lift at *d/c*=1. On the other hand, for $AR \geq 8$, a noticeable reduction of lift is observed near *d/c*=2 and becomes more significant with increasing *AR*.

When a wing locates far away from the ground, the induced motion from previous leading- and trailing-edge vortices increases the effective velocity of the wing, thus increasing the lift force. In case the wing locates near the ground (*d/c*=1), the trailing-edge vortex interacts with the ground and generates a secondary vortex at the wall. From mutual induction, the trailing-edge vortex moves away from the wall and interacts more strongly with the leading-edge vortex, which further increases the lift force (see vortices A and B in Figs. 2 and 3). For a low *AR* wing, wing-tip vortices (see C in Fig. 3) modify the evolution of leading- and trailing-edge vortices and reduce the induced motion from previous leading- and trailing-edge vortices. Therefore, the lift force of low *AR* wing is lower than that of higher *AR* wing (Fig. 1). For this reason, the ground effect is less significant for the case of low *AR* wing.

References

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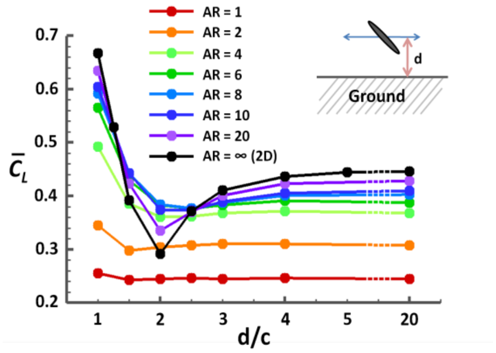

Figure 1: Time-averaged lift coefficients for flapping wings in ground effect

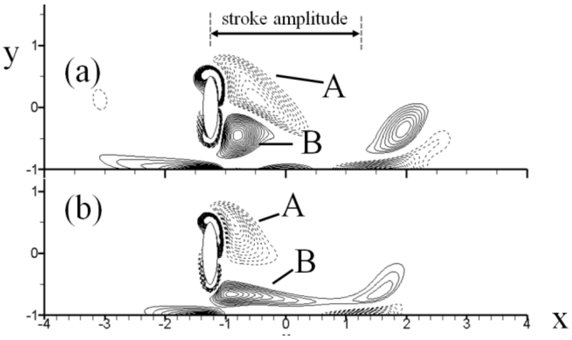

Figure 2: Contours of the instantaneous vorticity at the end of stroke (*t/T*=3.5) for *d/c*=1: (a) 2D simulation; (b) the mid-span cross-section for *AR*=2.

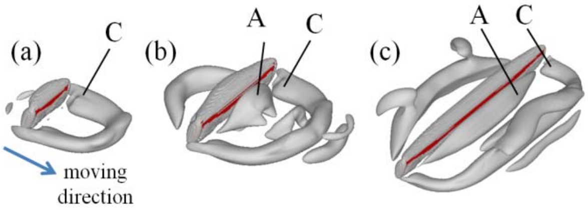

Figure 3: Instantaneous vortical structures at the early stroke (*t/T*=3.6) for *d/c*=1: (a) *AR*=2; (b) *AR*=4; (a) *AR*=10. The wing is denoted in red color.