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Numerical simulation of a two-dimensional flapping wing in advanced mode *

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Abstract: A two-dimensional model is built to describe the translation and the rotation of the hovering flapping movement. The equations of motion are derived for insect's flapping movement, and the model is implemented by the computational fluid dynamics (CFD) software FLUENT and it's user defined function (UDF). It is shown that the lift coefficient changes slowly in the intermediate stage, there are two areas in which the lift coefficient changes dramatically, and the drag coefficient behaves quite differently when flapping up and down. The vortex distribution, the pressure distribution, and the velocity vector distribution in the advanced mode at different times follow quite various rules.

Key words: Numerical simulation, micro flapping wing, advanced mode, unsteady aerodynamics, dynamic mesh

Introduction

The micro-flapping wing aircraft is an aircraft based on the bionic principle, as the flying birds and insects. Compared with the fixed wing and rotary wing aircraft, the main features of the micro-flapping wing aircraft are that they are integrated systems that integrate the functions of lifting, hovering and propelling, they can complete a long-distance flight with a small amount of energy, and with a stronger mobility. A very small Reynolds number (about 10^1-10^4 smaller) is involved, in which the viscosity effect of air increases greatly. In the boundary layer, the laminar flow separates, resulting in laminar separating bubbles and the aerodynamic characteristics are significantly different from those in a high Reynolds number situation[1]. The flight of flapping wings was studied extensively.

Zhang et al.[2] simulated the periodic motion of small insects by the dynamic hybrid grid technology and the unsteady method of incompressible flow based on the virtual compression technology. Bai et al.[3] simulated the hovering flight of a single flapping wing of fruit flies in three modes: the advanced mode, the symmetric mode and the delay mode, and combined with aerodynamic coefficients and flow structures, they analyzed the mechanism by which fruit flies obtain a high lift force in their hovering flight. Ohmiet et al.[4,5] studied the starting process of the vortex at a high attack angle with the wing's pitching movement, including the forms of the vortex, and the factors that affect the formation of the vortex. Triantafyllou et al.[6] proved that the structure of the trailing vortex has a great influence on the formation of the propulsion. Nskata et al.[7] presented a new model of flapping-wing aerodynamics, called a CIQSM, based on a combination of the CFD data and the quasi-steady modelling. Tay et al.[8,9] used a numerical simulation method to investigate the validation of the immersed boundary method and the flapping micro-aerial vehicle. The aerodynamic performance of the flexible flapping wing was investigated through numerical simulations based on the fluid-structure coupling method[10]. Banazadeh and Taymourtash[11] presented the modeling and the simulation of open loop dynamics of a rigid body insect-like flapping wing. MH Dickson's research indicates that the turning phase of insect's wings will affect the direction of the first peak lift force and it's emergence moment, and that the flapping wing flight has a unique advantage in using the trail flow to

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obtain a part of lift force, which leads to a conclusion that the flapping wing could absorb the energy of the trailing flow. Based on the insect wing study a two-dimensional single flapping wing model is built, and the dynamic mesh technique and the UDF function are used to simulate the flight of a flapping wing in the advanced mode. The unsteady mechanism is studied and some useful conclusions are drawn.

1. The model

This paper takes the NACA0012 wing as the two-dimensional simplified wing section, and studies the insect's flapping motion in the state of the hovering flight. The controlling parameters for the wing moving up and down are set symmetrically, and the axis of rotation is set a quarter chord length from the leading edge. The following functions in the model are adopted to describe the translation and the rotation of the hovering flapping movement. The velocity function[12] is expressed as:

$$u(\tau) = u_m \sin\left(\frac{\pi\tau}{\Delta\tau_t}\right) \text{ accelerate on} \tag{1a}$$

$$u(\tau) = u_m \text{ uniform velocity} \tag{1b}$$

$$u(\tau) = u_m \sin\left[\frac{\pi + \left(\tau - \frac{\tau_c}{2}\right)\pi}{\Delta\tau_t}\right] \text{ decelerate on} \tag{1c}$$

where τ is the time, u_m is the maximum speed of the translational motion, $\Delta\tau_t$ is the total time of the translational motion, and τ_c is the flapping cycle.

The angular velocity function[12] of the rotation motion is expressed as

$$\omega(\tau) = \pm\omega_m\left[1 - \left(\cos\frac{2\pi\tau}{\Delta\tau_r} + \Delta\phi\right)\right] \tag{2}$$

where ω_m is the maximum angular velocity, $\Delta\tau_r$ is the total time of the pitching rotation, and $\Delta\phi$ is the phase difference of the rotation and the translation.

Some main physical parameters are:

$$\tau_c = 0.02\ \text{s}, u_m = 3.5\ \text{m/s}, \Delta\tau_t = 2.8\ \text{ms},$$

$$\omega_m = 349.07, \Delta\tau_r = 6.0\ \text{ms}$$

The attack angle is 30°, the rotation angle is 120°, and the leading phase is 8.0%. The calculation area is a rectangle of 0.16 m×0.06 m, and the chord length of the wing NACA0012 is $c = 0.01\ \text{m}$. The four edges of the calculation field are static wall boundaries, and the boundary of the wing is the dynamic wall boundary. The triangular unstructured grids are used in this model. The total number of the grids is 4.67×10^4. The movement of the flapping wing has a high speed, it behaves as in the turbulence model. The smooth spring model and the local reforming model are used to produce the dynamic grids.

2. The results and discussions

2.1 *Lift and drag coefficients*

Figure 1 shows the lift and drag coefficients in a cycle, the vertical axis is the lift or drag coefficients, and the abscissa is the time, covering the range of 0-1. As shown in the Fig.1(a), the lift coefficient changes slowly in the intermediate stage, and there are two areas in which the lift coefficient changes dramatically. In the range of –0.05-0.02, the lift coefficient reduces rapidly and then has a rapid increase in the other direction and the lowest value of the lift coefficient increases to 2.23 quickly. In this stage the attack angle becomes an obtuse angle due to the fact that the flapping wing turns in the advance phase. In the end of the turning phase, the flapping wing turns into the other phase, in which the wing keeps a same attack angle flapping and the lift coefficient decreases rapidly from the first peak 2.23 to 0.07, and then it turns into the translation motion, in which the attack angle and the velocity keep unchanged, the lift coefficient turns into the rising and stable stages. In the range of 0.25-0.38, the lift coefficient comes into its second rising stage and it reaches the peak value. In this rising stage, the flapping wing keeps in a same attitude of pitching nose-up. After that, the wing turns into the position of its stalling angle, so that the lift coefficient decreases rapidly to negative values. Figure 1(b) shows that the drag coefficient behaves quite differently when flapping up and down. When in the range of 0-0.05, the drag coefficient is positive, there are two peaks, and also the velocity increases rapidly. In this stage, the flapping wing keeps in an attitude of pitching nose-up. While in the range of 0.50-0.10 the drag coefficient is negative and also sees two valley values.

2.2 *The vortex distribution of the flapping wing*

Figure 2 shows the vortex distribution at different times. The interaction between the vortex and the flapping wing is a significant factor of the high lift coefficient. With a proper angle of the flapping wing, a high lift force can be achieved. As shown in the pic-