Numerical simulation of 3D rigid wing hovering flight

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Abstract. In this paper, we propose a new CFD numerical simulation method, which combines the ALE program independently developed by our research group and commercial software CFX. The feasibility and accuracy of this CFD method are verified by simulating hovering flight of 3D rigid wing. By analyzing the flow field, it is believed that LEV attached to the upper surface of the wing is the main reason for generating large lift during downstroke, and delayed stall mechanism play a important role.

1. Introduction

Flies in nature has long been a source of inspiration for human to design aircraft. With the development of Micro Air Vehicles (MAV), people are more and more interested in flapping-wing flight of insects. Studying the aerodynamic characteristics of insects is of great significance for revealing the biological evolution process and designing aircraft. In this paper, we propose a new CFD numerical simulation method, which combines the ALE program independently developed by our research group and commercial software CFX. In order to verify the feasibility and accuracy of this CFD numerical simulation method, the aerodynamic performance of a single dragonfly hindwing during hovering flight is analyzed and compared with Sun and Lan results [1].

2. Method

The steps of the CFD numerical simulation method proposed in this paper are as follows:

(1). According to the measured parameters of real dragonfly wing [2], a simplified 3D model is established. Mesh the model and export the mesh information.

(2). The grid conversion program developed by professor Xiaohui Su is used to transform the exported grid information into grid file suitable for ALE program operation.

(3). Given the motion mode of dragonfly wing and imported grid file in ALE program, the motion of the wing in a period is simulated, and the mesh node information of each time step is exported.

(4). Using the Junction Box Routine of CFX, the grid node information of the corresponding instant is read into the solver of CFX before start of time step.

(5). The periodic motion of the wing model under a given flapping mode is realized by a user-defined program.
3. Model setup

3.1. Geometry description

The hindwing of dragonfly is modeled as a rigid flat plate with span length \( R = 4.6 \text{cm} \), mean chord length \( c = 1.12 \text{cm} \), and thickness \( h = 0.0112 \text{cm} \). The distance from the symmetry plane to the root of the wing is \( 0.61 \text{cm} \). The axis of rotation is located at a distance of 0.28cm from the leading edge of the wing. The simplified geometric model of the dragonfly hindwing is shown in Fig. 1.

![Figure 1. The simplified geometric model of the dragonfly hindwing.](image)

3.2. Mesh information

The wing is enclosed in a spherical fluid domain with a radius of 30cm. There are about 113,000 tetrahedral cells in the entire model, including 2786 grid cells on the wing surface. The grid diagram of the flow field and the wing surface are shown in Fig. 2 and Fig. 3, respectively.

![Figure 2. Grid of flow field.](image)  
![Figure 3. Grid on the wing surface.](image)

3.3. Flapping mode of wing

The translation and flip rotation of the wing are controlled by the flapping angle \( \Phi(t) \) and the angle of attack \( \alpha(t) \), respectively. The angular velocity of flapping angle and the angle of attack are defined as follows:

\[
\dot{\Phi}(t) = -2\pi\phi_0 \sin(2\pi ft) \\
\dot{\alpha}(t) = 0.5\alpha_0 \left[ 1 - \cos\left(2\pi \frac{t-t_r}{\Delta t_r}\right) \right] \quad t_r \leq t \leq t_r + \Delta t_r
\]

where \( f = 36 \text{Hz} \); \( \phi_0 = 34.5^\circ \); \( \alpha_0 = 20000 \text{deg/s} \); \( t_r \) is the time when the wing start to rotation; and \( \Delta t_r \) is the duration of the stroke reversal.

3.4. The setting of CFX solver

In this paper, the wing begins to move periodically in still air. The density of the air is 1.185kg/m3, the dynamic viscosity of the air is 1.831\( \times 10^{-5} \text{kg/m/s} \). Transient analysis of the wing model was carried out for 30 periods, with the time step set to 5.56\( \times 10^{-6} \text{s} \) and the total time set to 0.834s. The solution settings are shown in Table 1.
**Table 1.** Setting table of CFX solver.

| Item                | Setting                  |
|---------------------|--------------------------|
| Analysis Type       | Transient                |
| Material of Fluid   | Air at 25°C              |
| Turbulence Model    | Laminar                  |
| Initial Condition   | State of Rest            |

| Boundary Condition  | Outer boundary: Opening |
|---------------------|--------------------------|
|                     | Inner boundary (wing): No Slip Wall |

4. Results and analysis

4.1. Verification of grid convergence

In this paper, four sets of grids are tested. The total number of grids in the model is 35566, 68497, 113614 and 233150, respectively, as shown in Table 2.

**Table 2.** Grid convergence verification.

| Item                        | The number of grid cells on the wing surface | Total number of grid cells | Total number of nodes |
|-----------------------------|---------------------------------------------|----------------------------|-----------------------|
| Grid 1                      | 1,024                                       | 35,566                     | 6,566                 |
| Grid 2                      | 1,024                                       | 68,497                     | 12,058                |
| Grid 3                      | 2,786                                       | 113,614                    | 19,995                |
| Grid 4                      | 6,084                                       | 233,150                    | 40,746                |

Four monitoring points are selected along the edge of the wing model, as shown in Fig. 4. They move along with the movement of the wing, and their coordinates at the initial time are as follows:

- point1(X=4.194cm, Y=2.253cm, Z=1.791cm);
- point2(X=4.324cm, Y=1.957cm, Z=2.024cm);
- point3(X=2.164cm, Y=-0.0075cm, Z=1.496cm);
- point4(X=0.44cm, Y=0.504cm, Z=0.065cm).

![Figure 4](image)

**Figure 4.** The position of the monitoring points on the wing model

![Figure 5](image)

**Figure 5.** The instantaneous pressure of the monitoring points under different grids.
Fig. 5 shows the instantaneous pressure of four monitoring points at 0.81265s under different grids. As shown in figure, with the number of grids increases, the instantaneous pressure at the four monitoring points gradually tends to be stable. The relative error of the instantaneous pressure corresponding to grid 3 and grid 4 is within 3.24%. Fig. 6 shows the time courses of vertical force coefficients and thrust coefficients of the 30th period for different grids. The vertical force coefficient and the thrust coefficient increase slightly at the peak with the increase of the grid quantity. The vertical force coefficient and thrust coefficient corresponding to grid 3 and grid 4 tend to be basically uniform. Therefore, grid 3 has reached the convergence requirement.

4.2. Comparison of results

As can be seen from Fig. 7(a), the vertical force coefficient is obviously increased at the peak of the downstroke and slightly decreased at the trough and peak of the upstroke. As can be seen from Fig. 7(b), the thrust coefficient is relatively large in the downstroke, and the development trend of the thrust coefficient in the upstroke is basically the same, but there is a certain degree of downward deviation.

The mean vertical force coefficients of present model and Sun [1] are 0.736 and 0.675, respectively, and the relative error between them is about 9%. Assuming that the four wings of a dragonfly can
generate the same lift, the mean vertical force calculated in this paper can balance twice the dragonfly weight (754mg, Norberg [3]), which is consistent with Sun and Lan [1] results.

Generally speaking, the development trend of vertical force coefficient and thrust coefficient in one period is consistent with the results of Sun and Lan [1], with only a slight difference in amplitude. The reason for this difference may be that the shape of the wing is slightly different. The wing used by Sun and Lan [1] was truncated at the tip of the wing, while the wing in this paper has a sharper tip.

4.3. Lift generation mechanism

Fig. 8 shows the iso-vorticity surface plots at different instants in a period, with the value of vorticity is \(-18400s^{-2}\). Figures (a), (b), (c) and (d) describe the downstroke, and Figures (e), (f), (g) and (h) describe the upstroke. At the time \(t/T=0\), the wing began to accelerate downward movement, and the edge of the wing still have vortices that did not shed in the last cycle. When \(t/T=0.12\), the vortex in the last cycle gradually sheds, and a leading edge vortex (LEV) is generated at the leading edge, a trailing edge vortex (TEV) is generated at the trailing edge, and a tip vortex (TV) is generated at the wingtip. The three vortices are connected end to end to form a new vortex ring. The vortex ring moves downward along with the wing and gradually increases in size. LEV always adheres to the wing surface, while TEV gradually sheds, as shown in figs.8 (c) to (e). At \(t/T=0.5\), the wing began to accelerate upward movement. The vortex ring gradually sheds to the underside of the wing, as shown in figs. 8 (f) to (h).

![Figure 8](image)

**Figure 8.** Iso-vorticity surface plots at different instants in a period.

Take a cross section parallel to the plane of symmetry at a distance of 0.65 of the span out from the root of the wing. Fig. 9 shows the pressure contours of the cross section at different instants in a period. Figures (a), (b), (c) and (d) describe the downstroke, and Figures (e), (f), (g) and (h) describe the upstroke. As can be seen from fig. 9 (b), LEV and TEV form negative pressure domain on the upper surface of the wing, and the pressure difference between the upper surface and the lower surface will generate a vertical upward lift. As the wing accelerates downward movement, the pressure difference gradually increases, and the lift also increases. The first crest of the lift appears at about \(t/T=0.224\). At stroke reversal, LEV attached to the upper surface of the wing rotates clockwise along with the wing and then sheds, as shown in figs. 9 (d) to (g).

We can clearly observe that a new vortex ring completes the process from formation, development to shedding in one cycle, and LEV attached to the upper surface of the wing is the main reason for
generating large lift during downstroke. During upstroke, the shed vortex ring has little effect on the wing, and only generates a small lift.

![Pressure contours at different instants in a period (0.65R).](image)

**Figure 9.** Pressure contours at different instants in a period (0.65R).

5. Conclusion
In this paper, the aerodynamic performance of a single dragonfly hindwing during hovering flight has been analyzed by using a new CFD numerical simulation method which combines the ALE program developed by our research group and commercial software CFX. A few of conclusions are made as follows:

(1). The development trend of vertical force coefficient and thrust coefficient in a period is consistent with the results of Sun and Lan [1], with only a slight difference in amplitude, which shows the feasibility and accuracy of this new method.

(2). LEV attached to the upper surface of the wing is the main reason for generating large lift during downstroke, and delayed stall mechanism play a important role.

(3). During upstroke, the shed vortex ring has little effect on the wing, and only generates a small lift.

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