Numerical Investigation on Lift Force Generation Mechanism of Clap and Fling Motion Using Unstructured ALE Method

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ABSTRACT

To study the lift generation mechanism and energy expenditure of clap and fling motion for insect flight, an unstructured mesh finite volume ALE method is developed. To solve mesh deformation problems during clap and fling motion, we adopt two mesh modification techniques. A 2D elliptical wing model is used to validate our solver by comparing the solutions to the already published numerical and experimental results. We analyzed the lift generation mechanism of clap and fling motion. The paper also released the comparison of Cl and energy expenditure between the single wing hovering motion and clap & fling. Conclusions have been made: the wake capture and delayed stall contribute to the lift generation while the rapid pitch mechanism decreases the lift. Clap and fling motion generate less lift but consume less energy, which means that it can generate more lift as consuming the same energy compared to single hovering motion by quantitative analysis.

KEYWORDS
ALE method; moving boundary; clap and fling; lift generation mechanism, energy expenditure

INTRODUCTION

The study of insect flight is due to two reasons [1], one is from the biologists who need to understand the aerodynamic force production, energy expenditure,
evolution and so on; the other one is from the engineers who desire design small robots like micro air vehicles (MAV). And aerodynamics is one of the two investigated aspects of the mechanics of insect flight. An insect could not support its weight if studied with traditional quasi-steady aerodynamics theory from Weis-Fogh [2]. Because of this discovery, the study of insect flight has been focused on its unsteady aerodynamics. Until now, the key attribute of unsteady flapping wing aerodynamics found to help generate the high lift include clap and fling, rapid pitch mechanism, wake capture, delayed stall of leading edge vortex (LEV), tip vortex and passive pitching mechanism [3].

Clap and fling is the earliest unsteady lift generation mechanism found by Weis-Fogh [4]. After this study, Lehmann et al. [5], Sun and Yu [6], Miller and Peskin [7, 8], Gillebaart et al. [9] and Arora et al. [10] conducted experimental and numerical research on this mechanism, which could enhance lift generation at low Reynold number.

To simulate clap and fling motion, high precision and stable numerical methods are of great importance. Moving mesh problems must be overcome to simulate insect flight aerodynamics, which is obviously a difficult task. Until now, three kinds of numerical methods are adopted by most researchers and can be found in many literatures, including immersed boundary method (IBM), overset grid method and arbitrary Lagrangian-Eulerian method (ALE). But interpolation is needed for both IBM and over-set grid method. The ALE methodology combines the best features of both Eulerian and Lagrangian formulations. The essence of the ALE is that mesh motion can be chosen arbitrarily from Margolin [11]. Compared to the previous two methods, ALE should be more advantageous because of its body conforming mesh, robustness and accuracy as long as remeshing is not required according to Batina [12] and Johnson & Tezduyar [13].

From the cited works, only Gillebaart et al. [9] adopted ALE method to simulate clap and fling, but the mesh topology was changed. And the energy expenditure of clap and fling has not been investigated. So in this paper, an ALE method is developed based on our previous research work by Tai et al. [14] to investigate the unsteady mechanisms of clap and fling. The proposed ALE method can allow large wing displacement and rotation, including a pair of wings in close proximity and without changing mesh topology.

The structure of this paper is as follows: the ALE model is introduced briefly in Section 2. In Section 3, a test case is reported for the purpose of model validation. In Section 4, clap and fling motion are simulated and its lift generation mechanism is analyzed. The energy expenditure is calculates as well. Conclusions are made in the last section.

**GOVERNING EQUATIONS**

The incompressible unsteady Navier-Stokes governing equations, modified by the ACM dual time steps and ALE in non-dimensional vector form, are as follows:

\[
C \frac{\partial \mathbf{W}}{\partial \tau} + K \frac{\partial \mathbf{W}}{\partial t} + \nabla \cdot \mathbf{F}_e = \nabla \cdot \mathbf{F}_v \tag{1}
\]
Where \( W = \begin{bmatrix} p \\ u \\ v \end{bmatrix} \), \( F_c = \begin{bmatrix} (u-u_m)U + p\delta_y \\ (v-v_m)U + p\delta_y \end{bmatrix} \), \( F_v = \begin{bmatrix} (1/Re) \cdot \nabla \cdot u \\ (1/Re) \cdot \nabla \cdot v \end{bmatrix} \)

\[
K = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1/\beta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

where \( W \) is the vector of dependent variables and \( F_c \) and \( F_v \) are the convective flux, and viscous flux vectors, respectively. \( \beta \) is a constant called artificial compressibility whose value affects the solution convergence to steady state. \( K \) is the unit matrix, except its first element is zero and \( C \) a preconditioning matrix. \( U_m = u_m + v_m \) denotes mesh velocity vector, \( \mu \) the molecular viscosity coefficient, \( Re \) the Reynolds number.

**Discretization of the ALE Governing Equations**

Equation (1) is discretized by the finite volume method on an unstructured triangular grid and a cell-vertex scheme is adopted here, i.e., all the values of the solution vector \( W \) are stored at the vertices of the triangular grid cells and a control volume is constructed around each vertex as shown for a vertex \( P \) in Fig. 1. The specific discretization method can be seen in the previous work [14].

![Figure 1. Illustration of control volume.](image)

**Mesh Modification**

In this paper, two mesh modification methods have been applied to deal with mesh deformation problems.

The aim of the first mesh modification is to redistribute the nodal points using a smoothing algorithm. The formula used is as follows:

\[
Coor\_xy(is) = \frac{1}{nbseg} \sum_{i=1}^{nbseg} Coor\_xy(i)
\]

(2)

where \( nbseg \) is the number of the edges associated with the operating vertice, \( is \). The above mesh modification procedure is not applied to moving boundary vertices.

The second mesh modification method is employed after a certain period of time by using the following formula:
\[ \text{Displacement}_{\text{mod}(y_{\text{end}}, T_{\text{period}})}^{0} = \text{Coor}_{x_{\text{end}}(y_{0})} - \text{Coor}_{x_{\text{end}}(y_{\text{end}})} \] 

where \( T_{\text{periods}} \) is the period of clap and fling motion.

**VALIDATION**

In the present study, the motion function in Wang [15] is adopted. The translation and rotation motions are controlled by \( x(t) \) and \( \alpha(t) \) respectively. The function of translation and rotation motion are shown below:

\[ x(t) = \frac{A_0}{2} \left[ \cos(2\pi f_0 t) - 1 \right] \]  

(4)

\[ \alpha(t) = \frac{\pi}{2} + \alpha \sin(2\pi f_0 t + \phi) \]  

(5)

where \( A_0 \) is translational amplitude, \( f \) is flapping frequency, \( \alpha \) is angular amplitude and \( \phi \) is the phase difference between translation and rotation motions.

The corresponding Reynolds number can be derived based on velocity expression derived:

\[ \text{Re} = \frac{U_{\text{max}} c}{\nu} = \frac{\pi f_0 A_0 c}{\nu} \]  

(6)

where \( \nu \) is kinematic viscosity, \( c \) is elliptical chord.

Both Wang’s computational results [15] and the experimental results [16] are compared with those obtained in this study in Fig. 2. Fig. 2 presents drag coefficients from different methods, which shows that result from the present model agree well those of Wang et al. [15] and Dickinson et al. [16]. Moreover, compared with Wang’s numerical results, the present model produces sharper Cd profile near the low drag coefficient region with lower Cd value. Considering the results obtained from the above test cases, it is concluded that the present ALE model is well able to simulate air flow over a 2D flapping wing.

![Figure 2. Comparison of force coefficients between the present simulations, experimental results [16] and Wang’s simulations [15].](image-url)

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RESULTS AND DISCUSSIONS

The kinematics of the left wing are described as follows: \( A0/c=3.185, f0=0.1\text{Hz}, \alpha=\pi/4, \varphi=0, \text{Re}=100 \). The right wing is the mirror image of the left wing at all times during their motions. The translational and rotational equations of the left wing are the same as (4) and (5). Thick ellipse of \( 1/10c \) is used for wings in the present study. The motions of the wings are sketched in Figure 3. Initially, the distance between these two wings is \( 1/2c \), with their chord lines in parallel along the vertical direction and the wings start to move away from each other in the fling stroke first, which is then followed by the clap stroke. The two wings both rotate around their centers.

![Figure 3. Track of clap and fling motion.](image)

The lift coefficient is shown in Fig. 4. The lift coefficient has three peak values. And there is no minimal lift between two peaks in lift in one half stroke. The vorticity contours at different time instants are shown in Fig. 5. At \( t/T=0.1 \), the first peak corresponds to the wake capture. At this time instant, the new LEV and trailing edge vortex (TEV) interact with old LEV and TEV. Because the direction of new LEV and TEV rotation are opposite to those of old ones', it is believed that the lift force is mainly generated due to vortex-vortex interaction. At \( t/T=0.3 \), the second peak corresponds to the delayed stall of the LEV. The attached LEV creating a region of negative pressure, results in the second lift peak. At this instant, the wings encounter the TEVs generated in the last stroke, which have opposite signs and have not dissipated yet. At \( t/T=0.46 \), the minimum lift is due to the rapid pitch mechanism. The left wing is rotating in clockwise direction at a large angular velocity (biggest at \( t/T=0.5 \) according to the motion equation). The angular velocity results in the increase of the flow velocity in the left side of the wing near the trailing edge and decrease of the flow velocity on the right side of the wing near the leading edge. The pressure decreases in the left side of the wing near the trailing edge but increases in the right side of the wing near the leading edge, which is similar to that of the right wing. In the clap stroke, the wings start to approach. At \( t/T=0.6 \), the wake capture and following delayed stall of LEV result in the third Cl peak. But the wings meet no TEV generated in the last stroke anymore, so the peak in lift at \( t/T=0.8 \) is smaller than that at \( t/T=0.3 \).

![Figure 4. The distributions of lift coefficient for the left wing in one period.](image)
The comparison of $C_l$ and Energy expenditure be-tween single wing hovering motion and clap & fling is shown in Table 1. The calculation of energy expenditure follows the treatment used by Sane and Dickson (2001). From Table 1, $C_l$ and energy expenditure of clap and fling decreases compared to single wing hovering motion. While the ratio of $C_l$ to energy expenditure increases by 159%, which means that clap and fling motion generate more lift consuming the same energy compared to single hovering motion.

Table 1. THE COMPARISON OF $C_l$ AND ENERGY EXPENDITURE BETWEEN SINGLE WING HOVERING MOTION AND CLAP & FLING.

| hovering case     | $C_l$ | $P$  | $C_l/P$ |
|-------------------|-------|------|---------|
| Single wing       | 0.31  | 0.96 | 0.32    |
| Clap & fling      | 0.28  | 0.33 | 0.83    |

CONCLUSION
An unstructured mesh incompressible flow solver based on ALE has been developed and used to investigate clap and fling motions. The accuracy and capability of the present ALE model are validated and assessed using a 2D elliptical wing hovering case. Good agreements with experimental results and other numerical solutions are obtained. By simulating clap and fling, it can generate more lift consuming the same energy compared to single hovering motion.

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