A study on the aerodynamic characteristics of airfoil in the flapping adjustment stage during forward flight

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Abstract. The aim of this study is to investigate the aerodynamic characteristics of a flapping airfoil in the adjustment stage between two specific flight patterns during the forward flight. Four flapping movement models in adjustment stage are firstly established by using the multi-objective optimization algorithm. Then, a numerical experiment is carried out by using finite volume method to solve the two-dimensional time-dependent incompressible Navier-Stokes equations. The attack angles are selected from -5° to 7.5° with an increase of 2.5°. The results are systematically analyzed and special attention is paid to the corresponding changes of aerodynamic forces, vortex shedding mechanism in the wake structure and thrust efficiency. Present results show that output aerodynamic performance of flapping airfoil can be improved by the increasement of amplitude and frequency in the flapping adjustment stage, which further validates and complements previous studies. Moreover, it is also show that the manner using multi-objective optimization algorithm to generate a movement model in adjustment stage, to connect other two specific plunging motions, is a feasible and effective method. Current study is dedicated to providing some helpful references for the design and control of artificial flapping wing air vehicles.

1. Introduction

Birds and insects fly by flapping their wings in the air to get enough aerodynamic force to support and propel them. Even though the external aerodynamic environment has a sudden changed, they can still keep the flight state steady by varying the flapping motion of wing. It has been unanimously recognized that disclosing these flight mechanisms of flying creatures is be very helpful for the development of artificial Micro Air Vehicle (MAV). Numerous experimental studies on flapping wings of birds or insects in a forward flight have been conducted [1-4], pertaining to aerodynamic forces, control-abilities and propulsive characteristics of flapping wings. Schouveiler et al (2005) experimentally investigated the influences of Strouhal number and the maximum attack angle on propulsive performance of a harmonically plunging airfoil [5]. Many numerical investigations on oscillating airfoil have been also carried out. Tuncer and Platzer (1996) investigated the mechanisms of thrust generation for a single flapping airfoil by employing a multiblock Navier-Stokes solver, where the unsteady flow filed around the flapping airfoil was analyzed [6]. Lewin and Haj-Hariri (2003) simulated the flow characteristics and power coefficients of an elliptical airfoil heaving sinusoidally over a range of frequencies and amplitudes [7]. However, most previous numerical studies on flapping flight are concerned about the aerodynamic performance of a certain specific stable
flapping motion during forward flight. While the investigation on the transition stage between two stable flapping motion states are not so much. In actual flapping flight, the moment of wings needs to be adjusted in terms of the output needs and external flight environment. The aerodynamic characteristics of the wings during the adjust stage have a significant effect of on stability of the flapping flight. Accordingly, this study focus on revealing the aerodynamic performance of plunging airfoil in adjustment stage and the changing of aerodynamic characteristics while the flapping motion changed. Multi-objective optimization algorithm used to optimize the flapping modes of plunging airfoil in adjustment stage. The power coefficients changing at different attack angles with different flapping mode in adjustment stage are also studied in this work. A NACA0014 airfoil is employed and the two-dimensional governing equations of fluid flow is solved in the finite volume method. Though the effect on spanwise flow is not considered in this work, the present results still can be useful to reveal the fundamental aerodynamic characteristics of flapping wing in the adjustment stage during forward flight.

2. Solution Method

2.1. Problem description

A two-dimensional NACA0014 airfoil with chord c is employed in this study. The plunging airfoil with attack angles range from -5° to 7.5°, is located in a uniform flow field. Fig.1 gives a schematic configuration of the flapping airfoil in the forward flight. \( h_0 \) is dimensionless amplitude measured from the mean position. \( U_\infty \) is the velocity of the uniform flow.

![Fig.1 Schematic configuration of a rigid airfoil undergoing a plunging motion in a uniform flow.](image)

2.2. Method of generating motion in adjustment stage

Before and after the adjustment stage, the airfoil plunge in the specific stable motions, and are all described by the sinusoidal equation \( h(t) = A_i \sin(2\pi f_i t) \), \( i = 1, 2 \). \( A_1, A_2 \) are the amplitude of motion before and after adjustment stage, respectively. \( f_1, f_2 \) are the frequency of motion before and after adjustment stage, respectively. \( T_1 = 1 / f_1, T_2 = 1 / f_2 \) are the frequency of motion before and after adjustment stage, respectively. In current study, the transition time in the adjustment stage is set as 0.5T_2. Figure 2 give a Kinematics specification of three stages.

![Fig.2 Kinematics specification of three stages.](image)
In this study, to ensure the three stages can be effective continuous and the sudden step change do not exist, the Fourier equation is used to describe the movement mode of airfoil in the adjustment stage. The Fourier equation is as follows.

\[ h(t) = a_0 + \sum_{i=1}^{n} (a_i \cos(i\omega t) + b_i \sin(i\omega t)) \]  \hspace{1cm} (1)

Where \( a_0, a_i \) and \( b_i \) are coefficients of Fourier equation.

In order to establish the Fourier plunging motion of airfoil in the adjustment stage, NAGA-II which is one of solid effective multi-objective optimization algorithms [8-9] is selected to optimize the trajectory.

Two objective functions have been established in this work. One is used to keep both displacement and velocity of the airfoil continue. In adjustment stage, the motion of airfoil should be unidirectional and no stationary. The continuous of airfoil’s displacement can be described as a continuous curve between start point and ending point of adjustment stage in the Cartesian coordinate system, and the motion’s unidirectional can be measured by the track length of the curve. So function \( F_1(a_0, a_i, b_i) \) is used to measure the track length of the airfoil, and defined as:

\[ F_1(a_0, a_i, b_i) = \int_{t_1}^{t_2} \sqrt{h'(t)^2 + 1} \, dt \quad (i= 1, 2, 3,...,n) \]  \hspace{1cm} (2)

In order to simplify calculation, using function \( \min f_1(a_0, a_i, b_i) \) to take place of function \( F_1(a_0, a_i, b_i) \) as a objective function and \( \min f_1(a_0, a_i, b_i) \) can be written as:

\[ \min f_1(a_0, a_i, b_i) = \int_{t_1}^{t_2} \sqrt{h'(t)^2 + 1} \, dt \quad (i= 1, 2, 3,...,n) \]  \hspace{1cm} (3)

The other objective function derives from the control of the amplitude of the acceleration in the adjustment stage. For the artificial flapping wing vehicles, the flap of wings is driven motor. The acceleration of the wings is related to the output of the motor. A huge sudden change on the output of motor is detrimental, and sometimes can’t be achieved. So a constraint function is used to limit the magnitude of the acceleration in the adjust stage.

The acceleration equation is derived from above displacement equation (1), and is as follows:

\[ a(t) = \sum_{i=1}^{n} (-a_i^2 \omega^2 \sin(i\omega t) - b_i^2 \omega^2 \cos(i\omega t)) \]  \hspace{1cm} (4)

Another,

\[ a \sin(x) + b \cos(x) = \sqrt{a^2 + b^2} \sin(x + \varphi) \]  \hspace{1cm} (5)

And

\[ \sin \varphi = \frac{b}{\sqrt{a^2 + b^2}}, \cos \varphi = \frac{a}{\sqrt{a^2 + b^2}} \]  \hspace{1cm} (6)

Then,

\[ a(t) = -\omega^2 \sum_{i=1}^{n} (i^2 \sqrt{a_i^2 + b_i^2} \sin(i\omega t + \varphi_i)) \]  \hspace{1cm} (7)
Where

\[ \sin \varphi_i = \frac{b_i}{\sqrt{a_i^2 + b_i^2}}, \quad \cos \varphi_i = \frac{a_i}{\sqrt{a_i^2 + b_i^2}} \]  \hspace{1cm} (8)

The constraint condition is

\[ -\omega^2 \sum_{i=1}^{n} (i^2 \sqrt{a_i^2 + b_i^2} \sin(i\omega t + \varphi_i)) \leq a(t) \leq \omega^2 \sum_{i=1}^{n} (i^2 \sqrt{a_i^2 + b_i^2} \sin(i\omega t + \varphi_i)) \]  \hspace{1cm} (9)

Present work established another function \( F_2(a, b) \) to measure the maximum acceleration as the another objective function to keep the acceleration amplitude within reasonable bounds in adjustment stage. And \( F_2(a, b) \) defined as:

\[ F_2(a, b) = \omega^2 \sum_{i=1}^{n} (i^2 \sqrt{a_i^2 + b_i^2}) \]  \hspace{1cm} (10)

So present work established function \( \min f_2(a, b) \) as the other objective function to control the amplitude of the acceleration in the adjustment stage, and objective function \( \min f_2(a, b) \) defined as:

\[ \min f_2(a, b) = \omega^2 \sum_{i=1}^{n} (i^2 \sqrt{a_i^2 + b_i^2}) \]  \hspace{1cm} (11)

2.3. Numerical equations and solver

The governing equations for unsteady, incompressible and viscous fluid flow can be written in the following form

\[ \nabla \cdot U = 0 \]  \hspace{1cm} (12)

\[ \frac{\partial U}{\partial t} + \nabla \cdot F = 0 \]  \hspace{1cm} (13)

With the two-dimensional Cartesian components, \( F_{kj} \) is given by

\[ F_{kj} = (U_j - \hat{U}_j)U_k + \delta_{jk}P - \frac{1}{Re} \frac{\partial U_k}{\partial x_j} + u_j \mu_k \]  \hspace{1cm} (14)

Where \( U_jU_k \) is the Cartesian velocity component, \( \hat{U}_j \) is the mesh velocity, \( P \) is the pressure and \( \delta_{jk} \) is the Kronecker Delta number. The Reynolds stress tensor \( u_j \mu_k \) is given by:

\[ u_j \mu_k = \frac{2}{3} k \delta_{jk} - v_t \left( \frac{\partial U_j}{\partial x_k} + \frac{\partial U_k}{\partial x_j} \right) \]  \hspace{1cm} (15)
Where \( v_t \) is the eddy viscosity determined by the turbulence model and \( k \) is the turbulent kinetic energy. The above time-dependent Navier-Stokes equations are solved by using the finite volume method [10,11] and the Shear Stress Transport (SST) k-omega. Mode in the present work. One can refer to Menter (1993) for a detailed description of the SST model [12]. The Pressure Implicit with Splitting of Operators (PISO) algorithm [13, 14] is employed to deal with the coupling between the pressure and velocity. The third-order accurate QUICK scheme [15] is used to discrete the convective terms. Fig.3 shows a schematic diagram of the computational domain around the airfoil. The whole computational domain is 18c \((L_x)\) long and 10c \((L_y)\) wide. A conformal-hybrid grids system that consists of quadrangular meshes in an internal domain around the airfoil and triangular meshes in the outer field is shown in Fig.4. The complete inner mesh moves according to the wing kinematic and a dynamic deformable remesh method in accordance with Geometric conservation law method [16] is used in the outer field. A serial tests for grid independent and time step independent were conducted before actual calculations were carried out. Based on these tests, element number about \(4.2 \times 10^4\) and time step 0.0025T are selected for all the cases.

Fig.3 The boundaries around the computational domain

Fig.4 Computational grid around the plunging airfoil.

The incoming flow runs from the left to right. At the inlet of the computational domain, a uniform profile is prescribed:

\[
U = U_\infty \tag{16}
\]

The outlet of the computational domain is far away from the airfoil, and a boundary condition of fully developed flow is given by:

\[
\frac{\partial U}{\partial x} = 0 \tag{17}
\]

The no-slip boundary condition is specified at the airfoil surface and a symmetry boundary condition [17] is applied at the lateral faces of the computational domain. The influence of this symmetry condition has been investigated and found to be sufficiently adaptive. The simulation starts assuming the fluids is initially at rest.

The Reynolds number, which characterizes the effects of viscous, is defined as:

\[
Re = \frac{U_\infty c}{\nu} \tag{18}
\]

Where, \( \nu \) is the density of fluid and \( \nu \) is the dynamic viscosity.

The Strouhal number, which characterizes the periodicity in a flow field, is defined as:

\[
St = \frac{2h_0 c}{U} = \frac{kh_0}{U} \tag{19}
\]
Where $f$ is the frequency of plunging motion. $k = \frac{c}{U_\infty}$ is the reduced frequency. Current results use the quantity $kh_0$ to categorize.

The lift and drag coefficients are computed from:

$$
C_l = \frac{2F_y}{\rho csU_\infty^2}, \quad C_d = \frac{2F_x}{\rho csU_\infty^2}
$$

(20)

Where $s$ is the surface area per unit span-wise length of the airfoil and $F_y$ and $F_x$ are instantaneous lift and drag forces, respectively. These forces are calculated from the integration of the pressure and the viscous force on the surface of the airfoil.

The validation of the numerical algorithm for the flapping cases has been conducted in our previous work [18,19] and the results have been compared with related experimental and numerical results published in the literature. That numerical code is reliable for qualitatively analyzing flow characteristics around static and flapping airfoils.

2.4. Other important parameters

The averaged thrust and lift can be evaluated as:

$$
\tilde{F}_{th} = -\frac{1}{T} \int_0^{T/2} F_y(t)dt
$$

(21)

$$
\tilde{F}_l = \frac{1}{T} \int_0^{T/2} F_x(t)dt
$$

(22)

Where $F_x$ and $F_y$ and represent the instantaneous force components in $x$ and $y$ directions respectively. Then, the mean vertical force coefficient $C_v$ is defined as:

$$
C_v = \frac{2\tilde{F}_l}{\rho csU_\infty^2}
$$

(23)

The mean thrust coefficient $C_{Thm}$ is defined as:

$$
C_{Thm} = \frac{2\tilde{F}_{th}}{\rho U_\infty^3 cs} = \frac{1}{T} \int_0^{T/2} (-C_d)dt
$$

(24)

The averaged consumption power $\tilde{P}_i$ and power coefficient $\delta$ are given by

$$
\tilde{P}_i = \frac{1}{T} \int_0^{T/2} F_y(t)\dot{V}_h(t)d(t), \quad \delta = \frac{2\tilde{P}_i}{\rho U_\infty^3 c}
$$

(25)

Where $F_y(t)$ represents the instantaneous lift in the $y$ direction and $V_h(t)$ is the instantaneous heaving velocity of the wing is: $V_h(t) = \ddot{h}/\dot{t}$.

The averaged out power and power coefficient from thrust force are written by
\[
\ddot{P}_0 = -\frac{1}{T} \int_0^{T/2} F_x(t) U_\infty d(t), \quad \delta_T = 2 \frac{\ddot{P}_0}{\rho U_\infty^3 c}
\]  

Where \( F_x(t) \) is the instantaneous lift in the x direction.

The thrust efficiency is defined by

\[
\eta = \frac{\ddot{P}_0}{\dot{P}_i} = \frac{\delta_T}{\delta}
\]

3. Results And Discussion

3.1. Optimization results

In this study, the adjustment stage is classified as four cases, which are decrease flapping amplitude, increase flapping amplitude, decrease flapping frequency and increase flapping frequency. In each case, the plunging motion of the airfoil is first established by using the NAGA-II optimization. After series of multi-objective optimization, the results four cases are respectively depicted in Fig.5(a) to (d). It should be noted that the every point in Figure 5 represent an array of kinematic equation of the plunging airfoil in the adjustment stage. Then, we selected reasonable kinematics form the optimization results as shown in Fig. 6, and used them in next aerodynamic investigation.

![Fig.5 The optimized Result of the plunging motion in four cases of adjustment stage.](image)

![Fig.6 The kinematic displacement equations of three stage.](image)

3.2. Comparison on aerodynamics characteristics

In this study, the Reynolds number is kept at \( 10^4 \) and \( k_0 \) in the adjustment stage ranges from 0.67 to 1.04, which results in the Strouhal number range from 0.213 to 0.331. To investigate the aerodynamic performance of plunging airfoil in adjustment stage, the drag coefficient and lift coefficient of four cases are illustrated in Fig. 7 to Fig. 10. The negative drag coefficients indicate that the output thrust is positive. First, it can be seen that the instantaneous time signal of force coefficients in the adjustment stage are remarkably different from the other stages. The variation on amplitude and frequency of plunging airfoil will affect the maximum effective output load in the forward flight. Either flapping amplitude decreases or flapping frequency reduction, can both reduce the peak values of both lift and
drag coefficients. When the flapping frequency increased, the maximum lift coefficient is also increased. Moreover, the first peak of time signal of lift coefficient is remarkably enhanced. It should be also noted that the output thrust of the plunging wing in the adjustment stage does not necessarily increase as the frequency or amplitude increased as shown in Figure 8 (b) and Figure 10 (b). While either the frequency or amplitude is decreased, the output instantaneous thrusts reduce, as shown in Figure 7 (a) and Figure 9 (a).

To further investigated the aerodynamic characteristics in the adjustment stage, the averaged values of thrust coefficient and vertical force coefficient at different attack angles is compared in Figure 11. As shown in Figure 11, the attack angles are range from -5° to 7.5° with an increment of 2.5° for each cases. It is seen that the averaged values of thrust coefficient decreases as the attack angle increased. The averaged vertical force coefficient monotonically increases with the attack angle.
Fig. 11 Variations of averaged thrust force coefficients and averaged vertical force coefficients when the attach angle is from -5° to 7.5°.

The vorticity contours around the plunging airfoil for four cases are shown in Fig. 12, respectively. In order to facilitate the quantified comparison on the wake structure, the vorticity contour of a complete period when the plunging motion is sinusoidal equation before adjustment stage is shown in Figure 12(a). The beginning of the adjustment stage is at \( t=0 \) instant. After \( t=0.5T \) instant, the adjustment stage is over and next new stage starts, as shown figure 12(b) to (d). The vortex shedding plays an important role in the variation of aerodynamic forces. It is seen that the vortex shedding at the leading edge and trailing edge of the plunging airfoil are substantially influenced in the adjustment process. Especially, the shape of trailing edge vortices is very different with the one of sinusoidal plunging motion, as shown in figure 12(b) to (d). The trailing edge vortices at the three adjustment cases are a little smaller and weaker than that of no adjustment case (e.g. Fig 10 at time instant of 0.5T marked with red circle). This variation corresponds to the decrease in the output thrust as shown in above figure 7 to figure 9.
To further investigate the effective output load and thrust efficiency of the plunging airfoil, the averaged consumption power coefficient, the ratio of mean lift to averaged consumption power, the thrust efficiency are calculated. The payload provided by the unit input power for four adjustment cases is characterized by $C_v/d$ as shown in Figure 13. It can be observed that the values of $C_v/d$ during the four adjustment cases are increasing slightly with the attack angles. Further, it is also found that the decreasing frequency case is easier to get higher output lift force with a lower input power and keep efficient flight than other three adjustment cases. In addition, the thrust efficiency at different $kh_0$ at same attack angle, is also depicted in Fig.14. As shown in Figure 14, the highest thrust efficiency appears at $\alpha = -5^\circ$ and the corresponding Strouhal number is 0.26.

4. Conclusion
A NAGA-II multi-objective optimization algorithm is used to establish the flapping movement models in adjustment stage. Four adjustment cases are systematically investigated. Then, a comprehensive numerical study on the aerodynamic performance of a plunging NACA0014 airfoil at Reynolds number $10^4$ has been carried out by using finite volume method. The aerodynamic forces and corresponding wake structures of the airfoil are detail analyzed and the thrust efficiencies are presented. Current results show the increasement of plunging amplitude or frequency can enhance the output lift force in the adjustment stage during forward flight. The decrease of plunging amplitude or frequency will result in less lift force and less thrust force. However, the output thrust does not necessarily increase as the plunging amplitude increases in the adjustment stage. This study also found that the decreasing frequency adjustment case is much easier to get higher output lift force with a lower input power than others three adjustment cases. This interesting observation is very helpful for the further study on the aerodynamic performance of take-off stage and landing flight, and need be further studied. This study also indicates that the manner using multi-objective optimization algorithm to generate a movement model in adjustment stage, to connect other two specific plunging motions, is a feasible and effective method. These findings can be used to guide further study the
aerodynamic analysis on forward, take-off stage and landing flapping flight, and also provide some helpful information for improvement of control-abilities of artificial flapping wing air vehicles.

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