Numerical investigation on the propulsive efficiency of flapping airfoil with different up-down plunge models

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Keywords: *flapping wing, plunge model, unsteady flow, vortex street*

Abstract

A systematic study of the influence of up-down plunge models with different time ratios of down-stroke duration to up-stroke duration on the performance of a forward flight NACA0014 airfoil is carried out through numerical solutions of two-dimensional incompressible Navier-Stokes equations using a multigrid mesh method. Special attention is paid to the vortex shedding mechanism of nonsymmetrical motion and the influence of oblique attack angle. The attack angle is selected from -5° to 10° with an interval of 2.5° and for each attack angle seven different time ratios are examined. For the cases with the same reduced frequency and the plunge amplitude, the vortex pattern in the wake and the traveling direction of the vortex street are predominantly determined by the plunge motion. The nonsymmetrical plunge motion adjusts the time of the leading edge vortex separation which may results in higher propulsion than the symmetrical motion. For each plunge motion, the traveling direction of the vortex street is also affected by the oblique attack angle which causes a significant change in propulsion and lift. The present work confirms that both the trust and lift of the flapping airfoil can be improved by a nonsymmetrical plunge motion.

1 Introduction

The unsteady viscous fluid flow around a flapping wing is of practical importance and has received a great deal of attention. Creature flying can be very instructive in disclosing the mechanisms of such flow and there have been a number of studies carried out. However, how the different plunging motions alter the forces and hence the trust and lift on a flapping wing when the wing is in a forward flight is still not fully understood. This work attempts to investigate the influences of up-down plunge motions on the aerodynamic performance of a forward flight airfoil by analyzing the aerodynamic characteristics of a forward flight NACA0014 airfoil with different up-down plunge motion.

Numerous experimental as well as numerical studies on the flapping motion during forward flight of flyers have been reported in open literatures, pertaining to the forces, controlability and the propulsive characteristics of flapping wings (e.g. Weis-Fogh, 1956; Zarnack, 1988; Dudley and Ellington, 1990; Tobalske and Kenneth, 1996; Willmott and Ellington, 1997; Schilstra and Van Hateren, 1999; Lai and Platzer,1999; Hoon, Seung Y etc, 2004: Tian etc, 2006). Previous experimental studies have found that wake pattern of forward flight is associated with the Strouhal number, Reynolds number, amplitude of plunge and the attack angle of wing. It has been noted that the down-stroke duration is different from that of up-stroke for some creatures. However, how the duration difference influences the aerodynamic performance is still unclear. To capture all the relevant details of the influence in the flow just by experimental observations is very difficult, and it is not feasible to find a representative wing kinematics of the free forward flight to predict the likely aerodynamic consequences of control. Besides experimental investigations and theoretical analysis, numerical simulation has become another very effective approach and many

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computational studies have been carried out to study the flapping mechanisms of a flapping airfoil having the same duration time for up and down strokes [e.g. Tuncer and Platze, 1996; Lewin et al, 2003; Zhu et al 2008]. It has been found that the separation of the leading edge vortices at low heaving frequencies leads to diminished thrust and the efficiency decreases for higher frequencies when the airfoil plunges in a symmetrical pattern.

From the above discussion, it is obvious that there have been relatively less studies on the flapping mechanics of a plunge motion with different up and down stroke duration time. Accordingly, the present work aims to increase the fundamental understanding of a flow across a NACA0014 airfoil plunging with equal or unequal up-stroke and down-stroke duration. A finite volume method is applied to solve the two-dimensional time dependent incompressible Navier-Stokes equations. It is expected that the present results are of fundamental use in exploring the aerodynamic features of the flow around a flapping wing and in getting into physical understanding of creature flying mechanisms.

2 Description of the model

2.1 Kinematics

The inspiration of the present type of heaving with different time ratio between down-stroke and up-stroke duration comes from the kinematics of some insects [1, 3, 6] such as the desert locust, the hawkmoth etc. with forward flight. The experimental data of wing-beats with different duration times for down-stroke and up-stroke is fitted in a form of Fourier series as described by equation (1). Some conversion factors have been used to ensure that the down-stroke begin at the upper branch of the amplitude and to keep all the stroke amplitude with $2h_0c$ where h_0 is non-dimensional amplitude and c is the chord length of the wing.

The displacement h with different up-down plunge duration can be expressed by Fourier equation as follows

$$h = \left\{ a_0 + \sum_{n=1}^{n=m} \left(a_n \cos\left(n * w * t + c_n \right) \right) \right\} c + \left\{ \sum_{n=1}^{n=m} \left(b_n \sin\left(n * w * t + d_n \right) \right) \right\} c \qquad (1)$$

where t is the time, a_0, a_n, b_n and d_n are constants, w denotes the flapping frequency defined by $2\pi/T$ and T is flapping period. The effect of different time ratio τ between down and up stroke duration is analyzed in figure 1 where τ = 0.60, 0.80, 0.82, 1.00, 1.22, 1.26 and 1.68 are selected. Though the kinematics contains many individual idiosyncrasies, the variation on the velocity and acceleration between the different half strokes can be always successive. When τ =1.0, the wing motion follows a symmetrical pattern. The displacement is limited to the cosinusoidal function identified as one special Fourier equation which keeps all the coefficients at zero expect $a_1 = h_0 = 0.4$.

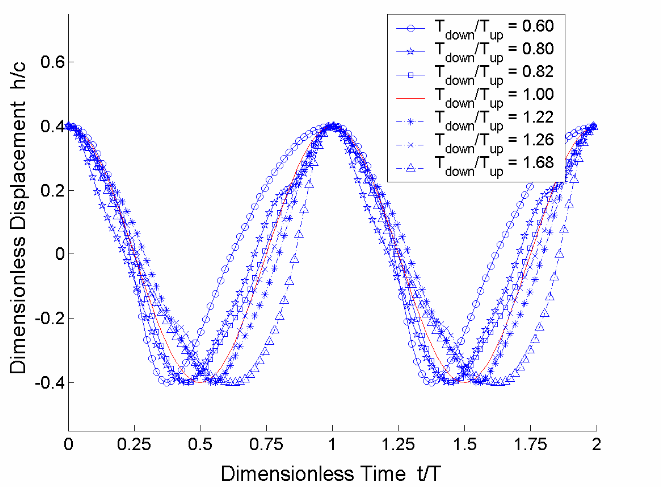


Fig. 1 Kinematics of the airfoil with different ratio τ between down and up stroke duration

2.2 Forces and power

The period-averaged consumption power rate $\overline{P}$ is defined as

$$\overline{P} = \frac{1}{T} \int_0^T F_n(t) \frac{dS_n}{dt} dt , \qquad (2)$$

where $F_n(t)$ represents the instantaneous generated total force components in the normal direction of the wing surface and dS_n/dt

denotes the traveling speed of the airfoil as it executes the plunge motion.

The period-averaged thrust force can be evaluated as

$$\overline{F}_x = \frac{1}{T}\int_0^T F_x(t)dt\,, \qquad (3)$$

where $F_x(t)$ represents the instantaneous generated force components in x-direction of the wing surface.

The period-averaged input power coefficient δ is determined by

$$\delta = \frac{\overline{P}}{\left(\frac{1}{2}\rho U_\infty^2 cs\right)U_\infty}\,, \qquad (4)$$

where ρ is density of fluid, s the surface area per unit spanwise length of the airfoil and U_∞ free stream velocity.

The period-averaged thrust power coefficient ε is given by

$$\varepsilon = \frac{\overline{F}_x U_\infty}{\left(\frac{1}{2}\rho U_\infty^2 cs\right)U_\infty} = C_{Thm} = \frac{1}{T}\int_0^T(-C_d)dt\,, \qquad (5)$$

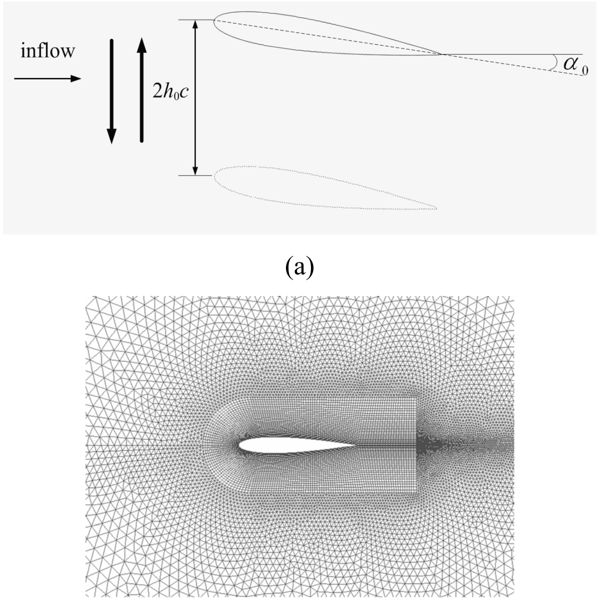
where C_{Thm} is the mean thrust coefficient and C_d the drag coefficient.

The propulsive efficiency λ is defined as

$$\lambda = \frac{\varepsilon}{\delta}\,. \qquad (6)$$

3 Governing equations and solver

As shown in Fig.2, viscous flow over an airfoil with chord c of infinite span undergoing a plunging motion with a constant initial angle is considered. The computational domain is $18c$ in horizontal direction and $10c$ in vertical direction. After a great deal of grid independent tests, a grid system with 4.2×10^4 elements is chosen and a non-dimensional time step 0.0025 is selected. In each time interval, a rigid grid method is used in the internal domain around the airfoil and a dynamic deformable remesh method in accordance with Geometric conservation laws method [14] is applied in the outer field.



(a)

(b)

Fig. 2 (a) Schematic configuration of rigid NACA0014 airfoil; (b) Close-up views of the computational grid

The dimensionless governing equations for two-dimensional, unsteady, incompressible fluid flow can be expressed as follows

$$\frac{\partial u_i}{\partial x_i} = 0\,, \qquad (7)$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\frac{\partial u_i}{\partial x_j} - \overline{u_i^{'}u_j^{'}}\right] \qquad (8)$$

$$\overline{u_i^{'}u_j^{'}} = \frac{2}{3}k\delta_{ij} - \nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (9)$$

where u is the velocity vector, the pressure p is normalized by ρU^2, $\rho\overline{u_i^{'}u_j^{'}}$ is the Reynolds stress, δ_{ij} is the Kronecker Delta number.

At the inflow, a uniform profile for the streamwise velocity is prescribed. A fully developed outflow boundary condition is given at the downstream boundary. A symmetry boundary condition is applied on the upper and lower boundaries of the computational domain. The non-slip boundary conditions are specified at the airfoil surface. The calculation starts assuming the fluids is initially at rest. The Reynolds number is kept at 10^4. The Strouhal number of current models is 0.255. The conservation equations subjected to the aforementioned boundary conditions are solved using the shear stress transport (SST) turbulence model coupled with the conformal-hybrid grids method [15]. The PISO algorithm [16] is employed to deal with the coupling between the pressure and velocity, and the third-order accurate QUICK scheme [17] is used to discrete the convective terms. The residual smoothing approach is also applied to accelerate the convergence in solutions in each time step.

4 Results and discussion

The present numerical code is first validated by comparing the experimental results of Tuncer and Kaya [18] and other numerical result of Miao and Ho [19]. The comparison is show in Fig. 3 where the drag coefficient is plotted against the non-dimensionlal time $t' = tU_\infty / c$ for flow over the airfoil spending the same time in the up- and down-stroke duration. It can be seen that the present calculation is reasonably accurate which confirms that the numerical code is reliable for predicting the fluid forces for the flow over a flapping wing with a plunging model.

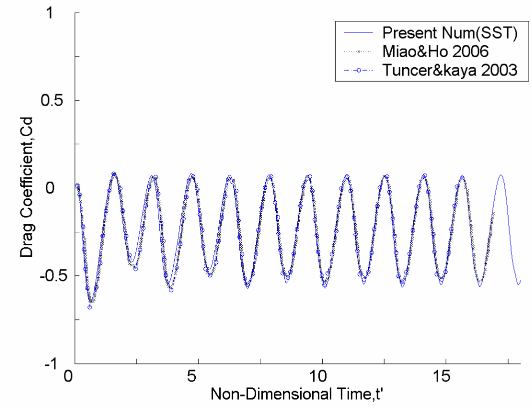
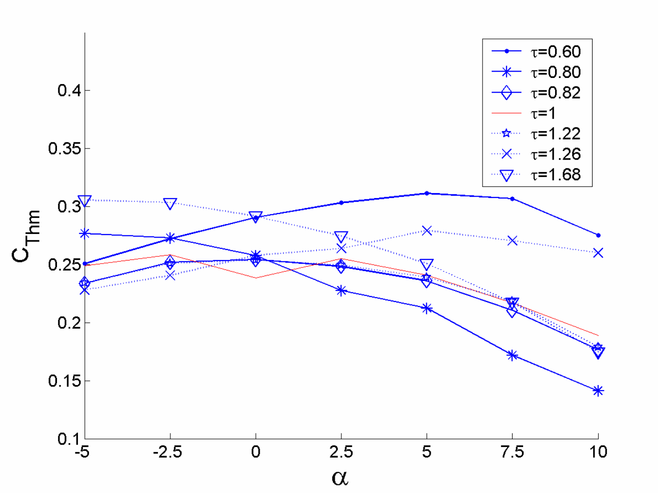
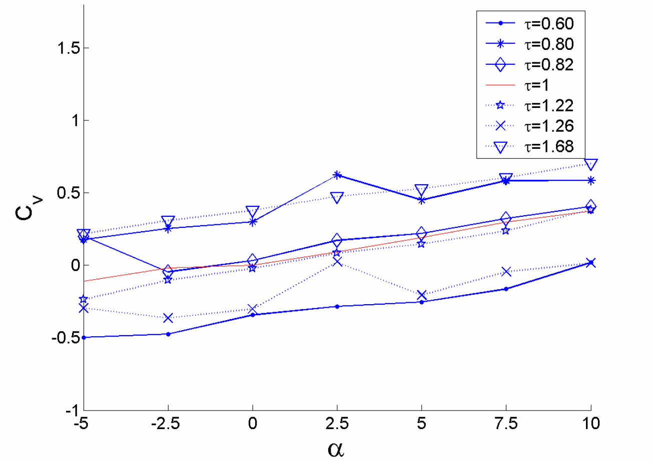


Fig. 3 Comparison of drag coefficient with results of Tuncer et al. and Miao et al.

In order to facilitate the comparison on the effect of different plunging models, the reduced frequency $k = wc/U_\infty$ is kept at 2. Fig. 4(a) shows the variation of the averaged thrust coefficient C_{Thm} against the attack angle α for different plunging time ratios. It can be observed immediately from the figure that the nonsymmetrical motions produce bigger average thrust than the symmetrical motion when the attack angle α is zero. It also seen that the trend of the change with the plunging time ratio for different angle α is different. The plunge motion has a significant effect on the thrust when the wing flight forward with fixed inclination. Whether an asymmetrical plunge motion produces higher thrust than a symmetrical one is affected by the initial angle α_0. The similar phenomenon was experimentally observed by Willmott and Ellington [6]. They found that the hawkmoth increases in forward speed tended to be accompanied by an increase in stroke angle and a decrease in body angle. Current study implies that the thrust force can be changed by adjusting the nonsymmetrical character of motion when the angle of attack can not be changed.



(a)



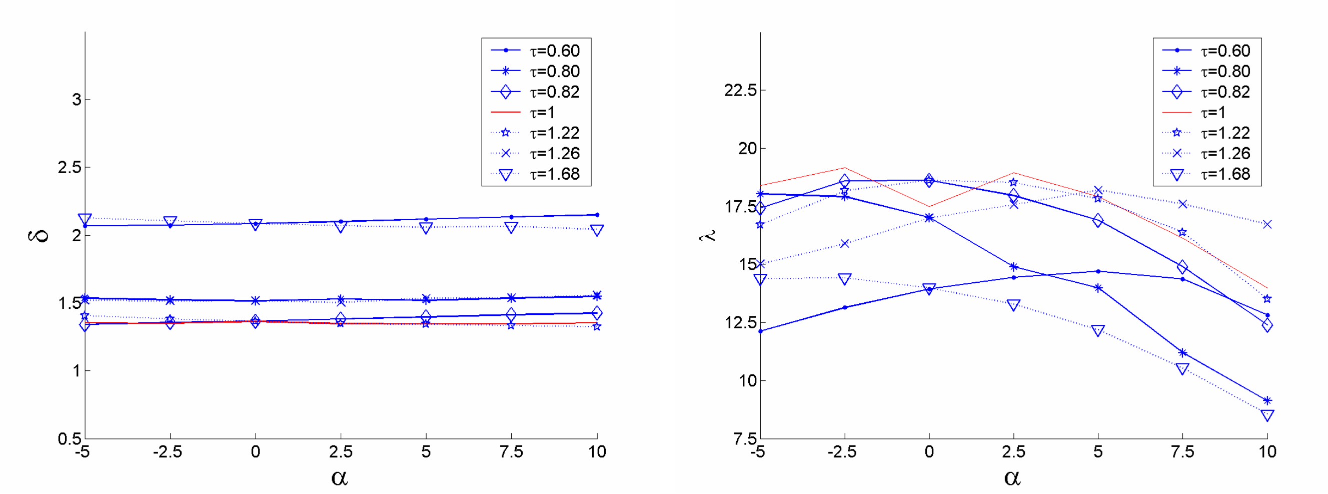
(b)

Fig. 4 The period-averaged thrust coefficients (a) and vertical force coefficients (b) with respect to the angle α when k=2.

The variation of the mean vertical force coefficients C_V against the attack angle α for different plunging time ratios is given in Fig. 4(b). The mean vertical force produced in one cycle by the symmetrical motion is found to be increase with the attack angle from -5° to 10°. For the nonsymmetrical plunge motion, the curves are no longer monotonically increase. The changes of the period-averaged input power coefficients δ and the propulsive efficiency λ for different plunging time ratios are plotted in Fig. 5(a) and 5(b) respectively. The averaged power coefficient appears to have only a very little change with the attack angle for each plunging motion (see Fig. 5(a)). The propulsive efficiency of the symmetrical movement can be improved by keeping the cross-section with a small angle with respect to the incoming flow when the wing travels at a uniform speed (Fig. 5(b)). The propulsive efficiencies of the nonsymmetrical plunge motions are not always high because the flight needs some compensation inputs for the longitudinal forces which results in vertical oscillations so as to meet a constant speed forward flight.

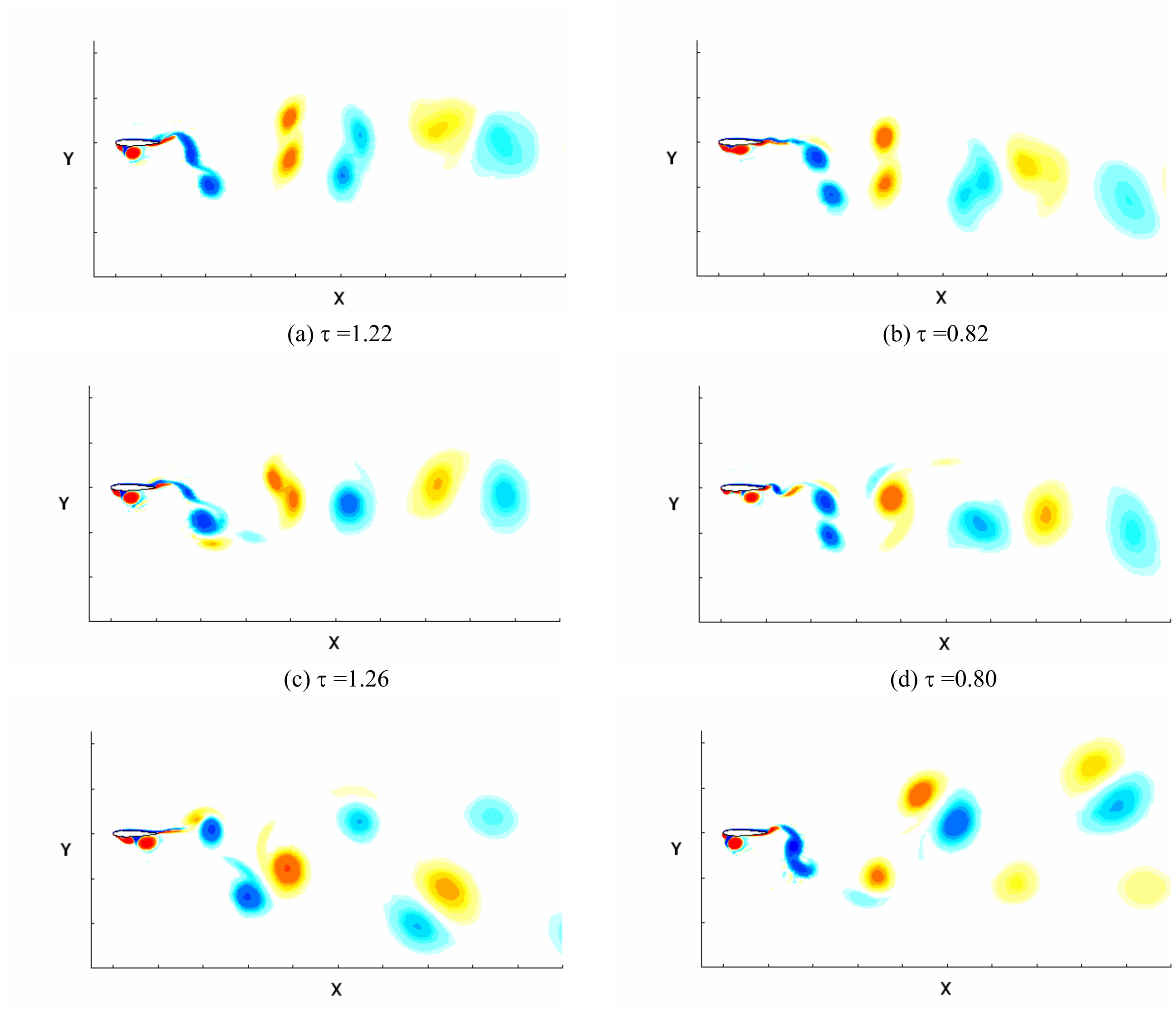
In the symmetrical plunging case, the wake structure is associated with the amplitude h and the reduced frequency k when the initial angle is zero as suggested by Lewin and Hai-hariri [12]. The present results show that there are always thrusts existed with the opposite direction of the incoming flow. The alternate vortex shedding of the model corresponds to the reverse Von Kármán vortex street which is in agreement with the experimental research of Von Kármán and Burgers [20].

To investigate the aerodynamic performance of the nonsymmetry plunging motion, the vorticity structure in the near wake is presented in Fig. 6. The counterclockwise vorticity marked with red colour and clockwise vorticity with blue one so that the structure of the reverse Von Kármán or classical Von Kármán streets can be easily identified. It is noted that the vortex patterns in the near wake for different plunging motions are quite different. The figures show the evolution behavior of the leading edge vortices (LEV) and the trailing edge vortices (TEV) of the airfoil for different plunge motions. There is a clear correlation observed from the figures that the vortex patterns in the near wake decided by the formation and the growth of both the LEV and the TEV, and also affected by the interaction between them. This is quite similar to that observed numerically by Lewin and Haj-hariri using a symmetry plunge model. Gopalkrishnan et al. [21] had similar experimental observations. Also the present study explores that the fate of the LEV and how it interacts with the TEV can be adjusted by the input motion of the flapping wing. The number of vortices shed per shedding cycle can be two or more which can be adjusted by the unsymmetrical plunge motion even when the reduced frequency and amplitude keep constant, While the analogous results of the symmetrical plunging appear at a higher Strouhal number.



(a) (b)

Fig. 5 Interrelationship between the input power coefficient δ and the propulsive efficiency λ with respect to angle α.



(a) τ =1.22

(b) τ =0.82

(c) τ =1.26

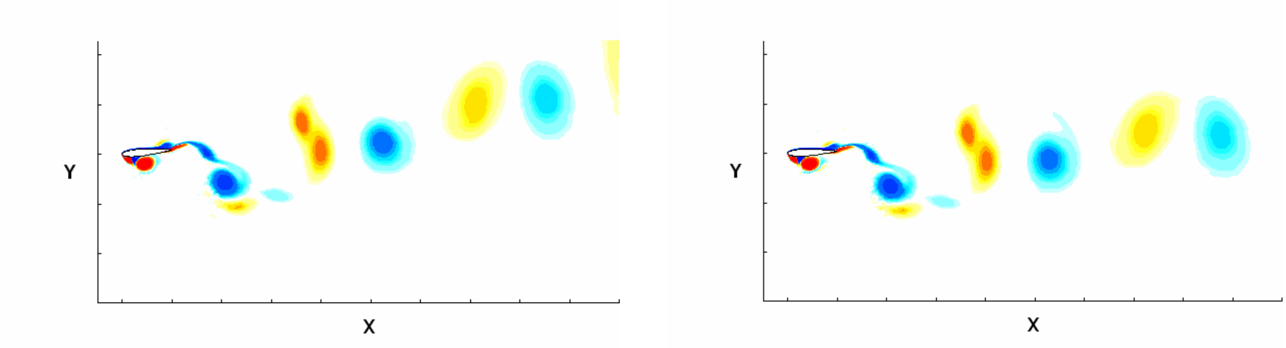
(d) τ =0.80

(e) τ =0.60

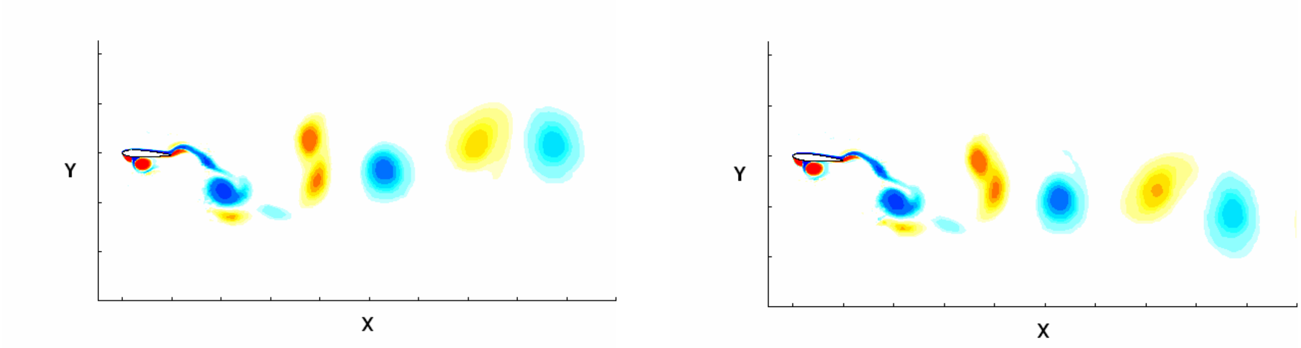
(f) τ =1.68

Fig.6 Vorticity contour plot for nonsymmetry plunge with different down-up time ratio when α =0° (blue: clockwise, corresponding to negative vorticity values).

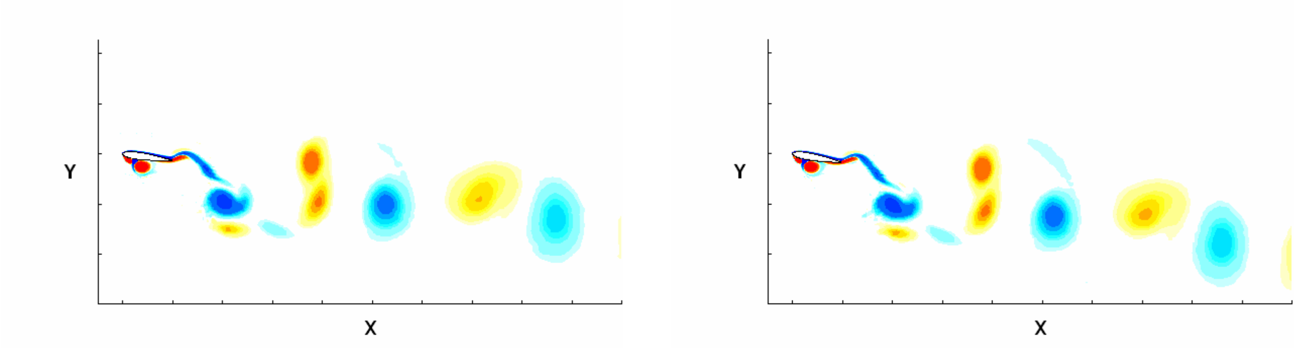
It is found that for the same plunge motion the influence of the attack angle on the formation，the separation time of the vortices and the structure of the vortex street are quite limited. The important effect of the attack angle is on the evolution of the vortex street in the near wake. It is seen that as the attack angle increases traveling direction of the vortex street changes greatly. Therefore once the plunge motion is designed the corresponding vortex structure is determined. Another interesting finding is that when τ = 0.8, 0.82, 1.68, the LEV remains attached to the surface of the airfoil for each stroke which results in a higher lift as shown in Fig. 4(b). This phenomenon is similar to the numerical study of Wang [22] for the symmetrical plunge motion. The attack angle has significant effect on the traveling direction of the vortex street. For instance, when τ=1.26, the formation of vortex shedding are quite similar except the inclination of the vortex street (see Fig. 7) which also happens for a symmetric plunge motion. Additionally, the intensity of vortices in the near wake changes as the angle α increases. These results reveal that the vortex derived from the interaction between the LEV and TEV is predominantly determined by plunge motion and affected by the attack angle. The thrust and lift are decided by the formation, shedding and evolution of vortices which can be greatly affected by the plunge motion.



(a) $\alpha = -5°$ (b) $\alpha = -2.5°$



(c) $\alpha = 2.5°$ (d) $\alpha = 5°$



(e) $\alpha = 7.5°$ (f) $\alpha = 10°$

Fig.7. Vorticity contour plot for nonsymmetry plunge with down-up time ratio τ=1.26 when the wing at highest position. (blue: clockwise, corresponding to negative vorticity values).

5 Conclusions

A systematic study of the influence of up-down plunge motion with different time ratios on the performance of a forward flight NACA0014 airfoil is carried out in a numerical simulative method. The wake structure and the corresponding propulsive performances of the airfoil have been studied. With a symmetrical plunge motion, the wake structure of the airfoil is associated with the plunge amplitude and the reduced frequency when the initial attack angle is zero, as suggested by Lewin and Hai-hariri. The present results show that there are always thrusts existed with the opposite direction of the incoming flow where the reverse Von Kármán vortex street appears. This is in agreement with the experimental research of Von Kármán and Burgers.

It is found that the nonsymmetry of a plunge motion is one of significant factors to improve the performance of the flapping wing. The asymmetry of the plunge affects the formation of leading (LEV) and trailing (TEV) edge vortices and their interaction, including the direction of motion of the vortex sheet. The combination of these effects can lead to higher propulsive efficiency and thrust for some unsymmetric flapping cases. For each unsymmetric plunge, the propulsive efficiency is also related to attack angle. These results suggest that the thrust performance and the loads of the flapping vehicles can be improved by mean of adjusting the nonsymmetrical factors such as the time ratio between up-stroke and down-stroke duration over a forward flight. Future studies will be considering the effect of deformation caused by load distribution along the wing surface, and computation on the three-dimensional rigid model to investigate the spanwise flow is also necessary.

Acknowledgement

The work described in this paper was supported by a grant from National Natural Science Foundation of China (Project number No. 90715031). The financial support is gratefully acknowledged.

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