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RESEARCH PAPER

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A flow control mechanism in wing flapping with stroke asymmetry during insect forward flight*

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Abstract A theoretical modeling approach as well as an unsteady analytical method is used to study aerodynamic characteristics of wing flapping with asymmetric stroke-cycles in connection with an oblique stroke plane during insect forward flight. It is revealed that the aerodynamic asymmetry between the downstroke and the upstroke due to stroke-asymmetrical flapping is a key to understand the flow physics of generation and modulation of the lift and the thrust. Predicted results for examples of given kinematics validate more specifically some viewpoints that the wing lift is more easily produced when the forward speed is higher and the thrust is harder, and the lift and the thrust are generated mainly during downstroke and upstroke, respectively. The effects of three controlling parameters, i.e. the angles of tilted stroke plane, the different downstroke duration ratios, and the different angles of attack in both down- and up-stroke, are further discussed. It is found that larger oblique angles of stroke planes generate larger thrust but smaller lift; larger downstroke duration ratios lead to larger thrust, while making little change in lift and input aerodynamic power; and again, a small increase of the angle of attack in downstroke or upstroke may cause remarkable changes in aerodynamic performance in the relevant stroke.

Keywords Insect forward flight · Wing flapping · Stroke asymmetry · Oblique stroke plane · Theoretical modeling.

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1 Introduction

Insects are the most abundant form of life on earth, with average body size of (3–5) mm. Miniaturization of the insect body is a tendency of the evolutionary process among winged insects, yielding a profusion of diverse miniaturized forms for the majority of insects.

Wing flapping which consists of upstroke, pronation, downstroke and supination, is a common locomotion mode for insect flight, which has been regarded as an efficient specific mechanism to overcome the small-scale aerodynamic limitation of flying-wing performance. In fact, the flight of millimeter-sized insects depends on a wing-beat with high frequencies usually in excess of 100 Hz. Therefore, the Reynolds numbers in these cases are in a range of $Re = 10^2 \sim 10^3$ and the reduced frequencies are much greater than the value $k = 0.5$ which has been taken by Lighthill [1] as an upper limit of the quasi-steady flow assumption. So wing flapping of common-sized insects makes the surrounding flow field highly unsteady and viscous. Later, you may find in the present theoretical modeling approach that the similarity parameter of high flow unsteadiness represented by the reduced frequency (or by the Strouhal number St) plays a dominant role in this case, so that wing flapping may provide large unsteady aerodynamic forces which break through the steady aerodynamic limit in low Re conditions.

Insects are innately able to regulate their wing flapping mode by changing many kinematic parameters to attain the expected locomotion, e.g. hovering, forward flight, fast turning, etc. In the last decade, people began to study the unsteady flapping aerodynamics for small insects in hover. For example, Dickinson, et al.[2] built a dynamically scaled robotic model of a hovering fruit fly ($Re = 136$, $f = 145$ Hz), equipped with sensors at the base of one wing capable of directly measuring the time course of aerodynamic forces, in addition to quantified flow visualizations during the pronation and the supination process. They found that the enhanced unsteady aerodynamic lift comes not only from delayed stall effects in the up and downstroke, already described by Ellington, et al.[3] who have made flow visualizations on a mechanical flapper model mimicking the hovering hawkmoth wing (of centimeters in size), but also from two rotational phases of pronation and supination which may contribute as much as 35% of the total lift. In the experiment, Dickinson, et al. considered a flapping mode with a horizontal stroke plane and with symmetric stroke-cycles, which is the prevalent case in insect hovering, and studied the aerodynamic responses by changing one of flapping kinematic parameters, i.e. different timing of the rotational phase relative to stroke reversal (advanced, symmetric and delayed rotational mode). Sun, et al.[4], by using computational fluid-dynamic analysis based on Navier-Stokes equations, studied the unsteady aerodynamics of the model fruit fly wing used in the above experiments and validated the main results of Dickinson, et al.[2]. Further, Sun, et al.[5] studied the lift and power requirements of hovering flight in one species of fruit fly for advanced, symmetric and delayed rotational modes and concluded that on the basis of calculated results for power expenditure, symmetrical mode should be used for long duration flight and the other two modes for flight control and maneuvering. Wang [6] also investigated the unsteady aerodynamics for two-dimensional wing flapping in insect hovering flight, but with an oblique stroke plane, by solving the Navier-Stokes equations.

According to relevant literature and original data [7–9], the wingbeat cycles are quite similar in very different species of insects. The main features of the wing stroke during forward flight of all volant animals are its tilted stroke plane and its asymmetry [10], which are distinguished from the horizontal stroke plane and symmetric stroke-cycles in the popular insect hovering flight [8].

In forward flight, the stroke cycle is asymmetric in several respects [11]. Firstly, relative to the body, the lower (abdominal) portion of the stroke is much shorter than the upper (dorsal) part, which is a three-dimensional feature. Secondly, the duration of downstroke is always longer than that of upstroke, so the downstroke to upstroke duration ratio cannot be less than 1. And thirdly, the aerodynamic angle of attack (the angle between the mean wing chord and the stroke plane) during downstroke is always different from that during upstroke. A tilted stroke plane appears as another important feature in forward flight for many insects. All these factors strengthen the stroke asymmetry, the generated upward force is significantly increased during the downstroke and diminished in the upstroke [9].

Up to now, the aerodynamic analyses of insect forward flight is rare, particularly for wing flapping with asymmetric stroke-cycles. Wang [12] investigated the vortex shedding and frequency selection for a two-dimensional wing heaving obliquely in a constant incoming flow by a computational fluid dynamic method. Sun and Wu [13] published their numerical work on aerodynamic force generation and power requirements in forward flight in a fruit fly with modeled wing motion, in which they only accounted for the tilted stroke plane, and maintained the symmetric stroke-cycles.

Recently, Fry, Sayaman, and Dickinson [14] have captured the wing and body kinematics of free-flying fruit flies as they performed rapid flight maneuvers and studied the aerodynamic forces on a smart robotic model. They found that a fly generates rapid turns with surprisingly subtle modifications in wing motion, which nonetheless generate sufficient torque for the fly to rotate its body through each turn. A backward tilt of the stroke plane and an increase in stroke amplitude of the outside wing (relative to the turning fly) are two specific characteristics contributing to the forces and yaw torque. They also mentioned that other parameters, such as subtle changes in the angle of attack relative to the stroke path, may also play a role.

Based on the above-mentioned review, it is very necessary to study unsteady flapping aerodynamics further for the stroke asymmetry in insect forward flight.

The present paper tries to answer why the stroke asymmetry of wing flapping is popularly used in insect forward flight and how these influencing kinematic parameters are used to regulate the aerodynamic forces. First of all, a flapping model and a theoretical modeling approach, as well as an unsteady analytic method are applied to study the aerodynamic characteristics of wing flapping in insect forward flight, which are appropriate to reveal flow physics in changing parameters of wing flapping. Then, based on predicted results for examples of given kinematics with stroke asymmetry, some peculiar aerodynamic performance in question is explored and checked with some viewpoints, e.g. in Ref. [9]. And finally, an investigation is made of the aerodynamic effects of some controlling parameters, i.e. the angles of the tilted stroke plane, the different downstroke duration ratios, and the different angles of attack during down and up-stroke.

2 Wing flapping model and kinematic parameters

Ellington [15] has mentioned that the morphological diversity of the insects is apparent. The ratio of wing span to mean chord, known as the aspect ratio, varies from 5.7 to 11.6, with an average value of 8.3. The mean wing thickness is typically about 0.057% of the wing length, ranging from 0.015% to 0.106%. Based on these wing data, it is reasonable to assume a rigid wing of negligible thickness and flexibility, which is the first approximation to most insect wings. To some extent, the three-dimensional wings can be approximated by a 2-D thin flat plate, which can simplify the theoretical analysis for wings of large aspect ratio. This wing model is convenient for the study of complex insect motions and will be of benefit to analyze the basic unsteady flow mechanisms in insect flight [16].

Insect wing kinematics involves two translational phases (upstroke and downstroke) and two quick turning phases (pronation and supination) shifting its leading edge to its rear side during stroke reversals. Consequently, insect wing flapping may be modeled as combined plunging and pitching oscillations of a 2-D flat plate. The trajectory of its pitching axis aligns in a straight line, or shaped like figure "0" and figure "8". Here, we only discuss the mode of straight-line wing flapping.

Next, the kinematic parameters will be defined step by step.

Firstly, Fig.1 gives a sketch of the flapping mode, where β is the angle between the stroke plane (SP) and the horizontal line, α_{up} and α_{down} are the aerodynamic angles of attack relative to the stroke plane during the up- and downstroke, respectively, and X is the stroke amplitude, which is always 4-5 times that of wing chord length c.

Secondly, according to the Ellington's definition [8], advance ratio (J) is used to define the magnitude of forward flight velocity, which is non-dimensionalized by the mean wing-tip velocity in a stroke-cycle. But here, it is defined as

$$J = V/(10fc), \tag{1}$$

where V is the forward flight velocity, and f is the flapping frequency. The reference velocity ($U_0 = 10fc$) is very close to the mean velocity $2fX$ in a cycle ($X = 4 \sim 5c$). The former is a better reference quantity because it releases the stroke amplitude X, an important variable in insect flapping flight, which will be studied in another paper. So, all the physical quantities can be non-dimensionalized by two references: U_0, and c.

Thirdly, t_{up} and t_{down} (indicated in Fig.1) are the durations of up- and downstroke. Here, let's define the downstroke duration ratio t_{down}/t_c to describe the asymmetric duration of strokes, where $t_c(t_c = 1/f)$ is the period of a flapping cycle.

Fourthly, the flapping kinematics in the present asymmetric stroke-cycle case are assumed by referring to Dickinson et al. [2] and Sun et al. [4,5]. During the downstroke or upstroke, the translational speed takes a constant value except near the beginning and the end of a stroke. The variation of non-dimensional velocities in downstroke and upstroke, u_d and u_u, may be described as follows:

$$u_u = \begin{cases} u_{u0} \sin k_{u\_ac} & \text{accelerated stage,} \\ u_{u0} & \text{constant velocity,} \\ u_{u0} \sin(k_{u\_de}\tau + \pi) \;\; \tau = t - t_{\mathrm{up}} & \text{decelerated stage,} \end{cases} \tag{2}$$

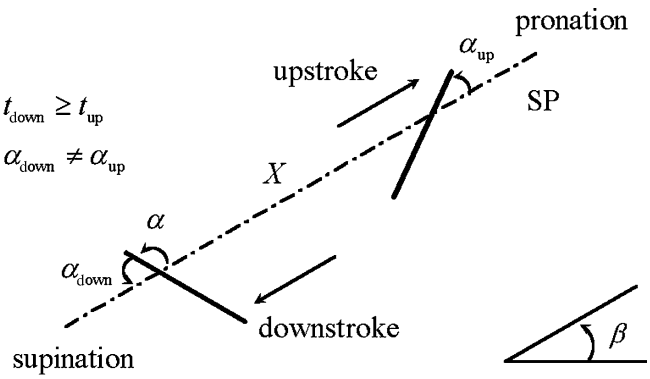

Fig. 1 Sketch of the flapping mode. The flat plate represents a cross-section of flapping wing in the chord direction. t_{down} and t_{up} are the durations of down- and up-stroke. α_{down} and α_{up} are the aerodynamic angles of attack relative to the stroke plane during down- and up-stroke, respectively, β is the angle between the stroke plane (SP) and the horizontal line, and X is the stroke amplitude

$$u_d = \begin{cases} u_{d0} \sin(k_{d\_ac}\tau + \pi) \;\; \tau = t - t_{\mathrm{up}} & \text{accelerated stage,} \\ u_{d0} & \text{constant velocity,} \\ u_{d0} \sin k_{d\_de}\tau \;\; \tau = t - t_c & \text{decelerated stage,} \end{cases} \tag{3}$$

where, u_{d0} and u_{u0} are the constant (maximum) velocity in the middle of down- / upstroke, respectively, k_{d_ac} and k_{d_de} (k_{u_ac} and k_{u_de}) are angular frequencies during the accelerated and decelerated stages near the beginning and the end of downstroke (upstroke). Equations (2) and (3) must satisfy the stroke-reversal conditions at the end of each stroke, i.e.,

$$\begin{matrix} u_d = u_u = 0 \\ \dot{u}_d = \dot{u}_u \end{matrix} \qquad (t = 0, t_{\mathrm{up}}) \tag{4}$$

and the angular frequencies k_{d_ac}, k_{d_de}, k_{u_ac}, k_{u_de} must satisfy the equations

$$(\pi/k_{u\_de} + \pi/k_{d\_ac})/2 = \Delta t_{t\_sup}, \tag{5}$$

$$(\pi/k_{d\_de} + \pi/k_{u\_ac})/2 = \Delta t_{t\_pro}, \tag{6}$$

where $\Delta t_{t\_sup}(\Delta t_{t\_pro})$ is the duration of the de-/accelerated stage near the end of downstroke (upstroke) and the beginning of the upstroke (downstroke). In a whole stroke cycle, the amplitude of the downstroke must be equal to that of the upstroke, i.e.,

$$\int_{\text{upstroke}} u_u \mathrm{d}t = \int_{\text{downstroke}} u_d \mathrm{d}t = X/c. \tag{7}$$

Then translational velocities u_d and u_u can be determined by the following parameters: the stroke amplitude X/c, the period of a stroke-cycle t_c, the downstroke duration ratio t_{down}/t_c, and the durations Δt_{t_sup} and Δt_{t_pro}.

Lastly, the two rotational phases in a flapping stroke-cycle, i.e. supination and pronation, need to be defined. During the supination, the angle α (as shown in Fig.1) changes from $\pi - \alpha_{\mathrm{down}}$ to α_{up} and the angular velocity is given by

$$\dot{\alpha} = 0.5\dot{\alpha}_{\max}[1 - \cos(2\pi t/\Delta t_{r\_sup} + \pi + \varphi_{sup})], \tag{8}$$

where Δt_{r_sup} is the period of supination, φ_{sup} is the rotational phase difference relative to the translational stroke, and

$$\int_{\text{supination}} \dot{\alpha} = \alpha_{\mathrm{up}} - (\pi - \alpha_{\mathrm{down}}). \tag{9}$$

So the supination can be determined by two parameters, Δt_{r_sup} and φ_{sup}. Also, the pronation can be determined similarly by another two parameters, Δt_{r_pro} and φ_{pro}.

In this paper, the effects of the rotational axis a during supination/pronation and the rotational phase differences φ_{sup} and φ_{pro} will not be discussed. The axis a is set at a quarter of chord length from the leading-edge, φ_{sup} and φ_{pro} are set at zero. Now, the kinematic parameters have been defined and the flapping motion can be determined.

3 Theoretical aerodynamic modeling

A theoretical modeling approach has been proposed by Yu et al. [16] to study insect wing flapping. A brief description of it will be given below.

For the flow excited by the flapping wings of small insects, which is highly unsteady, the Strouhal number should be the dominant parameter of similarity, which governs the character of the flow and makes its viscous effect of minor importance. It is reasonable to model this highly unsteady and viscous flow as follows: (i) the unsteady flow field outside the wing is mostly inviscid; (ii) the unsteady boundary layer on the wing surface is very thin and attached; (iii) in case of the high angle of attack, free shear layers are shed from both the leading and trailing edges of the wing, which leads to vortex shedding. This model may be further simplified into: (i) the entire flow field around the insect wing is potential and incompressible; (ii) the viscous effect of the boundary layer could be accounted for indirectly by imposing Kutta conditions on both the leading and trailing edges; (iii) discrete vortices are shed from the leading and trailing edges.

Consequently, the governing equation used in the present flow model is the unsteady Laplace equation,

$$\nabla^2\phi = 0, \tag{10}$$

where ϕ is the perturbation velocity potential. It should satisfy the boundary conditions on the flat plate and in the infinite region. Also, it must satisfy the Kutta conditions at two sharp edges.

In this incompressible potential flow, the moving flat plate can be replaced by the distribution of sources (or sinks) on its upper and lower surfaces. So the perturbation velocity potential ϕ includes two parts, ϕ_1 and ϕ_2,

$$\phi = \phi_1 + \phi_2. \tag{11}$$

ϕ_1 is the velocity potential induced by the moving sources (or sinks), and ϕ_2 is one induced by the distributed discrete vortices. Therefore, the flow around the moving flat plate can be solved in a conformally transformed plane by the elemental solutions of the distributed sources (or sinks) and the discrete point vortices shed from both the leading and trailing edges [16], which is different from the previous theoretical frames proposed by Wu [17] and Żbikowski [18].

Based on the theory of vortex dynamics [19], the aerodynamic force ($\boldsymbol{F}$) acting on the 2-D flat plate is proportional to the changing rate of the first-order moment of vorticity in the whole field and the aerodynamic moment (M) is proportional to the changing rate of the second-order moment of vorticity, i.e.,

$$\boldsymbol{F} = -\rho\frac{\mathrm{d}}{\mathrm{d}t}\int \boldsymbol{r}\times\boldsymbol{\omega}\mathrm{d}V, \tag{12}$$

$$M = \frac{1}{2}\rho\frac{\mathrm{d}}{\mathrm{d}t}\int r^2\omega\mathrm{d}V, \tag{13}$$

where $\boldsymbol{\rho}$ is the fluid density, $\boldsymbol{r}$ is the position vector and $\boldsymbol{\omega}$ is the vorticity. Then the input aerodynamic power is determined by

$$P = -(\boldsymbol{F}\cdot\boldsymbol{V} + M\cdot\dot{\alpha}). \tag{14}$$

The lift, F_L, and the thrust, F_T, are the components of the total force, perpendicular and parallel to the horizontal plane respectively, which should balance with the weight and the air drag in insect forward flight. The lift, thrust and input power coefficients, denoted by C_L, C_T and C_P, respectively, are defined as follows:

$$C_L = F_L/(0.5\rho U_0^2\cdot c),$$
$$C_T = F_T/(0.5\rho U_0^2\cdot c),$$
$$C_P = P/(0.5\rho U_0^3\cdot c). \tag{15}$$

Because the reference velocity U_0 is chosen in direct proportion to the flapping frequency f, the dimensional aerodynamic forces and input power are in direct proportion to the square and the third power of f, respectively.

This theoretical aerodynamic modeling approach as well as an unsteady analytic method has been validated in Ref. [16], which is able to give qualitatively correct and quantitatively reasonable aerodynamic forces as an efficient and cost-saving method.

4 Results and discussion

In order to analyze the aerodynamic characteristics for the stroke asymmetry of wing flapping during insect forward flight, we have assumed a wing flapping model and defined the kinematic parameters in section 2. But at present, there are few kinematic data of wing flapping mastered by entomologists in insect forward flight, particularly with asymmetric stroke-cycles, which is prevalently used by insects. On the basis of existing data from the experiments [2, 14] and CFD computations [4, 5, 13] in model fruit-fly wing flapping during hovering and forward flight, the kinematic data are set in Table 1. Then the aerodynamic characteristics of wing flapping with the stroke asymmetry will be investigated in the following subsection, and the aerodynamic effects of different controlling parameters will be discussed sequentially.

In the following predicted examples, advance ratios are taken from 0.0 to 0.6, representing a forward flight velocity in still air in the range between 0 and 1.6 m/s for fruit flies.

4.1 Aerodynamic characteristics of wing flapping with asymmetric stroke-cycles

Based on the parameters given in Table 1, Fig.2 describes the variation of non-dimensional stroke velocity U and the

Table 1 Values of the kinematic parameters in insect forward flight

t_{down}/t_c	α_{down}	α_{up}	β	X/c	$\Delta t_{t\_sup}/t_c$	$\Delta t_{t\_pro}/t_c$	$\Delta t_{r\_sup}/t_c$	$\Delta t_{r\_pro}/t_c$
0.55*	35°	35°	30°	4.5	0.18	0.18	0.36	0.36

* The value comes from the Ref.[14] (Fig.2B).

angular velocity $\dot{\alpha}$ with time, and Fig.3 shows the flight path of the wing axis through the air at the advance ratio $J = 0.1$ for the present 2-D wing flapping with stroke asymmetry.

The aerodynamic characteristics, C_L, C_T and C_P varying with time have been predicted by the present theoretical modeling approach, as shown in Fig.4. It is noted that the variation tendency of each family of $C_L(t)$, $C_T(t)$, or $C_P(t)$ curves for different advance ratios is similar with each other and tells us their common features as follows. Firstly, the lift curve has two positive peaks near the beginning and the end of every downstroke, but has a relatively smaller magnitude of the peaks in every upstroke. Secondly, the thrust curve has two positive peaks in every upstroke, but has negative values in every downstroke. Thirdly, the input aerodynamic power curve has two positive peaks in every downstroke and every upstroke.

Based on the predicted data (Fig.4), the mean values of lift, thrust and input aerodynamic power coefficients $\bar{C}_L$, $\bar{C}_T$ and $\bar{C}_P$ in each upstroke, each downstroke and a whole stroke-cycle are given in Table 2A, 2B and 2C. Considering that during insect forward flight, the inclined rearward stroke plane makes the downstroke and the upstroke to be, respectively, upwind and downwind motions to some degree, that in turn enhance and diminish the stroke aerodynamic effects in sequence, which are intensified in the case of increasing the forward flight velocity. Then it is easy to understand the following aerodynamic mechanisms in a stroke cycle for different advance ratios. Table 2A indicates that the downstroke generates the major part of the lift, while the upstroke contributes the minor part; increasing the advance ratio will increase not only the proportion of the major to the minor part of lift, but also the total value of $\bar{C}_L$. Table 2B mentions that the upstroke produces the positive thrust, while the downstroke makes the negative thrust (i.e. wing drag); and increasing the advance ratio leads to decreasing not only these two parts of thrust separately, but also the total value of $\bar{C}_T$. Table 2C reveals that increasing the advance ratio decreases the mean input power in the upstroke, while increasing that in the downstroke, so that the total value of $\bar{C}_P$ in a stroke cycle shows little change.

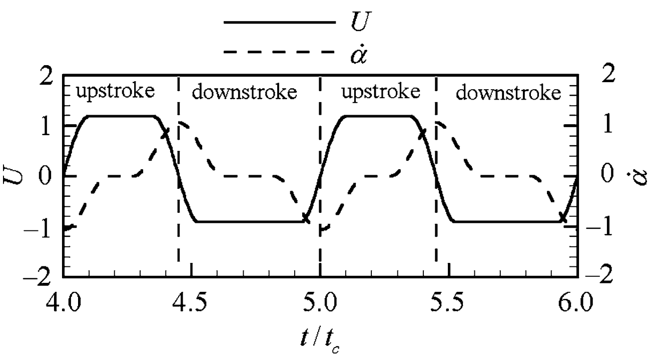

Fig. 2 Variation of non-dimensional stroke velocity U and angular velocity $\dot{\alpha}$ (pronation or supination) with time in the stroke plane

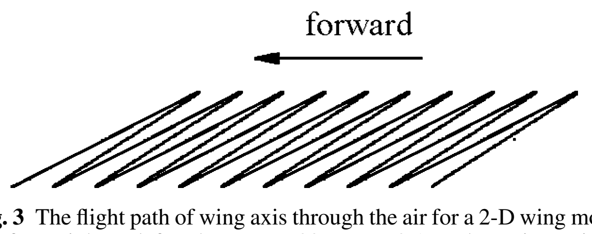

Fig. 3 The flight path of wing axis through the air for a 2-D wing moving from right to left, where $\beta = 30°$, $J = 0.1$, and rotation axis is located at a quarter of c from leading-edge of wing

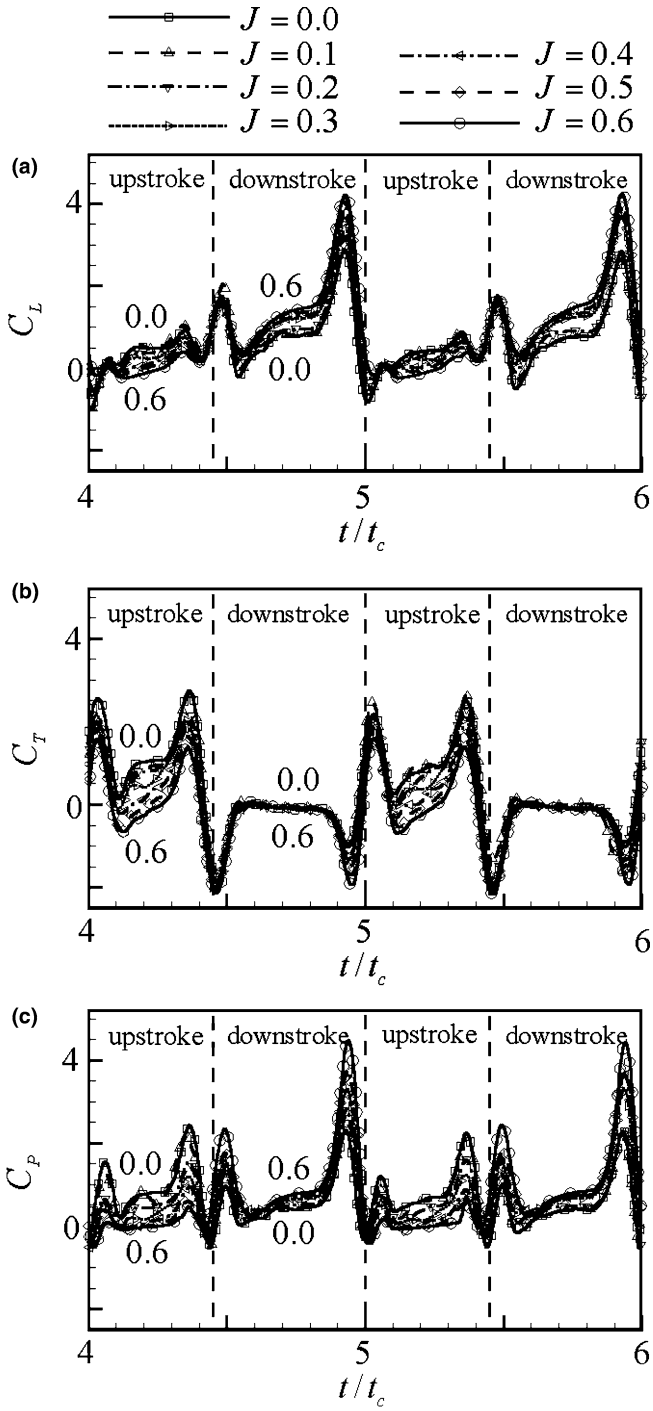

Fig. 4 Variation of the total aerodynamic characteristics (C_L, C_T and C_P) with time for asymmetric stroke-cycles at different advance ratio (J)

Table 2A Mean lift coefficient $\bar{C}_L$, when $t_{\rm down}/t_c = 0.55$, $\alpha_{\rm down} = \alpha_{\rm up} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	0.3300	0.9111	0.6496
0.1	0.3544	0.9666	0.6910
0.2	0.2945	1.070	0.7208
0.3	0.2467	1.354	0.8559
0.4	0.1767	1.449	0.8768
0.5	0.1310	1.558	0.9159
0.6	0.07551	1.637	0.9346

Table 2B Mean thrust coefficient $\bar{C}_T$, when $t_{\rm down}/t_c = 0.55$, $\alpha_{\rm down} = \alpha_{\rm up} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	1.158	−0.2573	0.3794
0.1	1.098	−0.2398	0.3622
0.2	0.8722	−0.3023	0.2262
0.3	0.7487	−0.3695	0.1337
0.4	0.5270	−0.4034	0.01531
0.5	0.3076	−0.4422	−0.1048
0.6	0.1395	−0.4910	−0.2073

Table 2C Mean input power coefficient $\bar{C}_P$, when $t_{\rm down}/t_c = 0.55$, $\alpha_{\rm down} = \alpha_{\rm up} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	0.8540	0.5626	0.6938
0.1	0.7411	0.6218	0.6755
0.2	0.4998	0.7314	0.6273
0.3	0.3270	0.9610	0.6758
0.4	0.1888	1.082	0.6800
0.5	0.1030	1.185	0.6984
0.6	0.04383	1.349	0.7615

In order to investigate the aerodynamic responses to the downstroke duration ratio, i.e. a main kinematic parameter of asymmetric stroke-cycles, we calculated two examples of $J = 0.3$: one with the symmetric stroke-time $t_{\rm down}/t_c = 0.5$ and another with the asymmetric stroke-time $t_{\rm down}/t_c = 0.55$, and compared these predicted results in Table 3. In fact, in this asymmetric case where the downstroke takes longer time than the upstroke, it means that the insect wing moves faster in the upstroke than in the downstroke, so that the aerodynamic forces are enhanced in the upstroke and diminished in the downstroke. It is noted in Table 3 that in comparison with the symmetric case, $\bar{C}_L$ and $\bar{C}_T$ in the upstroke of the asymmetric case increased by 47% and 31%, respectively, while in the downstroke the mean lift and the mean wing drag decreased by 17% and 13%, respectively, so that in a whole cycle, $\bar{C}_L$ had a small decrement by 5%, $\bar{C}_T$ increased remarkably by 82%, and $\bar{C}_P$ decreased by 9%. This means that the main influence of $t_{\rm down}/t_c > 0.5$ consists in enlarging the mean thrust, reducing a little input power and keeping the mean lift almost constant.

Again, the influences of stroke asymmetry in angles of attack ($\alpha_{\rm down} > \alpha_{\rm up}$) are shown in Table 4, where the predicted results in the asymmetric case ($\alpha_{\rm down} = 45^\circ$, $\alpha_{\rm up} = 35^\circ$) may be compared with that in the symmetric case ($\alpha_{\rm down} = \alpha_{\rm up} = 35^\circ$) as shown in Table 2. It is noted that an increase of $\alpha_{\rm down}$ brings a remarkable increase of $\bar{C}_L$, $\bar{C}_P$ and a decrease of $\bar{C}_T$ in the downstroke, but has little influence on $\bar{C}_L$, $\bar{C}_T$ and $\bar{C}_P$ in the upstroke.

4.2 Flow control mechanism in stroke-asymmetric wing flapping

As mentioned above, insects should regulate a lot of kinematic parameters in wing flapping to get the desired lift and thrust, balancing with the weight and the air drag, respectively, during forward flight. So, it is important to know the aerodynamic responses to changing each of stroke-asymmetric kinematic parameters, including the angle of the tilted stroke plane (β), the downstroke duration ratio ($t_{\rm down}/t_c$), and the different angles of attack in down- and up-stroke ($\alpha_{\rm down}$ and $\alpha_{\rm up}$).

In the following cases, the predicted mean aerodynamic forces and the mean input aerodynamic power have been time-averaged in 10 stroke cycles.

(1) Effects of the angle of the stroke plane (β)

Now, let's study the aerodynamic responses to varying the angle of the stroke plane $\beta = 25^\circ \sim 60^\circ$ for the problem of given kinematics (Table 1). The predicted results, as shown in Fig.5, indicate that for any advance ratio (J), increasing β is accompanied with decreasing $\bar{C}_L$, increasing $\bar{C}_T$ and most likely decreasing $\bar{C}_P$. Therefore, the angle of the stroke plane β is a key kinematic parameter for regulation of the thrust force in insect flight. When the forward flight velocity becomes larger, insects should tilt more obliquely their stroke plane rearward to get larger thrust to overcome the air drag which increases with the flight velocity.

(2) Effects of varying downstroke duration ratio ($t_{\rm down}/t_c$)

The previous problem with given kinematics (Table 1) has been recalculated but with varying $t_{\rm down}/t_c = 0.375 \sim 0.625$ and the predicted curves of the mean lift $\bar{C}_L$, mean thrust $\bar{C}_T$ and mean input power $\bar{C}_P$ are shown in Fig.6.

Table 3 Comparison of the mean aerodynamic characteristics between the conditions of symmetric and asymmetric stroke-cycles

	Asymmetric ($t_{\rm down}/t_c = 0.55$)			Symmetric ($t_{\rm down}/t_c = 0.5$)		
	upstroke	downstroke	cycle	upstroke	downstroke	cycle
$\bar{C}_L$	0.2467	1.354	0.8559	0.1673	1.628	0.8976
$\bar{C}_T$	0.7487	−0.3695	0.1337	0.5699	−0.4228	0.07355
$\bar{C}_P$	0.3270	0.9610	0.6758	0.2308	1.241	0.7359

Table 4A Mean lift coefficient $\bar{C}_L$, when $t_{\mathrm{down}}/t_c = 0.55$, $\alpha_{\mathrm{down}} = 45^\circ$ and $\alpha_{\mathrm{up}} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	0.361 7	0.872 8	0.642 8
0.1	0.347 2	1.218	0.826 4
0.2	0.319 2	1.389	0.907 5
0.3	0.245 9	1.711	1.052
0.4	0.189 3	1.719	1.031
0.5	0.143 2	1.979	1.153
0.6	0.074 57	2.062	1.168

Table 4B Mean thrust coefficient $\bar{C}_T$, when $t_{\mathrm{down}}/t_c = 0.55$, $\alpha_{\mathrm{down}} = 45^\circ$ and $\alpha_{\mathrm{up}} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	1.262	−0.358 7	0.370 5
0.1	1.199	−0.543 9	0.240 5
0.2	1.099	−0.565 6	0.183 7
0.3	0.707 0	−0.711 7	−0.073 26
0.4	0.571 8	−0.729 8	−0.144 1
0.5	0.404 2	−0.851 7	−0.286 6
0.6	0.146 6	−0.909 7	−0.431 4

Table 4C Mean input power coefficient $\bar{C}_P$, when $t_{\mathrm{down}}/t_c = 0.55$, $\alpha_{\mathrm{down}} = 45^\circ$ and $\alpha_{\mathrm{up}} = 35^\circ$

J	upstroke	downstroke	cycle
0.0	0.912 5	0.616 5	0.749 8
0.1	0.739 8	0.960 5	0.861 1
0.2	0.554 5	1.100	0.854 4
0.3	0.295 7	1.483	0.948 6
0.4	0.209 0	1.578	0.962 0
0.5	0.108 3	1.908	1.098
0.6	0.077 21	2.092	1.186

For different forward velocities, the variation tendencies of each $\bar{C}_L$, $\bar{C}_T$, or $\bar{C}_P$ with increasing t_{down}/t_c are similar, i.e. mean lift shows almost no change, mean thrust increases, and mean power decreases, so that when $t_{\mathrm{down}}/t_c < 0.5$ mean input power is much larger than that in the case of $t_{\mathrm{down}}/t_c > 0.5$.

It tells us that the asymmetric flapping with $t_{\mathrm{down}} > t_{\mathrm{up}}$ may have benefits of getting larger thrust, reducing a little input power and keeping the lift almost unchanged and so it is popularly used in insect forward flight.

(3) Effects of different angles of attack during down- and up-stroke (α_{down} and α_{up})

The previous problem is recalculated again with given kinematics (Table 1), but with varying $\alpha_{\mathrm{down}} = 10^\circ \sim 60^\circ$ and $\alpha_{\mathrm{up}} = 10^\circ \sim 60^\circ$ separately. The predicted results $\bar{C}_L$, $\bar{C}_T$, and $\bar{C}_P$ are given in Fig.7 for varying α_{down} and in Fig.8 for varying α_{up}. It's found that for different forward velocities, the variation tendencies of each $\bar{C}_L$, $\bar{C}_T$, or $\bar{C}_P$ with increasing α_{down} or α_{up} are similar. The flow control mechanism in varying α_{down} and α_{up}, may be summarized as follows. An increase of α_{down} is accompanied with a lift increase and a thrust decrease, but an increase of α_{up} leads to a thrust increase and almost no lift variation. It means that the lift may be regulated mainly by changing α_{down} and the thrust mainly by varying α_{up}. This confirms further the conclusion that the lift is produced and mainly regulated in the downstroke and the thrust mainly in the upstroke.

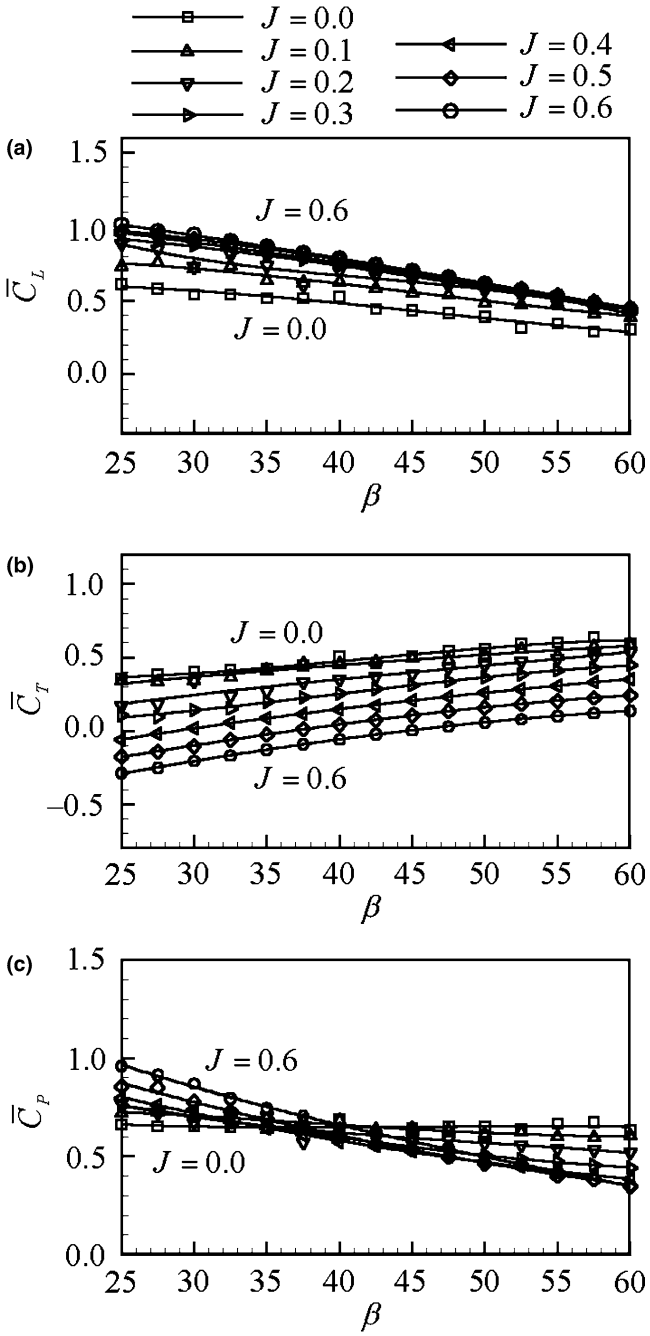

Fig. 5 Mean aerodynamic lift ($\bar{C}_L$), thrust ($\bar{C}_T$) and input power ($\bar{C}_P$) during a flapping cycle versus the angle of stroke plane (β). ($t_{\mathrm{down}}/t_c = 0.55$, $J = 0.0 \sim 0.6$)

5 Conclusions

In this paper, we have studied the flow physics and aerodynamic characteristics of wing flapping with asymmetric

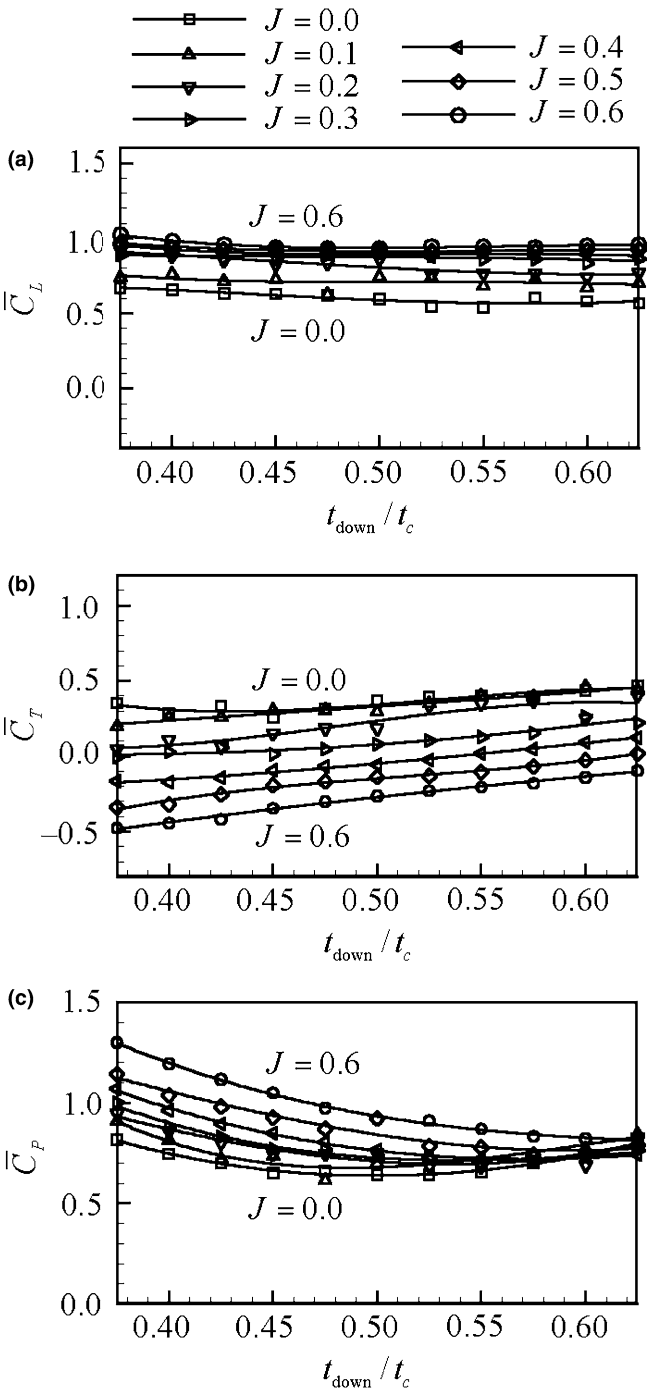

Fig. 6 Mean aerodynamic lift ($\bar{C}_L$), thrust ($\bar{C}_T$) and input power ($\bar{C}_P$) during a flapping cycle versus the downstroke duration ratio (t_{down}/t_c). ($t_{\mathrm{down}}/t_c = 0.55$, $J = 0.0 \sim 0.6$)

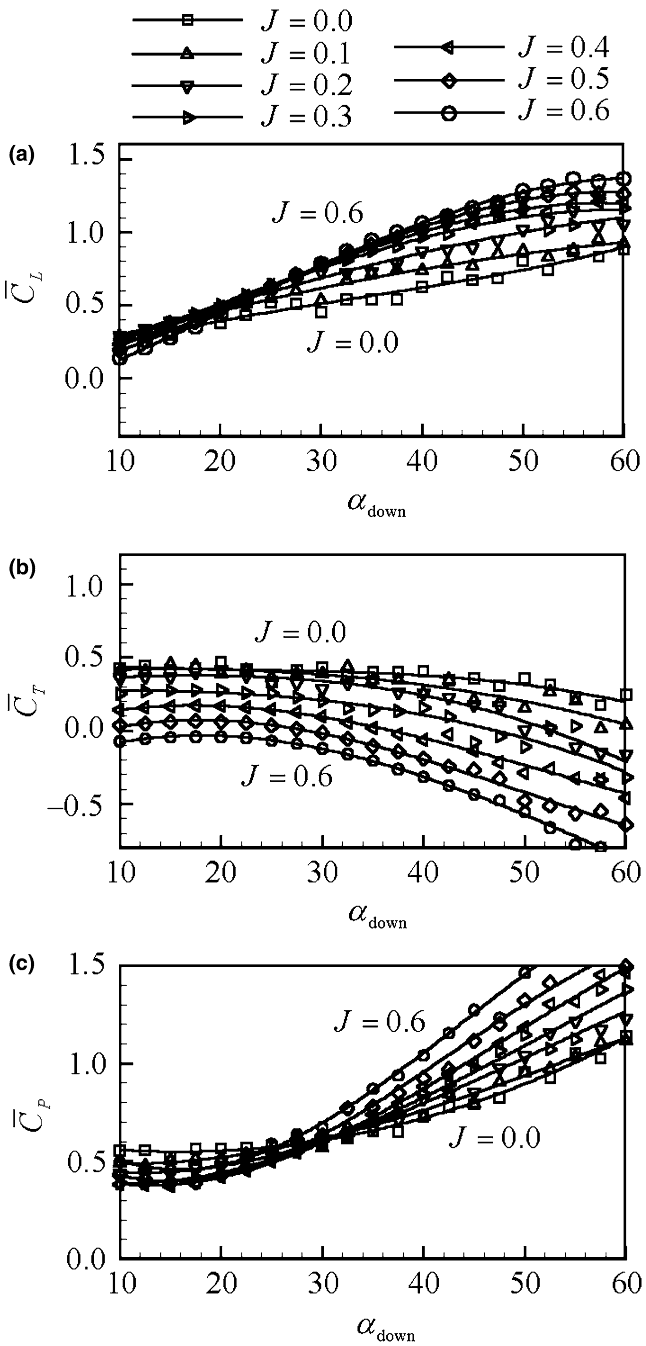

Fig. 7 Mean aerodynamic lift ($\bar{C}_L$), thrust ($\bar{C}_T$) and input power ($\bar{C}_P$) during a flapping cycle versus the aerodynamic angle of attack during downstroke (α_{down}). ($t_{\mathrm{down}}/t_c = 0.55$, $J = 0.0 \sim 0.6$)

stroke-cycles in connection with an inclined rearward stroke plane during insect forward flight by using a theoretical modeling approach as well as an unsteady analytic method.

An inclined rearward stroke plane is necessary to produce the lift and thrust, balancing with the insect body weight and the air drag faced in forward flight separately, and makes aerodynamic asymmetry between the downstroke and upstroke which become in some degree upwind and downwind motions, respectively. In fact, the upwind or downwind motion in turn will enhance or diminish the aerodynamic forces, which will be intensified with increasing forward flight velocities. The present predicted results revealed the aerodynamic performance of wing flapping in relation with a fixed oblique stroke plane as follows. Regarding lift generation, the downstroke produces the major part of the lift, while the upstroke does the minor part; and increasing the

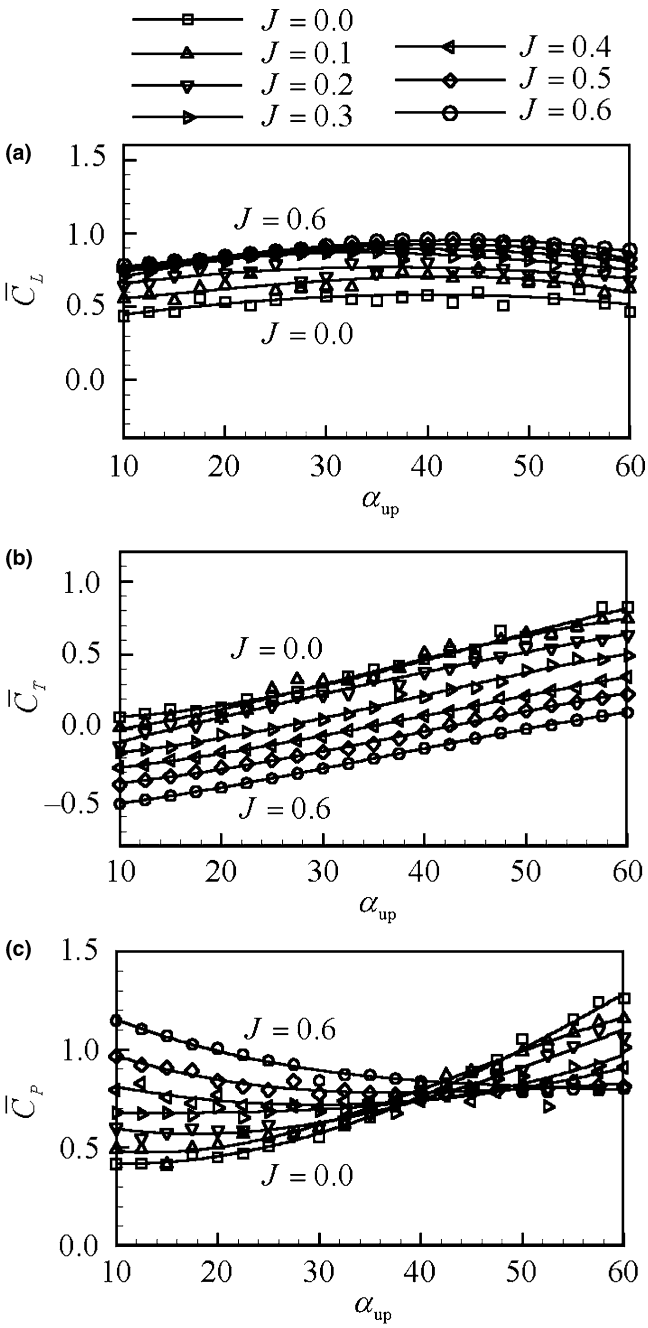

Fig. 8 Mean aerodynamic lift ($\bar{C}_L$), thrust ($\bar{C}_T$) and input power ($\bar{C}_P$) during a flapping cycle versus the angle of attack during upstroke (α_{up}). ($t_{down}/t_c = 0.55$, $J = 0.0 \sim 0.6$)

advance ratio will enlarge not only the proportion of the major to the minor part of lift, but also the total value of mean lift in a stroke-cycle. As for thrust formation, the upstroke generates the positive thrust, while the downstroke does the negative thrust (i.e. wing drag); and increasing the advance ratio leads to decreasing not only these two parts of thrust separately, but also the total mean value of thrust. With relation to the aerodynamic input power requirement, increasing the advance ratio decreases the mean input power in the upstroke, while increasing another part of input power in the downstroke, so that the total value of mean input power in a cycle remains almost constant.

In view of the above-mentioned fact that for a fixed inclination angle of the stroke plane, an increase of forward velocity leads to an increase of the total mean lift and a decrease of the mean thrust, this specific aerodynamic performance cannot be matched with the force balance requirement for forward flight in which the mean thrust should increase with the forward velocity to overcome the air drag and the mean lift should be unchanged to balance with the insect weight. Therefore, it is important to know how the insect regulates some key kinematic parameters of flapping to modulate the aerodynamic asymmetry between the down- and up-strokes.

To regulate the angle of the stroke plane is the first effective step. Our study has shown that for any advance ratio, increasing the angle of stroke plane (β) is accompanied with decreasing the mean lift, increasing the mean thrust, and most likely decreasing the mean input power.

The application of asymmetric stroke-time, represented in the paper by the downstroke duration ratio (t_{down}/t_c) may be another effective selection. When the downstroke takes a longer time than the upstroke, in other words, the mean velocity of the downstroke is smaller than that of the upstroke, so that the aerodynamic forces are enhanced in the upstroke and diminished in the downstroke. Our study has shown that the main influence of $t_{down}/t_c > 0.5$ consists in enlarging the mean thrust, reducing a little mean input power, and keeping the mean lift almost unchanged.

The use of unequal angles of attack in the down- and up-stroke ($\alpha_{down} \neq \alpha_{up}$) may be a tuning device for modulation of the aerodynamic performance of the down- or up-stroke separately. Our study has shown that an increase of α_{down} is accompanied with the lift increase and the thrust decrease, but an increase of α_{up} leads to the thrust increase and almost no lift variation. It means that the lift may be modulated mainly by changing α_{down} and the thrust mainly by regulating α_{up}.

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