Effect of twist, camber and spanwise bending on the aerodynamic performance of flapping wings

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Abstract
Insect wings change its shape dynamically through the interactions of the structure, and the aerodynamic and inertial forces when flapping, which can greatly affect its aerodynamic performances. While the detailed change of the wing shape has been extensively measured with high-speed photogrammetry, its implications on the flapping wing aerodynamics are poorly understood. In order to clarify the linking between the wing deformation and the flapping wing aerodynamics, the aerodynamic effect of the wing deformation in terms of the twist, the camber and the spanwise bending have been systematically investigated by means of the computational fluid dynamic analyses of a hovering hawkmoth with artificially deformed flapping wings. With the appropriate magnitude and phase, the twist and the camber are found to enhance the aerodynamic efficiency of flapping wing by redirecting the aerodynamic force vector on the wing so as to reduce the drag or increase the lift. The spanwise bending can increase the aerodynamic force without the redundant increase in aerodynamic power by appropriately adjusting the speed of the wing. We specified the magnitude and the phase of deformation that give the highest efficiency in the range of the study, and pointed out that, while the twist and the camber can enhance the efficiency, the deformation beyond the optima can reduce the aerodynamic efficiency drastically. The results in this study revealed the aerodynamic contributions of each kind of wing deformation, and will be of great implications for the design of bio-inspired micro air vehicles.

Keywords: Flapping wing, Flexible wing, Wing deformation, Aerodynamics, Efficiency, Hovering

1. Introduction

Insect flight is thought to give a great inspiration to develop novel unmanned aerial vehicles, because of their highly stable and efficient flight. Their maneuver is achieved by generating and tuning the aerodynamic forces on their wings. Their flapping motion is known to utilize several unsteady aerodynamic mechanisms such as leading-edge vortex (Birch & Dickinson, 2001; Ellington et al, 1996), rotational mechanisms (Bomphrey et al, 2017; Dickinson et al, 1999) and clap-and-fling (Weis-Fogh, 1973). While the flapping wing kinematics, and hence the aerodynamic forces, are controlled finely by their steering muscle (Dickinson & Tu, 1997), the kinematics especially around the distal area of the wing can also be adjusted passively by the wing deformation. Photogrammetric reconstruction has helped to quantitatively identify the dynamic deformation of flapping wings in insects such as hoverflies, locusts, hawkmoths, butterflies and beetles (Le et al, 2013; Walker et al, 2009a; b; 2010; Zheng et al, 2013b). The shape changes are passively determined by the interaction of the aerodynamic and the inertial forces, and the multi-scale wing structure consisted of various non-linear elements such as the wing veins tapered toward wing tip (Combes & Daniel, 2003; Lehmann et al, 2011; Steppan, 2000), the flexible joint by a soft rubber-like protein, called resilin (Weis-Fogh, 1960), the corrugation (Rees, 1975) and the non-linear hinges (Wootton, 1981).

The flexibility is possibly accounted for by the thin and light structure of the wings as a consequence of the great demand to reduce the mechanical power consumption for overcoming its inertia, but several studies suggested that the
wing deformation, which is passively controlled by the inherent wing structure, can enhance the aerodynamic performances of flapping wings. Comparisons of aerodynamic performances between measured and artificial wing kinematics confirmed that the twist can enhance the efficiency of locusts, butterflies, and beetles in forward flight (Le et al, 2013; Young et al, 2009; Zheng et al, 2013b). The camber may not affect at high angles of attack corresponding to realistic flapping wings (Du & Sun, 2010; Usherwood & Ellington, 2002), but it is also confirmed that the positive camber can enhance the lift-to-drag ratio of the revolving wings by tilting the force normal to the wing surface around the leading edge at higher angles of attack (Harbig et al, 2013).

The previous studies point out the importance of the wing deformation in insect wings in terms of the aerodynamic force generation and the efficiency. However, it is still difficult to maximize the performance of the flapping wings for bio-inspired micro aerial vehicles, because of the poorly understood aerodynamic effect and design principle of the flapping wing deformation. In this study, aiming at providing thorough understanding of the aerodynamic consequence of the wing deformation, we have performed systematic study utilizing an in-house computational fluid dynamic (CFD) analyses. Prescribed dynamic deformation, in terms of the twist, the camber and the spanwise bending, are given to the rigid and flat wings of a hovering hawkmoth. Aerodynamic effects of the magnitude and the phase of the shape changes are discussed in terms of the vertical force generation, the power consumption and the aerodynamic efficiency. The mechanism to enhance the aerodynamic efficiency of flapping wing is further investigated on the basis of the flow visualizations and the kinematic adjustment by the wing deformation.

2. Materials and methods

2.1. Morphological, kinematic and aerodynamic model of flapping wings

A hovering hawkmoth is utilized as a model insect in this study. In order to incorporate its morphological, kinematic and fluid dynamic model, we employed a bio-inspired dynamic flight simulator (Liu, 2009; Nakata & Liu, 2012a). The morphological model of a flapping wing is constructed by tracing the outline of the wing of a hawkmoth, Agrius convolvuli (figure 1a). While the hawkmoths are four-winged flyers, the fore- and hind-wings are assumed to be a single unit in this study since, unlike the other four-winged flyers such as dragonflies, they are not controlled separately. In order to model the three-dimensional motion of the flapping wings, the left and right wings are modelled separately as different blocks with a global grid to give outer boundary conditions for local wing blocks. Definition of the wing kinematics is given in figure 1b. The kinematic model is constructed from the measured kinematics of a hovering hawkmoth (Willmott & Ellington, 1997) but simplified by the 1st order Fourier series as shown in figure 1c. The stroke plane is assumed to be horizontal in this study. The wing is artificially deformed with respect to the wing-fixed coordinate system, and rotated with the simplified kinematics. While the wing base is always rotated with the simplified kinematics, the kinematics of the cross sections around wing tips are, therefore, adjusted from the simplified kinematics. A fortified Navier-Stokes solver for the dynamically moving multi-blocked overset-grid system (Liu, 2009) is employed in this study. The governing equation of the CFD simulator is the unsteady, three-dimensional and incompressible Navier-Stokes equations. The simulator is validated by the comparisons against the several experimental results (Liu, 2009; Nakata & Liu, 2012a). The grid and time step refinements of the current model were performed in the previous study (Liu, 2009). The non-dimensional time step is set to be 0.01, but, in order to keep the accuracy, we used 0.005 for some of the cases with larger deformation. The parameters are summarized in table 1.

Figure 1  Morphological and kinematic models of a hovering hawkmoth. (a) A wing of Agrius convolvuli with a computational model for CFD analyses. (b) Definition of the flapping angles. (c) Time-series of the simplified positional (black), feathering (blue) and elevation angle (green). The measured kinematics are shown by broken lines.
2.2. Wing deformation

In order to evaluate the effect of the wing deformation on the flapping wing aerodynamics, the twist, the camber and the spanwise bending are separately given to the rigid and flat wings before the wing rotation at wing base in this study. Based on the detailed measurement of the wing shape of hoverflies (Walker et al, 2010), the twist is assumed to be the linear variation of the angle around the spanwise axis from wing base to wing tip (figure 2a). The twist is positive when the angle of attack at around wing tip is reduced during downstroke. The camber is the chordwise bending of the cross sections, and, in the real insect wing, the chordwise flexion can occur locally at the wing vein junctions with a rubber-like protein, called resilin (Haas et al, 2000; Mountcastle & Combes, 2013). We simplified the camber by assuming that each cross section deforms into arc shape without local flexion. The camber is defined as the ratio between the local distance between the leading and trailing edges and the deflection at the middle of the chord (figure 2b). The 20 to 80 % of the wing span from the wing base have the constant camber with the smooth decay toward the wing base and tip as shown in figure 2d, which is based on the measurement of hoverflies (Walker et al, 2010). The positive camber is assumed to be convex toward anatomically dorsal surface of the wings. The spanwise bending is modeled by the rotation of each cross section around chordwise axis. The bending angle, which is defined by the elevation of the cross sections (figure 2c), is assumed to be linearly distributed from the wing base to the wing tip. The spanwise bending is positive when the wing is bent upward during downstroke. We take the twist and the bending at the wing tip, and the camber at the middle of the span as the representative of each deformation.

Based on the profile of the computed deformation of the flexible wings in the previous computational study (Nakata & Liu, 2012b) and measurements (Walker et al, 2010), a smoothed squared wave is used for the dynamic twist and camber, while the sinusoidal curve is used for the spanwise bending (figure 2e,f). The “symmetric” deformation is assumed to be largest at the middle of each half-stroke. Such deformation can happen if the aerodynamic force is dominant forces on the wing, while, in the actual insect wings, the deformation is advanced because of the existence of the inertial force of the wing as can be seen from the result of the computational fluid-structure interaction analyses.

Table 1   Parameters for computational fluid dynamic analyses.

| Wing length/mm | Mean chord length/mm | Wing beat frequency /Hz | Wing beat amplitude /rad | Reynolds number | Reduced frequency | Grid | Non-dimensional time step |
|----------------|----------------------|------------------------|-------------------------|-----------------|------------------|------|---------------------------|
| 50.5           | 18.3                 | 26.1                   | 2                       | 6300            | 0.3              | 45 x 65 x 25 (wing) | 0.005-0.01 |

Figure 2   Definition of (a) twist, (b) camber and (c) spanwise bending. The flat and deformed wings are shown by blue and grey surfaces, respectively. (d) Spanwise distribution of the camber. Time-series of delayed (-5 %), symmetric and advanced (5 %) (e) twist or camber with smoothed squared curve, and (f) the spanwise bending with sinusoidal curve. The grey lines in (e,f) represent the twist and the spanwise bending resulted from the computational fluid-structure interaction analyses (Nakata & Liu, 2012b).
In this study, the phase of each deformation is ranged from – 5 % (18 degrees, delayed) to 5 % (18 degrees, advanced) from the symmetric deformation. The range of the magnitude is determined on the basis of the previous computational study on the hawkmoth (Nakata & Liu, 2012b) and measurements of hoverfly’s wing kinematics (Walker et al., 2010).

2.3. Aerodynamic performance

Aerodynamic performance of flapping wings is evaluated in terms of the vertical force and aerodynamic power consumption to flap the wing, and the aerodynamic efficiency. The aerodynamic forces are evaluated by a sum of inviscid and viscous flux over the wing surface. Details can be found in a previous study (Nakata & Liu, 2012a). We mainly focused on the cycle-averaged force, power and efficiency, since the wingbeat frequency of insect flapping wing is relatively higher than the natural frequency of the insect body, and, therefore, the dynamic changes due to the flapping can be neglected when discussing the dynamics and energetics of the flapping wing flyers as proposed in previous studies on the flight stability (Sun & Xiong, 2005; Taylor & Thomas, 2002). The aerodynamic efficiency is the ratio between the aerodynamic power and the induced power that is computed by the product of the vertical force and the mean downwash velocity on the virtual surface in the vicinity of the wing (Nakata & Liu, 2012a). The efficiency, therefore, denotes how much power is used to generate the vertical force to achieve hovering out of the input power for moving the wing in air.

3. Results

The aerodynamic performances of dynamically twisted flapping wings are summarized in figure 3a. The aerodynamic power and the vertical forces are decreased with increasing the magnitude of the twist (figure 3ai and aii). The efficiency is maximized at around 20-30 degrees in the range of the study. The phase advance increases the vertical force in the same way with the rotation of the whole wing (Dickinson et al., 1999), but the aerodynamic power is increased at the same time. The aerodynamic efficiency is, therefore, maximized when the rotation is close to symmetric or slightly delayed (2.5 %). The twist higher than the maxima reduces the aerodynamic efficiency.

The advanced camber requires slightly higher aerodynamic power, but the camber doesn’t affect the aerodynamic power consumption (figure 3bi) so much. On the other hand, the vertical force is increased by the camber of up to 20 %. The aerodynamic efficiency is, therefore, maximized at around the camber of 10-20 %. The delayed camber (-5 %) shows higher aerodynamic efficiency with the camber of 20 %. The camber higher than the maxima drastically reduces the aerodynamic efficiency down to the similar, or even lower, level of the flat wing.

The spanwise bending, especially with the advanced phase, greatly increases both the aerodynamic power and the vertical force. The increase becomes marginal when the phase is delayed. Efficiency is slightly enhanced when the bending angle is 5 degrees, but is reduced when the bending angle is higher than 10 degrees.

The signs of the deformations are determined on the basis of the simulated or measured wing deformation; the negative deformation may, therefore, be physically unrealistic with the insect wing if the deformation is passive. In this study, the negative deformations turned out to reduce the aerodynamic efficiency drastically (figure 3aiii, biii, ciii).

4. Discussion - enhancement of aerodynamic performance through wing deformation

We deem the aerodynamic efficiency to be one of the most important performances for the hovering insects and the bio-inspired flapping wing for micro aerial vehicles. In order to clarify the mechanism of the enhancement of the performances, we, therefore, focused on the magnitude and the phase of each deformation that maximize the aerodynamic efficiency in the range of the study. As a summary, figure 4 describes the time-series of the aerodynamic forces and powers, and aerodynamic force vectors on the flapping wings averaged over half-stroke with respect to the horizontal stroke plane. In figure 4c, the aerodynamic efficiency becomes better when the vectors are closer to the vertical, since the wing generates the vertical force efficiently. The force magnitude and angle are summarized in table 2. Figure 5 further summarizes the near-field wake and pressure distribution around the wings at the middle of the downstroke. The time instant in figure 5 is chosen to visualize the flow field when the aerodynamic powers and forces are close to maxima during half stroke (vertical lines in figure 4a,b).

In comparison with the flat wing (black), the twist (30 degrees, 2.5 % delay) is found to delay and reduce the peak of aerodynamic powers and forces, while slightly increases the aerodynamic power during the stroke reversal (figure...
Figure 3  Effects of the magnitude and the phase of (a) the twist, (b) the camber, and (c) the spanwise bending on (i) the cycle-averaged aerodynamic power, (ii) the cycle-averaged vertical force and (iii) the aerodynamic efficiency.

Figure 4  Aerodynamic powers and forces on the flapping wings with optimal deformations. Time-series of (a) the aerodynamic powers and (b) the aerodynamic vertical forces. The vertical lines represent the time instant for figure 5. (c) Aerodynamic force vectors on the flat (black), the twisted (red) and the cambered (green) wings, and the wing with spanwise bending (blue) with respect to horizontal stroke plane. The forces are averaged over a half-stroke and the three-dimensional vectors are projected on to the symmetric plane. The thinner vector shows the moving direction of the wing.
The force vector generated by the twisted wing is clearly closer to the vertical than the flat wing (figure 4c). The twist reduces the magnitude of the aerodynamic force, which are evident from the weak pressure associated with the leading-edge vortex (figure 5b,iii,iv), but reduces more drag than the lift because of the lower angle of attack. The camber reduces the peaks of the aerodynamic power, but enhances the vertical force from the beginning of each stroke to the maxima (figure 4a,b). As a result, the force vector is shifted upward (figure 4c). The negative pressure at the leading edge is reduced by the camber, but the pressure decreases more gently toward the trailing edge than the other wings (figure 5c,iii,iv). The cambered wing generates the lift by the negative pressure around the leading edge (figure 5c,iii) where the local angle of attack is closer to horizontal (Harbig et al, 2013). The camber, therefore, can increase

Table 2  Force magnitude and angle of the aerodynamic force vectors on the flat, twisted, cambered wings and the wing with spanwise bending during downstroke.

|                  | Force magnitude (mN) | Force angle (deg) |
|------------------|----------------------|-------------------|
| Flat             | 14.3                 | 37.1              |
| Twist            | 7.8                  | 52.1              |
| Camber           | 14.3                 | 42.4              |
| Spanwise bending | 15.1                 | 37.7              |

Figure 5  Near-field wake and the pressure distribution around the middle of (a) the flat, (b) the twisted and (c) the cambered wings, and (d) the wing with spanwise bending. (i) The iso-Q surface around the wing, (ii) the surface pressure distribution on the wing, (iii) the distribution of the flow vectors and the pressure on the chordwise plane, and (iv) the chordwise distribution of the pressure on the top (solid lines) and the bottom (dashed lines) surface. The grey lines in (iv) represent the line of the flat wing. The cutting plane in (iii) and (iv) is shown by grey surface in (i).
the lift, reducing the drag. As shown in figure 4a,b, The peaks of powers and vertical forces are increased by the spanwise bending (5 degrees, symmetric). While keeping the force direction, the spanwise bending can enhance the force magnitude, which is accounted for by the stronger negative pressure at the leading edge (figure 5dii,iii,iv).

The twist affects the aerodynamic performance of flapping wings by adjusting the time-histories of angle of attack at the distal part of the flapping wings. The time-histories of feathering and positional angles, and angular velocities of flat and twisted wings are shown in figure 6a. The power and force are reduced by the lower angle of attack at the distal part of the wings (figure 4a,b) because of the smaller leading-edge vortex (figure 5bi,iii) and lower negative pressure around the leading edge (figure 5bii,iv) in comparison with the flat wing (figure 5a). Since the lift-to-drag ratio of the rotated wing is maximized at the angle of attack around 20 degrees (Dickinson & Götz, 1993), the aerodynamic efficiency is, however, maximized when the twist at the middle of the stroke is about 30 degrees which reduces the angle of attack at wing tip down to 20 degrees with the wing base kinematics in this study. Higher twist than 30 degrees is thought to reduce the lift more than the drag, and therefore reduces the aerodynamic efficiency. The phase advance enhances the vertical force, and also increases the power consumption. The dynamic changes in the twist can add extra speeds at the stroke reversals (figure 6aii), which contributes to increase the aerodynamic forces during the stroke reversal via the rotational drag (Bomphrey et al, 2017), while the extra rotational speed slightly increases the aerodynamic power at stroke reversal (figure 4a). It is important to note that, if the twist is induced passively, the power consumption for rotation may not be necessary to be supplied from the wing base, and, therefore, the force increase due to the twist may be efficient mechanism for the flexible wings. The twist can be distributed along span more complicately than the linear distribution, but we expect that the resultant angle of attack and rotational speed around the distal part of the flapping wing mainly determine the aerodynamic performance of twisted wings.

The camber redirects the aerodynamic forces on the flapping wings. The local angle of attack around the leading edge, and, hence, the pressure at the leading edge (figure 5civ) are reduced by the camber. The cambered wing can, however, generate strong negative pressure (figure 5ci,iii) associated with the leading-edge vortex (figure 5ci,iii), which keeps the negative pressure higher toward the middle of the wing chord (figure 5civ). The lower local angle of
attack and the relatively strong negative pressure account for the increase of the vertical force (figure 4b,c) and the slight decrease in aerodynamic power. Under the definition of the camber in this study, the aerodynamic efficiency is maximized with the delayed positive camber of 20%, which is close to the value (15%) that is reported to maximize the lift-to-drag ratio of the revolving wings (Harbig et al., 2013). The camber of 30%, however, decreases the aerodynamic efficiency down to the level of the flat wing, owing to the reduction in the vertical force (figure 3bii). This is attributable to the local angle of attack at trailing edge that may exceed 90 degrees with the camber of 30% (purple line, figure 7a). As a consequence, while the flow is attached on the wing with 20% camber (figure 7b), the flow separation is clearly seen at the trailing edge of the wing with 30% camber (figure 7c). The separation bubble at the leading-edge is also enlarged, which is thought to be due to negative angle of attack at the leading edge (figure 7a). These flow separations are thought to decrease the vertical force drastically. The shape of the camber may, therefore, affect the aerodynamic performance, since the flow can be separated at the local flexion that is observed in the flapping wings of real insects such as locust (Walker et al., 2009a) or hawkmoth (van den Berg & Ellington, 1997).

The spanwise bending affects the aerodynamic performance of flapping wings by adjusting the wing kinematics at distal area of the flapping wings (figure 6b). It is clearly seen that not only the wing beat amplitude, but also the phase of the positional angle, are adjusted by the spanwise bending (figure 6bi). The curve of the angular velocity is skewed so as to increase the wing tip speed from middle to the end of each half stroke (figure 6bii), which results in the stronger leading-edge vortex (figure 5di,iii) and negative pressure (figure 5dii,iv). As a result, the aerodynamic force and the power are increased especially when the spanwise bending is advanced. The spanwise bending mainly affects the speed of the wing, rather than adjusting the angle of attack of the flapping wings. The aerodynamic forces and powers are, therefore, greatly affected, but the efficiency is maintained at the level of the flat wings. The spanwise bending is difficult to avoid when designing the flexible wings for flapping wing, since the wing can be assumed as a cantilever and the bending torque is higher than the torque to generate the other kind of deformation. For flapping wing micro air vehicles, thick spurs are sometimes used to support the wing shape (Tanaka et al., 2015), stopping such bending, but the results in this study suggest that the mild spanwise bending may be favorable in terms of the aerodynamic force production and the efficiency.

We specified that the twist and the camber have a great impact on the aerodynamic efficiency, and there are the optimal twist and camber. The precise control of the magnitude of the twist and the camber may be difficult, since the flapping wings of insects or micro air vehicles are deformed passively through the interaction between the unsteady aerodynamics of flapping wings and the nonlinear structural deformation. It is important to note that, in such case, it is
better to design the flapping wings so as to be twisted or cambered slightly lower than the optima since, for example, the increase of the camber of 20 to 30% leads more reduction in the aerodynamic efficiency than the decrease of the camber of 20 to 10%.

From the results of the study, we could deduce the aerodynamic consequences of each deformation of flapping wings. It should be noted, however, that the values of optima can be different when the wing shape or wing kinematics at the wing base is different, because the kinematics at the distal area of the wing is determined by the combination of the wing deformation and the wing angles at the wing base. For example, the nose-down twist and the positive camber, which are confirmed to enhance the aerodynamic efficiency, are widely observed in various insects such as hoverflies, locusts, hawkmoths, butterflies and beetles (Le et al, 2013; Walker et al, 2009a; b; 2010; Young et al, 2009; Zheng et al, 2013a; Zheng et al, 2013b), while the negative twist and camber greatly reduce the aerodynamic efficiency. However, because of the difference in wing shape, wing kinematics and Reynolds number, it is still difficult to conclude the quantitative benefit of the wing deformation in those insects from the results in this study, while some studies confirmed that the wing deformation can enhance the aerodynamic performances (Du & Sun, 2010; Le et al, 2013; Young et al, 2009; Zheng et al, 2013b) in the similar manner to this study. At the different Reynolds numbers, the appropriate magnitude and phase of the twist and the spanwise bending are thought to be beneficial similarly since they affect the aerodynamic performance through the adjustment of the angle of attack and the wing tip speed (figure 6). The camber may also improve the aerodynamic performance even at the different Reynolds numbers, since its benefit was confirmed for rotating wings at Reynolds numbers of 120 and 1,500 in a previous study (Harbig et al, 2013).

Fluid-structure interaction may further enhance the aerodynamic performance by finely, but passively, adjusting the wing kinematics of flapping wings in response to the unsteady aerodynamics around the flapping wings. Delayed burst of the leading-edge vortex (Nakata & Liu, 2012b), which is numerically confirmed to be caused by the passive deformation of the wing, is one of the example of the flexible wing’s aerodynamic response. The efficiency is the index focused mainly in this study, but the passive wing deformation may also have other benefit, such as the mitigation of collision damage (Mountcastle & Combes, 2014) or the passive response to the aerodynamic disturbances.

4. Conclusion

In this study, the effect of the twist, the camber and the spanwise bending with various magnitudes and phases on the aerodynamic performance of flapping wings is investigated through the systematic computational fluid dynamic analyses. We focused on the cycle-averaged force and power, since the wingbeat frequency is relatively higher than the natural frequency of the flapping wing flyer. With the appropriate magnitude and phase, the twist and the camber are found to be able to enhance the aerodynamic efficiency of flapping wings by mainly reducing the drag, or increasing the lift, respectively. The spanwise bending can increase the aerodynamic force with marginal effect on the aerodynamic efficiency. The twist and the spanwise bending enhances the aerodynamic performance by adjusting the kinematics at distal area of the wings, while the camber is confirmed to redirect the aerodynamic forces on the flapping wings. The redundant twist and camber beyond the optima may, however, lead to the drastic reduction in aerodynamic efficiency. Because the flapping wing is usually deformed passively by the aerodynamic and inertial forces, the results in this study point out the importance of, not only the deformation, but also the structural design of the flapping wings of insects and the bio-inspired flapping-wing aerial vehicles in terms of their aerodynamic performances.

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