Aerodynamic mechanisms in bio-inspired micro air vehicles: a review in the light of novel compound layouts

Long Chen¹, Yanlai Zhang¹, Chao Zhou¹, Jianghao Wu¹

¹School of Transportation Science and Engineering, Beihang University, No. 37 Xueyuan Road, Beijing, People’s Republic of China
E–Mail: zcqh821@163.com

Abstract: Modern designs of micro air vehicles (MAVs) are mostly inspired by nature’s flyers, such as hummingbirds and flying insects, which results in the birth of bio-inspired MAVs. The history and recent progress of the aerodynamic mechanisms in bio-inspired MAVs are reviewed in this study, especially focused on those compound layouts using bio-inspired unsteady aerodynamic mechanisms. Several successful bio-mimicking MAVs and the unsteady high lift mechanisms in insect flight are briefly revisited. Four types of the compound layouts, i.e. the fixed/flapping-wing MAV, the flapping rotary wing MAV, the multiple-pair flapping-wing MAV, and the cycloidal rotor MAV are introduced in terms of recent findings on their aerodynamic mechanisms. In the end, future interests in the field of MAVs are suggested. The authors’ review can provide solid background knowledge for both future studies on the aerodynamic mechanisms in bio-inspired MAVs and the practical design of a bio-inspired MAV.

1 Introduction

Escaping from gravity and flying in the sky has been a dream for human beings for centuries. Since the first successful take-off of Wright brothers using a homemade aircraft, numerous scientists and engineers have focused on this worldwide aspiration and thus stimulated the development of aeronautics and its relevant disciplines [1]. The creation of modern aircraft, such as aeroplanes and helicopters, provides us with an opportunity to achieve a comfortable long-trip within a couple of hours. Given the rich experience in aerodynamics and aircraft design over the last century, the development of aircraft further diversifies into several trends and the function of aircraft has been widely expanded besides passenger transport. One of those tendencies is unmanned and micro-miniature, which motivates the born of micro air vehicles (MAVs). The concept of MAV was first proposed by the Defence Advanced Research Projects Agency (DARPA) in the 1990s [2], with the capacity of remote control and signal communications. A list of detailed design specifications for MAVs is given in Table 1. Compared to conventional large-scale aircraft, the MAV shows great superiority in the concealment of its movement and the agility within tiny space due to the limited wingspan and weight. Therefore, the MAVs are aimed at the usage in national defence and infrastructure construction, such as the military reconnaissance, emergency rescue and land survey under extreme environmental conditions.

To date, the design of MAV and its subsystems has been widely studied and several layouts have been proposed and tested using prototypes. Early designs of a MAV were mostly conducted by a downscaling of conventional aircraft layouts, e.g. the fixed-wing MAVs [3–5] and rotary-wing MAVs [6–8]. Specifically, a fixed-wing MAV utilises a motor to rotate the propeller, generating the thrust for forward flight, whereas the lift is produced by the wing. The wingspan and weight of most fixed-wing MAVs are <0.15 m and 0.1 kg, respectively, such as the ‘MicroStar’ [3] (Fig. 1a), ‘Black Widow’ [4] (Fig. 1b) and ‘Trochoid’ [5] (Fig. 1c). The remote control is achieved by the on-board global positioning system module and autopilot. Due to the high lift-drag ratio of the fixed-wing layout in forward flight, the payload capacity and flight duration of a fixed-wing MAV are superior to other layouts for a high-speed cruise. However, the lift generation of a fixed-wing MAV is attributed to the forward speed, thus a hover flight is impracticable for a fixed-wing MAV. In addition, the strong friction effect in low Reynolds number (Re) regime confines the aerodynamic performance and control efficiency of a fixed-wing MAV. Consequently, the fixed-wing MAV is replaced by the rotary-wing MAV and other bio-inspired layouts as a result of the improvement in MAV design and the unfolding of aerodynamic mechanisms in low Re regime.

The rotary-wing MAV, one of the most popular layouts, is an alternative that can easily achieve both hover flight and forward flight. According to the counter-torque solution, the rotary-wing MAV layouts can be further classified into three branches, i.e. main/tail rotor layout, coaxial rotor layout, and multiple-rotors layout, such as the ‘Black Hornet’ [6] (Fig. 2a), ‘μFR-II’ [7] (Fig. 2b) and ‘mesicopter’ [8] (Fig. 2c). It has been found that the rotary-wing MAV can outplay other layouts with respect to the aerodynamic efficiency in lift generation [9, 10]. Moreover, the achievement of hover flight enables high-quality real-time monitoring and signal communication in rotary-wing MAVs. Thanks to the rapid development in microelectromechanical systems (MEMS), the design of rotary-wing MAVs has engaged in being more improved considering the size, stability, and agility. However,

Table 1 Detailed specifications for MAVs

| Specifications          | Value          |
|------------------------|----------------|
| wing span, m           | <0.15          |
| Weight, kg             | <0.1           |
| range, km              | 1–10           |
| duration, min          | 60             |
| maximum flight height, km | 0.15        |
| maximum flight speed, m s⁻¹ | 15         |
| payload, kg            | 0.02           |

Fig. 1 Several prototypes of fixed-wing MAVs [3–5] (a) MicroStar, (b) Block widow, (c) Trochoid
One of the favourable solutions may be inspired by natural flyers, e.g. flying birds and insects, the flight mechanism of which has been extensively studied over the last two decades. Specifically, the flying insects, such as fruit fly and dragonfly, can achieve sustained hover and agile manoeuvres by flapping their wings at high frequency [11]. Their body size and excellent flight performance coincide with the requirement of MAV design. Besides, the flight stability and turbulence of insects in the gust and turbulent environment is also impressive [12, 13]. However, according to conventional aircraft design, the balance between strong flight stability and agile manoeuvrability for a specific layout is difficult. Therefore, the outstanding performance of insect flights has received extensive attention and considerable research has been conducted to uncover the mystery from a multidisciplinary perspective of biology, physics, and engineering. The bio-inspired layouts thus become the focus of MAV design recently with several feasible prototypes having been proposed [14, 15].

In this review paper, a revisit of direct bio-mimicking MAV layout is carried out, followed by a brief introduction of unsteady high lift mechanisms in insect flight. More importantly, the novel compound layouts that take advantages of bio-inspired aerodynamic mechanisms are then introduced in detail. Finally, some possible research interests of bio-inspired MAVs in the future are suggested in the last section.

2 Bio-inspired MAVs
2.1 Bio-mimicking layouts for MAVs

Most early bio-inspired MAV layouts are directly mimicking the kinematics of insect wings, i.e. bio-mimicking flapping-wing MAVs. The observation of insect flight done by Ellington [16], Ennos [17], Dudley and Ellington [18], as well as Willmott and Ellington [19], provided a detailed database of wing kinematics including more than ten species of insects, e.g. flies, mosquitoes, bees, moths, and beetles. The flapping motion of insect wings is mostly confined to a plane, i.e. the stroke plane, which is nearly horizontal for most species during hover. During forward flight, most of the insects tilt their stroke plane (while keeping the angle between the stroke plane and longitudinal body axis constant), similar to the tilt of rotor plane in a helicopter, thus projecting the lift into the forward direction to generate thrust (Figs. 3a and b).

Note that most birds flap their wings up and down to simultaneously generate thrust and lift for their flight [21, 22], which is obviously distinct to insect flight. There is an exception in bird flights, i.e. the hummingbird flight, that an insect-like flapping pattern is applied to the wings [20, 23] (Fig. 3c). Compared to flying insects, the weight and dimension of a hummingbird are closer to the specifications of MAV design and the wing beat frequency is significantly lower, which is more convenient for mechanical design and manufacture. Therefore, the hummingbird-like flapping-wing MAV is one of the first proposed bio-mimicking layouts [24–27], as listed in Fig. 4.

In addition, the rapid development of MEMS boosts the born of tiny bio-mimicking flapping-wing MAV that is close to the scale (or even at the same scale) of real insects [28, 29], as listed in Fig. 5. The design of those bio-mimicking flapping-wing MAVs is mostly based on bees, i.e. insect-like flapping-wing MAVs. A conventional actuator (e.g. servomotor) and transmission system (e.g. crank-slider) are not suitable for those small-scale layouts considering the manufacturing and mechanical efficiency. Thus, novel actuators (e.g. piezoelectric materials) combined with a simple amplifier of the output oscillation (e.g. a lever) are often used in those layouts to achieve the desired wing kinematics and power efficiency. For a detailed review on the actuator for flapping-wing MAVs around insect scale, please refer to [31]. However, as the payload capacity of those insect-like flapping-wing MAVs is much lower than that of hummingbird-like flapping-wing MAVs, most of the insect-like flapping-wing MAVs are hard-wired to a separate power source on the ground. Note that one of the insect-like flapping-wing MAVs, the ‘Robofly’ from the University of Washington, successfully achieved the first wireless take-off using a 976 nm laser as a remote power source [30]. According to recent development in wireless charging for cell
AeroVironment Inc. as a part of the DARPA nano air vehicle mechanism and the on-board flight controller, improve motion precision. The design of flexible wing was iterated for hundreds of times via both simulations and experiments to find four-bar linkage-based flapping mechanism, a string-based flapping mechanism, and the RoboFly from University of Washington [30].

Another 21 g hummingbird-like flapping wing MAV (KUBeetle in Fig. 4c) was presented by the researchers from Konkuk University [26]. A combination of four-bar linkage and pulley-string mechanisms was applied as the lightweight flapping mechanism that can achieve a flapping amplitude of about 190°. The enlarged flapping amplitude provided a chance for the wings to clap together at dorsal and ventral stroke reversals and thus the clap-and-flings mechanism was implemented to enhance the lift generation [32]. A gearbox with a reduction ratio of 20.6:1 was used and the mechanism was driven by a coreless DC motor. The wing configuration was also investigated to improve both aerodynamic and mechanical efficiency. To generate desired control torques, the location of the trailing edges at the wing root was manipulated by three sub-micro servos to modulate the wing rotation angle [33]. A micro on-board gyroscope was used to sense the pitch, roll and yaw rates, and the flight stability was achieved by a microcontroller using a proportional–derivative (PD) feedback control (Fig. 8).

The RoboBee proposed by the group in Harvard (Fig. 5a) was one of the most prominent bio-mimicking flapping-wing MAVs around insect scale [28]. Using the novel design and manufacturing methodology, i.e. ‘smart composite microstructures’, a high precision manufacturing and good reputability were achieved in this mesoscale handling. The flapping motion was generated by a pair of voltage-driven piezoelectric bimorphs (as the actuator) combined with an amplifier at a frequency of about 120 Hz and a stroke amplitude of 110°, which was close to real insects. The wing rotation was realised by passive compliant flexures at the wing root [34]. The final dual-actuator design weighs 80 mg with a wingspan of 0.03 m and is capable of producing 1.3 mN lift at a power consumption of 19 mW. Due to the limited payload capability, the sensing and controller computation were performed off-board and the control signal was sent via the power wire. The attitude and rates of the robot were computed based on the motion reconstruction of the robot in a virtual volume viewed by eight cameras [35]. The same control strategy, i.e. an adjustment of flapping amplitude and mean flapping position, was implemented here to generate the control torques. The flight controller can be separated into three distinct modules, i.e. body attitude control, lateral position control, and altitude control. In flight tests, the robot can stably hover about a fixed point with an error on the order of one body length and quick manoeuvres between two fixed points in the space (Fig. 9).

Note that, a single pair of horizontally flapping wings was employed to generate sufficient lift in both branches of bio-mimicking flapping-wing MAVs. The wing kinematics was well tuned and controlled by the on-board controllers and autopilot to ensure an acceptable aerodynamic efficiency. Despite the impressive performance of those bio-mimicking MAVs, the lift generation for a single pair of flapping wings is still limited. In addition, as the dimension and flapping frequency for the bio-mimicking MAV increases, the inertial effect of the oscillating components in the mechanism becomes significantly strong, which results in a steep increase in input power and a sharp drop in overall efficiency. Therefore, several novel compound MAV layouts, which utilises the aerodynamic mechanisms inspired by insect flight, are proposed recently to improve the payload capacity of MAV.

2.2 Novel compound layouts for MAVs

In general, most of the compound layouts for MAVs can be regarded as a combination of fixed-wing, rotary-wing, and brushless DC motor and the reduction ratio was 19.75:1 for the gearbox. The polyester-membrane-based wings were inspired by the Nano Hummingbird, with a wingspan around 0.16 m. The entire flapping mechanism can produce a lift about 15.8 g at a power consumption of 4 W while flapping at 24 Hz. In addition, they proposed an alternative to generate the control torques by modulating the flapping amplitude and offset (mean flapping position), which is more intuitive and wing-design-friendly compared to the method proposed in the Nano Hummingbird (Figs. 7c and d).

Here, a review of the design and aerodynamic performance of several world-famous bio-mimicking flapping-wing MAVs is provided. The ‘Nano Hummingbird’ was developed by AeroVironment Inc. as a part of the DARPA nano air vehicle program and was first unveiled in 2011 [24]. It has a mass of 19 g and a wingspan of 0.165 m, with the capability to hover for several minutes and fly forward up to 6.7 m/s. Instead of a conventional four-bar linkage-based flapping mechanism, a string-based flapping mechanism was applied to the final prototype to ensure the lightweight, high efficiency, long duration and easy fabrication (Fig. 6a). Multiple strands of strings were used in parallel to improve motion precision. The design of flexible wing was iterated for hundreds of times via both simulations and experiments to find the suitable design for both hover and forward flight, with a minimum cost of power (Fig. 6b). A hybrid control strategy of the wing rotation, i.e. a combined wing twist and rotation modulation, was employed to produce the pitch, roll and yaw torque using the tailless control approach (Fig. 6c). The commercial-off-the-shelf microcontroller and MEMS rate gyroscope technology were applied on an in-house designed circuit board for stability augmentation and remote control of the robot.

Unlike the Nano Hummingbird, the hummingbird-like robot designed by the group from Université Libre de Bruxelles used a three-dimensional (3D) printed slider cracker mechanism to generate the oscillation and a four-bar linkage to amplify the motion to the desired flapping amplitude of 120° [25], as shown in Figs. 7a and b. The flapping mechanism was driven by a 7 mm string-based flapping mechanism, optimised wing, hybrid control mechanism and the on-board flight controller, and Aerodynamic performance compared to flying creatures in nature.

phones, we believe that the insect-like flapping-wing MAVs can finally fly freely in the sky via powerful wireless charging.

The RoboBee from Harvard University [28] and the PIEzoelectric-actuated MAV from Shanghai Jiao Tong University [29] were successfully presented in 2011. The piezoelectric actuators were employed to generate sufficient lift in both branches of bio-mimicking flapping-wing MAVs. The wing kinematics was well tuned and controlled by the on-board controllers to ensure an acceptable aerodynamic efficiency. Despite the impressive performance of those bio-mimicking MAVs, the lift generation for a single pair of flapping wings is still limited. In addition, as the dimension and flapping frequency for the bio-mimicking MAV increases, the inertial effect of the oscillating components in the mechanism becomes significantly strong, which results in a steep increase in input power and a sharp drop in overall efficiency. Therefore, several novel compound MAV layouts, which utilise the aerodynamic mechanisms inspired by insect flight, are proposed recently to improve the payload capacity of MAV.

2.2 Novel compound layouts for MAVs

In general, most of the compound layouts for MAVs can be regarded as a combination of fixed-wing, rotary-wing, and
flapping-wing layouts. For example, the fixed/flapping-wing layout proposed by Jones and Platzer [36] (Fig. 10a) attached a biplane-pair of trailing wings to a conventional fixed-wing layout. The biplane-pair of trailing wing undergoes plunging motion to generate thrust for forward flight. However, due to the limitations in hover flight, this combination received less attention. Another famous compound layout is the flapping rotary wing (FRW; Figs. 10b and c), which has been widely studied over the last few decades [37–39]. An FRW undergoes a rotating motion with concomitant vertical flapping and periodic variation of the angle of attack (also known as the pitching motion). The vertical flapping and pitching motion can generate thrust on each wing and result in a reduction of driven torque for the revolving motion. There exists an equilibrium that no driven torque is required to rotate the wing and thus the counter torque phenomenon is not observed. It has been proved that a well-tuned FRW can achieve a much higher lift generation than a rotary wing (RW) with the same power expenditure. In addition, there is another branch of flapping-wing MAVs that employs multiple pairs of flapping wings, e.g. the X-wing ‘DelFly-II’ [40] (Fig. 10d) and the ‘Quad-thopter’ [41] (Fig. 10e). These concepts aimed to enhance the wing–wing interaction, which can involve novel unsteady aerodynamic mechanisms for a higher cycle-averaged lift while retaining most of the high lift generation of a single flapping wing. One more possible compound layout is the cycloidal rotor [42] (Fig. 10f), where several blades are rotated around a horizontal axis that is perpendicular to the direction of flight. The blade span is parallel to the axis of rotation, where the angle of attack of each blade is varied periodically about the airfoil quarter-chord. The cycloidal rotor can thus generate a net cycle-averaged force in any direction normal to the axis of rotation, which can be further decomposed into lift and thrust.

In conclusion, the feasibility of the compound layouts using FRW, multiple pairs of flapping wings and cycloidal rotor has been validated using the prototype test. A successful take-off of the prototype is achieved for all those three concepts. Moreover, due to the similarity to the bio-mimicking flapping-wing MAVs, a bio-inspired flight control has been realised in the ‘DelFly-II’ [43]. Within this review, previous studies and explanation on the aerodynamic mechanisms of those compound layouts are introduced in detail, which we hope can provide an overview of this field and serve as a guideline for future research.

3 Aerodynamic mechanisms in bio-inspired compound MAV layouts

3.1 High lift mechanisms of insect flight

As mentioned above, most bio-inspired MAVs employ the aerodynamic mechanisms of insect flight (including hummingbirds) to improve the lift generation and flight stability. Insects flap their wings at high frequency to generate a strong unsteady flow in the vicinity of the wing and thus generate enough lift to support their weight and manoeuvres. Early studies based on the hypothesis of steady flow failed to predict the lift generation of insect flight [44, 45], suggesting their strong lift generation is subjected to unsteady mechanisms, i.e. the high lift mechanisms. To date, several unsteady high lift mechanisms have been presented and an overview is provided here as background knowledge. For details, see previous reviews [46–48].

One of the first proposed unsteady high lift mechanisms is related to the ‘clap and fling’ wing motion observed in the small wasp Encarsia formosa [49], as shown in Fig. 11d. Before each down stroke, the leading edges of the wings meet first and wait for the impingement of the wings, i.e. ‘clap’. At the start of the following down stroke, the leading edges separate first and thus the wings open like a book, i.e. ‘fling’. Weis-Fogh suggested that the fling motion might speed up the circulation generation and thus lift generation on the wing pair, as one wing with its circulation can be regarded as the starting vortex of the other wing. This hypothesis
Thus, the ‘dynamic stall’ is also referred as the ‘absence of stall’ hypotheses have been given based on the steady-state leading-edge vortex (LEV) due to the fling motion. Experiments done by Maxworthy proved the generation of a prolonged attachment of LEV using a simplified revolving wing model. Further model given by Lighthill and the flow visualisation using smoke lines revealed that the powerful entrainment of the vortex wake shed in the previous stroke, which was first observed to exist in a 2D flapping wing model. The ‘wing rotation’ mechanism, also known as the rotational lift mechanism, is explained by the increase of circulation on the wing due to the quick pitch-up motion. It was further found that an advanced wing rotation, i.e. the majority of the wing rotation was conducted before the stroke reversal, can result in an obvious lift peak during the end of a stroke. Note that, the effect of the wing rotation mechanism is renamed as the rapid acceleration and the rapid pitch-up mechanism in the study of Sun and Tang.

3.2 Aerodynamic mechanisms of novel compound MAV layouts

3.2.1 Fixed/flapping-wing MAV: The fixed/flapping-wing MAV was a derivative for fixed-wing MAVs, where the conventional propeller was replaced by a ‘bio-inspired’ propeller, e.g. the biplane-pair of trailing wings undergoing plunging motion. As demonstrated by Knoller-Betz effect, the resultant force generated by a plunging wing with the incoming flow was tilted forward in both down stroke and upstroke, which results in a projection of resultant force in the forward direction, i.e. the generation of thrust. The flow behaviour of plunging air foils was thus extensively studied and the generation of thrust was then related to the formation of reverse Karman vortex street. The Strouhal number (defined as the ratio of mean plunging velocity over free stream velocity) further increases, the flow pattern will be deflected randomly. For previous studies on plunging air foils, please refer to refs. [70–77]. Inspired by this phenomenon, the thrust generation of the biplane-pair of plunging wings was experimentally studied in a wind tunnel at both large and small scales [36]. The results encourage the feasibility of small-scale plunging wings as a propeller for MAVs. As shown in Fig. 12a, the small-scale plunging wings can retain the forward motion to a forward speed beyond 5 m/s. Further prototype tests in a pendulum arrangement (as an approximation of forward flight) showed that the fixed/flapping-wing MAV can propel itself around the central axis and equilibrated at a rotating speed close to the results in wind tunnel experiments. Flow visualisation experiments using smoke lines revealed that the powerful entrainment of the plunging wing can suppress the occurrence of a stall for the fixed wing (Fig. 12b) and the unsteady laser Doppler velocimetry (LDV) results also proved the existence of the significant entrainment effect of the plunging wing.

3.2.2 Flapping rotary wing (FRW) MAV: The FRW MAV was inspired by the dragonfly flight, where two pairs of wings flap in a deviated stroke plane with periodical pitching (Fig. 13a). Each pair of wings can generate cycle-averaged lift and thrust simultaneously. If the leading edge and trailing edge of one of the

Fig. 9 Details of the design of RoboBee from Harvard University [28, 34, 35]
(a) Piezoelectric-driven flapping mechanism, (b) Trajectory for a lateral manoeuvre, (c) Schematic showing piezoelectric ceramic actuator bending profile

Fig. 10 Novel bio-inspired MAV layouts [36–42]

Fig. 11 Overview of the unsteady high lift mechanisms in insect flights [48]

was further modelled by Lighthill and the flow visualisation experiments done by Maxworthy proved the generation of a leading-edge vortex (LEV) due to the fling motion. As the wing accelerates at a high angle of attack since the onset of each stroke, the ‘dynamic stall’, i.e. stall delayed for a short time, is another candidate for explaining the high lift generation. Dickinson and Gotz proposed that the generation of LEV during the acceleration could enhance the lift within the first 4–5 chord length of travel, after which the lift drops due to the shedding of LEV. However, it is further proved that the LEV is stably attached to the wing during the entire stroke in most insect flights. Thus, the ‘dynamic stall’ is also referred as the ‘absence of stall’, and numerous studies have been focused on explaining the prolonged attachment of LEV using a simplified revolving wing and its related aerodynamic performance. Several hypotheses have been given based on the steady-state characteristics, such as the spanwise flow convection, tip-vortex induced downwash, Coriolis effects, vorticity tilting and stretching and vorticity annihilation. However, due to the limited stroke amplitude in insect flight, the LEV formation, rather than the steady-state characteristics, may play a more important role in the ‘dynamic stall’. Note that early aerodynamic studies of insect flight using a 2D flapping wing model gave a reasonable approximation of recent 3D experiments and simulations, which further confirmed the significance of LEV formation. Chen et al. recently studied the time-resolved LEV dynamics during its formation on a revolving wing and the LEV formation can be separated into three stages according to the behaviour of vorticity convection and tilting and stretching. Their findings also emphasised the significance of the LEV formation in insect flight rather than the steady-state behaviour. In spite of this, there is no doubt that the prolonged attachment of LEV (due to unsteady LEV formation or vorticity balance of the steady-state LEV) contributes to sustaining the high lift generation of the wing during the translating phase around mid-stroke.

The lift generation of an insect wing also experiences a peak at the beginning and end of each stroke, which is explained by the ‘wake capture’ and ‘wing rotation’, respectively. The ‘wake capture’ mechanism can be regarded as an increase of effective fluid velocity due to the vortex wake shed in the previous stroke, which was first observed to exist in a 2D flapping wing model. The ‘wing rotation’ mechanism, also known as the rotational lift mechanism, is explained by the increase of circulation on the wing due to the quick pitch-up motion. It was further found that an advanced wing rotation, i.e. the majority of the wing rotation was conducted before the stroke reversal, can result in an obvious lift peak during the end of a stroke. Note that, the effect of the wing rotation mechanism is renamed as the rapid acceleration and the rapid pitch-up mechanism in the study of Sun and Tang.

IET Cyber-Syst. Robot., 2019, Vol. 1 Iss. 1 pp. 2-12
wings are reversed while keeping the same flapping and pitching motion, the thrust generation on the wings will be transformed into a torque (Fig. 13b). The wing pair is thus rotated due to this driving torque and finally arrives at equilibrium if the rotating degree of freedom is allowed around the central shaft. Consequently, the wing motion of an FRW can be regarded as a combination of wing rotation in the horizontal plane, concomitant vertical flapping, and periodic pitching. The concept of FRW was further expanded to a parameter space where the equilibrium of rotating torque is not achieved, i.e. a drive torque for revolving is required or an output torque results around the central shaft. Here, a detailed review of previous studies on the aerodynamic mechanisms of this layout is given.

The concept of FRW was first proposed by Fitchett in 2007 [37] and several prototypes have been presented since then. Specifically, the FRW motion in Fitchett et al. [38] was achieved by an aluminium mechanism (‘flotor’ shown in Fig. 10b), which was mounted on a load cell to measure the lift generation. The pitching motion of the wing was passively achieved due to the wing deformation. Their experiments proved that the existence of the equilibrium of rotating torque in an FRW and the lift enhancement of an FRW compared to pure rotating wings. Moreover, Guo et al. designed and fabricated a simple, reliable and lightweight FRW using the crack-slider mechanism [38]. They also presented a methodology to extract the unsteady aerodynamic force generated by the FRW from the measured dynamic force. They further improved the prototype by replacing the motor by a piezoelectric actuator, and the dynamic behaviour of the model was analysed using the finite element method [79]. A 2D computational fluid dynamics (CFD) computation combined with the theoretical method was also employed as the first attempt to uncover the aerodynamic mechanism of this FRW (Fig. 14).

The numerical studies on the aerodynamic mechanisms of an FRW are introduced and summarised here. Wu et al. first conducted a 3D CFD simulation of a wing undergoing FRW-like motions and a comparison of flow between flapping wings and FRWs was also provided [80]. Compared to a purely flapping wing, it was shown that enhancement of cycle-averaged lift can be generated when the wing starts to rotate, while the cycle-averaged rotating torque decreases. The LEV was generated alternatively on both upper (in down strokes) and lower surfaces (in upstrokes) and kept attached to the surface. They further explored the effect of flapping amplitude, mean angle of attack, pitching amplitude, the ratio of the period of flapping to the rotation and Reynolds number. Results indicated that an increase of pitching amplitude and Reynolds number is the only way to increase both cycle-averaged lift and rotational torque. The effects of wing pitching and rotational speed on the aerodynamic performance of an FRW were then interrogated via CFD simulations [78]. Considering a fixed pitching amplitude (i.e. 80°), the lift increases with the down stroke angle of attack. However, a large down stroke angle of attack is not encouraged to achieve a high rotating speed. In addition, the effects of geometric parameters on the aerodynamic performance of FRW was unfolded by Wang et al. [82], considering the maximum camber, radius of second area moment, wing shape, spanwise twisting and aspect ratio. Several suggestions to the design of an FRW were given in their parameterised study. The power consumption of an FRW is then compared to RWs and flapping wings with Re ranging from 0 to 12,000, (Fig. 12) Suppression of the stall on the fixed wing due to the flapping motion of the biplane pair trailing wings

**Fig. 12** Propelling performance of a fixed/flapping MAV [36]
(a) Thrust generation of a 15 cm prototype with Re ranging from 0 to 12,000, (b) Suppression of the stall on the fixed wing due to the flapping motion of the biplane pair trailing wings

The FRW was regarded as compensation between flapping wings and RWs, because the FRW can generate significantly higher lift than RWs but at the cost of relatively higher power consumption (but is still lower than flapping wings). Using CFD-modified quasi-steady models, numerical optimisation of FRW kinematics was done by Li et al. under the constraints of aspect ratio (AR) and Re [83]. Their results also suggested that the FRW could produce the highest aerodynamic lift when compared to RWs and flapping wings but with moderate power efficiency. Note that the wing rotation was prescribed in above-mentioned numerical studies. Wen et al. further modelled the passive wing rotation feature of an FRW with two blades at a low Re around 1000 [81]. The quasi-steady model was applied to model the unsteady aerodynamic force generation and the solving of dynamic motion was interrogated. Their results indicated that the passive wing rotation is a continuous dynamic process, which first accelerates and then converges into an equilibrium state due to the interaction of aerodynamic thrust, drag force and wing inertia. This dynamic interplay can thus result in a unique time-lag phenomenon in the lift generation.

In parallel, experimental studies in either air or oil environment were also conducted. Exclude the researches based on the ‘flotor’, Zhou et al. also measured the rotational speed and cycle-averaged
At \(\alpha = 0^\circ\), the aerodynamic performance of an FRW [85] is shown. Further analysis showed that the pitching effects could be mainly decomposed into the LEV-mediated pressure component and geometric projection component (Figs. 16–18).

The effect of passive pitching of the wing caused by the wing flexibility can significantly increase the lift generation (Fig. 15). Wu et al. further performed experiments to make clear the effect of flapping motion and pitching motion on the aerodynamic performance of an FRW at \(Re = 1500\) [87, 88]. The experiments were conducted by operating a dynamically-scaled robot in an acrylic tank filled with mineral oil. To extract the net aerodynamic force from the dynamic measurements, all experiments were repeated in the air to estimate the inertial components. The flow details were obtained using 3D CFD simulations based on the wing kinematics in the experiments. For a revolving wing imposed with a vertical flapping motion, a drag reduction phenomenon was observed at zero angle of attack (\(\alpha\)) [87]. This reduction is linearly dependent on Strouhal number and the rotating equilibrium state was similar to that in 2D heaving plates. The generation of a reverse Karman vortex street was also seen in this fully 3D case, which resulted in the drag reduction. Note that this reduction of drag can be further enhanced when a pitching motion is further imposed [88]. However, the introduce of flapping motion to a revolving wing at positive angles of attack can lead to an increase of revolving drag, although an increase of cycle-averaged lift is achieved simultaneously. When pitching motion is further introduced, the drag increase phenomenon for a flapping-perturbed revolving wing at \(\alpha = 20^\circ\) is replaced by a reduction of drag and a self-rotating equilibrium can be achieved as the Strouhal number increases. It was further found that, besides the lift enhancement, the power loading (PL) of a revolving wing at \(\alpha = 20^\circ\) can be improved using pitching–flapping motion with large pitching amplitude but small Strouhal number. Note that a driven revolving torque is still required for this favourable state. The effects of the phase angle between flapping and pitching motion were also discussed in this study and advanced pitching can improve the reduction of external driving torque for revolving. Further analysis showed that the pitching effects could be mainly decomposed into the LEV-mediated pressure component and geometric projection component.

3.2.3 MAV with multiple pairs of flapping wings: One of the most intuitive methods to improve the lift generation of a biomimicking flapping-wing MAV is to apply multiple pairs of flapping wings, similar to the idea of quadrotors. However, the arrangement of multiple pairs of wings can be X-shape (two pairs),
tandem (two pairs) and square (four pairs), each of which involves distinct wing-wing interactions that can affect the aerodynamic performance.

The X-shape arrangement is one of the most successful layouts with multiple pairs of flapping wings. The ‘DelFly-II’ prototype was introduced here as an example, which uses an X-shaped flapping-wing mechanism combined with tails for lift generation and attitude control. The clap and peel motion of two wing pairs, similar to ‘clap and fling’, is expected to enhance the LEV formation during the translational phase and thus unsteady lift generation. Clercq et al. found that the peel, instead of the clap, contributed significantly to the lift generation through particle image velocimetry (PIV) experiments [40]. Further direct force measurement of the prototype revealed that a phase different occurred in the variation of forces, i.e. the lift peak of the low-frequency case precedes that of the high-frequency case [89]. A similar phase lag was also observed in the temporal wing deformation, which was obtained by a stereo-vision system. It was recently proposed, which aimed to enhance the clap and fling mechanism between wing pairs. However, the stroke amplitude of a single wing pair was limited, e.g. the tailless Quadcopter proposed by Wagter et al. [41]. The main advantages of this square arrangement are easy to produce and control. A differential lift can be generated by the wing pairs (which is similar to quadrotors) and thus generates the desired pitch and roll torque. To generate the yaw torque, two pairs of wings are tilted clockwise and the others are tilted counter-clockwise. A detailed measurement of aerodynamic forces and torques were conducted in their study and successful flight tests were achieved both indoor and outdoor.

3.2.4 Cycloidal rotor MAV: Unlike other bio-inspired MAVs, the unsteady flapping motion of the wing is not seen in the concept of cycloidal rotor MAV. However, the cycloidal rotor uses a periodic variation of blade angle of attack to introduce the unsteadiness. Note that, the periodic pitching wings, which are inspired by the undulating motion of fishes, can also result in a similar flow structure and aerodynamic performance to plunging wings. For previous studies on periodic pitching wings, please refer to refs. [94–96].

To date, most of the studies on cycloidal rotor within the MAV scale were conducted by Chopra and his colleagues in the University of Maryland. The hover performance of a small-scale cycloidal rotor was first experimentally measured and its feasibility to MAV was thus proved [97]. The effects of the number of blades, blade pitch angle, and rotational speed on thrust output and power requirements were then investigated. Based on their findings, a cyclo-MAV utilising two three-blade cycloidal rotors (6 inches of diameter) was proposed with a gross weight of 240 g. The effects of blade airfoil shape and blade flexibility were examined in their following study [42]. A higher blade pitch angle was found to improve the PL of the cycloidal rotors, whereas large bending and torsional flexibility of the blades had a deleterious effect on performance. A PIV measurement was then performed and the generation of LEV was observed as the evidence of dynamic stall (Fig. 20). Benedict et al. further analysed the aero-elastic characteristics of the cyclo-MAV using both second-order non-linear beam and finite element method and multi-body-based large deformation theory [98]. Their analysis showed that the reduction in the thrust generation of the flexible cycloidal rotor may be attributed to the large nose-down elastic twisting of the blades in the upper half cylindrical section. An optimisation of kinematics through experiments was also carried out [99] and the effect of flow curvature during a forward flight was elucidated in their recent paper [100].

4 Future research interest

4.1 Novel aerodynamic mechanisms in insect flight

According to the research on insect flights over the last two decades, the underlying aerodynamic mechanisms of most flying insect species, e.g. flies, bees, moths etc., are explained, such as the ‘clap and fling’, ‘dynamic stall’, ‘rotational lift’ and ‘wake capture’ mechanisms. However, there are still plenty of flying insect species in nature, utilising unique wing geometry and kinematics and thus novel aerodynamic mechanisms. For example, butterflies flap their low AR wings at a much lower frequency compared to flies and bees [101]. The pitching and deviation motion of a butterfly wing is not obvious, whereas the motion of the head and abdomen is significant, indicating a strong coupling of wing and body motions. The flight of beetles, such as ladybugs, is also underexplored, where a strong interaction of the hard shell and the flexible wing is observed [102]. Recent studies have proposed the novel evolution of LEV, trailing edge vortex and tip vortex was first visualised (Fig. 19).

The tandem arrangement of multiple pairs of flapping wings is fundamentally mimicking the wing kinematics of dragonfly and thus employs the aerodynamic mechanisms of dragonfly flight. To be brief, the aerodynamic mechanisms of dragonfly flight can be found in [91–93] and will not be presented here. Compared to the X-shape arrangement, the square arrangement of four pairs of flapping wings was recently proposed, which aimed to enhance the clap and fling mechanism between wing pairs. However, the stroke amplitude of a single wing pair was limited, e.g. the tailless Quadcopter proposed by Wagter et al. [41]. The main advantages of this square arrangement are easy to produce and control. A differential lift can be generated by the wing pairs (which is similar to quadrotors) and thus generates the desired pitch and roll torque. To generate the yaw torque, two pairs of wings are tilted clockwise and the others are tilted counter-clockwise. A detailed measurement of aerodynamic forces and torques were conducted in their study and successful flight tests were achieved both indoor and outdoor.

Fig. 17 Effect of pitching motion on cycle-averaged lift generation and PL of a pitching-flapping-perturbed revolving wing at α = 20° [88]

(a) Cycle-averaged lift (C_l), (b) PL, (c) Instantaneous vertical force generation for the cases with St = 0.56, (d) Instantaneous horizontal force generation for the cases with St = 0.56

Fig. 18 Explanations for the enhancement of aerodynamic performance of a pitching–flapping–perturbed revolving wing with St = 0.56 and α = 20° at four typical time steps [88]

IET Cyber-Syst. Robot., 2019, Vol. 1 Iss. 1, pp. 2-12
This is an open access article published by the IET and Zhejiang University Press under the Creative Commons Attribution-NonCommercial-NoDerivs License (http://creativecommons.org/licenses/by-nc-nd/3.0/)
aerodynamic mechanism in some specific flying insect species, such as the ‘smart wing rotation’ in mosquitos [103], the ‘paddling’ in hoverflies [104] and the drag-based mechanisms in tiny wasps [105]. One possible branch of future studies is to further step into the world of flying insects, especially those with distinct wing and body kinematics. Using high-fidelity CFD simulations and dynamically-scaled experimental setups, their underlying aerodynamic mechanisms can be well clarified, which can improve our understanding towards the insect flight, and more importantly, may motivate new concepts in bio-inspired MAV design.

4.2 Bio-inspired flight control strategy and its application in MAV

Bio-inspired MAVs utilise the aerodynamic mechanisms found in insect flight to generate enough lift to support their weight, as well as to perform agile manoeuvres. However, the flight control strategy of a bio-inspired MAV is still not fully studied. For a bio-mimicking flapping-wing MAV, the control strategy can be directly adapted from that in their natural counterparts. Due to the small size of flying insects and hummingbirds, our knowledge on the role of complex muscle structures in wing kinematic control of those species is still limited, not to mention the ‘black box’ of neuroscience in their brains. An alternative methodology is the previous numerical modelling of insect flight control involving aerodynamics and body dynamics [106–109], which is convenient to implement in MAV design but leaves the ‘black box’ of neuroscience unresolved. Although several bio-inspired flight control strategies have been successfully implemented in prototypes following this methodology, most of them are an artificial mechanical design to achieve the desired variation of wing kinematics, rather than a complete bio-inspired strategy. Future studies may be focused on demonstrating the flight control strategies in real insects and hummingbirds and the application of those strategies in bio-mimicking MAVs. In addition, as most novel compound MAV layouts are not directly mimicking the wing kinematics of insects or hummingbirds, e.g. the FRW, there is still no effective control strategy. The application of bio-inspired flight control strategy to those MAVs can be another challenge in the future.

5 Conclusion

The MAVs, a miniature of unmanned techniques, has been extensively studied recently due to their superb performance and world-wide application. To date, considerable MAV layouts have been proposed, within which the bio-inspired layouts are argued to be one of the most successful solutions. Therefore, the aerodynamic mechanisms of bio-inspired MAVs are reviewed in this study focused on recent progress in the novel bio-inspired compound layouts, e.g. the FRWs. We started with a brief introduction of the history of MAVs and the bio-inspired MAV layouts are separated into two branches, i.e. the direct bio-mimicking layouts and other compound layouts that take advantages of bio-inspired aerodynamic mechanisms. Several successful bio-mimicking layouts are further introduced in terms of the design, fabrication, aerodynamic performance and flight control. In addition, the unsteady high lift mechanisms in insect flight are revisited, followed by a detailed introduction of bio-inspired compound layouts. Recent progress on the aerodynamic mechanisms on the fixed/flapping wing layout, the FRW layout, the multiple-pair flapping-wing layout, and the cycloidal rotor layout are reviewed specifically. A well-designed FRW is proven to be an alternative MAV layout for a task with much higher payload at the cost of slight (or even no) decrease in PL. Future study interests in the field of MAVs are also suggested, where the unfolding of novel aerodynamics mechanisms in other flying insect species and the application of bio-inspired flight control strategies are among the most attractive topics.

6 Acknowledgment

This research was supported by the National Natural Science Foundation of China (NSFC, grant no. 11672022) and the Academic Excellence Foundation of BUAA for Ph.D. Students.
Zhou, C., Wu, J.H., Guo, S.J., Ashraf, M.A., Young, J., Lai, J.C.S.: 'Oscillation frequency and amplitude effects on plunging airflow', *AIAA J.*, 2009, 47, (11), pp. 2685–2697

Young, J., Lai, J.C.: 'On the aerodynamic forces of a plunging airfoil', *AIAA J.*, 2015, 54, (1), pp. 103–121

Ashraf, M.A., Young, J., Lai, J.C.S.: 'Oscillation frequency and amplitude effects on plunging airflow propulsion and flow periodicity', *AIAA J.*, 2012, 50, (11), pp. 2308–2324

Wu, J.H., Qiu, J., Zhang, Y.L.: 'Automated kinematics measurement and performance of flexible and rigid plunging airfoils', *Fluid Struct.*, 2015, 54, pp. 103–121

Zhou, C., Zhang, Y.L., Wu, J. H.: 'Unsteady aerodynamic forces and power consumption of a micro flapping rotary wing in hovering flight', *J. Bionic Eng.*, 2018, 15, (2), pp. 298–312

Guo, S.J., Li, D.C., Wu, J.H.: 'Theoretical and experimental study of a piezoelectric flapping wing rotor for micro aerial vehicle', *Aerospace Sci. Technol.*, 2012, 23, (1), pp. 429–438

Wu, J.H., Wang, D., Zhang, Y.L.: 'Aerodynamic analysis of a flapping rotary wing at a low Reynolds number', *AIAA J.*, 2015, 53, (10), pp. 2951–2966

Wen, Q.Q., Guo, S.J., Li, H., et al.: 'Nonlinear dynamics of a flapping rotary wing: modeling and optimal wing kinematic analysis', *Chinese J. Aeronaut.*, 2018, 31, (5), pp. 1041–1052

Wang, D., Wu, J.H., Zhang, Y.L.: 'Effects of geometric parameters on plunging rotary wings at Low Reynolds numbers', *AIAA J.*, 2018, 56, (4), pp. 1372–1387

Li, H., Guo, S.J., Zhang, Y.L., et al.: 'Unsteady aerodynamic and optimal kinematics of a micro flapping wing rotor', *Aerospace Sci. Technol.*, 2017, 63, pp. 167–178

Zhou, C., Wu, J.H., Guo, S.J., et al.: 'Experimental study on the lift generated by a flapping wing rotor applied in a micro air vehicle', *Proc. Inst. Mech. Eng. G, J. Aerosp. Eng.*, 2014, 230, (11), pp. 2083–2093

Chen, L., Zhang, Y.L., Wu, J.H.: 'Study on lift enhancement of a flapping rotary wing by a bore-hole design', *Proc. Inst. Mech. Eng. G, J. Aerosp. Eng.*, 2018, 232, (13), pp. 2315–2322

Wu, J.H., Qiu, J., Zhang, Y.L.: 'Automated kinematics measurement and aerodynamics of a bioinspired flapping rotary wing', *J. Bionic Eng.*, 2017, 14, (4), pp. 726–737

Wu, J.H., Chen, L., Zhou, C., et al.: 'Aerodynamics of a flapping-perturbed revolving wing', *AIAA J.*, 2018, to appear

Chen, L., Wu, J.H., Zhou, C., et al.: 'Unsteady aerodynamics of a pitching-flapping-perturbed revolving wing at low Reynolds number', *Phys. Fluids*, 2018, 30, (5), p. 051903

Percin, M., van Oudheusden, B.W., de Croom, et al.: 'Force generation and wing deformation characteristics of a flapping-wing micro air vehicle 'Delfly II' in hovering flight', *Bioinspir. Biomim.*, 2016, 11, (3), p. 036014

Deng, S., Percin, M., van Oudheusden, et al.: 'Numerical simulation of a flexible x-wing flapping-wing micro air vehicle', *AIAA J.*, 2017, 55, (7), pp. 2295–2306

Wang, J.K., Sun, M.: 'A computational study of the aerodynamics and forewing-hindwing interaction of a model dragonfly in forward flight', *J. Exp. Biol.*, 2005, 208, (19), pp. 3785–3804

Sun, M., Huang, H.: 'Dragonfly forewing-hindwing interaction at various flight speeds and wing phasing', *AIAA J.*, 2007, 45, (2), pp. 508–511

Wang, J.Z., Russell, D.: 'Effect of forewing and hindwing interactions on aerodynamic forces and power in hovering dragonflies', *Phys. Rev. Lett.*, 2009, 99, (14), p. 148101

Amiralei, M.R., Alighanbari, H., Hashemi, S.M.: 'An investigation into the effects of unsteady parameters on the aerodynamics of a low Reynolds number pitching airfoil', *J. Fluid Struct.*, 2010, 26, (6), pp. 979–993

Yilmaz, T., Ol, M., Rockwell, D.: 'Scaling of flow separation on a pitching low aspect ratio plate', *J. Fluid Struct.*, 2010, 26, (6), pp. 1034–1041

Tian, W., Bodling, A., Liu, H., et al.: 'An experimental study of the effects of pitch-pivot-point location on the propulsion performance of a pitching airfoil', *J. Fluid Struct.*, 2016, 60, pp. 130–142

Sinha, J., Parsons, E., Chopra, I.: 'Hover performance of a cycloidal rotor for a micro air vehicle', *J. Am. Helicopter Soc.*, 2007, 52, (3), pp. 263–279

Benedict, M., Mattaboni, M., Chopra, I., et al.: 'Aerelastic analysis of a micro-air-vehicle-scale cycloidal rotor in hover', *AIAA J.*, 2011, 49, (11), pp. 2430–2443

Benedict, M., Jarugumilli, T., Chopra, I.: 'Experimental optimization of MAV-scale cycloidal rotor performance', *J. Am. Helicopter Soc.*, 2011, 56, (2), pp. 22005–22005

Benedict, M., Jarugumilli, T., Lakshminarayan, V., et al.: 'Effect of flow curvature on forward flight performance of a micro-air-vehicle-scale cycloidal-rotor', *AIAA J.*, 2014, 52, (6), pp. 1159–1169

Dudley, R.: 'Biomechanics of flight in neotropical butterflies: morphometrics and kinematics', *J. Exp. Biol.*, 1990, 150, (1), pp. 37–53

Van Tuong, T., Le, T.Q., Byun, D., et al.: 'Flexible wing kinematics of a free-flying beetle (Rhinoceros beetle Tropysylla dichotoma)', *J. Bionic Eng.*, 2012, 9, (2), pp. 177–184

Bomphey, R.J., Nakata, T., Phillips, N., et al.: 'Smart wing rotation and trailing-edge vortices enable high frequency mosquito flight', *Nature*, 2017, 544, (7648), pp. 92–95

Zhu, H.J., Sun, M.: 'Unsteady aerodynamic force mechanisms of a hoverfly hovering with a short stroke-amplitude', *Phys. Fluids*, 2017, 29, (8), p. 086101

Cheng, X., Sun, M.: 'Very small insects use novel wing flapping and drag principle to generate the weight-supporting vertical force', *J. Fluid Mech.*, 2018, 855, pp. 646–670

Sun, M., Xiong, H.: 'Dynamic stability of a hovering bumblebee', *J. Exp. Biol.*, 2005, 208, (3), pp. 447–459

Zhang, Y.L., Sun, M.: 'Oscillatory flight stability of a hovering model insect: lateral motion', *Acta Mech. Sin.*, 2010, 26, (2), pp. 175–190

Liang, B., Sun, M.: 'Nonlinear flight dynamics and stability of hovering model insects', *J. R. Soc. Interface*, 2013, 10, (85), p. 20130269

Wu, J.H., Sun, M.: 'Floquet stability analysis of the longitudinal dynamics of two hovering model insects', *J. R. Soc. Interface*, 2012, 9, (74), pp. 2033–2046