Chinese Journal of Aeronautics, (2016), 29(5): 1159–1177

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

REVIEW ARTICLE

Flapping wing micro-aerial-vehicle: Kinematics, membranes, and flapping mechanisms of ornithopter and insect flight

Mohd Firdaus Bin Abas [a], Azmin Shakrine Bin Mohd Rafie [a], Hamid Bin Yusoff [b], Kamarul Arifin Bin Ahmad [a,*]

[a] *Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[b] *Faculty of Mechanical Engineering, Universiti Teknologi MARA Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia*

Received 6 July 2015; revised 27 July 2015; accepted 22 August 2015
Available online 27 August 2016

KEYWORDS

Flapping wing kinematics;
Insect;
Membrane wing;
Micro-air-vehicle;
Ornithopter

Abstract The application of biomimetics in the development of unmanned-aerial-vehicles (UAV) has advanced to an exceptionally small scale of nano-aerial-vehicles (NAV), which has surpassed its immediate predecessor of micro-aerial-vehicles (MAV), leaving a vast range of development possibilities that MAVs have to offer. Because of the prompt advancement into the NAV research development, the true potential and challenges presented by MAV development were never solved, understood, and truly uncovered, especially under the influence of transition and low Reynolds number flow characteristics. This paper reviews a part of previous MAV research developments which are deemed important of notification; kinematics, membranes, and flapping mechanisms ranges from small birds to big insects, which resides within the transition and low Reynolds number regimes. This paper also reviews the possibility of applying a piezoelectric transmission used to produce NAV flapping wing motion and mounted on a MAV, replacing the conventional motorized flapping wing transmission. Findings suggest that limited work has been done for MAVs matching these criteria. The preferred research approach has seen bias towards numerical analysis as compared to experimental analysis.

1. Introduction

For the past several decades, demands on smaller unmanned-aerial-vehicles (UAVs) are increasing. Reducing the size of a UAV will set new challenges as smaller size is as equivalent as smaller wingspan, and thus for flapping wing UAVs, smaller lift and thrust force values will be generated from a single flapping cycle. Therefore, smaller UAVs will have to face complex

* Corresponding author.
E-mail address: aekamarul@upm.edu.my (K.A. Bin Ahmad).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.08.003
1000-9361

air flow characteristics, such as wake capture, due to flight conditions bounded within the low Reynolds number regime (Re < 15000). Small UAVs are then coined in with the term micro-aerial-vehicles (MAVs). The high demands for such improvements have made researchers sought to nature's best fliers, ranging from small birds to small insects, for example, a typical house/fruit fly. The research trend started with the initial idea of how birds, or scientifically referred to as ornithopters, fly with superb efficiency and how its wing mechanism affects its ability to maintain aerodynamic superiority and gain air dominance. Early works on fluid flow, its behavior, and active flow control have been summarized in a comprehensive review by Collis et al.[1] regarding the theory and how to effectively control the predicted fluid flow, and the issues arise from numerical and experimental approaches on active flow control.

During the last 5 years, several researches on ornithopter-type MAV development have been reported. Initial research was developing from experimental and numerical approaches of 2D flapping airfoils. As the research grows deeper, the need for a 3D flapping wing modeling and simulation arises for a more accurate performance-based predictions, despite cost factors. There are a vast amount of variables to consider in the attempt to optimize a flapping wing configuration, such as endurance and optimum aerodynamic capabilities. Strang studied the flapping flight of pterosaurs and analyzed its flapping flight efficiency.[2] Jackowski then published a guideline regarding the design and construction of an unmanned ornithopter, displaying specific variable considerations in optimizing flapping wing efficiency.[3] Bunget observed an alternative in increasing such efficiency by adopting a bat's flapping wing mechanism and created a bio-inspired MAV which is then termed BATMAV.[4] The ability of a bat to hover in mid-air is due to its unique flapping pattern of its wings, in which the wings produce positive lift during down-stroke and up-stroke as well, with efficient pitch control.

Numerical approaches in research development are also equally important as experimental approaches, but dealing with modeling and simulation necessary for numerical analyses have presented its own challenges, especially when fluid-structure-interaction (FSI) is concerned. Bansmer et al.[5] and Gomes et al.[6] conducted experimental and numerical studies of airfoils with regards to FSI; the former focus more on the structural aspects, such as the rigidity and the flexibility of the seagull hand-foil-inspired airfoil, while the latter focus on laminar FSI aspects.

Aiding the FSI research, Mazaheri and Ebrahimi conducted experimental investigations, using modern computational power and experimental setups, on the aerodynamic performance of a flapping wing vehicle in forward flight[7] and hovering flight under the effects of chord-wise flexibility.[8] They also performed a series of wind tunnel tests to investigate the cruise performance of a typical flapping wing MAV and published it shortly after.[9] Li and Nahon conducted a numerical investigation as well and recommended a more systematic approach of thrust force estimation for nonlinear dynamics of a flapping wing MAV.[10]

Multi-body dynamics was also a hot debating topic among researchers which is far from resolved until today and still presents opportunity for future improvements. Grauer and Hubbard[11] argued that flapping wing MAV researches using insect modeling have overshadowed those using ornithopter modeling due to abundance of insect aerodynamics data. Most of the insect models utilized rigid wing over flexible wing and calculations regarding aerodynamic loads are simply carried out in quasi-steady sense instead of considering FSI. He also did a study of a flapping wing ornithopter in the aspect of inertial measurements obtained from the ornithopter's flight data.[12]

Till today, research on ornithopters is still on the fast track, though there are significant reductions in literature since insect-inspired MAV became the next new lead in MAV development. De Croon et al.[13] published a paper on the design, aerodynamics, and control based on visual input of their MAV creation, termed DelFly. Insect-inspired researches have been blooming in both numerical and experimental aspects. For example, Nagai et al.[14] conducted numerical and experimental investigations of a dynamically scaled mechanical model in a water tunnel in order to examine the aerodynamics of insect-inspired flapping wing MAV. Numerical approaches may have more advantages but it is inevitable that high technological aid comes with a high price to pay, as well as time consumption. As concluded by Liu and Aono,[15] it takes up to 10 h to simulate only 4 flapping cycles of a hawkmoth model. Zhang et al.[16] even proposed a justification where an MAV can be treated as a rigid body with only 6 degrees of freedom in order to simplify the model and reduce time and cost of the simulation.

Ever since the ''bee-paradox'' phenomenon, researchers are particularly interested in the structural, kinematic, and aerodynamic aspects of small-sized insects, as to how these insects can hover and fly despite conventional flight theories. As of current insect-inspired MAV research development, the trend has shown that researchers have been focusing a lot on dragonfly's wing structure and flight performance. Hord and Lian,[17] Kim et al.,[18] Levy and Seifert,[19] Levy,[20] and Murphy and Hu[21] have conducted specific studies on the unique corrugated airfoil profile of a typical dragonfly's wing. Furthermore, Kim et al.[18] and Levy[20] focused their studies on the performance and flow features of a corrugated wing during glide motion (low Reynolds number). The research on dragonflies keeps on developing rapidly and the interest of researchers has been significantly converted towards paired wings (tandem) analyses instead of single wing analyses. There are a lot of variables to consider when conducting researches regarding tandem wing configuration, such as the gap distance between the paired wings,[22] the phase angle of each wing,[22,23] the aerodynamic performance,[24–26] and even the endurance of the wings when subjected to harsh conditions.[27] As a result, Lian et al.[28] compiled and summarized their previous works and published it recently in a comprehensive review manner.

Shyy et al.[29] also made a comprehensive review on the aerodynamics and aeroelasticity of a variety of flapping wing MAVs, mainly on insect-inspired bio-mimicry. The present review will serve as a small extension and as possible validated data for future sequel of the comprehensive review on both aspects of ornithopter- and insect-type flight. Data analyses and comparisons from the previous comprehensive reviews[28,29] will not be elaborated again in the present review but related references will be provided.

The objective of this review is to provide essential information on ornithopter- and insect-type flapping wing kinematics and membrane wing structures and their contribution towards generated lift, thrust, and drag forces in summarized form. A general guideline regarding Reynolds number regime will be presented as well, later in this review.

The contents of this review are arranged as follows: first, an introduction on bio-mimicry system is presented and then mimicking flying animals is discussed, followed by summarized ornithopter and insect flapping wing kinematics and membrane wing structures, and the contribution of both towards generated lift, thrust, and drag forces. Research approaches, flapping wing mechanisms, flow mechanisms, other important aspects (general guideline is included here), critical issues, and recommendations are discussed afterwards. Finally, a conclusion is presented as a closing statement.

2. Bio-mimicry system

Bio-mimicry is a term for the attempt to imitate nature's living organism in what that particular organism performed best at. Generally, airplanes utilize the fluid flow surrounding its airfoil-shape wings and can only manipulate the fluid flow to a certain limit under high speed state (high Reynolds number regime). Unlike those steel birds, nature presents fliers that can fully manipulate the flow around its wings and can even keep itself afloat in midair, in a calm, almost stagnant flow environment (low Reynolds number regime), by flapping its wings accordingly.

There are two types of natural fliers: birds (also known as ornithopters as referred by biologist) and insects, in which the latter has a higher degree of complexity when it comes to flight kinematics, in order to fly and hover in an extremely low Reynolds number flow condition. In the present paper, a brief review is presented on the type of animal selected for mimicry purposes and its importance as visualized in studies by previous authors.

2.1. Mimicking flying animals

In this section, flapping wing birds and insects that researchers have been greatly interested in are summarized. There are two types of flapping wing flight, namely ornithopter flight and insect flight. These researches have been summarized according to its relevance of study towards the specific flight type, in terms of flight kinematics (flapping pattern, wing's degree-of-freedom (DOF), chordwise/spanwise flexibility, and tail-aid stabilization), membrane wing structures (types of material used to construct wing's membrane structure), and their contributions towards lift, thrust, and drag force generations, which will be discussed in later sections.

Flapping airfoil researches[30–35] serve as the fundamental researches to obtain a much more basic information on the characteristics of fluid flow surrounding a flapping 2D airfoil, which is an important intellectual asset in order to accurately predict and anticipate the more complex fluid flow surrounding a flapping 3D wing, in other words, a 2D airfoil with spanwise characteristics.

Researches on bats[36–40] are mostly focused on the membrane structure of its wings. The material used, scalloping properties and generated vibrations are reviewed. Most of the reviewed papers on birds are stated as generic birds[41–49] which have a spanwise measurement range of 10–100 cm. A number of researches refer to the well-established 'Cybird P1'ornithopter[7,8,50] modeled by Kim et al.,[51] few focus on small-sized birds such as magpies[52] and passerines,[53] and just one kind of research is based on DeLaurier's[54] pterosaur model.[42]

For researches on insects, dragonfly is currently the most favorite research subject due to its unique figure-of-eight flapping wing motion, corrugated wing profile, and forward flight, hovering, and hovering-forward flight transition kinematics within an extremely low Reynolds number regime.[26,28,29,55–57] Researches on flies,[29,58] bees,[29,58–60] hoverflies,[61–63] wasps,[29] locusts,[29,58] and beetles[64] are also summarized in this paper. Butterflies[65] and hawkmoths[29,58] are unique insects in which its flapping wing motion is quite similar to an ornithopter's.

Another unique research subject is the hummingbird.[29,66–69] Hummingbird is the only known bird to have advance insect-like flight abilities and has been classified under the insect section in this review.

2.2. Kinematics of flapping wings

In this section, the kinematics of flapping wings for both, ornithopters and insects are reviewed separately, in order to predict the intersection point between researches done for ornithopters and insects. The contributions of flapping wing kinematics toward lift, thrust, and drag force generations are also reviewed later in this section.

2.2.1. Ornithopter

Ornithopter flight, or generally known as bird flight, has only 2 degree-of-freedom (DOF), in which the first one is the main flapping motion and the other one is the slight deviation from the stroke plane (out-of-plane flapping motion).[58] As compared to insect flight, which consists of 3 degree-of-freedom, the third degree, the active wing rotation is replaced by passive wing rotation in ornithopter flight (also known as 'feathering').[49] Passive rotation is caused by the mass inertial force of the wings during flapping. In turn, it simplifies the kinematics of ornithopter flight, as if the wing rotation works automatically.

In 2D airfoil cases, wing rotation can also be termed 'pitching' in order to gain effective angles of attack relative to the flapping wing leading edge, and flapping can be termed as 'plunging', which describes the flapping motion respective to the stroke plane. Researches on the pitch-plunge mechanism of an airfoil are really important before attempting a 3D flapping wing analysis, as done by Unger et al.[30] and Ashraf et al.,[31] to give us a better idea of what to anticipate when analyzing a 3D flapping wing, where the former adopted the airfoil profile of a seagull's 'hand-foil' and the latter investigated the effects of varying thickness and camber of a NACA airfoil on propulsion performance. For 3-D airfoil analysis attempts, several researchers[7,8,50] adopted the flapping wing mechanism from 'Cybird P1' remotely controlled ornithopter by Kim et al.[51] for forward flight analysis,[7] hovering analysis,[8] and to assess aerodynamic benefits of flapping flight as compared to fixed-wing soaring flight, respectively.

As MAVs decrease in size, the complexity of fabrication and airflow characteristics within the Reynolds number range of operation increases as well. A magpie has been taken as an inspiration to develop a small-scale ornithopter with single flapping frequency for simple and dominant flapping-wing motion.[52] The main difficulty of ornithopter design comes from the fact that there is almost no knowledge about what the most important design parameters are and how they affect each other to flapping-wing flight dynamics. Among other optimization analyses, findings show that a tail-wing adoption could improve ornithopter's longitudinal flight stability in the presence of continuous flapping motion of its wings.[43,44,53] It has also been concluded by Park and Yoon[45] that an ornithopter smaller than 10 cm benchmark should follow the features of much smaller insects based on their wings and flight mechanisms.

2.2.2. Insect

As mentioned in the ornithopter section, insect flight has 3 degree-of-freedom: the main flapping motion, the slight deviation from the stroke plane, and the active wing rotation. As described by Orlowski and Girard[58] and Mahjoubi and Byl,[69] the 3 degree-of-freedom of an insect's wings can be defined such that the wing tip traces a figure-8 pattern with respect to the wing root, which dragonflies are popular of. Tandem wing configuration is also a unique feature observed in a dragonfly's flight[26,28] where Sun and Lan[26] did an in-depth research on the interaction between the fore- and hind-wings. In general, there are two types of insect wing kinematics: water treading and normal hovering, which effectively utilize complex flight features, such as rapid pitch rotation, wake capture, delayed stall and vortex generation, under extremely low Reynolds number regime.[58]

For the same purpose as discussed in the ornithopter section, studies on 2D 'flapping' airfoil under low Reynolds number regime are important and serve as a fundamental knowledge in the attempt of analyzing a 3D flapping wing kinematics, especially the complex kinematics of insect flight. An insect generally flaps its wings in a figure-of-eight pattern during hovering, as studied by several researchers namely Amiralaei et al.,[33] Amiralaei et al.,[35] Fenelon and Furukawa,[55] Hamamoto et al.,[57] and Nguyen and Byun[59]. As stated by Amiralaei et al.,[33] an inclined figure-of-eight pattern has substantial drag forces, which contribute to the required hovering force, and as compared to a horizontal figure-of-eight pattern, the vertical figure-of-eight motion plays a substantial role in the generation of the unsteady forces. Both findings by Amiralaei et al.[33] and Nguyen and Byun[59] agree that flapping wing mechanism with symmetrical rotation around mid-chord axis is the most efficient for hovering. Other than that, the symmetrical rotation is the most efficient for forward flight as well and a flapping mechanism with delayed rotation around the quarter-chord axis can be made simple by a passive rotation mechanism (similar to ornithopter flight).[59] Leading towards 3D flapping wing kinematic advancements, research done by Sun et al.[26] shows that a dragonfly's 3D flapping wing has a significant effect on lift coefficient's reduction as compared to its 2D flapping airfoil counterpart.

Leading edge vortices are common and important to flapping wing aerodynamics at extremely low Reynolds number, which corresponds to the hummingbird and insect flight regimes.[29] Inspired by insect's and hummingbird's flight,[68] the research done by Rakotomamonjy et al.[66] states that a MAV will supposedly fly at very low forward speeds when it is not hovering. An interesting research has been done by Phan et al.,[64] where a fabricated beetle's flapping wing system has achieved stable vertical takeoff by implementing inherent pitching stability, achieved by center-of-gravity and aerodynamic center alignment.

Another interesting research has been done by Fujikawa et al.,[65] where a small flapping robot has been fabricated from the inspiration of a butterfly's flight. A butterfly's flight is actually quite similar to an ornithopter's flight, as the fore- and hind-wings are attached together, forming only a pair or wings. The major difference is that the abdomen of butterflies moves in an anti-phase manner with its flapping wing motion to gain better aerodynamic performance.

2.3. Contribution of flapping wing towards aerodynamic performance

In this section, the contribution of both ornithopter and insect flapping wing kinematics toward lift, thrust, and drag force generations are reviewed and summarized separately in Tables 1 and 2, due to the large gap between the range of magnitude of the respective forces generated by ornithopters and insects, which is not suitable to be compared directly.

According to Tables 1 and 2, the contribution towards drag reduction seems limited, but not entirely neglected. It is due to the fact that thrust generation is directly related to drag generation, just in the opposite direction. The magnitude of thrust force generated is equivalent to the resistance projected by the rigid frame, which holds the flapping wing model in place, towards the advancement of the model by the thrust force generated. This is an experimental approach example which describes the inseparable relationship between generated thrust and drag forces, which most researchers decided to simplify their analysis by presenting their results solely on generated lift and thrust forces, where generated drag force can be obtained by means of thrust references. The summary on the contribution of ornithopter's flapping wing kinematics towards generated lift, thrust, and drag forces shows that the number of researches done for all three force generations are well-balanced. However, for insects, the summary suggests that most researches are focused on the generated lift force, which is logical, in the attempt to fully understand the hovering mechanism of these figure-of-eight masters.

2.4. Membrane wing structures

In this section, the membrane wing structures for both, ornithopters and insects are reviewed separately in order to differentiate the type of research conducted for ornithopters and insects, respectively. The contributions of membrane wing structures toward lift, thrust, and drag force generations are also reviewed, later in this section.

2.4.1. Ornithopter

Ornithopter-type MAV depends on its flexible membrane wing structure to initiate passive wing rotation to produce required aerodynamic forces, such as lift and thrust, for hovering and forward flight.[49] In order to produce high performance membrane wing structures, aerodynamic-featured wing profile needs to be inherent in the design of the membrane wing.[47] Studies on optimal airfoil are presented by Unger et al.[30] and Srinath and Mittal,[34] where the former investigated the propulsion efficiency of a light and flexible airfoil based on a

Table 1 Contributions of ornithopter's flapping wing kinematics.

Force	Ref.	Adopted model	Motion	Contribution
Lift	7	Gen. bird	Flapping	Lift force is almost independent of flapping frequency for low flapping frequency
	42		Pitching, flapping, pitch-flap	Lift force is dominantly produced by pitching motion
	44		Flapping	Moderate increase of AOA is advantageous to average lifting force production
	50		Flapping	Lift augmentations due to flapping motion were found to decrease exponentially as advance ratio increases
Thrust/propulsive efficiency	7	Gen. bird	Flapping	The average thrust value increases with respect to flapping frequency
	8		Flapping	Thrust and power increase with increasing flapping frequency
	41		Flapping	Increasing frequency will result in more thrust coefficient (higher wing torsional stiffness)
	42		Pitching, flapping pitch-flap	Thrust force is dominated by flapping motion
	44		Flapping	Moderate increase of AOA is advantageous to average thrust force production
	50		Flapping	Thrust generated due to flapping motion would decrease monotonically with increasing orientation angle
	58	Flap. airfoil	Flapping	Propulsion velocity increases with both flapping frequency and amplitude
Drag	32	Flap. airfoil	Flapping	If flow is subjected to drag forces, it will have friction wake shape downstream of body
	42	Gen. bird	Pitching, flapping pitch-flap	Drag force is dominated by flapping motion

'hand-foil' of a seagull on the flexibility features inherent in the airfoil design.

The use of a flexible membrane allows the wing to passively change its relative angles of attack and camber during flapping.[42] Ashraf et al.[31] did a systematic evaluation on the effects of varying thickness and camber of a thrust producing, harmonically pure plunging and combined pitching and plunging NACA airfoil on its propulsion performance. Both Heathcote et al.[46] and Hu et al.[50] did a research on wings with varied flexibility to investigate the contribution and aerodynamic performance of each wing. As concluded, a wing with medium flexibility was found to have the best aerodynamic performance for soaring flight but proved to be the worst for flapping flight, which implies the importance of choosing the right membrane flexibility for specific application.

Bats have been one of the most studied subjects in the field of membrane wing research. Bat-inspired researches have been conducted by a number of researchers,[36–39] where they investigated the effect of trailing-edge scalloping on aerodynamic coefficients, studied on low aspect ratio rectangular membrane wing, focused on deformation and oscillation of a pre-strained compliant membrane, and worked on the effects of membrane pre-strain and excess length on the unsteady aspects of fluid–structure interaction, respectively.

2.4.2. Insect

As compared to ornithopter's membrane wing structures, insects have unique membrane wing characteristics, especially regarding its wing profile. Termed 'corrugated' wing profile, this unique corrugated feature of an insect's membrane wing has been reviewed by Lian et al.[28] and has been studied by Levy and Seifert[56] and Meng et al.[70] Agreed by all of them, the corrugated wing profile provides no significant aerodynamic advantages. Instead, it provides superior structural performance.

In the attempt to fully understand an insect's membrane wing structure, a study by Orlowski and Girard,[71] which is then reviewed by Orlowski and Girard,[58] points out the importance of including the mass effects of the wings when accounting for stability, as it can have a significant effect on the position and orientation of a fabricated insect-inspired flapping wing MAV. A review on earlier researches by Shyy et al.[29] has shown that membrane wing structures undergoing flapping motion can interact with leading-edge-vortices (LEV) by adjusting the projected wing area normal to flight direction under acceptable aero-elastic considerations, resulting in redistribution and enhancement of lift and thrust.

A research on producing optimal airfoil shapes for insect flight wing profile has been conducted by Srinath and Mittal[34] by maximizing lift, minimizing drag, and thus minimizing drag-to-lift ratio. Another research has been conducted by Fujikawa et al.,[65] which was inspired by a butterfly's flight. A butterfly presents a new set of challenges, where its flight consists of combined wing-flapping and abdomen-shifting movements, in a simultaneous action where the abdomen of a butterfly will shift in an anti-phase manner with the flapping stroke of its wings.

Table 3 presents summarized details on the materials used to fabricate membrane wing structures of ornithopter- and insect-type flapping wing models. Note that the information presented in Table 3 is a brief summary based on solid, recorded details from its respective research papers, and does

Table 2 Contribution of insect's flapping wing kinematics.

Force	Ref.	Adopted model	Motion	Contribution
Lift	28	Dragonfly	Pitch-plunge	Tandem wing with flapping fore and stationary hind wing is the best at minimizing variation of forces encountered while maximizing lift generated in increasing oscillations
	29	Bee, dragonfly, fly, hum-bird, hawkmoth, locust, wasp	Clap-fling	Wing tip vortices can contribute to lift generation rather than just drag on the wing during hover under unsteady flow
	33	Flap. airfoil	Inclined figure-of-eight	Inclined figure-of-eight allows for the contribution of lift force in vertical lift resulting in more efficient upstrokes
	35		Pitching	Amplitude of oscillation and reduced frequency do not have a noticeable effect on lift curve slopes
	55	Bee	Inclined figure-of-eight	Ratio of body drag of insect to its weight is equal to ratio of horizontal thrust coefficient to vertical lift coefficient
	65	Butterfly	Flapping	Unsteady and 3D vortices are the main factor in generating lift
	26	Dragonfly	Realistic horizontal figure-of-eight (azimuthal-pitching rotation)	Approximately 35% of total vertical force is contributed by lift force of wings; lift coefficient for 3D wing is approximately 20% less than its 2D airfoil counterpart
	63	Hoverfly	Inclined figure-of-eight	Approximately 51% of vertical force is contributed by drag force
Thrust/ propulsive efficiency	23,28	Dragonfly	Pitch-plunge	Hind-wing sees phase shift in thrust generation when flapping with 90°/180° phase lag
	29	Bee, dragonfly, fly, hum-bird, hawkmoth, locust, wasp	Clap-fling	Within suitable range of spanwise flexibility, effective AOA and thrust forces of plunging wing are enhanced due to wing deformations
	26	Dragonfly	Realistic horizontal figure-of-eight (azimuthal-pitching rotation)	Tandem wings interaction effect reduces thrust required to hover on fore- and hind-wings by 14% and 16%, respectively, as compared to single wing configuration
	63	Hoverfly	Inclined figure-of-eight	Major thrust force (86%) is produced during downstroke, in comparison with upstroke
Drag	33	Flap. airfoil	Inclined figure-of-eight	Quoted that inclined figure-of-eight patterns have substantial drag forces, which contribute to required hovering force
	35		Pitching	Min. drag coefficient is not affected substantially by investigated parameters except at high oscillation amplitudes and high Reynolds numbers
	26	Dragonfly	Realistic horizontal figure-of-eight (azimuthal-pitching rotation)	Use drag force as a major source to support dragonfly's weight when hovering with large stroke plane angle (approximately 65% of total vertical force)
	63	Hoverfly	Inclined figure-of-eight	Approximately 49% of vertical force is contributed by lift force

not represent a full and complete analysis on membrane wing structures. Data analyses and comparisons regarding membrane materials from Shyy et al.[29] review will not be elaborated again here. Details can be obtained from the authors' respective review paper.

2.5. Contribution of membrane wing towards aerodynamic performance

In this section, the contribution of both ornithopter and insect membrane wing structures toward lift, thrust, and drag force generations are reviewed and summarized separately in Tables 4 and 5, due to the differences in wing profile between ornithopters and insects, which are not suitable to be compared directly.

According to the summary on ornithopters in Table 4, generated thrust and drag forces have an inseparable relationship where drag force is the opposite projection of thrust force, which explains the limited references provided for direct drag reduction contribution. It also shows that researches conducted on the contributions of ornithopter's flapping wing kinematics and membrane wing structures towards generated lift, thrust, and drag forces are equally important. In Table 5, it is clearly shown that researches on insect's membrane wing structures are not dominant compared to insect's flapping wing kinematics studies. The focus was on the design of the wing's corrugated profile.[28,56,70] The aerodynamic advantages provided by the membrane wing structures of an insect are assumed minimal as compared to the advantages provided by its flapping wing kinematics (in hovering and forward flight), which is why the membrane wing of an insect is commonly assumed as a rigid flat plate with sharp leading- and trailing-edge. Therefore, researchers have turned their focus on investigating the increasingly popular of insect flapping wing kinematics.

2.6. Research approaches

There are two types of research approaches: experimental and numerical approaches. In this section, the research approaches

Table 3 Detail on membrane materials.

Type	Ref.	Adopted model	Material	Young's modulus E	Thickness
Ornithopter	7	Gen. bird	Nylon	4.0 GPa	50 μm
	8		Nylon	4.0 GPa	0.05 mm
	30	Flap. airfoil	Plain weave glass, unidirectional carbon	1.0, 0.9, 0.8 (relative to reference value)	1.0, 0.9, 0.8 (relative to reference value)
	31				6%–50% of 2D NACA symmetric airfoils
	34				12.00%, 5.4%, 2.4%, 2.3% (thickness-to-chord ratio)
	36	Bat	Latex	1.36 MPa	0.102 mm
	37		Latex	2.2 MPa	0.2 mm
	38		Latex	0.9 MPa	
	37		Latex	2.2 MPa	0.2 mm
	40		Polycarbonate coated polypropylene		
	41	Gen. bird	Mylar		
	42				
	44		Ethylene		0.3 mm
	46		Nylon, PDMS rubber	5 GPa, 250 kPa	
	50		Wood, nylon, latex	2800:15:1 (ratio)	200, 70, 120 μm
Insect	17,28,72	Dragonfly	Isotropic material (chitin)	6.1 GPa	1%–6% (of 1 cm chord length)
	34	Flap. airfoil			12.00%, 5.4%, 2.4%, 2.3% (thickness-to-chord ratio)
	56	Dragonfly			5.5% (of chord length)
	58	Hawkmoth, locust, bee, fly			
	65	Butterfly	Plastic wrap		
	62	Hoverfly			3.0% (of chord length)
	71	Gen. insect			3.0% (of chord length)

Table 4 Contributions of ornithopter's membrane wing structures.

Force	Ref.	Adopted model	Material	Contribution
Lift	34	Flap. airfoil		*
	36	Bat	Latex	**
	38	Bat	Latex	***
	50	Gen. bird	Wood, nylon, latex	****
Thrust/propulsive efficiency	30	Flap. airfoil	Plain weave glass, unidirectional carbon	*****
	31			******
	41	Gen. bird	Mylar	*******
	46		Nylon, PDMS rubber	********
	50		Wood, nylon, latex	*********
Drag	34	Flap. airfoil		**********
	36	Bat	Latex	***********

Notes:
* Excess lift is due to large peak, extended region of high suction on upper surface, high pressure on lower surface.
** Flow-induced vibration of membrane cells increases lift coefficient of the wing.
*** At low *Re*, lift coefficient increases monotonically with angle of attack.
**** Wood wing has better lift compared to nylon and latex wings in flapping flight until in deeply unsteady regime.
***** With aid of temporal adaptive stiffness, improvement of propulsive efficiency could be noticed.
****** Cambered airfoil offers little to no benefit over symmetric airfoils in terms of time averaged thrust coefficient and propulsive efficiency.
******* Peak propulsive efficiencies increases with increasing wing torsional stiffness and flapping frequencies.
******** A limited degree of flexibility was observed to be greatly beneficial.
********* Latex wing has the best thrust generation performance for flapping flight.
********** Minimization of drag results in an airfoil with a sharp leading edge.
*********** Scalloping the trailing-edge of the wing decreases the drag coefficient to a greater extent than the lift coefficient.

Table 5 Contributions of insect's membrane wing structures.

Force	Ref.	Adopted model	Material	Contribution
Lift	34	Flap. airfoil		*
	62	Hoverfly		**
	70	Gen. insect		***
Thrust/propulsive efficiency	29	Bee, dragonfly, fly, hum-bird, hawkmoth, locust, wasp	Ref.[29]	****
	62	Hoverfly		*****
	70	Gen. insect		******
Drag	34	Flap. airfoil		*******
	56	Dragonfly		********
	62	Hoverfly		*********
	70	Gen. insect		**********

Notes:
* Excess lift is due to large peak, extended region of high suction on upper surface and high pressure on lower surface.
** Lift produced by deformable wing is larger than rigid wing by 10%, difference in lift is mainly caused by camber deformation.
*** Wing corrugation decreases mean lift by less than 5%.
**** Thrust of teardrop element; effective AOA decreases with increasing rear foil's flexibility. Within certain range, thrust increases with increasing chordwise flexibility due to increased projected area.
***** Propulsion required to maintain hover condition is based on aerodynamic power; deformable wing requires 5% less power compared to rigid wing.
****** Propulsion required to maintain hover condition is based on aerodynamic power, wing corrugation has almost no effect on required power.
******* Minimization of drag results in an airfoil with a sharp leading edge.
******** Geometric variations which reduce vortices' amplitude will reduce drag values.
********* Effect of wing deformation increases drag force by approximately 4% (mainly due to camber deformation).
********** Wing corrugation has almost no effect on mean drag.

taken for ornithopter- and insect-type flight investigations are reviewed in order to observe the pattern of approaches frequently adopted to investigate each flight type.

2.6.1. Experimental approach

A summarized experimental research approaches towards the development of ornithopter- and insect-inspired MAVs as shown in Tables 6 and 7. Flight mode, wing planform, wingspan/AR, *Re*/velocity, *k*/*St* (Reynolds number, *Re*, reduced frequency, *k*, and Strouhal number, *St*) and focus have been listed for easy reference.

2.6.2. Numerical approach

A summarized numerical research approach towards the development of ornithopter- and insect-inspired MAVs is as shown in Tables 8 and 9. Flight mode, aerodynamic model, structural model, FSI related, and CFD software used by the authors have been listed for easy reference.

According to Tables 6–9, similar to previous analyses on flapping wing kinematics and membrane wing structures, both experimental and numerical research approaches toward ornithopter flight investigations are well-balanced. However, for insect flight investigations, numerical research approach is dominant over experimental research approach. This confirms the assumption of the inability to fabricate a reliable insect-type flapping wing prototype for experimental investigations, due to high mechanical complexities and very small size limitations. Therefore, a large number of numerical researches need to be conducted in order to gain better understanding of insect's flapping wing flight before a reliable prototype can be fabricated. In addition, numerical research approach is less likely to be costly and time-consuming.

2.7. Flapping wing mechanisms

Under this section, the types of mechanical flapping systems adopted in designing an effective propulsion configuration for a flapping wing prototype fabrication are briefly reviewed. The latest flapping wing technologies are divided into two main categories: motorized transmission wings and piezoelectric transmission wings, which will be elaborated in separate sub-sections as shown below.

2.7.1. Motorized transmission wings

An effective mechanical flapping system is important in order to produce sufficient lift and thrust forces required for flying a flapping wing MAV. The term motorized refers to the dependence of a motor to supply the necessary driving force to perform flapping wing motion. For an ornithopter-type flapping wing flight, a simple four-bar crank rocker mechanism is commonly used to transform the rotational motion of an electric motor into a harmonic flapping motion.[7,8,41,45,50] A typical four-bar crank rocker mechanism is shown in Fig. 1.[7]

When concerning a smaller size ornithopter,[43,44] or an insect with ornithopter-like flapping wing kinematics, such as a butterfly,[65] a smaller and more compact mechanical flapping system configuration than a four-bar crank rocker mechanism is required. Therefore, a slider crank is introduced, as shown in Fig. 2.[60]

An effort on producing an effective mechanical flapping system for an insect flapping wing kinematics, typically a dragonfly, has been done, termed 'modified slider crank' (MSC), which utilizes a rotary actuator to simultaneously generate active rotation and flapping of its wings.[55] This amazing innovation can be seen in Fig. 3.[54]

Table 6 Ornithopter's summarized experimental research approaches.

Ref.	Flight mode	Wing planform	Wingspan/ AR	*Re*/ velocity	*k*	Focus	Test method	Specification
7	Forward	Semi-elliptical	80 cm	6–12 m/s		Flight performance	Wind tunnel	*
8	Hover	Semi-elliptical	80 cm	10^4 to 5×10^4	0.54–0.64	Chord-wise flexibility	In lab	**
36	Forward	Rectangular (normal and scalloped)	5	6–12 m/s		Scallop performance	Wind tunnel	***
37	Forward	Rectangular	2	5–10 m/s		Flow-induced vibrations	Wind tunnel	****
39	Forward	Rectangular	450 mm	5–10 m/s		Membrane pre-strain and excess length	Wind tunnel	****
40	Forward	Moth-like	30.5 cm	11 m/s		Multi-purpose MAV	On field	*****
41	Forward and hover	Semi-elliptical	100 cm	2–8 m/s	0.7–4.0	Propulsion	In lab	******
44	Forward	Rectangular	15 cm	16733	0.1–0.3	Design and flight analysis	On field	*****
45	Forward	Semi-elliptical	10–36 cm	6232.19–21538.46		MAV size comparison	On field	*******
46	Forward	Rectangular	300 mm	30000	1.82	Span-wise flexibility	PIV incorporated water tunnel	********
50	Forward	Elliptical	36.8 cm	1–10 m/s		Membrane flexibility	Wind tunnel	*********

Notes:
* Large, closed-loop, low-speed, open test section wind tunnel.
** Test bed with rig consists of flapping mechanism powered by low inertia DC motor.
*** Closed-loop, low-speed, closed rectangular test section with high resolution, 3-component external balance (force-balance testing).
**** Closed-loop, low-speed, open-jet wind tunnel with circular working section.
***** Strictly design and performance testing.
****** Test stand with incorporated capability force measurement and data acquisition, high-precision load sensor, tachometer.
******* Design and performance testing.
******** Closed-loop, free-surface, rectangular test section water tunnel with LDV system, horizontal shaker, binocular strain gauge force balance, high shutter speed digital video camera, TSI PIV system.
********* Low-speed, open jet test section wind tunnel with high-sensitive force-moment sensor cell.

Table 7 Insect's summarized experimental research approaches.

Ref.	Flight mode	Wing planform	Wingspan/ AR	*Re*/ velocity	Focus	Test method	Specification
55	Hover	Tapered	9 cm		Steering mechanism	In lab	*
64	Vertical	Elliptical	125 mm	10 cm/s	Inherent pitching stability	On field	**
65	Forward and vertical	Butterfly-like	120 mm		Motion analysis during takeoff	In lab and on field	***
63	Hover	Actual hoverfly's wing	6.93–9.70 mm	240–330	Wing kinematic and aerodynamic analyses	In lab	****

Notes:
* Strictly design and performance testing.
** Design and performance testing with high-speed camera clarification.
*** Design and performance testing with high-speed camera picture reference.
**** Hover flight observation of actual hoverflies done in enclosed flight chamber using three orthogonally aligned synchronized high-speed cameras.

2.7.2. Piezoelectric transmission wings

As the demands on even smaller MAV rose, the fabrication process needs to be reconsidered and redesigned to accommodate all of the essential mechanisms into a very small body frame. It is undeniable that the motor mounted onto the MAV contributes the most weight and the vibration caused by the motor could be a possible factor of instability during flight.

Therefore, researchers need to find a better alternative solution in order to realize the fabrication of pico-aerial-vehicle (PAV). One of the most creative breakthroughs is the direct application of piezoelectric material substituting the heaviest and crucial part of an MAV, the motor itself. From here-on-after, the piezoelectric material used to produce flapping wing mechanism will be termed piezoelectric transmission.

As compared to motorized transmission, piezoelectric transmission generates an electrical field due to the chemical reaction that took place when external mechanical forces are applied onto the piezoelectric materials. Piezoelectric materials consist of specific solid materials such as crystals or ceramics

Table 8 Ornithopter's summarized numerical research approaches.

Ref.	Test subject	Structure	Flight mode	*Re*	Numerical technique	Mesh type	Node/element	Turbulence model	FSI
30	SG04 airfoil	2D, flexible	Forward	10^5	URANS	Block-structured grid, five-stage multi-grid, ALE and GCL solved	6917/6996	*	Yes
31	Symmetric and cambered NACA airfoils	2D, rigid	Forward	200, 2000, 20000, 2×10^6	Navier–Stokes, UPM	Structured grid, sliding grid, fixed and moving mesh	901×101 grid points	**	No
32	NACA 0014 airfoil	2D, rigid	Forward	10000 20000 30000	Navier–Stokes	UDF, structured grid, dynamic mesh layering and conformal mesh	16300 quadrilateral cells, 5056 triangular cells	***	No
34	Airfoil parameterized via 4th order NURBS curve	2D, rigid	Forward	10^4	Navier–Stokes	Structured and unstructured mesh via Delaunay triangulation, mesh moving scheme	46730 nodes, 93156 triangular elements	****	No
38	Pre-strained compliant membrane airfoil	2D, flexible	Forward	38416, 141500	Navier–Stokes	Uniform and non-uniform structured mesh	77044 cells for low *Re*, 86060 cells for high *Re*	*****	Yes
44	Planar membrane NACA 2412 wing	3D, rigid, rectangular	Forward	27942	Navier–Stokes	C-type grid, non-constructive grid	854090 grid points	******	No

Notes:
* Cell-centered scheme, convective fluxes are treated with 2nd order-accurate central differencing scheme with scalar dissipation, BSL is used on single grid basis.
** Re = 200–2000 is assumed laminar; Re = 20000 is treated with laminar assumption and SA; $Re = 2\times10^6$ is treated with SA; flow field is simulated using unsteady incompressible solver with 2nd-order upwind spatial discretization.
*** No turbulence model was employed due to auto-propelled-airfoil-influenced flow field; full implicit coupling is obtained from implicit discretization of pressure gradient terms in momentum equations and mass flux on cell faces.
**** Stabilized FEM based on SUPG/PSPG stabilizations, L-BFGS algorithm is used as optimizer.
***** For low Re, flow is assumed laminar, performed with high relaxation factor values, based on PISO algorithm, for high Re, k-ω model was employed, performed with low relaxation factor values, based on SIMPLE algorithm, both PISO and SIMPLE velocity discretizations are based on 2nd-order upwind scheme.
****** PRESTO was employed for pressure terms, SIMPLE was employed for speed-pressure field coupling, 2nd order implicit algorithm was employed for time accuracy.

which accumulates electrical charges when there is a form of mechanical force applied to them. Vice versa, when an electrical field is applied, the piezoelectric materials will deform, producing effective displacement of about 0.1%. The deformation of the piezoelectric materials is called piezoelectric effect.

The effective displacement of utilizing "raw" piezoelectric materials will have limited capabilities and are not practical for most manufacturing application due to its minimal displacement percentage. Therefore, other than the application of "direct" and "parallel pre-stressed" actuators, the displacement percentage can be amplified up to 1% or even more by taking advantage of the expansion of the piezoelectric materials (horizontal deformation) and the displacement amplifier mechanism (such as a resonant builder device). At resonance frequency, the implementation of piezoelectric materials as a substitution to conventional motor for flapping wing MAV applications can maximize the overall flapping angle as shown in Fig. 4.[73]

The extensive uses of piezoelectric materials are limitless due to its robust deformation. Lee et al. mounted a flexible piezoelectric actuator underneath the wings of his ornithopter-type MAV to gain camber control during flapping flight. When an electrical field is fed, the actuator will deform and control the camber of the wings with its deformation (see Fig. 5).[74]

Applications toward insect bio-mimicry have advanced tremendously to a very small size termed PAV. At this very small "state", the contribution of individual parts towards overall weight is very crucial due to minimal payload and for a typical MAV, the motor will surely contribute the most weight. Therefore, replacing the motorized transmission with piezoelectric transmission is a beneficial modification at which not only the overall weight can be significantly reduced, but also the implementation of piezoelectric transmission can eliminate the need for sophisticated gears which reduces the power efficiency and accuracy of the motor as it transfers from one gear to another.

With the gears gone, the size of the body (the casing to cover the gear system) can be reduced as well, making the overall design of an MAV less bulky, achieve better aerodynamics, and achieve even smaller fabrication scale which suits the term pico (an even smaller scale than nano-aerial-vehicle (NAV)). Mateti et al. designed and fabricated a PAV termed LionFly which utilizes piezoelectric transmission wings with built-in flexure hinges to replace the need for gears and promote pas-

Table 9 Insect's summarized numerical research approaches.

Ref.	Test subject	Structure	Flight mode	*Re*	Numerical technique	Mesh type	Node/element	Turbulence model	FSI
33	Thin ellipsoidal airfoil	2D, rigid	Hover	37.5, 75, 150	Navier–Stokes	O-type grid	8800 cells within 1st layer	*	No
34	Airfoil parameterized via 4th order NURBS curve	2D, rigid	Forward	10^4	Navier–Stokes	Structured mesh, unstructured mesh via Delaunay triangulation, mesh moving scheme	46730 nodes, 93156 triangular elements	**	No
35	NACA 0012 airfoil	2D, rigid	Hover	555–5000	Navier–Stokes	O-type grid	26000 cells	***	No
56	Geometric variations of simplified dragonfly airfoil	2D, rigid, corrugated	Forward	6000	Navier–Stokes	C-type grid, structured mesh and unstructured mesh (triangular)	64000 points		No
65	Convex wing	3D, flexible, rectangular	Forward and vertical		Navier–Stokes	FEM, unstructured grids, high spatial accuracy, hexahedron element	500000 nodes	****	No
26	Realistic dragonfly's fore- and hind-wings	3D, rigid, rectangular	Hover	1350	Navier–Stokes	Moving overset grids, O-H type grid for wings, Cartesian grid for background, employed domain connectivity functions	$29 \times 77 \times 45$ wing grid points, $90 \times 72 \times 46$ background grid points	*****	No
60	Realistic bumble-bee's wing	3D, rigid, rectangular-like (rounded leading edge, LE/trailing edge, TE)	Hover	1326	Navier–Stokes	O-H type grid	$71 \times 73 \times 96$ grid points	******	No
61	Realistic hoverfly's wing	3D, rigid, rectangular-like (rounded LE/TE)	Hover		Navier–Stokes	O-H type grid	$93 \times 109 \times 78$ grid points	*******	No
62	Simplified hoverfly's wing	3D, flexible, rectangular-like (rounded LE/TE)	Hover	800	Navier–Stokes	Dynamically deforming grid	$109 \times 90 \times 120$ grid points		No
71	Variations of corrugated insect wings	3D, rigid, corrugated	Hover	35–3400	Navier–Stokes	O-H type grid, moving grid system	$70 \times 110 \times 70$ grid points for corrugated wings, $86 \times 99 \times 114$ grid points for flat-plate wing	********	No
63	Simplified hoverfly's wing	3D, rigid, rectangular-like (rounded LE/TE)	Hover	240–330	Navier–Stokes	O-H type grid, moving grid system	$100 \times 99 \times 130$ grid points	********	No

Notes:
* 2nd order central differencing scheme for convective and diffusive terms, 2nd order Euler implicit scheme for temporal discretizations, resulting linear system of equations is treated with PCG solver, SIMPLE algorithm is used for pressure–velocity coupling.
** Stabilized FEM based on SUPG/PSPG stabilizations, L-BFGS algorithm is used as optimizer.
*** Convective and diffusive terms are discretized based on 2nd order central differencing scheme, transient terms are based on 1st order Euler implicit scheme, resulting linear system of equations is treated with PCG solver, P-V coupling was obtained using PISO algorithm.
**** ALE method was used for wing boundary movement, SMAC method was adopted for fast computation, SUPG method was employed to stabilize computation, Galerkin method was employed.
***** Employed 2nd order, three-point backward difference for time derivatives. Introduced pseudo-time elements to solve time discretized momentum and continuity equations. Employed 2nd order central differences for viscous fluxes. Employed upwind differencing based on flux-difference splitting technique for convective fluxes. Employed 3rd order upwind difference at interior points and 2nd order upwind differencing at points next to boundaries.
****** Utilized fluid velocity components and pressure at discretized grid points for each time step to obtain pressure and viscous stress on wing/body surface.
******* Similar to Sun and Xiong[60] with different test subject.
******** Similar to Sun and Lan[26] with different test subject.

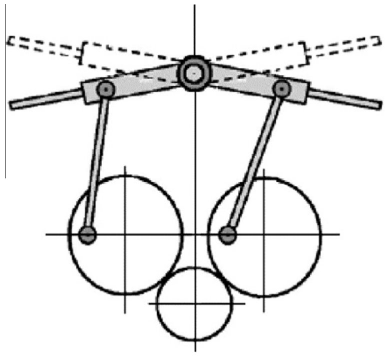


Fig. 1 Typical four-bar crank rocker mechanism.[7]

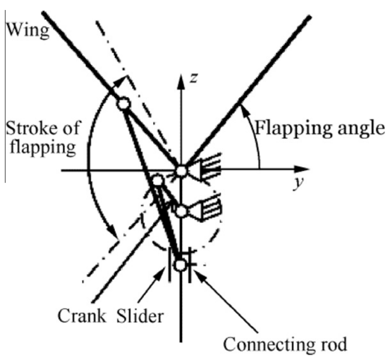


Fig. 2 Slider crank mechanism.[60]

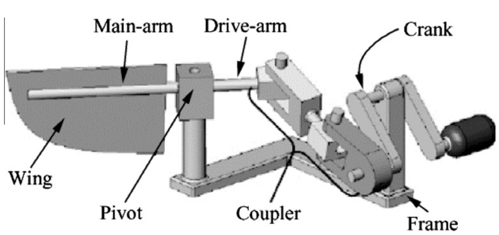


Fig. 3 Modified slider crank mechanism.[54]

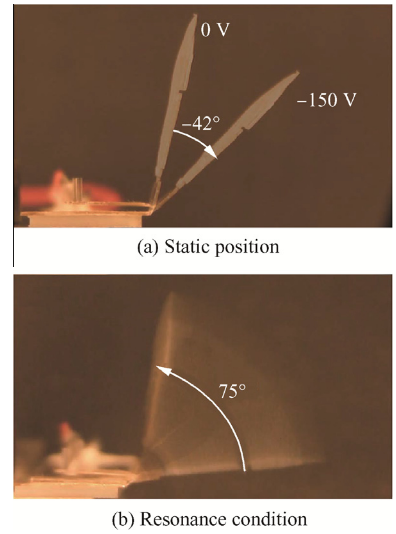


Fig. 4 Wing motion at static position and resonance condition (75 V, 45 Hz).[73]

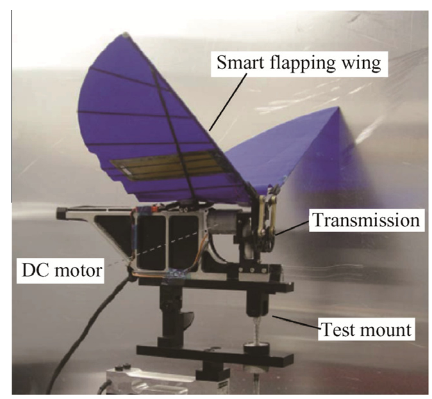


Fig. 5 Application of flexible piezoelectric actuator for camber control.[74]

sive wing rotation as shown in Figs. 6 and 7.[73,75] A previous research by Sreetharan and Wood has seen the same concept but with different designs as shown in Fig. 8.[76] Research on materials used to fabricate wings that are mounted onto the piezoelectric transmission has also been conducted by Tanaka et al. as shown in Fig. 9.[77]

Later on, the application of piezoelectric materials was implemented as an alternative flapping wing transmission system for the tandem configuration flapping wing unmanned aerial vehicles as well. Kumar and Hu[78] conducted an experimental research on the tandem piezoelectric flapping wings to investigate the wake flow characteristics of such flapping wing configuration based on a series of preliminary works related to tandem piezoelectric flapping wings' flow structures.[79,81]

Most importantly, piezoelectric materials was introduced into the field of flapping wing unmanned aerial vehicles smaller than MAV (NAV/PAV) as a new form of transmission in order to replace previously developed motorized transmission which contributes too much weight, consumes a lot of space, rigorously vibrates if mounted on smaller scale unmanned vehicles, and presents high fabrication complexity due to gear mechanisms. The simplicity of implementing piezoelectric transmission as compared to motorized transmission can even be observed physically without detailing each individual, functional part. Fig. 10 shows the physically observable simplicity of piezoelectric transmission compared to motorized transmission.

From the comparison shown in Figs. 6, 7 and 10, it has been proven that a motorized transmission flapping wing system is too bulky to be mounted on a tiny bio-mimicry body frame and the smallest motor available and easily obtained from local distributors is the pager motor, which overloads the tiny body frame in more ways than one. The advantages of utilizing a piezoelectric transmission can be divided into two categories; direct advantages and supporting advantages. The direct advantages are small, light, simple arrangement, simple to operate, superb accuracy, and no gears are needed. Furthermore, the secondary advantages are directly related to the fact that small size unmanned aerial vehicles will have small wings with small aspect ratios and are subjected to com-

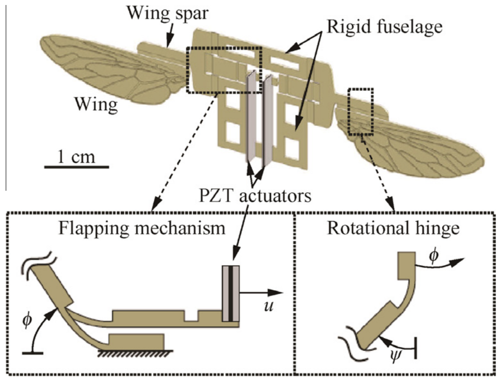


Fig. 6 Conceptual drawing of LionFly.[75]

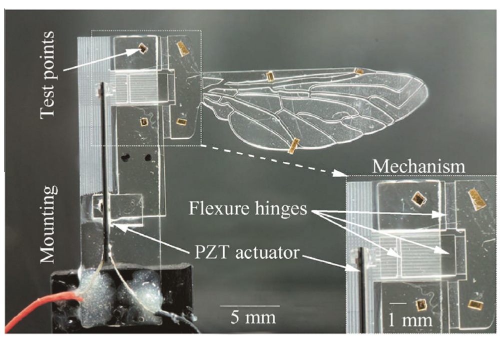


Fig. 7 Photograph of LionFly prototype LF07.[73]

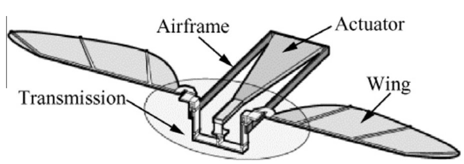


Fig. 8 Insect-type flapping wing MAV design.[76]

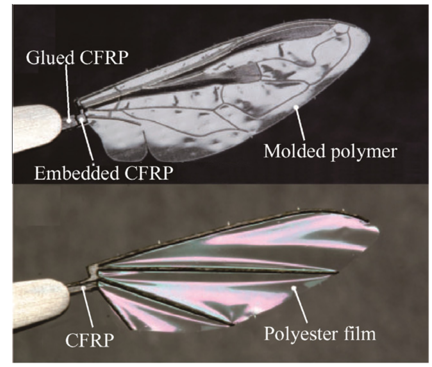


Fig. 9 Photos of fabricated corrugated wings (CFRP = carbon fiber reinforced polymer).[77]

plex, unsteady, and low Reynolds number flow field. Therefore, high wing flapping frequency is required to produce enough lift and thrust forces for flapping flight, which piezoelectric transmissions can definitely deliver.[82] This technology has yet to be fully applied on a larger scale such as to an MAV. With all the advantages overshadowing the disadvantages, it is not impossible to take advantage of this technology and redefine the core of MAV technology where payload limitation will be lifted and the transition-Reynolds-regime duelers such as small ornithopters and large insects (MAV based on hummingbirds are barely revealed to the public and little research data are known) can be realized with an efficient pair of transition-flow field-manipulating wings. The comparisons between motorized and piezoelectric transmission wings are essential in order to discretize the advantages and disadvantages of each transmission before designing a blueprint.

Motorized transmission wings are mostly used for large to medium-size UAVs (MAVs are subjected to 15 cm wingspan length limitation), bulky (the conventional motor adds up a lot of the total mass of the MAV), and noisy. Furthermore, more gears/mechanical parts need to be considered to tune the torque power/frequency as the torque/frequency is non-tunable. By using motorized transmission wings, an MAV will be able to propel heavier wing load (therefore, higher inertial effects) but will be unable to operate at Nano-precision. The wings are typically made from non-conductive materials carbon fiber.

Piezoelectric transmission wings are applied for nano- to pico-scale UAV (existed because of space and size limitations; deforms/bends and stretches to produce flapping motion of attached wings), does not require a motor, and less noisy (detectable noise only at high frequency). Furthermore, no gears are required (only the piezoelectric material and the wing structure are required, which the wing structure can be from the same material as the piezoelectric material) and torque/frequency is tunable due to adjustable electrical current input. By using piezoelectric transmission wings, an MAV will be able to effectively propel small scale wings with Nano-precision (such as insect wings due to small aspect ratio, light, thin, and low inertial effects). On the other hand, if the wings are made with the same material as the piezoelectric material, they might be exposed to electrical surge and durability against harsh weather is questionable (heat/cold/sandy).

2.8. Significant difference in flapping wing flow patterns

According to the research references reviewed, the utilization of vortices occurring on either the leading edge (LE) or trailing edge (TE) have been tremendously leaning towards insect-inspired researches. It is well understood that ornithopters does not significantly utilize LE and TE vortices as the vortices decay (the occurrence of vortex-shedding) at the wake of the ornithopters' flapping wings. Furthermore, wing tip vortices have a more significant effect towards ornithopter-type flapping wing motion as portrayed by Tsai and Fu[44] and Fujikawa et al.[65]; the latter proves that butterflies (ornithopter-like flapping wing motion), with elastic membrane wings, generate effective separation vortices and utilize those wing tip vortices to produce large lift. Fig. 11 below shows examples of wing tip velocity vector[44] and pressure contour[65] diagrams.

The LE and TE vortices do not significantly affect aerodynamic forces produced by ornithopter's flight as much as they do towards insect's flight due to a lot of criteria; insects flap its wings multiple times faster than ornithopters and it has the ability to achieve motionless hover (flapping motion is almost

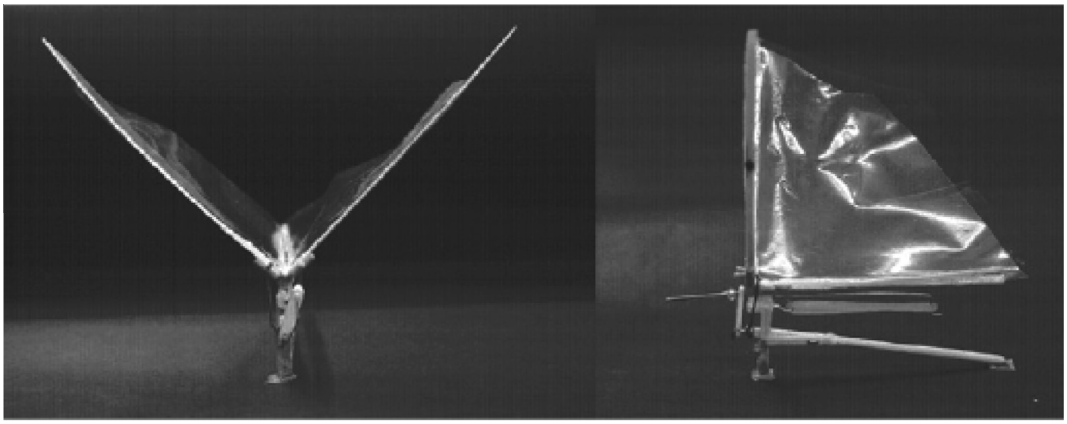
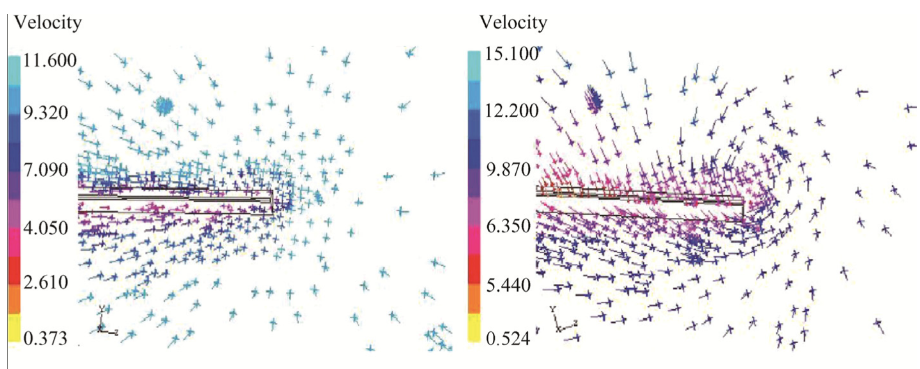
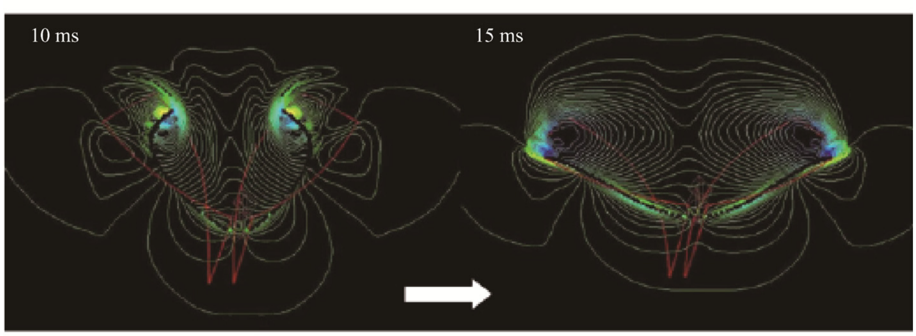


Fig. 10 Physical observation of motorized transmission wings.



(a) Velocity vector



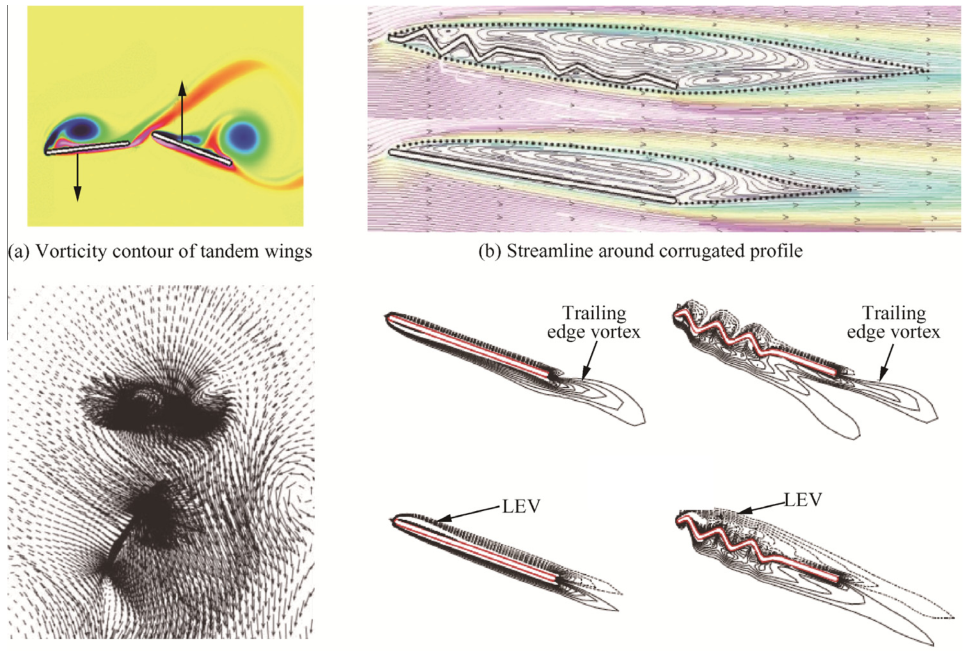
(b) Pressure contour

Fig. 11 Velocity vector[44] and pressure contour[65] during downstroke.

fully horizontal) with large angles of incidence,[26,62,70] insects have a unique corrugated wing profile,[28,70] and dragonflies even have tandem wing configuration to promote wing-wing (fore- and hind-wings)[26,28] and vortex-vortex (constructive or destructive)[26] interactions. Therefore, insects take better advantage of utilizing LE and TE vortices to produce aerodynamic forces than ornithopters. Lian et al.[28] have done a very thorough review on the characterization of tandem and corrugated wings and Shyy et al.[29] have systematically summarized recent progress in flapping wing aerodynamics and aeroelasticity, which will not be explained in this review paper as details of their researches can be obtained from their original review papers, respectively. Fig. 12 below shows examples of flow patterns and vortex structures of corrugated and tandem wing configuration.

2.9. Other important aspects

There are other important aspects or parameters which have to be considered in the research field of flapping wing MAV. These 'dimensionless' parameters are the fundamentals of MAV research, in which these dimensionless parameters define the relevance of the termed 'micro' and the application of such small 'aerial vehicles' under low influence of wind speed. These dimensionless parameters are Reynolds number, Re, reduced frequency, k, and Strouhal number, St.



(a) Vorticity contour of tandem wings (b) Streamline around corrugated profile

(c) Velocity vector of tandem wings (d) Vorticity plots of corrugated model wing

Fig. 12 Vorticity contour of tandem wings,[27] streamline around corrugated profile,[27] velocity vector of tandem wings[81] and vorticity plots of corrugated model wing.[85]

Re is the most important dimensionless parameters which defines and differentiates the flow field regime of which an aerial vehicle will have to fly through and effectively manipulate the flow field characteristics to produce constructive aerodynamic forces in order to keep it afloat and maintain flying performance. Inspired by natural fliers (birds and insects), a flapping wing MAV can effectively manipulate the low *Re* flow field in its environment to its advantage by generating lift, thrust, and drag forces to sustain its flight state, whether for hovering of forward flight. Natural fliers are experts in high-speed maneuvers under very low *Re* condition. As reported by Park and Yoon,[45] large birds have a wing chord *Re* larger than 15000 but still within 1×10^5 range, small birds to large insects having *Re* between 1000 and 15000, and small insects having *Re* between 100 and 1000. Fig. 13 shows a plotted Reynolds number versus wing length graph.[45]

A benchmark can be summarized to point out the obvious line of differences and possible intersection and interaction between species (birds/bird-like and insects/insect-like) and its respective flight type (ornithopter, ornithopter-like, insect, and insect-like). These differences in species-flight type swapping can be significant in narrowing the specific needs of a research based on proven facts and figures of previous researches. As seen in Table 10, guidelines are made for flight type, wing kinematics, and Reynolds number for each respective species, which suggest a significant relationship between the size of a species and the wing kinematics it adopts to be able to fly within specific Reynolds number regime.

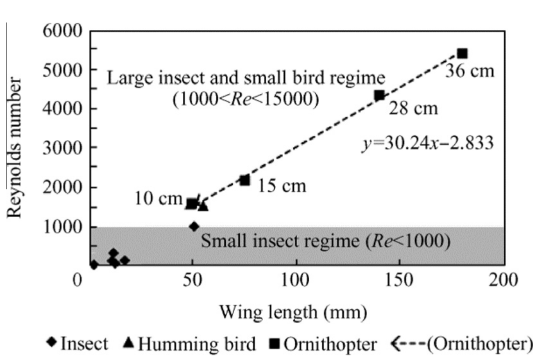


Fig. 13 Reynolds number vs wing length.[45]

As seen in Table 10, the Reynolds number approximation is in good agreement with Park's report. The intersection area where ornithopter's and insect's species and flight type swapped falls within the "small birds to large insects" Reynolds number regime. This indicates that large insects might have had adopted specific ornithopter-like flight characteristics to enable them to fly within the "transition-dominated" Reynolds number regime.

Each research should be classified as detailed as possible. For example, to create a large size insect-type flapping wing MAV, one must understand that the wing aerodynamics of the MAV should be able to withstand the air flow characteristics presented by the Reynolds number regime it flies in by utilizing its complex 3 DOF wing kinematics. Vice versa, to create a small size ornithopter-type flapping wing MAV, one must be able to anticipate the unsteady air flow characteristics and to utilize those characteristics to the MAV's advantages; the latter proves to be much more difficult to accomplish using a 2 DOF wing kinematics, with the third DOF limited to the capability of the MAV's wing to passively rotate its flexible membrane structure.

Therefore, as summarized in Table 8, a hypothesis can be made, that the insect flight type and insects with ornithopter-like flight type can withstand unsteady air flow characteristics

Table 10 Summarized guidelines.

Type	Species	Flight type	Wing kinematics	Re approximation	Ref.
Ornithopter	Pterosaur	Ornithopter	Generic (2 DOF)	Birds (Re > 6628)	42
	Magpie				52
	Bat				36–40
	Hummingbird	Insect-like	Complex (3 DOF)	Small birds-large insects	29,66,67
Insect	Hawkmoth	Ornithopter-like	Generic (2 DOF)	($1412 \leqslant Re \leqslant 6628$)	29,58
	Bee	Insect	Complex (3 DOF)		29,58–60
	Butterfly	Ornithopter-like	Generic (2 DOF)	Small insects (Re < 1412)	65
	Beetle	Insect	Complex (3 DOF)		64
	Dragonfly				26,28,29,55,56
	Locust				29,58
	Hoverfly				61–63,70
	Wasp				29
	Fly				29,58

and achieve better flight performance within Reynolds number range of 1000–15000 as compared to small birds (small size ornithopter flight type MAV). Therefore, in order to survive, small birds possesses insect-like flight type with 3 DOF wing kinematics for better flight efficiencies, as demonstrated by the flight of hummingbirds.[29,66,67] Details regarding Re analysis and comparison presented in this review are brief and only serve as a simple reference. Further analysis and in-depth details are required to properly address the importance of Re, thus, future works are necessary.

Reduced frequency is also an important dimensionless parameter which characterizes the unsteadiness of flapping motions caused by a complicated mix of periodic pitching, plunging, and surging (horizontal motion).[28] Smaller birds tend to have higher reduced frequencies and fly under more unsteady flow conditions than larger birds due to higher flapping rate/lower flight velocity.[83]

Further explained by Lian et al.,[28] the Strouhal number, which is another important dimensionless parameter, is often used as a measure of flight efficiency. As cited from Taylor et al.,[84] the Strouhal number of 42 different species of bats, birds, and insects in cruise flight fell within a narrow range between 0.2 and 0.4, which indicates that the Strouhal number can be used as a guideline for flapping wing design efficiency optimizations. Therefore, reduced frequency and Strouhal number, as well as Reynolds number, have proven to be an important set of dimensionless parameters and are worth of future reviews.

3. Critical issues

Micro-aerial-vehicle researches are still ongoing and rapidly growing. As research extends towards new ground, issues will definitely be addressed in parallel with the depth of the research. Issues which are deemed critical and require further research are listed as follows:

(1) Most of the researches conducted for ornithopter- and insect-type flapping wing MAV, either experimental or numerical, consider the wings to be an isolated case, where the influence of the flapping wing motion towards other parts of the MAV's body and vice versa, are neglected for calculation simplicity. Multi-body dynamics are addressed in a limited number of research papers such as by Grauer et al.[11] and Pfeiffer et al.,[52] which require further investigations for better understanding of its nature.

(2) Most researches neglect the mass of the wings in which the consideration of wing's mass could significantly affect the stability, orientation, aerodynamic performance, and flight trajectory of an MAV.[58]

(3) Inherent stability during flight is still an issue. Most MAVs use complex control systems and actuations to maintain its stability in mid-air, which require multiple expertise and high expenses. More researches on inherent stability such as by Phan et al.[64] are needed.

(4) Research on transition flight, such as from hover mode to forward flight mode, from rest mode to flight mode (take-off), from flight mode to rest mode (landing), or from walking mode to flight mode and vice versa, is currently limited as well. Bachmann et al.[40] and Shin et al.[85] did design MAVs capable of transition flight but none of them applied flapping wing system.

(5) Limited research is available on small scale ornithopter-type MAVs. Research is either focused on standard/large sized ornithopter-type MAVs or insect-type MAVs. A magpie-inspired flapping wing MAV has been conducted by Pfeiffer et al.[52] More research is needed to support future development.

(6) Research on MAV endurance towards harsh environments is limited to gust environment only.[27,28] Limited or no research has been conducted for endurance testing towards other types of harsh environments such as rain, snow, or even sandstorm.

(7) Breakthrough piezoelectric application discoveries are limited to Nano- and Pico-scale unmanned vehicles due to size minimization demands.[73,75] Utilization of piezoelectric transmission on MAVs is yet to be fully understood as researches on the particular application, such as a research done by Sreetharan and Wood,[76] are limited.

(8) FSI implementations are also limited. The current number of research done using FSI approach is still insufficient for us to truly understand the nature of coupled software.

4. Recommendations

Research on the development of MAV has been conducted for a very long time but there is still a lot of room available for improvements. Recommendations to overcome the stated issues in Section 2.8 and other additional recommendations for future development of MAV are as listed below:

(1) Multi-body dynamics research needs to grow as it is important to consider every part of an MAV in determining a more accurate stability and aerodynamic performance analyses.
(2) Similar to multi-body dynamics research, future MAV research should include the mass of the wings in determining a more accurate stability, orientation, aerodynamic performance, and flight trajectory of a MAV. Thus, future research is still in need of multi-body dynamics and wings' mass related analyses.
(3) Inherent stability is also a wide open research area. Research regarding inherent stability during flight is very important in order to simplify the flapping wing system, minimize expertise required to design and fabricate an MAV, and reduces fabrication cost.
(4) Room for improvements are also available for MAV innovations such as multi-purpose micro-aerial-land-vehicle (MALV)[40] and wall-climbing MAV.[85]
(5) Future research on small scale ornithopter-type MAVs is very important in order to satisfy size limitation without sacrificing the simplicity of an ornithopter's flapping wing mechanism and aerodynamic characteristics.
(6) The endurance of a MAV should be further tested in different harsh environments such as rain, snow, and even sandstorm in order to produce an all-weather MAV.
(7) FSI is also a potential research area because it is a newly adopted methodology. Using FSI approach, the effects of airflow towards wing structure can be simultaneously quantified with the effects of wing structure towards airflow characteristics.
(8) Future research is also open for further development of a control scheme inspired by human memory and learning concept for wing motion control of MAVs such as by Song et al.[67]
(9) Adopting piezoelectric transmission system could significantly reduce the overall weight of a typical motorized transmission MAV and presents a very simple piezoelectric effect mechanism which does not require complex geared automations while saving up storage space. Therefore, the required lift and thrust forces of such MAV to counteract its own weight in order to hover and fly forward will be reduced desirably. In addition, the extra payload and storage capacities available will enable multiple mounts of better performing devices such as high-definition cameras and sensors.
(10) A three-dimensional mechanism may be extended further to provide a more accurate quantitative experimental flapping data to gain further understanding of avian flight.[80]
(11) The investigation of the flow analysis of the flapping wing can be performed by particle image velocimetry (PIV) techniques technology.[86]
(12) A more powerful computer is required given that the flapping wing must be developed in a fine mesh to avoid lower memory problem and obtain accurate results.[86]

5. Conclusions

A review on flapping wing micro-aerial-vehicle of both ornithopter- and insect type flapping wing flights has been conducted. The contribution ornithopter- and insect-type flapping wing kinematics and membrane wing structures have been summarized and presented systematically in table form. General guidelines have been presented as well to aid in narrowing the scope of research and to determine specific approaches. As a conclusion from the guidelines, a possible scope for future MAV development has been determined. Issues of which previous researchers have come upon have been listed for future reference and await further improvements. All in all, this review paper provides a new set of references which can be beneficial for literature reviews of future researches.

Acknowledgments

The authors wish to thank all contributing researchers for their enthusiastic effort in realizing the potential of bio-mimicry in unmanned aerial vehicles' development of all sizes and all the feedbacks given to support the production of this review, as recognized in the figures and tables.

References

1. Collis SS, Joslin RD, Seifert A, Theofilis V. Issues in active flow control: theory, control, simulation, and experiment. *Prog Aerosp Sci* 2004;**40**(4):237–89.
2. Strang KA. Efficient flapping flight of pterosaurs [dissertation]. Stanford: Stanford University; 2009.
3. Jackowski ZJ. Design & construction of an autonomous ornithopter [dissertation]. MA: Massachusetts Institute of Technology; 2009.
4. Bunget G. *BATMAV a bio-inspired micro-aerial vehicle for flapping flight* [dissertation]. NC: North Carolina State University; 2010.
5. Bansmer S, Radespiel R, Unger R, Haupt M, Horst P. Experimental and numerical fluid–structure analysis of rigid and flexible flapping airfoils. *AIAA J* 2010;**48**(9):1959–74.
6. Gomes JP, Yigit S, Lienhart H, Schaefer M. Experimental and numerical study on a laminar fluid–structure interaction reference test case. *J Fluids Struct* 2011;**27**(1):43–61.
7. Mazaheri K, Ebrahimi A. Experimental investigation on aerodynamic performance of a flapping wing vehicle in forward flight. *J Fluids Struct* 2011;**27**(4):586–95.
8. Mazaheri K, Ebrahimi A. Experimental investigation of the effect of chordwise flexibility on the aerodynamics of flapping wings in hovering flight. *J Fluids Struct* 2010;**26**(4):544–58.
9. Mazaheri K, Ebrahimi A. Optimization of the cruise flight dynamics of a flapping wing vehicle based on experimental aerodynamic data. *J Aerosp Eng ASCE* 2012;**25**(1):101–7.
10. Li Y, Nahon M. Modeling and simulation of nonlinear dynamics of flapping wing MAV. *AIAA J* 2011;**49**(5):969–81.
11. Grauer Jr JA, Hubbard JE. Multibody model of an ornithopter. *J Guid, Control, Dynam* 2009;**32**(5):1675–9.
12. Grauer Jr JA, Hubbard JE. Inertial measurements from flight data of a flapping-wing ornithopter. *J Guid, Control, Dynam* 2009;**32**(1):326–31.

13. De Croon GCHE, de Clerq KME, Ruijsink R, Remes B, de Wagter C. Design, aerodynamics, and vision-based control of the DelFly. *Int J Micro Air Veh* 2009;**1**(2):71–97.
14. Nagai H, Isogai K, Fujimoto T, Hayase T. Experimental and numerical study of forward flight aerodynamics of insect flapping wing. *AIAA J* 2009;**47**(3):730–42.
15. Liu H, Aono H. Size effects on insect hovering aerodynamics: an integrated computational study. *Bioinsp Biomim* 2009;**4**(1):015002-1–0150021-3.
16. Zhang YL, Wu JH, Sun M. Lateral dynamic flight stability of hovering insects: theory vs numerical simulation. *Acta Mech Sin* 2012;**28**(1):221–31.
17. Hord K, Lian Y. Numerical investigation of the aerodynamic and structural characteristics of a corrugated airfoil. *J Aircr* 2012;**49**(3):749–57.
18. Kim WK, Ko JH, Park HC, Byun D. Effects of corrugation of the dragonfly wing on gliding performance. *J Theoret Biol* 2009;**260**(4):523–30.
19. Levy DE, Seifert A. Simplified dragonfly airfoil aerodynamics at Reynolds numbers lowers than 8000. *J Phys Fluid* 2009;**21**(7):071901-1–071901-17.
20. Levy DE. Flow features of a schematic dragonfly airfoil at glid [dissertation]. Tel-Aviv: Tel-Aviv University; 2010.
21. Murphy J, Hu H. An experimental investigation on a bio-inspired corrugated airfoil. Report No.: AIAA-2009-1087. Reston: AIAA; 2009.
22. Broering T, Lian Y. The effect of phase angle and wing spacing on tandem flapping wings. *Acta Mech Sin* 2012;**28**(6):1557–71.
23. Broering T, Lian Y, Henshaw W. Numerical investigation of energy extraction in a tandem flapping wing configuration. *AIAA J* 2012;**50**(11):2295–308.
24. Zhang G. Unsteady aerodynamics of a morphing tandem wing UAV. *J Aircr* 2012;**49**(5):1315–23.
25. English TG, Simpson JR, Landman D, Parker PA. An efficient split-plot approach for modeling nonlinear aerodynamic effects. *Qual Eng* 2012;**24**(4):522–30.
26. Sun M, Lan SL. A computational study of the aerodynamic forces and power requirements of dragonfly (*Aeschna juncea*) hovering. *J Exp Biol* 2004;**207**(11):1887–901.
27. Prater R, Lian Y. Aerodynamic response of stationary and flapping wings in oscillatory low Reynolds number flows. Report No.: AIAA-2012-0418. Reston: AIAA; 2012.
28. Lian Y, Broering T, Hord K, Prater R. The characterization of tandem and corrugated wings. *Prog Aerosp Sci* 2013;**65**(1):41–69.
29. Shyy W, Aono H, Chimakurthi SK, Trizila P, Kang CK, Cesnik CES, et al. Recent progress in flapping wing aerodynamics and aeroelasticity. *Prog Aerosp Sci* 2010;**46**(7):284–327.
30. Unger R, Haupt MC, Horst P, Radespiel R. Fluid–structure analysis of a flexible flapping airfoil at low Reynolds number flow. *J Fluids Struct* 2012;**28**(1):72–88.
31. Ashraf MA, Young J, Lai JCS. Reynolds number, thickness and camber effects on flapping airfoil propulsion. *J Fluids Struct* 2011;**27**(2):145–60.
32. Benkherouf T, Mekadem M, Oualli H, Hanchi S, Keirsbulck L, Labraga L. Efficiency of an auto-propelled flapping airfoil. *J Fluids Struct* 2011;**27**(4):552–66.
33. Amiralaei MR, Alighanbari H, Hashemi SM. Flow field characteristics study of a flapping airfoil using computational fluid dynamics. *J Fluids Struct* 2011;**27**(7):1068–85.
34. Srinath DN, Mittal S. Optimal aerodynamic design of airfoils in unsteady viscous flows. *Comp Meth Appl Mech Eng* 2010;**199**(29):1976–91.
35. Amiralaei MR, Alighanbari H, Hashemi SM. An investigation into the effects of unsteady parameters on the aerodynamics of a low Reynolds number pitching airfoil. *J Fluids Struct* 2010;**26**(6):979–93.
36. Hubner JP, Hicks T. Trailing-edge scalloping effect on flat-plate membrane wing performance. *Aerosp Sci Technol* 2011;**15**(8):670–80.
37. Rojratsirikul P, Genc MS, Wang Z, Gursul I. Flow-induced vibrations of low aspect ratio rectangular membrane wings. *J Fluids Struct* 2011;**27**(8):1296–309.
38. Molki M, Breuer K. Oscillatory motions of a prestrained compliant membrane caused by fluid–membrane interaction. *J Fluids Struct* 2010;**26**(3):339–58.
39. Rojratsirikul P, Wang Z, Gursul I. Effect of pre-strain and excess length on unsteady fluid–structure interactions of membrane airfoils. *J Fluids Struct* 2010;**26**(3):359–76.
40. Bachmann RJ, Boria FJ, Vaidyanathan R, Ifju PG, Quinn RD. A biologically inspired micro-vehicle capable of aerial and terrestrial locomotion. *Mech Mach Theory* 2009;**44**(3):513–26.
41. Pourtakdoust SH, Aliabadi SK. Evaluation of flapping wing propulsion based on a new experimentally validated aeroelastic model. *Sci Iran, Trans B: Mech Eng* 2012;**19**(3):472–82.
42. Djojodihardjo H, Ramli ASS, Wiriadidjaja S. Kinematic and aerodynamic modelling of flapping wing ornithopter. *Proc Eng* 2012;**50**(1):848–63.
43. Lee JS, Kim JK, Han JH, Ellington CP. Periodic tail motion linked to wing motion affects the longitudinal stability of ornithopter flight. *J Bion Eng* 2012;**9**(1):18–28.
44. Tsai BJ, Fu YC. Design and aerodynamic analysis of a flapping-wing micro aerial vehicle. *Aerosp Sci Technol* 2009;**13**(7):383–92.
45. Park JH, Yoon KJ. Designing a biomimetic ornithopter capable of sustained and controlled flight. *J Bion Eng* 2008;**5**(1):39–47.
46. Heathcote S, Wang Z, Gursul I. Effect of spanwise flexibility on flapping wing propulsion. *J Fluids Struct* 2008;**24**(2):183–99.
47. Perez-Rosado A, Philipps A, Barnett E, Roberts L, Gupta SK, Bruck HA. *Compliant multifunctional wing structures for flapping wing MAVs*. The Society for Experimental Mechanics, Inc.; 2014.
48. Gerdes JW, Cellon KC, Bruck HA, Gupta SK. Characterization of the mechanics of compliant wing designs for flapping-wing miniature air vehicles. *Exp Mech* 2013;**53**(9):1561–71.
49. Whitney JP, Wood RJ. Aeromechanics of passive rotation in flapping flight. *J Fluid Mech* 2010;**660**(1):197–220.
50. Hu H, Kumar AG, Abate G, Albertani R. An experimental investigation on the aerodynamic performances of flexible membrane wings in flapping flight. *Aerosp Sci Technol* 2010;**14**(8):575–86.
51. Kim SW, Jang LH, Kim MH, Kim JS. Power-driven ornithopter piloted by remote controller. United States patent US 6550716 B1.2003.
52. Pfeiffer AT, Lee JS, Han JH, Baier H. Ornithopter flight simulation based on flexible multi-body dynamics. *J Bion Eng* 2010;**7**(1):102–11.
53. Su JY, Yang JT. Analysis of the aerodynamic force in an eye-stabilized flapping flyer. *Bioinspir Biomim* 2013;**8**(4):1–8.
54. DeLaurier JD. An aerodynamic model for flapping wing flight. *Aeronaut J R Aeronaut Soc* 1993;**97**(964):125–30.
55. Fenelon MAA, Furukawa T. Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator. *Mech Mach Theory* 2010;**45**(2):137–46.
56. Levy DE, Seifert A. Parameter study of simplified dragonfly airfoil geometry at Reynolds number of 6000. *J Theoret Biol* 2010;**266**(4):691–702.
57. Hamamoto M, Kotani T, Nakano I, Ohta Y, Hara K, Murakami T, Hisada T. Investigation on force transmission of direct-drive thorax unit with four ultrasonic motors for a flapping micro aerial vehicle. *Adv Robot* 2014;**28**(3):133–44.
58. Orlowski CT, Girard AR. Dynamics, stability, and control analyses of flapping wing micro-air vehicles. *Prog Aerosp Sci* 2012;**51**(1):18–30.

59. Nguyen TT, Byun D. Two-dimensional aerodynamic models of insect flight for robotic flapping wing mechanisms of maximum efficiency. *J Bion Eng* 2008;**5**(1):1–11.
60. Sun M, Xiong Y. Dynamic flight stability of a hovering bumblebee. *J Exp Biol* 2005;**208**(3):447–59.
61. Sun M, Wang JK. Flight stabilization control of a hovering model insect. *J Exp Biol* 2007;**210**(15):2714–22.
62. Du G, Sun M. Effects of wing deformation on aerodynamic forces in hovering hoverflies. *J Exp Biol* 2010;**213**(13):2273–83.
63. Mou XL, Liu YP, Sun M. Wing motion measurement and aerodynamics of hovering true hoverflies. *J Exp Biol* 2011;**214**(17):2832–44.
64. Phan HV, Nguyen QV, Truong QT, Truong TV, Park HC, Goo NS, et al. Stable vertical takeoff of an insect-mimicking flapping-wing system without guide implementing inherent pitching stability. *J Bion Eng* 2012;**9**(4):391–401.
65. Fujikawa T, Hirakawa K, Okuma S, Udagawa T, Nakano S, Kikuchi K. Development of a small flapping robot Motion analysis during takeoff by numerical simulation and experiment. *Mech Syst Sig Process* 2008;**22**(6):1304–15.
66. Rakotomamonjy T, Ouladsine M, Moing TL. Longitudinal modeling and control of a flapping-wing micro aerial vehicle. *Control Eng Pract* 2010;**18**(7):679–90.
67. Song YD, Weng L, Lebby G. Human memory/learning inspired control method for flapping-wing micro air vehicles. *J Bion Eng* 2010;**7**(2):127–33.
68. Chang K, Rue J, Ifju P, Haftka R, Schmitz T, Tyler C, et al. *Analysis of thrust production in small synthetic flapping wings*. The Society for Experimental Mechanics, Inc.; 2014.
69. Mahjoubi H, Byl K. Efficient flight control via mechanical impedance manipulation: energy analyses for hummingbird-inspired MAVs. *J Intell Robot Syst* 2014;**73**(1):487–512.
70. Meng XG, Xu L, Sun M. Aerodynamic effects of corrugation in flapping insect wings in hovering flight. *J Exp Biol* 2011;**214**(3):432–44.
71. Orlowski CT, Girard AR. Modeling and simulation of nonlinear dynamics of flapping wing micro air vehicles. *AIAA J* 2011;**49**(5):969–81.
72. Kesel AB, Philippi U, Nachtigall W. Biomechanical aspects of the insect wing: an analysis using the finite element method. *Comp Biol Med* 1998;**28**(4):423–37.
73. Mateti K, Byrne-Dugan RA, Rahn CD, Tadigadapa SA. Monolithic SUEX flapping wing mechanisms for pico air vehicle applications. *J Microelectromech Syst* 2013;**22**(3):527–35.
74. Lee JS, Han JH, Kim DK. Camber-adjustable flapping wing air vehicles. *8th international conference on ubiquitous robots and ambient intelligence (URAI)*; 2011.
75. Mateti K, Byrne-Dugan RA, Rahn CD, Tadigadapa A. Wing rotation and lift in SUEX flapping wing mechanisms. *Smart Mater Struct* 2013;**22**(1):1–11.
76. Sreetharan PS, Wood RJ. Passive torque regulation in an underactuated flapping wing robotic insect. *Auton Robots* 2011;**31**(2):225–34.
77. Tanaka H, Whitney JP, Wood RJ. Effect of flexural and torsional wing flexibility on lift generation in hoverfly flight. *Integ Comp Biol* 2011;**51**(1):142–50.
78. Kumar AG, Hu H. An experimental investigation on the wake flow characteristics of tandem flapping wings. *6th AIAA theoretical fluid mechanics conference*. Reston: AIAA; 2011.
79. Clemons L, Igarashi H, Hu H. An experimental study of unsteady vortex structures in the wake of a piezoelectric flapping wing. *48th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*. Reston: AIAA; 2010.
80. Wang K, Vaidya U, Ganapathysubramanian B, Hu H. Experimental data analysis of the vortex structures in the wakes of flapping wings. *28th AIAA applied aerodynamics conference*. Reston: AIAA; 2010.
81. Kumar AG, Hu H. Flow structures in the wakes of tandem piezoelectric flapping wings. *28th AIAA applied aerodynamics conference*. Reston: AIAA; 2010.
82. Bidakhvidi MA, Shirzadeh R, Steenackers G, Vanlanduit S. Experimental study of the flow field induced by a resonating piezoelectric flapping wing. *Exp Fluids* 2013;**54**(11):327–35.
83. Shyy W, Berg M, Ljungqvist D. Flapping and flexible wings for biological and micro air vehicles. *Prog Aerosp Sci* 1999;**35**(5):455–505.
84. Taylor GK, Nudds RL, Thomas ALR. Flying and swimming animals cruise at a Strouhal number tuned for high power efficiency. *Nature* 2003;**425**(6959):707–11.
85. Shin JU, Kim D, Kim JH, Myung H. Micro aerial vehicle type wall-climbing robot mechanism*IEEE RO-MAN: the 22nd IEEE international symposium on robot and human interactive communication*. Piscataway (NJ): IEEE Press; 2013.
86. Yusoff H. Experimental and numerical investigations on the performance of flexible skin flapping wing for micro aerial vehicle application [dissertation]. Penang: Universiti Sains Malaysia; 2013.

Kamarul Arifin Bin Ahmad is an associate professor and Ph.D. supervisor at the Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), Malaysia. He received his Ph.D. degree from Queen's University of Belfast in 2006. His main research interests are aerodynamics and computational fluid dynamics (CFD).