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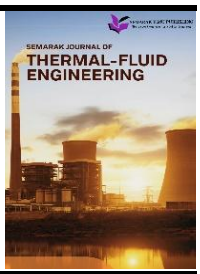

Bioinspired of Natural Flyers: Flapping-Wing Micro-Aerial-Vehicle

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ABSTRACT

Nature creatures like birds and insects can fly during harsh weather with significantly diversified superficial structures on their bodies. The innovation of bioinspired designs through biomimicry has been implemented to improve modelling and simulation of real-life birds and insects to attain a better understanding of the wing's critical features, kinematic motion, and its aerodynamic behaviour, thus development a much realistic Flapping-Wing Micro-Aerial-Vehicle. This paper reviews a part of previous MAV research developments which are of significant novelty and contribution from small birds to big insects, within the transition Reynolds number regimes. Findings suggest that limited work has been done. Limited experimental research has been done compared to numerical research for the insect-like MAV due to replication difficulties of high flapping frequencies and complex miniature prototypes.

1. Introduction

FWMAVs have been extensively studied in recent years, and they have the potential to greatly improve capabilities in areas such as environmental monitoring, surveillance, and military and security operations [1-3]. As technology continues to advance, Micro Aerial Vehicles (MAVs) are developing quickly and becoming increasingly versatile. Their compact size makes them well-suited for use in areas with limited accessibility or harsh environments. They are highly agile, difficult to detect, and are expected to be cost-effective to produce. Additionally, MAVs have the ability to carry heavier payloads, maintain stability, and have longer endurance [4].

Military drones are commonly used for reconnaissance and tracking enemies in areas where they may be hiding, but are unable to camouflage themselves from detection by anti-drone systems. MAVs, on the other hand, are useful in emergency situations such as search and rescue missions during natural disasters like floods, earthquakes, and landslides due to their speed, safety, and reliability. Both military and civilian applications rely heavily on the aircraft's ability to operate effectively in windy conditions. However, research on the effect of wind gusts on the aerodynamic

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performance of flapping wing micro air vehicles has been limited, with most studies conducted using two-dimensional models. Additionally, there has been little research on the response of flapping wings to lateral gusts [5].

MAVs, whether they have fixed-wing, rotary-wing, or flapping-wing, are more susceptible to wind disturbances than natural flying creatures such as birds and insects. They also have lower payload capacity and are less able to maintain stability and fly during rainy and windy weather. Birds and insects are able to fly during harsh weather conditions due to the diverse structural features on their bodies [4,6,7]. FWMAV have the potential to be more maneuverable and efficient than conventional fixed-wing flights, particularly in the dynamic range of Reynolds numbers between 1 to 10^4, which is suitable for small-sized MAVs [8]. The development of FWMAVs requires extensive research to address the mechanical complexity, limited components, battery sizes, weight requirements for flight operation, and aerodynamic effects under different conditions. In addition to solving problems specific to FWMAVs, this research and development can also contribute to other related fields [9].

2. Overview of Micro Aerial Vehicles

Hassanalian and Abdessattar [3] have proposed a new classification system for drones that combines existing systems and provides a more comprehensive categorization. MAVs, which fall under this classification, typically have a length of 15 cm to 100 cm, weight between 50 g and 2 kg, and are able to fly at low speeds. These vehicles have a wide range of uses, such as monitoring hazardous areas, identifying specific targets, and mapping an area. Mwongera [4] proposed a categorization of MAVs into three types: flapping wing, fixed-wing, and rotary-wing, as shown in Figure 1.

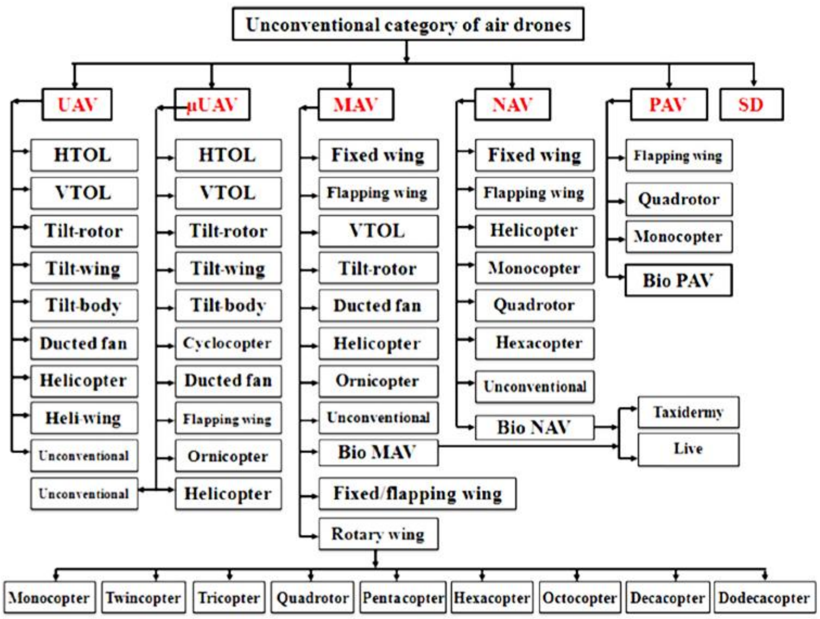

Fig. 1. Different types of air drones [3]

2.1 Flapping Wing MAV

As technology continues to advance and unmanned air vehicles become smaller, flapping wing flight is being re-evaluated as a bio-inspired alternative to traditional fixed-wing and rotary-wing flight. This is because flapping flight combines the functions of lifting, hovering, and propulsion, making it capable of long-distance flight with less energy and greater maneuverability [10-12]. FWMAVs have gained attention due to several reasons, such as their bio-inspired design, low noise levels, reduced harm on human contact, and alternative propulsion system that enables better efficiency and agility for low Reynolds number flight conditions [5,13].

Engels *et al.,* [10] and Mwongera [4] have noted that FWMAVs are better suited for indoor operations than rotary-wing MAVs due to their ability to fly quietly, reducing their detectability and making them more suitable for close-quarters monitoring. Yang *et al.,* [14] have demonstrated that the flapping wing motion generates a counter-clockwise vortex above the trailing edge and a clockwise vortex below the trailing edge, which results in forward thrust and lift. Bomphrey and Ramiro [15] have outlined that one of the most notable features of generating aerodynamic force through periodic flapping motion is that it is largely determined by the physics of separated flows and vortex dynamics. This includes the avoidance of stall through an integrated leading-edge vortex (LEV) and the enhancement of lift through the clap-and-fling interaction of wings [15].

2.2 Fixed Wing MAV

Mwongera [4] has noted that this type of MAV was primarily designed for outdoor surveillance, such as monitoring city streets and alleys, and is unable to hover or take off and land on short runways. Additionally, they have a low operating speed and limited collision avoidance capabilities. Yang *et al.,* [14] has noted that typical fixed-wing aircraft generate clockwise vortices above the trailing edge and counter-clockwise vortices below the trailing edge, resulting in backward thrust and drag.

2.3 Rotary Wing MAV

Rotary wing MAVs have the capability to perch, which allows them to conserve energy while still completing their mission. They can also be designed to be small in size, with a lower payload capacity but longer endurance [4]. Xin *et al.,* [16] designed a new FWR-MAV (Flapping-Wing Rotary Micro Aerial Vehicle) with a weight of 32 grams, a flapping frequency of 20 Hz, and three flapping wings made of carbon fiber composite wing beams and polyethylene membranes that can rotate freely around the center while flapping, as illustrated in Figure 2. The FWR-MAV comprises of three parts: the lift-producing system, the attitude control mechanism, and the avionic system.

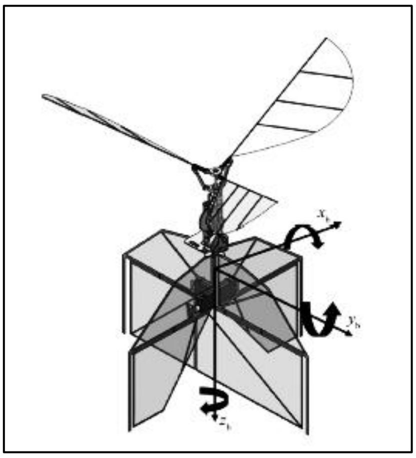

Fig. 2. A novel flapping wing rotary MAVs invented by Dong *et al.,* [16]

3. Biomimicry of Natural Flyers

3.1 Ornithopter-Liked MAV

Birds, bats, and insects are among the most skilled and remarkable flying creatures, possessing extraordinary flight abilities that have allowed them to survive in their environment for over 150 million years as a result of natural selection and evolution [7,17,18]. Birds and flying insects have exhibited exceptional flight performance due to the superior aerodynamic efficiency of their flapping wings at low Reynolds numbers [16]. Studies have found that larger wings can provide more lift and that long, narrow wings can perform long-distance gliding. The structure of feathers and wing morphology, particularly the airfoil shape, plays a significant role in generating lift and thus in the outstanding flight performance of these creatures. Therefore, the biomimetic model of the airfoil is crucial in the aerodynamic performance of FWMAV [19].

According to Geissler and Wall, it is well-known that the wings of birds and insects have flexible components that can bend in both the spanwise and chordwise directions [20]. Shyy *et al.,* [21] have noted that the high degree of flexibility of animal wings leads to dynamic fluid-structure interactions and that the flapping kinematics and complex maneuvers of natural flyers result in strongly interconnected nonlinearities in fluid mechanics, aeroelasticity, flight dynamics, and control systems. Mwongera [4] has studied how natural fliers use flexible wings to create high lift-coefficient surfaces that allow for longer glide durations.

Shyy *et al.,* [1] have also noted that natural flyers are able to fly at a wide range of speeds and altitudes because they can produce enough lift by increasing their wing speed relative to the air and changing their effective angle of attack. As the size of the flyer decreases, the Reynolds number and the ratio of wing to body mass also decrease, but the flapping frequency increases. Many small fliers with low wing-to-body mass ratios, such as hummingbirds and insects (with the exception of butterflies), have much faster flapping time scales than their body's reaction time scales, as noted by Shyy *et al.,* [1] (Figure 3). MAVs come in different sizes and shapes, and research on the aerodynamic properties of flapping wings is limited. Compared to the flight of birds, insects, and bats, the artificial flapping wing is less efficient. Traditional aerodynamics, which primarily focuses on fixed-wing and rotary-wing flight patterns, has difficulties in explaining the flapping wing's high lift mechanism, as pointed out by Zhao *et al.,* [19].

Xinyu *et al.,* [22] have stated that bio-inspired kinematics such as the cambered owl-like airfoil, can improve lift during the downstroke, resulting in a notable enhancement in lift production with a higher peak and positive lift over a longer period of the flapping cycle. While the downstroke generates the greatest force, it also causes the most drag, this is why barn owls are able to fly at lower speeds than pigeons with lighter airfoils due to their thick and high camber wings. Additionally, this design is more cost-effective as it consumes less power compared to sine waves [22]. According to Yang *et al.*, [14] the length of the downstroke was longer than the duration of the upstroke in high-speed photography results. Both experimental and computational results showed that the peak amplitude of positive lift was greater than the peak amplitude of negative lift.

According to Phan and Hoon [23], the design of a flapping-wing MAV must include methods to adjust the wings during flight to provide enough upward force to counteract the weight of the body, as well as methods to control torque to maintain attitude. Pohly *et al.,* [24] explained that flapping wing motion requires two types of power: inertial power and aerodynamic power. Inertial power is the energy needed to accelerate and decelerate an object in a vacuum. Each flapping cycle requires a certain amount of aerodynamic power to counteract the aerodynamic forces opposing the wing motion, which are generated by the flapping and pitching of the wing [24].

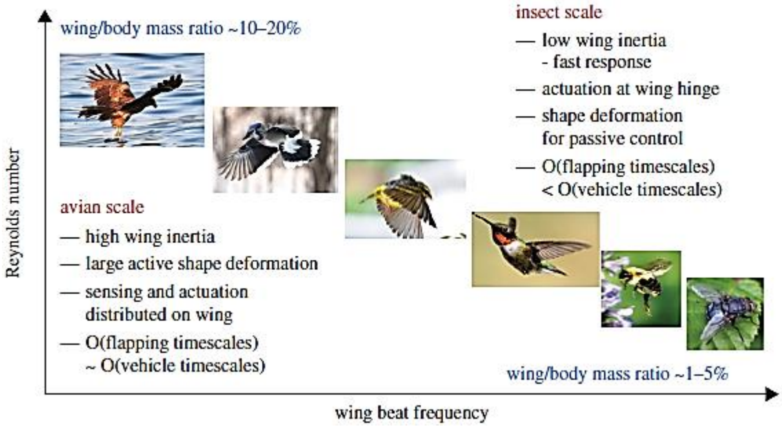

Fig. 3. The Reynolds number, flapping frequency, and wing/body mass ratio in biological flapping flight [1]

3.2 Insect-Liked MAV

Designing an insect-inspired tailless FWAV is more challenging than a bird-inspired tailed vehicle because of the lack of flight stability control, as noted by Phan and Park. Insect-like FMAVs have difficulty generating enough aerodynamic force with simple upper and lower flapping wings, and so require complex wing movements and high-frequency flapping, as stated by Tan *et al.,* [9] and Nguyen *et al.,* [25].

A slight asymmetry in a flapping wing generates a non-periodic signal at high frequency, resulting in significant vibration and inertia of the entire flapping system. Insects typically have two or four small wings that flap at wide angles and relatively high frequencies, and they twist their wings at the end of each upstroke and downstroke to generate sufficient aerodynamic force, as noted by Nguyen *et al.,* [25]. Mwongera [4] have noted that the interactions of the Leading-Edge Vortex (LEV) within the flow regime is an area of great interest for a decade. Wake capture contributes Leading-Edge Vortex (LEV), added mass effect, high wingbeat frequency, and rotational drag is unique aerodynamics characteristics that could be investigated for better understanding the flight performances and insect wing motion efficiencies during fly [4,23]. Nabawy and William [26] defined that role of LEV as a lack of stall mechanism/model under steady conditions for aerodynamic behavior.

Significant progress has been made by Ellington in understanding the aerodynamic mechanics of insect flight. The wing stroke of an insect is typically divided into four kinematic phases: two translational phases (upstroke and downstroke), during which the wings sweep through the air at a high angle of attack, and two rotational phases (pronation and supination), during which the wings rapidly rotate and reverse direction. Insect-like flapping-wing flight is intrinsically unstable, and an insect must actively adjust its wing kinematics to remain airborne [27], as shown in Figure 4. The fling creates a bound vortex for each wing, and the downstroke lift can be higher than normal.

Insect-like flapping-wing flight is intrinsically unstable, and an insect must actively adjust its wing kinematics to remain airborne. Insect-inspired flapping-wing MAVs are challenging to design, as they require methods to adjust the wings during flight to provide enough upward force to counteract the weight of the body, as well as methods to control torque to maintain attitude, and also need to include active control to stabilize the flight [8,23]. Biomimetics has played an important role in the recent advancements in the design and construction of these MAVs, and sensing systems have also been an important area of focus [28].

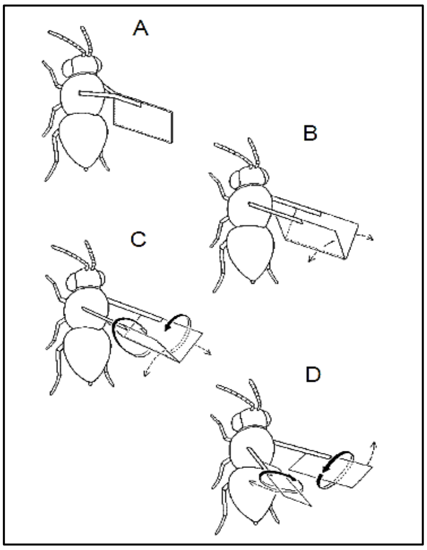

Fig. 4. At the end of the upstroke, the wings clap together (A), then fly apart (B, C) before the start of the downstroke (D) [27]

3.3 Advancements in Biomimicry

Smaller UAVs will have to face complex air flow characteristics, such as wake capture, due to flight conditions bounded within the low Reynolds number regime (*Re*<15000). The high demand for such improvements has made researchers seek 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. The summary on the contribution of ornithopter’s flapping wing kinematics towards generated lift, thrust, and drag forces shows that the number of research done for all three force generations are well-balanced, as shown in Table 1. However, for insects, the summary suggests that most research 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 [6].

Table 1
Contributions of ornithopter and insect flapping wing kinematics [6]

Type	Forces	Reference	Adopted model	Flapping motion	Contribution
Ornithopter	Lift	Mazaheri and Ebrahimi [29]	Gen. bird	Flapping	Lift force is almost independent of flapping frequency for low flapping frequency.
		Djojodihardjo *et al.,* [30]		Pitching Flapping Pitch-flap	Lift force is dominantly produced by pitching motion.
		Tsai *et al.,* [31]		Flapping	Moderate increase of AOA is advantageous to average lifting force production.
		Hu *et al.,* [32]		Flapping	Lift augmentations due to flapping motion were found to decrease

Type	Forces	Reference	Adopted model	Flapping motion	Contribution
		Hu *et al.,* [32]		Flapping	exponentially as advance ratio increases.
	Thrust/ propulsive efficiency	Mazaheri and Ebrahimi [29]	Gen. bird	Flapping	The average thrust value increases with respect to flapping frequency.
		Mazaheri and Ebrahimi [33]		Flapping	Thrust and power increase with increasing flapping frequency.
		Pourtakdoust and Karimain [34]		Flapping	Increasing frequency will result in more thrust coefficient (higher wing torsional stiffness).
		Djojodihardjo *et al.,* [30]		Pitching flapping pitch-flap	Thrust force is dominated by flapping motion.
		Tsai and Yu [31]		Flapping	Moderate increase of AOA is advantageous to average thrust force production.
		Hu *et al.,* [32]		Flapping	Thrust generated due to flapping motion would decrease monotonically with increasing orientation angle.
		Orlowski and Anouck [35]	Flap. airfoil	Flapping	Propulsion velocity increases with both flapping frequency and amplitude.
	Drag	Benkherouf *et al.,* [36]	Flap. airfoil	Flapping	If flow is subjected to drag forces, it will have friction wake shape downstream of body.
		Djojodihardjo *et al.,* [30]	Gen. Bird	Pitching flapping pitch-flap	Drag force is dominated by flapping motion.
Insect	Lift	Lian *et al.,* [37]	Dragonfly	Pitch-plunge	Tandem wing with flapping fore and stationary hind wing is best at minimizing variation of forces encountered while maximizing lift generated in increasing oscillations.
		Shyy *et al.,* [38]	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.
		Amiralaei *et al.,* [39]	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.
		Amiralaei *et al.,* [40]		Pitching	Amplitude of oscillation and reduced frequency do not have a noticeable effect on lift curve slopes.
		Fenelon and Tomonari [41]	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.
	Thrust/ Propulsive Efficiency	Fujikawa *et al.,* [42], Broering et al., [43] and Lian *et al.,* [37]	Butterfly Dragonfly	Flapping Pitch-plunge	Unsteady and 3-D vortices were the main factor in generating lift. Hind-wing sees phase shift in thrust generation when flap with 90°/180° phase lag.

Type	Forces	Reference	Adopted model	Flapping motion	Contribution
		Shyy *et al.,* [38]	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.
	Drag	Amiralaei *et al.,* [39]	Flap. airfoil	Inclined figure-of-eight	Quoted that inclined figure-of-eight patterns have substantial drag forces, which contribute to required hovering force.
		Amiralaei *et al.,* [40]		Pitching	Min. drag coefficient is not affected substantially by investigated parameters except at high oscillation amplitudes and high Reynolds numbers.

3.4 Challenges

As noted by Geissler Berend [20], small birds, insects, and bats have narrow wings with a pointed leading edge, which leads to the development of concentrated vortices at the wing's leading edge, but they are still able to maintain high-power efficiency. Mimicking insect flight requires a mechanism to provide a wide flapping angle, a wing rotation mechanism to produce aerodynamic forces even during the upstroke, and a control method for flight stability and manoeuvrability without horizontal and vertical stabilizers, as stated by Nguyen *et al.,* [25]. However, creating an insect-like MAV that performs effectively in real-world situations is challenging due to current technology limitations and a lack of understanding of insect flight, as noted by Hassanalian and Abdessattar[3].

There are other important aspects or parameters which must be considered in the research field of flapping wing MAV. These 'dimensionless' parameters are the fundamentals of MAV research, in which it defines the relevance of the term 'micro' and the application of such small 'aerial vehicles' under low influence of wind speed. Reynolds number (*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 the flow field characteristics of which it must effectively manipulate to produce constructive aerodynamic forces to keep it afloat and maintain flying performance [6].

Natural flyers such as birds and bats have a high Reynolds number above 50,000 (turbulence flow) while insects have a low Reynolds number ranging from 100 to 10,000 (laminar flow) according to Mwongera *et al.,* [4]. Relatively little is known about how well animals can navigate complex and unfavourable airflows or about the flight control mechanisms they use to minimize the effects of turbulent winds, as pointed out by Ravi *et al.,* [44]. As reported by Park and Kwang-Joon [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. Figure 5 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 research based on proven facts and figures of previous research [6]. As seen in Table 2, 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.

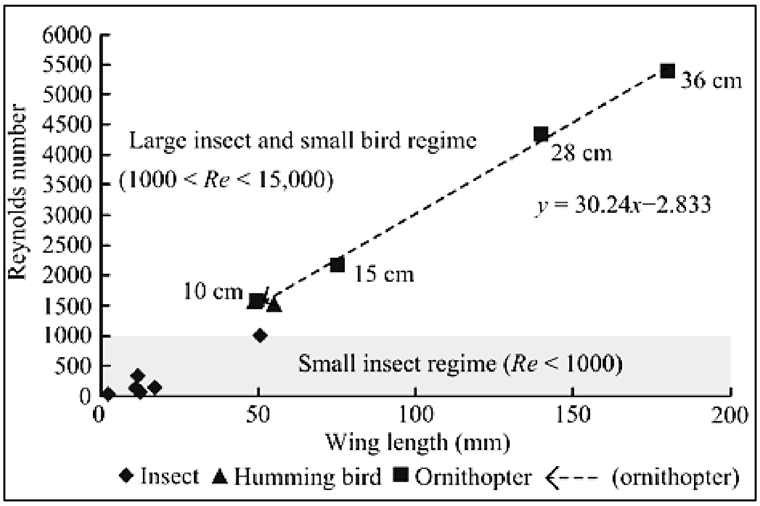

Fig. 5. Reynolds number versus wing length [45]

Table 2
Summarized guidelines [6]

Type	Species	Flight type	Wing kinematics	*Re* Approximation	Related Reference
Ornithopter	Pterosaur Magpie Bat	Ornithopter	Generic (2 DOF)	Birds (*Re*>6628)	Djojodihardjo *et al.,* [30] Pfeiffer *et al.,* [46] Hubner and Hicks [47], Rojratsirikul *et al.,* [48], Molki and Breuer [49], Rojratsirikul *et al.,* [50], Bachmann *et al.,* [51]
	Hummingbird	Insect-like	Complex (3 DOF)	Small birds- large insects (1412≤*Re*≤6628)	Shyy *et al.,* [38], Rakotomamonjy *et al.,* [52], Song *et al.,* [53]
Insect	Hawkmoth	Ornithopter-like	Generic (2 DOF)		Shyy *et al.,* [38], Orlowski and Anouck [35]
	Bee	Insect	Complex (3 DOF)		Shyy *et al.,* [38], Orlowski and Anouck [35], Nguyen Doyoung [54]
	Butterfly	Ornithopter-like	Generic (2 DOF)	Small insects (*Re*<1412)	Fujikawa *et al.,* [42]
	Beetle Dragonfly	Insect	Complex (3 DOF)		Phan *et al.,* [55] Lian *et al.,* [37], Shyy *et al.,* 38], Fenelon and Tomonari [41],
	Dragonfly				Levy and Avraham [56]
	Locust				Shyy *et al.,* [38], Orlowski and Anouck [35]
	Wasp Fly				Shyy *et al.,* [38] Shyy *et al.,* 38], Orlowski and Anouck [35]

As seen in Table 2, 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 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, which 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 [6].

4. Development of FWMAVs

4.1 Experimental Research

Research on developing such MAVs has included the development of a bee-sized robot named RoboBee by Zhang *et al.*, [57] which was found to require specialized digital computation due to present battery technologies and low power microprocessor solutions (Figure 6). They reduced power consumption and size by integrating features such as energy harvesting/power conversion, clock production, and data processing into a monolithic system. Deng *et al.* studied force generation and in-wake flow field visualization using a miniature force transducer and phase-locked Particle Image Velocimetry at a low-speed wind tunnel shown in Figure 7. They also investigated the in-ground effect on aerodynamic characteristics [2].

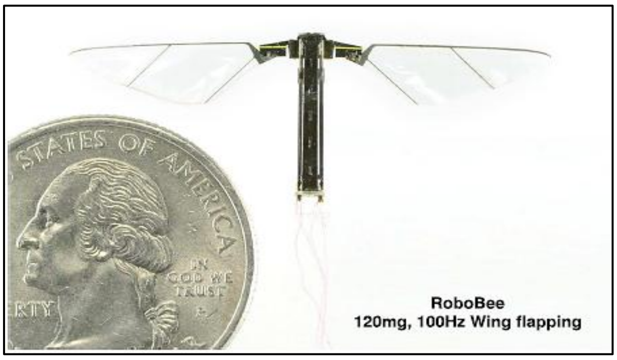

Fig. 6. RoboBee is a biologically inspired bee-sized micro air vehicle [57]

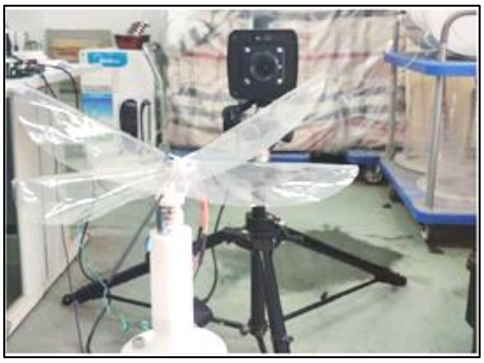

Fig. 7. Phase angle identification setup using ellipse wing profile with 260 mm of wingspan [2]

Yang *et al.,* [58] developed an FWMAV that has a total mass of 220 g, a wingspan of 50 cm, endurance that lasts for 30 minutes, and a range of 4 km shown in Figure 8. They developed an FWMAV with a high-efficiency flapping flight that drastically lowered its existing avionics mass and dramatically improved battery technology. Lankford *et al.,* [59] fabricated a wing model consisting of a stiff carbon fiber frame covered by a thin Mylar membrane film resulting in a total wing weight of 3 g where the wingspan and thickness were 15.24 cm and 1.6 mm, respectively. Flowfield measurements were taken using time-resolved, two-component PIV with a double-pulsed Nd-YLF laser.

Ma *et al.,* [60] developed an FWMAV based on the Diptera (flies) model, which weighs 80 mg, has a wingspan of 3 cm, and is capable of generating more than 1.3 mN of lift force, with a flapping frequency and wing stroke amplitude of 120 Hz and 110°, respectively. All electromechanical components of the robotic fly were made using smart composite microstructures, carbon fiber reinforced composites were used to produce structural parts, and articulation was achieved using polyimide film flexure hinges [60].

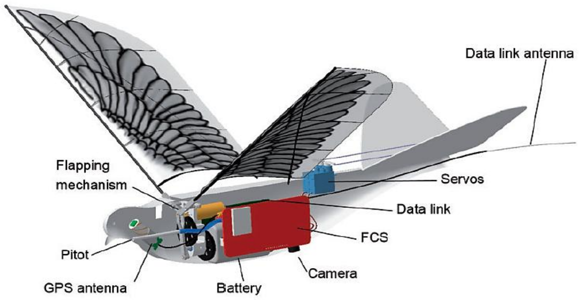

Fig. 8. A biomimetic FWMAV called Dove [58]

Crall *et al.,* [61] performed an investigation on the flight performance of bumblebees under realistic turbulence in a wind tunnel and found that turbulent flow affects both body stability and wing kinematics, but only at environmental relevant speeds. In turbulent conditions, bees exhibited a small but statistically significant increase in wingbeat frequency. This increase in wingbeat frequency may allow the bee to maintain its flight stability and control in turbulent conditions by reducing the time between wing strokes and thus decreasing the delay in updating control input to wing kinematics which is a vital factor in insect flight control [61].

Mishra *et al.,* [62] developed a prototype ornithopter named Falcon 24, which is a bio-robotic surveillance equipment designed for control devices and integrated communication. The prototype had a rigid wing with a wingspan of 300 mm and a flapping frequency of 17 Hz for forward flight. The wing kinematics were achieved by using a crank mechanism and gears with motors. The fuselage was made of lightweight carbon fiber reinforced plastic, resulting in a total weight of 3g for the frame. Nguyen *et al.,* [63] improved the flapping performance of the prototype by increasing the flapping frequency by 47%, from 17 Hz to 25 Hz. This resulted in a greater forward velocity and an increase in thrust from 2g to about 3g. They were able to decrease the wing's inertia while maintaining its stiffness by using a higher battery capacity, improved motor performance, and lightweight and high strength materials such as carbon prepreg and thin Kapton film (Figure 9).

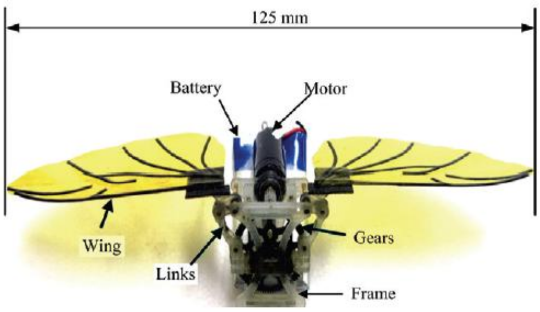

Fig. 9. Modified flapper model [63]

4.2 Numerical Research

CFD is a powerful tool for simulating the aerodynamics of flapping wing MAVs at the insect scale, but it has its limitations. High computational power and time are required to run accurate simulations, and it may not fully capture the complexity of the unsteady aerodynamics of flapping wings. Additionally, the results from CFD simulations need to be validated with experimental data to ensure their accuracy and reliability. Despite these limitations, CFD can still provide valuable insights into the aerodynamics of flapping wing MAVs and aid in the design and optimization of these vehicles [4,8,64].

Meng and Mao [64] research compared the aerodynamic forces and flows of corrugated and flat-plate wings that mimic the wing kinematics of bumblebee forward flight. They found that wing corrugation had a minor impact on aerodynamic forces, with the large angle of attack being the dominant factor in shaping the flow around the wing. Additionally, for separated flow, aerodynamic forces were found to be less affected by wing morphology [64]. Mohamed *et al.,* [65] designed a 3D model of MAV that mimicked the size of an adult-sized locust, with a body length of 60 mm and a wingspan of 120 mm. The low Reynolds number of the MAV model was simulated using the Pheonics solver, which utilized lift enhancement mechanisms such as tip vortex, wake capture, LEV & TEV. The results showed that the aerodynamic performance of the MAV's that mimic locust was superior to traditional types that mimic dragonflies and birds [65].

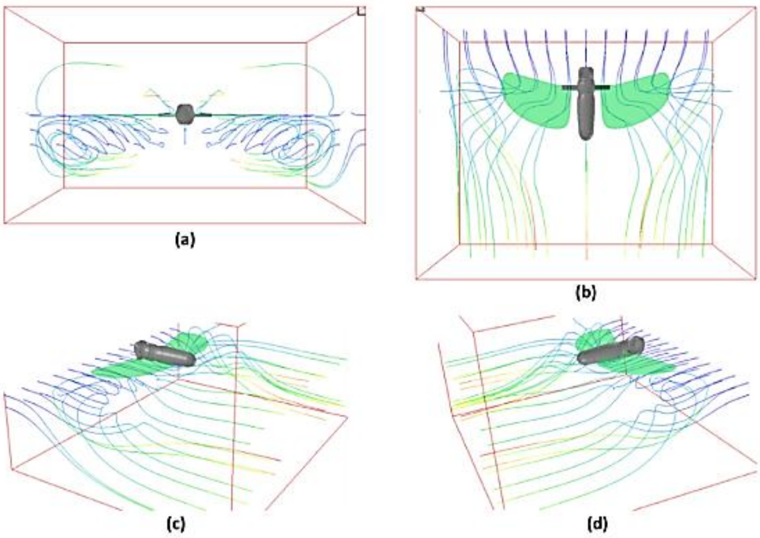

Fig. 10. Flow patterns under MAV during half stroke at different views (a) Front (b) Top (c) Left 3D (d) Right 3D [65]

In Figure 11, Bie *et al.,* [66] and their colleagues created a tailless fixed-wing unmanned aerial vehicle (FW-UAV) that takes inspiration from bats. The FW-UAV has a wingspan of 1.68 meters, weighs 289 grams, can cruise at a stable flight speed of 6.8 meters per second, and maintains an average angle of attack of 4.1 degrees and a flapping frequency of 3.7 Hz. The maximum wingbeat amplitude for this species is around 90 degrees. The FW-UAV's skeleton is constructed from carbon fiber rods, and the wings are covered with a polyester fiber material [66].

The use of a flexible wing with a membrane skin to reflect passive chordwise deformation, capable of cruising outdoors, demonstrates that the tailless design is effective for flapping wing UAVs. According to the results of computational fluid dynamics (CFD) simulations, the bat-inspired UAV has the potential to support greater take-off weight at different flapping frequencies and angles of attack. Yao and Yeo pointed out that experiments with natural subjects are challenging due to the small size of insects and the difficulties in accurately predicting their behavior. They developed an FWMAV model of hummingbird hawkmoth with a flapping frequency of 70 Hz, a wingspan of 20.2 mm, and a sweeping amplitude of 115 degrees. For simplicity, the basic cyclic wing kinematics were assumed to be sinusoidal [8].

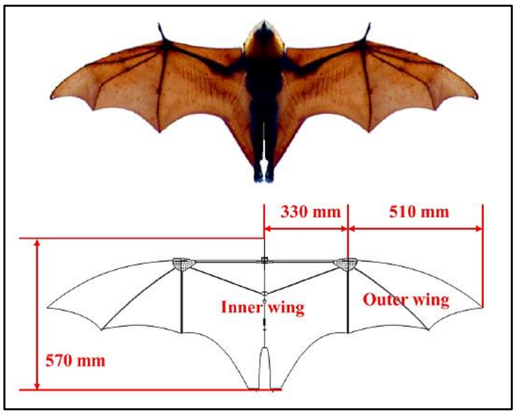

Fig. 11. Bat-inspired UAV [66]

Nguyen and Jae-Hung [67] designed a flexible flapping wing MAV model based on the hawkmoth species Manduca sexta and analyzed the wing structure using the finite-element method. They found that during high-speed flight, the body pitch amplitude of a flexible FW-MAV modeled after an insect is greater than that of a rigid FW-MAV. At low speeds, the aerodynamic characteristics of flexible wings are superior to those of rigid wings, due to the repositioning of the wings in relation to the body. During hovering and low-speed flight, wing flexibility decreases pitch damping, amplifying body pitch oscillation. Zhao *et al.,* [19] and their team conducted a computational analysis of the effects of camber on aerodynamic performance using the Fluid-Structure Interaction (FSI) module of the COMSOL Multiphysics software. The results indicate that a specific camber of airfoil can improve the aerodynamic properties of a flapping wing [19].

Yang *et al.,* [14] designed a 20 cm wingspan FWMAV called "Golden Snitch" with a wing membrane thickness of 24 micrometers made of polyethylene terephthalate (PET). They used the COMSOL Multiphysics Simulation to compare the flow patterns, time history, and waveforms of lift force, as well as the impact of FSI on the 3D surface profile of the flexible wings over a full flapping cycle because of its aeroelasticity between numerical and experimental results. They found that the lift error or fluctuation generated using COMSOL Multiphysics increased as the flapping angle decreased and there were limitations in assigning different materials for the wing [14].

Meng and Mao [68] used high-speed cameras to measure the wing kinematics of fruit flies flying forward, then calculated the numerical flows of the flapping wing using the incompressible Navier-Stokes equations, which were numerically solved using moving overset grids as the governing equations. They found that during the middle of a half-stroke, fast-pitching-up rotation and delayed-stall mechanics generate a significant amount of aerodynamic force [68].

Geissler *et al.,* [40] used a compressible flow time-accurate 2D-Navier-Stokes (Spalart Allmaras equation) for a turbulence model to study the dynamic stall control on flapping wing motion limited to forward flight environments. They found that, since the flex center of a leading-edge deformation is located on the lower surface during the downstroke, this type of deformation has a significant effect on the LEV's strength. The transition lines are accumulating at the surface twist during most of the downstroke, where the flow is turbulent downstream of the twist over most of the downstroke. They also found that during the upstroke motion, the lower surfaces behave identically to the upper surfaces during downstroke and vice versa. As with FWR-MAV, dynamic stall control increases forward thrust, propulsion efficiency, and the flight envelope of a helicopter. In the domain of incompressible laminar flow, where natural flyers such as small birds and insects operate, it is of great interest to examine the effect of a further lowering in Re number [40].

Abas [69] studied the numerical investigation of the optimum flight performance for a Kingfisher's wing model under multiphase conditions by comparing the rigid and flexible flapping wing using the Transition SST (Second Order Upwind) turbulence model. The flapping frequency ranges from 11 Hz to 21 Hz and wingspan is 60 mm. The study considered validations from experimental, meshing, time step, and flapping cycle dependency test. The results showed that the flexible flapping wing performed better during rainy conditions than the rigid wing [69]. Engels *et al.,* [10] and their team designed a bumblebee model with a 13.2 mm wing length and tested it in forward flight at 2.5 m/s (laminar flow) with homogeneous isotropic turbulence (HIT). Figure 12 shows the wake generated under laminar inflow conditions [10].

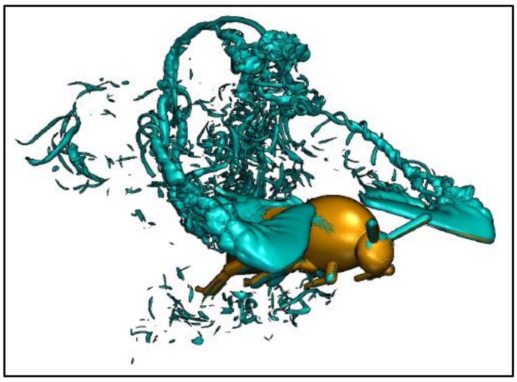

Fig. 12. Visualization isosurface of vorticity magnitude: Wake generated bumblebee under laminar inflow conditions [10]

Jones and Nail [5] designed a flapping-wing model based on the profile of the fruit fly's wing (Drosophila melanogaster). They performed a CFD analysis of the aerodynamic response of a flapping wing to downward, frontal, and lateral gusts using the 3D unsteady compressible Reynolds-Averaged Navier–Stokes equations with the Spalart–Allmaras turbulence model for various ranges of wingspan, speed, and mass MAV. The results showed that the aerodynamic coefficients of a flapping wing are strongly dependent on the orientation of the wing and gust velocity vectors [5].

5. Summarized Research Approaches

Table 3 and Table 4 summarize the experimental and numerical research approaches towards the development of FWMAVs. The tables include the adopted model, flight mode, wingspan, flapping frequency, method, contribution on the research field, and research gap for easy reference. Both ornithopter and insect-like MAVs research studies were found from hovering to forward flight conditions as references.

According to Table 3 and Table 4, like previous analyses between experimental and numerical research, the numerical investigation of insect flight is superior to experimental research. This verifies the hypothesis that it is difficult to fabricate a viable insect-type flapping wing prototype for experimental investigations due to mechanical complexity and size constraints. Before a viable prototype can be manufactured, it is necessary to do a significant amount of computational study in order to gain a better understanding of insect wing flapping flight.

Table 3
Summarized experimental research

Ref.	Adopted model	Flight mode/ speed	Wing span	Flapping frequency	Exp. method	Contribution	Research gap
Zhang *et al.,* [57]	Bee	Take off and hover	5 cm	100 Hz	In lab testing	Power-saving and size reduction using monolithic system integration.	No aerodynamics and structure analysis were conducted.
Deng *et al.,* [2]	Dragonfly	Forward flight at 2 m/s	26 cm	12-18 Hz	Wind tunnel	Force generation in-wake and flow field visualization.	Lack of structure analysis.
Yang *et al.,* [58]	Pigeon	Forward flight at 8 -12 m/s	50 cm	4-12 Hz	Wind tunnel and flight testing	High-efficient flapping flight reducing its integrated system mass.	Unable to come out high efficiency performance of flapping wing.
Ma *et al.,* [60]	Diptera flies	Take off and hover	3 cm	130 Hz	In lab testing	Wing kinematic and flight control and stability.	No aerodynamic analysis.
Crall *et al.,* [61]	Bumble-bee foragers	Forward flight at 0-4 m/s	3 cm	160-180 Hz	Wing tunnel testing	Bumblebee flight performance in field realistic turbulence.	No aerodynamic analysis.
Mishra *et al.,* [62]	Bird	Forward flight	30 cm	17 Hz	Flight testing	Surveillance equipment with integrated communication and control devices	No Aerodynamic and structure analysis were conducted.
Nyugen *et al.,* [25]	Beetle	Forward flight	12.5 cm	25 Hz	In lab testing	Thrust and lift generation.	Lack of aerodynamic and structure analysis.
Meng and mao [64]	Bumblebee	Forward flight at 0-4.5 m/s	AR = 3.28	150 Hz	3D URANS	Wing corrugation effect on aerodynamic forces and flow field visualization.	Lack of structure analysis

Table 4
Summarized numerical research

Ref.	Adopted model	Flight mode/ speed	Wingspan/ aspect ratio	Flapping frequency	Num. method	Contribution	Research gap
Mohamed *et al.,* [65]	Locust	Forward flight at	12 cm	19-40 Hz	3D Navier Stokes	Thrust and lift generation and flow pattern visualization.	Turbulence model selection not specified
Bie *et al.,* [39]	Bat	Forward flight	168 cm	3-7 Hz	RANS with SST k-ω	Thrust and lift generation and flow pattern visualization.	Multiphase flow and gust condition not tested
Yao and Yeo [8]	Humming-bird hawkmoth	Hover	20.2 mm	70 Hz	3D NS	Thrust and lift generation and flow pattern visualization.	No Fluid-Structure Interaction (FSI)

Ref.	Adopted model	Flight mode/ speed	Wingspan/ aspect ratio	Flapping frequency	Num. method	Contribution	Research gap
Lackford *et al.,* [59]	Insect wing (Semi-elliptical)	Forward flight at 6.3 m/s	AR = 2.38 15.24 cm	5 Hz	3D URANS using OVETURNS solver	Aerodynamic forces production and flow pattern visualization of leading-edge vortex formation and shedding.	Lack of structure analysis
Pohly *et al.,* [24]	Insect wing (Semi-elliptical)	Hover	AR = 2-6	17-155 Hz	3D Navier Stokes	Introduce the scaling method for determine approximate wing size and kinematic values.	Forward flight and multiphase flow not tested
Nyuyen and Jae-Hung [70]	Hawkmoth Manduca sexta	Hover and forward flight	4.85 cm	62.7-192.5 Hz	3D Coupling methods: unsteady panel method and extended un- steady vortex-lattice method.	FSI approach, wing flexibility effects on flight performance, Lift and drag force production, flow pattern visualization.	Poor mesh quality
Zhao *et al.,* [19]	Cambered membrane airfoil	Forward flight at 25 m/s	25 cm	1.5-3 Hz	3D Navier Stokes	FSI approach and optimal camber length improve the aerodynamic characteristics.	Lack of validation results
Yang *et al.,* [14]	Golden Snitch	Forward flight at 1-3 m/s	20 cm	14-15 Hz	3D Navier Stokes	Flow pattern visualization and lift and thrust production.	High percentage of error results and limitation of assign different material using COMSOL Multiphysics.
Meng and Mao [68]	Fruit flies	Forward flight	2.69- 2.98 mm	153-213 Hz	Navier Stokes	Fast-pitching-up rotation and the delay-stall mechanisms, flow pattern visualization and lift and drag production.	Lack of structure analysis and multiphase flow.

Ref.	Adopted model	Flight mode/ speed	Wingspan/ aspect ratio	Flapping frequency	Num. method	Contribution	Research gap
Geissler and Berend [20]	NACA 0012	Forward flight	-	0.5 Hz	2D Navier Stokes (Spalart Allmaras)	Mean thrust generation and flow field visualization.	Laminar flow not explored yet.
Abas [69]	Kingfisher	Forward flight at 4.4-8.8 m/s	6 cm	11-21 Hz	3D NS	Lift, drag and thrust generation, flow field visualization and multiphase flow condition.	Hover flight and gust condition not investigated.
Engels *et al.,* [10]	Bumblebee	Forward flight at 2.5 m/s	13.2 mm	150 Hz	3D NS	Lift, drag and thrust generation and flow field visualization under heavy turbulence.	Only focus on single phase flow and frontal gust.
Jones and Nail [5]	Fruit fly	Forward flight at 1-10 m/s	1-15 cm	160 Hz	3D URANS (Spalart Allmaras)	Flow field visualization and lift, drag and thrust generation.	Lack of structure analysis and flexibility of the wing.

6. Conclusion

MAVs size keep decreasing along with progress in sensor technologies for better performance and agility. Most research has succeeded in developing ornithopter-like MAV prototypes for experimental investigation, but a few research able to develop insect-like MAV prototypes due to size limitations and high mechanical complexities. Numerical research approach for insect-like MAV is more dominant over experimental approach because it is cheaper, however, more time-consuming. Most research confirms that flexible wing structure increases lift generation during flapping flight and has almost no effect on the dynamic stability characteristics of longitudinal and lateral flight. Fluid-structure interaction (FSI) approach is of great interest to explore the effect of aerodynamic and structure analysis during flight. The material properties and wing shape are critical factors to consider when designing a flapping flight system to avoid catastrophic effects of oscillatory contact, which can be particularly severe in structures made of fatigue-prone materials.

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