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Review on Passive, Active, and Hybrid Adaptive-Morphing Flapping Wing for Energy Efficient Bird Sized UAV

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Abstract

Unmanned aerial vehicles (UAVs) with flapping wings are a promising bio-inspired technology that offers special benefits like increased agility, energy efficiency, and adaptability for both natural and urban settings. Recent developments in flapping wing UAV development are examined in this review, with particular attention paid to material innovations, aerodynamic optimization, and passive and active morphing mechanisms. Quantitative evidence across multiple studies indicates that passive morphing such as elastic joints and borehole designs can reduce power consumption by 10–27% and enhance lift generation by 16–40%, while active morphing enabled by actuators and smart materials improves maneuverability, stability, and load adaptability in dynamic flight conditions. Aerodynamic interactions have been better understood thanks to computational tools like Computational Fluid Dynamics (CFD) and experimental techniques like wind tunnel testing, which have also yielded important insights into performance optimization. Despite these advances, persistent challenges remain in computational cost, structural complexity, and sustained energy efficiency during extended missions. Unlike previous reviews that focus mainly on kinematics or control, this work uniquely integrates a cross disciplinary synthesis of morphing mechanisms, materials, and aerodynamic modeling to identify performance tradeoffs and emerging trends. Future research directions include AI-assisted control architectures, adaptive composite materials, and hybrid morphing designs that can transform flapping wing UAVs from laboratory prototypes into field ready systems for environmental monitoring, surveillance, and confined space operations.

1. Introduction

Unmanned aerial vehicles (UAVs) with flapping wings represent a novel application of biomimicry. The ability of these systems to generate both lift and thrust through wing motion makes them unique. Unlike rotary wing UAVs that consume a lot of energy and traditional fixed wing UAVs that depend on forward motion for lift, flapping wing UAVs are designed to perform best in hover and low speed flight. These parameters allow them to function in confined, high motion environments such as cities and forests [1], [2].

Flapping wing UAVs may range in size from that of an insect to that of a bird to larger systems. Bird sized UAVs (generally 0.5-0.6 m wingspan) seem to be the most appropriate for the design-to-weight and maneuverability to payload ratios. 'Moderate sized' systems exhibit superior lift-to-drag ratios and energy efficiency as compared to their insect sized counterparts [3], [4]. Similar to pigeons and hummingbirds, these

UAVs are also capable of hovering, gliding, and full flight transitions, increasing the versatile nature of their applications [3], [5].

The inherent flight mechanics of birds also influence the evolution of passive morphing strategies in flapping wing UAVs. This phenomenon improves energy efficiency during flight by utilizing the natural flexibility of wing materials and structures to adjust to aerodynamic forces without the need for external energy input. For example, the flapping cycle bends and twists the wings to maximize lift and thrust production, simulating the natural deformation seen in avian flight [4], [5]. Fig.1 depicts a snapshot sequence of a peregrine falcon flying level, with its wings tucked during the upstroke and fully extended during the downstroke. Passive flexibility can optimize aerodynamic performance while reducing power consumption, as demonstrated by this natural wing morphing. However, active morphing allows UAVs to quickly adapt to changing environmental conditions by using actuators and intelligent materials to dynamically change wing shapes or incorporate features like controlled perforations [4], [5].

Fig. 1 *Snapshot of a peregrine falcon during level flight* [6]

Although flapping wing UAVs offer a number of advantages, their widespread application is hindered by several major challenges. The primary problem is energy inefficiency, which is particularly problematic when hovering or flying forward for long periods of time because it takes a lot of energy to flap continuously. Structural problems, like the requirement to maintain designs that are both robust and lightweight, add complexity to these systems [1]. Furthermore, current designs' adaptability is limited by their inability to maintain stability and control in erratic or multi modal environments [3], [4].

Enhancing the energy economy is essential for increasing flight times and allowing UAVs to transport increasingly sophisticated payloads. Researchers have recently investigated the integration of hybrid passive active morphing systems, which combine the accuracy of active mechanisms with the energy saving benefits of passive morphing. For instance, research on elastic wing designs demonstrates that optimum flexibility can reduce power consumption by 10% while increasing lift generation by up to 16% [2] (details in Section 4.1). However, there are still few experimental validations for such hybrid systems, particularly in UAVs the size of birds [5].

For flapping wing UAVs to operate in real world environments, aerodynamic adaptability is just as important as energy economy. Corrugated or perforated wings are examples of bio-inspired designs that enhance thrust efficiency and stabilize airflow during different flight stages. It is still difficult to strike the ideal balance between passive and active adaptations, though [3], [5].

Flapping wing UAVs have revolutionary potential, but their practical use is limited by major challenges: energy inefficiency during extended flight affects both payload capacity and operational duration, and their utility is further limited by their poor stability and agility in turbulent conditions, which are further compounded by structural complexity, as designs, especially for bird sized UAVs, must balance durability, aerodynamic perfection, and lightweight construction. To overcome these challenges, innovative strategies that combine passive and active morphing processes are required, which should exploit the accuracy of controlled modifications and the energy saving benefits of natural deformations. These gaps could be filled by a hybrid passive active morphing wing design, which would allow bird sized UAVs to operate steadily, effectively, and adaptively under a variety of dynamic circumstances.

2. Flapping Wing UAVs: An Overview

Ornithopters, another name for flapping wing UAVs, are modeled after the complex flight systems of insects and birds. With features like increased agility, reduced noise, and the capacity to function in constrained areas, these designs seek to replicate the intricate wing kinematics and aerodynamic benefits seen in nature [7]. Da Vinci's theories were the first to attempt flapping wing flying, and military, environmental, and surveillance requirements have fueled more recent advancements [8]. Over the past few decades, these UAVs have been the focus of extensive research and development due to their special qualities, such as hover ability and effective agility in a variety of situations [9].

The development of flapping wing UAVs heavily relies on biomimicry. To create UAVs that can replicate the effectiveness and capabilities of these natural fliers, researchers have extensively examined the flight kinematics of birds, bats, and insects. For example, as Fig. 2 below illustrates, bird like UAVs like "Robo Raven" and "RoboFalcon" have shown sophisticated flapping systems that mimic joint movements and elliptical wingtip motions seen in nature [6], [10].

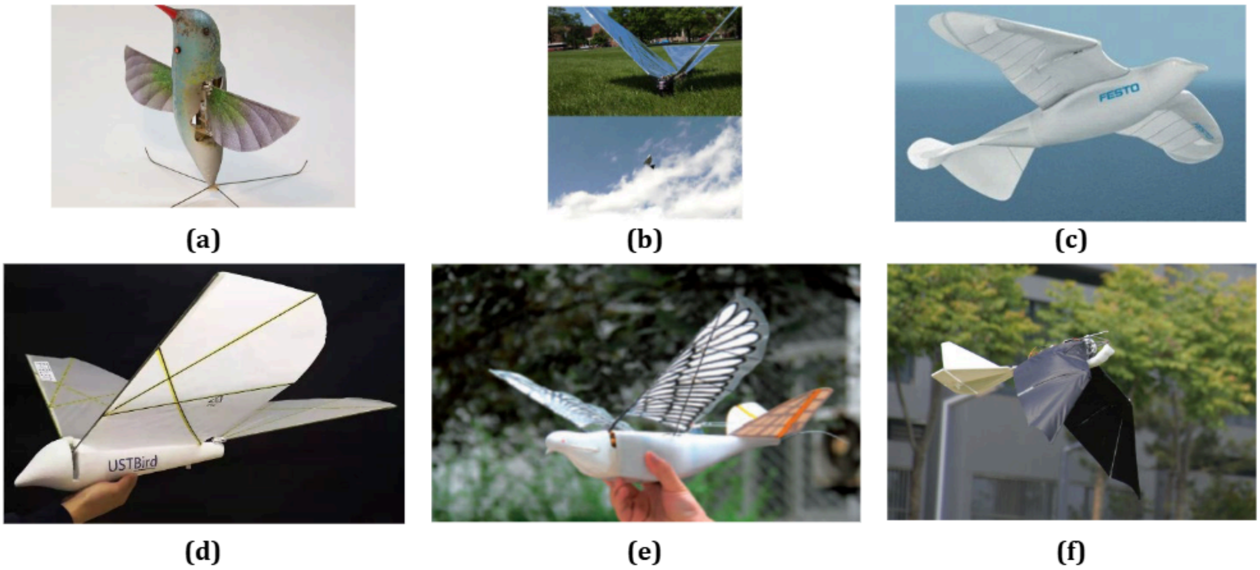

Fig. 2 *International BFAVs: (a) Nano Hummingbird* [10]*; (b) Robo Raven* [11]*; (c) USTBird* [12]*; (d) HIT-Phoenix* [13]*; (e) Dove* [14]*; (f) RoboFalcon* [6]

Developments in lightweight materials, control systems, and quick prototyping have enabled the enhancement of flapping wing UAVs. These UAVs have been able to acquire aerodynamic qualities that are comparable to those of insects and birds by using materials that can mimic the wing deformation of natural fliers. Longer operating times have also been made possible by recent efforts to integrate solar cells into UAV wings [15]. To reduce size and improve agility, deployable wings made of materials such as shape memory alloys and origami folding have been developed [15]. These developments are demonstrated by a number of flapping wing micro air vehicles (FWMAVs), such as the SJFly, KU-Beetle, NUS-Roboticbird, DelFly Nimble, and RF powered aircraft, as illustrated in Fig. 3. These designs show how several methods can be used to achieve bio-inspired flying characteristics and show how cutting edge materials and control systems can be integrated [15].

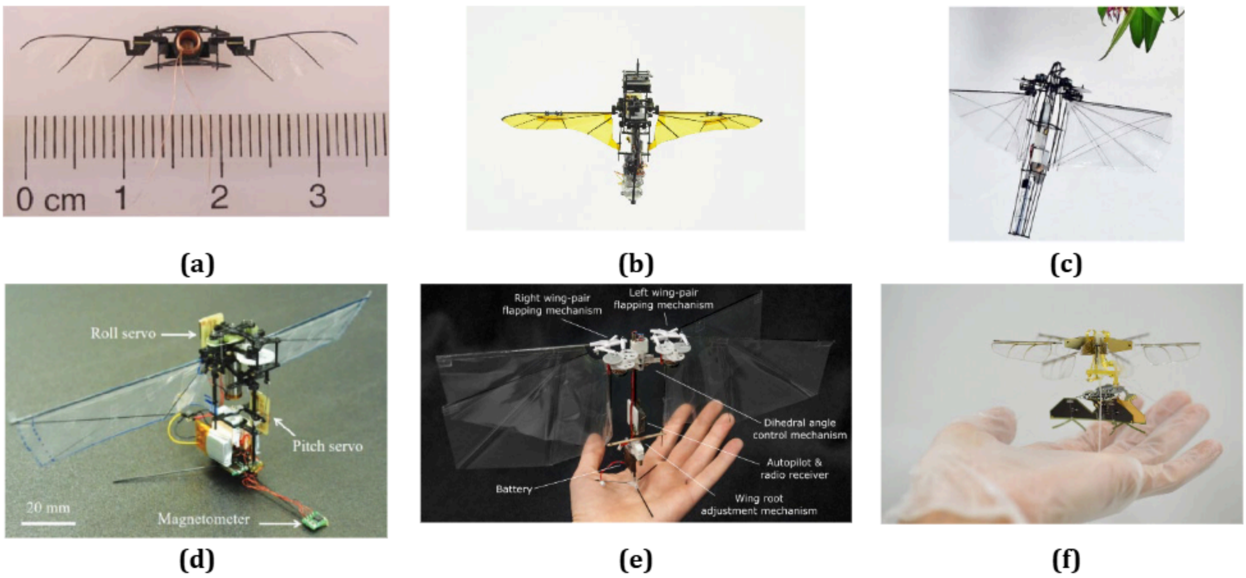

Fig. 3 *Several typical FWMAVs. (a) SJFly I* [16]*; (b) KUBeetle* [17]*; (c) NUS-Roboticbir* [18]*; (d) KUBeetle-S* [19]*; (e) DelFly NimBl* [20]*; (f) RF-powered aircraft* [21]

Bird sized flapping wing UAVs have distinct advantages over both larger and smaller micro sized UAV designs. When operating at moderate Reynolds numbers, these UAVs can achieve higher aerodynamic efficiency and carry more cargo than micro sized designs. Larger wingspans and a lower frequency of flapping make these UAVs suitable for outdoor environments, as they also increase stability in choppy conditions. Because they are more nimble and agile than larger models, bird sized UAVs perform better in confined spaces and on missions that call for accuracy and stealth. Their ability to alternate between gliding and flapping further enhances energy efficiency for applications such as environmental monitoring and reconnaissance [7], [22].

To accomplish precise control and wing flapping, birds use a complex system of direct and indirect flying muscles. The pectoralis and supracoracoideus, two direct flight muscles, are principally in charge of propelling the upstroke and downstroke, respectively. The supracoracoideus muscle guarantees wing elevation during the recovery stroke, particularly at lower speeds, while the pectoralis muscle, which is the most significant and strongest, supplies the thrust required for lift and forward motion. Indirect flying muscles, on the other hand, alter wing twist, stabilize during maneuvers, and act on the skeletal structure to modify wing form and orientation. Together, these muscles generate the efficient and rhythmic movements needed for flight, and depending on ecological requirements, species specific modifications may improve stability, endurance, or agility [23].

Several research teams have developed innovative UAVs with bird sized flapping wings, drawing inspiration from avian flight. For example, Han *et al.* [22] talk about ways to improve flapping mechanics, like using compliant materials to mimic the flexibility of bird wings. Fang *et al.* [7] highlight UAV prototypes with improved control systems and altered wing kinematics for stable and energy efficient flying. Notable designs that show the potential of bird sized UAVs under challenging flight conditions include prototypes with articulated wing structures and hybrid actuation mechanisms that enhance aerodynamic performance and adaptability. The development of UAVs the size of birds depends on the use of materials that are both lightweight and durable. Many designs use advanced composites, like carbon fiber reinforced plastics, to cut weight without compromising structural integrity. To replicate natural deformation during flapping and increase energy efficiency, flexible and elastic materials are frequently employed in wing components. For instance, recent studies have investigated the incorporation of smart materials into flapping mechanisms to enhance lift and thrust in real time. These materials balance strength, flexibility, and weight to provide reliable performance in a range of flight conditions.

The primary focus of flapping wing UAVs is on control and stability. Because of its unstable and nonlinear flight dynamics, scientists have been developing advanced control systems that can stay stable while performing intricate maneuvers. To manage the quick and complex changes in flight dynamics, sophisticated control algorithms have been created, such as adaptive flight controllers [15]. As an example, it has been demonstrated that the bird like Flapping Wing Air Vehicle (BFAV) employs adaptive control algorithms for position, trajectory tracking, and formation control, which makes it ideal for demanding operational settings [9].

Despite recent improvements, flapping wing UAVs still struggle with energy management, aerodynamic efficiency, and stability in the face of external disturbances. Current research emphasizes the need for better fluid structure interaction models and efficient power management to improve flight endurance [9]. Researchers are also looking into passive morphing techniques to enhance the wings' flexibility in response to shifting aerodynamic loads to increase stability and maneuverability [24]. Combining passive and active morphing technology is an exciting direction for future research that could lead to UAVs that can automatically change the configuration of their wings in response to changes in their surroundings.

3. The Aerodynamics of a Flapping Wing

3.1 Energy Efficiency

Energy efficiency in flapping wings UAVs have been studied using a combination of analytical and experimental techniques to increase aerodynamic performance while reducing power consumption. A bio-inspired flapping wing MAV's aerodynamic performance was evaluated in wind tunnels by Deng *et al* [25]. They used force transducers and phase locked particle image velocimetry (PIV) to visualize wake structures and measure aerodynamic forces. Their study examined the effects of wing flexibility and flapping frequency on power loading. They discovered that clap-and-fling flexible wings generated significant momentum surpluses, reducing energy consumption. Wake visualization data validated the improvements in aerodynamic efficiency and demonstrated the significance of wing flexibility in improving flying energy efficiency. Nian *et al.* [26] also investigated the aerodynamic benefits of attaching an airfoil to the root of a flexible flapping wing. They developed a semi-empirical, cycle averaged mathematical model using data from wind tunnels and measured forces and moments using a multi-axis load cell. Their findings, which showed improved climbing performance and reduced power requirements during takeoff, theoretically and experimentally validated the airfoil equipped wing's increased energy efficiency. To demonstrate the practical application of their aerodynamic testing, Fig. 4 depicts the experimental setup utilized by Nian *et al.* [26], which includes the installation of FW10 in a wind tunnel.

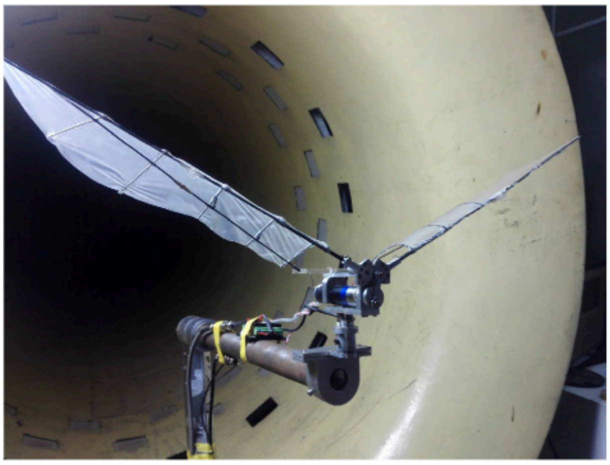

Fig. 4 *Experimental device with FW10 installed* [26]

3.2 Lift and Thrust Force

A flapping wing's lift can be broken down into inertial, circulation, added mass, and viscous dissipation components, as illustrated in Fig. 5 [43]. By changing the local geometry and time varying kinematics, morphing throws this balance off. For instance, wing extension or bending affects the added mass forces due to fluid inertia, while camber or twist changes circulation and vortex dynamics, and transferring structural mass influences the inertial contribution to lift. As morphing can either increase wetted surface losses or decrease flow separation, viscous dissipation is more unpredictable. This breakdown offers a helpful starting point for comprehending how morphing influences the time and phase of aerodynamic forces in addition to their magnitude. This decomposition provides a useful foundation for evaluating how different morphing strategies can enhance aerodynamic efficiency, as demonstrated in recent experimental and numerical studies.

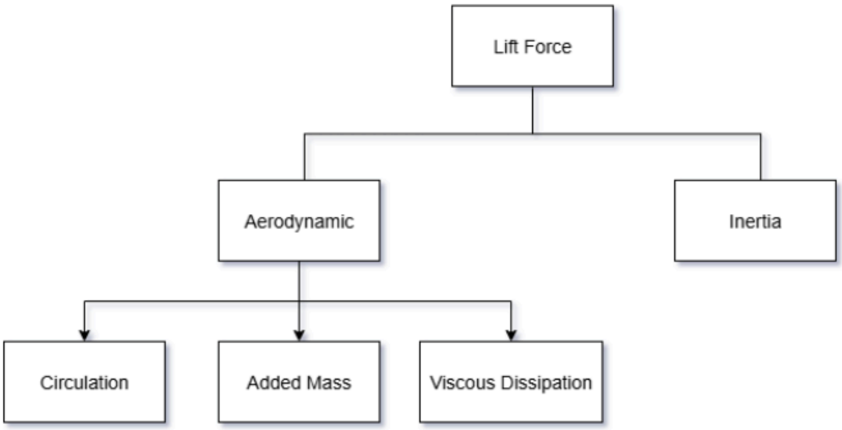

Fig. 5 *Decomposition of lift forces in flapping wings and the influence of morphing*

Through creative wing designs and reliable validation techniques, lift and thrust optimization in flapping wing UAVs has improved. In wind tunnel studies, Yang *et al.* [27] investigated flapping mechanisms with adjustable leading edge twisting, measuring aerodynamic forces with a six axis load cell. Their research demonstrated that designs featuring constrained twisting enhanced lift generation by 64% when comparing mechanisms equipped with mechanical stoppers to those lacking such limitations. MATLAB generated airfoil cross sections and Kwon3D stereophotography, which recreated 3D wing geometry, were used to confirm the experimental data and reveal the dynamic stroke modifications that increased lift. Using wind tunnel testing, numerical simulations, and flight tests to optimize wing shapes, Meng *et al.* [28] concentrated on large scale flapping wings intended for high altitude applications. They evaluated several wing platforms and materials by measuring forces and moments using six axis sensors. With confirmation from neural network models and high altitude flight testing, the study discovered that elliptical planforms and higher wing stiffness enhanced lift and thrust generation, validating the aerodynamic benefits under various atmospheric conditions. The ground test bench employed in their wind tunnel experiments is presented in Fig. 6, which illustrates the large scale setup used to evaluate the aerodynamic performance of different wing designs.

Fig. 6 *Ground test bench for flapping mechanism* [28]

4. Bio-Inspired Wing Morphing

4.1 Passive Morphing Mechanisms

The development of flapping wing UAVs depends on passive morphing mechanisms, which offer the possibility of improved energy efficiency and adaptive control without the need for extra active actuation systems [29]. Passive morphing can greatly improve overall flight performance and stability by causing wing modifications through aerodynamic forces [30]. The inspiration came from the natural deformation of insects and birds.

To optimize elements like lift, thrust, and maneuverability, passive morphing frequently uses elastic or flexible parts that let the wing bend naturally while in position. Fang *et al.* [31] discussed how hidden feathers in bird like UAVs can increase lift and passive stability during dynamic maneuvers by delaying vortex detachment at high angles of attack. The study showed how passive aeroelastic elements, like hidden feathers, can aid in stabilizing flapping wing UAVs under difficult flight conditions using particle tracking velocity (PTV).

The optimization of elastic wings for passive morphing utilizing an elastic joint system that adapts to aerodynamic forces naturally was investigated [2]. The researchers equipped a bird scale E-Flap ornithopter, which has a 1.5 m wingspan and a total mass of 0.65 kg, with an elastic joint wing designed to introduce controlled asymmetry during the flapping cycle. The system was optimized and validated through free flight experiments at a flapping frequency of 3.49 Hz, forward speed of 3.81 m/s, and Reynolds number of approximately 1×10^4. Under these conditions, the elastic wing achieved an average lift of 0.72 kg, compared with 0.63 kg for the rigid configuration, representing about a 16% improvement in lift and an estimated 10% reduction in power consumption. Similarly, up to 5% improvement in takeoff weight lift and about 27% reduction in power consumption were achieved [32] through the design of compliant joints for asymmetric passive deformation. Aerodynamic asymmetry with incoming flow, however, requires more investigation. The flapping wing robot with elastic wings in Fig. 7 illustrates how these techniques can be used in practice, showcasing their potential for energy savings and aerodynamic efficiency [2], [32].

Fig. 7 *Flapping wing robot equipped with an elastic wing* [2]

The potential of passive morphing to increase maneuverability in turning flight was examined [33]. Their research demonstrated that passive changes to the wing pitch angle could successfully lower rotational damping and improve maneuverability by providing the wing structure with greater torsional flexibility. Wing torsion creates a passive pitch imbalance that reduces the need for active modulation by opposing forces that would otherwise make quick aerial maneuvers difficult.

It has also been shown that passive morphing lowers the energy consumption of UAVs with flapping wings [34]. The study suggests that passive morphing systems could offer a workable way to achieve energy efficient flight while simultaneously enhancing mobility and stability. Conversely, active morphing actively modifies the wing's shape in real time by using actuators that require more energy.

Focus on passive morphing devices is driven by the need to reduce energy consumption while preserving aerodynamic adaptability. The findings from [2], [33], and [34] are particularly noteworthy because they demonstrate how passive deformation can improve lift and stability. Additionally, borehole designs have been investigated as a passive morphing strategy to improve aerodynamic performance in flapping rotary wings. Long *et al.* [35] experimentally confirmed that perforated wings could mitigate the effects of negative lift during the upstroke. The significance of optimizing geometric parameters and hinge stiffness for improved performance was highlighted by Chen *et al.* [36], who extended this work by adding an elastic cover that passively opens and closes during wing motion, achieving up to a 40% increase in lift. Most recently, Chen *et al.* [37] showed that borehole designs increase lift generation and reduce negative lift in forward flight by minimizing pressure differences across the hinge and creating a secondary leading edge vortex. A comparison of an intact wing and a perforated wing test model is shown in Fig. 8, which is taken from [36]. It highlights the impact of geometrical variations on aerodynamic performance. To fully realize the potential of borehole designs, more research and optimization are required, despite these developments [27], [28], [29].

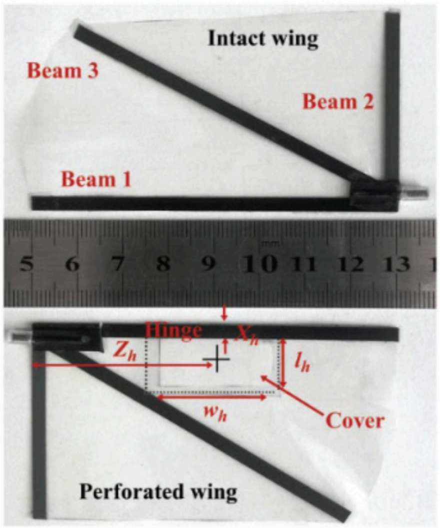

Fig. 8 *An intact and perforated wing test model* [36]

Passive morphing can naturally and effectively improve flapping wing UAVs. Borehole designs are particularly noteworthy among the techniques examined because of their capacity to increase lift and decrease negative lift during upstrokes. Studies [35], [36], [37] demonstrate their versatility and efficacy by showing lift increases of up to 40%. Therefore, borehole designs are a particularly attractive approach for energy efficient UAVs.

While other strategies, like hidden feathers and elastic joints, enhance stability and agility, borehole designs provide a special blend of energy savings and aerodynamic adaptation. Because their performance depends on optimizing factors like shape and material qualities, they are a suitable candidate for further study. By focusing on this strategy, UAVs can become more reliable and effective, assisting advancements in both commercial and military applications.

4.2 Active Morphing Mechanisms

UAVs, which allow for real time aerodynamic force optimization, are inspired by the mechanisms of active morphing in flapping wings, which allow birds to adaptively alter their wing configurations while in flight. Active morphing improves flight efficiency, stability, and maneuverability by precisely altering wing shape using actuators and other intelligent materials [38].

A variety of active morphing techniques inspired by bird flight, including wing sweep, dihedral, twist, and camber, have been discussed in detail in [34]. Actuators that dynamically modify wing and tail shapes while in flight are used to actively regulate these morphing approaches, giving UAVs greater control authority and facilitating their ability to react to variations in aerodynamic conditions. To maintain stability and regulate lift and drag forces across various flight regimes, wing morphing—such as adaptive twist and camber adjustment—is very advantageous. Furthermore, active tail morphing is essential for improving pitch and roll control, which is necessary for stable flying, especially while performing quick maneuvers.

For large scale bio-inspired UAVs, Savastano *et al.* [39] demonstrated a high performance morphing wing that combines active and passive morphing techniques. Piezoelectric actuators and servo motors, which dynamically modify the wing shape and wingtip folding to improve aerodynamic performance during various flight stages, were used to accomplish active morphing. Through real time wing configuration modification made possible by the active morphing technology, the UAV's maneuverability, payload capacity, and energy consumption were all improved. According to the study, the UAV's payload grew by about 34%, and its cruising speed doubled when these active morphing features were added. It also used less energy because it was able to glide during certain phases. Fig. 9 provides a practical implementation of this revolutionary wing design by showcasing the created wing incorporated with the E-Flap system [39].

Fig. 9 *Developed wing integrated in the E-Flap* [39]

The impact of active morphing on the aerodynamic performance of flapping wings during a V-formation flight was examined by Billingsley *et al.* [40] in 2021. To determine how various active morphing techniques could increase aerodynamic efficiency, the study employed active bending and twisting of the wings, which were modelled using the first and second mode configurations of a cantilever beam. According to the findings, active morphing considerably improved the UAV's propulsive effectiveness when compared to rigid wing designs, particularly when bending and twisting were combined. A five member V-formation at a 140° formation angle was the ideal arrangement, where the active morphing systems allowed for less drag and increased aerodynamic efficiency. This study emphasizes how crucial active morphing is to preserving energy efficient configurations in flapping wing UAVs.

Riault *et al.* [41] examined the work loop dynamics of the pigeons' humerotricipital muscle to demonstrate the purposes of active wing morphing during flight. The study found that to adapt aerodynamic forces to changing conditions, the pigeon actively modulates the wing structure while in flight. We call this process "active morphing." Pigeons actively contract muscles such as the humerotricis to perform a range of wing morphing functions, such as wing retraction and extension. These actions improve their lift output, stability, and maneuverability. The findings show that active morphing not only contributes to lift and thrust output but also reduces the energetic cost of maintaining stability in challenging scenarios by controlling aerodynamic forces during complex aerial maneuvers.

4.3 Hybrid Approaches

By employing both passive and active mechanisms, hybrid morphing techniques can optimize performance. For example, a hybrid morphing flap system that combines cambering and trailing edge flapping showed superior aerodynamic performance in high lift designs [42]. Additionally, active flow control methods in conjunction with morphing can increase aerodynamic efficiency by managing flow separation and reattachment. Table 1 presents a systematic comparison of the benefits, drawbacks, and mechanisms of various morphing strategies, including hybrid, active, and passive.

Table 1 *Comparison of morphing approaches*

Aspect	Passive Morphing	Active Morphing	Hybrid Morphing
Energy Efficiency	High—due to reduced power consumption	Moderate—requires active control	Potentially high, combining benefits
Complexity	Lower—simpler mechanisms	Higher—requires sophisticated control	Moderate to high, depending on design
Robustness	High—can withstand impacts	Variable—depends on the control system	High, combining passive robustness
Aerodynamic Performance	Improved lift and efficiency	Enhanced lift and thrust	Optimized for specific conditions

4.4 Implications of Morphing on Flight Stability and Control

A flapping wing's lift can be broken down into inertial, circulation, added mass, and viscous dissipation components, as illustrated in Fig. 9 [43]. By changing the local geometry and time varying kinematics, morphing throws this balance off. For instance, wing extension or bending impacts the added mass forces through fluid inertia, camber or twist alters circulation and vortex dynamics, and transferring structural mass affects the inertial contribution to lift. As morphing can either increase wetted surface losses or decrease flow separation, viscous dissipation is more unpredictable. This breakdown offers a helpful starting point for comprehending how morphing influences the time and phase of aerodynamic forces in addition to their magnitude. Since circulation, additional mass, and inertia control the transient reactions that the flapping wing must balance during maneuvering, these changes in turn have a significant impact on flight stability and control.

For flapping wing UAVs, morphing technology significantly affects flight stability and control in addition to increasing aerodynamic efficiency. Stability derivatives and control efficacy are directly impacted by morphing, which modifies aerodynamic forces and moments by changing wing shape during the flapping cycle [34]. According to bird influenced research, changes in span and aspect ratio cause the aerodynamic center to shift, which affects static stability margins and enhances pitch control authority [34]. Through complex tail and wing morphing, such as incidence, spread, rotation, sweep, dihedral, twist, camber, and even the use of the alula (Fig. 10(d)–(e)), birds achieve control authority, as illustrated in Fig. 10. Conventional aircraft, on the other hand, use separate control surfaces such as ailerons, rudders, and elevators (Fig. 10(c)). These additional degrees of freedom allow avian inspired morphing to modify the location of the aerodynamic center and, consequently, the static stability margins.

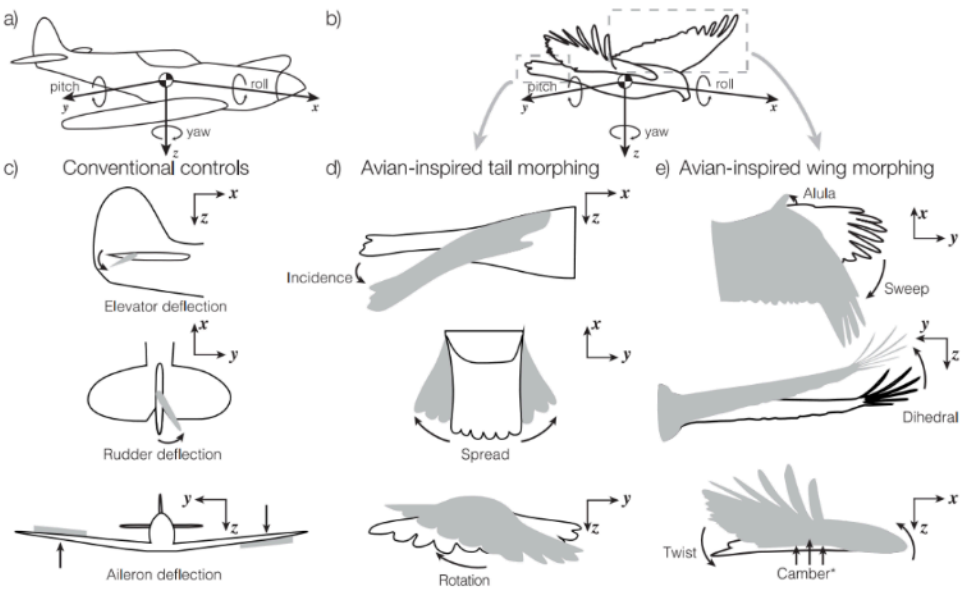

Fig. 10 *Active flight controls for (a) Aircraft; and (b) Birds are investigated. The degrees of freedom in (c) Conventional aircraft control differ substantially from those in the avian; (d) Tail; and (e) Wings* [34]

Symmetric spanwise adaptation improves the lift-to-drag ratio and offers more pitch stability throughout a broad range of Reynolds numbers, according to experimental studies using discrete feather like morphing wings [44]. Large scale UAV tests verified that integrated morphing strategies maintain pitch stability during cruise and maneuvering [39], while complementary work on morphing–flapping coupled configurations showed that active bending and camber morphing stabilize transitional flight phases by decreasing oscillatory motion and increasing lift coefficient [45], [46].

Morphing is equally important in lateral control. Asymmetric span folding, sweep morphing, and differential twist generate rolling moments comparable to those of conventional ailerons by redistributing lift along the wing, enabling agile roll movements without the use of external control surfaces [6], [44]. Hybrid morphing wings have shown that adaptive dihedral and wingtip folding can provide strong roll authority while preserving overall stability margins [39]. Dynamic spanwise retraction and stretch improve aerodynamic efficiency and lessen unstable load oscillations, which improves flight stability and aids in roll balance [47].

It has also been shown that morphing techniques enhance directional stability. For instance, by moving the aerodynamic center, sweep morphing can enhance yaw stability in the presence of gust disturbances [34]. Inspired by avian feathers, discrete wing morphing configurations enhance lateral directional stability, lessen generated drag, and diminish wingtip vortices [44]. Nonplanar morphologies, such as differential twist or gull like dihedral twist, produce stabilizing yawing moments and help to preserve heading control, according to experiments on morphing coupled flapping prototypes [46].

5. Flapping Wing System Design and Analysis

5.1 Flapping Mechanisms and Materials

Xiao *et al.* [48] compiled materials and flapping mechanisms for flapping wing micro aerial vehicles (FWMAVs). These consist of string based systems for twisting wings, crank slider linkages for torque balancing, and motor direct drives for precise motion control. Common material choices include lightweight composites like CFRP, metal alloys for structural components, and flexible membranes for wings. By maximizing the flapping amplitude (44°–190°), hover frequency (13.3–35 Hz), and mass efficiency (10.8–62 g), these designs show gains in aerodynamic and energy efficient performance. Table 2 shows the variety of hybrid driven flapping mechanisms by assembling representative prototypes and their system attributes, such as the number of wings, motor type, flapping frequency, and power supply.

Table 2 *Flapping wing system characteristics of varieties of hybrid driven mechanisms*

Prototypes	No. of wings	Motor	Flapping frequency	Wingspan	Flapping angle	Power supply	Year
Nguyen's NUS robotic bird crank-slider-rocker mechanism [18]	4	Brushless motors and linear servos	12–14 Hz	22 cm	90	220 mAh LiPo battery	2019
Agile bioinspired morphing coupled flapping wing mechanism [6]	2	Brushless motor	6-12 Hz	1.2 m	110	Li-Po battery (3S 850 mAh)	2022
Pigeon like FWMAV [49]	2	Brushless motor	4-12 Hz	60 cm	60	Lithium battery	2022
Cloud Owl [28]	2	Brushless DC motor	4-6 Hz	1.82 m	45	Li-Po battery, 16.8 V, 10.5 Ah	2023
Double-cracker-rocker [50]	4	Servo and small motor	15 Hz	28 cm	50	7.36 mNm torque at 4.2 V	2020

Prototypes	No. of wings	Motor	Flapping frequency	Wingspan	Flapping angle	Power supply	Year
Smaller yoke within the Scotch-yoke mechanism [51]	2	DC motor	21.6 Hz	24 mm	-	3-10V DC	2020
Hassanalian's FWMAV [52]	4	Motor	20 Hz	-	-	battery	2020
Single crank-double rocker mechanism [25]	2	Micro motor	30 Hz	19 cm	160	7.4V	2021

Material selection also plays a crucial role in determining the flexibility, durability, and aerodynamic efficiency of flapping wing systems. Phan and Park [19] examined the materials and structural concepts used in insect scale flying robots. At larger scales, DC motors combined with crank-rocker or string based transmission systems are often adopted for propulsion, while piezoelectric actuators are preferred at micro- and milli-scales because of their high energy density and low weight. For wing construction, polydimethylsiloxane (PDMS) and SU-8 are commonly used for their flexibility and lightweight strength, whereas carbon fiber spars and venation reinforced membranes improve structural integrity. To enhance lift and efficiency, designers frequently optimize wing geometry, sweep amplitude, and flapping frequency. Table 3 compiles representative examples of wing membrane and frame materials used across various models, providing a concise overview of material selection strategies for different scales and actuation types.

Table 3 *Materials for the wing membrane and frame from wing models*

Type	Material
Membrane materials	Insects' membrane [53]
	Polyimide [54]
	Parylene [55]
	Flexible PVC [56]
	Natural rubber [57]
	Polyethylene [57]
	Polydimethylsiloxane [55]
	Polyurethane [55]
Frame materials	Insect's vein [55]
	PLA [58], [6]
	Titanium [59]
	CFRP [60]
	Carbon fiber [6], [61]
	Carbon/epoxy composite [61]

5.2 Flapping Wing Analysis Method

To assess and improve the aerodynamic performance of flapping wing designs, wind tunnel testing is essential. One study that tested bionic flapping wings with three dimensional complex motion found that increasing the flapping frequency and wind speed greatly improved lift, confirming computer simulations and improving flying parameters [32]. Another study examined the impact of affixing airfoils to flapping wing roots and found that while endurance and range somewhat decreased, climbing ability, cruise velocity, and maneuverability were all improved [26]. These results demonstrate how crucial wind tunnel testing is for improving flapping wing designs and establishing a connection between structural changes and flight performance.

Computational fluid dynamics (CFD), which enables detailed analyses of aerodynamic forces and interactions, is an essential tool for investigating the unstable aerodynamics of flapping wings. Cai *et al.* [62] introduced a CFD data driven aerodynamic model (CDAM) to predict the flapping aerodynamics of bumblebee like wings. By accurately estimating forces, torques, and power consumption across a variety of flight scenarios, including forward flying and hovering, this model showed its potential for optimizing flight performance through precise kinematic analysis. Similarly, Pan *et al.* [63] used CFD simulations to study flexible wings modelled after dragonflies. The benefits of biomimetic designs for vertical takeoff and hovering were highlighted by their discovery that moderate flexibility increases lift and power efficiency in flapping wing rotor MAVs. Xue *et al.* [64] combined computational fluid dynamics (CFD) and computational structural dynamics (CSD) to model the connections between wing motion and body vibration in flapping MAVs. By emphasizing the effect of vibration on aerodynamic performance and demonstrating that CFD can accurately depict multi body dynamics, their research yielded vital information for MAV design. However, CFD is computationally demanding and time consuming, particularly for large scale simulations or models that incorporate complex fluid structure interactions [2]. This makes it less practical for iterative design or real time optimization, despite its crucial role in confirming designs and exposing intricate aerodynamic phenomena.

6. Conclusion

Research on flapping wing UAVs has progressed in several areas, including structural design, aerodynamic modeling, and morphing strategies. The sections that highlight particular achievements and the issues that still need to be resolved make up this review. The following points provide a summary:

1) Flapping Mechanisms and Materials

The selection of materials and mechanisms largely governs the performance of flapping wing systems. Bio-inspired designs utilizing lightweight composites, elastic joints, and compliant linkages have enhanced aerodynamic efficiency and structural durability. At smaller scales, crank–rocker and string based mechanisms have proven effective for simulating insect like wingbeats, whereas brushless motor–driven systems are better suited for larger ornithopters. Material innovations such as PLA, CFRP, and carbon fiber offer high stiffness-to-weight ratios, while flexible membranes like PVC, polyimide, and PDMS enable passive deformation and lift enhancement. Nevertheless, challenges remain regarding long term material fatigue, repeatability, and the durability of smart materials under sustained flapping loads.

2) Flapping Wing Analysis Methods

Advances in aerodynamic analysis methods have deepened understanding of unsteady flow phenomena and performance optimization. Experimental wind tunnel investigations have verified that increasing flapping frequency and airflow velocity improves lift generation, while modifications such as root mounted airfoils enhance climb capability and maneuverability. Complementary computational approaches, including data driven CFD based models like CDAM, have successfully predicted aerodynamic forces, torques, and power under both hovering and forward flight conditions. Coupled CFD–CSD simulations further captured the influence of body vibration on aerodynamic performance, though the high computational cost still limits their use in large scale parametric design studies.

3) Passive, Active, and Hybrid Morphing

Morphing technologies, both passive and active, have provided flapping wing UAVs with greater adaptability and control authority. Passive morphing strategies, including torsional flexibility, elastic joints, and borehole perforated wings, have been shown to reduce energy consumption and increase lift by up to 40% while mitigating negative lift during upstrokes. Active morphing, achieved through actuators such as servos or piezoelectric, allows real time adjustment of sweep, dihedral, and camber, thereby improving thrust, payload capacity, and stability. Large scale UAV implementations have demonstrated payload gains of approximately 34% and doubled cruising speeds through such hybrid servo-piezoelectric systems. Hybrid morphing approaches that integrate trailing edge flapping with cambering show particularly promising improvements in aerodynamic efficiency, underscoring the value of coordinated mechanical and material adaptation.

4) Aerodynamic Performance and Energy Economy

Enhancing aerodynamic performance while maintaining energy economy remains a core design objective. Wind tunnel studies have revealed that flexible wings employing clap-and-fling kinematics can generate substantial momentum surpluses, thereby lowering power consumption. Additional aerodynamic refinements such as leading-edge twist limitation, which increases lift by up to 64%, and root airfoil attachment, which improves takeoff performance demonstrate the measurable benefits of targeted design modifications.

5) Control Strategies and Flight Stability

Control strategy development continues to be a decisive factor in achieving stable and autonomous flight. Adaptive controllers applied to bird scale flapping UAVs, such as the BFAV prototype, have improved trajectory tracking and formation stability. Similarly, bio-inspired reflex based mechanisms have enhanced stability under turbulence, though their integration remains constrained by structural complexity and payload limitations.

All things considered, a more distinct technical roadmap for flapping wing UAVs has been shaped by the combined advancements in mechanisms, materials, morphing techniques, aerodynamic analysis, and control. The work under review demonstrates how inventions that started out as lab ideas have gradually developed into workable designs that might be able to meet practical needs in environmental sensing, surveillance, and operations in limited spaces. This synthesis demonstrates the maturity that has already been attained as well as the opportunities that remain.

Future studies should focus on coordinated advancements in materials, mechanisms, modeling, and control that bring flapping wing UAVs closer to practical deployment. First, to guarantee long operational lifetimes under repeated flapping loads, it will be essential to develop resilient composite membrane architectures and fatigue resistant smart materials. To maximize control authority and minimize energy costs, parallel mechanical design efforts should concentrate on hybrid morphing mechanisms that enable smooth transitions between passive compliance and active actuation. To produce precise and timely forecasts appropriate for closed loop control and design optimization, more work should be done on reduced order and AI assisted aerodynamic models. Innovations in energy harvesting, ultra-light actuators, and high-energy-density storage will extend endurance; at the same time, careful investigation of scaling laws and miniaturization strategies will enable transfer of performance gains across size ranges. Finally, advancing real time adaptive control through machine learning, together with tighter integration of lightweight sensing, camouflage, or mission-specific payloads, will be essential for robust operation in turbulent, cluttered, and mission oriented environments. Pursuing these integrated directions promises to close the gap between laboratory prototypes and field-ready flapping-wing UAVs for surveillance, environmental monitoring, and confined-space applications.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper, as follows: ***study conception and design:*** *Guo Jiaqing, Mohd Faisal Abdul Hamid;* ***literature collection and review:*** *Guo Jiaqing;* ***analysis and interpretation of literature:*** *Guo Jiaqing, Ermira Junita Abdullah, Mohd Faisal Abdul Hamid;* ***draft manuscript preparation:*** *Guo Jiaqing;* ***manuscript review and revision:*** *Mohd Faisal Abdul Hamid, Ermira Junita Abdullah. All authors reviewed the results and approved the final version of the manuscript.*

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