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A Review of Flapping-Wing Micro Air Vehicles (MAVs)

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Abstract:
Flapping-Wing Micro Air Vehicles (MAVs) are inspired by the flight mechanisms of insects, birds, and other small flying animals. These vehicles offer significant potential for a variety of applications, including environmental monitoring, reconnaissance, search-and-rescue operations, and many others. The development of MAVs involves complex interdisciplinary research in aerodynamics, wing mechanics and kinematics, control systems, and materials science. This review paper presents a comprehensive analysis of the current state of research in flapping-wing MAVs, focusing on bio-inspired wing morphology, aerodynamic performance, wing flexibility, the mechanics behind successful flight, and material selection. The paper also addresses challenges such as stability, manoeuvrability, and the integration of artificial muscles for wing actuation.

Keywords: *Bioinspiration, Morphology, Aerodynamics, Actuation, Flexibility, Stability, Materials, Challenges, Control, Efficiency*

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I. INTRODUCTION

Flapping-wing flight has evolved over millions of years in nature, and its efficient performance has inspired a new generation of autonomous flying vehicles. Micro Air Vehicles (MAVs) powered by flapping wings aim to mimic the aerodynamic principles of insect and bird flight to achieve enhanced manoeuvrability and energy efficiency. While traditional fixed-wing UAVs (Unmanned Aerial Vehicles) are widely used in various applications, MAVs offer the potential to navigate through confined spaces, hover in place, and even perform complex aerial manoeuvres.

This review synthesizes recent advancements in flapping-wing MAVs, with a focus on the bio-inspiration behind wing design and aerodynamics. We will explore the various wing morphologies, the role of wing flexibility, the actuation mechanisms that power these wings, and the computational models used to simulate and optimize flight dynamics.

II. WING MORPHOLOGY AND AERODYNAMICS

2.1 Insect-Inspired Wing Designs

Insect wing morphology varies widely across species, with each design optimized for specific flight capabilities. This diversity in wing shape and structure offers valuable insights into improving the performance of Micro Air Vehicles (MAVs). Research into artificial insect wings has shown that the flexibility and complex shapes of natural insect wings contribute significantly to their efficient flight performance. In particular, the wings of insects like dragonflies, butterflies, and beetles are designed to optimize aerodynamics, leading to improved flight stability and performance. Shang et al. (likely 2025) explored how replicating the aerodynamic properties of these wings can enhance the lift-to- drag ratio in MAV designs. By mimicking the structure and movement of real insect wings, researchers aim to improve MAV flight efficiency and stability.

Although most current MAV wings are planar, there is growing evidence that adding three-dimensional features— such as camber (curvature) or corrugation (a wavy structure)—can further optimize their performance. These 3D

features can help to improve lift production, which is crucial for hovering and efficient flight. They also play a

significant role in controlling dynamic bending and twisting during flight. When wings deform, especially during the upstroke, they can lead to rapid changes in aerodynamic properties, such as altering the airflow and vortex interactions around the wings. This flexibility allows MAVs to adapt to varying flight conditions, enhancing their maneuverability and overall efficiency.

The study of insect wing morphology and the integration of 3D features into MAV designs offer promising advancements in optimizing aerodynamics. By replicating the natural dynamics of insect wings, researchers can create more efficient and stable MAVs that are capable of performing complex aerial maneuvers with greater energy efficiency

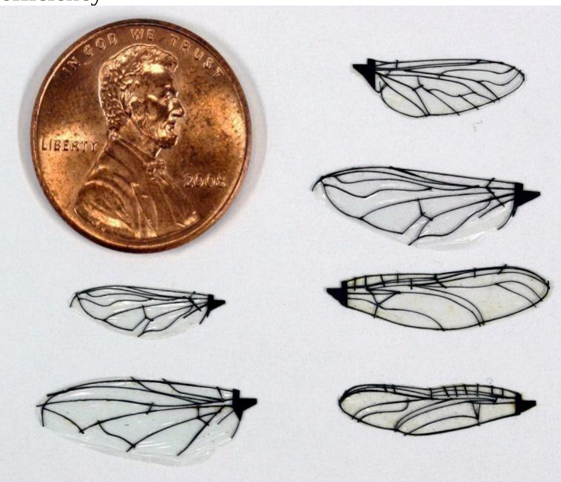

Fig 1. A comparison of robber fly wings next to a Lincoln cen scale. Robber flies, also known as assassin flies.

The dragonfly, with its unique wing kinematics and flexible wing structure, serves as a key model for MAV design. In particular, the interaction between the forewing and hindwing in dragonflies, which creates a highly effective aerodynamic interaction, has been studied to optimize wing movements for stability and manoeuvring. The fluttering motion of butterfly wings has also inspired the design of morphing wings that can adapt in real time to dynamic flight conditions. (1)

2.2 Computational Fluid Dynamics (CFD) in Wing Design

Recent advancements in flapping-wing Micro Air Vehicles (MAVs) have seen a significant rise in the use of Computational Fluid Dynamics (CFD) to model and simulate the complex aerodynamics involved in low-Reynolds number flows around flapping wings. CFD is crucial for understanding aerodynamic phenomena such as wing separation, vortex formation, and the interaction of aerodynamic forces during flight. These simulations enable researchers to capture the intricate details of how air moves around flapping wings, including vortex shedding and how these vortices interact with the wing and surrounding airflow.

For instance, studies like those by Liu et al. (2025) have focused on simulating these dynamic interactions to understand how different wing shapes and configurations affect flight performance. CFD simulations provide valuable insights into optimizing wing geometry to improve the lift-to-drag ratio, stability, and overall efficiency of MAVs. This approach allows researchers to test a wide range of wing designs without the need for physical prototypes, saving both time and resources. (2)

The use of CFD not only helps in refining the aerodynamics of MAVs, but it also contributes to reducing drag, enhancing lift and thrust, and improving energy efficiency. Furthermore, CFD simulations play a key role in improving the maneuverability and flight dynamics of these bio-inspired vehicles. In summary, CFD tools have become indispensable for advancing the design and functionality of flapping-wing MAVs, providing essential data that leads to more efficient and effective designs. (3)

III. ACTUATION AND WING FLEXIBILIT

3.1 Smart Wing Actuation Systems

In flapping-wing Micro Air Vehicles (MAVs), one of the most significant challenges is developing actuation systems capable of replicating the complex, dynamic motions of biological wings. Biological wings, such as those of insects and birds, move with incredible precision and adaptability, which is crucial for effective flight control. To address this challenge, researchers have turned to Shape Memory Alloy (SMA) actuators, which have shown great potential in mimicking the wing movements found in nature.

SMA actuators are materials that change shape when exposed to heat, exploiting a unique property of these alloys called the "shape memory effect." When heated, SMAs revert to a pre-set shape, allowing them to produce controlled deformations in the MAV wings. This ability to change shape in a highly controlled manner enables precise manipulation of wing motions, allowing for

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the same kind of complex movements required for effective flapping flight. As a result, SMAs offer the precision and flexibility needed to control the deformation and movement of MAV wings in real time.

One of the major advantages of SMA actuators is their lightweight and flexible nature, making them particularly well- suited for the small-scale design of MAVs. These characteristics are critical because MAVs need to maintain low weight to improve energy efficiency and flight duration. The use of SMAs in actuation systems also allows for the creation of morphing wings that can adapt to changing flight conditions, enhancing both the maneuverability and stability of the vehicle. For example, during flight, SMA actuators can adjust the shape of the wings to optimize aerodynamic properties such as lift and drag, enabling the MAV to fly more efficiently.

Overall, SMA actuators have become a key technology in advancing the performance of MAVs, enabling them to achieve more effective and energy-efficient flight dynamics, similar to the biological systems they seek to emulate. (4)

3.2 Flexible Wings for Enhanced Performance

In flapping-wing Micro Air Vehicles (MAVs), wing flexibility plays a vital role in improving maneuverability, efficiency, and overall flight performance. Unlike rigid wings, flexible wings can dynamically adjust their shape during flight, allowing the vehicle to respond more effectively to varying flight conditions. Research has demonstrated that flexible wings can significantly enhance lift and thrust by exploiting aerodynamic phenomena such as wingtip vortices and delayed stall.

Wingtip vortices are spirals of air created at the tips of wings during flight. On rigid wings, these vortices can reduce aerodynamic efficiency by contributing to drag. However, flexible wings can alter their shape in response to airflow, minimizing the intensity of these vortices and thereby reducing drag. Additionally, flexible wings can exploit the delayed stall effect, a phenomenon in which the wing remains aerodynamically efficient at higher angles of attack for longer periods than rigid wings. This delayed stall enhances the vehicle's lift generation and stability, making the vehicle more efficient and capable of maintaining stable flight in different flight regimes.

The dynamic adaptability of flexible wings allows for optimized performance in diverse flight conditions, whether hovering, performing sharp maneuvers, or transitioning between different flight speeds. Flexible materials, such as thin polymers or composite materials, enable wings to bend, twist, and change shape during each flap cycle, mimicking the adaptive nature of biological wings. These adaptive wing shapes contribute to improved energy efficiency by reducing drag and enhancing lift and thrust production.

Incorporating flexible wings into MAV design ultimately leads to better maneuverability, more efficient energy usage, and improved performance in complex flight environments. As MAVs continue to evolve, the use of flexible wings will remain a key area of research, allowing these vehicles to better mimic the flight dynamics of natural fliers, such as insects and birds.

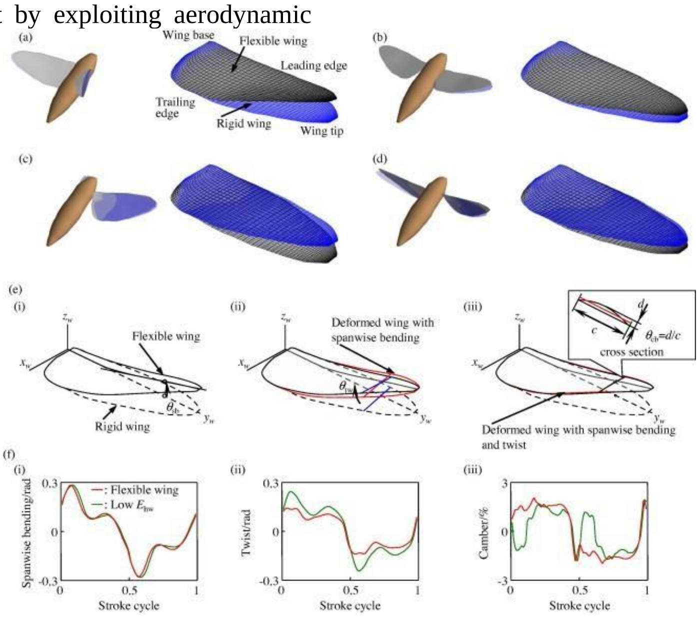

Fig 2. An analysis of flexible and rigid wings, likely airfoils, undergoing deformation and bending during a stroke cycle.

3.3 Bio-Inspired Muscle Actuators

In the design of flapping-wing Micro Air Vehicles (FWMAVs), one of the primary challenges is developing actuation systems that can accurately replicate the complex and efficient movements of biological wings. Traditional motors are often too heavy and energy-consuming for small-scale MAVs, making them unsuitable for such applications. To address this, researchers have explored alternative actuation technologies, with electroactive polymers (EAPs) and piezoelectric actuators emerging as promising substitutes. These materials offer significant advantages for MAVs, particularly due to their lightweight nature and high-performance actuation capabilities.

Electroactive polymers are materials that change shape or size when stimulated by an electric field, making them highly suitable for replicating the flexible, morphing motion of biological wings. EAPs are lightweight, flexible, and capable of producing large deformations, which makes them ideal for use in the wings of MAVs. The use of EAPs in MAVs can lead to more efficient energy consumption while enabling precise control of wing movements, enhancing both the maneuverability and stability of the vehicle.

Similarly, piezoelectric actuators, which generate mechanical movement in response to an electric field, are also being investigated for their potential in MAVs. These actuators are known for their high precision, fast response times, and ability to generate substantial force despite being very compact and lightweight. Piezoelectric actuators can drive the motion of MAV wings with great accuracy, facilitating the fine control necessary for hovering, fast maneuvers, and energy-efficient flight.

Both EAPs and piezoelectric actuators offer significant advantages over traditional motors in terms of size, weight, and power efficiency, making them essential for small-scale MAV designs. The ability to use these materials as artificial muscles for wing actuation not only enhances the flight dynamics of MAVs but also contributes to their energy efficiency, improving their operational lifespan and reducing the need for heavy power sources. As a result, these technologies play a critical role in advancing the capabilities of bio-inspired FWMAVs, helping them to achieve more lifelike flight patterns and extend their range of applications. (4)

IV. STABILITY, MANEUORIBILITY AND CONTROL SYSTTEM

4.1 Dynamic Stability of Flapping-Wing MAVs

Dynamic instability in flapping-wing flight presents a significant challenge for the control and stability of Micro Air Vehicles (MAVs). Unlike traditional fixed-wing aircraft, which experience relatively stable aerodynamic forces during flight, flapping-wing MAVs generate complex, time-varying forces that are continuously changing throughout each wingbeat. This dynamic behavior results in the generation of unsteady airflow, vortex formations, and varying lift and drag forces, which can lead to instability if not properly managed. The varying forces acting on MAVs during flight make stability analysis more complicated, as the system must constantly adjust to fluctuating conditions in real- time.

In their study, researchers focused on understanding the dynamic behavior of MAVs in different flight conditions, particularly how these forces change with variations in wing motion, airspeed, and external disturbances. The complex nature of flapping-wing aerodynamics necessitates the development of more sophisticated models and simulation tools to predict and manage these dynamic instabilities. To address this, various approaches have been proposed, including computational modeling techniques that help simulate the interaction between the wings and the surrounding airflow. Researchers employ dynamic models to predict how different wing morphologies and motion patterns contribute to instability or stability. By simulating different flight scenarios, they can identify when and why MAVs become unstable and work to develop compensation mechanisms. These compensatory systems can include adjustments to wing kinematics, real-time control adjustments, or the incorporation of flexible materials that allow for adaptive responses to dynamic forces. (6)

Understanding these dynamic behaviors is crucial for improving the overall stability and control of flapping-wing MAVs. The development of models to predict instability and implement corrective actions allows for the creation of more reliable MAV designs capable of maintaining stable flight under varying environmental and flight conditions. As a result, such research is essential in advancing MAV technology and making it more adaptable and practical for real-world applications, such as surveillance, search-and-rescue, and environmental monitoring.

4.2 Manoeuvring and Flight Control

In flapping-wing Micro Air Vehicles (MAVs), manoeuvrability is essential for performing tasks such as hovering, making sharp turns, and navigating through confined or cluttered environments. Achieving this level of control requires precise manipulation of wing movements to facilitate fine adjustments in flight dynamics. Unlike traditional fixed-wing aircraft, where aerodynamic control is relatively straightforward, flapping-wing MAVs require more complex flight control systems due to the dynamic nature of wing movement and the time-varying aerodynamic forces generated during flight. (7)

Recent advancements in flight control algorithms have played a crucial role in enhancing the manoeuvrability of MAVs. Specifically, adaptive control and model-predictive control (MPC) strategies have been particularly effective in improving the agility and autonomy of these vehicles. Adaptive control strategies adjust the control inputs based on real-time feedback, allowing the MAV to continuously adapt to changing flight conditions and disturbances. This makes MAVs more responsive to environmental changes, ensuring stable flight even in complex or unpredictable conditions.

Model-predictive control (MPC), on the other hand, uses dynamic models to predict future states of the vehicle based on current flight conditions and control inputs. It enables the MAV to anticipate and respond to disturbances before they affect flight performance, allowing for smooth and precise manoeuvres. By incorporating predictions of the MAV's future behavior, MPC can optimize control inputs to minimize errors and enhance stability, which is particularly valuable during sharp turns, sudden changes in altitude, or while hovering in confined spaces.

These advanced control algorithms not only improve the overall stability of MAVs but also contribute to their performance in challenging flight environments. As a result, they play a key role in enabling MAVs to perform complex aerial tasks with high precision. The continued development and refinement of these flight control strategies are essential for enhancing the capabilities of MAVs in practical applications such as surveillance, search-and-rescue missions, and environmental monitoring. (5)

V. MATERIAL SELECTION IN MAVs

Material selection is a critical factor in the design and performance of Flapping-Wing Micro Aerial Vehicles (MAVs), as the materials used must meet the unique demands of these vehicles. Flapping-wing MAVs are subject to complex dynamic stresses due to their wing motion, and the materials selected must not only be lightweight but also durable and flexible to endure repeated movement. The choice of materials impacts the overall performance of the MAV, influencing factors such as aerodynamics, maneuverability, energy efficiency, and structural integrity. (8)

5.1 Lightweight Composites

A key requirement for MAVs is minimizing weight while maintaining strength and durability. Carbon fiber and glass fiber composites are two commonly used materials for constructing the frame and structure of MAVs. These composites are known for their high strength-to-weight ratios, which are crucial in small-scale designs where every gram counts. Carbon fiber, in particular, offers excellent stiffness and tensile strength, making it ideal for creating the lightweight yet robust framework needed to support the MAV's wings and actuation systems

5.2 Shape Memory Alloys (SMAs)

Shape Memory Alloys (SMAs) have gained prominence in MAV design due to their unique properties. SMAs are materials that can change shape in response to heat, offering a mechanism for precise and efficient control of wing deformation. This characteristic makes SMAs particularly well-suited for wing actuation systems, as they can mimic the complex wing motions of natural fliers, such as insects and birds, by contracting and expanding with temperature changes. The ability to alter wing shape with minimal weight addition provides MAVs with improved maneuverability and enhanced aerodynamic performance.

5.3 Electroactive Polymers (EAPs) and Piezoelectric Actuators

Another promising technology for actuation systems in MAVs is Electroactive Polymers (EAPs). EAPs are materials that change shape when an electric voltage is applied, making them similar to muscle-like actuators. They offer lightweight, flexible, and efficient movement, which is essential for small-scale MAVs where energy efficiency and low weight are paramount. Piezoelectric actuators, which generate mechanical displacement when subjected to an electrical field, are also explored as an alternative to traditional motors. These actuators can provide precise control over small movements, contributing to more responsive and efficient wing flapping.

5.4 Flexible Wings and Polymeric Materials

Wing flexibility plays a crucial role in the aerodynamic performance of MAVs. To replicate the flexible nature of insect wings, polymeric materials like polyimide films and silicone-based foams are frequently used. These materials allow the wings to dynamically bend and twist during flight, optimizing lift generation and improving stability. By using flexible materials, MAVs can better exploit aerodynamic effects such as wingtip vortices and delayed stall, leading to enhanced thrust and efficiency.

5.5 Bio-Inspired Materials and Nanocomposites

Bio-inspired materials are also being incorporated into MAV design to mimic the properties of natural wings. Bio- mimetic composites replicate the natural venation patterns of insect wings, enhancing the flexibility and aerodynamic properties of the wings while also improving their structural integrity. These materials help optimize the lift-to-drag ratio, improving the MAV's overall performance during flight. Nanocomposites, which incorporate advanced materials such as carbon nanotubes or graphene, are being explored for their ability to enhance the strength and flexibility of MAVs without significantly adding weight. These composites can improve the load-bearing capacity of MAVs while maintaining high efficiency. (6)

5.6 Lightweight Metals

In addition to composites and polymers, lightweight metals such as titanium alloys and aluminum are commonly used in the construction of MAV frames and actuation systems. Titanium alloys are favored for their strength, lightness, and resistance to corrosion, making them ideal for use in demanding environments. Aluminum, known for its excellent strength-to-weight ratio and easy machinability, is often used in the structure and propulsion systems.

The combination of these advanced materials—ranging from lightweight composites to bio-inspired materials, SMAs, and electroactive actuators—enables MAVs to achieve high performance in terms of efficiency, maneuverability, and durability. Each material plays a vital role in optimizing the various components of the MAV, from the wings and actuation systems to the overall structural integrity.

VI. CONCLUSION

The Flapping-wing Micro Air Vehicles (MAVs) have made significant strides in mimicking the flight dynamics of insects and birds, offering unique advantages in terms of manoeuvrability, agility, and energy efficiency. The ongoing research in bio-inspired wing morphology, actuation systems, and aerodynamic optimization continues to push the boundaries of MAV performance. However, challenges such as stability, efficient actuation, and energy limitations remain, necessitating further advancements in both design and control systems. Future developments, particularly in hybrid MAVs and the use of advanced materials, hold the potential to enhance their versatility and practical applicability in a wide range of real-world scenarios. Overall, the integration of bio-inspired mechanisms, cutting- edge materials, and advanced control strategies promises a new generation of MAVs with unprecedented capabilities.

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