DESIGN SELECTION FOR A MICRO AIR VEHICLE

CHỌN LỰA THIẾT KẾ CHO MỘT PHƯƠNG TIỆN BAY THEO TIÊU CHUẨN KÍCH CỠ MICRO

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ABSTRACT

This study reviews past and current research on unmanned aerial vehicles (UAVs) to determine the optimal design for a miniature air vehicle (MAV) intended for operation in confined spaces. By comparing various design concepts, we identify the flapping-wing configuration as the most suitable for our application. We then explore the fundamentals of flapping flight, including wing kinematics and unsteady aerodynamic mechanisms. Our proposed wing kinematics, inspired by hummingbirds, incorporate lift-enhancing aerodynamic effects such as the Wagner effect and the added mass effect. Lastly, an analysis of existing flapping MAVs and NAVs, based on their actuators and structural designs, guides our selection of the most appropriate MAV configuration.

Keywords: *UAV; MAV; Flapping wing; Insect-wing kinematic.*

TÓM TẮT

Bài báo tổng hợp những nghiên cứu trong lĩnh vực máy bay không người lái (UAV) với mục đích lựa chọn ra một thiết kế phù hợp cho một phương tiện bay theo tiêu chuẩn kích cỡ micro (MAV) hoạt động trong môi trường bị hạn chế. Nghiên cứu này đã chỉ ra rằng loại cánh đập là phù hợp nhất với ứng dụng mong muốn. Đi sâu và chi tiết, bài báo cũng đã trình bày các nguyên tắc cơ bản của loại hình bay cánh đập, bao gồm động học cánh, cơ chế khí động học. Nhóm tác giả đã quyết định bắt chước động học cánh của chim ruồi và tìm thấy một số cơ chế nâng cao khí động học như hiệu ứng Wagner và hiệu ứng khối lượng được thêm vào. Cuối cùng, việc xem xét các MAV hiện có theo cơ cấu chấp hành và cấu trúc của chúng đã giúp lựa chọn các thành phần cấu thành nên của MAV của nhóm tác giả.

Từ khóa: *UAV; MAV; Cánh đập; Quỹ đạo cánh côn trùng.*

1. INTRODUCTION

An unmanned aerial vehicle (UAV), commonly known as a drone, is an aircraft that operates without a human pilot on board. Compared to manned aircraft, UAVs were initially deployed for missions considered too “dull, dirty, or dangerous” [1] for humans. Micro Air Vehicles (MAVs), introduced by the Defense Advanced Research Projects Agency (DARPA) in the 1990s, are a class of miniature UAVs with a maximum dimension of 15 cm and a weight of up to 100 grams. Once limited to hobbyists and children's toys, MAVs quickly attracted interest from both military and civilian sectors due to their portability, discreetness, and reduced risk in case of a crash. As a result, various MAV designs – including fixed-wing, rotary-wing, and flapping-wing models – have been developed and deployed across multiple fields.

However, research on MAVs faces several challenges due to their size constraints. The most significant difficulty arises from low Reynolds numbers (Re), which lead to unsteady aerodynamic effects that impact flight stability [2]. Additionally, their small size demands higher energy density. Despite significant progress [3], [4], there is still ample room for improvement, particularly in payload capacity, maneuverability, and, most critically, flight endurance.

In this study, we will review past and current research on UAVs to determine the optimal design for our bird-sized MAV, capable of operating in enclosed and confined environments.

2. PROPOSAL FOR SELECTING THE WING TYPE

Existing MAVs can be classified into three main categories based on their lift generation mechanism: fixed-wing, rotary-wing, and flapping-wing. Each of these categories is described in the following sections.

2.1. Fixed wing

Fixed-wing UAVs operate similarly to traditional airplanes. They are introduced first due to their consistent thrust-to-lift ratio, relatively simple flight control, and well-established mathematical models. Fixed-wing MAVs are particularly suitable for outdoor applications where maximizing flight duration is essential. Forward thrust is typically generated by one or more propellers, and onboard microcontrollers are often required to enhance stability.

According to DARPA, fixed-wing MAVs offer the best performance in terms of size and weight [5]. However, they rely on continuous forward motion to generate lift, preventing them from hovering or maneuvering in confined spaces. As a result, they do not align with the objectives outlined in the General Introduction. The wing type discussed in the next section may provide a more maneuverable alternative for MAV design.

2.2. Rotating wing

The ability to take off vertically, hover, and move slowly in any direction makes rotary-wing vehicles highly attractive, particularly for use in confined urban environments or indoors. Their applications are diverse, including ☞

indoor navigation, civil reconnaissance, public security, mapping, surveying and monitoring, digital elevation modeling, general photography, and more.

However, an analysis of the figure of merit (FM) in [6] revealed poor performance for MAV-scale rotors, resulting in limited hovering endurance. Additionally, only a few rotary-wing systems integrate additional sensors. The FM decreases from 0.8 for conventional manned rotorcraft to between 0.45 and 0.55 for existing MAVs. This poor aerodynamic performance is due to a low operating Reynolds number and increased relative viscous effects.

In general, both fixed-wing and rotary-wing designs have been extensively studied over the years. However, they all face challenges related to vehicle miniaturization and reduced Reynolds numbers. These limitations have driven researchers to explore flapping-wing mechanisms.

2.3. Flapping wing

The flapping-wing concept draws inspiration from birds and insects, which generate both lift and thrust by flapping their wings. MAVs fall within the size range of the smallest birds and the largest insects. At this scale, these vehicles experience significant viscous effects due to a lower Reynolds number. As shown in Figure 1, smaller flying animals or vehicles correspond to lower Reynolds numbers. Additionally, the constant acceleration and deceleration of the wings during stroke reversal create highly unsteady aerodynamic conditions. However, nature has already mastered this flight mechanism, prompting researchers to replicate the flapping-wing technique of birds and insects in laboratory experiments.

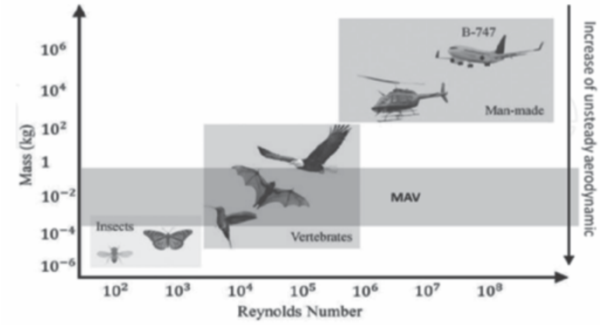


Figure 1. Reynolds number range for flying bio-systems and flying vehicles adapted from [7].

It is important to differentiate between bird-like and insect-like flight techniques, as they operate on fundamentally different principles. Birds primarily move their wings up and down while making slight adjustments to the angle of attack during flight. This motion simultaneously generates both lift and thrust, though the thrust is relatively weak, requiring forward motion to sustain flight. As a result, most birds cannot hover, except for hummingbirds, which employ an insect-like wing movement. In contrast, insects flap their wings along a nearly horizontal plane [8], with significant and rapid variations in the angle of attack. These large changes allow insect-inspired flying mechanisms to achieve a higher lift-to-weight ratio than bird-like methods, enabling them to hover, take off, and land vertically. Additionally, insects demonstrate remarkable flight capabilities, including hovering, flying backward, and recovering from impacts–all while maintaining efficient energy consumption. Despite these advantages, current flapping-wing micro air vehicle (MAV) designs still underperform compared to fixed-wing and rotary-wing MAVs. However, ongoing research continues to explore ways to improve their flight efficiency.

To summarize, various MAVs (as of 2014) are analyzed in relation to weight and flight duration, as illustrated in Figure 2. Different colors–violet, blue, and red–represent fixed-wing, rotary-wing, and flapping-wing vehicles, respectively. Fixed-wing MAVs, such as the Micro Star and Black Widow [9], demonstrate longer endurance compared to other designs but lack hovering ability and tend to have a higher mass, making them less suitable for certain applications. Rotary-wing MAVs, including the Crazyflie [10] and Ladybird, excel in hovering, vertical takeoff, and landing, making them highly maneuverable and suitable for indoor use. However, their flight duration is generally short and decreases significantly as their size is reduced, as seen with the Picoflyer. At smaller scales, flapping-wing designs tend to perform better than both fixed-wing and rotary-wing MAVs. For instance, the Delfly II [11], which has a similar weight to the Crazyflie, can fly eight minutes longer, and when compared to the Ladybird, which is twice its weight, it lasts nine minutes more. Nonetheless, not all small flapping-wing MAVs surpass rotary-wing designs; exceptions like the Black Hornet [12] perform as efficiently in hovering as the AV Hummingbird [13].

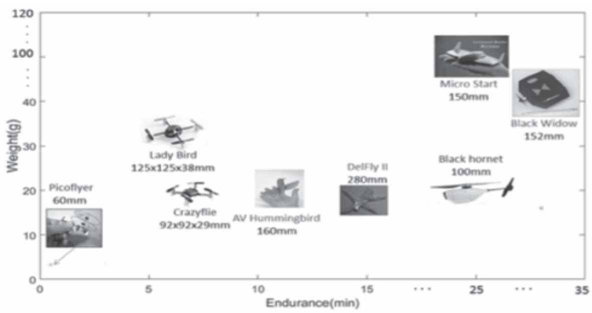


Figure 2. Relationship between weight and flying time of existing MAVs (2014 data). Names of fixed, rotary, and flapping-wing vehicles are in violet, blue, and red, respectively. Only crucial dimensions corresponding to each wing category are displayed to indicate the vehicle size. For instance, wingspan depicts the size of flapping and fixed-wing MAVs, while the 3D dimensions of quadrotor and rotor diameter are used for other rotary-wing vehicles.

To develop a MAV capable of operating in enclosed and confined spaces, the fixed-wing design discussed in Section 2.1 is not a viable option due to its inability to hover. The rotary-wing type, described in Section 2.2, offers excellent maneuverability; however, its flight endurance significantly decreases as the vehicle size is reduced. In contrast, the final category, which utilizes insect-like wing kinematics, appears to be the most suitable, as it combines both versatility and durability. Consequently, this last category is the best fit for achieving the intended objective.

3. WING KINEMATIC SELECTION AND AERODYNAMIC

The remarkable flight abilities of insects and birds are largely attributed to their wing kinematics and the aerodynamic forces they generate. In nature, these two groups exhibit distinct flight mechanisms based on their wing-flapping strategies. While most birds flap their wings in a predominantly vertical motion with minor adjustments to wing pitch, insects utilize a nearly horizontal flapping plane with significant variations in pitch angle [14].

Compared to birds, insect wing kinematics are more intricate. Although there are multiple variations, the fundamental movements can be categorized into four main motions: downstroke, supination, upstroke, and pronation, as illustrated in Figure 3. The downstroke and upstroke involve translational movement along the stroke plane, whereas supination and pronation consist of rotational movement around the wing's pitch axis. At the end of each stroke, the wing reverses direction and adjusts its pitch angle for the next cycle. Even during the translational phase, the angle of attack continuously varies, typically averaging ☞

around 35° at a 70%-span position [15]. Throughout the flapping cycle, the wing tip traces a banana-shaped or figure-eight pattern in the stroke plane. By altering the stroke plane's slope and adjusting the symmetry between half-strokes, insects can achieve forward and backward flight as well as hovering.

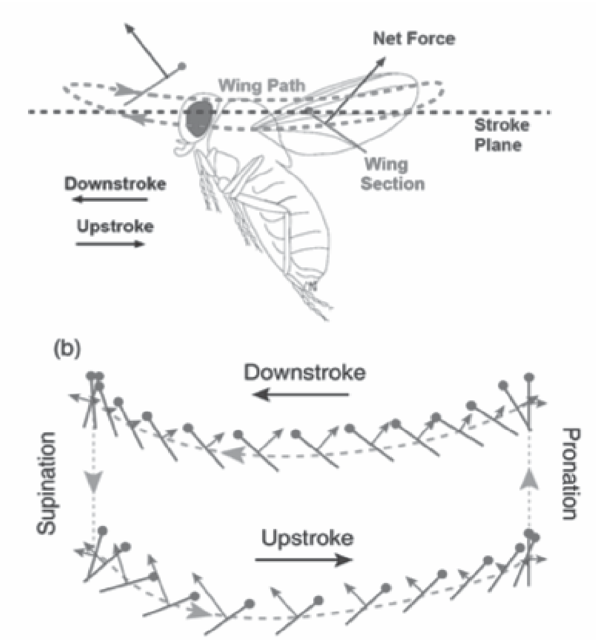


Figure 3. Basic flapping wing kinematics: a) Wing path described by the trajectory of a particular wing chord; b) Snapshots of this wing chord during upstroke and downstroke demonstrating its translational motion and stroke reversal including supination and pronation [16], [17].

In summary, insect-inspired bioflight provides a highly maneuverable and hover-capable solution for MAV designs.

Alongside insect-inspired wing kinematics, a wide range of aerodynamic mechanisms have the potential to enhance MAV performance. However, these unconventional effects are challenging to model and replicate due to the complexity of their interactions, and many aspects remain unexplored. Despite this, their benefits are undeniable. For example, selecting an appropriate flexible component for a passive flapping wing can enhance lift through improved wing rotation, a phenomenon known as the Kramer effect [18]. Another notable mechanism is the clap-and-fling effect, utilized in designs such as the Delfly [11] and the Mentor [19], which helps generate additional lift. Further details on these mechanisms can be found in [2].

4. WING ACTUATION MECHANISM SELECTION

Birds and insects rely on powerful muscles to actuate their wings, but the structural configurations differ significantly based on their size. Since birds are relatively large, they have the capacity to integrate muscles, feathers, and multiple joints into their wings. Bird wings consist of three main joints–shoulder, elbow, and wrist–where the breast muscles power wing beats, while smaller muscles refine wing shape during flight. This enables birds to adjust both wing span and shape, allowing them to adapt to different flight modes [20].

In contrast, insect wings are simpler in structure, primarily consisting of a membrane and veins, with minimal shape variation during each stroke. However, their flight mechanism is unique due to the way their muscles are attached to the wings. Insects generate flapping motion through two primary methods [21]. The first involves direct flight muscles, commonly found in four-winged insects like dragonflies and damselflies. This system allows agile movement but limits flapping frequency. The second method uses indirect flight muscles [22], seen in advanced insects such as bees and flies. Here, the muscles interact with the thorax, functioning as a resonant structure, allowing insects to flap their wings at much higher frequencies with synchronized motion.

5. REVIEW OF COMPONENT SELECTION FOR FLAPPING MAVS

5.1. Flapping-Wing Actuators

To replace the powerful flight muscles found in nature, one of the most common solutions for MAVs is the use of DC motor-driven actuators [11], [23], [24], [25]. These motors are widely used due to their ability to generate large output angles with a low operating voltage. Additionally, they are durable, easy to control, and already widely applied in macro-scale robotics, making them a practical choice for MAV propulsion.

5.2. Tail, Sail, and Tailless Designs

Flapping-wing MAVs can achieve passive stability without requiring an onboard autopilot or inertial measurement unit by incorporating a tail or sail, which act as dampers for rotational movements [11]. Similar to fixed-wing aircraft, a tail can be used to control flight direction.

A tailless configuration more closely resembles the flight of insects but results in passive instability. Consequently, maintaining stable flight requires a sophisticated control system involving an inertial measurement unit, a control mechanism, and precise wing movement regulation. The Nano Hummingbird [26] was the first tailless MAV to achieve controlled flight, while the Harvard RoboBee [27] remains the smallest and lightest nano air vehicle (NAV) capable of hovering with external control. The BionicOpter, modeled after a dragonfly, was developed by Festo [28] as a technology demonstrator.

5.3. Number of Wings

Traditional MAV designs often mimic bird wings, as seen in the Robo Raven and RoboBee [29], [30], [31], with two wings that may operate dependently or independently. Other designs, inspired by dragonflies, feature two pairs of wings flapping in parallel stroke planes, as demonstrated by the BionicOpter [28]. Some MAV configurations, like the Delfly, do not directly replicate natural flyers but instead use two pairs of wings flapping in the same stroke plane. This arrangement enhances lift by taking advantage of the clap-and-fling effect.

5.4. Wing Rotation Principles

The ability to adjust the angle of attack plays a crucial role in lift generation. Birds and insects actively manipulate wing rotation through their natural wing structures. Researchers have successfully replicated this process in mechanical MAV designs by controlling both the angle of attack and wing membrane twisting [25], [26]. However, these mechanisms are complex, require precise engineering, and significantly increase the overall weight of the vehicle.

To address these challenges, passive wing pitch mechanisms have been introduced. Observations of hovering insects such as dragonflies, fruit flies, and hawkmoths reveal that aerodynamics and wing inertia alone can induce wing rotation without muscular input [32]. This passive approach has been successfully implemented in various flapping-wing MAVs [24], [33], [34], [35], [36], [37], [38]. In many cases, a flexible component is integrated into the wing structure to facilitate passive rotation. Some designs use flexibility ☞

in the leading edge to generate twisting motion [34], while others incorporate stoppers to limit wing rotation at a specific angle [37], [36]. However, stoppers can lead to vibrational instabilities and potential wing damage. While active wing pitch control provides greater precision, it also adds weight and complexity, making it more suitable for MAVs with higher payload capacity. In contrast, lightweight passive wing pitch mechanisms are more commonly found in both MAVs and NAVs.

In general, DC motors remain the preferred choice for MAV actuation. The decision to use a tail, sail, or tailless configuration depends on the specific design goals. A sail simplifies control but reduces versatility and deviates from natural flight dynamics. A tail enhances maneuverability but adds complexity to linkage mechanisms and increases overall weight. Tailless designs, particularly those with two or four wings, closely resemble biological flyers but require advanced electronic control systems to maintain stability. Ultimately, for the MAV under consideration, a passive wing pitch mechanism provides the most effective balance between weight, complexity, and flight performance.

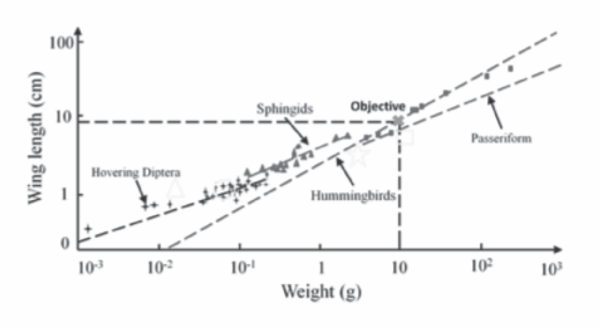
6. SUMMARY AND DESIGN MOTIVATION

After evaluating different types of MAVs based on wing configurations in Section 2, flapping-wing designs emerged as the most promising, particularly for small-scale vehicles. Sections 3 and 4 explored insect-inspired wing kinematics and actuation mechanisms, emphasizing the aerodynamic challenges faced when designing small flying vehicles. These challenges, however, open opportunities for performance improvements, such as utilizing the clap-and-fling effect or delaying stall. Section 5 provided a comprehensive review of existing MAVs, categorized by their actuators and geometric structures, offering valuable insights from previous research. Building upon this knowledge, the final MAV design is now determined.

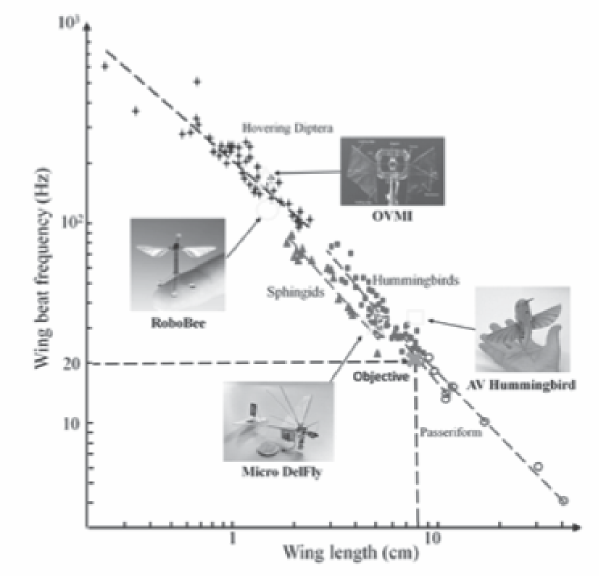
An insect-like MAV is undoubtedly the most suitable choice, closely resembling the hummingbird in terms of size and weight. The hummingbird stands out as the only bird capable of hovering with wing kinematics similar to insects, making it an ideal biological model for this design.

With the goal of developing a hummingbird-inspired flapping MAV, two key specifications must be defined: wingspan and total mass. Figure 4a illustrates a linear relationship between the weight and wing length of natural flyers, indicating that heavier flyers possess longer wings. Based on this correlation, the appropriate wing length for the MAV can be selected according to its total weight. Considering the available materials, the estimated total mass of the vehicle, including the electrical circuit and battery, is approximately 10 grams. Using the hummingbird as a reference (red dashed line in Figure 4a), this weight corresponds to a wing length of approximately 8 cm.

Additionally, Figure 4b plots wing length against flapping frequency in natural flyers, helping to estimate the MAV’s required flapping frequency. The data suggests that insects flap their wings at higher frequencies than birds, with frequency increasing as wing length decreases. Several successful flapping-wing MAVs are included in this comparison to validate the bio-inspired approach. Designs such as RoboBee and OVMI align with insect-like flight characteristics, while DelFly Micro and Nano Hummingbird fall within the bird-like category, specifically matching hummingbirds. Given a wing length of 8 cm, the 10-gram MAV fits within the hummingbird's range, suggesting an optimal flapping frequency close to 20 Hz.



a)



b)

Figure 4. Relationship between a) wing length and total mass, b) wing length and flapping frequency, adapted from [39]

With a defined flapping frequency and target mass, selecting a suitable actuator becomes possible. As discussed in Section 5.1, a motor is a practical option for flapping MAVs, offering a wide range of input power options. Furthermore, using a motor simplifies construction, reduces manufacturing complexity, and minimizes assembly challenges, making it a highly efficient choice for this design.

7. CONCLUSION

In conclusion, after reviewing various UAV designs and relevant theories, the decision was made to develop a flapping-wing MAV modeled after the hummingbird. This design features a 10-gram mass, an approximate wing length of 8 cm, a flapping frequency near 20 Hz, and is powered by electric DC motors.❖

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