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Experimental Studies of Tail Shapes for Hummingbird-Like Flapping Wing Micro Air Vehicles

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ABSTRACT The stability of flying of a hummingbird-like flapping-wing micro air vehicle (MAV) has been challenging. In this paper, experimental studies are reported on the tail shapes of hummingbird-like flapping-wing MAVs, since tails play an important role in-flight stability. Dynamics parameters of hummingbird tails are firstly studied and evaluated. Then man-made tails inspired by the natural hummingbirds are designed, manufactured and optimized for experimental tests. The results show that lift generated by the tail is independent of a fan angle, whereas the pitch moment is related to the fan angle. Further, the tail can be applied to stabilising hovering twin-wing flapping wing MAVs.

INDEX TERMS Hummingbird tail, flapping wing MAV, hovering flight, tail design, tail fabrication.

I. INTRODUCTION

Currently, many of flapping-wing MAV inspired by the natural flyers from large birds to tiny insects are studied. Hummingbirds, as the smallest birds in the world from about 2 grams to nearly 20 grams [1] have been studied by plenty of researchers, due to not only the agile flight and manoeuvrability but also hovering flight. However, many elements, such as the aerodynamics of flapping wings, body dynamics, sensory system, neural control and wing, and tail action, result in the superiority of hummingbird flight, shown in Fig. 1. These elements make a complex close-loop to achieve amazing flight capability. To understand the interaction between these various systems, many studies on natural hummingbirds are done including aerodynamics, wings, tails, morphology, etc. For example, hummingbirds have distinctive morphology compared with other birds, like hummingbird forearm bones and the upper arm are significantly shorter [2], so they can fly in hovering. Hummingbirds are characterized by high flapping frequency, small strains and a highly supinated wing orientation during upstroke or down-stroke that generate lift force in both halves of the stroke cycle. In hovering, the body axis is inclined at a desirable angle and wing flaps an eight-like pattern in the vertical plane, see in Fig. 1. And their wings are connected by the muscles and skeletal joints and may flex or rotate different segments according to aerodynamic demands.

Hummingbird's super agility has highly attracted attention and currently inspired the development of flapping-wing MAV since they are able to perform the desired task in a dangerous or inaccessible environment such as aerial photography, patrolling, search and rescue, law enforcement, aerial mapping, terrain reconnaissance, etc. Over the last decade, the studies of hummingbird's morphology were done, such as muscles [3], skeleton structure [4], [5], aerodynamics [6]–[9], wings [10]–[13] and tails [14]. Besides, some researchers have developed flapping-wing MAVs inspired by the nature flyers such as bee, beetle, dragonfly, hummingbird such as Harvard Robobee [15], Nano-hummingbirds [16], KUBeettle [17], Delfy [18], Flowerfly [19], Festo-Dragonfly [20], Festo-Butterfly [21], Colibra [22], Giant hummingbird [23] and Festor-Seabirds [24]. And a review concerning natural hummingbird to hummingbird-like flapping wing MAV is comprehensively

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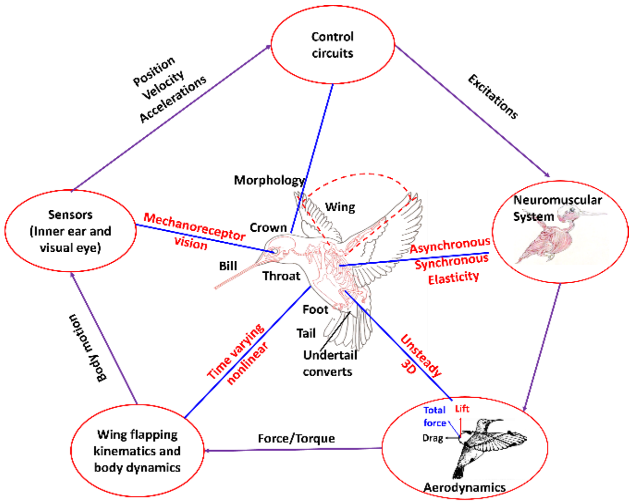

FIGURE 1. Elements in the flapping wings of a hummingbird.

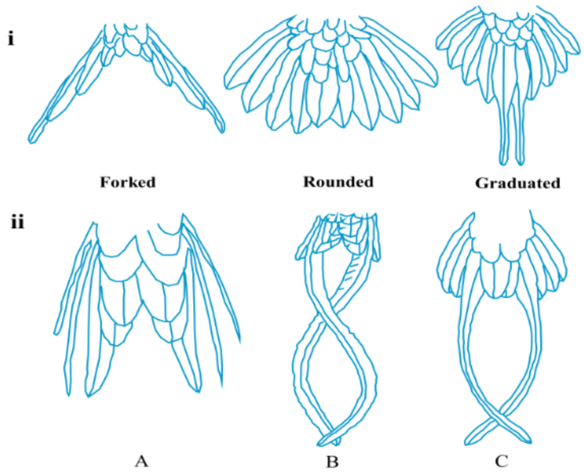

FIGURE 2. Examples of Hummingbirds' tails: i) generic tails of hummingbirds: fork, rounded, and graduated; ii) special tails of hummingbirds: A-C.

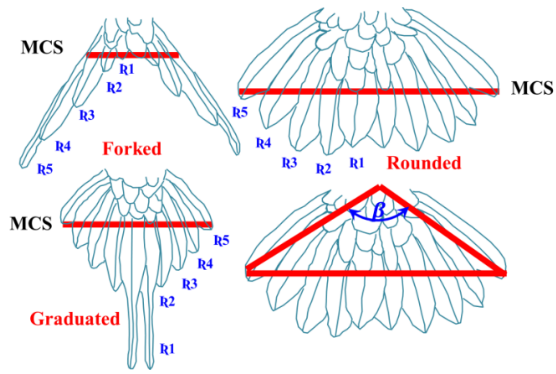

FIGURE 3. Tail shape and spread angle. R is represented the rectrix feather of a tail.

studied by Nan [25]. However, these flapping wing MAVs are almost tailless. In nature, the tails play an important role in maintaining stability over a range of flight speeds and in generating lift and drag to help with roll, pitch and yaw turning and slow flight, since they vary as much as their wings, or even more [26]. Therefore, the aerodynamic performance studies of tail shape are meaningful and significant for a stable flight of flapping wing MAVs.

In this paper, the natural hummingbird's tail morphology is studied first, followed by designing, testing and optimizing the artificial tails. Then the aerodynamic performance of tails is evaluated through experiments, with results and discussions presented.

II. TAILS DESIGN AND STUDY

A. MORPHOLOGY OF TAILS

The tail shapes and morphology of birds are naturally selected by gender. The birds' tails have intricate and distinct shapes particular in sexually dimorphic species. Many birds have a long and elaborate tail as a sexual ornament since long and elaborate tails can enhance mating success for female choice [27]. However, flight performance might constraint such ornamental diversity [14].

Universally, the birds that need high manoeuvrability to feed aerially and avoid a collision in cluttered environments have longer tails, whereas birds with high lift-to-drag ratio have relatively short tails since a long tail could reduce a bird's overall lift-to-drag ratio [14]. Although different birds select different tail shapes, they have a common feature, namely, the tails play an aerodynamic role in flight and produce lift and drag [28]. Birds' tail directly affects stable flight, and they can use their tails to operate body turns. In terms of a natural glider, they perform symmetrically banked turns and reorient laterally the vertical force, and the yaw turn is finally realized [30], whereas hummingbirds realize pure yaw turns by just flapping wings symmetrically [29] or asymmetrically [31]. Meanwhile, hummingbird may use tail spreading to avoid extreme sideslip, roll, and pitch in a short time [32], particular in turbulent surroundings, hummingbird may increase aerodynamic force and/or improve stability by increasing mean stroke amplitude, stroke plane angle and tail fanning angle [33].

The generic tail shape has 7 different categories such as squared, forked, rounded, double-rounded, cleft, wedged and graduated. Then to investigate 18 species natural hummingbirds, the fan-shaped, squared, forked, notched (Cleft) and rounded tails are general, which takes up 50%, 16.7%, 16.7%, 11.1%, and 5.6%, respectively. Some examples of general hummingbird's tail see in Fig. 2 (i) and the special tail shapes are not discussed in this paper, seen in Fig. 2 (ii).

All hummingbirds have five bilateral pairs of rectrices (the tail feathers are called rectrices) that individually vary in length and shape [14]. The number of rectrices is marked from medial R_1 to lateral R_5, seen in Fig. 3. From such figure, outer tail feathers are longer than the middle pair in the forked tail, and feathers increase in length from the central pair to the outer pair. That is, R_5 is the longest of rectrice, whereas

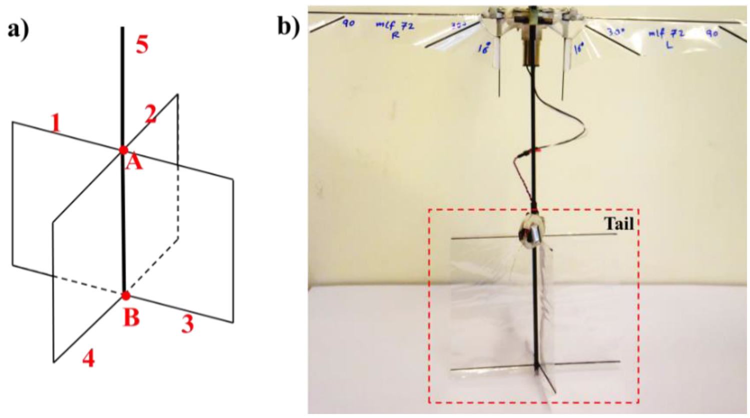

FIGURE 4. **Cross-X shape tail mode (a): Fixing four carbon bars on the prepared tools before glueing bar 5 on points A and B, then cutting out four suitable pieces Maylar to glue on the frame before making well; and (b) tail prototype.**

R_1 is the shortest one. By contrast, as for graduated tails, R_1 is the longest and R_5 is the shortest rectrix. All rectrices in rounded tails are of almost the same length, feathers increase in length from the outer pair to the middle pair. The length of the longest rectrix is 20% more than that of the shortest one.

Bird's tail can be controlled independently, but they are spread the same degree on each side when flying. The maximum continuous span (MCS) is the widest distance of the unbroken surface area of a tail, from R_5 to R_5 on both lateral sides. The spread angle is the angle between the outermost rectrices presented by β, seen in Fig. 3. When this angle is above a critical value, the gap between individual tail feathers appears. By contrast, the edges of neighbouring tail feathers overlap when this angle is smaller than the critical angle. Therefore, the tail surface (S_t) [14] can be roughly approximated as

$$S_t = \frac{1}{2} R_n^2 \beta \tag{1}$$

where, R_n is the average length of the tail feather.

B. FORK RATIO

In nature, there are various kinds of tail shapes such as a forked tail, squared tail, rounded tail, graduated tail, wedged tail. The square, forked and rounded tails are the basic, other tail shapes can derive from these three types. Fork ratio (FR) is rather important, which normally determines the tail shape. It is defined as the R_5 length divided by the R_1 length, which is presented as

$$\mathrm{FR} = \frac{R_5 \text{ length}}{R_1 \text{ length}} \tag{2}$$

When the fork ratio is higher than 2 (FR > 2), the tail shape can be roughly defined as an elongated forktail. The optimal fork ratio is FR $= 2$ at $\beta = 120°$ [26], but this spread angle is not general. After that, it is also explored that the optimal fork ratio is 1.2 when $\beta = 67°$. When the fork ratio is in the range of $1.2 <$ FR < 2, the tail shape can be regarded as a moderate fork. As for the rounded tail, the fork ratio is in $0.83 <$ FR < 1.2, whereas the graduated tail may be achieved at FR < 0.83.

C. TAIL ASPECT RATIO

Tail aspect ratio (AR_t) [34], similar wing aspect ratio, is a measure of the shape of the tail and impacts the aerodynamic performance. It is defined as the square tail span divided by tail surface, which is given by

$$AR_t = b_t^2 / S_t \tag{3}$$

where, b_t is the tail span which can be calculated by $b_t = 2R_5 sin\frac{\beta}{2}$ and S_t is the tail surface.

Combination of Equation (1) and (3), the tail aspect ratio can be rewritten as

$$AR_t = \frac{b_t^2}{S_t} = \frac{2b_t^2}{R_n^2 \beta} \tag{4}$$

According to the equation, the tail aspect ratio in certain species is obtained, which is summarized in Table 1.

To compare morphologies, the spread angle is hypothesized to be constant, whereas the spread angle actually varies with flight posture.

III. AERODYNAMICS OF HUMMINGBIRDS

A. TAIL DESIGN

As has been mentioned earlier, the goal of the present study is to find the tail performance on stable flying. We firstly started with a Cross-X shape of a tail as a basic tail and it is similarly designed by existing flapping wing MAVs Flowerfly [19], seen in Fig. 4. The components of the tail assembly include a frame from carbon bars, tube and tail platform itself, made of Mylar membrane. Mylar was chosen due to its light-weight, strong and durable. The tail has two sub-frames, then fixed down by glue. The tails themselves are hand-made. Production of a tail takes about 40 mins as well as is repeatable. Unfortunately, it is easier to tear and break down when flapping-wing MAV with tail flaps in high

TABLE 1. Tail aspect ratio in certain species (adapted by [34]).

Species	Kestrel	Sparrowhawk	Peregrine falcon	Black kite	Pigeon	Buzzard	Gull	Eagle
AR_t	0.3	0.4	0.6	0.7	2.1	1.5	1.8	1.8

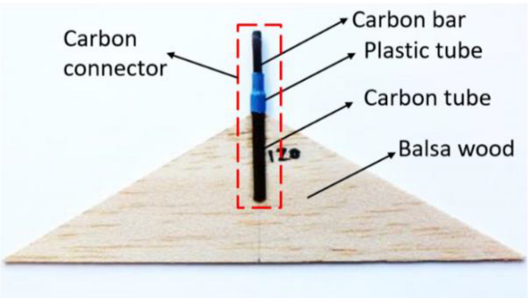

FIGURE 5. Baseline tail after assembly. 2 To install the tail, a 3 tube with slot was made before the tail was put it into the 4 slot and then was glued. Then, it was attached to the 5 flapping mechanism with a connecter.

TABLE 2. Specification of the tested detail materials.

Tail type material	Thickness
Balsa wood	1.0 mm
Balsa wood	1.5 mm
Balsa wood	2.0 mm

frequency. Therefore, such a tail shape study is stopped. But, importantly, via experimental study on such tail, we found that the lift and pitch moment was proportional to the tail position, which promoted us to study further on different tails. Also, such kind of the tail was successfully applied to the passive stability of flying [35].

After that, another tail inspired by the natural hummingbirds was designed. The components of the tail assembly include a frame from carbon tubes, and the tail planform itself, made of balsa wood with 1 mm that not influence planform deformation when flapping, see Fig. 5. The balsa wood was selected as it is a light-weight yet strong and durable material. The 1 mm thickness was chosen as thinner material was too prone to tearing. Other materials, such as 1.5 mm, 2.0 mm, were also tested, but the achieved performance was slightly worse due to higher weight, see Table 2. So the other material is not studied in this paper.

The tails themselves are hand-built. However, a manufacturing technique different from other flapping wing MAV like Defly, shown in Fig. 6, was developed to achieve sufficient repeatability. Production of a tail takes about 20 mins. In order to fix well tail into the carbon connector, the tail is glued into it.

Before producing the tail, the tail is designed using CAD software (Solid Edge), then prints it. The manufacturing tail mainly has six steps, seen in Fig. 6: 1) the printed paper is taped on the platform then fixed it, 2) The curve contours of the future tail are firstly cut out, 3) the straight contours are cut out. 4) The cut tail shape paper is put onto the balsa wood and taped it. 5) and 6) cutting the tail along the contours of the tail. Then the tail is made.

To design the tail, the natural hummingbird tail is investigated. According to the relation between the maximum length of tail feature and body mass of hummingbirds [27], 20 g weight of hummingbirds is approximately response to about the 70 mm length of the maximum length of tail, seen in Fig. 7. Therefore, the maximum tail, 70 mm – long, is made.

We started with the 70 mm length as a basic, which was used throughout the development of the tail study. To understand the effect of each parameter, we adopted an iterative process and varied only one parameter at a time. In total, 3 different tails were built and tested. Their parameters are presented in Table 3. From discussed above, the optimal fork ratio is 2 at $\beta = 120°$, whereas when $\beta = 67°$ the optimal fork ratio is 1.2. Thus, the tail performance with two spread angles is to be studied in this paper. First, the effect of the spread angle was investigated. Tail-R_{67} and Tail-R_{120} were made keeping the same shape, but the tail surface, aspect ratio, and span are different. Second, to investigate the shape effect, keeping the same spread angle, aspect ratio and Span, the tail surface and tail shape are changed.

B. EXPERIMENT SETUP

To investigate the tail's aerodynamic performance, an experimental setup consisting of a force balance, voltage amplifiers, and a digital signal processing system (DSP) was constructed. Its overview is illustrated in Fig. 8. The setup was used to measure the motor voltage, current, flapping frequency (about 25 Hz), force and moment generated by the tail. In this study, double beam cantilever force sensors with strain gages in full-bride configuration, coming from low-cost precision scales, were used. Their advantage is that they are insensitive to the axial force as well as to the bending moment. The designed balance uses two of these single axis force sensors, so that lift and moment can be measured at the same time. The measured forces when flapping are relatively small (order of 0.01 N), but of a lift and drag, which tends to excite the vibration in the system. So the measured efforts are a combination of aerodynamics and inertial forces.

The working principle of the force balance is shown in Fig. 8 (b). The robot, represented by the lift force L and the moment M, is connected to the right end of the lower beam,

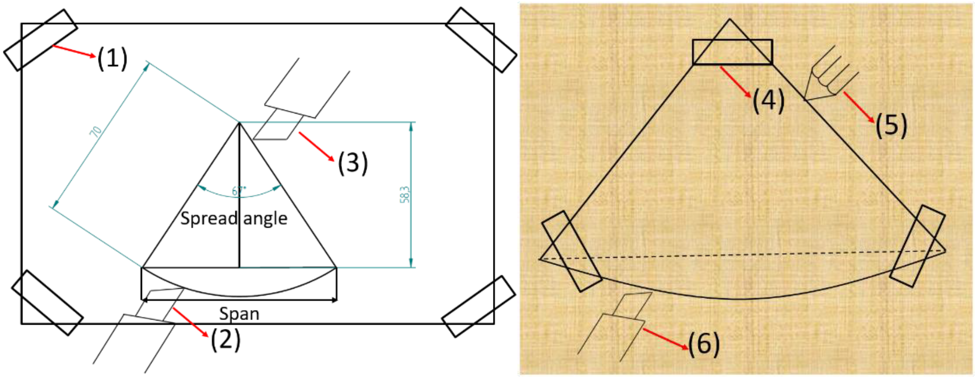

FIGURE 6. The principle steps of tail production.

TABLE 3. The geometric parameters of tail.

	Spread angle β	Tail Surface S_t(mm^2)	AR_t	Span b_t (mm)
Tail-R_{67}	67	2863.5	2.08	77.2
Tail-R_{120}	120	5128.7	2.86	121.2
Tail-T_{120}	120	2123.1	2.86	121.2

R- Rounded tail, T - Triangular tail. R_{67} is the rounded tail with 67°, R_{120} is the rounded tail with 120°, and T_{120} is the triangular tail with 120°.

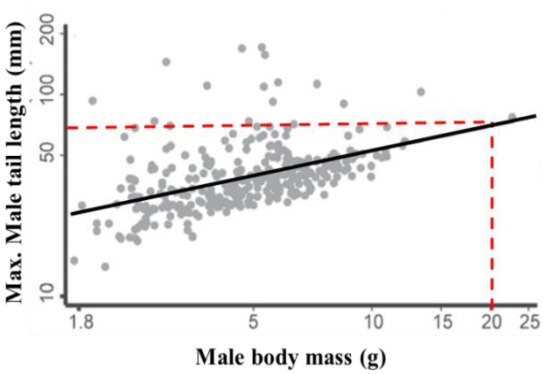

FIGURE 7. The relation maximal male tail length against body mass of natural hummingbird (adapted by [14]).

which can rotate around hinge point C. the left end of this beam is connected to sensor 2. The hinge at point C is held by a base, which also holds sensor 2. This whole assembly is connected to sensor 1. The sensor forces are obtained by the static equilibrium of the balance as

$$S_1 = L \tag{5}$$

$$S_2 = \frac{M + LA_1}{A_2} \tag{6}$$

The assembled force balance is given in Fig. 8 (c). Each sensor is connected to custom build an electronic circuit that provides stabilized power to the bridge and amplifies the bridge output. The balance is designed to measure the pitch moment of the flapping prototype. Moreover, the prototype attachment can be rotated by 90° to also measure the roll moment. The experiment setup in detail sees in paper [36].

The developed hummingbird-like flapping wing MAV was applied in this study, seen in Fig. 9. The flapping wing MAV prototype is composed of four main components: the driving brushed DC motor, flapping mechanisms, wings, and tail. The frame and links are 3D printed using Digital-ABS composite photopolymer material and Stratasys PolyJet technology. A gear with injection-moulded gears is applied. The links are connected by aluminium and steel rivets. The wing bars are made of the carbon-fibre-reinforced polymer rods.

IV. RESULTS AND DISCUSSION

We present the experimental results of the mean lift force and moment generated by the tails in this section. In this study, the tail, no flapping, is fixed on the robot in an assigned angle position and then robot is fixed on the experiment setup. We use the same robot prototype and wings over the testing and then measured the lift force and moment. For each tail, we set the tail at five different fan angle positions. Fan angle (α) varies from −15° (tail down) to 15° (tail up), seen in Fig. 10. (Fan angle can be regard as tail flapping amplitude in this paper.) The wings, made of Mylar with 90 mm length, the aspect ratio of 9.3, are applied in this study. The DC motor is operated at 3 V responding to the flapping frequency at 25Hz. The motor can be operated even at higher voltages where, however, a slow performance decrease was observed over time due to increased temperature and wear

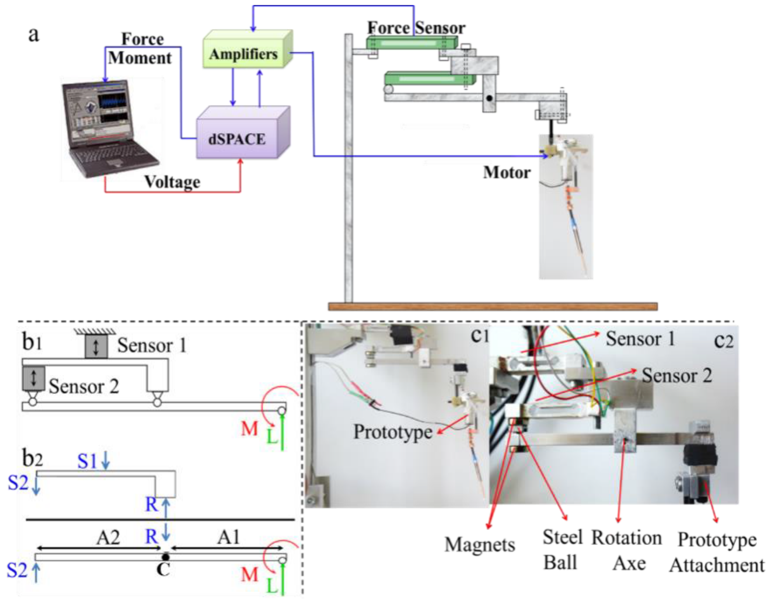

FIGURE 8. The experimental setup. Schematic diagram of the complete setup (a), the working principle with a free body diagram (b1+b2), the photos of the physical implementation (c1+c2) [36].

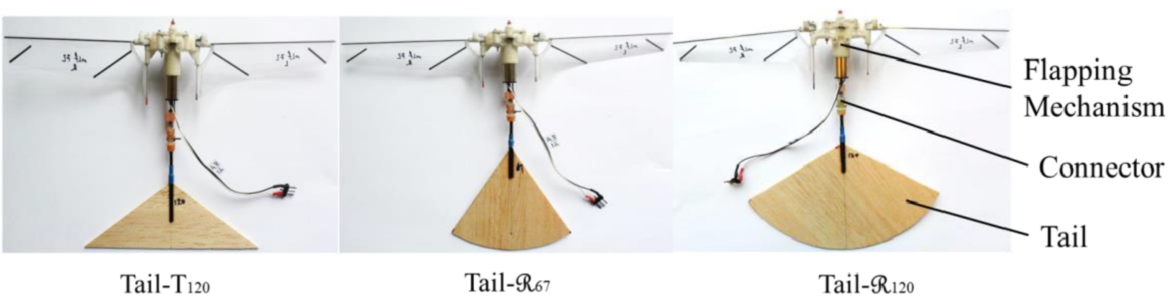

FIGURE 9. Assembled prototype with wing and tail.

of the brushes. Each measurement sequence was carried out three times in a row, and we present the data in the form of mean values. The measurement error is approximately ± 0.5 mN for the lift and $\pm$ 0.05 N.mm for the moment. The other parameters (voltage, current, flapping frequency) are averaged in the same way. The flapping frequency is estimated from the variation of the motor current due to varying load within a single wingbeat. The current signal is low-pass filtered and the period of the variation is detected online. Thanks to a high sampling rate of the digital signal processing system (2 kHz), and subsequent averaging over the measurement interval, a prevision below 0.1 Hz was achieved.

The aim of the study is to assess the aerodynamic performance for three kinds of tails. To fairly compare the tail performance, the same voltage and flapping frequency of the wing were set up for each test. The measurement results are highlighted in marks, which are presented in II. From this figure, it is observed that the generated force of tail is approximately constant in five positions, which is different from the states that hummingbird might increase aerodynamic force and/or improve stability by increasing the mean stroke amplitude, anatomical stroke plane angle and tail fan angle [37] as well as different from the test results of Cross-X shape tail. This may be because the flapping-wing robot's body is fixed on the frame, and the tail is rigid without a camber angle. Also, it is found that the lift rises with tail surface and spread angle increase through comparing tail R_{67} and R_{120}, shown in II (left). However, by comparing the tail R_{67} and T_{120}, the generated force by tail R_{67} is slightly smaller than that of tail T_{120}, although the tail surface of tail R_{67} is slightly greater than that of tail T_{120}, this might be related to the spread angle and tail shape. The force generated by tail R_{67} and T_{120} is similar, so the pitch moment generated by both kinds of tails is equally similar, which is considerably less than that of tail R_{120}.

Overall, the tails play a significant role in stable flying by generating force and moment, so it can be utilized to the

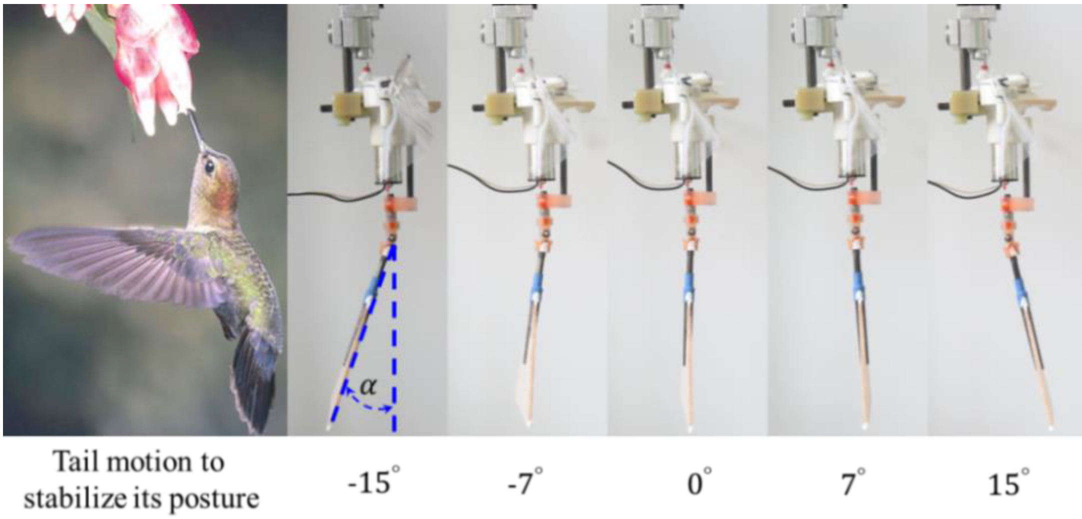

FIGURE 10. Hummingbirds control tail to stabilize the attitude (left), and tail position varies from −15° to 15° (right). (A connector is made and utilized to connect the tail and prototype and can be turned so that the tail can be adjusted).

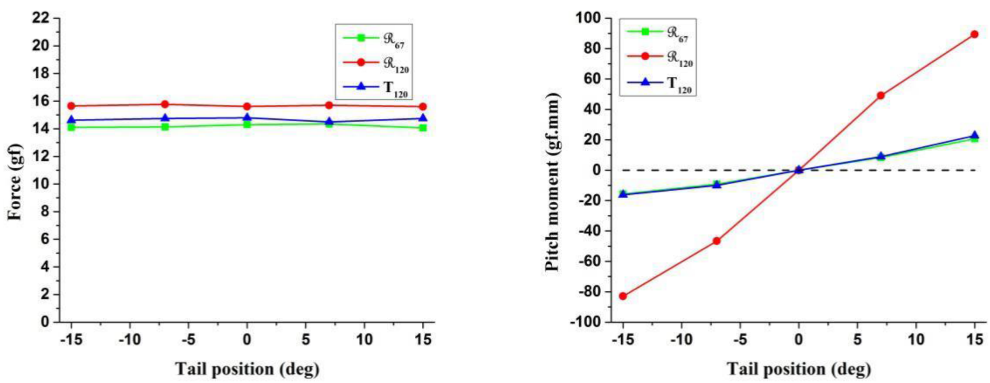

FIGURE 11. Lift vs. tail position (left), pitch moment vs. tail position (right).

flapping wing MAVs to stabilize its flight. That is to say, the posture of flapping-wing MAVs can be performed via adjusting the position of the tail, which is firstly presented and trialled in twin-wing hovering flapping wing MAVs. In the previous study of twin-wing hovering flapping wing MAVs, the wing twist modulators [17], [23], [38], [39] were universally employed to produce pitch and roll moment then achieved the stability of flapping wing MAVs.

Our future research includes the following aspects: (1) MAV applications to agriculture, such as autonomous pollination [40]; (2) high efficiency and reliability in design for the MAV's key components [41]–[47] using new AI algorithms, with the support of the parallel CIAD framework [48].

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