Aerodynamic performance of a bird-inspired morphing tail

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Abstract
Flying animals such as insects, bats, and birds have acquired the ability to achieve diverse and robust flight patterns in various natural environments. Their sophisticated morphologies, kinematics, and dynamics have motivated engineers to develop bioinspired flying robots. Particularly, the capabilities of morphing wing and tail controls in birds have received significant attention. Such controls are expected to introduce novel mechanisms to achieve flight stabilization while maintaining high maneuverability with a low energy cost. While the control of tail posture and motion is considered to exhibit a significant influence on flight performance, there have been few studies focusing on control with multiple degrees of freedom in small flying robots. In this study, we developed a bird-inspired morphing tail mechanism; a model was fabricated and investigated its aerodynamic performance through wind tunnel experiments. The results indicate that the tail attitude can be controlled effectively to enable the enhancement of aerodynamic performance in terms of mechanical efficiency and controllability. We also verified that controlling the tail attitude is redundant in the control of aerodynamic force and moment production, implying the potential capability to achieve stable flight control strategies in response to various disturbances. Therefore, our results indicate that tail-attitude-based aerodynamic control may be able to cope with the conflicting requirements of improving stability and maneuverability of flyers.

Keywords : Bird tail, Tail feather, Aerodynamic performance, Drone, Micro air vehicle (MAV)

1. Introduction

Flyers such as birds and drones are affected by unpredictable winds originating from the atmospheric boundary layer (Watkins et al., 2020). Wind disturbances pose a challenging problem for drones. In contrast, birds are equipped with functions to achieve stable flight in unpredictable winds based on long-term evolution. They have enriched sensory organs called mechanoreceptors in their bodies and are able to detect changes in wind speed and pressure using these organs to react to disturbances (Brown and Fedde, 1993; Xu et al., 2014). For example, Altshuler et al. (2014) described the function of mechanoreceptors that slowly adapting receptors like Merkel cells and Ruffini endings sense the forces that sustain the deformation of feathers and skin, such as wind speed and stall (Necker 1985), whereas vibration receptors like Herbst corpuscles function to discriminate the high-frequency elements of flow disturbances (Hörster 1990). Besides, it has been observed that a common kestrel can hover at a point in strong wind, called wind-hovering, by adjusting the attitude of its wings and tail (Videler et al., 1983). In addition to their superior vision and equilibrium organs, such birds' advanced flight techniques seem to be aided by their sensory organs that are sensitive to the airflow variations. Remarkable flight capabilities such as wind-hovering and long-distance migration can inspire the design of drones that can fly more efficiently.

Birds have a variety of flight modes that are used in different scenarios, including flapping, gliding, and soaring. Flapping is common among all birds and the flapping motion generates the thrust and lift forces required for flight by moving the wings up and down while properly adjusting the lead-lag, feathering angle, and stroke plane angle (Videler, 2006). Larger species are more likely to perform gliding and soaring flights more frequently because their heavier weights require a large amount of energy for flapping (Williams et al., 2020). Gliding flight is a method for efficiently traveling long distances by converting the sinking velocity gained with altitude loss into forward speed and lift force. Soaring flight is a type of gliding performed by capturing updraft wind, which makes it possible to fly for a long time or gain altitude without flapping. Not limited to updrafts, some sea birds show another soaring technique, called dynamic soaring, in which they can continue to fly by gaining energy from horizontal winds, such as shear winds above the sea surface (Sachs, 2005). It is thought that birds fly by appropriately switching between these flight modes and adjusting the balance between efficiency and maneuverability. To flap their wings and maintain balance while flying in complex winds, birds have the ability to transform their body shapes, which is known as morphing. The avian body is covered by a large number of feathers that form smooth body surfaces during morphing. It has been reported that the morphing function of avian wings is crucial to their aerodynamic performance (Harvey et al., 2022).

The tail and its morphing mechanism, in conjunction with the morphing of wings, are unique features of birds. The tail is actuated independently of the main wings (Gatesy and Dial, 1993). It is thought to provide benefits in terms of the aerodynamic efficiency, controllability, and stability during flight (Balmford, 1993; Sachs, 2007; Thomas, 1993a, 1993b, 1996a, 1996b). It has been observed that a large soaring bird constantly uses the movement of its tail for turning maneuvers (Gillies et al., 2011). The remarkable mechanism of bird morphing has inspired ideas that facilitate the development and improvement of artificial flyers. Various types of flying robots modeled based on birds have been developed in previous studies (Folkertsma et al., 2017; Gerdes et al., 2014; Yang et al., 2018). For example, adding a morphing function to the wings of a bird-inspired aerial robot has been studied to improve maneuverability in terms of turning performance by asymmetrically changing the area of left and right wings to create an imbalance in lift force. (Luca et al., 2017). A micro air vehicle with a limited two-degree-of-freedom tail mechanism has also been proposed (Parga et al., 2007). However, examples of models developed with morphing tail mechanisms are limited (Ajanic et al., 2020; Chang and Lentink, 2019; Nickols and Lin, 2017) and knowledge of how well a morphing tail extends the envelope of an actual flight robot has not yet been acquired.

In this study, mainly aiming to elucidate the mechanism of attitude control by birds using the tail, we investigated the role of tail attitude in the flight performance of a bird-inspired aerial robot by fabricating a morphing tail inspired by avian tail feathers and evaluating its aerodynamic characteristics. The three components of the aerodynamic forces and moments along each axis were measured using a six-axes force sensor in a wind tunnel while the attitude of the tail was varied in terms of the tilt, elevation, and rudder angles relative to the body.

2. Method

2.1 Feathered tail mechanism for a bird-inspired robot

A tail mechanism inspired by avian tail feathers was fabricated for a bird-inspired flying robot. The robot is composed of three main elements: the body, wings with Clark-Y airfoils, and tail mechanism (Fig. 1(A)). The specifications of the robot design (Table 1) were determined by referring to the size of a kestrel. The airframes of the robot were made of 3D-printed polylactide (PLA) with a hollow structure to reduce weight. To smoothen the body surfaces, the main body was covered with fusiform shells and the surfaces of the hollow wings were covered with polypropylene sheets. The artificial tail feathers were designed to spread in a fan form, where each feather consisted of a 3D-printed PLA frame and polyamide membrane.

The tail mechanism has three degrees of freedom based on the tilt, elevation, and rudder angle relative to the body (Fig. 1(B)). The positive tilt angle is the counter-clockwise direction viewed from the rear of the robot. The positive elevation angle is the direction in which the tail is lowered downward as viewed from the side of the robot. Each tail angle is independently actuated using a micro servo motor (HS-40, Hitec Multiplex Japan Inc.) with a driving controller (Arduino Uno). A tilt-control servo motor is mounted on the rear side of the main body (red parts in Fig. 1(B)), behind which the servo motor for elevation-control is connected (blue parts in Fig. 1(B)). The two servo motors that control the rudder of the tail feathers are located at the rear end (green parts in Fig. 1(B)). This rudder-control mechanism replicates the yaw shift of a bird's tail by independently spreading or narrowing both sides of the feathers proximally. Each tail feather overlaps, forming a complete tail with a spread angle of 160° when fully spread and 80° when minimally furled.

2.2 Wind tunnel experiments

We measured the aerodynamic forces of the robot mounted on a six-axes force and moment sensor (PFS020YA500G6, Leptrino Inc.) in a wind tunnel to measure its aerodynamic performance (Figs. 2(A) and 2(B)). The

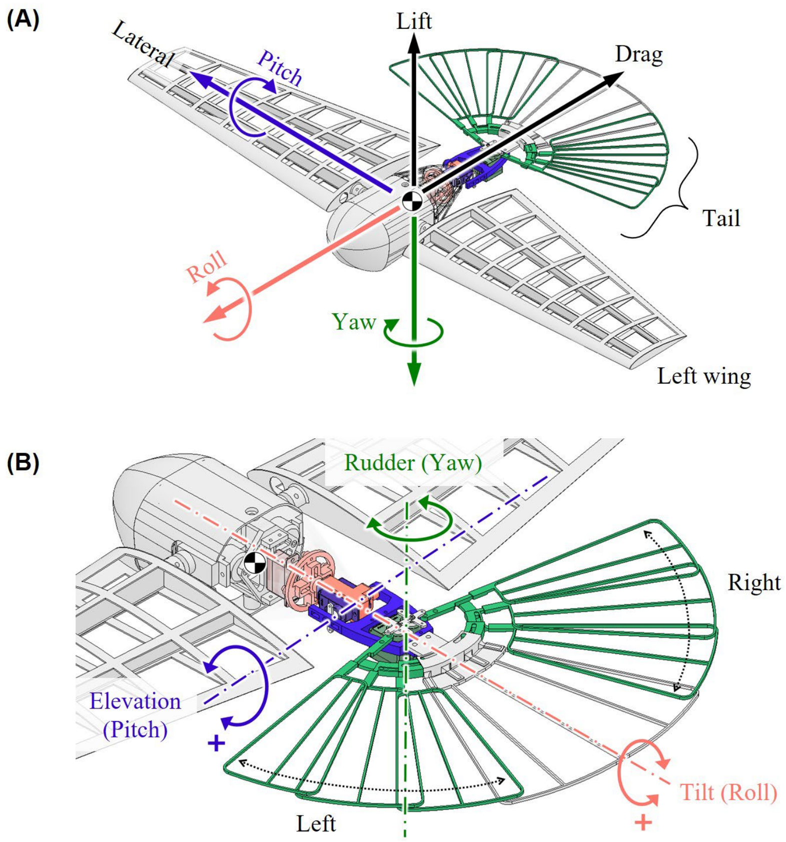

Fig. 1 Design of bird-inspired robot with a morphing tail mechanism. (A) Overview of the entire body from the diagonal-forward-left angle. (B) Overview of tail mechanism with tilt, elevation, and rudder motions from the diagonal-backward-left angle.

voltage values of the force sensor were logged by a PC through an A/D converter (NI-9205, National Instruments Corp.). Measurements were performed twice for 5 s at a sampling rate of 1000 Hz.

These experiments were conducted in a closed-loop wind tunnel at Chiba University (Ikeda et al., 2018), which has a test volume of 1.0 × 1.0 × 2.0 m. The robot was placed in the center behind the opening of the wind tunnel (Figs. 2(A) and 2(B)). The nose of the robot faced the direction of the flow and the body was oriented horizontally. To generate a lift force sufficient to support the weight of the robot (198 g), the angle of incidence of the main wings was set to 7° and the wind speed (U) was set to 9 ms^{-1}. Measurements were conducted with the main wings passively deflected upward by the lift force with the dihedral of an approximately 6° (Fig. 2(D)).

We evaluated the effects of the tail attitude on the aerodynamic performance for several different attitudes (Table 2). The actual angle of the deflected tail in the flow was measured using a camera (D5300, Nikon Corp.). The motion ranges listed in Table 2 are the results of considering the limits of the actuating performance of the servo motor under aerodynamic forces. Actual views of changes in the elevation, tilt, and rudder angle of the tail are presented in Figs. 2(C), 2(D), and 2(E), respectively.

The forces and moments measured by the sensor were converted into aerodynamic forces (lift, drag, and lateral forces) and moments (pitch, roll, and yaw moments), respectively, based on the axes defined in Fig. 1(A). The positive direction of drag force is along the flow, and the positive direction of lift force is perpendicular to the drag force and upward of the robot. The positive direction of the lateral force is toward the right when the robot is viewed from the rear. The dimensionless coefficients were then calculated using Eqs. (1), (2), and (3), where, ρ is the air density and S_w is the total area of the main wings. The mean chord length of the wing c was used as the reference length to calculate the pitch moment coefficients in Eq. (4), and spanwise length of the wing b was used as the reference length to calculate the roll and yaw moment coefficient in Eqs. (5) and (6). Additionally, the lift/drag ratio (L/D), which is related to efficiency, was calculated from the lift and drag forces.

$$\text{Lift coefficient} = \frac{2\ \text{Lift}}{\rho U^2 S_\mathrm{w}} \tag{1}$$

$$\text{Drag coefficient} = \frac{2\ \text{Drag}}{\rho U^2 S_\mathrm{w}} \tag{2}$$

$$\text{Lateral coefficient} = \frac{2\ \text{Lateral}}{\rho U^2 S_\mathrm{w}} \tag{3}$$

$$\text{Pitch moment coefficient} = \frac{2\ \text{Pitch}}{\rho U^2 S_\mathrm{w} c} \tag{4}$$

$$\text{Roll moment coefficient} = \frac{2\ \text{Roll}}{\rho U^2 S_\mathrm{w} b} \tag{5}$$

$$\text{Yaw moment coefficient} = \frac{2\ \text{Yaw}}{\rho U^2 S_\mathrm{w} b} \tag{6}$$

3. Results

3.1 Aerodynamic force and efficiency

It was found that the L/D, i.e., the flight efficiency of the robot, was adjusted by controlling the elevation angle of the tail (Fig. 3(A-i)).Moving the tail downward increased the L/D as a result of increased lift force (Fig. 3(B-i)). In contrast, moving the tail upward resulted in smaller lift and greater drag, resulting in lower efficiency (Fig. 3(C-i)). A similar trend was observed when the area of the tail was changed or when the tail feathers were shifted to the right side (Figs. 3(A-ii), (B-ii), and (C-ii)). However, efficiency began to decrease above a certain elevation angle because the rate of increase in drag exceeded the rate of lift (Figs. 3(A-i) and (A-ii)).

It was also observed that changes in the tilt angle of the tail while maintaining a downward elevation could generate a lateral force in the yaw direction while maintaining a high L/D (Fig. 3(A-iii)). Conversely, L/D remained consistently low for upward elevation of the tail, regardless of changes in the tilt angle. In both cases of up and down tail elevation, the changes in efficiency with the variation of the tilt angle were marginal. This is because the lift and drag forces do not change with a change in the tilt angle (Figs. 3 (B-iii) and (C-iii)). However, the absolute values of the lateral force increase linearly according to changes in the tilt angle (Fig. 3(D-iii)). This means that changing the tilt angle can control yawing without affecting efficiency.

Some curves of the aerodynamic forces according to changes in the elevation and tilt angles exhibited asymmetry with respect to the reference angle of 0° (e.g., Figs. 3(C-i), (C-ii), and (D-iii)), which can be attributed to the influence of the wake generated by the supporting column to fix the robot with the force sensor, as shown in Figs. 2(C) and 2(D). Additionally, because the tail is affected by the downwash of the wings, the interaction between the wings and tail may have affected the aerodynamic performance of the robot.

3.2 Aerodynamic moments

3.2.1 Pitch moment

The elevation of the tail controls the pitch moment relative to the vertical direction of the head of the robot. When the elevation angle of the tail is between −5° and 0° (slightly upward or nearly horizontal), the pitch moment is small (Fig. 4(A-i)). Bending the tail downward outside this range causes a monotonic increase in the negative pitch moment, which induces the head to move downward. Conversely, bending the tail upward increases the positive pitch moment due to the large negative lift generated by the tail behind the body, which causes the head to move upward. The effect of the tail on the pitch moment is more evident for a larger tail area (Fig. 4 (A-i)). For example, if a wind disturbance such as a gust increases the lift produced by the wings and increases the positive pitch moment, which may cause a stalling due to head-up, the negative pitch moment obtained by manipulating the elevation angle of the tail can help to recover the attitude.

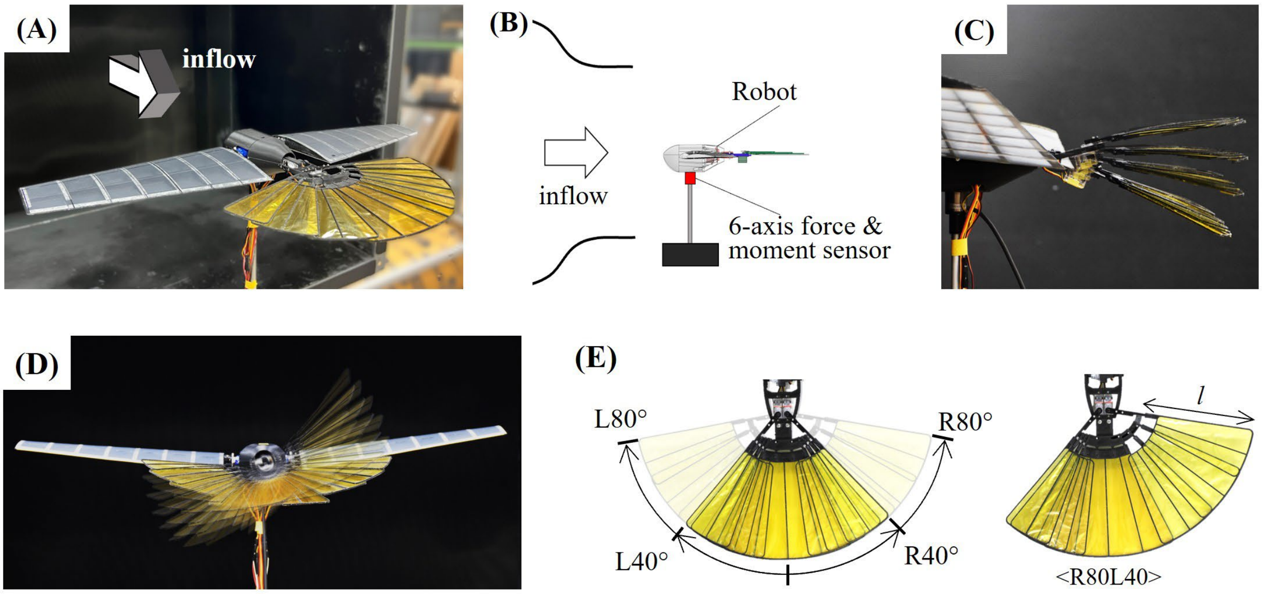

Fig. 2 Setup for wind tunnel experiments. (A) Viewpoint from the diagonal-backward-left angle. (B) Schematic diagram of the setup from the side view (not in scale). (C) Elevating movement of the tail feathers viewed from the side. (D) Tilting movement viewed from behind. (E) Rudder movement viewed from the top.

Table 1 Specifications of the bird-inspired robot

Dimensions	Symbol	Units	Value
Wingspan	b	m	0.6
Wing area	S_w	m^2	0.05
Mean wing chord	c	m	0.1
Aspect ratio	AR	-	6
Taper ratio	TR	-	0.5
Tail feather length	l	m	0.1
Tail area (R40L40 / R60L60 / R80L80)	S_t	m^2	0.0069 / 0.010/ 0.014
Total mass	m	g	198
Moment of inertia around tilt axis (R80L80)	I_t	g·mm^2	32,000
Moment of inertia around elevation axis (R40L40 / R60L60 / R80L80)	I_e	g·mm^2	115,000 / 106,000/ 89,000
Moment of inertia around rudder axis	I_r	g·mm^2	62,000

Table 2 Attitudes of the morphing tail

Postures	Tilt	Elevation	Right Rudder	Left Rudder
Elevating with R80L80 (max spread)	0°	−8 ~ 12°	80°	80°
Elevating with R40L40 (min spread)	0°	−10 ~ 18°	40°	40°
Elevating with R60L60 (mid spread)	0°	−9 ~ 15°	60°	60°
Elevating with R70L50	0°	−9 ~ 15°	70°	50°
Elevating with R80L40	0°	−9 ~ 15°	80°	40°
Tilting with elevation down (max spread)	0 ~ 50°	12°	80°	80°
Tilting with elevation up (max spread)	0 ~ 50°	−8°	80°	80°

It was also found that the pitch moment does not change significantly with respect to the change in tilt angle (Fig. 4(A-ii)). Tilting the tail generates a lateral force, but the changes in the lift acting on the pitch moment are small. Even for changes in the rudder angle of the tail with the same tail area, the pitch moment curves exhibit a similar trend. This indicates that rudder control does not contribute to generating the pitch moment.

3.2.2 Roll moment

The roll moment is generated either by attitude changes with a combination of rudder and elevation or by a combination of tilt and elevation. The variation rate of the roll moment with changes in the elevation angle increases when the bias of the tail rudder angle is greater (Fig. 4(B-i)). It was also determined that the roll moment changes with the tilt of the tail (Fig. 4(B-ii)). However, the amount of roll moment generated by the tail is limited compared to the pitch moment because the length of roll moment arm around roll axis from the tail is expected to be shorter than that of pitch moment arm around pitch axis.

These results are similar to those of the Rudder-R60L60 with the maximum and minimum tail areas. Changing the tail area does not affect the roll moment curve with respect to the elevation change. Therefore, the results of Rudder-R80L80 and R40L40 are omitted from Fig. 4(B-i). The roll moment is not equal to zero at an elevation angle of 0° possibly due to the slight difference in the angle of attack between the left and right wings. Therefore, it should be considered that the effect of the tail on the roll moment (Fig. 4(B-i)) includes a slight positive offset.

3.2.3 Yaw moment

One approach to change the yaw moment is to change the rudder angle of the tail with a bias to the right or left. It was determined that the yaw moment changes when the rudder angle of the tail is gradually deflected to the right side while maintaining the same wing area of the tail (Fig. 4(C-i)). Despite having the same tail area, the yaw moment almost doubles when the tail is biased by 10° to the right (Rudder-R70L50 to R80L40) with the tail pointing 15° downward. A yaw moment is obtained only when the elevation angle of the tail is either downward or upward. When the tail feathers are approximately horizontal, the tail area projected on the plane which is perpendicular to the inflow is small, thus a lateral and drag forces which generate yaw moment are not obtained.

Another approach to control the yaw moment is to change the tilt angle of the tail. It was determined that a greater lateral force and yaw moment can be obtained by increasing the tilt angle, rather than biasing the tail rudder (Figs. 4(C-i) and 4(C-ii)). For instance, a slight tilt angle of approximately 10° provides a yaw moment equivalent to that when the rudder angle of the tail is fully shifted to the right. However, the tilt movement of the tail also generates roll and pitch moments simultaneously, even though the rate of change is low (Figs. 4(A-ii), 4(B-ii), and 4(C-ii)).

Just as in the case of the roll moment, changing the tail area has little effect on the yaw moment with respect to the elevation change. The results for Rudder-R80L80 and R40L40 are similar to the yaw moment curve for Rudder-R60L60. Therefore, they are omitted from Fig. 4(C-i).

4. Discussion

In this study, the aerodynamic forces on a bird-inspired robot were measured to evaluate the role of attitude changes in the tail during flight. It was experimentally confirmed that flight efficiency and controllability can be improved by changing the attitude of the tail. It was also determined that there is redundancy in how the tail generates aerodynamic moments associated with roll, pitch, and yaw control. Here, we also present a discussion of the applicability of the proposed tail to a flying robot with references to previous studies.

First, differences between the morphing of a real bird tail and the artificial tail fabricated in this study should be considered. Real birds change their tail shape by spreading or narrowing tail feathers. The number of tail feathers varies between species. For example, pigeons and kestrels have 12 tail feathers, whereas turkeys have 18 (Gatesy and Dial, 1996). The two central feathers are directly connected to the pygostyle and the other feathers on each side are spread or narrowed (Gatesy and Dial, 1996). These tail components are controlled by muscles and are functionally decoupled from the rest of the trunk and hind limbs (Gatesy and Dial, 1993). Our morphing tail mechanism was fabricated by imitating the fixed central feather and moving feathers on both sides of a bird tail. This mechanism can change the shape of the tail in a fan shape with only six feathers, that are fewer than the tail feathers of a real bird. Unlike the complex musculoskeletal actuation of birds' tail, our tail mechanism is directly driven by four micro servo motors to reproduce the three-degrees-of-freedom posture changes of the tail similar to that of a bird. However, our current mechanism cannot furl the tail feathers into a smaller shape as seen in real birds, and improving the design to achieve this is a task to be tackled in the future study.

It was demonstrated that a combination of an adequate elevation angle of the tail and its area results in greater efficiency. Variable lift and drag forces based on tail elevation, which affect efficiency, were confirmed in this study and noted in a previous study (Ajanic et al., 2020, Parga et al., 2007). Greater tail elevation angles do not necessarily lead to higher efficiencies because the elevation angles must remain within an appropriate range. Therefore, our experimental findings indicate that it is not necessary to vary the elevation angle of the tail significantly to enhance efficiency. The L/D with the tail fully spread was also relatively low based on a decrease in lift (Figs. 3(A-i) and (B-i)). Based on a study using a simple aerodynamic model, it was estimated that the power required for flight could be reduced when flying at

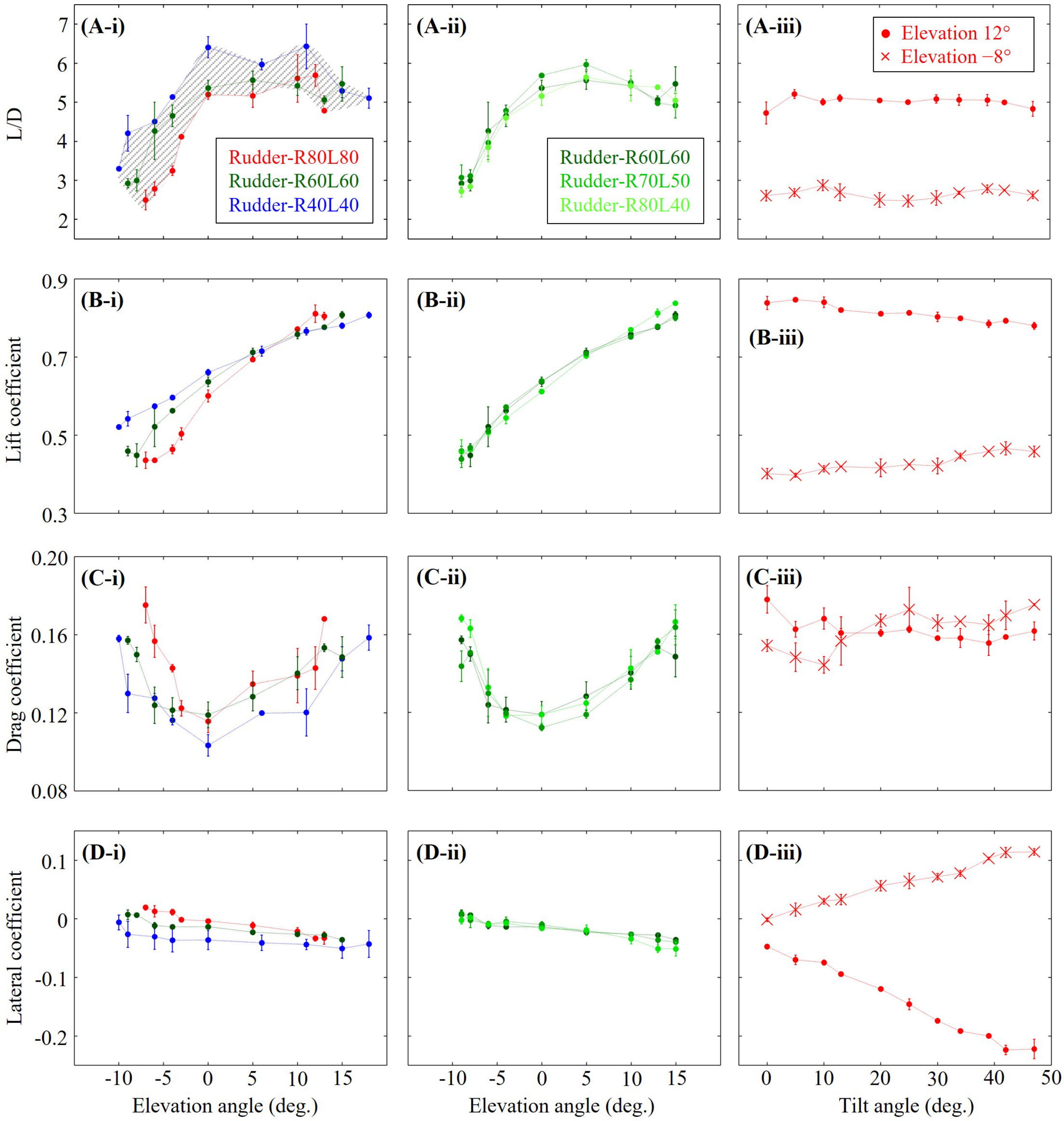

Fig. 3 Effects of (i,ii) elevation angle ((i) with symmetric and (ii) asymmetric tail) and (iii) tilt angle on the (A) lift/drag ratio, (B) lift coefficient, (C) drag coefficient, and (D) lateral force coefficient.

low speeds with the tail spread or at higher speeds with the tail narrowed (Thomas, 1996a). Following this logic, our experimental wind speed was relatively high and the L/D with the spread tail was worse than that with the furled tail, which is qualitatively consistent with the conclusion that it is more efficient to furl the tail. Our experimental L/D curves exhibited gaps between when the tail was fully spread and narrowed (hatched area in Fig. 3(A-i)), indicating that the tail has redundancy in terms of efficiency adjustment. Control of the tail area may be helpful when passing through narrow spaces, where it is difficult to elevate the tail significantly. Conversely, when L/D adjustment based on tail area control is weakened by damaged tail feathers, adjustment based on the elevation angle may be able to compensate for this effect. Therefore, redundancy in the function of adjusting flight efficiency by tail wing can help improve the reliability of flyers.

It was determined that the attitude change of the tail elevation angle is the most useful method for controlling the pitch movement of the bird-like robot, rather than changes in the tail shape (Fig. 4(A-i)). However, this result does not deny the potential benefits of pitch control based on changes in tail area, which is frequently performed by birds (Gillies

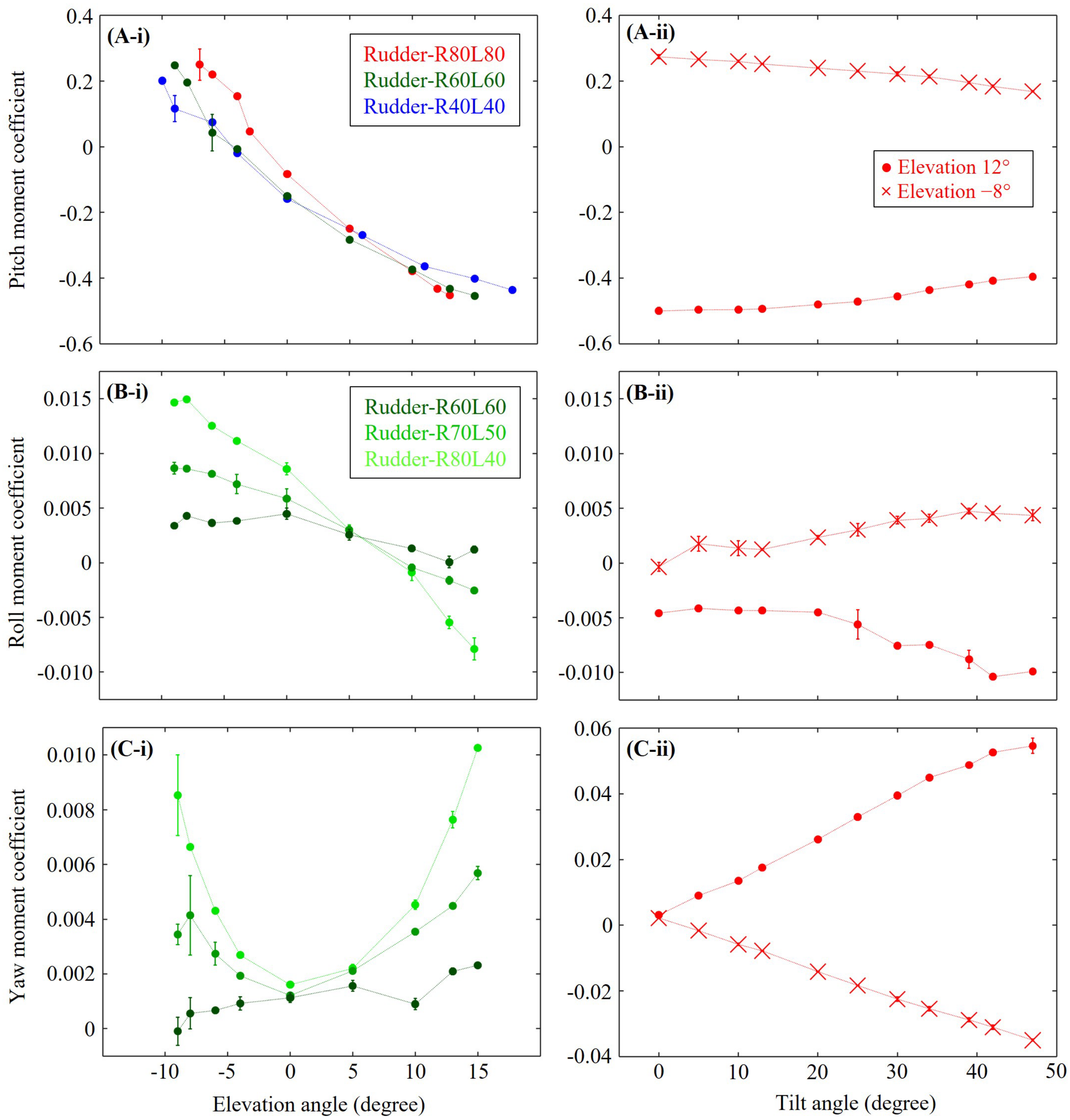

Fig. 4 Effects of (i) elevation angle and (ii) tilt angle on the (A) pitch, (B) roll, and (C) yaw moment coefficient.

et al., 2011). When switching the perspective to a robot configuration and considering the costs associated with tail movements, the moment of inertia must be considered because the actuation power of a small actuator that can be mounted on a bird-size robot is limited. The moment of inertia about the elevation axis of the tail is greater than that about the rudder axis. Additionally, the elevating motion with a widely spread tail incurs additional costs based on fluid resistance. Controlling the rudder angle, which varies the tail area with a smaller moment of inertia at a given elevation angle, is thought to be a superior option for fine-tuning the pitch moment at a smaller cost.

In comparison to the pitch moment controlled by tail elevation, the roll moments controlled by the tail rudder and tilt movements were relatively minor (Figs. 4(B-i) and 4(B-ii)). Considering the geometric arrangement of a bird's body, these results are reasonable because the roll moment can be controlled based on the lift difference between the right and left wings (Gillies et al., 2011, Parga et al., 2007). Birds generate lift differences by varying the twisting angles (i.e., angles of attack) or wing areas between the left and right wings. Even in the case of a flying robot, it is intuitive that the primary control of the roll moment is performed by the main wings. For example, Lishawk succeeded in generating a difference in the lift and roll moment by tucking wings asymmetrically (Ajanic et al., 2020). Aircraft use ailerons to generate a difference in lift and morphing mechanisms have been designed specifically for small aerial robots (e. g., Luca et al., 2017, Stanford et al., 2007). Our results indicate that the benefits of the roll moment generated by the tail are limited to supporting subtler control, rather than agile maneuvers (Harvey et al., 2022).

The yaw moment is clearly controllable by rudder and tilt changes in the tail. In particular, it was quantitatively determined that the yaw moment was greater when the tail was tilted than when the rudder angle was biased. It is also apparent from our study that tilting the tail is an effective method for obtaining a yaw moment because tail tilt does not significantly change the lift-drag ratio or other aerodynamic moments (Figs. 3(A-iii), 4(A-ii), and 4(B-ii)). In the real world, it is common for birds and aircraft to roll their bodies and make banked turns when they need to turn quickly (Gillies et al., 2011) and it is unlikely that the yaw moment of the tail will be able to produce such turns by itself. However, in cases such as aerial imaging, it is necessary to change direction slowly without banking. In aircraft, such yaw turns can be made with a rudder, but in birds, it has been shown that such slow turns can also be made by tilting the tail wing. Additionally, it is considered that the tilt rotation of the tail functions to actively improve the yaw stability as an alternative to the vertical tail of an aircraft (Thomas, 1993a). However, if stability is a priority, the use of a vertical tail, that improve yaw stability of aircraft, could be more effective. On the other hand, if turning performance is a priority, it may be effective to reduce the stability by utilizing a morphing tail wing.

The results of this study show that each angle of a tail affects the forces/moments of several axes simultaneously. When the tail is applied to an aerial robot, it may be more desirable from the perspective of simplification of design and control if the moments around each axis can be controlled separately at each angle of the tail. Therefore, this complexity should be taken into account when using tails for attitude control of flying robots.

5. Conclusion

In this paper, we developed a bird-inspired tail mechanism with three degrees of freedom associated with tilt, elevation, and rudder. Through wind tunnel experiments, we confirmed that both the aerodynamic performance and maneuverability of a bird-inspired flying robot can be controlled by adjusting its tail attitude. The tail mechanism was further verified to be redundant in the production of aerodynamic forces and moments, which may provide an effective approach to achieve flight stabilization under complex conditions with wind gusts in unsteady natural environments. Our results point to the capability and importance of tail-based control strategies employed by birds for adjusting aerodynamic forces and moments.

Utilizing a tail-based control strategy to achieve flight stabilization and maneuvers in unpredictable winds for both birds and bird-inspired flying robots remains an important topic for further research. Active and passive control mechanisms in biological flyers such as insects, bats, and birds are considered to play a crucial role in achieving diverse, robust flight patterns in various complex conditions (Liu, 2020). The wind tunnel measurements conducted in this study indicate that a morphing tail can assist in the active control of aerodynamic force production. An investigation of morphing tail effects on active body attitude control under untethered conditions will be conducted in the future.

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