The 4th International Conference on Design Engineering and Science, ICDES 2017
Aachen, Germany, September 17-19, 2017

Motion Analysis of Turning Mechanism Toward Developing a Butterfly-style Flapping Robot

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Abstract

In this study, in order to achieve turning flight for butterfly-style flapping flight, we first analyzed the flight motion of a butterfly and then performed flight experiments using flapping robots designed based on the analysis results. Flight analysis of a butterfly revealed no difference between the left and right swept-forward angles during forward flight, whereas there was an average difference of up to 9.9deg during yaw turning flight. Based on this flight analysis, a flapping robot was designed and fabricated, which had a total weight of 505mg, a wing span of 120mm, and a difference between the left and right swept-forward angles of 10deg. The two cases of flight performance were investigated in terms of the rotational direction of an actuator and the symmetry of swept-forward angle. The rotational direction of the actuator affected the posture for even the flapping robot with the symmetric wings. On the other hand, the flapping robot with the asymmetric wings changed the roll and yaw angles by 18.8deg and 28.8deg during two strokes. These results revealed that the difference between the left and right swept-forward angles generated roll and yaw moments that compensate the effect by the rotational direction of the actuator and turned the robot.

Keywords: small flapping robot, butterfly, turning flight, swept-forward angle

1 Introduction

Since flapping flight is a flight mode that is often used in nature and enables versatile flight motions such as sharp turns, vertical takeoff, and hovering, numerous flapping robots have been studied [1]-[4]. This flight mode has different characteristics depending on the scale of a living creatures. Large-scale species, such as hawks and eagles, ascend using the air bump phenomenon and fly mainly by gliding. On the other hand, small-scale species, such as hummingbirds and butterflies, fly agilely using only flapping flight without exploiting the air bump phenomenon. For this reason, various small-scale flapping robots, and particularly, insect-scale flapping robots, have been developed [5]-[9]. Wood *et al*. [5] developed a fly-scale robot using a piezoelectric element and achieved vertical flight. Hu *et al*. [6] fabricated artificial dragonfly wings and analyzed the lift and thrust when the fore and hind wings flap with a phase difference. Moreover, although they developed a dragonfly-style robot, its flapping frequency was approximately 7Hz, which is lower than that of a real dragonfly. These robots have not yet achieved practical autonomous flight, because it is difficult to reproduce the flapping frequency and many degrees of freedom (DOFs) of the wings involved in motions such as lead-lag, feathering, and flapping motions. For example, the flapping frequency of a fly or a bee exceeds 100Hz, which is extremely difficult to achieve without a heavy motor system consisting of gears, a motor, a driver, and an external power supply. Moreover, since the dragonfly has four wings, which perform not only flapping, but also lead-lag and feathering, the dragonfly-style robot requires many actuators and a complex link mechanism. However, it makes the motion control complex and increases the dissipation by link friction. As a result, the flight performance deteriorates.

To overcome such challenges, we have previously developed a butterfly-style flapping robot with a mass of 500mg and a wingspan of 120mm [10], [11]. This robot has a low flapping frequency of 10Hz and achieves flapping, lead-lag, and abdomen swinging motion with only one DOF. Furthermore, we have analyzed the mechanism of the pitch posture control using the flapping robot and demonstrated that the pitch posture was controlled by the position balance between the center of mass and the swept-forward angle [12]. From this, in this study, we analyze the turning flight (i.e., the rotation around the yaw axis) of a butterfly and investigate the parameters affecting the turning flight. We then focused on the obtained dominant parameters and clarify the relationship with the straightness characteristic using the flapping robot. Finally, we implement the obtained mechanism for the flapping robot and demonstrate the turning flight experimentally.

The remainder of this paper is organized as follows. In Section 2, we analyze the turning flight of a butterfly. In Section 3, we describe the developed butterfly-style flapping robot and an experiment on turning flight conducted using the flapping robot. Finally, in Section 4, we conclude this paper and outline future work.

2 Turning characteristics of a butterfly

To investigate the turning parameters affecting the turning flight, we analyzed the flight motion of a swallowtail butterfly (*Papilio xuthus*) based on the images obtained by a 3D high-speed camera system consisting of x, y, and z cameras [13]. The butterfly examined had a wingspan of 104mm, a forewing chord of 23mm, a hindwing chord of 49mm, and a mass of 498mg (**Fig. 1**). The camera (DITECT: HAS-D3) had a frame rate of 1000fps, a shutter speed of 1/5000s, and an image resolution of 1280×1024pixels. **Figure 2** illustrates the definitions of the flight parameters. The posture of a butterfly is expressed by roll, pitch, and yaw angles, i.e., X_B, Y_B, and Z_B axis rotations. The angle (lead-lag angle) between the spanwise direction (Y_B) and the leading edge line of the forewing is referred to as the swept-forward angle if the angle is positive, whereas this angle is referred to as the sweepback angle if the angle is negative. In this study, we use the lead-lag angle. The radius of curvature of the turning trajectory is positive when a butterfly turns counterclockwise, i.e., left.

Based on the above conditions, we photographed the forward and turning flights of a butterfly during one stroke (approximately 100ms). **Figure 3** shows stroboscopic images (as viewed from above the X-Y plane) of the turning flight of a butterfly. The trajectory of the thorax, the body vector, and the velocity vector indicate that the butterfly first changed its yaw posture and then gradually changed its traveling direction. **Figure 4** shows thorax trajectories on the X-Y plane for the forward and turning flights and **Figs. 5** and **6** indicate the stroke histories of roll and yaw angles, respectively. While the radius of curvature of forward flight was -730mm (13.8 body length), that of the turning flight was -52mm (1.0 body length). Hence, the radius of curvature of the turning flight was approximately 14 times smaller than that of the forward flight. The roll angles for the forward and turning flights varied by 12.2deg and 33.6deg, respectively (Fig. 5). The difference was 21.4deg. On the other hand, the yaw angles for the forward and turning flights varied by 10.2deg and 71.1deg, respectively (Fig. 6). The difference was 60.9deg. These results indicate that the turning flight of a butterfly was generated by a combination of the roll and yaw angles. **Figures 7** and **8** show the stroke histories of the flapping and lead-lag angles. While no difference was found between the left and right lead-lag angles during the forward flight, the average difference of 9.9deg was observed during the turning flight. Based on these results, we focus on the difference between the left and right lead-lag angles, i.e., asymmetric wing control, and investigate the relationship between the posture and the asymmetric lead-lag angle in a flight experiment using the fabricated flapping robot.

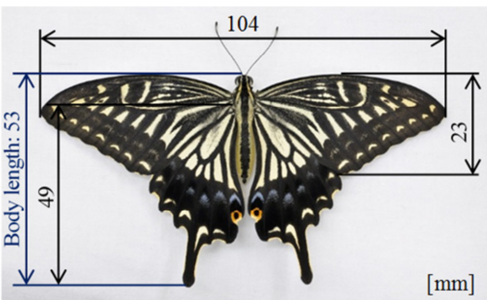

Fig. 1 Overview of a swallowtail butterfly

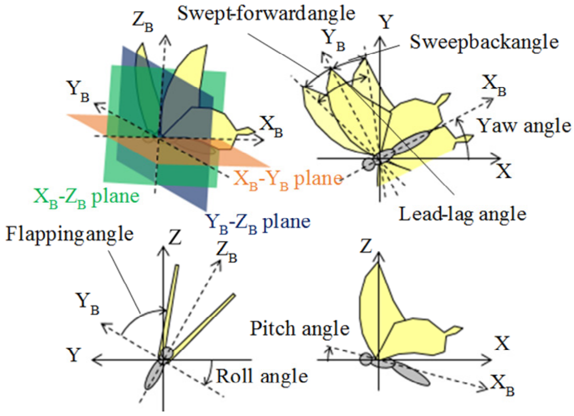

Fig. 2 Definition of flight parameters for analysis

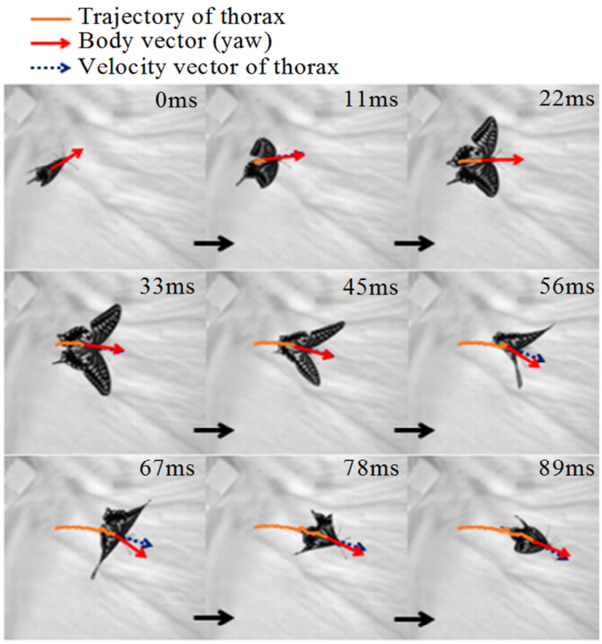

Fig. 3 Stroboscopic photographs of a butterfly: turning flight of a butterfly

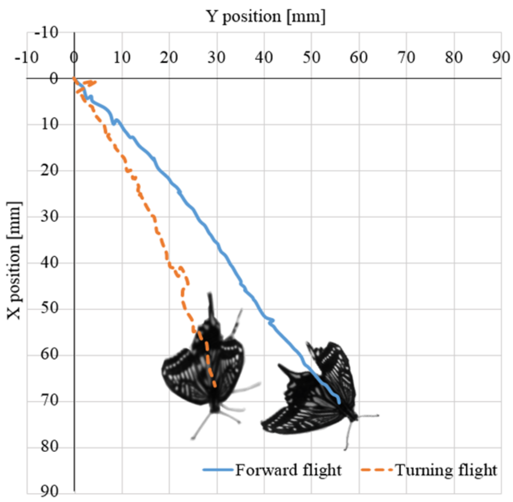

Fig. 4 Thorax trajectory of a butterfly as viewed from above the X-Y plane (forward flight and turning flight)

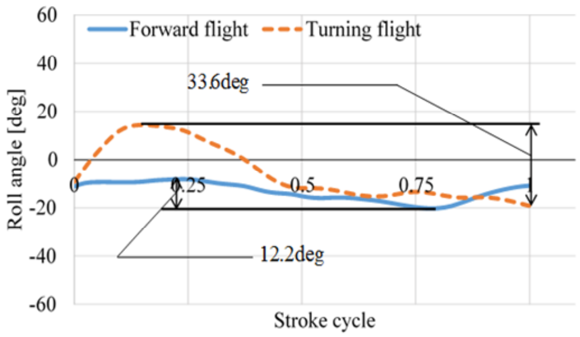

Fig. 5 Stroke history of roll angles (forward flight and turning flight)

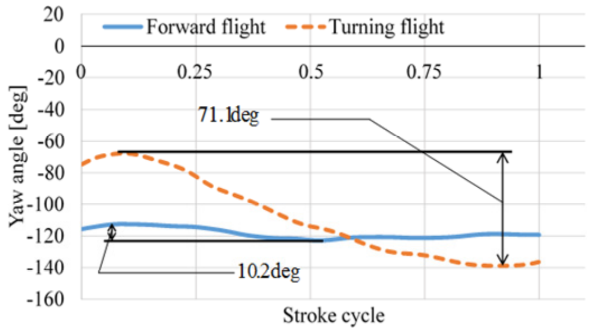

Fig. 6 Stroke history of yaw angles (forward flight and turning flight)

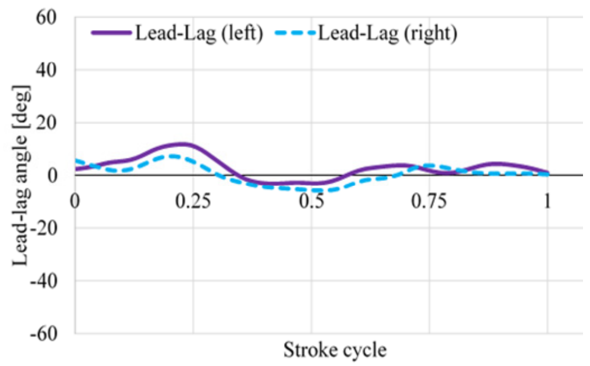

Fig. 7 Stroke history of lead-lag (left) and lead-lag (right) angles during forward flight

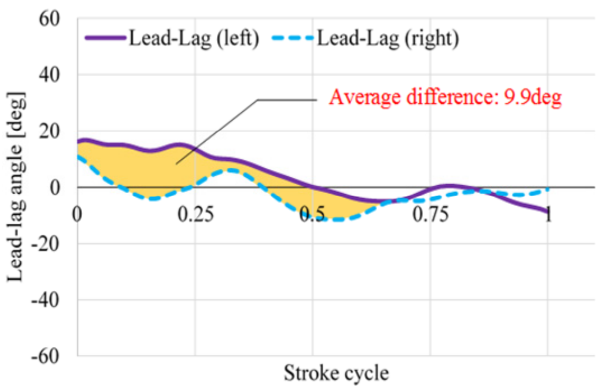

Fig. 8 Stroke history of lead-lag (left) and lead-lag (right) angles during turning flight

3 Motion analysis of the turning mechanism

3.1 Parameters of flapping robots

Figure 9 shows the fabricated flapping robot, which has a wingspan of 120mm, a forewing cord of 30mm, a hind wing cord of 60mm, and a total mass of 505mg. The robot body and the wing veins were fabricated from bamboo and the wing membrane is 2μm thick polyethylene film. Four wings are driven by one DOF, i.e., a rubber motor having high power density. A simple slider-crank mechanism and elastic links were used to realize the large flapping motion [11]. In this flapping mechanism using a rubber motor, the actuator rotates only in one direction during flight. Here, to investigate the effect by the rotational direction of the actuator and to demonstrate the turning flight by the asymmetric wings, we fabricated three types of flapping robot and set four models (**Table 1**) for two cases of experiment (**Table 2**). **Figure 10** illustrates a schematic diagram of the actuator rotation as viewed from below in Fig. 9. Models A and B have symmetric wings. Model A rotates the rubber motor counterclockwise, whereas Model B rotates the rubber motor clockwise. On the other hand, Models AL and AR have asymmetric wings. Model AL rotates the rubber motor counterclockwise and has a swept-forward angle of 10deg for the left forewing, whereas Model AR rotates the rubber motor counterclockwise and has a swept-forward angle of 10deg for the right forewing. Note that this swept-forward angle of 10deg is based on the fact that the average difference of the left and right lead-lag angle of a butterfly was 9.9deg during the turning flight in Section 2. Additionally, this angle can prevent the shortage of lift by losing the overlap between the fore and hind wings and generating the clearance gap. Case 1 investigates the relationship between the straightness and the rotational direction of the actuator using Models A and B. Case 2 investigates the relationship between the turning flight and the asymmetry of the left and right swept-forward angles using Models A, AL, and AR and verifies the feasibility of steering control using the swept-forward angle.

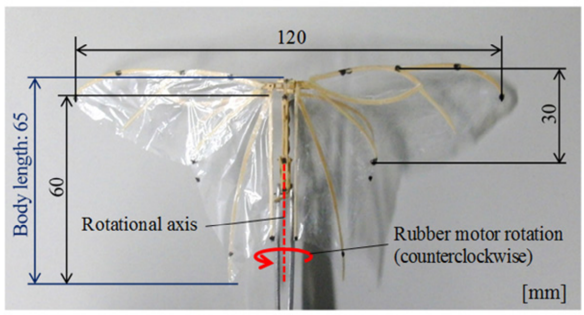

Fig. 9 Fabricated flapping robot

Table 1 Specifications of flapping robots

Model	Rotational direction	Swept-forward angle [deg]		
		Left	Right	Symmetry
A	Counterclockwise	0	0	Sym.
B	Clockwise	0	0	Sym.
AL	Counterclockwise	10	0	Asym.
AR	Counterclockwise	0	10	Asym.

Table 2 Experimental cases

Experimental case	Models for comparison
Case 1	Models A and B
Case 2	Models A, AL, and AR

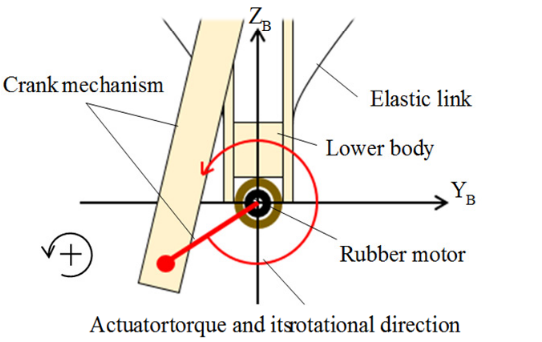

Fig. 10 Definition of the actuator rotation as viewed from the rear

3.2 Results and discussion

3.2.1 Case 1: Characteristics for rotational direction of the actuator

We performed three flight experiments for Case 1 using Models A and B. **Figure 11** shows the average thorax trajectory on the X-Y plane and **Figs. 12** and **13** indicate the stroke histories of the average roll and yaw angles. The average radii of curvature of Models A and B were 791mm (12.2body length) and -712mm (11.0 body length), respectively. The radii of curvature were approximately bilaterally symmetric. The roll angles of Models A and B varied by 7.1deg and -11.5deg, respectively, whereas the yaw angles varied by 3.8deg and -10.3deg, respectively (Figs. 12 and 13). The transition tendencies of the yaw and roll angles for Models A and B were similar qualitatively and were relatively symmetric with respect to the 0deg line. The reason is the influence of the load torque of the actuator at the top and bottom dead points.

Based on these results, we found that the rotational direction of the actuator affected the posture, especially, the roll and yaw angles. Hence, counterclockwise rotation of the actuator (Model A) rotates the roll posture in the positive direction (counterclockwise) and rotates the yaw posture in the positive direction (counterclockwise), whereas clockwise rotation of the actuator (Model B) rotates the roll posture in the negative direction (clockwise) and the yaw posture in the negative direction (clockwise). Note that we define these postures normalized in consideration of this rotational effect as the reference angles (0deg) for following discussion.

3.2.2 Case 2: Characteristics for asymmetric swept-forward wings

We performed three flight experiments for Case 2 using Models A, AL, and AR. **Figures 14** and **15** show stroboscopic images (as viewed from above the X-Y plane) of Models AL and AR, respectively. The trajectory of the thorax, the body vector, and the velocity vector indicate that these models first changed their yaw posture and then gradually changed their traveling direction, as was the case for the turning flight of the butterfly. **Figure**

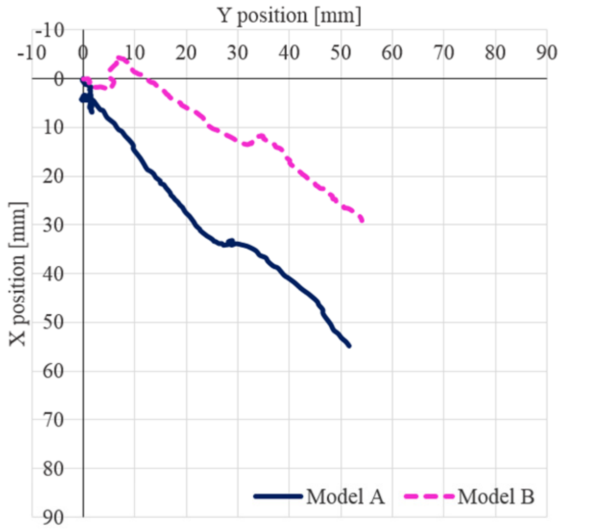

Fig. 11 Thorax trajectory of the flapping robot as viewed from above the X-Y plane (Models A and B)

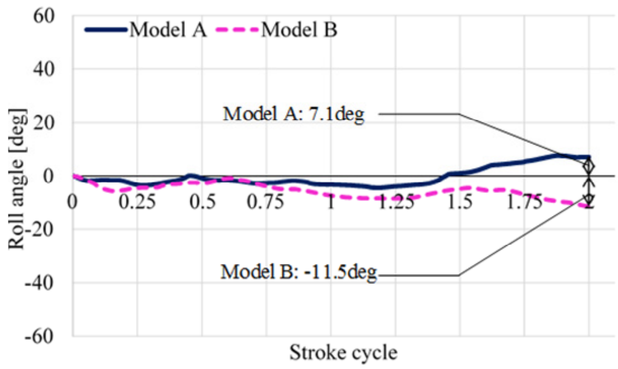

Fig. 12 Stroke history of roll angles (Models A and B)

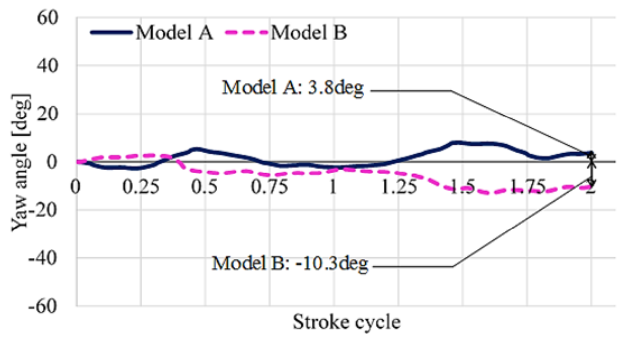

Fig. 13 Stroke history of yaw angles (Models A and B)

16 shows the average thorax trajectory on the X-Y plane and **Figs. 17** and **18** indicate the stroke histories of average roll and yaw angles, respectively. The thorax trajectories of Models AL and AR tended to shift to the right and left, respectively, of the trajectory Model A. The average radii of curvature of Models AL and AR were -235mm (3.6 body length) and 175mm (2.7 body length), respectively, i.e., not symmetric. The reason is due to the mechanism of the actuator rotational direction mentioned above. The roll angles of Models AL and AR shifted to

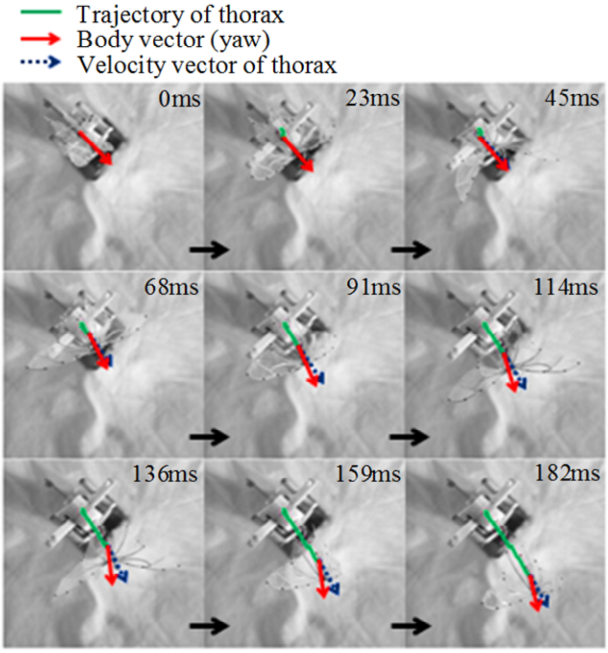

Fig. 14 Stroboscopic photographs of the flapping robot: Model AL

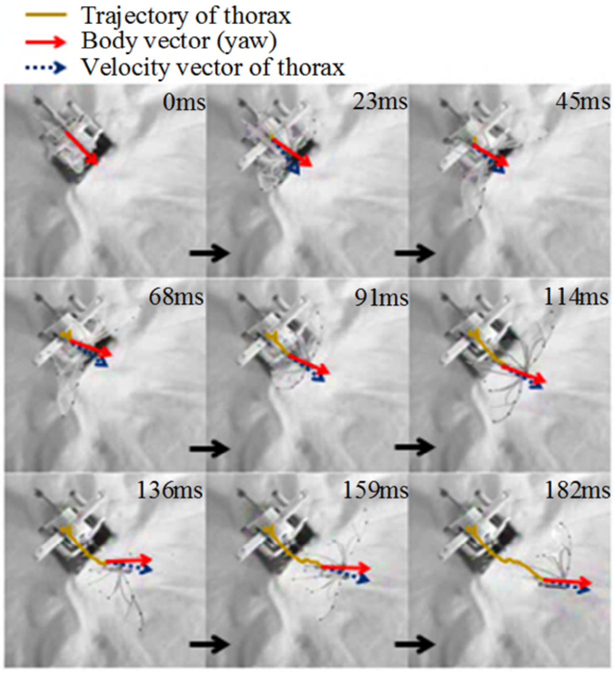

Fig. 15 Stroboscopic photographs of the flapping robot: Model AR

the negative (-20.7deg) and positive (16.8deg) directions from the reference roll angle of Model A (Fig. 17). Like the thorax trajectory, this mechanism depends on the actuator rotational direction. The yaw angles of Models AL and AR also shifted to the right (-26.2deg) and left (31.3deg) from the reference yaw angle of Model A (Fig. 18). These shifts are due to the reason that the asymmetric wing with the different swept-forward angles changed the aerodynamic center of the left and right wings and

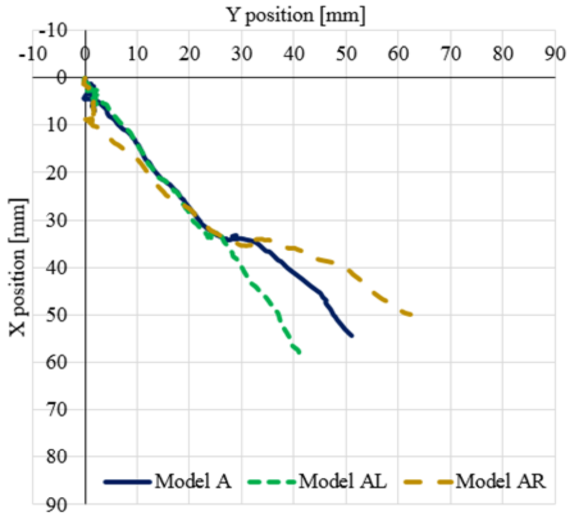

Fig. 16 Thorax trajectory of the flapping robot as viewed from above the X-Y plane (Models A, AL, and AR)

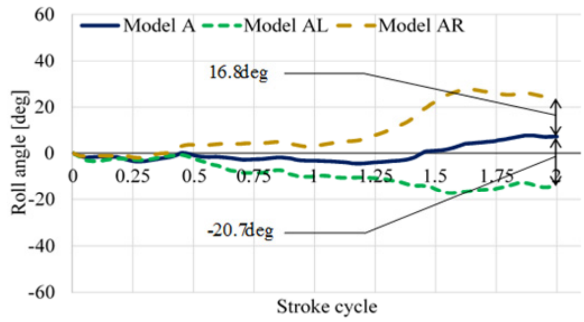

Fig. 17 Stroke history of roll angles (Models A, AL, and AR)

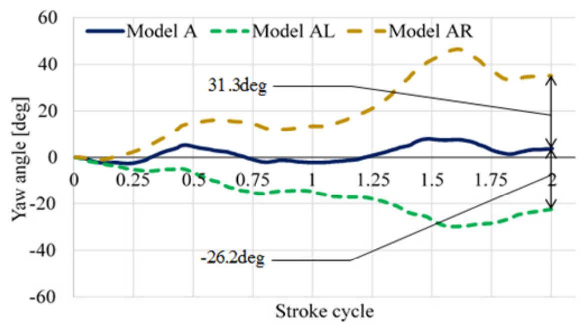

Fig. 18 Stroke history of yaw angles (Models A, AL, and AR)

generated the roll and yaw moments for the center of mass. To indicate this consideration quantitatively, we need to grasp the mechanism of the posture change by visualizing the reaction forces on the wings. From the discussion above, we conclude that the asymmetric swept-forward wings can control the roll and yaw posture and compensate the effect by the rotational direction of the actuator.

4 Conclusion

In this study, in order to realize turning flight in a flapping robot, we analyzed the turning flight of a butterfly and performed the turning flight experiment using flapping robots based on flight analysis results. Flight analysis of a butterfly revealed that the radius of curvature of the turning flight was approximately 14 times smaller than that of forward flight and that the turning flight was generated by the combination of the roll and yaw angles. In addition, the average difference between the left and right swept-forward angles during the turning flight was 9.9deg. Based on this result, we fabricated three types of flapping robot and set four models having a different rotational direction of an actuator or an asymmetric swept-forward angle of 10deg. The experimental results showed that the rotational direction of the actuator affected posture and varied the roll angle by 9.3deg and the yaw angle by 7.1deg, even if the wings were symmetric. On the other hand, the asymmetric wing changed the aerodynamic centers of the left and right wings, generated roll and yaw moments about the robot's center of mass, and caused the body to turn. The roll and yaw angles were changed by 18.8deg and 28.8deg, respectively, during two strokes. These results revealed that the difference between the left and right swept-forward angles generated roll and yaw moments that compensate the rotational direction of the actuator effect and turned the robot.

In the future work, we intend to clarify the turning mechanism by visualizing and analyzing the change of reaction force, pressure, and flow lines generated by the asymmetric wings.

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Received on December 28, 2016
Accepted on March 21, 2017