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A Study on Glide Characteristics of a Small Flapping Robot

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Abstract

In this paper, we analyze flight characteristics, such as glide ratio and attitude stability, of a butterfly-style flapping robot. Although flapping flight allows vertical takeoff, hovering, sharp turn, and efficient migration, which are not possible for conventional fixed-wing aircraft, gliding is also important in terms of conserving energy, even for a small flapping insect. Here we aim to develop an insect-scale flapping robot that can transition flapping and gliding flights and experimentally analyze the flight characteristics of a tailless flyer. The experimental analysis by a fabricated flapping robot having a mass of 459mg, a wingspan of 122mm, and an aspect ratio of 2.47 revealed that the robot had a glide ratio of 4.10 for an angle of attack of 18.4deg (pitch angle: 4.55deg) and a flight velocity of 1.81m/s. Moreover, gliding with a dihedral angle of 10deg created lateral stability and recovered the attitude from an initial roll angle of 60deg after descending 45.1cm (8.51 body lengths). On the other hand, the body mechanism that the center of gravity was located under the point of lift (the center of pressure) created longitudinal stability and recovered the attitude from an initial pitch angle of 30deg during the descent of 41.2cm (7.77 body lengths).

Keywords: small flapping robot, glide characteristics, attitude stability, tailless airplane

1 Introduction

Recently, various types of multicopter have been proposed and developed from the viewpoints of simple control, vertical takeoff and landing, and stable hovering [1]-[3]. Kumar *et al.* [4], [5] presented a decentralized method for various operations by a group of multicopters. Nonami *et al.* [6] described potential commercial applications of drones, such as an aerial photography, transportation, and infrastructure inspection, and the future prospects. While the multicopter has some significant advantages over conventional flight platforms and is a promising technology, problems such as very short flight duration and noise generated by the blades remain. As a solution to the former problem, Suzuki *et al.* [7] proposed an automated battery replacement system for unmanned aerial vehicles (UAVs).

A number of bird-style flapping robots have also been proposed and developed, which, in addition to having the abilities of the multicopter, can fly agilely [8], [9]. Insect-style flapping robots are very tiny and have attract attention as next generation flying robots [10]-[12]. However, despite the fact that some types of butterflies migrate more than 2000km (at a rate of 200km/day), the flight duration of the tiny flying robot is very short because of its small payload, i.e., limited capacity to carry batteries. This is why butterflies use not only flapping but also gliding in order to conserve energy. Thus, it is very important to analyze the glide characteristics of the tailless flapping flyer and to develop a flapping robot capable of transitioning between flapping and gliding flights.

From this point of view, in this paper, we fabricate a butterfly-style flapping robot and analyze its flight characteristics for glideing and its attitude stability. The proposed tailless robot with four wings has the same mass and scale as a typical swallowtail butterfly. Here we experimentally investigate the flight characteristics, such as the glide ratio (lift/drag ratio), angle of attack, and flight velocity during steady flight. In addition, we perform flight experiments starting from various initial roll and pitch angles and analyze the lateral and longitudinal stability mechanism of the robot.

The remainder of this paper is organized as follows: In Section 2, we describe the butterfly-style flapping robot and the flight parameters. In Section 3, we investigate and discuss the glide characteristics. We then analyze the lateral and longitudinal stability of the robot in Sections 4 and 5, respectively. Finally, in Section 6, we conclude the paper and outline future works.

2 Butterfly-style flapping robot

2.1 Definition of flight parameters

In order to analyze the flight performance of the butterfly-style flapping robot, we first define the butterfly coordinate system and the attitude parameters (**Fig. 1**). The attitude of the robot is described in terms of the roll (x), pitch (y), and yaw (z) axis rotation angles. The dihedral angle is defined as middle of the flapping stroke angle and the swept-forward angle is defined as middle of the lead-lag stroke angle. The glide ratio is the ratio of the horizontal traveling distance and the vertical descent distance (A/B) during steady flight, and is equivalent to the lift/drag ratio. Note that during the gliding, the flapping and lead-lag angles are fixed as the dihedral and sweep-forward angles, respectively. In addition, while the pitch angle is the angle for horizontal surface (ground surface), the angle of attack is the angle for the traveling direction (oncoming air).

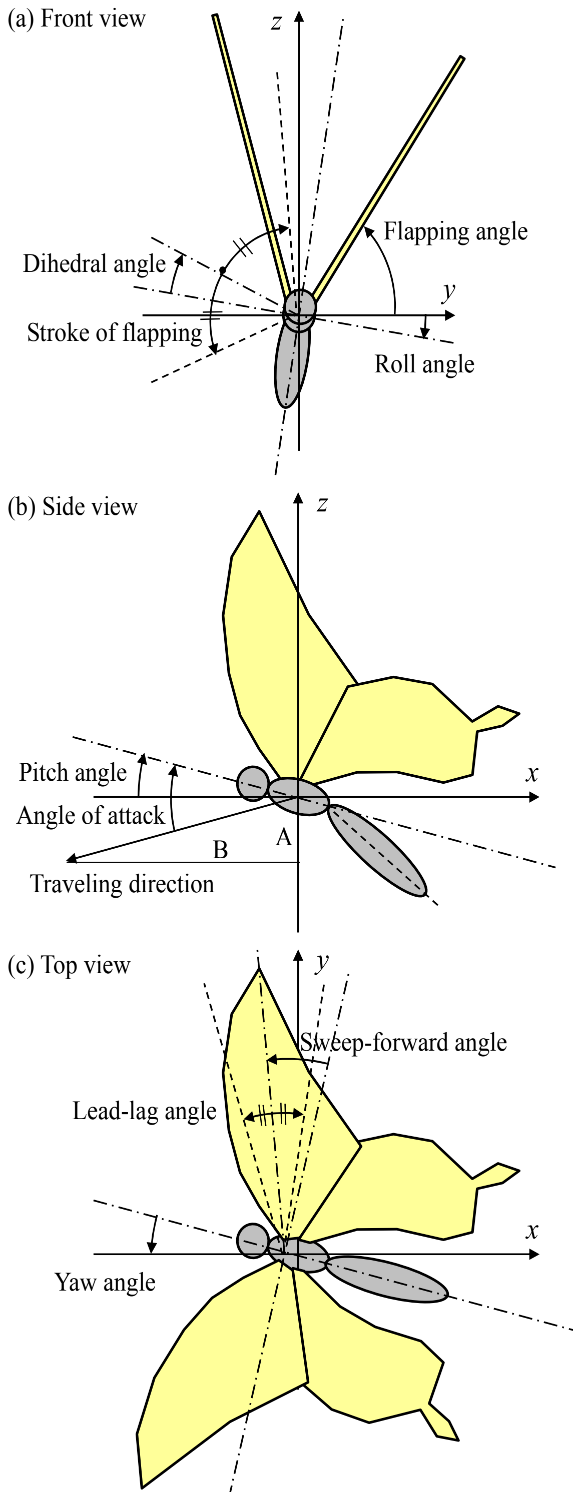

Fig. 1 Flight parameter definition

2.2 Fabricated butterfly-style flapping robot

Figure 2 shows the flapping robot fabricated of carbon fiber reinforced plastic (CFRP). The wings are 2ηm-film membranes of polyethylene and have a wing vein rigidity distribution such that the vein rigidity of the leading edge is high and the vein rigidity of the trailing edge is low. The total mass of the robot was 459mg, its wingspan was 122mm, and the body length was 50mm. The aspect ratio of its wings was 2.47 and the wing area was 50cm^2. These dimensions are approximately the same as those of a swallowtail butterfly, although the wing mass ratio was slightly higher because the wing veins of a butterfly are hollow and light, whereas those of the robot are solid. The initial dihedral angle was set to 10deg and the sweep-forward angle was set to 0deg, based on the results of our previous study [12]. Note that, since the wing is elastic, the dihedral angle is slightly changed by external forces during flight. In **Fig. 2**, the black points are used for image processing. These points are tracked using three high-speed cameras. The center of gravity is located 5.5mm below the wing.

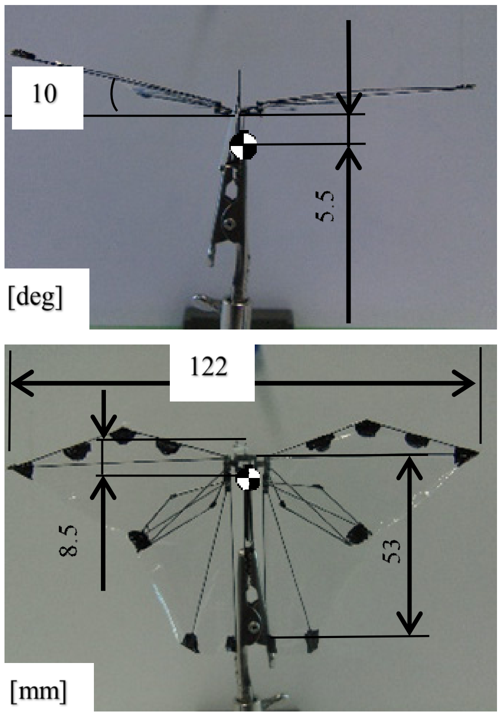

Fig. 2 Fabricated butterfly-style flapping robot

3 Glide characteristics

In order to investigate its glide characteristics, we dropped the robot (initial velocity: 0m/s) and photographed the robot from the x, y, and z directions using three high-speed cameras having a resolution of 1,600pixels×1,600pixels at 500fps. The flight parameters were then calculated by image processing. Note that, although the analysis space is approximately 1.5m×1.5m×1.5m, the robot flies farther. The robot must be captured by all three cameras for 3D image processing.

Figure 3 shows the time histories of the roll, pitch, and yaw angles for three trials and **Fig. 4** shows the trajectory of the thorax (the chest of the body). Assuming that the steady flight is subject to the condition: the pitch angle and the velocity are approximately constant after the flight during 200ms (two strokes of a butterfly flapping with 10Hz), that is, practically, the absolute pitch angular velocity is less than 250deg/s and the absolute acceleration is less than 1.0G (9.8m/s^2), the gliding from 200ms to 430ms was considered to be a period of steady flight. Based on these considerations, the glide ratio in this trial was 4.10 (average: 3.90, standard deviation (std.): 0.79), the pitch angle was 4.55deg (average: 5.62deg, std.: 1.32deg), the angle of attack was 18.4deg (average: 21.1deg, std.: 5.15deg), and the velocity was 1.81m/s (average: 1.75m/s, std.: 0.11m/s), i.e., 34.1 body lengths/s (average: 32.9 body lengths/s, std.: 2.0 body lengths/s). Here, **Table 1** shows the glide ratio for various gliders [13]. The glide ratio of our robot exceeded slightly that of a sparrow (a small bird). Generally, there is a tendency for the glide ratio to increase as the aspect ratio increases. Thus, our flapping robot with a small aspect ratio of 2.47 and a large glide ratio of 4.10 has good flight performance. Although a wandering albatross has a great glide ratio of 19, it rarely flaps its wings. Although the attitude was unstable due to disturbances during low-velocity flight before reaching constant terminal velocity flight (the beginning of descent phase), the roll attitude almost recovered by the dihedral angle mechanism and the pitch attitude also recovered without the tail wing, i.e., the horizontal stabilizer. Note that, since the wing area is reduced when the body rolls, the lift also decreases and the robot tends to descend.

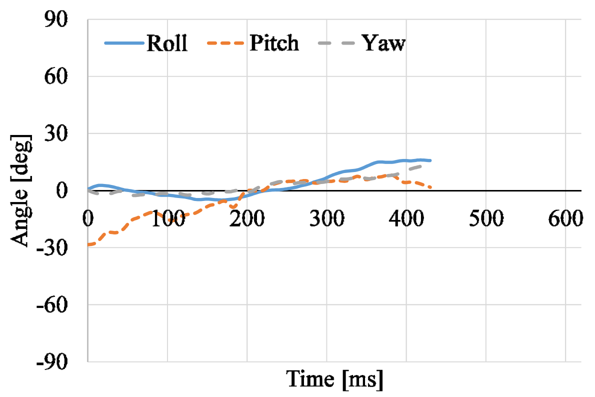

Fig. 3 Time histories of roll, pitch, and yaw angles during glide

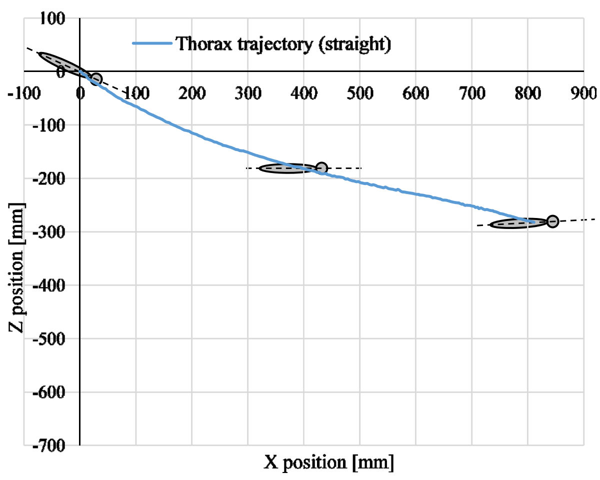

Fig. 4 Y-z trajectory of the thorax d**uring glide**

Table 1 Aspect and glide ratios

Flyer	Aspect ratio	Glide ratio
Fruit fly	5.5	1.8
Bumblebee	6.7	2.5
Sparrow	5.3	4.0
Wandering albatross	15.0	19
Hang glider	7	8
Boeing 747	7	15

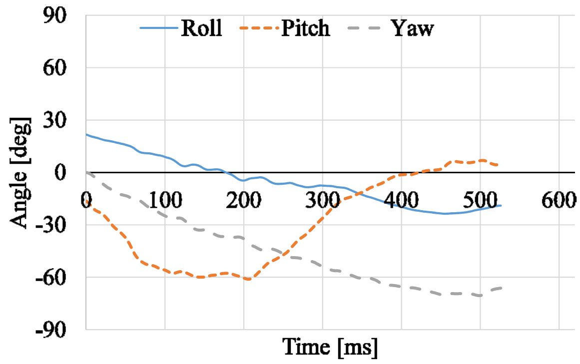

Fig. 5 Time histories of roll, pitch, and yaw angles during glide from an initial roll angle of 30deg

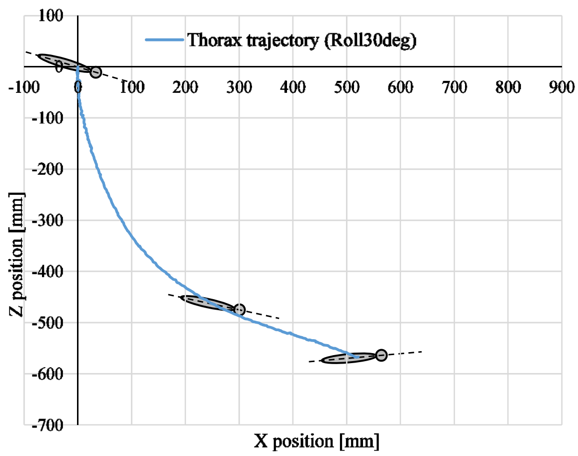

Fig. 6 Y-z trajectory of the thorax during glide from an initial roll angle of 30deg

4 Roll attitude recovery mechanism

In order to investigate the roll recovery mechanism, i.e., the lateral stability, we dropped the robot (initial velocity: 0m/s) at initial roll angles of 30deg (Case R1) and 60deg (Case R2), photographed its flight, as described in Section 3, and calculated its flight parameters by image processing. Attitude stability is very important for an airplane and lateral stability is generated by the sweepback and dihedral angles in the case of a conventional fixed-wing aircraft. Here, we first investigated the lateral stability of a glider with thin, elastic, low-aspect-ratio, sweep-forward, dihedral wings, and no tail wing.

Figures 5 and **7** show the time histories of the roll, pitch, and yaw angles during gliding starting from initial roll angles of 30deg and 60deg, respectively, and **Figs. 6** and **8** show the y-z trajectories of the thorax. The flight after 526ms (Case R1) and 622ms (Case R2) could not be analyzed, because the robot left the field of view of the z camera. Based on the results shown in these figures, we found that the attitudes of Cases R1 and R2 were recovered after descending 46.8cm (8.83 body lengths) and 45.1cm (8.51 body lengths), respectively, before achieving constant terminal velocity. Hence, the roll attitude recovered during the descent phase. As in the case of a fixed-wing aircraft, lateral stability is assumed to be achieved by means of the dihedral angle. Interestingly, Case R2 with an initial roll angle of 60deg recovered the attitude slightly faster than Case R1 with an initial roll angle of 30deg. However, the overshoot in Case R2 was larger than that in Case R1.

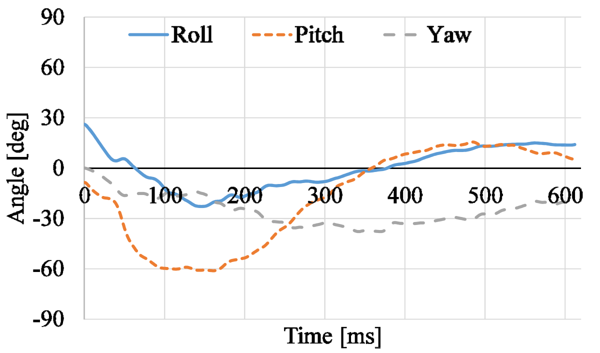

Fig. 7 Time histories of roll, pitch, and yaw angles during glide from an initial roll angle of 60deg

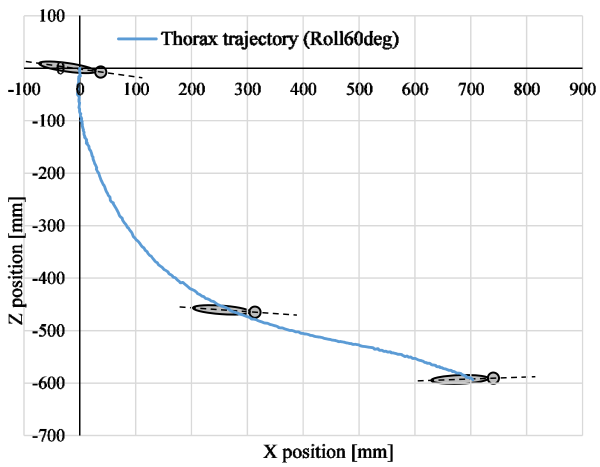

Fig. 8 Y-z trajectory of the thorax during glide from an initial roll angle of 60deg

5 Pitch attitude recovery mechanism

In order to investigate the pitch recovery mechanism, i.e., longitudinal stability, we dropped the robot (initial velocity: 0m/s) at an initial pitch angle of 30deg (Case P1), photographed the robot as described in Section 3, and calculated the flight parameters through image processing. Longitudinal stability is generated by the horizontal tail in the case of a conventional fixed-wing aircraft. Here, we investigated the longitudinal stability of a glider with thin, elastic, low-aspect-ratio, sweep-forward, dihedral wings and no tail wing.

Figure 9 shows the time histories of the roll, pitch, and yaw angles during gliding starting from an initial pitch angle of 30deg and **Fig. 10** shows the y-z trajectory of the thorax of the robot. Based on the results shown in these figures, we found that, in Case P1, the attitude of the robot recovered while descending 41.2cm (7.77 body lengths). Hence, the pitch attitude was also recovered during the descent phase. Conventional fixed-wing aircraft achieve longitudinal stability by means of a horizontal tail wing, whereas airship and parachute create longitudinal stability by arranging the center of gravity under its point of lift. In addition, flying wing aircraft without a tail achieve longitudinal stability by means of active control and characteristic twisted wing tips generating downforce [14]. As indicated by the image analysis, the wings of our robot did not bend or twist during the attitude recovery phase. However, in this study, the center of gravity of the robot should be under the point of lift (the center of pressure). Thus, it is assumed that the longitudinal stability mechanism as well as airship and parachute create existed. Clarification of the longitudinal stability mechanism involving wing bending and twisting requires further analysis. Fluid analysis by a computer fluid dynamics (CFD) will clarify this mechanism.

5 Conclusions

In this paper, we fabricated a butterfly-style flapping robot and analyzed its flight characteristics for gliding and attitude stability. The glide ratio was 4.10 and exceeded slightly that of a sparrow. In addition, the mechanism with a dihedral angle of 10deg created lateral stability and recovered the attitude from an initial roll angle of 60deg. On the other hand, another mechanism that the center of gravity is located under the point of lift (the center of pressure) created longitudinal stability and recovered the attitude from an initial pitch angle of 30deg.

Analyzing the attitude stability mechanism by CFD, achieving longitudinal stability through wing bending and twisting, and transitioning between flapping and gliding flight are subjects for future research.

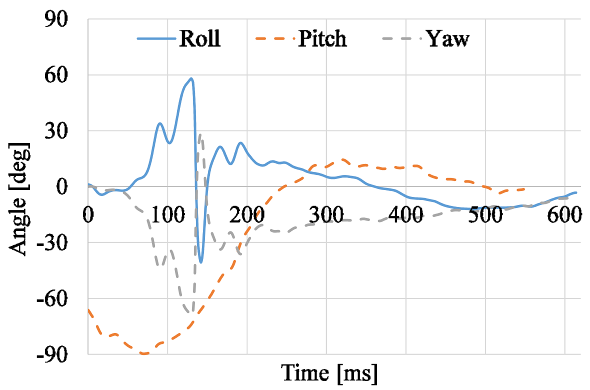

Fig. 9 Time histories of roll, pitch, and yaw angles during glide from an initial pitch angle of

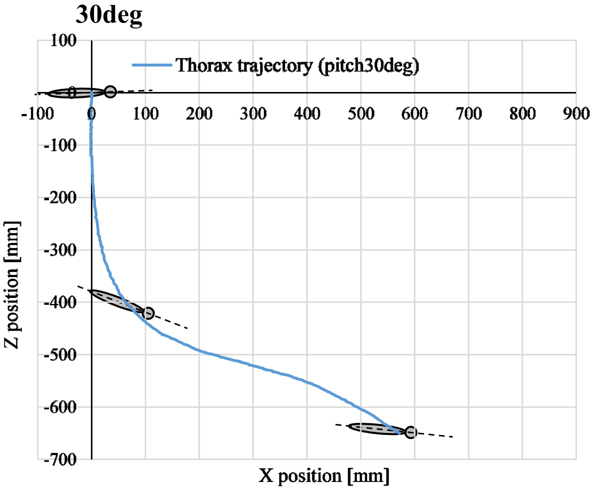

Fig. 10 Y-z trajectory of the thorax during glide from an initial pitch angle of 30deg

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