

EFFECT OF MORPHOLOGICAL CHANGES ON THE AERODYNAMIC CHARACTERISTICS OF THE WING AND TAIL FEATHERS OF A TAXIDERMY BLACK-TAILED GULL

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Abstract

Focusing on birds as an example of morphing wings, which autonomously transform flexible wings, aeronautical engineers and ornithologists have conducted wind tunnel experiments using a taxidermy model of a black-tailed gull. This study aims to clarify the aerodynamic function of the black-tailed gull's characteristic M-shaped "gull-wing" posture and tail feather deformation. While these morphological changes in the main wing and tail feathers are well known in ornithology, they are not fully understood from an engineering perspective. In this study, we developed a reconfigurable taxidermy model and measured the effects on aerodynamic characteristics of adjusting the wing and tail feathers of a single specimen. This approach, which bridges ornithological knowledge and engineering methods, allows for direct comparison of the aerodynamic characteristics of different wing shapes and eliminates discrepancies that arise when using multiple specimens. Using JAXA's 6.5m x 5.5m large-scale low-speed wind tunnel, we were able to obtain basic aerodynamic data, and we report the results here.

Keywords: Wind Tunnel Experiment, Aerodynamic Characteristics, Morphing Wings, Taxidermy Birds, Ornithology

1. Introduction

In recent years, research into morphing wings, which can autonomously change shape during flight, has been actively pursued from various perspective[1]-[8]. Progress has been made in the development of small, high-power actuators and flexible, highly durable composite wing structures. These advances have contributed to improving the aerial maneuverability and environmental adaptability of unmanned aerial vehicles (UAVs).

In particular, in the field of bioinspired robotics, various flying robots have been developed by imitating the flight motion of living organisms such as birds and insects, learning from their excellent aerodynamic characteristics and motion control capabilities. For example, the SmartBird, developed by Festo in Germany, is a lightweight air vehicle modeled after a seagull, achieving efficient flight by combining gliding and flapping [9]. Furthermore, numerous flying robots modeled after insects and small birds have been reported, including a small unmanned aircraft modeled after a goshawk by the Swiss Federal Institute of Technology in Lausanne (EPFL) and Harvard University's RoboBee [10].

Meanwhile, research has been reported in which live birds are flown in wind tunnels to visualize the flow field in order to clarify the actual flight mechanisms of birds [11]. However, it is difficult to accurately calculate the forces generated by living birds in flight. Therefore, the authors have conducted experiments in which they create stuffed specimens that closely resemble the shape of the bird in flight and measure the forces and moments generated using built-in sensors.

In this study, using stuffed specimens with configurable wings and tail feathers, we conducted wind

tunnel experiments to verify the effects on aerodynamic characteristics of changing the main wings to a gull-wing (M-shaped wing) configuration and changing the shape of the tail feathers, and report the results.

2. Wind Tunnel Experiments and Morphable Taxidermy Bird

2.1 Wind Tunnel Experiments

This experiment was conducted in a 6.5m x 5.5m large low-speed wind tunnel (LWT1) owned by the Japan Aerospace Exploration Agency (JAXA) Chofu Aerospace Center. Figure 1 shows the experimental setup. Measurements were taken using a 6-axis force sensor (Leptrino CFS018CA201U, Capacity: Fx=Fy=±100N, Fz=±200N, Mx=My=Mz=±1.0Nm) installed near the center of gravity inside the body. As a backup, we have installed another six-axis force gauge manufactured by Toyo Sokki (Capacity: Fx=Fy=±20kN, Fz=±40kN, Mx=My=±2Nm, Mz=±1Nm) on the top of the pitch angle adjustable stand. In this paper, aerodynamic characteristics are calculated based on measurements from the sensor installed inside the body. Therefore, the center of moment is the value relative to the sensor.

In this experiment, two experiments were conducted for each specimen: one to measure the aerodynamic characteristics at two wind speeds (5m/s and 10m/s) and with a pitch angle ranging from ±30 degrees; and another to measure the yaw angle ranging from ±10 degrees by rotating a turntable for five pitch angles(0, ±5, ±10 degrees). Note that the pitch angle in this experiment indicates the value of an inclinometer installed on the top surface of the stand, and does not necessarily correspond to the angle of the wing or body axis of the stuffed specimen.

As mentioned in the Ref[12], prior to the experiments at LWT1, actual wind tunnel tests were conducted at the open-type wind tunnel (test section:1.5mx2.0m, Max Wind Speed:18m/s) owned by the Central Research Institute of Electric Power Industry to verify safety.

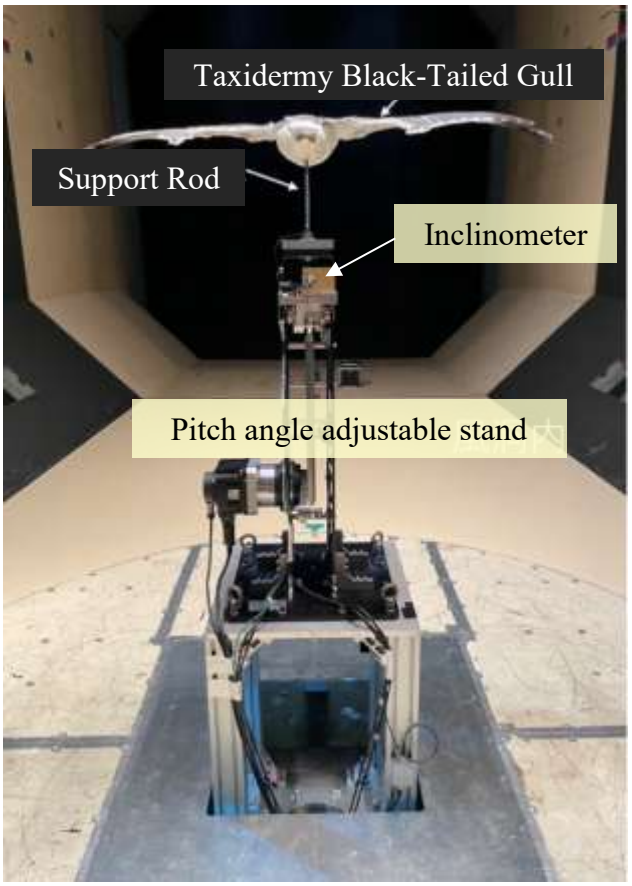


Figure 1 – Experimental Set Up.

2.2 Directions of Forces, Moments and Turntable Rotation

As mentioned earlier, in this paper we use data from the sensor installed inside the main body. Figure 2 shows the directions of the various forces and moments.

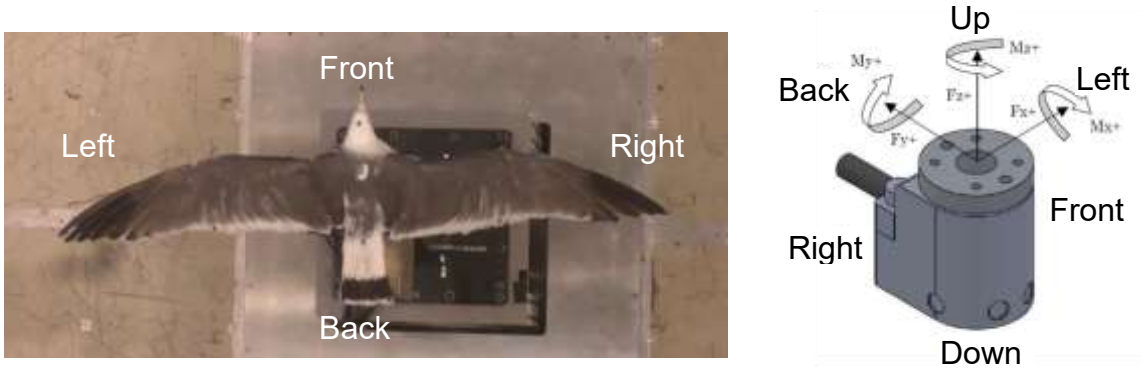


Figure 2 – Direction of forces and moments

The turntable was rotated to change the sideslip angle. Figure 3 shows the positive direction of the turntable's rotation. Taking into account the range of wind speeds in which black-tailed gulls actually fly, wind speeds were set at 5m/s and 10m/s. First, the pitch angle of the stuffed animal was changed within a range of ±30 degrees to measure the aerodynamic characteristics, and then the pitch angle was fixed at 0 and the turntable was slowly rotated within a range of ±10 degrees, and the aerodynamic characteristics were measured in the same way.

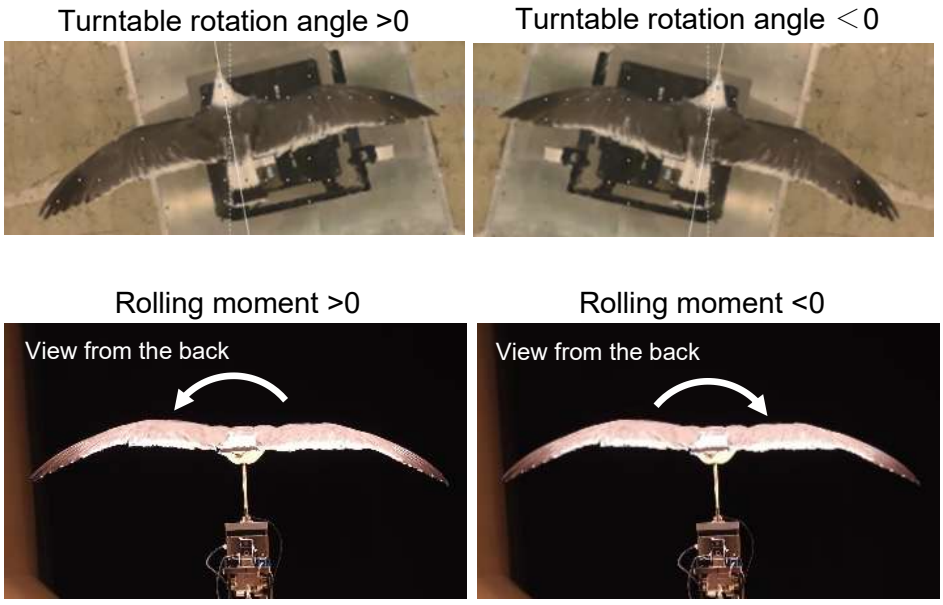


Figure 3 – Direction of turntable rotation angle and rolling moment

2.3 Taxidermy Bird with Configurable Wing and Tail Feathers

Stuffed gulls the authors have previously created using stuffed specimens of black-tailed gulls that had died in accidents could not be altered in shape. Therefore, in order to investigate aerodynamic characteristics under different configurations, it was necessary to create different specimens tailored to those specific configurations. However, this approach made it impossible to isolate the effects of individual variation. In this study, we prepared a specimen with reconfigurable wings. The torso and arms inside the specimen were designed based on CT scan data of an actual black-tailed gull and then 3D printed. The 3D printer used was a Flashforge Adventure 5M Pro (printing area 220 x 220 x 220 mm) and PLA filament was used.

A ball joint was used between the torso and upper arm (shoulder joint), and friction hinges were used in two places on each wing, between the humerus and forearm bone (elbow joint) and between the tip of the forearm bone and the carpal bone of the stuffed wing (wrist joint). After positioning the ball

joint of the shoulder joint, it was fastened with a screw through the access window at the front of the stuffed animal, and after positioning the elbow joint and wrist joint, it was confirmed in a preliminary wind test that they would not deform even under the specified wind speed. Figure 4 shows the two forms tested this time, BT-Gull 2024G (N form) and BT-Gull 2024G (M form). BT-Gull 2024G-N has a wingspan of 1.44m and a wing area of 0.265m^2. Although changes in the shape of the wings or tail feathers would result in changes in wingspan and wing area; however, for the sake of comparison, we used the values from BT-Gull 2024G-N to calculate the aerodynamic coefficients even when the wing shape changed.

Next, we designed a jig to connect the body and tail feathers and to support the tail feathers, allowing them to open and close, twist, and lower. The body and main wings are made of BT-Gull 2024G, and the main wings are in their normal form when the tail feathers are transformed. Figure 5 shows four forms of tail feathers. TC is when the tail is normally closed, TO is when the tail is open, TCT is when the tail is closed and rotated 30 degrees, and TCD is when the tail is closed and lowered 30 degrees.

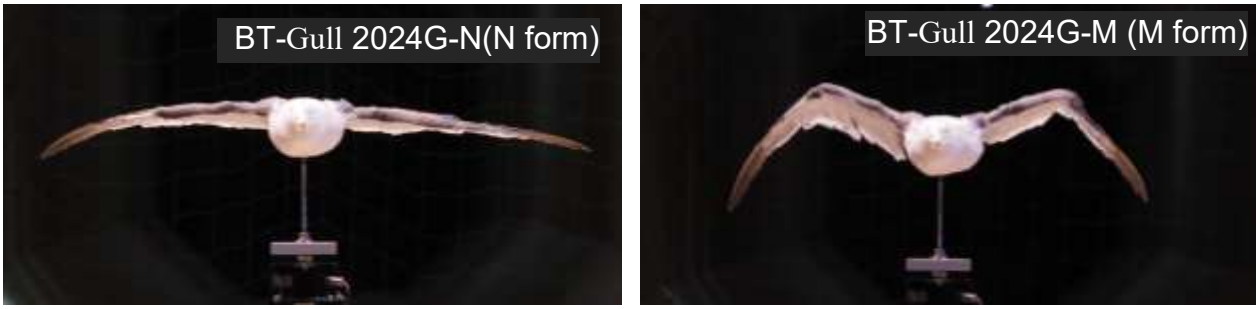


Figure 4 – Two types of main wings.

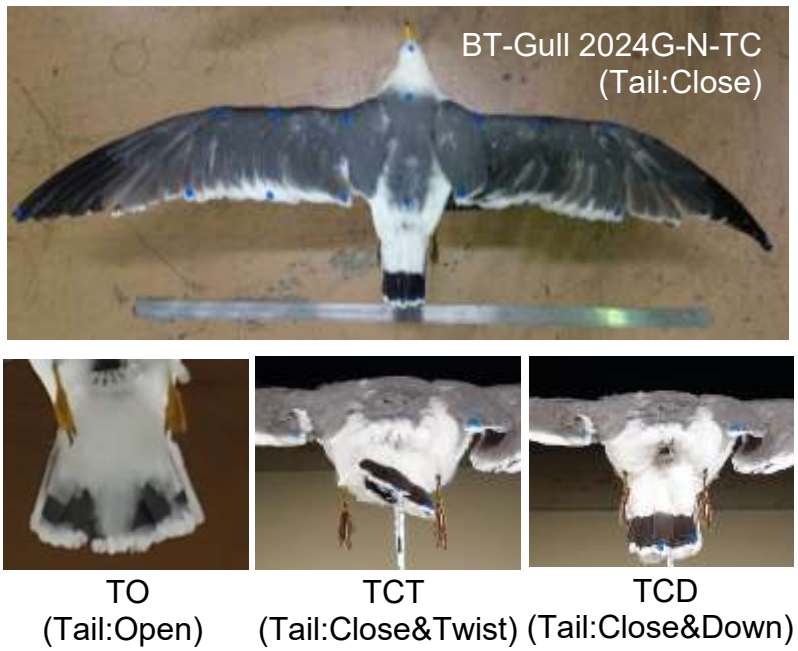


Figure 5 – Four types of tail feathers

3. Experimental Results

3.1 Aerodynamic Characteristics before Changing the Shape

The lift coefficient (CL) and drag coefficient (CD) of the BT-Gull 2024G-N are shown in Figures 6. The horizontal axis shows the pitch angle [degrees] at wind speed 10m/s. As in previous experiments, the lift coefficient is not particularly high, but the model is resistant to stalling, and an inflection point is observed near a pitch angle of zero. The minimum drag coefficient occurs at a pitch angle of approximately minus 15 degrees. Hysteresis has not been measured extensively.

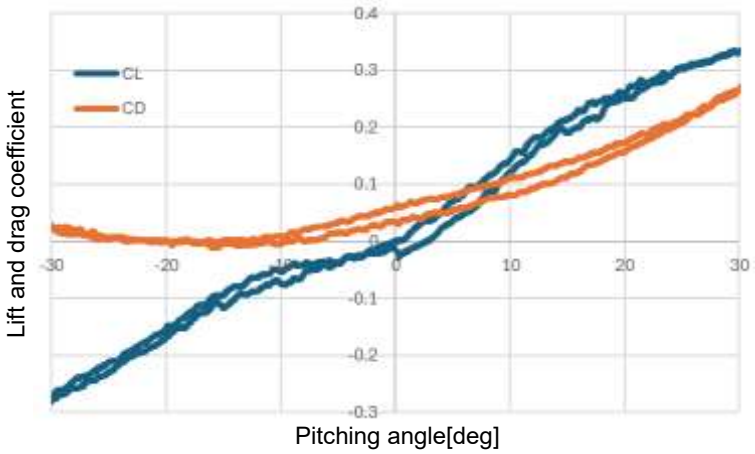


Figure 6 – Lift and drag coefficients of BT-Gull 2024G-N

Figure 7 shows the rolling moment of the BT-Gull 2024G-N at pitch angles of 0 degrees, 5 degrees, and 10 degrees when the wind speed is 10 m/s. We can see that there is a positive correlation between the yaw angle and the rolling moment when the wings are extended. Therefore, a moment is generated that turns the ventral side toward the direction of the incoming wind. We also recognize that the tilt increases as the pitch angle increases.

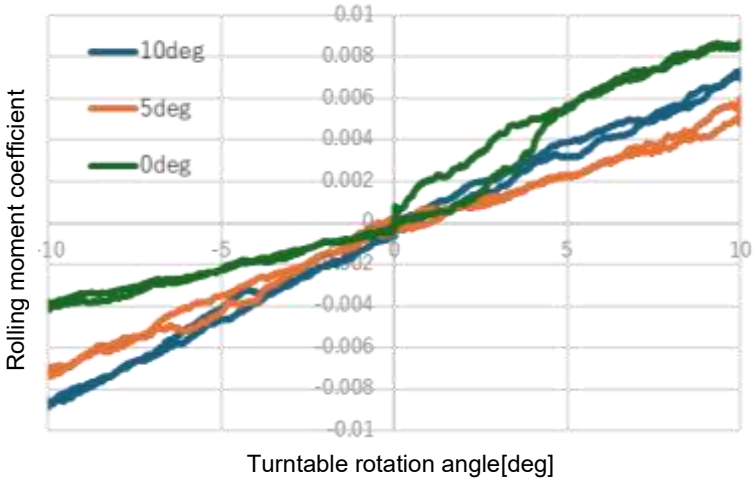


Figure 7 – Rolling moment coefficient for turntable rotation angle (BT-Gull 2024G-N)

3.2 Effects of Wing Shape Change

Figure 8 shows the rolling moment of the BT-Gull 2024G-M at pitch angles of 0 degrees, 5 degrees, and 10 degrees when the wind speed is 10 m/s. This figure shows that in the M-shaped configuration, there is a negative correlation between the yaw angle and the rolling moment. Therefore, a moment is generated that turns the aircraft away from the incoming wind.

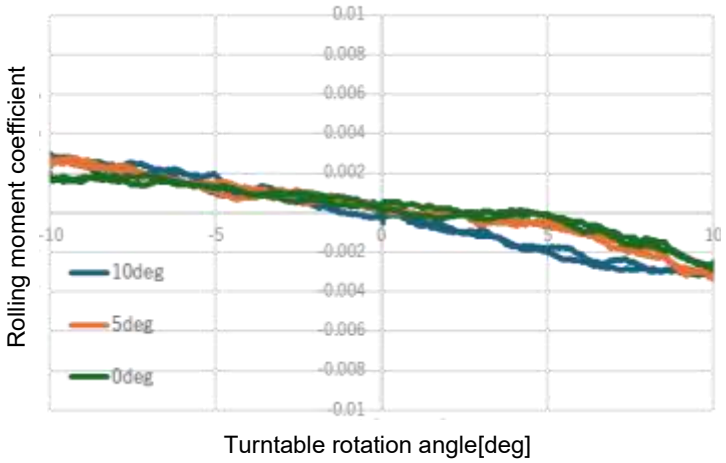


Figure 8 – Rolling moment coefficient for turntable rotation angle (BT-Gull 2024G-M)

3.3 Effects of Tail Shape Changes

Even when the tail feather configuration was changed, the relationship between the lift and drag coefficients and the pitch angle remained almost unchanged. The figure 9 shows the pitching moment coefficient as a function of pitch angle. The pitching moment coefficient as a function of pitch angle was not affected by the opening and closing or twisting of the tail feathers, but it can be seen that lowering the tail feathers did have an effect. When the tail feathers were lowered, the pitching moment remained positive even when the pitch angle was negative.

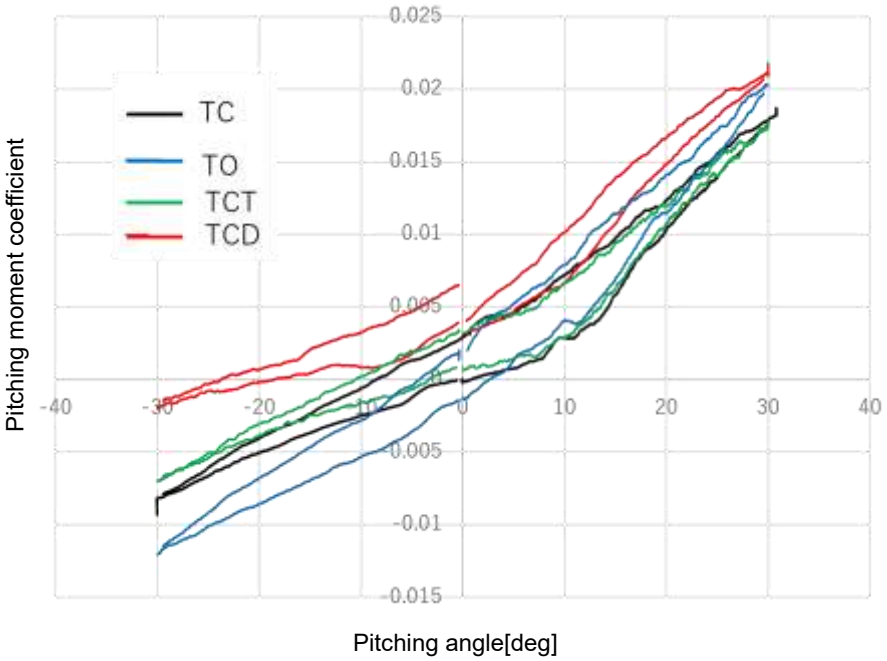
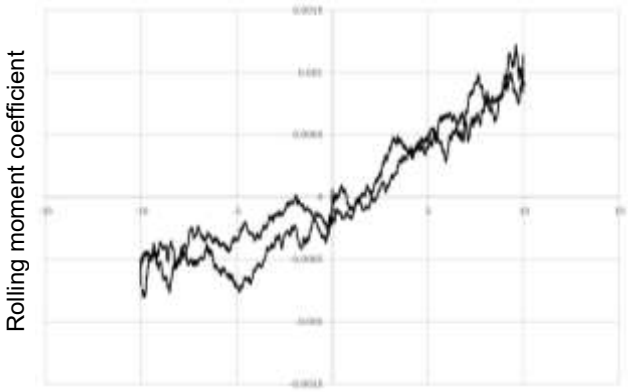
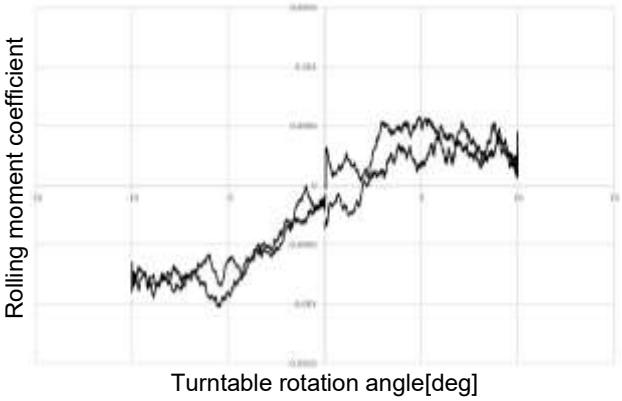


Figure 9– Pitching moment coefficient for pitching angle

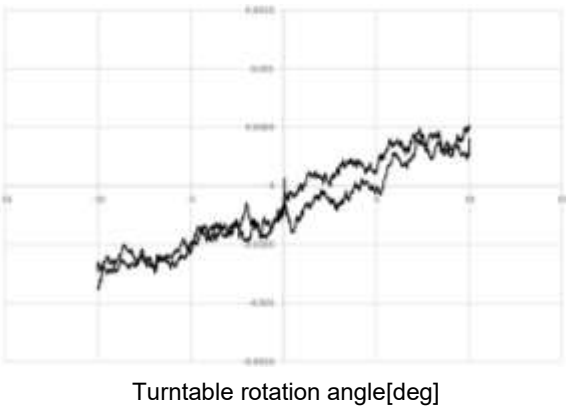
Figure 10 shows the rolling moment versus the rotation angle of the turntable. The rolling moment coefficient as a function of turntable rotation angle (yaw angle) was not affected by the opening and closing of the tail feathers. The twist and downward angle of the tail feathers have the effect of suppressing the rolling moment when the rotation angle of the turntable is positive.



(a) BT-Gull 2024G-N-TC



(b) BT-Gull 2024G-N-TCT



(c) BT-Gull 2024G-N-TCD

Figure 10– Rolling moment coefficient for pitching angle

4. Conclusion

In wind tunnel experiments using stuffed birds, in addition to the relationship between pitch angle and aerodynamic characteristics as previously studied, aerodynamic characteristics were measured by changing sideslip angle by rotating a turntable. The rolling moment generated exhibits the same restoring force as the dihedral effect and a high-wing aircraft. In contrast, it was revealed that when the main wing was modified into a gull wing, a rolling moment occurred in the opposite direction. It was also found that the tail feathers, which have a smaller area than the main wing, have a slight effect on the pitching moment and rolling moment depending on their twist and pitch angle.

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