Paper

Experimental Study on Directional Stability of Tumbling Plate

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Abstract: This paper describes the directional stability of the tumbling plate by measuring the trajectory of a paper piece that is shaped systematically. The tumbling phenomenon is considered to be an important phenomenon for aircraft flight safety because of the possibility of falling objects from the aircraft reaching far away. Therefore, this paper presents the result of measuring the trajectory of six configurations which shows that Concave configurations have directional stability while the Convex and Rectangular configurations are unstable. For generalization, the experimental result deducted using generalized equations into dimensionless values. Qualitative consideration is given to the relationship between the stall delay caused by sudden pitch motion and the phenomenon of the increase in the maximum vertical force coefficient (so-called Dynamic Lift), and the consistency with the dynamic lift wind tunnel test is shown.

Keywords: Tumbling, Directional Stability, Stereo Imaging,

1. Introduction

We often see leaves and thin pieces of paper falling while rotating in the air. The continuous rotation of such objects, which have no internal power source, by the action of the fluid force is called autorotation. There are various types of autorotation. In this study, we deal with tumbling in which vertical drop direction and rotation axis are in a vertical position. Tumbling is an important phenomenon in aerospace engineering and ballistics, not only as a purely academic interest in the falling motion of tree leaves and thin paper pieces but also as a prediction of the scattering range of fallen objects from air vehicles. There are many studies for analysis of the tumbling motion by making full use of analysis methods [1]~[3] [5], or establishing a mathematical model [4]. And also many studies have been conducted due to clarify the tumbling phenomenon and how the speed and glide ratio of the falling object change depending on conditions such as Reynolds number and aspect ratio [6] [7]. But the studies discussing about the stability of the direction of the falling object are rarely seen. On the other hand, the directional stability of tumbling objects has an important influence on the range reaching on the ground of falling objects, which is said to be common when landing gear down in approaching airports where the glide path is set above residential areas, and it is considered to be an event that has a significant impact on flight safety. In other words, a straight glide path of the falling object can reach a place away from the entry path, while a spiral mode described later in this paper has a limited reach. In nature, it is desirable to drop something close to the root of a plant, such as a leaf, to make nutrients, and some of them have a

Convex shape, and it is considered that they are intended to fall in a spiral mode.

Therefore, in this study, we carried out experiments in which typical flat paper pieces shaped systematically were allowed to freely fall in the air and measured the trajectory of tumbling plates. As a result, the relationship between the planar shape and the directional stability is examined aerodynamically.

2. Experimental Method

2.1 Models The model in this experiment has a span of 75 mm and an aspect ratio of 3.75 and is composed of six basic configurations, in which the dents and bulges were parametrically defined by a parabola. Here the meaning of configuration parameter is shown in Table 1.

In Table 1, we define SF and H_r as following:

SF: take the value of -1.0, -0.5, 0.0, 0.5, 1.0, 2.0 depends on the model shape

H_r : 10mm is used in this paper.

In addition, a_{cv} , H_{center} and H_{tip} are defined as Eq. 1, Eq. 2 and Eq. 3, respectively.

$$a_{cv} = \frac{3 \exp(SF)}{1 + 2 \exp(SF)} \quad (1)$$

Table 1: Configuration Parameter.

Config. Parameter	Meaning
SF	Shape factor
a_{cv}	Convex parameter
H_r	Half chord length of rectangular configuration
H_{center}	Hight at center
H_{tip}	Hight at tip

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Figure 1: Six Basic Configurations of Models (Scale is cm).

$$H_{center} = a_{cv}H_r \quad (2)$$

$$H_{tip} = H_r (-2a_{cv} + 3) \quad (3)$$

Here we define moment of inertia around the yawing axis

Figure 2: Models.

ratio to rectangular configuration I_{rat} as Eq. 4,

$$I_{rat} = I_2/I_{2s=0} \quad (4)$$

where I_2 is the moment of inertia around the yawing axis.

$$I_2 = \int_{-b/2}^{b/2} \left(C_{center}y^2 + (C_{tip} - C_{center}) \left(\frac{2y}{b} \right)^2 y^2 \right) dy \quad (5)$$

Here, b is span length.

The shape of the six models is shown in Fig. 1 and the specifications are shown in Table 2. In these shapes, the area and span are constant, and the shape of the leading and trailing edges is continuously changed from a convex shape close to a fallen leaf to a conversely concave shape in which the blade tip protrudes centered on a rectangle.

Figure 2 shows a photograph of the models. The back and surface of the models are painted in black and white, with a marker placed in the center, for stereoscopic viewing.

2.2 Experimental Apparatus The purpose of this study is to obtain the trajectory of the tumbling motion of free-falling plates through the air in an essential three-dimensional manner. To satisfy this requirement in the present study, the experiment was conducted in a closed room in which air was still.

Models described in section 2.1 were dropped from a releasing mechanism of a launching platform at around 2.0 m in height. The launching platform was built to ensure that the plate reaches a steady tumbling state and to eliminate the ground effects as much as possible. The releasing mechanism, which consists of two metal clamps to hold the plate horizontally and symmetrically. The initial releasing angle (angle between chord and gravity) was set at -25° to avoid collision between the device and model in this experiment. The outline of the experimental apparatus is shown in Fig. 3

Table 2: Specification of the Six Basic Configurations.

No.	SF	I_{rat}	Shape	Span (mm)	Aspect Ratio	Thickness (mm)	Weight (g)
I	-1.0	1.29	Concave	75	3.75	0.15	0.2
II	-0.5	1.14	Concave				
III	0.0	1.00	Rectangular				
IV	0.5	0.88	Convex				
V	1.0	0.79	Convex				
VI	2.0	0.68	Convex

Figure 3: Experimental Apparatus.

Figure 4: Release Device.

Figure 5: Frame combined model movement just after release.

and Fig. 4. Two video cameras are installed above the space parallel to the floor at a distance of 0.965 m.

These cameras are synchronized and the frame rate was set at 120 fps. Figure 5 shows the model movement just after release.

2.3 Data Processing Flow chart of data processing is shown in Fig. 6 in which general-purpose software used in the process are written.

The image data acquired by the two video cameras are decomposed for each frame, the two-dimensional coordinates projected on the floor surface are read after correcting the distortion of the image, and the three-dimensional coordinate data are processed by the method of the general

Figure 6: Flow chart.

Figure 7: Stereoscopic three-dimensional coordinates.

stereoscopic technique using the similarity rule of the triangle as shown in Fig. 7. We put the origin point of the world coordination at the camera center of the left camera. $P(x, y, z)$ is the three-dimensional position of the model center. (x_L, y_L) and (x_R, y_R) are model position projected on the floor in the left and right camera coordination. The three-dimensional position of the model can be calculated as Eq. 6, Eq. 7 and Eq. 8.

$$x = \frac{x_L T}{x_L - x_R} \quad (6)$$

$$y = \frac{y_L T}{x_L - x_R} = \frac{y_R T}{x_L - x_R} \quad (7)$$

$$z = \frac{fT}{x_L - x_R} \quad (8)$$

3. Experimental results

3.1 Trajectory After calculation of 3D cordites at the time frame, we can get the timewise x - y - z coordination and three-dimensional trajectory. Figure 8(a) shows the typical three-dimensional trajectories and Fig. 8(b) shows upward trajectories (x - y coordinates) of the six configurations obtained in this experiment. Here, x , y and z values are made dimensionless by the span length b .

As can be seen from this figure, the directional stability (when the direction of descending is about to bend by some disturbance, self-correct and descend linearly as shown in

(a) Typical Three-dimensional trajectories

(b) Trajectories Projected on x - y Plane

Figure 8: Typical Trajectories.

Figure 9: Typical self-corrected Straight Trajectory.

Fig.9 which is the x - y coordinate of configuration II, we will call the trajectory with such properties “Straight Trajectory”) of Rectangular (Configuration III) and Convex (Configuration IV ~ VI) are unstable, and they begin to fall spirally, while Concave (Configuration I, II) moves straight. On the other hand, in the free-fall within the range from the height performed this time, the trajectories of the straight line of the configurations IV and V were also observed. Table 3 shows the percentage of linearly descending trajectories obtained in 20 experiments for one configuration. As shown in Table 3, for the Convex configurations (I, II), the Straight Trajectory was obtained in all cases, and directional stability was thought to be stable. But for the configuration VI, the Straight Trajectory could not be obtained because it fell spirally in all cases. As for the configurations III ~ V, both of Straight Trajectory and spiral trajectory were found within the 20 times of present experiment, but it is considered that even in the case of Straight Trajectory, if falling continues, the movement will be shifted to the spiral motion by some disturbance.

Table 3: percentage of Straight Trajectory.

Configuration	Percentage of Straight Trajectory (%)
I	100
II	100
III	20
IV	20
V	15
VI	0

Figure 10: Glide Ratio.

3.2 Glide Ratio The falling trajectory calculated by Stereoscopic Technique was analyzed. Figure 10 shows the relationship between the I_{rat} and the glide ratio L/D . The glide ratio in the straight-line state is also shown for the configuration III ~ V which finally shifted to the spiral trajectory. Configuration VI is not shown in the figure because a straight-line state could not be obtained. The results show that the glide ratio increases as the transition from Concave to Convex increases. In the case of falling objects from an aircraft, the shape of objects that finally shift to the spiral trajectory has a limited reach distance, so it is considered there is a high possibility to reach the farthest for the shape of object that is close to the rectangular within the convex configuration ($L/D \approx 2.5$). Falling objects are most likely to occur during Gear Down at an altitude of 600 to 750 m (2000 ~ 2500 ft). In this case, the falling object may reach approximately 1.8 km sideways from the approach path.

3.3 Radius of Curvature Figure 11 shows the time variation of the typical radius of instantaneous curvature R of the configuration obtained from the trajectory projected on the x - y plane. (In Fig. 11, data of time range from 0.0 to 0.1(s) has been deleted because it is the transition period from release to steady state.)

We define dimensionless radius R' obtained as follows. The speed can be expressed by the following formula from the force balance formula when turning. Here, W is the total load on the surface and S is surface area and W/S is wing load, ρ is atmospheric density.

$$V^2 = \frac{2}{\rho} \frac{W}{S} \frac{1}{C_L \cos \theta} \quad (9)$$

Turning radius formula R is expressed as Eq. 10. Here, g is

Figure 11: Typical Time Variation of Configuration IV.

Figure 12: Dimensionless Radius of Concave of Finally Stable Radius of Curvature.

the acceleration of gravity.

$$R = \frac{V^2}{g \tan \theta} \quad (10)$$

By substituting Eq. 9 into Eq. 10,

$$R = \frac{2 \left(\frac{W}{S} \right)}{g \rho C_L \sin \theta} \quad (11)$$

From Eq. 11, the dimensionless radius of curvature R' is defined as Eq. 12.

$$R' = \frac{R g \rho}{\left(\frac{W}{S} \right)} \quad (12)$$

Figure 12 shows the dimensionless radius R' of the final stable radius of curvature of the configuration V and VI which shifted to the spiral trajectory among the configurations experimented in this study.

3.4 Velocity For generalization, from Eq. 13 of the balance between gravity and lift force. As well as the radius of curvature, we make the velocity to dimensionless value as in Eq. 14 using the atmospheric density ρ and wing load W/S .

$$mg = \frac{1}{2} \rho V^2 C_L S \quad (13)$$

$$V' = V \sqrt{\frac{\rho}{\left(\frac{W}{S} \right)}} \quad (14)$$

Figure 13: Vertical Velocity in the Spiral Trajectory.

Figure 14: Traveling Directional Velocity.

where C_L is the lift coefficient.

The vertical velocity W' in the spiral trajectory for configuration V and VI is shown in Fig. 13 and the traveling directional velocity U' in Fig. 14. For reference, Configurations from I to V are also shown with vertical velocity on a Straight Trajectory.

It shows that the vertical velocity increases from configuration V to VI, and the influence on the ground object when falling to the ground increases.

4. Aerodynamic Considerations on Directional Stability

In this section, the reason why the directional stability of the tumbling plate is caused by its planar shape is discussed.

The authors have conducted experiments on the phenomenon of stall delay and the increase in the maximum normal force coefficient (so-called “dynamic lift” or “dynamic stall”) caused by rapid pitch motion using a three-dimensional basic shape model in which flat wings are attached to a simply shaped fuselage in a high-wing condition. According to [8], the vertical force of a simple configuration model is measured by rapidly increasing the pitch angle of the model in which a flat-shaped main wing with a sweep angle changed is attached to a simple body set in a low-speed wind tunnel. And the maximum vertical force increases with an increase in the pitch angular velocity and its value changes with the change in the sweep angle $\Lambda_{1/4C}$ (suffix 1/4C means the value at 1/4 chord length) as shown

Figure 15: Sweep Angle Effect [8].

Figure 16: 16 Mean Dimensionless Angular Velocity.

in Fig. 15.

Here, k is the dimensionless angular velocity expressed in Eq. 15. And C_z is the vertical force to the uniform flow coefficient of the force vertical to the body axis and $(\Delta C_z \cos \alpha)_{\max}$ is the max value along the angle of attack α increase from static value.

$$k = \frac{\dot{\alpha} C}{2U_\infty} \quad (15)$$

Here, $\dot{\alpha}$ is pitch up speed and C is the mean aerodynamic chord, and U_∞ is the velocity of the uniform flow.

As reported in [3], the tumbling phenomenon described in this paper repeats the phenomenon in which vortices (dynamic lift) are generated and dissipated from the leading edge of a flat plate due to the rotation of the flat plate, as in the case of a dynamic lift. Figure 16 shows the dimensionless angular velocity k of each configuration based on the present experimental results which are expressed by the Eq. 16.

$$k = \frac{\omega C}{2U} \quad (16)$$

Where ω is angler velocity measured in the experiment and U is the instantaneous traveling directional velocity measured in the experiment.

Although comparing the value of k in this study with [8], the value is one order lager than [8], the trend of the phe-

Figure 17: Vorticity and Vertical Force [8].

Figure 18: Sweep Angle Effect on the Dynamic Lift.

nomenon of the dynamic lift will be strong along with k increases as Fig. 17. Where Ω means vorticity calculated from wind velocity measured by PIV (Particle Image Velocimetry). In [9], it has been confirmed that the effect of the dynamic lift becomes more significant as k increases in experiments in which the value of k up to about 0.6.

It is also shown that the sweep angle of the leading edge of the wing strongly affects the dynamic lift phenomenon because the dynamic lift phenomenon is affected by the strong vortex raised from the leading edge. Figure 18 shows the $(\Delta C_z \cos \alpha)_{\max}$ rearranged by the leading edge sweep angle from Fig. 15 which is arranged by the sweep angle of the 1/4 cord. Since the strong vortex generated from the leading edge is considered to occur in the sweep forward as well as the sweep back, the angle range of the leading edge of configuration (average leading-edge sweep angle of half span) in this experiment is also shown and which is converted into the leading edge sweep angle Λ . The figure also shows the range of the leading-edge sweep angle at the 1/4 span position of the configuration used in this study.

According to [8], the leading edge sweep angle is dominates to the dynamic lift phenomenon. The experimental results show that $(\Delta C_z \cos \alpha)_{\max}$ increases as Λ increases in the range where the leading edge sweep angle is relatively small. Although Fig. 15 shows $(\Delta C_z \cos \alpha)_{\max}$, the maximum value occurs at about $\alpha = 40^\circ$ to 50° , and when k increases, this $(\Delta C_z \cos \alpha)_{\max}$ occurs at a higher angle of attack, so the force increase is more remarkable in $C_z \sin \alpha$

Figure 19: Image of phenomenon.

(horizontal component = drag) than in $C_z \cos \alpha$ (vertical component = lift). We consider the directional stability in this paper based on this sweep angle effect.

As shown in Fig. 19, a case in which a sideslip angle $\Delta\beta$ is generated by some disturbance in the directional stability of a tumbling plate during a straight glide path is considered. In the Concave configuration (Fig. 19(a)), the model is considered to receive a yawing moment to reduce $\Delta\beta$ because the sweep angle of leading edge on the right-hand side increases while the leading edge on the left-hand side decreases. On the other hand, in the case of the Convex configuration, since the reverse phenomenon occurs as shown in (Fig. 19(b)), it is conceivable that it acts in the direction in which the sideslip angle becomes larger. From the above consideration, it is considered that the directional stability of the configuration in this study qualitatively agrees with the result obtained from the dynamic lift wind tunnel test.

5. Conclusion

To evaluate the directional stability of a free-falling flat plate, we conducted experiments in which a typical flat paper piece, shown in Fig. 1, was subjected to free-falling in air and measured the trajectory of the tumbling flat plate. As the result,

- (a) It was found that the shape having stability with respect to straight running was a concave configuration (configuration I, II) within the configurations (Fig. 1).
- (b) As the concave configuration becomes closer to the rectangular shape, the glide ratio increases, and the

possibility of reaching farther for falling objects from an aircraft increases.

- (c) It was found that the Radius of Curvature of the spirally falling configuration tends to settle to a constant value with the fall, and the value decreases as the Concave becomes deeper, and the area on the ground where the falling object from the aircraft may be reached decreases.
- (d) The speed of the falling object is as high as that of the Concave, and there is a higher possibility that the damage will be increased when the falling object from the aircraft hits the ground object.
- (e) It is found that the directional stability of tumbling phenomena qualitatively agrees with the wind tunnel experimental results of Dynamic Lift phenomena. It is necessary to carry out detailed analysis by wind tunnel tests or CFD in the future.

In this study, the tumbling plate was treated as a rigid body. However, since the falling objects from the aircraft are not only rigid bodies, but also less rigid objects such as rubber pieces fall during gear down, the influence of stiffness needs to be studied in the future study.

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