Proposal of a method to measure aerodynamic forces without using force sensors in wind tunnel testing of tumbling plates

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Abstract: A new wind tunnel test method is proposed to measure the aerodynamic forces act on the tumbling plate and the tension of the tow string in the wind tunnel not by using force sensors but by measuring the tow position. The tumbling phenomenon is considered to be an important phenomenon for aircraft flight safety because of the possibility of falling objects from aircrafts reaching far away or for knowing the behavior of falling roof tiles blown off by strong winds. Therefore, many tests to measure the force act on the tumbling plate in wind tunnel have been conducted. However, since the rotation of the test piece is accompanied by difficulties ex. support interference, movement restrictions, *etc.* However, according to present method, the aerodynamic forces act on the tumbling plate in wind tunnel can be measured optically in a non-contact manner, and an expensive force sensor is not required. Furthermore, it is also effective under conditions such as low wind velocity, in which the aerodynamic forces are buried in the measurement accuracy of the force sensors. This paper explains this wind tunnel test method from the viewpoint of dynamic balance and reports the results of verification wind tunnel test in which the effectiveness of this method was confirmed.

Keywords: Tumbling, Wind tunnel, Force sensor, Stereo Imaging,

1. Introduction

When an object falls in a fluid, continuous rotation by the action of fluid force is called autorotation. Autorotation performs various modes of motion by performing complicated motions according to the dimensions of a falling object, velocity, moment of inertia, aerodynamic characteristics, *etc.* As motion modes, tumbling, flat spin, corning, *etc.*, are known. Among the autorotation, the drop direction and the rotation axis are vertical is called tumbling.

Tumbling is known as natural phenomena such as leaves of trees and roof tiles blown away by typhoons, and important phenomenon in aerospace engineering and meteorology as well as scattering region estimation of satellite/rocket fragments damaged during atmospheric reentry and objects dropped from aircraft at random. 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], and some empirical equations have been proposed [8].

Although most of the studies so far have focused on measuring the position and posture of a test piece by optical position measurement and determining the velocity and force by its differential value by changing the basic parameters

and dropping it freely in the air or in a water tank, or on understanding physical phenomena by numerical analysis, most of them assume a motion in a two-dimensional plane perpendicular to the ground. Also, as a measuring method by the free fall, it is difficult to identify the aerodynamic force under specific attitude angle conditions especially associated with the lateral motion from the three-dimensional coordinates, because it is difficult to obtain data with desired conditions in the steady state because specifications such as the rotating rate and turning radius (sideslip angle) of free-falling tumbling motion are determined by the plate specifications such as the weight of the plate or the moment of inertia. And before that, we think it makes sense to directly measure the forces that cause the trajectory, rather than calculating it from the trajectory resulting from phenomenon. There are also some tests in which the force is measured by wind tunnel testing [9][10]. However, since the rotation of the test piece is accompanied by difficulties ex. support interference, movement restrictions, *etc.*, some tests are forced to rotate the test piece, and there is a possibility that the conditions are different from those of autorotation in which the fluid force is the original physical phenomenon and some tests are free rotation.

We have reported that the directional stability of the tumbling plates trajectory varies depending on the planar shape of the object. Since three-dimensional force measurement is indispensable for the detailed elucidation of this phenomenon, it is necessary to measure the force and moment applied to the lateral direction of the tumbling plate in the wind tunnel test. Therefore, we focused on the fact that

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Figure 1: Wind tunnel test image.

the tumbling plate has two rotating directions, one generates lift and the other generates downforce, and devised a new wind tunnel test method that calculate the aerodynamic forces act on the tumbling plate and the tension of the tow strings by measuring the three dimensional tow positions when the plate is towed by the string in the wind tunnel flow. In this report, the theoretical formula of this method is explained, and the effectiveness of this method is confirmed by the verification test. This method is unique to the wind tunnel tests for tumbling plates because it utilizes the fact that a tumbling plate has two rotating directions and the tumbling plate does not have a longitudinal moment with respect to the lateral axis.

2. Force Conversion Method by Position Measurement

Consider that both ends of a tumbling flat plate rotational axis to be held by two strings from the front in a wind tunnel (Fig. 1). The string and the rotational axis of the tumbling plate are connected so that it can rotate freely, and the other end of the strings are supported by the same width from the outside of the wind tunnel. For simplicity, the aerodynamic force or gravity acting on the strings itself shall be negligible (this assumption will be discussed later). Although it is known that the aerodynamic forces applied along the rotation cycle changes periodically in tumbling motion [7], we treat the forces that averages the change in one cycle in this study.

2.1 Symmetrical Case First, for simplification, consider a case where a plate is held in a symmetrical state in an air flow.

For aerodynamic forces divided equally to the left and right side, the forces on the left and right strings are equal, and only one of the strings must be considered.

As a wind tunnel fixed axis system, the X axis is taken in the uniform flow direction, the Z axis is taken upward, and the Y axis is taken rightward toward the uniform flow. (Fig. 2)

The rotational direction of the tumbling plate exists 2 cases. First case is the rotation taking an angular velocity vector in the positive direction of the Y -axis and second case is the rotation taking an angular velocity vector in the negative direction of Y -axis, and the former generates lift and

Figure 2: Forces in symmetrical case in wind tunnel.

the latter generates downforce. Here, the former is defined as the upper position and the latter as the lower position.

Let the unit vector in the X direction be $\vec{e}_x$, Z direction unit vector $\vec{e}_z$, and the unit vector in the tension direction of the string in the case of upper position be $\vec{e}T_u$, in the case of lower position be $\vec{e}T_l$.

The following relationship can be obtained from the equation of balance in X and Z directions.

$$\frac{D}{2} + T_u \vec{e}T_u \cdot \vec{e}_x = 0 \quad (1)$$

$$\frac{L}{2} - \frac{W}{2} + T_u \vec{e}T_u \cdot \vec{e}_z = 0 \quad (2)$$

$$\frac{D}{2} + T_l \vec{e}T_l \cdot \vec{e}_x = 0 \quad (3)$$

$$-\frac{L}{2} - \frac{W}{2} + T_l \vec{e}T_l \cdot \vec{e}_z = 0 \quad (4)$$

Where D means the drag force, L is lift force and downforce, W is weight of the model, T is the tension of the string.

If the weight of the test piece is known, the position of the plate end and the tension direction of the string are known from the three-dimensional position measurement, and the unknown numbers are the four scalar quantities of D , L , T_u , and T_l . Therefore, the unknowns can be obtained by solving Eq. 1 to Eq. 4 simultaneously.

Figure 3: Forces in non-symmetrical case in wind tunnel.

2.2 Non-Symmetrical Case Next, as a more general case, consider a case where the tumbling plate is held with an attitude angle in the airflow.

Now, assume that a tumbling plate in the uniform flow is held by right and left strings pulling to slightly different directions relative to the plate (Fig. 3). At this time, the tumbling plate is rotating in the direction of the white arrow at certain angle with respect to the uniform flow and is generating lift in the upward direction. In the figure, the XYZ axis is the axis system fixed to the wind tunnel, and the wind blows in the X direction.

Now, take the vector $\vec{a}$ from the left end point to the right end point of the tumbling plate in the direction of the rotational axis, and set the unit vector as $\vec{ea}$. Consider a plane containing $\vec{a}$ and the X axis and set the unit vector of its normal vector $\vec{n}$ and take the Z' axis in same direction. We can set $XY'Z'$ axis system and the sideslip angle β of the tumbling plate is an angle formed by $\vec{a}$ and Y' axis. We define the unit vector in the X , Y' direction as $\vec{ex}$, $\vec{ey}$, unit vector in Z direction as $\vec{ez}$. Unit vector in Z' direction is unified by $\vec{n}$.

The force acting on the tumbling plate can be divided into the forces acting on the right and left ends. The Lift force is divided into L_L and L_R acting in the Z' direction, the drag force is divided into D_L and D_R acting in the normal direction of the plane including the $\vec{a}$ and Z' axis, side force is divided into Y_L and Y_R acting in the direction of the rotational axis. The weight of the tumbling plate is expressed as W is divided into $W/2$ acting equally on the right and left sides in the Z direction. For the tension, the tension applied to the left and right strings are expressed as T_L and T_R , and the unit vector in the pulling direction of each of them is expressed as $\vec{eT_L}$, $\vec{eT_R}$.

The drag, side force and tension are expressed as follows using the unit vector.

$$\text{Drag: } D_L \vec{eD}, D_R \vec{eD}$$

$$\text{Side force: } Y_L \vec{ea}, Y_R \vec{ea}$$

$$\text{String Tension: } T_L \vec{eT_L}, T_R \vec{eT_R}$$

By measuring the three-dimensional position of the end point of the tumbling plate and the holding point of the

Figure 4: Forces in the XZ' plane.

string $\vec{a}$, $\vec{ea}$, and $\vec{eT_L}$, $\vec{eT_R}$ are obtained. $\vec{n}$ is obtained from the cross product of $\vec{ex}$ and $\vec{ea}$.

$$\vec{n} = \frac{\vec{ex} \times \vec{ea}}{|\vec{ex} \times \vec{ea}|} \quad (5)$$

And $\vec{ey}$ is,

$$\vec{ey} = \frac{\vec{n} \times \vec{ex}}{|\vec{n} \times \vec{ex}|} \quad (6)$$

Unit vector in the direction of drag force is,

$$\vec{eD} = \frac{\vec{ea} \times \vec{n}}{|\vec{ea} \times \vec{n}|} \quad (7)$$

Here, assume that the rotational direction of the tumbling plate is reversed to generate a downforce. At this time, the tumbling plate is located on a plane different from the XY' plane at the time of generating the lift force. Assume that the pulling direction of the string is adjusted and the sideslip angle in the plane in which the tumbling plate exists is set to the value of β .

Now, define the position at the time of generating the lift force is referred to as "upper" and at the time of generating the downforce is referred to as "lower", and express them to add the suffix of "u" and "l" respectively (use lowercase letters to distinguish between left and right suffixes L and R). Because the side slip angle matches,

$$\vec{ex} \cdot \vec{ea}_u = \vec{ex} \cdot \vec{ea}_l \quad (8)$$

In the XZ' plane, forces are balanced as shown in Fig. 4.

The forces is generated in the XY' plane as shown in Fig. 5.

Note that although in Fig. 4 and Fig. 5, upper and lower positions are expressed in the $XY'Z'$ plane for convenience, those planes are neither coplanar nor parallel (namely, $Y'_u \neq Y'_l$, $Z'_u \neq Z'_l$).

Figure 5: Forces in the XY' plane.

For each direction X , Y' , Z' the following equation of balance holds.

upper,

$$D_L \overrightarrow{eD_u} \cdot \vec{eX} + Y_{Lu} \overrightarrow{eD_u} \cdot \vec{eX} + T_{Lu} \overrightarrow{eT_{Lu}} \cdot \vec{eX} = 0 \quad (9)$$

$$D_L \overrightarrow{eD_u} \cdot \vec{eY_u} + Y_{Lu} \overrightarrow{eD_u} \cdot \vec{eY_u} - \frac{W}{2} \vec{eZ} \cdot \vec{eY_u} + T_{Lu} \overrightarrow{eT_{Lu}} \cdot \vec{eY_u} = 0 \quad (10)$$

$$L_L - \frac{W}{2} \vec{eZ} \cdot \vec{n_u} + T_{Lu} \overrightarrow{eT_{Lu}} \cdot \vec{n_u} = 0 \quad (11)$$

$$D_R \overrightarrow{eD_u} \cdot \vec{eX} + Y_{Ru} \overrightarrow{eD_u} \cdot \vec{eX} + T_{Ru} \overrightarrow{eT_{Ru}} \cdot \vec{eX} = 0 \quad (12)$$

$$D_R \overrightarrow{eD_u} \cdot \vec{eY_u} + Y_{Ru} \overrightarrow{eD_u} \cdot \vec{eY_u} - \frac{W}{2} \vec{eZ} \cdot \vec{eY_u} + T_{Ru} \overrightarrow{eT_{Ru}} \cdot \vec{eY_u} = 0 \quad (13)$$

$$L_R - \frac{W}{2} \vec{eZ} \cdot \vec{n_u} + T_{Ru} \overrightarrow{eT_{Ru}} \cdot \vec{n_u} = 0 \quad (14)$$

lower,

$$D_L \overrightarrow{eD_l} \cdot \vec{eX} + Y_{Ll} \overrightarrow{eD_l} \cdot \vec{eX} + T_{Ll} \overrightarrow{eT_{Ll}} \cdot \vec{eX} = 0 \quad (15)$$

$$D_L \overrightarrow{eD_l} \cdot \vec{eY_l} + Y_{Ll} \overrightarrow{eD_l} \cdot \vec{eY_l} - \frac{W}{2} \vec{eZ} \cdot \vec{eY_l} + T_{Ll} \overrightarrow{eT_{Ll}} \cdot \vec{eY_l} = 0 \quad (16)$$

$$-L_L - \frac{W}{2} \vec{eZ} \cdot \vec{n_l} + T_{Ll} \overrightarrow{eT_{Ll}} \cdot \vec{n_l} = 0 \quad (17)$$

$$D_R \overrightarrow{eD_l} \cdot \vec{eX} + Y_{Rl} \overrightarrow{eD_l} \cdot \vec{eX} + T_{Rl} \overrightarrow{eT_{Rl}} \cdot \vec{eX} = 0 \quad (18)$$

$$D_R \overrightarrow{eD_l} \cdot \vec{eY_l} + Y_{Rl} \overrightarrow{eD_l} \cdot \vec{eY_l} - \frac{W}{2} \vec{eZ} \cdot \vec{eY_l} + T_{Rl} \overrightarrow{eT_{Rl}} \cdot \vec{eY_l} = 0 \quad (19)$$

$$-L_R - \frac{W}{2} \vec{eZ} \cdot \vec{n_l} + T_{Rl} \overrightarrow{eT_{Rl}} \cdot \vec{n_l} = 0 \quad (20)$$

Since the unknowns in Eq. 9 to Eq. 20 are the following 12 scalars, all of them can be solved as simultaneous linear equations.

$D_L, D_R, L_L, L_R, Y_{Lu}, Y_{Ll}, Y_{Ru}, Y_{Rl}, T_{Lu}, T_{Ll}, T_{Ru}, T_{Rl}$

In these equations, it is a condition that β matches between the upper position and lower position, so the coefficients related to the attitude angle of the tumbling plate (ex. $\overrightarrow{eD_u} \cdot \vec{eX}, \overrightarrow{eD_u} \cdot \vec{eY_u}, \overrightarrow{eD_u} \cdot \vec{eY_l}, \overrightarrow{eD_u} \cdot \vec{eX}, \overrightarrow{eD_u} \cdot \vec{eY_u}, \overrightarrow{eD_u} \cdot \vec{eY_l}$, etc.), are obtained when the sideslip angle β is determined.

Table 1: Model Specification.

Model	Span l (m)	Chord C (m)	Thickness t (m)	Shaft Span b (m)	Weight* W (kg)	Moment of Inertia I (kg · m ²)
Basic					0.0035	
Middle	0.15	0.04	0.0012	0.245	0.0058	2.23E-13
Heavy					0.0082	

*: Shaft included. The weight of the plate only is 0.0017 kg.

Figure 6: Wind tunnel.

The lift L , the drag D , the lateral force Y , the rolling moment R and the yawing moment n of the tumbling plate are calculated in the following order.

$$L = L_L + L_R \quad (21)$$

$$D = D_L + D_R \quad (22)$$

$$Y = Y_{Lu} + Y_{Ru}, Y_{Li} + Y_{Ri} \quad (23)$$

$$R = (L_L - L_R) \cdot b/2 \quad (24)$$

$$n = (D_R - D_L) \cdot b/2 \quad (25)$$

where b is the lateral width of the shaft and the sideslip angle β is calculated according to the definition of dot product as follows,

$$\beta = \cos^{-1}(\vec{ea} \cdot \vec{ex}) - \frac{\pi}{2} \quad (26)$$

For Eq. 23, the side force measurement results can be calculated in duplicate from both upper and lower, but the difference is accepted as an error in this paper and is not a condition of the equation. In this method, only the specimen having no pitching moment around the side axis can be used.

3. Verification Wind Tunnel Test

Wind tunnel tests were carried out to confirm the measuring method described in Section 2.

Figure 7: Apparatus setup.

3.1 Wind Tunnel A vertical type closed return type wind tunnel (Fig. 6) of Aichi Institute of Technology was used for the verification test. The wind tunnel has a test section with dimensions of 0.6 m (W) × 0.6 m (H) × 1.5 m (L) and can be changed to open type test section by removing the test cart. The maximum wind speed is 50 m/s.

3.2 Model and Test Equipment The test model is a rectangular plate made of formed Polystyrene sheet, double sided. The specifications are shown in Table 1. Here weight includes the weight of the rotating shaft and ignores the moment of inertia of the shaft. Since Middle and Heavy models are manufactured by adding weights to the shaft of the Basic model, the increase in the moment of inertia due to the weight is ignored.

A brass shaft with a diameter of 1 mm is attached to the plate center line as rotating shaft, the length of the rotating shaft is 250 mm (the width between the miniature bearings is 245 mm), and the plate is drawn from the blowout surface of the wind tunnel with a #0.6 (0.12 mm) fishing line through miniature bearing. A setup apparatus of the wind tunnel test is shown in Fig. 7, and a photograph of the test model is shown in Fig. 8. The sideslip angle is set by changing the length of one side of the strings. Markers are attached to the plate near both ends, and the plate is cap-

Figure 8: Test model.

Table 2: Test Condition.

Model	Flow velocity U (m/s)	Length of the strings	Rotational Dorection
Basic	2.6	L&R same	Upper
		left + Δ	Lower
Middle	3.8	L&R same	Upper
		left + Δ	Lower
Heavy	4.9	L&R same	Upper
		left + Δ	Lower

tured by two cameras set to the test section side surface, projected on the grid wall of the back surface, the coordinates on the grid are read, and three-dimensional coordinates are obtained by using the stereoscopic technique. For verification, the fishing line is guided out of the wind tunnel through a metal tube in order to avoid exposure to wind and connected to a load cell to measure tension.

3.3 Test Conditions Table 2 summarizes the test conditions. In order to verify the method, the weight of the model was changed by attaching a small weight to the plate end position of the shaft. The appropriate uniform flow velocity is selected to achieve a balance with gravity and stability of the model depends on the weight of the model. Since it is difficult to match the sideslip angle between upper and lower, the same sideslip angle value was calculated by interpolation of the data by changing three sideslip angles.

3.4 Data Processing Flow chart of data processing is shown in Fig. 9 in which general-purpose software used in the process are written.

Slow videos were used to capture images assuming unsteady motion of the tumbling plate. The acquired images are decomposed into frames and combined into one image. From the image data acquired by the two cameras, the two-dimensional coordinates projected on the wall surface are read after correcting the distortion of the image and then averaging the unsteady motion, and the three-dimensional coordinate data are processed by the method of the general stereoscopic technique using the similarity rule of the triangle as shown in Fig. 10. We put the origin point of the world coordination at the camera center of the lower camera. $P(x, y, z)$ is the three-dimensional position of the point on the model. (x_U, z_U) and (x_L, z_L) are point position pro-

Figure 9: Flow chart.

jected on the aside wall in the upper and lower camera coordination.

The three-dimensional position of the point can be calculated as follows,

$$z = \frac{z_L T}{z_L - z_U} \quad (27)$$

$$X = \frac{x_L T}{z_L - z_U} = \frac{x_U T}{z_L - z_U} \quad (28)$$

$$y = \frac{f T}{z_L - z_U} \quad (29)$$

4. Experimental Results

At the beginning of Chapter 2, it was assumed that the force applied to the string itself can be ignored. For the confirmation, the result of measuring the deflection of the string from the picture obtained from the test result is shown in Fig. 11 as dashed line. From Fig. 11, the plate was pulled almost on a straight line, and the deformation caused by wind exposure cannot be measured. This is because the string used in this wind tunnel test was very light and thin. For this reason, in this paper, we assume that the force and gravity applied to the string are negligible compared with the forces of the plate, and we processed the data.

Figure 12 shows the comparison of string tension between measured by load cells and calculated from the position measurement of the plate. Different models are plotted (*i.e.*, different velocity and weight) together, and for clarity, left side value is plotted as negative β . Data of the load cell of the basic model is not shown in Fig. 12 because it can't be measured within the measurement accuracy of the load cell due to its light weight. It is known that the lift and drag of the tumbling plate vary depending on the angle of rotation of the tumbling plate in one cycle. However, since the output of the load cell used for the test device in this test was time-averaged, the result of the position measurement is also time-averaged. It can be seen that the force from the

Figure 10: Stereoscopic three-dimensional coordinates.

Figure 11: Deflection of the strings.

load cell and the force calculated from position measurement are coincide well.

For the middle model, the cause of the error in Fig. 12 is analyzed. The maximum value of the error between load cell measurement results and position measurement results was about 5%. Assuming that all this error is caused by the position measurement error in X-axis, the position error corresponds to 14 mm. This value is too large compared

Figure 12: Comparison of the tension of the string.

to the maximum error of a few millimeters obtained from the position measurement calibration results. On the other hand, assuming that all this error is caused by the model weight measurement error, the error corresponds to 0.3 g of the model weight. This error is barely within the accuracy range (0.1% of the maximum range) of the weight measuring device used in this wind tunnel test, and it is necessary to use a weight measuring device with higher accuracy for future improvement.

For about the angular velocity, as the weight of the Model increases, (*i.e.*, the flow velocity increases), it can be seen that the deviation increases slightly. As a result of detailed analysis, it was found that the test conditions at the upper and lower deviated slightly as the flow velocity increased. Fig. 13 shows the relationship between flow velocity and reduced frequency k . Definition of k is as follows,

$$k = \frac{\omega C}{2U} \quad (30)$$

Where ω is angler velocity measured in the experiment and U is the uniform flow velocity, C is plate chord length.

From Fig. 13, it can be seen that the deviation of k between upper and lower increases as the flow velocity increases. This is considered to be caused by the fact that the load applied to the model increases as the wind velocity increases, and especially in the lower case, a large load is generated. In the upper case, the model produces lift and the difference from gravity balances tension, whereas in the lower case, the resultant force of down force and gravity balances tension by causing down force and gravity to act in the same direction. At this time, as shown in Fig. 11,

Figure 13: Change in Reduced Frequency k .

tension acts on both ends of the shaft, but gravity and lift or down force act near the center of the model, causing the model to flex and deform slightly. The deformation causes the center of gravity of the model to deviate outward from the center of rotation. This deformation of the model makes the rotation unstable and generates vibration. In addition, this deformation creates an angle between the shaft and the miniature bearing to increase the frictional force of bearing. These effects are considered to reduce the rotational speed.

The authors have proposed the relation between the lift force of the tumbling plate and the so-called dynamic lift in [11]. The decrease of rotational speed decreases lift generated by dynamic lift. In this method, the aerodynamic force is calculated on the assumption that the aerodynamic conditions of upper and lower are the same, so the deviation of the aerodynamic conditions of upper and lower leads to a decrease in measurement accuracy. This difference is about 15% for the Heavy Model case in Fig. 13. According to [7], as shown in Fig. 14, a shift of about 15% of the rotational speed corresponds to a shift of about 10% of the CL at around the maximum slope. Where, CL_0 and CD_0 are the value of steady state ($\omega = 0$) and ω_0 is the stable value of angular velocity determined by wind velocity. The deviation of CL by about 10% is almost the same order as the maximum deviation of the tension of the string of Heavy Model in Fig. 12. Therefore, in this method, the rigidity of the model should be considered, or the test should be performed under the condition of small aerodynamic force. Alternatively, damping may be added to the string to suppress rotational vibration. Although because the purpose is to validate the methods in this paper, the wind velocity was increased in order to generate a large force to ensure the measurement accuracy of the load cell, small aerodynamic force condition is one of the advantages of this method.

From the viewpoint of directional stability and lateral stability, Yawing moment C_n and Rolling moment CR are shown in Fig. 15, Fig. 16. The definitions of C_n and CR is as follows,

$$C_n = \frac{n}{1/2\rho U^2 l^2 C} \quad (31)$$

$$CR = \frac{R}{1/2\rho U^2 l^2 C} \quad (32)$$

Here, ρ is fluid density, l is the lateral width of the plate.

Figure 14: Variation of drag and lift coefficients with ω/ω_0 [9].

Figure 15: Directional Stability.

Figure 16: Lateral Stability.

In Fig. 15 and Fig. 16, the heavy model case is excluded because the trend is slightly different for the reasons mentioned above. Although it seems that C_n and CR have certain value shift even at $\beta = 0^\circ$ because of asymmetry of the model or deviation of air flow, the trend as the sideslip angle increases, the value tends to decrease can be seen. This means the stability tends to become unstable at large sideslip angles. On the other hand, CR of the middle model tends to increase as the sideslip angle increases. This also means that the lateral stability goes to unstable. The asymmetry at $\beta = 0^\circ$ needs to be improved in the future.

The values of the plate lift coefficient CL and the drag coefficient CD obtained from the position measurement are plotted together with the graphs from the [8] in Fig. 17. The definition of the parameters found in the figures are as fol-

Figure 17: Comparison with the literature [8].

lows,

$$CL = \frac{L}{1/2\rho U^2 l C} \quad (33)$$

$$CD = \frac{D}{1/2\rho U^2 l C} \quad (34)$$

$$AR = 1/C \quad (35)$$

$$I^* = \frac{32I}{\rho C^4 l} \quad (36)$$

$$I = \frac{W l C^2}{12} \quad (37)$$

Here, I^* is inertia moment ratio, I is inertia moment of the plate.

Although the test conditions are different from those in the literature (measurement under the same test conditions is difficult because the test conditions are affected by many parameters such as rotation speed of the tumbling plate or the thickness ratio of the plate, *etc.*), or the effects of neglecting the aerodynamic forces on the shaft or strings, the trends are consistent. It should be noted that the force can be measured from the position measurement even for a light basic model, and the CL and CD calculated from the force can be obtained with reasonable results compared with literature.

5. Conclusion

A new wind tunnel test method was proposed to measure the aerodynamic forces act on the tumbling plate and the tension of the tow string in the wind tunnel not by using force sensors but by measuring the tow position. The method was verified through verification tests.

As a result, the effectiveness of this method was confirmed as follows,

- The tension measured from load cells coincided well with the tension calculated from the three-dimensional position measurement.
- The lift coefficient and the drag coefficient calculated from position measurement were also consistent with the values from the references.
- It was confirmed that the measurement by this method was effective even in the test of small forces act on the model which was buried in the measurement accuracy of force censors.
- In order to improve this new wind tunnel test method, it is necessary to consider conducting tests under the same aerodynamic conditions at upper and lower (ex. improve the stiffness of the model, *etc.*). And need the high accuracy of the weight measurement of the model.

In this paper, gravity and aerodynamic forces acting on the string itself were neglected in the wind tunnel test, but in the future, it is necessary to investigate the effects of the forces acting on the string in order to conduct a tests requires more accuracy.

In the future, we will investigate the physical phenomenon of the tumbling plate by tumbling test using this method and the relationship between the tumbling plate and dynamic lift

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