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Aerodynamic model of table tennis ball flying while spinning

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Aerodynamic Model of Spinning Table Tennis Ball

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Abstract–
We propose an academic model of spinning table tennis ball.The object of this study is the realization of table tennis robot.It is complex to analyze drag coefficient and lift coefficient of table tennis ball.To analyze this movement, we use Computational Fluid Dynamics software calculation.

Key Words: Table tennis ball, Sp parameter

1 Introduction

In the future, robots are expected to advance into daily life,
It is thought that it can coexist with humans and play an active part in various environments
You. To do so, the robot itself has visual perception,
Judgment requires safe, quick and accurate actions.
In our laboratory, we focus on sports as an example of this behavior.
Among them, I study table tennis movements with robots. Table
The ball recognizes the incoming ball and hits the target
Returning, time-constrained judgment and motion control are required.

In this study, a series of research on realization of table tennis robot 1) 2) One of 3) , flying while spinning in the air
Try to make the exercise model of table tennis ball more accurate
It is.

Table tennis is a game that controls the spin of the ball
Indeed, the spin of the ball is extremely important. Racket
Hit the ball with a ball
Not only changes in the trajectory when
The effect of spin is also significant on the trajectory of the
It is because it appears clearly.

High-speed camera (900fps: Hamamatsu Photonics) system
Translation speed and rotation of a table tennis ball flying in the air
A method to measure speed online has been proposed1) . So
Here we measure the time change of the pattern attached to the table tennis ball surface
(See Fig. 1 (a))
But the field of view of the high-speed camera is narrow,
It is suitable for measuring the ball launched from the machine
Suitable for measurement of ball flying in rally with human
It was not.

Ball

Feature point

Table

(a) High speed (900fps) (b) Medium speed (150fps)
Fig. 1: Camera view.

A medium-speed camera that can see the entire table tennis table (150fps: library) system (Fig. 1 (b)
), The rotational speed from the ball flight trajectory online
We proposed a measurement method4) . Where they fly in the air
Ball motion (aerodynamic model)
It utilizes the fact that it depends on resistance and lift. did
Therefore, the measurement accuracy of the rotational speed by this method is aerodynamic.
Depends on the accuracy of the drag and lift terms contained in Dell
It will be.

In this study, a bo that flies while spinning in the air
Focusing on the equation of motion that describes the motion of
The drag coefficient included in the term, the lift coefficient included in the lift term and
Make the relationship between translation speed and rotation speed of the ball more accurate
The purpose is to: Specifically, a sphere flying in the air
Body movements, eg the relationship between drag coefficient and Reynolds number
Has been investigated in the field of fluid mechanics and their
According to the knowledge, the translation speed used in a normal table tennis rally
Drag coefficient is almost constant at Reynolds number in the range of degrees.
is there. On the other hand, the ratio between spin and translation speed (dimensionless amount)
The relationship between the spin parameter and the drag coefficient and lift coefficient is
In the field of fluid mechanics, it is not always well understood
It seems to be.

In this study, the translation speed used in a normal table tennis rally
The drag coefficient and lift coefficient are within the range of degrees and rotation speed.
It can be approximated by a function with only pin parameters.
It starts from the expectation.

To see if this prediction is correct, first
Tunnel simulation using numerical fluid dynamics (CFD) analysis
Simulation of drag coefficient and lift coefficient
What kind of functions are translation speed and rotation speed?
Consider. Numerical result is based on least squares method and Akaike information criterion
Polynomial approximation using (AIC). Next, this result
Needs to be verified by experiments, but in this paper
We just describe the verification method.

The structure of this paper is as follows. In Chapter 2, the empty
Outline the equation of motion of a sphere flying in the air with spin.
Explain. Chapter 3 describes the results of computational fluid dynamics (CFD) analysis.
And a polynomial using the least squares method and AIC.
Here is the result of the approximation. Chapter 4 describes the verification method by experiment.
Is described briefly. Chapter 5 is a summary.

Aerodynamic model considering **two** spins

Fly in the air with constant spin $\omega \in R^3$
The movement of the table tennis ball is known to obey the following differential equation:

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It is 5) .

$$\ddot{\boldsymbol{p}}(t) = -\boldsymbol{g} + C_D \frac{\rho}{m} R^2 S_B \|\dot{\ } \textit{the p-} (T)\| \dot{\ } \textit{the p-} (T) + C_M \frac{\rho}{m} V_b \boldsymbol{\omega} \times \dot{\boldsymbol{p}}(t) \quad (1)$$

Where $\boldsymbol{p}(t) \in R^3$ is the position of the ball at time t, and $\boldsymbol{g} :=$ $[0\ 0\ g]^T$ and g are the gravitational acceleration, m is the mass of the ball, and ρ is Air density, $S_b := \frac{1}{\text{Two}} \pi r^2$, $V_b := \frac{4}{\text{Three}} \pi r^3$, r is the ball radius . Also, C_D, C_M is the drag coefficient, is the lift coefficient.

Drag coefficient C_D and the lift coefficient C_M is the Reynolds number Re and Is known to be a function of the spin parameter Sp That 6) 7) 8) 9) . Reynolds number Re is the ratio of inertial force to viscous force Is a dimensionless quantity representing

$$Re := \frac{2r\|\dot{\boldsymbol{p}}\|}{\nu} \quad (2)$$

Is defined as Where $\nu := \mu / \rho$ is the kinematic viscosity of air (μ is the viscosity coefficient). Also, the spin parameter Sp is Translation speed and spin (however, it is orthogonal to the translation speed vector) Is a dimensionless quantity that represents the ratio of

$$Sp := \frac{r\|\textbf{Omega} - (\textbf{Omega}^T \dot{\boldsymbol{p}} / \|\dot{\boldsymbol{p}}\|)\dot{\boldsymbol{p}}/\|\dot{\boldsymbol{p}}\|\|}{\text{The } \|\dot{\boldsymbol{p}}\|} = \frac{r\|\boldsymbol{\omega} \times \dot{\boldsymbol{p}}\|}{\|\dot{\ } \textit{the p-}\|^2} \quad (3)$$

. However, in the exercise of ordinary table tennis ball $\|\dot{\ }$ *the p-* $(T)\| \in$ $[0.5, 10]$ is in the range of m / s, thus, $r = 0.02$M, 1 At atmospheric pressure 20 $[nu = 1.512 \times 10^{-5}$ m 2 With / s, $Re \in$ $[1.323, 26.46] \times 10^3$ become, drag than 2 coefficient C_D You can see that does not depend on the Reynolds number Re .

(Fig. 2: $\log_{10} C_D$ vs. $\log_{10} Re$ 7)

In this paper, the drag coefficient C_D is Supinparame Function. Similarly, lift coefficient *We* also assume that C_M is a function with only spin parameters. Or later In the following, we will write $C_D(Sp)$ *and* $C_M(Sp)$.

(**3**) Drag drag by computational fluid dynamics (**CFD)** analysis Estimation of number and lift coefficient

Here using CFD analyzes, drag coefficient C_D and lift coefficient The number C_M spin parameter Sp ne a function such as throat Consider whether or not. The software used is 3D thermal fluid Analysis software "PHOENICS" (CHAM-Japan) is there.

In CFD analysis, simulations that simulate wind tunnel experiments were performed went. Inside the wind tunnel (rectangular box: $L_x L_y x L_z$ m) Position (x_b, y_b, z_b) to secure the table tennis ball, y foremost around shaft Spin at a constant speed ω_y rad / s. Wind tunnel air inlet The x side of = 0, outlets $x = L_x$ is a side of a straight The other side of the cube is a wall, with no air in / out And Translation speed V_x m / s in x- axis direction from wind tunnel inlet Of air.

Numerical results of CDF analysis are table tennis ball and wind tunnel (cuboid) Size ratio and how to cut the mesh of the wind tunnel (cuboid) Dependent. These conditions can be varied Results of the CFD analysis

- Minimize the effect of the wall while negligible Wind tunnel (cuboid)
- changes to the case fine from the case coarse and how to cut the mesh The numerical results have converged No. Fine mesh that seems to have converged sufficiently Mesh as coarse as possible

From the viewpoint of the wind tunnel, the size of the wind tunnel (cuboid) and the mesh We decided how to cut.

The size of the wind tunnel (cuboid) is $L_x = 0.5$ *M*, $L_Y = 0.25$ *M*, $L_Z = 0.25$ *m* , a fixed position of the ball is $x_b = 0.125$ *m*, $x_y = 0.125$ *m*, $x_z = 0.125$ *m* was.

Cross section 1

Cross section 2

Cross section 3

Fig. 3: Position of the cross sections

Cross section 1 Cross section 2

} } p } pp } p pp

} pp } ppp } pp p} } ppp p}

ZZ

} } p } pp } p pp

Y X

Cross section 3

p } p

ppp } pp ppp

Z

p } p

X

Fig. 4: CFD screen and computational grid

For the method of cutting the mesh, see the wind tunnel (cuboid) Is divided into 125 small rectangular parallelepipeds, and each small rectangular parallelepiped is shown in Table 1. One of eight types of meshes was used. In the wind tunnel Distribution of small rectangular parallelepiped and mesh used in the small rectangular parallelepiped Figure 4 shows the types.

On the translational velocity V_x *of the* air and the rotational velocity ω_y of the ball Is within the range expected from a regular table tennis rally. Parameter Sp is $0.1 < SP < 2.0$ in the range of 0 . One by one strange I thought about moving it. In particular

Table 1: computational grid

	x_m	y_m	z_m
I	0.005	0.005	0.005
II	0.005	0.001	0.005
III	0.005	0.005	0.001
IV	0.005	0.001	0.001
V	0.001	0.005	0.005
VI	0.001	0.001	0.005
VII	0.001	0.005	0.001

Fig. 6: Sp vs. C_D

VIII 0.001 0.001 0.001

- Fix $V_x = 3$ or $V_x = 5$
  Parameter Sp^* Ω_y is determined so that
- Fix $\omega_y = 100$ or $\omega_y = 300$
  Parameter Sp^* Determine V_x so that

We performed two steps. Table 2 shows some specific combinations. Shown in

Table 2: V_x and ω_y

	Sp^*	0.1	0.5	1.0	1.5	2.0
$V_x = 3$	ω_y	15	75	150	225	300
$V_x = 5$	ω_y	twenty five	125	250	375	500
	Sp^*	0.1	0.5	1.0	1.5	2.0
$\omega_y = 100$	V_x	20	Four	Two	1.33	1
$\omega_y = 300$	V_x	60	12	6	Four	Three

5, $V_x = 3\ m/s$, $omega_y = 62.8\ rad/s$ was set
It shows the pressure distribution among the CFD analysis results (pressure
The force value is small for blue and large for red. However, the blue line
Mesh shown, numerical table shown in red square
Ignore the indication measurement points. On the underside of the ball
Red pressure distribution is blue toward the rear and obliquely upward of the ball
Pressure distribution of color is seen, and a pressure difference occurs in the x- axis direction
At the same time, the symmetry of the pressure difference depends on the rotation of the ball.
You can see that it has collapsed.

Fig. 5: Pressure distribution obtained by CFD

From the pressure distribution as shown in Fig. 5, the ball
The pressure distribution to be used is obtained.
Fluid force use (F_x, F_y, F_z) is determined. Note that $F_y \approx 0$
It is easy to imagine that
Note that it was.
F_x drag coefficient of C_D a, F_z lift coefficient from C_M calculate the
Figures 6 and 7 show the results. The horizontal axis is the spin para
On the meter, the vertical axis shows the calculated lift coefficient and drag coefficient.
In Fig. 6, for the same spin parameter value,
The number of C_D is the value of are plotted, shown in Table 2
As shown, the same spin parameter value is different (V_x, ω_y)

Fig. 7: Sp vs. C_M

It is realized by the combination of and CFD analysis. This calculation
Fruits C_D spin parameters Sp can polynomial approximation at Resona
Arms have suggested that, at the same time the resistance coefficient C_D is
This shows that it is almost independent of the Reynolds number Re .
Similarly, from Fig. 7, C_M also spin parameter Sp multi with
It is likely to be Polynomial approximation, at the same time lift coefficient C_M also
You can see that it is almost independent of Reynolds number Re . Was
However, the spin parameter $Sp = 0.1$ of the case C_M value of
There is a large variation in As the cause, $Omega_Y$ is
Numerical calculation error due to small, Reynolds number Re and
There are various possibilities such as other hydrodynamic factors, but specific
Not done.
The results of CFD analysis (Figs. 6 and 7) were
Consider a small square approximation. Approximate drag coefficient C_D
An example shows the approximation method.
Data $D := \{ (Sp_i, C_{Di}) \mid i = 1, \cdots, N \}$ with respect to,
k-th order polynomial $f_k(x)$

$$F_K(X) := A_K X^K \text{ Tasu } A_{K-1} X^{K-1} \text{ Tasu } \cdots \text{ Tasu } A_1 X \text{ Tasu } A_0 \quad \text{(Four)}$$

The idea, the approximation error variance $Shiguma_E$ a

$$\sigma_e(a_k, \cdots, a_0) := \frac{1}{N} \sum_{i=1}^{N} | C_{Di} - f_k(Sp_i) |^2 \quad \text{(Five)}$$

And the Akaike Information Criterion (AIC)

$$AIC(a_k, ..., a_0, k) := N \ln \sigma_e(a_k, ..., a_0) + 2k \quad (6)$$

Is determined. At this time

$$\min_{a_k, ..., a_0, k} AIC(a_k, ..., a_0, k) \quad (7)$$

Gives the optimal order k and the optimal coefficient of the approximate polynomial $a_k, \cdots, a_0$ were obtained.
The lift coefficient C_M was also subjected to the same approximation method.
$N = 56$ data obtained by CFD analysis
Force coefficient C_D is second order polynomial, lift coefficient C_M is fourth order polynomial
Became optimal. The optimal coefficients are as shown in Table 3,
Figures 8 and 9 show how the data is approximated by polynomials.

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Table 3: Approximate polynomials

	a_2	a_1	a_0
C_D	-0.0747	0.3591	0.3682

	a_4	a_3	a_2	a_1	a_0
C_M	0.2313	-1.2055	2.2813	-1.9501	0.8254

Fig. 8: Sp- C_D data and AIC modeling.

Estimation of drag coefficient and lift coefficient by 4 experiments

Drag coefficient obtained by CFD analysis and polynomial approximation
Lift coefficient needs to be verified by experiment
is there.

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Fig. 9: Sp- C_M data and AIC modeling.

Medium-speed camera (150Hz)
High-speed camera (900Hz)
y
z
x
Medium-speed camera (150Hz)

Fig. 10: High speed camera and midle speed camera.

In the validation experiment, a medium-speed camera (150 fps) system was used
Table tennis ball flying in the air while spinning in the air
We will do this by measuring the trajectory of the robot. Ma
Also, if necessary, a high-speed camera (900fps) system
Measurement of spin (rotation vector) using measurement method [1]
I do.

4.1 Description of experimental equipment

Figure 10 shows an outline of the experimental setup. Ball launches automatically
Shot from the machine and the ball trajectory
measure. Immediately after launching from an automatic launcher
Is measured with a high-speed camera.

The ball trajectory data of the *k-th* trial obtained in the experiment is $P^{(k)}\{ \boldsymbol{p}_i^{(k)} \mid i = 1, \cdots, n_k \}$. Where $\boldsymbol{p}_i^{(k)} \in \mathrm{R}^3$
Is the time $t = \frac{1}{150} \times i$ This is the ball position vector at $\frac{1}{150} \times i$ seconds.

On the other hand, the initial value $\boldsymbol{x}_0^{(k)}$ corresponding to k trials of the experiment $= (\boldsymbol{p}(0), \dot{\boldsymbol{p}}(0))^{(K)}$ and the rotation vector $\boldsymbol{\omega}^{(K)}$ when you set up the
Time $t = \frac{1}{150} x\ i$ calculated from aerodynamic model (1)
Let the ball position vector in seconds be $\boldsymbol{p}_i(\boldsymbol{a}, \boldsymbol{x}_0^{(k)}, \boldsymbol{\omega}^{(k)})$.
Where $\boldsymbol{a} := (a_{D2}, a_{D1}, a_{D0}, a_{M4}, a_{M3}, a_{M2}, a_{M1}, a_{M0})$
.

Optimal estimation of drag coefficient and lift coefficient based on experimental data
The fixed value is

$$\min_{\boldsymbol{a}} \sum_{k=1}^{K} \left\{ \frac{1}{n_k} \sum_{i=1}^{n_k} \left| \boldsymbol{p}_i(\boldsymbol{a}, \boldsymbol{x}_0^{(k)}, \boldsymbol{\omega}^{(k)}) - \boldsymbol{p}_i^{(k)} \right|^{\text{Two}} \right\} \quad (8)$$

Obtain from

Note that without using a high-speed camera, the total rotation vector $\boldsymbol{\omega}^{(k)}$ was calculated
If no measurements are used, $W := \{ \boldsymbol{\omega}^{(k)} \mid k = 1, \cdots, K\}$
As

$$\min_{\boldsymbol{a}, W} \sum_{k=1}^{K} \left\{ \frac{1}{n_k} \sum_{i=1}^{n_k} \left| \boldsymbol{p}_i(\boldsymbol{a}, \boldsymbol{x}_0^{(k)}, \boldsymbol{\omega}^{(k)}) - \boldsymbol{p}_i^{(k)} \right|^{\text{Two}} \right\} \quad (9)$$

I will consider.

5 Conclusion

Using a numerical fluid dynamics analysis, a numerical system simulating a wind tunnel experiment
Ball used in table tennis rally from simulation
In the range of translational and rotational speeds, spin in air.
The drag coefficient and lift coefficient of a flying ball
With good accuracy and many functions as a function of spin parameters only.
It was found that the approximation (2nd and 4th order) was possible.

Future tasks are to verify the results obtained this time through experiments.
is there.

1) C.Liu, Y.Hayakawa and A.Nakashima; An On-Line Algorithm for Measureing the Transitional and Rotanation Velocities of a Table Tennis Ball, SICE JCMSI, Vol.5, No.4, pp.233–241, 2012.

2) C.Liu, Y.Hayakawa and A.Nakashima; Racket Control for a Table Tennis Robot to return a Ball, SICE JCMSI, Vol.6, No.4, pp.259–266, 2013.

3) Y.Hayakawa et al .; Ball TRajectory Planning in Serving Task for Table Tennis Robot, SICE JCMSI, Vol. 9, No.2, pp.50–59, 2016.

4) T.Okamoto, A.Nakashima and Y.Hayakawa; An On-line Estimation of Ball States for Prediction of Ball Trajectory with Aerodynamics Model, Proceedings of SICE Annual Conference 2013, 661-665, 2013.

5) Okada et al . : Ball not obtained by acquiring motion model from video Observational motion estimation, IEICE Journal D , Vol.J91-D, No. 12, pp. 2950–2960, 2008.

6) B. Oesterlé and T. Bui Dinh; Experiments on the lift of a spinning sphere in a range of intermediateaynolds numbers, Experiments in Fluids, Vol. 25, pp.16–22, 1998.

7) Mechanical Engineering Handbook, A5 Fluid Engineering, A5 ・ 97-A5 ・ 99 , Nippon Kikai The Japan Society of Mechanical Engineers, 1987.

8) Taniguchi et al . : Measurement of aerodynamic force acting on a rigid baseball, flow, Vol.25, pp.257–4, 2006.

9) Takami, Miyazaki, Himeno : Negative working on a sphere that spins back Magnus Force -Measurement by Flight Experiment-, Flow, Vol.28, pp.347–356, 2009.