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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

Table

Feature point

(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  $\omega \in \mathbb{R}^3$  The movement of the table tennis ball is known to obey the following differential equation:

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It is 5) .

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

Where  $\mathbf{p}(t) \in \mathbb{R}^3$  is the position of the ball at time  $t$ , and  $\mathbf{g} := [0 \ 0 \ g]^T$  and  $g$  are the gravitational acceleration,  $m$  is the mass of the ball, and  $S_B$  is the ratio of the wind tunnel (cuboid) size to the ball size. Air density,  $S_B := \frac{1}{\pi r^2}$ ,  $V_b := \frac{4}{3\pi r^3}$ ,  $r$  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 spin parameter  $Sp$  dependent. These conditions can be varied. Results of the CFD analysis

- Minimize the effect of the wall while negligible

Is known to be a function of the spin parameter  $Sp$

That is, Reynolds number  $Re$  is the ratio of inertial force to viscous force

Is a dimensionless quantity representing

$$Re := \frac{2r \|\dot{\mathbf{p}}\|}{\nu} \tag{2}$$

Is defined as Where  $\nu := \mu / \rho$  is the kinematic viscosity of air ( $\mu$  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

$$Sp := \frac{r \|\boldsymbol{\omega} - \boldsymbol{\omega}_T\|}{\|\dot{\mathbf{p}} - \dot{\mathbf{p}}_T\|} = \frac{r \|\boldsymbol{\omega} \times \dot{\mathbf{p}}\|}{\|\dot{\mathbf{p}} - \dot{\mathbf{p}}_T\|^2} \tag{3}$$

. However, in the exercise of ordinary table tennis ball  $\|\dot{\mathbf{p}} - \dot{\mathbf{p}}_T\| \in [0.5, 10]$  is in the range of m/s, thus,  $r = 0.02\text{M}$ , 1 At atmospheric pressure 20 [nu = 1.512 x 10<sup>-4</sup> m<sup>2</sup>/s, Re ∈ [1.323, 26.46] × 10<sup>3</sup> become, drag than 2 coefficient  $C_D$  You can see that does not depend on the Reynolds number  $Re$ .

Position ( $x_b, y_b, z_b$ ) to secure the table tennis ball, y foremost around shaft

Spin at a constant speed  $\omega_y$  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)

- 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  $L_x = 0.5\text{M}$ ,  $L_y = 0.25\text{M}$ ,  $L_z = 0.25\text{m}$ , a fixed position of the ball is  $x_b = 0.125\text{m}$ ,  $y_b = 0.125\text{m}$ ,  $z_b = 0.125\text{m}$  was.

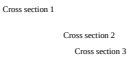


Fig. 3: Position of the cross sections

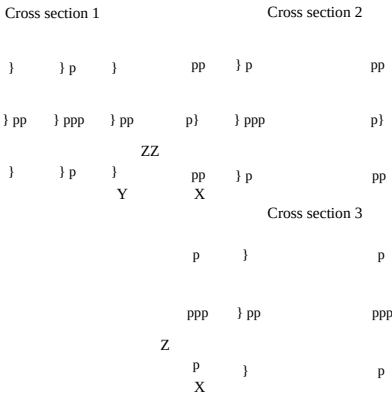


Fig. 4: CFD screen and computational grid

(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:  $L_x L_y L_z$  m)

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  $\omega_y$  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

VIII 0.001 0.001 0.001

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

5,  $V_x = 3\text{ m/s}$ ,  $\omega_y = 62.8\text{ rad/s}$  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  $C_D$ ,  $F_z$  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 ( $V_x$ ,  $\omega_y$ )

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  $D := \{ (Sp_i, C_{Di}) \mid i = 1, \dots, N \}$  with respect to,  
 $k$ -th order polynomial  $f_k(x)$

$$F_k(X) := A_k X^k + A_{k-1} X^{k-1} + \dots + A_1 X + A_0 \quad \text{(Four)}$$

The idea, the approximation error variance  $Shigma_E$  a

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

And the Akaike Information Criterion (AIC)

$$AIC(a_k, \dots, a_0, k) := N \ln \sigma_e(a_k, \dots, a_0) + 2k \quad \text{(6)}$$

Is determined. At this time

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

Gives the optimal order  $k$  and the optimal coefficient of the approximate polynomial  
 $a_k, \dots, a_0$  were obtained.

The lift coefficient  $C_M$  was also subjected to the same approximation method.  
Fig. 6 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					
$C_D$	$a_2$	$a_1$	$a_0$		
	-0.0747	0.3591	0.3682		
$C_M$	$a_4$	$a_3$	$a_2$	$a_1$	$a_0$
	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.

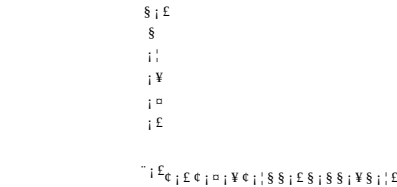


Fig. 9:  $Sp$ -  $C_M$  data and AIC modeling.

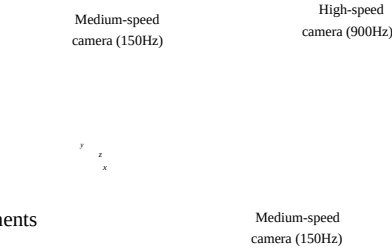


Fig. 10: High speed camera and middle speed camera.

In the validation experiment, a medium-speed camera (150 fps) system was used.

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 from the machine and the ball trajectory is measured. Immediately after launching from an automatic launcher

The ball trajectory data of the  $k$ -th trial obtained in the experiment is  $P_{(k)} = \{ \mathbf{p}_i^{(k)} \mid i = 1, \dots, n_k \}$ . Where  $\mathbf{p}_i^{(k)} \in \mathbb{R}^3$

Is the time  $t = 1/150 \times i$  seconds. This is the ball position vector at  $150 \times i$  seconds.

On the other hand, the initial value  $\mathbf{x}$  corresponding to  $k$  trials of the experiment (The  $\mathbf{p}_0^{(k)}$ , the  $\mathbf{p}_0^{(k)}$ ) and the rotation vector  $\boldsymbol{\omega}^{(k)}$  when you set up the Time  $t = 1$  calculated from aerodynamic model (1)

Let the ball position vector in seconds be  $\mathbf{p}_i^{(k)} = (\mathbf{a}_0, \boldsymbol{\omega}^{(k)})$ . Where  $\mathbf{a} := (a_{D2}, a_{D1}, a_{D0}, a_{M4}, a_{M3}, a_{M2}, a_{M1}, a_{M0})$

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

$$\min_{\mathbf{a}} \sum_{k=1}^K \left\{ \frac{1}{n_k} \sum_{i=1}^{n_k} \left\| \mathbf{p}_i^{(k)}(\mathbf{a}, \mathbf{x}_0^{(k)}, \boldsymbol{\omega}^{(k)}) - \mathbf{p}_i^{(k)} \right\|^2 \right\} \quad (8)$$

Obtain from

Note that without using a high-speed camera, the total rotation vector  $\boldsymbol{\omega}^{(k)}$  was calculated

If no measurements are used,  $\mathbf{W} := \{ \boldsymbol{\omega}^{(k)} \mid k = 1, \dots, K \}$

As

$$\min_{\mathbf{a}, \mathbf{W}} \sum_{k=1}^K \left\{ \frac{1}{n_k} \sum_{i=1}^{n_k} \left\| \mathbf{p}_i^{(k)}(\mathbf{a}, \mathbf{x}_0^{(k)}, \boldsymbol{\omega}^{(k)}) - \mathbf{p}_i^{(k)} \right\|^2 \right\} \quad (9)$$

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.

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