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Determinant Factors of the Table Tennis Game — Measurement and Simulation of Ball–Flying Curves —

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Abstract

This study examined the parameters influencing the aerodynamical flight of the table tennis ball. Firstly, to find out the whole range of combinations of table tennis ball speed and spin the ballistic ball curves were determined experimentally while two athlete's were playing. It was found that speed of the ball varied from 6 to 40 m/s and spin from 0 to ± 140 1/s. Secondly, the lift and drag coefficients of the ball $\mathbf{c_{LA}}$ and $\mathbf{c_{DA}}$ as a function of Reynoldsnumber and Spinparameter **SP** were calculated. It was found — with the spin as a parameter — that $\mathbf{c_{LA}}$**(SP)** increases from 0 (**SP**=0) up to 0.43 (**SP**=1.8) and then slowly goes down to 0.35 (**SP**=3.0) while $\mathbf{c_{DA}}$**(SP)** increases from 0.4 (**SP**=0) to 0.73 (**SP**=3.0). Thirdly, a numerical Runge–Kutta procedure was applied to simulate the recorded ball curves and to verify the calculation of $\mathbf{c_{LA}}$ and $\mathbf{c_{DA}}$ starting with the initial conditions of the recorded curves.It was found that differences between real and numerical table tennis curves are in the same order of magnitude as the diameter of the ball (≤ ±50 mm). These findings showed that it is possible to measure and to simulate ballistic table tennis curves with an accuracy which is within the accuracy of a high level table tennis athlete. This was the aim of the study from the point of view of a table tennis player.

Key words: table tennis, initial conditions, aerodynamics, ballistic curves, simulation

Introduction

During the last few years a lot of questions have been discussed about changes to international table tennis rules so as to make high level table tennis more attractive for spectators. Some of these questions still unanswered are:

1) What enlargement of the ball effectively influences the character of the game?
2) What height of the net could be adequate to make the game more attractive?
3) What are the consequences of reducing the foam thickness of table tennis rackets?
4) Should the covering of rackets be standardized?

In summary, all these aspects focus on the same question: What factors determine the table tennis game? This question was the starting point of this study. According to figure 1 which demonstrates the determinant factors of the table tennis game a hypothesis of this study is: While playing table tennis the athlete adapts to the ball by choosing the right racket and by applying individual techniques and tactics. Varying these

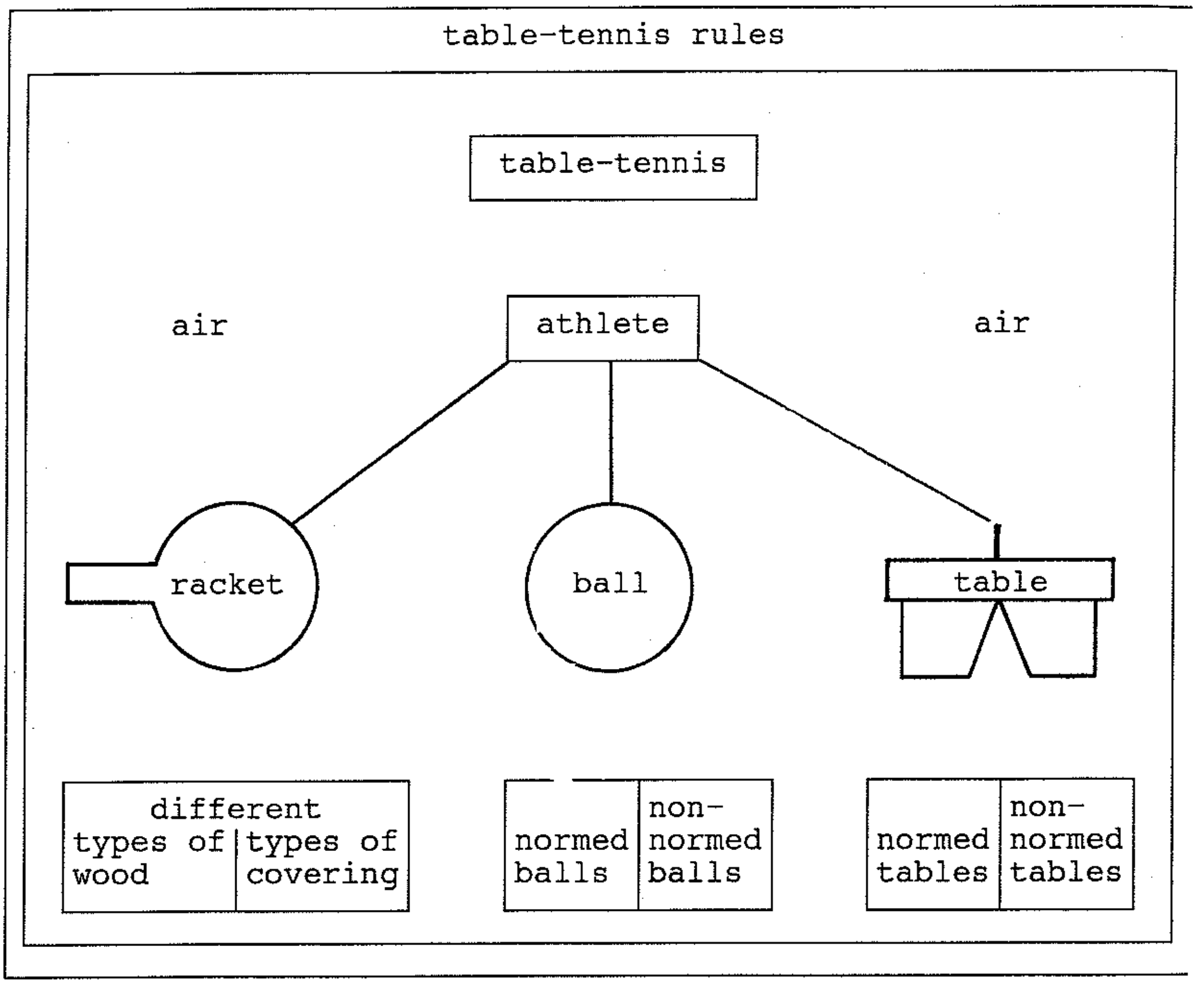

Fig. 1: Determinant factors of the table-tennis game

Table 1: Speed and spin conditions of the table-tennis ball

Technique	speed (m/s)	spin (1/s)
Counter	6 to 18	+ 20 to + 40
Smash	18 to 40	+ 0 to + 60
Topspin	12 to 20	+110 to +140
Shove	4 to 8	- 20 to - 60
Chop Defence	6 to 10	- 20 to -130

factors, the player tries to hit the ball in such a way that his opponent is forced to return it in a predicted way, according to his own anticipation.

Following this hypothesis and keeping in mind the development from the historical "ping pong" to today's high level sport of table tennis (1) the following conclusion can be made: Due to its low mass, its elasticity, its size and its form, the table tennis ball of celluloid, which is produced nearly unchanged since 1893, is the dominant factor in determining the character of the table tennis game. Hence, the aim of this study was to quantify the parameters influencing the aerodynamical flight of the table tennis ball.

Method

Based on the aerodynamics of the sphere as well as on international table tennis rules the flow characteristics of free flying rotating and non-rotating table tennis balls were discussed (2). In order to quantify the ballistic parameters of the table tennis ball, the following three steps were executed:

1) To find out the entire range of combinations of table tennis ball speed and spin, the ballistic ball curves were determined experimentally (3D-chronocyclography) while two athlete's were playing .

To determine spin and speed, the surface of the ball was marked with a red foil pencil. Multiple exposured slides (6*18 cm) of the ballistic curves were taken by two special cameras. A strobe with a frequency up to 160 Hz served as light source. The ball coordinates (x/y/z) were calculated by digitizing the center of the ball (using the coordinates of both cameras), the spin of the ball was calculated by twice digitizing the same two points on the marked surface (using the coordinates of the center of the ball to determine the projection of the ball, compare (2),p.62).

2) A table tennis simulator specially developed ((2), p.40) was used to simulate all possible ball curves varying systematically over the full range of initial conditions which were found experimentally. The prototype of the simulator was allowed to produce all necessary combinations of ball speed and spin and to measure the initial conditions.

The aim of this part was to calculate the lift and drag coefficients of accelerated movement $\mathbf{c_{LA}}$ and $\mathbf{c_{DA}}$ as a function of Reynoldsnumber and Spinparameter (**SP = u/v**) using the following model (compare (3)):

$$\vec{F} = \vec{D} + \vec{L} + \vec{G}$$

$$\vec{D} = -\tfrac{1}{2} c_{DA} * \rho * Av^2 * \hat{v}, \text{ with } A = \pi * R^2$$

$$\vec{L} = \tfrac{1}{2} c_{LA} * \rho * Av^2 * \hat{n}, \text{ with } \vec{n} = \omega \times \vec{v} \text{ and } \hat{n} = \vec{n} / n$$

$$\vec{G} = -m * \vec{g}$$

$$\omega = \vec{R} * \{\sin(\vartheta)*\cos(\varphi), \sin(\vartheta)*\sin(\varphi), \cos(\vartheta)\}$$

3) Numerical computer simulation was applied to the curves recorded to verify the model of part 2. To simulate ballistic table tennis curves numerically a Runge-Kutta procedure (4) was used. Starting with the initial conditions of the recorded curves the comparison of the coordinates between calculated and recorded curves demonstrated the reliability and validity of the model.

Results and Discussion

Characteristic speed and spin conditions of table tennis are specified in table 1. The lift and drag coefficients $\mathbf{c_{LA}}$ and $\mathbf{c_{DA}}$ for the accelerated movement of the free flying rotating table tennis ball as a function of Spinparameter **SP** with the rotational frequency **rot** as a parameter are shown in fig. 2 and 3. $\mathbf{c_{LA}}$**(SP)** and $\mathbf{c_{DA}}$**(SP)** were used to calculate the recorded ballistic curves. This led to the differences between numerical

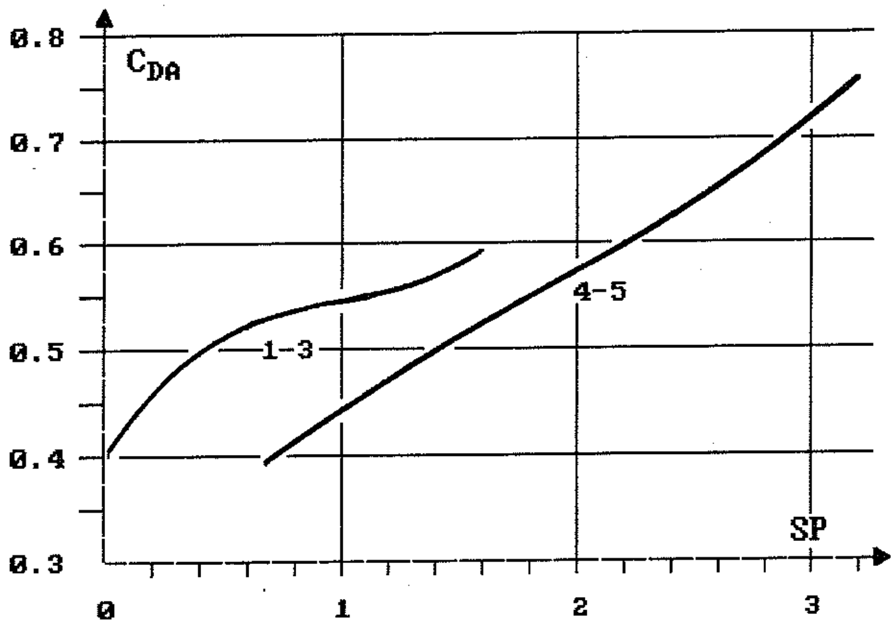

Fig. 2: c_{DA} = f(SP), 1-3: rot ≤ 80 1/s,
4-5: rot ≥ 100 1/s

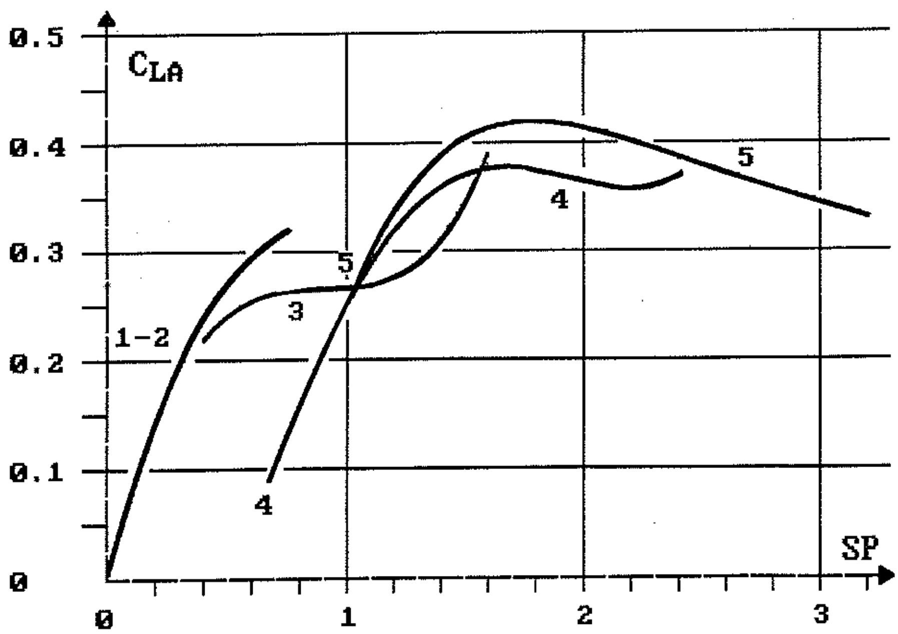

Fig. 3: c_{LA} = f(SP), 1-2: rot ≤ 40 1/s
3: rot ≈ 75 1/s
4: rot ≈ 110 1/s
5: rot ≈ 150 1/s

Table 2: Comparison of coordinates of calculated with recorded curves for rot ≤ 80 1/s

No.	rot [1/s]	SP_{t0}	SP_{te}	te-t0 [s]	RKx-x [mm]	RKy-y [mm]	RKz-z [mm]
	c_{DA}(1-3) and c_{LA}(1-2),(3)						
1209	15	0.06	0.14	0.24	17	-22	- 1
1206	15	0.07	0.11	0.29	6	- 9	- 6
1207	35	0.17	0.33	0.29	-13	16	0
1203	39	0.22	0.44	0.34	-44	- 3	21
1129	38	0.23	0.46	0.38	-47	-20	- 4
1120	38	0.29	0.55	0.47	-57	-29	11
1110	37	0.35	0.65	0.57	-42	- 5	15
1019	37	0.60	0.74	0.51	6	24	-15
1104	40	0.63	0.70	0.41	19	-11	- 2
1208	76	0.37	0.76	0.31	-50	2	22
1204	74	0.43	0.86	0.36	-61	14	76
1130	75	0.46	0.96	0.39	- 6	-19	49
1126	76	0.51	1.06	0.44	-38	0	0
1121	75	0.57	1.17	0.49	-54	45	3
1112	76	0.72	1.34	0.58	-66	7	-50
1105	75	1.15	1.37	0.38	4	-20	12
1020	76	1.20	1.48	0.54	-41	24	29

Table 3: Comparison of coordinates of calculated with recorded curves for rot ≥ 100 1/s

No.	rot [1/s]	SP_{t0}	SP_{te}	te-t0 [s]	RKx-x [mm]	RKy-y [mm]	RKz-z [mm]
	c_{DA}(4-5) and c_{LA}(4),(5)						
1205	110	0.63	1.14	0.33	21	19	69
0820	117	0.67	1.08	0.27	- 9	12	32
1201	113	0.67	1.30	0.36	13	21	3
0822	-120	0.75	1.30	0.31	-38	- 1	-22
1122	111	0.80	1.50	0.44	-48	-10	-21
0611	101	0.94	1.47	0.37	0	7	-11
1114	114	1.04	1.90	0.54	-24	3	20
1029	111	1.47	2.14	0.55	32	46	- 2
1021	115	1.85	2.31	0.48	- 9	4	30
1127	148	1.00	2.02	0.42	-32	18	37
1123	152	1.09	2.16	0.43	-43	-32	- 6
1116	152	1.36	2.70	0.50	16	-72	- 9
1107	153	1.69	2.89	0.54	-24	- 9	33
1101	152	2.01	3.05	0.53	-50	4	51
1022	150	2.39	3.09	0.45	-48	30	29

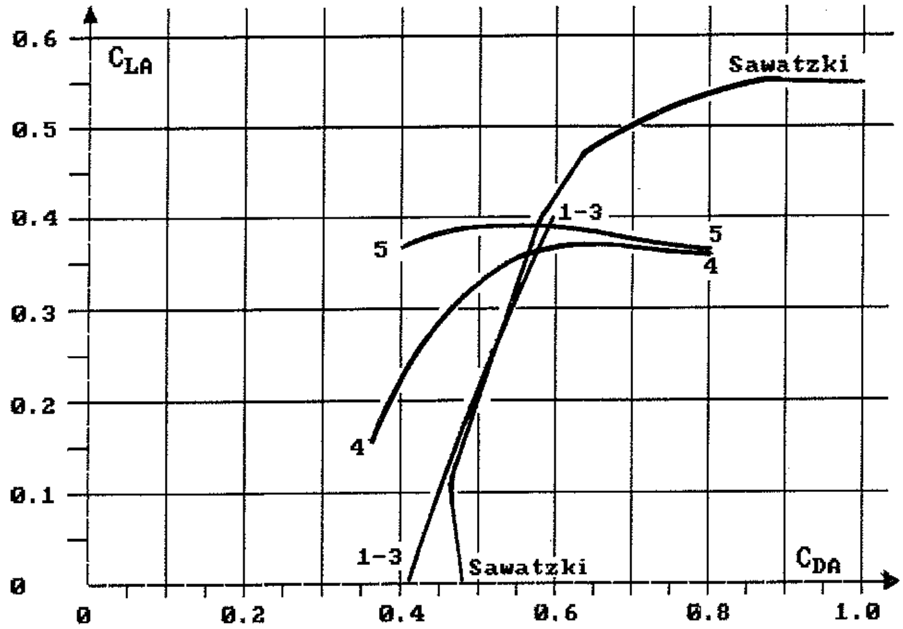

Fig. 4: Polars of the accelerated table-tennis ball in comparison to the polar of the non-accelerated smooth sphere of Sawatzki (5);
1-3: rot ≤ 80 1/s
4: rot ≈ 110 1/s
5: rot ≈ 150 1/s

and measured curves **(RKx–x,RKy–y,RKz–z)** in the order of magnitude of one ball diameter as documented in table 2 and 3. The comparison between real and numerical table tennis curves showed that it is now possible to measure and to simulate ballistic curves with an accuracy which is within the accuracy of a high level table tennis athlete. This was the aim of the study from the point of view of a table tennis player.

The noticed desultory reduction of the drag and lift coefficient above **rot** ≥ 100 1/s is very important for the situation in high level table tennis as described in the introduction, because the drag of a fast topspin ball does not increase —— how to be expected —— but it decreases and consequently favours fast table tennis. This fact is underlined particularly by figure 4 which shows the polars of the accelerated table tennis ball in comparison to the polar of the non–accelerated smooth sphere of Sawatzki (5) with **rot** as a parameter.

Nomenclature

Variable	Unit	Explanation
A	[m²]	sectional area of the ball
c_{DA}	[ ]	drag coefficient of accelerated movement
c_{LA}	[ ]	lift coefficient of accelerated movement
$\vec{D}$	[N]	drag force
$\vec{F}$	[N]	total force on the free flying ball
$\vec{g}$	[m/s²]	earth acceleration
$\vec{G}$	[N]	gravitation force
$\vec{L}$	[N]	lift force
m	[kg]	mass of the ball
$\hat{n} = \vec{n}/n = \hat{L}$	[ ]	standardized vector parallel with the lift
$\vec{n} = \omega \times \vec{v}$	[ ]	vector product angular velocity **x** speed
No.	[ ]	number of measured ball flying curve
RKx/RKy/RKz	[mm]	Runge–Kutta coordinates
rot	[1/s]	rotational frequency
R	[m]	radius of the ball
SP	[ ]	Spinparameter
t0	[s]	starting time of a ball flying curve
te	[s]	end time of a ball flying curve
u	[m/s]	rotational velocitiy
v	[m/s]	speed of the ball
x/y/z	[mm]	real coordinates
ρ	[kg/m³]	density of the air
ϑ	[°]	angle in the x–z–plane
φ	[°]	angle in the x–y–plane
ω	[°/s]	angular velocity of the ball

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