good player with average distance, so the values for the "All" case in Tables 1 and 2 are appropriate. Eq. (1) predicts that the 5 iron will carry 171m (187yds). This is 16m (17yds) short of the pin and 7m (7yds) short of the green. Leonard hits the 5 iron very well and comes up only 9m (10yds) short of the hole, but this is just short of the green, in heavy grass, with a bad lie, by a bunker. He makes a bogie and then loses to VJ Singh in a playoff. Eq. (1) predicts that a 4 iron would have carried 183m, safely on the green. The difference between winning and being tied for second is $575,000.

Instead of spending hours with multiple drivers and a launch monitor to get an extra couple of yards of distance, the golfer-caddie team may be better served by learning about the impact of height and wind on their shots.

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MEASUREMENT OF AERODYNAMIC FORCES EXERTED ON BASEBALLS USING A HIGH-SPEED VIDEO CAMERA

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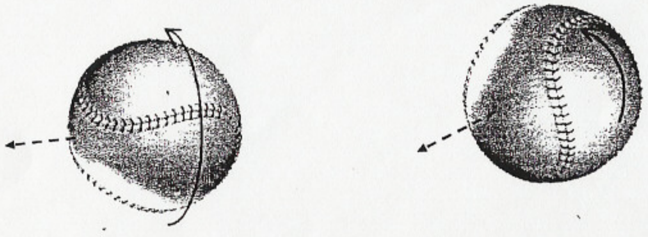
Using a high-speed video camera, we have recorded the trajectory and the rotation of a hard baseball thrown by real pitchers and newly developed pitching machines. The machines can throw a 'rifle-spin ball', whose rotational axis lies almost in the translational direction. We have determined the lift- and drag- coefficients by analyzing the video images. It turns out that the drag coefficient of a 'rifle-spin ball' is less than that of a 'fork-ball' and the lift coefficient is almost zero for both.

1. Introduction

There were several studies on the aerodynamics of a hard baseball. Watts and Ferrer [1] measured aerodynamic forces exerted on a baseball in a wind tunnel. The measured values of drag coefficients (*CD*) and lift coefficients (*CL*), however, were not accurate because the shaft used to support the ball.

In recent years, baseball pitchers throw various kinds of breaking balls, among which a 'rifle-spin ball' is a new variety. It rotates around an axis almost parallel to its translational direction. There are mainly two types of rifle-spin ball, those with four seams and those with two seams, with different axes of rotation relative to the seam on the surface (Figure1). Recently, Himeno [2-3] performed numerical simulations of the aerodynamic forces exerted on a hard baseball ($Re = 2.0\times10^5$). He found that the drag coefficient *CD* of a rifle-spin ball is substantially less than those of a fastball with backspin (about 0.3) and a fork-ball (about 0.4). In particular, *CD* of a four-seam rifle-spin is computed to be about 0.17, whereas the computed value of *CL* of a rifle-spin ball is almost zero.

Mizota et al. [4] measured the aerodynamic forces exerted on a rifle-spin ball in a wind tunnel. They suspended a hard baseball by thin piano wires in order to keep the aerodynamic contamination as small as possible. They measured a C_D of the rifle-spin ball which was almost the same as that of a fastball with backspin, which contradicts with the numerical results of Himeno [2-3].



(a) Four-seam gyro (b) Two-seam gyro

Figure 1: Translational directions and rotation axes of two types of rifle-spin ball

The main objective of this paper is to resolve the above contradiction. We record the trajectory and rotation of a thrown ball using a high-speed video camera. The aerodynamic properties such as C_D and C_L, are estimated by analyzing the video images.

2. Pitching Machine

Few pitchers can throw a rifle-spin ball, and the rotational axis of a rifle-spin ball thrown by a real pitcher does not coincide with the translational direction accurately. In order to make the measurements more reproducible, we developed a pitching machine able to align the rotational axis with the trajectory. We modified a usual pitching machine by inclining the two rollers (about 13 deg.), so that it can throw a rifle-spin ball. The axis of rifle-spin balls thrown by the machine always lies in the translational direction. However, the machine which we had prepared in the first trial damaged the ball surface, and the maximum speed of a rifle-spin ball thrown by it was less than 120 km/h. Therefore, we developed the second machine (Figure 2), where the material of the rollers was different and the performance of the motor increased. It can throw a hard baseball without damaging the ball surface with maximum speed 150 km/h or more.

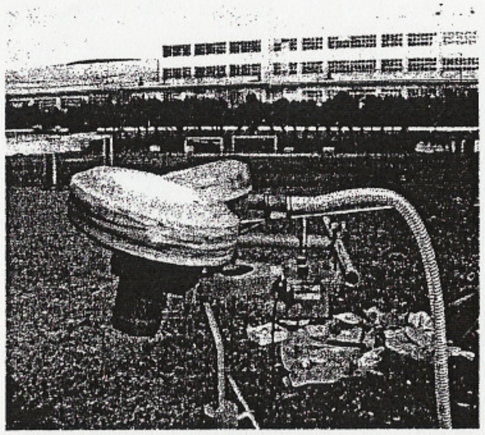


Figure 2: RSB-pitching machine (2nd version)

3. Measurements

We use a high-speed video camera that can record up to 1800 frames per second. We positioned the high-speed video camera 20 m rearward from the home plate. To stop the ball safely, above the home plate we mounted a transparent reinforced screen with a partitioned scale which allowed to locate the ball coordinates.

We record both the trajectory and rotation of a hard baseball thrown by several real pitchers and the newly developed pitching machines. We arrange three lamps which illuminated light-sheets, at regular intervals of 4.5 m from the home plate (see Figure 3). Figure 4 shows an example of the snapshot image.

We measure the time when the thrown ball passes the light-sheets and it hits the board at the home plate. We also record the y-pixels (the lateral coordinate) and the z-pixels (the vertical coordinate) as functions of the time.

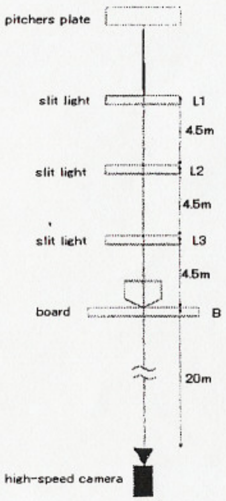


Figure 3: Configuration of Measurement

Figure 4: Snapshot Video Image

4. Method of Data Analysis

4.1 Determination of CD

The times when the ball passes L1, L2, L3 and B (shown Figure 2) are denoted as $t(1)$, $t(2)$, $t(3)$ and $t(4)$. It takes $t(2)$- $t(1)$, $t(3)$- $t(1)$ and $t(4)$- $t(1)$ for the ball to move 4.5m, 9m and 13.5m, respectively. We define u to be the x-component of the velocity, with u_0 being the value at $t(1)$. We can solve the equations of motion approximately as:

$$x = \frac{2}{D}\log(1+\frac{u_0 Dt}{2}). \qquad (1)$$

Here, D is related to the drag coefficient C_D by $D=C_D\rho\pi r^2/m$, where ρ is the air density, r is the radius and m is the mass of the ball. We determine D and u_0 by fitting the measured data to equation (1) via least squares to obtain C_D.

4.2 Determination of CL

We read out the z-pixels of the ball position from the video every ten frames. We can determine the z-coordinate using the z-pixel, the x-coordinate (1) and also from the scale on the screen. We define w to be the vertical velocity component, with w_0 being the initial value at $t(1)$.The z-component of the equations of motion can be expanded in a power-series as:

$$z \approx z_0 + w_0 t + (\frac{-g}{2} + \frac{Lu_0^2}{4} - \frac{Du_0 w_0}{4})t^2 + o(t^3). \qquad (2)$$

Here, the coefficient L is linked to the lift-coefficient C_L, by $L=C_L\rho\pi r^2/m$. We substitute t, z, D and u_0 for the expression and obtain z_0, w_0 and L by a least squares fit, again. C_L is computed from the value of L. Similarly, we can determine the lift-coefficient in the lateral direction.

4.3 Determination of the Spin Parameter (SP)

Watts and Ferrer [1] proposed the relation C_L=SP for a fastball with backspin (which is valid for C_L less than about 0.3). Here, SP is the non-dimensional parameter proportional to the angular velocity of the ball. We can determine the rotation rate f from the video images by tracing the trajectory of a particular marker-point on the ball surface. The spin parameter is computed from $V=\sqrt{u_0^2+w_0^2}$ as the magnitude of the initial velocity:

$$SP = \frac{2\pi rf}{V}. \qquad (3)$$

5. Results and Discussions

The results of analysis for C_D and C_L with SP and f are shown in Tables 1, 2 and 3. The relation between C_D and Re is plotted in Fig.5. We identify a thrown ball to be a 'true' rifle-spin ball, only if the axis of rotation is aligned with the translational direction within 5mm on the ball surface. We find that for the rifle-spin ball, SP is about 0.23 (= tan13°).

Table 1. Aerodynamical coefficients of a rifle-spin ball

f [rps]	u_0 [m/s]	C_D	C_L	SP
31.58	34.24	0.265	0.047	0.206
33.96	34.75	0.238	0.081	0.219
29.51	32.83	0.353	-0.045	0.201
27.69	29.15	0.379	-0.030	0.212
25.71	25.29	0.380	0.001	0.228

Table 2. Aerodynamic coefficients of a fastball with backspin

	f [rps]	u_0 [m/s]	C_D	C_L	SP
	27.78	30.66	0.322	0.216	0.211
	31.25	32.30	0.302	0.236	0.225
	33.33	32.65	0.306	0.216	0.237
	35.29	38.47	0.287	0.201	0.213

Table 3. Aerodynamic coefficients of a fork-ball

	f [rps]	u_0 [m/s]	C_D	C_L
	12.5	31.55	0.417	0.001
	6.21	23.73	0.438	0.092
	0.25	26.29	0.417	0.021
	8.22	34.26	0.447	0.027

The C_D of a fastball with backspin is about 0.3 and that of a forkball is over 0.4. These results are consistent with the numerical results by Himeno [2-3] and the experimental results by Mizota et al. [4]. C_D of a rifle-spin ball is about 0.35 for the Reynolds-number $\mathrm{Re} < 1.6 \times 10^5$. No significant difference between C_D of a four-seam rifle-spin and that of a two-seam ball is found in our study, in contrast to the study by Mizota et al., who found the former (about 0.36) is slightly larger than the latter (about 0.27). When Re is increased over 1.7×10^5, C_D of a rifle-spin ball shows a tendency of rapid decrease with Re. This is in sharp contrast to the C_D of a fastball with backspin and that of fork-ball, which are almost independent of Re within the range considered here. It should be noted that the 'drag-crisis' occurs when Re is about 1.5×10^5 [5], in a wind-tunnel experiment with a sphere with suitable roughness, whereas that of a smooth sphere occurs at Re about 3.0×10^5 [5]. At present, the details of the drag crisis of a spinning baseball remain unclear. The C_L of a rifle-spin and a fork-ball is estimated to be almost 0, while that of a fastball with backspin is around 0.2 (which coincides with SP).

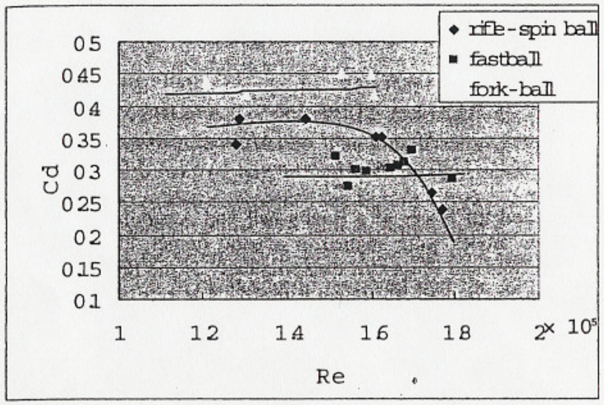


Figure 5: C_D as a function of Re

Triangles: fork-ball, diamonds: rifle-spin ball, square: fastball

6. Conclusions

We have performed field measurement of aerodynamic forces acting on a hard baseball using a high-speed video camera, and obtained the following results from the data analysis:

- The C_D of a rifle-spin ball is considerably larger than the computed value.
- No significant difference between C_D of a four-seam rifle-spin and that of a two-seam rifle-spin is observed.
- The C_D of a rifle-spin ball decreases with an increase of Re.
- The C_L of a rifle-spin and a fork-ball is almost 0, while that of a fastball with backspin is about 0.2.

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