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In situ drag measurements of sports balls

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Abstract

Aerodynamic drag on sports balls is typically measured in wind tunnels. There is a concern that fixtures needed to support the ball in a wind tunnel may influence its drag. Measurements under game conditions have been attempted, but are difficult to interpret from the data scatter and are not controlled. The following considers drag measurements from a ball propelled through static air in a laboratory setting. High speed light gates were used to measure drag, including the effects of ball rotation. Drag was observed to depend on the ball speed, rotation, roughness, and orientation. A so-called drag crisis was observed for a smooth sphere and was comparable to wind tunnel data. Rough sports balls, such as a baseball, showed evidence of a small drag crisis that was less apparent than the smooth sphere.

Keywords: drag; sport ball aerodynamics; drag crisis, drag measurements.

1. Introduction

Understanding the flight of a ball involves two aerodynamic properties, lift and drag. Lift can be described as the force, not including gravity, on a ball that is directed perpendicular to the ball's trajectory. Drag is the force, F_d, in the direction opposing the ball's flight path [1]. The drag coefficient, C_d, is found from [2]

$$C_d = \frac{2F_d}{\rho A V^2} \tag{1}$$

where ρ is the density of air, A is the cross sectional area of the ball, and V is the speed of the ball. Drag is a function of surface roughness, velocity, and orientation of the ball. It is convenient to use a non-dimensional form of velocity, expressed in terms of the Reynolds number, R_e, defined by

$$R_e = \frac{VD}{\nu} \tag{2}$$

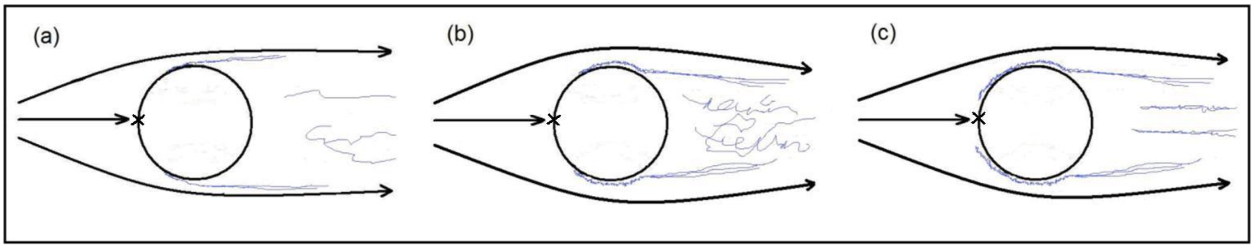

Figure 1 - Flow over a smooth cylinder: (a) $R_e < 3x10^5$, flow stays laminar in the boundary layer until 80° where it separates; (b) $3x10^5 < R_e < 3x10^6$, flow separates at 80° becomes turbulent and reconnects before separating again at 120 degrees; (c) $3x10^6 < R_e$, flow is turbulent in the boundary layer on the front and stays turbulent until separating at 120°. The stagnation point is identified by "X" in each figure.

where *D* is diameter of the ball and υ is kinematic viscosity of air. The effect of speed on drag can be described by three characteristic ranges, as illustrated in Figure 1. At low Reynolds number, (a), flow is laminar until separation occurs at roughly 80° from the stagnation point [3]. When the Reynolds number is increased, region (b), the separation region becomes turbulent and attaches itself again, carrying the separation point to the backside of the ball to about 120° from the stagnation point. As the separation point moves to the back of the ball, drag is reduced. The reduction in drag can be large and occur over a small change in the Reynolds number. Region (b) is referred to as the Drag Crisis, and often occurs at game speeds. As the Reynolds number is increased further, region (c), the flow becomes completely turbulent in the boundary layer just after the stagnation point, causing the drag to increase again.

The drag crisis has been observed on a smooth sphere for many years. Millikan and Klein [4] explored the drag crisis in their free flight test finding C_d on a smooth sphere as low as 0.08. Achenbach [5] analyzed how surface roughness on a sphere can change behaviour in the critical Reynolds region. His data suggested that as surface roughness increased on a sphere the drag crisis was induced at a lower Reynolds number and was less severe. Frohlich [6] also analyzed how surface roughness can change the behaviour of the drag crisis. Frohlich went on to explain if a baseball acted like a rough sphere, the drag crisis could help explain the behaviour of pitched or batted baseballs. Alaways, Mish, and Hubbard [7] analyzed baseball pitches by triangulating ball location from video taken during the 1996 Summer Olympic Games. Their data showed evidence of a drag crisis with a drag coefficient as low as 0.16. An improved video tracking system involving Major League Baseball (PITCHf/x) [8] showed little evidence of a drag crisis, however.

The effect of ball rotation has primarily been directed towards lift. To the authors' knowledge, the only study involving rotational drag on a sports-like ball is that of Bearman and Harvey who rotated dimpled spheres resembling a golf ball in a wind tunnel [9]. They found drag increased with rotation. Mehta attributed the drag increase with lift effects [10].

The following considers the effect that surface roughness, velocity, orientation and rotation have on the drag force. The study was conducted in a laboratory setting to improve the accuracy of drag measurements over that achievable in game conditions. Balls were projected through static air to avoid interaction with ball support devices used in wind tunnel experiments.

2. Methods and experimental setup

The change in ball speed was found using two light boxes that measured both the position and speed of the ball. The study examined six different sports balls. The translational velocity ranged from 17.9 m/s to 60.8 m/s.

A pneumatic sabot style air cannon was used to project baseballs with no rotation to study the effect of seam orientation. A high speed video camera (1000 fps, 10^{-4} s shutter speed) was used to record each shot to verify correct orientation and flight path. A three wheeled pitching machine (HomePlate, Sports Tutor) was used to project balls with controlled angular velocity. The three wheels were oriented 120° apart with the lower wheel aligned in the vertical direction. Tracking software was used to determine the angular velocity of each pitch.

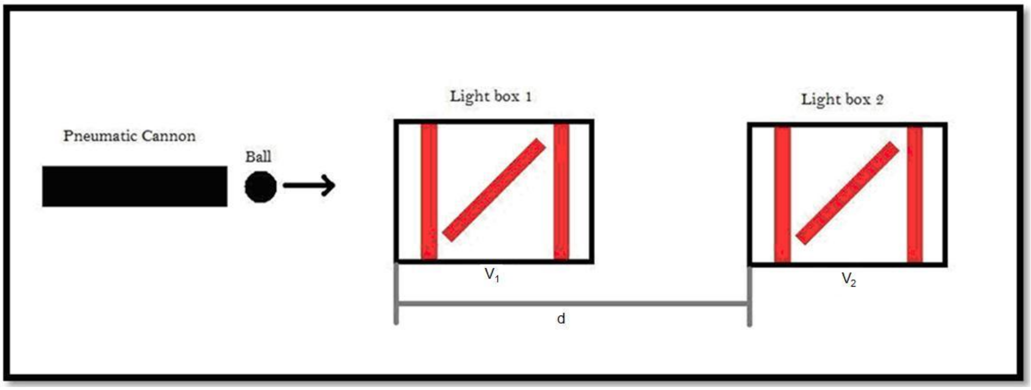

Figure 2. Diagram showing arrangement of pitching device and light boxes used to measure ball speed and location.

Once the ball was released from the pitching device, it began its path through the light boxes. Each box had an opening of 0.367 meters by 0.495 meters to allow enough room for a ball to enter and exit without contacting the inner walls. Each light box consisted of three pairs of light gates (Ibeam, ADC) as shown in Figure 2. Each light gate was rigidly mounted and levelled inside the light box. Velocity was found from the two vertical gates placed 0.419 meters apart. Lift was found from the change in the ball's vertical position, which was measured from the light gates mounted at 45°.

The light boxes were placed between 4 and 5 meters apart. Balls travelling at lower speeds used the closer light box spacing, while high ball speeds used the larger light box spacing. The change in velocity between the boxes ranged from 0.5-1.75 m/s. The light boxes were squared to each other and the pitching machine using a laser level. The drag force, F_d, was found from [11]

$$F_d = m\frac{V_2^2 - V_1^2}{2d} \tag{3}$$

where $V_1$and V_2 are the speeds from the first and second light boxes, respectively, m is the ball mass, and d is the distance between the light boxes.

3. Samples

The sabot style air cannon allowed ball orientation to be controlled. Two different orientations of the baseball and cricket ball were used. As shown in Figure 3, a normal orientation positioned stitches perpendicular to the airflow and a parallel orientation positioned stitches parallel to the air flow. The study comprised baseballs, softballs (89 and 97 mm diameter) cricket balls, golf balls and smooth spheres.

Figure 3. Diagram showing the normal (a) and parallel (b) orientations. Black arrows indicate the airflow direction, white arrows indicate the ball rotation axis.

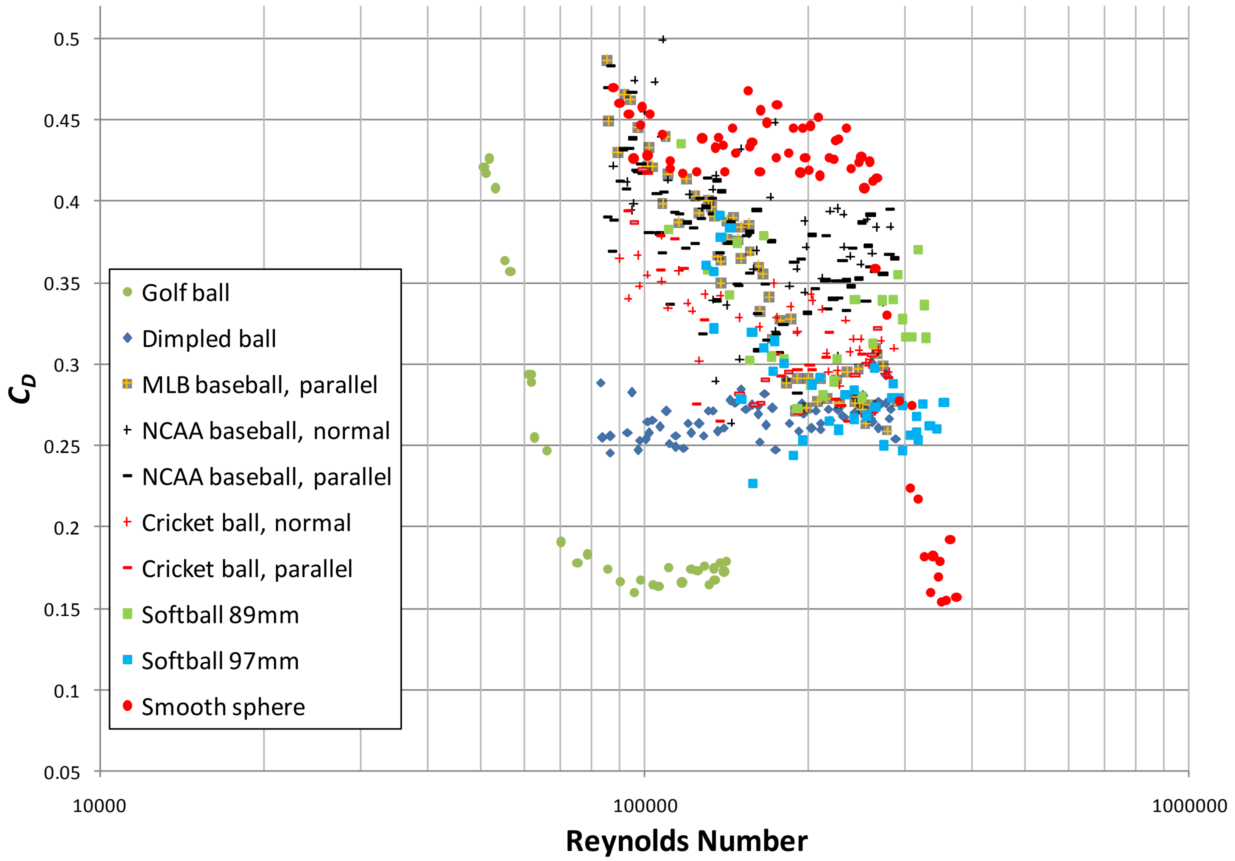

Figure 4. Coefficient of drag for all test balls.

4. Results

The drag coefficient (without ball rotation) is shown for all the sports balls from this study as a function of Reynolds number in Figure 4. The drag crisis is most apparent for the golf ball and smooth sphere. The drag crisis of the smooth sphere is comparable with previous work [5], but had less magnitude and occurred at a lower Reynolds number ($2x10^5$ vs $3x10^5$) [5]. As expected, the dimpled surface of the golf ball caused a drag crisis at a lower Reynolds number than the smooth sphere. The optimized dimple pattern of the golf ball appears to help maintain the relatively large magnitude of its drag crisis. While the stitched balls (baseballs, softballs, and cricket balls) show C_d decreasing with increasing speed (Figs. 5, 6, and 7), the magnitude of their “drag crisis” was significantly smaller than the smooth sphere and golf ball.

The study included balls with flat and raised stitches. Scatter in drag was larger for the balls with raised seams (NCAA baseball and 89 mm softball). The arrangement of the stitches likely plays a role in the drag crisis. As shown in Figure 1, the drag crisis is a result of turbulence developing in the boundary layer of the ball. The stitches trip the boundary layer earlier than a smooth sphere inducing turbulence and moving the flow separation point to the backside of the ball. In the normal orientation, the stitches are close to the flow separation point, which is apparently fixed to the stitch location for balls with raised seams. For smooth spheres, the separation point (and drag) depends on the air speed. For balls with raised seems, the separation point (and drag) depends on variation in ball orientation and air speed. It is not surprising, therefore, that the parallel orientation of the cricket ball exhibited the largest drag crisis; as the stitches are removed from the separation point in this orientation, providing a relatively smooth flow surface.

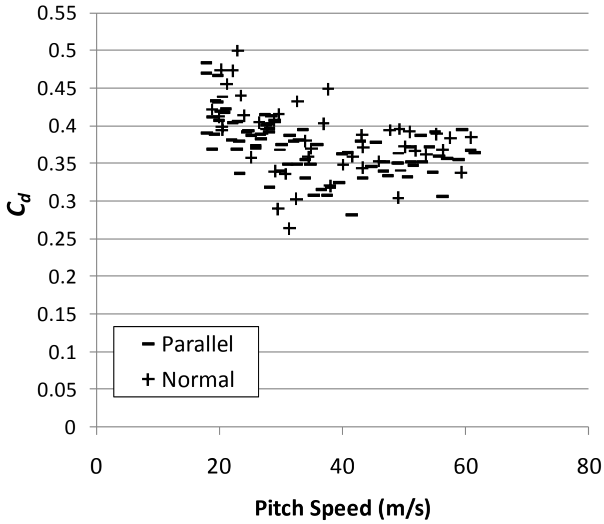

Figure 5. The drag coefficient of NCAA baseballs in the normal and parallel orientations.

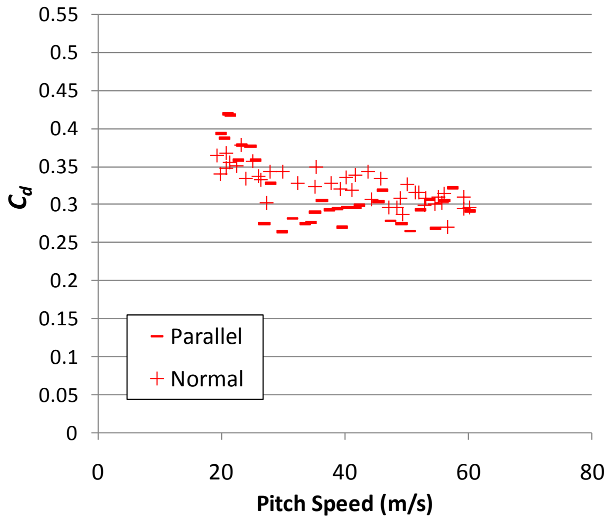

Figure 6. The drag coefficient of cricket balls in the normal and parallel orientations.

Balls with raised seams (NCAA baseball and 89 mm softball) exhibited a higher relative C_d and a drag crisis at a lower relative Reynolds number. Both trends are consistent for balls of higher relative roughness.

The effect of spin on C_d for baseballs and dimpled pitching machine balls are shown in Figure 8. The translational velocity for the rotating balls ranged from 27 to 44 m/s with angular velocities from 22 to 4731 rpm. The balls were rotated in a normal or 4-seam orientation as defined in Figure 3. The rotational and linear velocities were normalized according to [12]

$$S = \frac{\omega r}{v} \tag{4}$$

where S is the spin factor, ω is the angular velocity, and r is the ball radius. Similar to rotating dimpled spheres observed elsewhere [9], drag on a baseball was observed to increase with spin but with less magnitude. While the effect is small, it is measurable and affects the ball flight. The NCAA ball had an average C_d of 0.34 and 0.41 for non-rotating and rotating conditions, respectively. To illustrate the effect of rotation on drag, the dimpled pitching machine ball without rotation is included in Figure 8 over the same translational velocity range as the rotating balls.

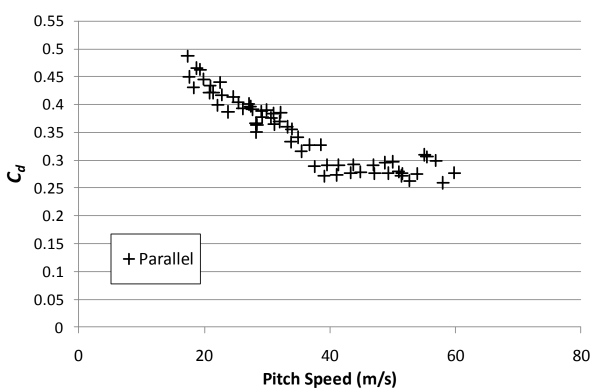

Figure 7 – Drag coefficient of MLB baseballs in the parallel orientation.

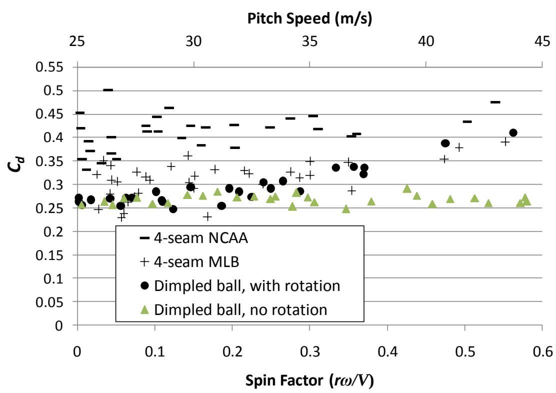

Figure 8. Drag coefficient of baseballs rotating in the normal and parallel oreintations compared to a dimpled baseball.

Pitched balls (including knuckleballs) usually have some rotation and therefore do not achieve the low C_d observed in Figure 7. Thus, in play one should expect pitched balls to have a drag coefficient between 0.3 and 0.4. However for pitchers like Tim Wakefield, who can deliver a ball with no rotation, a pronounced drag crisis is more likely to occur, where the C_d could be as low as 0.26.

5. Concluding remarks

The preceding has considered the drag of sports balls obtained by projecting the balls through still air. A sabot style air cannon provided ball controlled orientation without rotation, revealing the sensitivity of drag to the stitch orientation. The drag of non-rotating balls was comparable to previous experiments. Smooth spheres, golf balls, and balls with flat seams showed a strong drag crisis, while raised seam balls showed only a weak drag crisis. Rotation had a measurable effect on drag, increasing the average C_d on a baseball by 20%. It is difficult to pitch baseballs with no rotation. Hence, most baseball pitches will have a C_d of 0.35 (the average drag observed for rotating balls).

References

[1] R. K. Adair, *The Physics of Baseball.* 3rd ed. (HarperCollins Publishers, New York, 2002), pp. 5-40.

[2] C.T. Crowe, F. D. Elger, J. A. Roberson. Engineering Fluid Mechanics. 8th ed. (John Wiley & Sons, Hoboken, 2005) pp 440.

[3] R. L. Panton. Incompressible Flow. 3rd ed. (John Wiley, Hoboken, 2005) pp 324 - 34.

[4] C.B. Millikan, A.L. Klein. "The effect of turbulence. An investigation of maximum lift coefficient and turbulence in wind tunnels and in flight," Aircraft Engineering, Vol 5, 169-74, 1933.

[5] E. Achenbach. "The effects of surface roughness and tunnel blockage on flow past spheres," Journal of Fluid Mechanics, Vol. 65, 113-25 (1974).

[6] C. Frohlich. "Aerodynamic drag crisis and its possible effect on the flight of baseballs," American Journal of Physics, 52, 325-34 (1984).

[7] L. W. Alaways, S. P. Mish, M. Hubbard. "Identification of Release Conditions and Aerodynamic Forces in Pitched-Baseball Trajectories," Journal of Applied Biomechanics, Vol. 17, 63-76 (2001).

[8] A. M. Nathan. "Analysis of PITCHf/x Pitched Baseball Trajectories," 2007. University of Illinois, 8 July, 2009 <http://webusers.npl.illinois.edu/~a-nathan/pob/>

[9] P. W. Bearman, and J. K. Harvey. "Golf ball aerodynamics," Aeronautical Quarterly, Vol. 27, 112-22 (1976).

[10] R. Mehta. "Aerodynamics of Sports Balls," Ann. Rev. Fluid Mechanics, 1985. 17, 151-75 (1985).

[11] R. D. Knight. Physics for Scientists and Engineers. Vol. 1 (Pearson Education, Boston, 2007).

[12] A. M. Nathan. "The effect of spin on the flight of a baseball.," American Journal of Physics, 76 (2), 119-24 (2008).