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Drag on sports balls using Doppler radar

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Abstract

Aerodynamic drag on sports balls is typically measured in laboratory wind tunnels or by projecting balls through still air. With the advent of Doppler radar and sophisticated tracking software, pitched and hit balls can be tracked throughout the trajectory in game conditions. The following considers drag measurements from balls hit in a game setting using a Doppler tracking system. The effects of spin, seam height, and velocity on drag were explored. The trends were compared to laboratory drag measurements from balls projected through still air. Balls with raised seams had, on average, higher drag than flat seam balls. Over speeds representative of play conditions, the ball drag coefficient decreased with increasing ball speed. It was also found that an increase in spin rate did not correlate to an increase in the drag coefficient.

Keywords: drag, radar, sport ball aerodynamics, drag measurements.

1. Introduction

As tracking systems become more prevalent in sports, the ability to study drag during ball flight has improved. Drag is an aerodynamic force that opposes motion, and its effects are often expressed by a drag coefficient, C_d which varies for different objects. It is calculated using

$$C_d = \frac{2F_d}{\rho A V^2} \quad (1)$$

where ρ is the density of air, A is the cross sectional area of the ball, V is the speed of the ball, and F_d is the force of drag [1]. The drag coefficient has been found to vary with ball orientation, surface

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roughness, velocity, and spin rate. The latter three will be explored in this paper. It is conventional to normalize velocity and air properties to the non-dimensional Reynolds number, R_e, defined by

$$R_e = \frac{\nu D}{V} \tag{2}$$

where D is the diameter of the ball and ν is kinematic viscosity of air. As a ball travels along its trajectory it experiences two major aerodynamic drag regions. The regions are distinguished by the location of the flow separation from the surface of the ball. The first region is defined by $R_e < 3x10^5$; in this region flow in the boundary layer is laminar until separation occurs at approximately 80° from the stagnation point of the ball [2]. The second region, $3x10^5 < R_e < 3x10^6$, flow separates at 80° and reattaches at 120° from the stagnation point where the boundary layer flow is classified as turbulent. This region is referred to as the drag crisis and is characterized by a significant drop in the drag coefficient over a very small change in Reynolds number.

The effect of velocity on the drag coefficient has been explored by many researchers. It is well known, for instance, that the drag coefficient decreases as the ball velocity increases. Achenbach explored this phenomenon with balls of varying roughness in a wind tunnel [3]. He found that as surface roughness increased, the drag crisis initiated at lower speeds, increasing the overall drag coefficient. Over the region of $10^5 < R_e < 2x10^5$ he found the drag to be within $0.1 < C_d < 0.5$.

With the effect of velocity on drag defined, studies have considered the effect of spin rate on drag for different types of balls. Using a wind tunnel Asai et al. found that increasing the spin rate of soccer balls dramatically increased the C_d [4], similar to what Bearman and Harvey found using golf balls [5]. Alam et al. used wind tunnel data for tennis balls to show that drag increased with spin rate, but found that the increase in drag was not as dramatic as previous studies [6]. They noted scatter in their results, in some cases exceeding the effect of spin rate, which they could not attribute to measurement error.

More recently, Kensrud projected spinning and non-spinning balls through still air, using light gates to measure the change in velocity [7]. He found that along with spin rate, orientation and roughness play a major role in drag. Kensrud's data also indentified relatively large scatter in the drag of baseballs in comparison to smooth spheres and softballs. This comparison showed that the aerodynamic complexity of seams significantly changed the repeatability of drag.

The advent of tracking systems such as Doppler radar allows the ball to be observed in dynamic conditions like that experienced during a game. The system used for this research was a continuous wave (CW) Doppler radar system. It consisted of a single antenna continuously emitting an electromagnetic signal. The signal was reflected off the ball and received by three antennas offset horizontally and vertically from the emitting antenna. The position of the ball, reported in elevation and azimuth angles, was proportional to the change in phase of the reflected signal. The radial velocity of the ball was obtained from a shift in the frequency of the reflected signal [8]. This change in frequency is known as the Doppler effect [9]. Along with a measurement of the range of the object from the radar, the complete velocity vector and trajectory of the ball can be found. The advantage of using a CW system is its ability to measure the spin rate of the ball from the frequency spectrum.

An aim of this work was to compare the drag of balls hit in play to that obtained from laboratory measurements. This includes the effects of spin rate (ω) and seam height on the coefficient of drag. Coupling these with the dynamic conditions that a ball undergoes during a game provided a picture of the complexity in describing aerodynamic forces in game conditions.

2. Methods and experimental setup

A 10 GHz Doppler radar was placed 9 meters behind home plate in a straight line toward the pitcher, giving it a full view of the field. The radar used a coordinate system with the origin at the tip of home plate, the x axis runs toward the pitcher, the y axis upward and the z axis points to the catcher's right. Therefore a pitched ball primarily moves in the $-x$ direction. From the measured data the components of the velocity, $V_x(t)$, $V_y(t)$, and $V_z(t)$, of the ball were recorded. A constant jerk model of the form

$$V_x(t) = At^2 + Bt + C \tag{3}$$

was used to fit the trajectory, where A, B, and C were found using a least squares fit and t was time. The derivative of Eq. 3 resulted in the acceleration of the ball. The angle between the velocity and acceleration vectors was determined from their dot product. This angle was then used to calculate the acceleration opposing the velocity of the ball (i.e. drag), after subtracting the effects of gravity. Using the atmospheric temperature and pressure conditions, C_d was calculated using Eq. (1).

Data was recorded for baseballs hit by collegiate level baseball players and pitched from a two wheeled pitching machine. The baseballs were NCAA approved and represented a raised seam style ball. Data for softballs was collected from men's and women's slow pitch games from the ASA Championship Series. The softball was a 0.52 COR, flat seam slow pitch ball. The data was from several games during one day of the tournament.

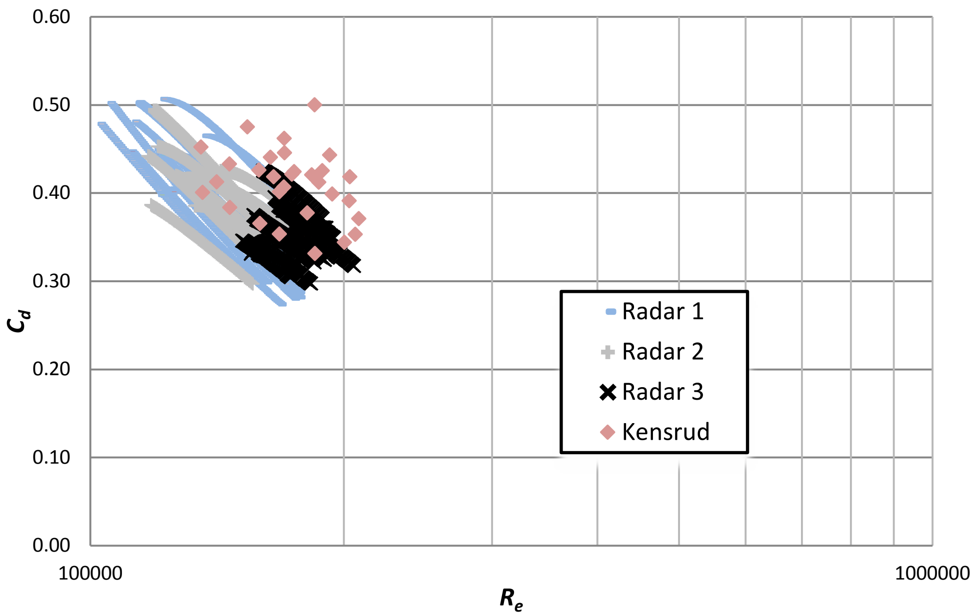

Figure 1. Coefficient of drag for raised seam baseballs of varying initial spin rates. Kensrud[7], $100 < \omega < 4000$; Radar 1, $3000 < \omega < 4000$; Radar 2, $2000 < \omega < 3000$; Radar 3, $1000 < \omega < 2000$.

3. Results

Since ball acceleration was obtained from the derivative of its velocity, the acceleration (and hence drag) was sensitive to noise in the measured data. The part of the ball flight with the most noise occurred at the beginning of the hit and after the apex of its trajectory. Accordingly data prior to 0.5 s after impact and data after the apex were not considered, effectively minimizing the effect of signal noise on ball drag. The drag coefficient is shown for raised seam baseballs as a function of Reynolds number in

Figure 1. The radar results correlate well with results from balls projected through still laboratory air [7]. The range of C_d was similar to previous studies for drag in the region $10^5 < R_e < 2x10^5$ [10]. While the C_d decreased rapidly over a small change in R_e, it was not apparent if this represented a drag crisis. The decrease in drag does however occur at similar R_e as previous studies where a drag crisis was observed [3]. To establish the existence of a drag crisis, data outside the R_e of game play is needed. This suggests that in comparison to other sports, such as golf, the drag crisis in baseball and softball plays a relatively small role. For instance the difference in drag between tests is comparable to the difference in drag during a single test.

The magnitude of the change in the drag coefficient during the ball's flight, ΔC_d, depended on the ball's spin rate. Balls with $\omega < 2000$ saw $\Delta C_d \approx 0.1$, while with $\omega > 2000$ saw $\Delta C_d \approx 0.2$. The differences in ΔC_d for balls experiencing more or less spin can be attributed to the trajectory of the ball. Baseballs with $\omega < 2000$ rpm had lower trajectories than those hit with higher spin rates, resulting in shorter flight times, smaller changes in velocity, and therefore a smaller change in C_d. The average ω of hit balls was 2086 and 1586 rpm for baseballs and softballs respectively. The slower ω of the softballs, relative to baseballs, was due to the higher rotational inertia of the larger diameter softball and the lower rotational inertia of the smaller diameter softball bat.

The drag coefficient for flat seamed softballs is shown in Figure 2 as a function of Reynolds number. Major League Baseball (MLB) Baseballs have a flat seam similar to softballs and are included in Figure 2 for comparison [7]. The drag of the flat seamed softballs obtained from radar measurements in a game setting agreed with the drag of the MLB balls projected through still air in a laboratory setting. At $R_e = 2x10^5$ the flat seamed balls had $0.2 < C_d < 0.3$, while for the raised seam balls $0.3 < C_d < 0.4$. This is similar to the trend seen by Achenbach that smoother balls experience a lower C_d at similar Reynolds numbers. The larger scatter observed in the drag for both types of hit balls compared to laboratory data may be due to ball orientation, environmental forces (wind), and spin rate.

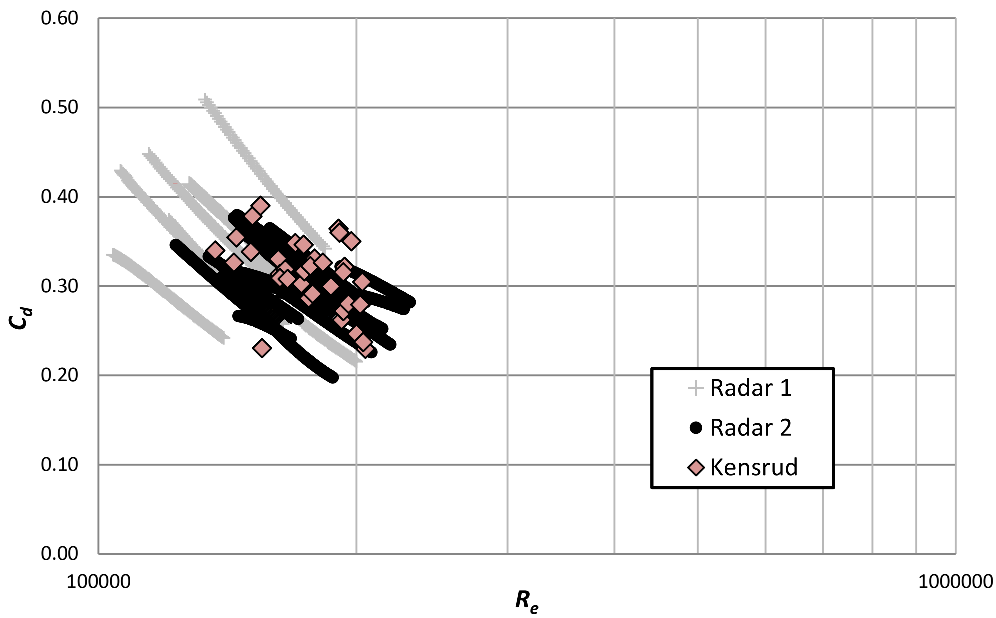

Figure 2. Coefficient of drag for flat seamed softballs and baseballs of varying initial spin rates. Kensrud [7], $100 < \omega < 4000$ (MLB baseballs); Radar 1, $2000 < \omega < 3500$ (softballs); Radar 2, $900 < \omega < 2000$ (softballs).

The effect of spin on C_d for raised seam and flat seam balls is shown in Figures 3 and 4, respectively. The rotational and linear velocities were normalized using a spin factor, S

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

where ω is the angular velocity, and r is the ball radius[11]. The speed of the baseballs ranged from 23 to 40 m/s and 700 to 4000 rpm while the speed of the softballs ranged from 17 to 39 m/s and 400 to 3800 rpm. For individual hits the results show an increase in C_d with an increasing S. The trend of increasing C_d with increasing S could be from a large change in V compared to a small change in ω. This is most apparent for trajectories with large S, where the flight time is longer and the change in V is greater.

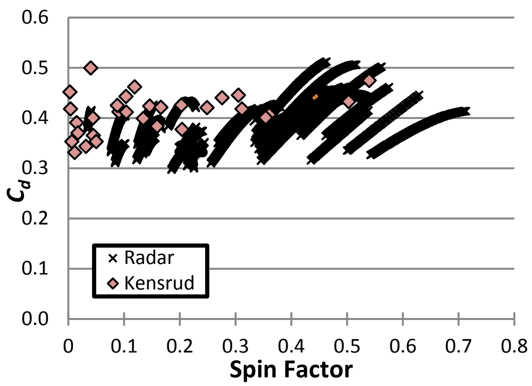

Figure 3. Drag coefficient of raised seam baseballs at varying velocities.

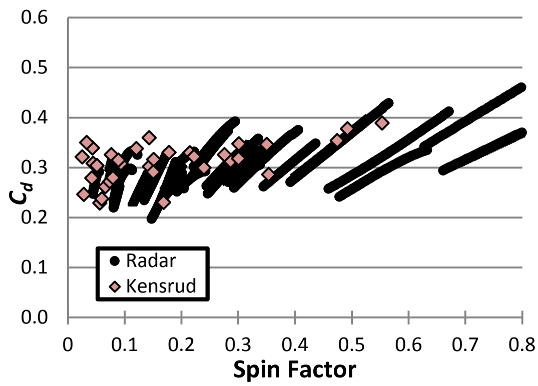

Figure 4. Drag coefficient of flat seamed softballs and baseballs (Kensrud) at varying velocities.

The effect of spin on C_d for baseballs and softballs at constant translational velocity is shown in Figures 5 and 6, respectively. Data points were taken from several different hits at the point in the trajectory when the balls were traveling at V = 32m/s. When V is held constant, the trend of increasing C_d with incresing spin rate is not apparent, which may also be observed in Figs. 1 and 2. Hits with high spin rates (4000 rpm) decay to about 2400 rpm at their appex [12]. Thus, in Figs. 1 and 2, if spin rate has a strong effect on drag, the data labled Radar 2 would start where Radar 1 ends; and the data labeled Radar 2 would start where Radar 3 ends. Instead all the data start in nearly the same range of C_d, illustrating the insensitivity of spin rate on ball drag.

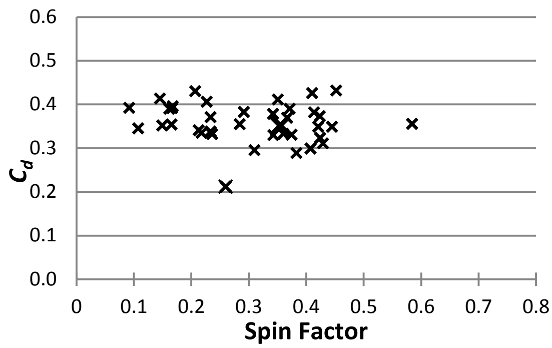

Figure 5. C_d of raised seam baseballs at V = 32 m/s

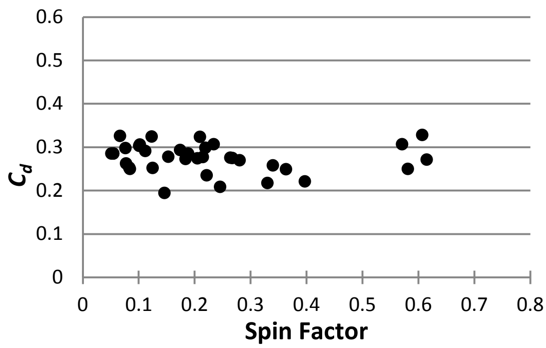

Figure 6. C_d of flat seam softballs at V = 32 m/s

4. Summary

This study has considered the drag of baseballs and softballs hit under game conditions using Doppler radar. Drag measured in game conditions was similar to that measured in a laboratory setting at the same R_e, providing relevance in the use of radar for determining aerodynamic forces. Due to the limited range of ball speeds occuring in play, a definitive drag crisis was not observed from the radar results. A drop in C_d was found at a similar R_e to other studies in which a drag crisis was observed. By comparing balls with different stitch heights, it was observed that balls with flat seams expierence $0.2 < C_d < 0.45$, and those with raised seams expierence $0.25 < C_d < 0.5$. Under the game conditions considered in this study, the drag coefficient was observed to decrease with increasing speed and was not sensitive to the spin rate of the ball. The results also give insight into the scatter associated with drag measurements of baseballs and softballs. In many cases the scatter in drag was greater than the effect of ball speed and spin rate. Studies that do not consider the large contribution of scatter on drag may incorrectly interpret its effect.

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