The drag coefficient of tennis balls

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ABSTRACT: The aim of this study is to gain an understanding of the motion of a tennis ball during flight. A wind tunnel was used to measure the aerodynamic forces on a tennis ball, and hence calculate their drag coefficients at wind speeds up to 136mph. The drag coefficient was relatively constant with increasing velocity for each brand of ball tested, and a larger ball had a similar drag coefficient to a standard sized ball. It was found that raising or lowering the nap increased or decreased the drag coefficient by almost 6%. In conclusion, a larger drag force on a tennis ball can be achieved through an increase in diameter or raising the nap of the ball.

INTRODUCTION

The trajectory of a tennis ball is determined by the gravitational and aerodynamic forces acting on it during its flight. Although it is well known that a rotating sphere will have both drag and lift forces acting on it, this paper documents a non-spinning ball.

The drag force is a function of the ball characteristics and the fluid through which it passes. Equation 1 shows the relationship between drag force and drag coefficient,

$$F_D = \frac{1}{2}\rho v^2 A C_D \tag{1}$$

where: F_D is the drag force
ρ is the density of the fluid within which the ball is projected
v is the velocity of the fluid
A is the projected area of the ball
C_D is the coefficient of drag

Thus, from the rules of dimensional analysis:

$$C_D = f\left[\frac{\rho v d}{\mu}\right] \tag{2}$$

where: $$\frac{\rho v d}{\mu} = \text{Reynolds number} = \text{Re} \tag{3}$$

μ is the dynamic viscosity of the fluid within which the ball is projected
d is the projected diameter of the ball
and the kinematic viscosity is given by μ/ρ

To achieve a complete understanding of the aerodynamic characteristics of the trajectory of a tennis ball, all possibilities should be investigated. The fastest shot used in tennis is the serve and top male competitors have been recorded serving at speeds of 149mph. This relates to an Re of approximately $2.75\text{x}10^5$.

Aerodynamic studies on spheres are limited, and on tennis balls negligible, generally related to specific shot types (Stepanek, 1988). There have been two main methods used in previous work: one involving dropping a ball through the airflow of a wind tunnel (Davies, 1949); the second utilises a 3 component wind tunnel balance, generally using a larger model ball (Bearman and Harvey, 1974). It is important that the object being tested remains a true representation of the original and obviously the best method of this is to use the original unmodified version.

Previous work with spheres of varying roughness (Achenbach, 1974) has documented the change in C_D at increasing velocities. It is well known that the C_D of a sphere can reduce dramatically due to a transition in the boundary layer from laminar to turbulent flow. This transition would reduce the drag force on the ball, hence reduce the rate of retardation, thus working against slowing the game down. For a smooth ball this occurs at an Re of approximately $3.5\text{x}10^5$, whereas in a slightly roughened ball it occurs at an Re of approximately $1\text{x}10^5$. A tennis ball is certainly not smooth, in fact it may be considered extremely rough and hence it is entirely reasonable to expect such a transition to occur in play.

METHODS OF OBTAINING HIGH Re

Equation 3 can be used to assess the methods available to obtain increased values of Re. There are several methods available, many of which have been used previously;

1. Decrease the kinematic viscosity either by increasing the density of the fluid (e.g. use water); or decreasing the dynamic viscosity of the fluid (i.e. lower temperature). Water would be absorbed into the nap thus changing the aerodynamics properties and the required change in dynamic viscosity is large.
2. Increase the size of the object being investigated. A scaling of the nap would be required to remain a true model of the original object.
3. Use high wind speeds using a standard tennis ball. This not only gives a true representation, but if a selection of balls is used it is possible to forge a comparison.

APPARATUS

WIND TUNNEL

A suitable, fully instrumented, wind tunnel was found at the University of Cambridge Engineering Department, UK. The wind tunnel is rated with a maximum wind velocity of approximately 138mph, with a working section of 5.5ft x 4ft.

3 COMPONENT WIND TUNNEL BALANCE SET-UP

A 3 component wind tunnel balance is attached to the wind tunnel above the working section. Tennis balls are attached to a sting, which is connected to the 3 component wind tunnel balance via fine wires.

Force is translated from the sting assembly within the wind tunnel via the fine wires, weighted down to ensure tension. It is important that the sting assembly is rigid to ensure that all force applied to the ball and sting is translated to the 3 component wind tunnel balance. Whilst the 3 component wind tunnel balance can be used to find the drag force, lift force and pitching moment, this paper is only interested in the forces due to drag.

The sting is designed to be as aerodynamic as possible (i.e. with a small self-drag) whilst being strong enough to sustain the forces exerted at the high wind speed.

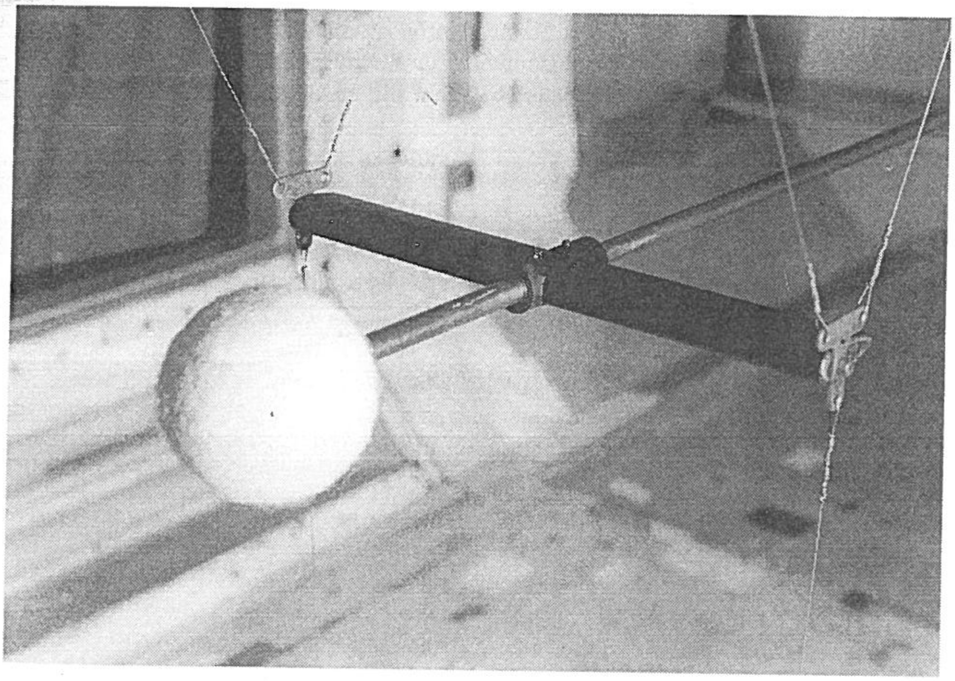

Figure 1 Close-up image of the front portion of the sting, used to translate force on tennis ball to the 3 component wind tunnel balance.

Figure 1 shows a close up of the front portion of the sting. It is constructed from 10mm diameter rod parallel to the airflow with an aerofoil section perpendicular to the airflow. The design criteria for the sting is as follows:

1. The length from the aerofoil to the back wire must be 24 inches.
2. The overall length of the aerofoil section should be approximately 12 inches, with equal amounts on either side of the main length.
3. The distance between the aerofoil and the tennis ball should be sufficient to prevent disturbance whilst short enough to prevent re-attachment of the streamlines before the aerofoil section.

Custom made brackets are connected at each end of the aerofoil section and at the rear of the 10mm diameter rod. They are oriented to enable movement around the horizontal axis perpendicular to the direction of airflow. There are five wires connecting the sting to the 3 component wind tunnel balance, two at each end of the aerofoil section at an angle to the vertical to help with stability, three wires drop down from the sting. Weights are attached at the bottom of each wire outside of the wind tunnel, suspended in oil for damping.

The sting assembly has an overall drag force which must be subtracted from the total drag force when the tennis ball is attached to it. Drag forces on the sting and wires would ideally be zero to minimise subtraction errors. The design of the sting component perpendicular to airflow can be optimised for minimal drag with the use of shrouds. A shroud is positioned upstream of the aerofoil and it is designed to deflect the airflow such that the drag force on the aerofoil is reduced. There will be additional blockage effects caused by the shrouding thus reducing the maximum velocity available from the wind tunnel. The relative gain will be discussed later in the paper.

METHOD

The investigation considered five different tennis balls, differing both in construction and nap. All balls used for testing were brand new and had not been subjected to any prior treatment and were;

- standard sized normal pressurised
- standard sized pressurised with 'fluffed up' nap
- standard sized pressurised with shaved nap
- 2% larger normal pressurised
- standard sized permanent pressure

By using this set of tennis balls, the effect of both construction and surface properties on the flight of the ball can be analysed. The selection of standard sized pressurised balls were used to simulate different levels of wear of a ball during a game.

The balls were attached to the sting in such a way that the sting and ball assembly was a rigid object. Care was taken to ensure that the orientation of the ball and seam was the same in each test. The wind velocity was increased from zero to approximately 138mph in equal increments giving 22 readings over the complete range.

Drag forces on the ball and sting assembly are transmitted to the 3 component wind tunnel balance. Displacement transducers are used to measure the movement of the balance and the output converted to drag force.

DETERMINING DRAG FORCES

Initially, forces on the sting and wires were determined without a tennis ball attached. In an effort to replicate the flow patterns when the ball is attached, a ball was placed just in front of the sting.

Due to the scatter in the data, a quadratic function was fitted to the force/velocity data for the sting and wires. Drag force on the ball was determined by subtracting the drag force on the sting and wires (calculated using a quadratic function) from the total drag force of the ball and sting assembly.

RESULTS

OBTAINING C_D

A digital manometer attached to the wind tunnel was used to give the dynamic pressure across the working section. Using Bernoulli's equation it is possible to show that,

$$\Delta P = \frac{1}{2}\rho v^2 \tag{4}$$

where: ΔP is the dynamic pressure

The diameter of the ball was measured using a projection device calibrated using a smooth sphere of known dimension. This process is repeated on three axes of each ball to obtain the average diameter.

The temperature in the working section increased at high wind velocities and was carefully monitored to ensure correct values of density were used in equation 1.

Figure 2 gives a graph of C_D versus Re for a standard, large, shaved, and fluffed up pressurised ball and a permanent pressure ball. The figure shows that the pressurised ball with the fluffed up nap has a higher C_D than the normal pressurised ball, which in turn had a higher C_D than the pressurised ball with the shaved nap. It appears that the C_D changed by 6% due to raising or lowering the nap. The average C_D for the standard sized normal pressurised, 2% larger normal pressurised and the standard sized permanent pressure balls were the same at approximately 0.53.

The results show that C_D is constant for the range of Reynolds numbers tested.

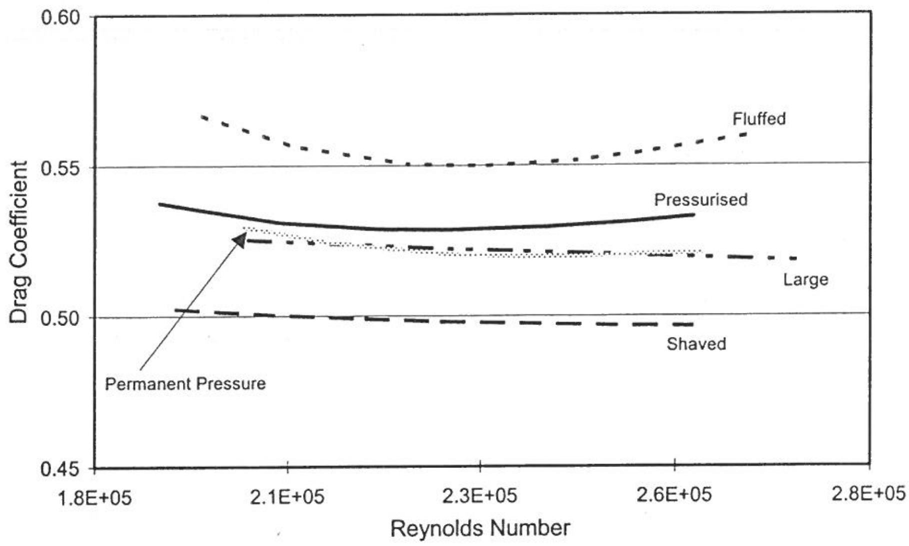

Figure 2 Graph of drag coefficient against Re for 5 balls tested.

A computational trajectory model has been developed to predict the flight of a tennis ball. Figure 3 shows predicted trajectories for a shot of 90mph, 1 degree above horizontal and 1 metre above the ground for the set of tennis balls studied here. Any difference in flight is due to either surface properties (i.e. C_D) or size.

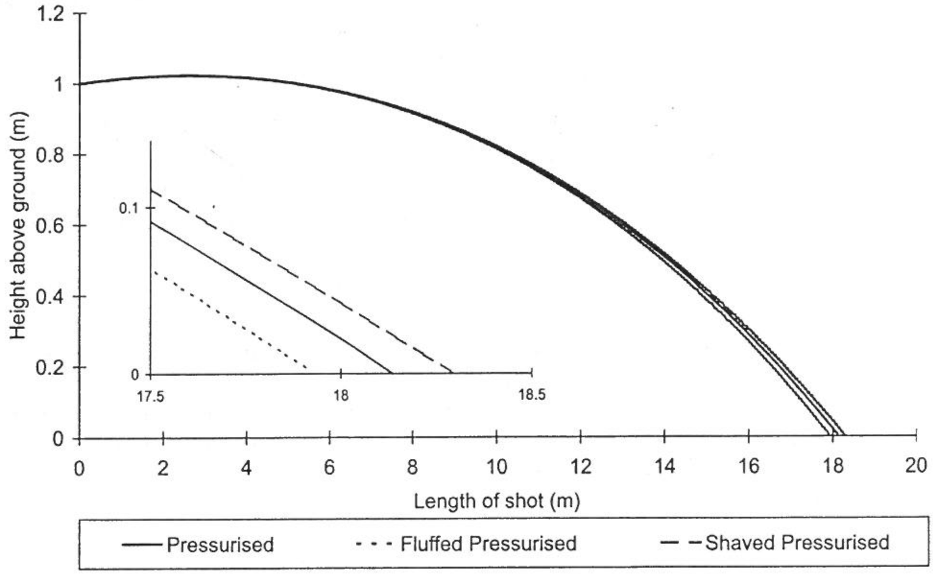

Figure 3 Graph showing the predicted trajectory for a standard ball, a ball with raised nap and a ball with reduced nap. The inset shows a close-up view of the area of impact with the ground.

The shaved ball travels furthest since it has the smallest C_D value, whilst the ball with the raised nap travels least far. Raising or reducing the nap makes a difference of $\pm$200mm in the impact point on the court.

DISCUSSION

C_D OF A TENNIS BALL

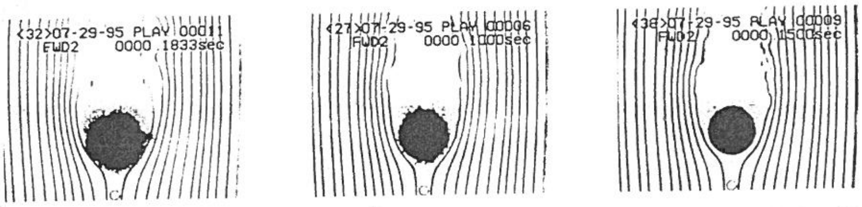

Figure 4 Flow visualisation around three different tennis balls: left, fluffed; middle, normal; and right, shaved (inverted image).

C_D is composed of two components: pressure drag, related to the size of the ball; and surface drag, related to the roughness of the ball. Figure 4 shows smoke flow around three different tennis balls at a Reynolds number of approximately 2 x 10^4. The size of the wake down wind of the ball is an indication of the pressure drag, the wider the wake, the higher the drag force. The width of the wake is dependent on the point of separation of the flow streams, early separation induces higher drag forces. The point of separation is dependent on surface roughness and wind speed, separation will occur earlier on a roughened ball or at increasing wind speeds.

Whilst the camera has remained stationary between tests, it is immediately apparent that they look to be different in size. The wake of the fluffed ball is wider than that of the normal ball, which in turn is larger than that of the shaved ball which is showing signs of re-attachment. The drag coefficient is non-dimensional, hence the difference in size has been accounted for. However, the results shown in Figure 2 show a difference in C_D, which can only be accounted for by the change in surface roughness.

CONSTANT C_D FOR ALL Re

It was anticipated that a sudden drop in C_D may be observed due to a transition from laminar to turbulent flow in the boundary layer. The results obtained show no transition point, which implies that a tennis ball can be considered to have a constant value of C_D for the values of Re tested.

USE OF SHROUDS

Shrouds were installed at the time of assessing the drag force on the sting alone. The drag force was reduced by approximately 10% with the shrouds in place, however, the reduction in wind speed was approximately 3% and the flow became unstable around the shroud at high velocities. It was decided that the benefits from using shrouds was not substantial for this sting configuration, and were not used in this testing.

ACCURACY OF RESULTS

It can be seen that all of the results shown thus far have been for high values of Re. The results obtained at low velocities are unusable, even after smoothing the data. The method by which the F_D is obtained with this 3 component wind tunnel balance is inherently inaccurate at low wind speeds due to the small changes in F_D. The balance point is determined visually using an analogue meter, the needle of which barely moves at the low velocities. The balance has been modified to give a digital readout of potential difference, the sensitivity of the displacement transducers continues to limit accuracy.

CONCLUSIONS

The drag coefficient of a tennis ball is relatively constant with increasing Reynolds number. Standard sized normal pressurised, larger normal pressurised and the standard sized permanent pressure have similar drag coefficients of 0.53.

Raising/lowering the nap leads to an increase/decrease in drag coefficient of approximately 6%, when compared to results for a standard ball.

An increased diameter does not lead to transition to a low drag regime at high Re.

An increase in diameter will produce a higher drag force, which will lead to the receiver having extra time to react.

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