DETERMINATION OF THE COEFFICIENT OF DRAG OF THREE DIFFERENT TENNIS BALLS USING A WIND TUNNEL

Steve Chadwick, Steve Haake, University of Sheffield, U.K.

INTRODUCTION: Most of the previous studies of the aerodynamic properties of sports balls [1, 2] have dealt with golf balls [3, 4, 5, 6] and baseballs [7, 8, 9, 10]. In the case of golf, there have been several changes over the years regarding both surface and content of the balls, all as part of the constant effort to make the balls fly further. The research regarding baseball and cricket deals more with the understanding of the aerodynamic effects on the ball when thrown in different manners. In tennis, however, most of this work has been involved with the tennis racket and its interaction with the ball. Studies regarding aerodynamics are very limited, generally specific to a typical shot, such as the top spin lob [11]. This paper documents some preliminary investigations into the phenomena of the aerodynamics of tennis balls. The study has used a wind tunnel and three differing tennis balls to determine the coefficient of drag over a range of Reynolds number.

METHOD: The investigation considers three different tennis balls, differing both in construction and quality of ‘nap’. The nap is the outer cloth surface of the tennis ball. The three ball types used are as follows: a pressurised ball fresh from its container; a ‘permanent’ pressure ball fresh from its container; and a well worn pressurised ball showing significant visual reduction in quality and overall bulk of nap.

The force acting on a non spinning tennis ball to slow it down during flight can be written as;

$$\mathrm{F_D} = \frac{1}{2}\rho \mathrm{A C_D} \nu^2 \qquad (1)$$

where, F_D is the drag force, ρ is the density of the air, A is the projected area of the ball, C_D is the coefficient of drag and ν is the relative velocity of the air over the ball. The component of force in the horizontal direction can be found using;

$$\mathrm{F_D}\cos\theta = \mathrm{m}\frac{\mathrm{d}(\mathrm{n_w} - \mathrm{n_x})}{\mathrm{dt}} \qquad (2)$$

where, m is the mass of the tennis ball, ν_w is the velocity of the wind, ν_x is the velocity of the ball in the direction of the wind and x, y and θ are defined in figure 1. Both θ and ν change a negligible amount during the trajectory since the ball is also accelerating due to gravity, and θ can be determined from the direction of motion of the tennis ball at a time t.

Each of the three tennis balls were subjected to wind speeds from 0 to 26.5ms^{-1}. At each speed the three balls were dropped through the working section of the wind tunnel. The device used for dropping the tennis balls was designed to drop without spin and released the ball electronically. The resulting ‘trajectory’ of the ball as a direct result of the wind acting on it was captured digitally using a KODAK Motioncorder high speed video taking pictures at 400 frames per second with a shutter speed of 1/1000 second. The resulting images were subsequently captured on a video recorder for further analysis. Figure 1 shows an image containing every

2^{nd} frame captured from the video using a digitising card mounted in a PC. The images were imported into a sophisticated image processing package (OPTIMAS 6.0) where pictures from successive frames were analysed to find the deflection from a straight drop.

The part of the trajectory able to be viewed through the wind tunnel access window, was approximately 230mm long and lasted approximately 0.06 second. At 400 frames per second, this gives up to 13 frames that can be captured.

To obtain the drag coefficient of the ball, its motion is analysed. Three points on the circumference of the ball were chosen on each image giving the co-ordinates of its centre. The centre co-ordinates were then used to produce a graph of deflection of the ball due to the wind against time. The chart in figure 2 shows the displacement in the direction of the air flow versus time for the three balls at two different wind speeds. The two velocities used in figure 2 are; Low V = 20 ms^{-1} and High V= 26.5 ms^{-1}. These velocities were selected to show how differing balls can act in similar manners at different air flows. The curves on the chart are 2^{nd} order polynomials giving x as a function of t. The second derivative of this function gives $\frac{d}{dt}\left(v_w - v_x\right)$ and thus can be used with equations 1 and 2 to give C_D.

RESULTS: Due to wear and differing manufacturers, the balls studied were of different diameters and it may be expected that a differing diameter would affect the drag. Thus, to create a form of comparison between the three balls, the drag coefficient was plotted against Reynolds number. Reynolds Number, Re, is a dimensionless term relating to fluid flow and is defined as;

$$\mathrm{Re} = \frac{\rho v A}{\mu} \qquad (3)$$

where, μ is the viscosity of the fluid.

Figure 3 shows C_D versus Re for the three balls studied. It can be seen that the worn pressurised ball with the significant removal of nap has a lower coefficient of drag when compared with the balls with brand new nap. For the two balls of similar surface condition, it is observed that the coefficient of drag is the same within the error bars. This result makes it possible to establish a relationship between the surface properties of balls and the resulting C_D, that is, the rougher the surface the larger the C_D. The errors were determined by approximating the maximum and minimum errors found from data collection and applying them to the chart in fig 2; the changes to the function used to calculate C_D gives the errors.

A computational model has been developed to predict the trajectory of a tennis ball. With this model it is possible to alter parameters such as the coefficient of drag and predict the effect on the flight of the tennis ball. Using the results from these tests on a ball hit horizontally with initial velocity 26ms^{-1} and zero spin, it was estimated that the ball with the significant removal of nap would travel 1m further than the balls with unspoiled nap, fig 4.

The model has been designed with input criteria of; initial velocity, initial spin, initial direction of motion, coefficient of drag, coefficient of lift, mass of ball, radius of ball, density of air and initial height. When there is a complete understanding of the aerodynamics of the tennis ball, it will be possible to change any one or a selection of these components and note the effect of the change on the flight of the ball.

DISCUSSION: The maximum value of Reynolds number used in this investigation was approximately 1.1 x 10^5. A service in a tennis game can be up to 145mph (230km/h), this speed relates to a Reynolds number of approximately 2.6 x 10^5. Future research will use either a higher velocity or a larger ball diameter to take into account the larger Reynolds numbers relevant to tennis.
The value of C_D for a smooth sphere at a similar Re is 0.44 [4], golf balls and baseballs have a value of approximately 0.5 [3, 9]. Generally the rougher the sphere the greater the C_D with a limiting maximum value of approximately 0.8 [11]. Within the range of Re used, the flow of air around the ball is laminar with a turbulent wake since the values of C_D for fully turbulent flow are much lower [12]. The wake is the major cause of drag and the size of the wake represents the magnitude of the drag force at low velocities.

CONCLUSIONS: A system using a wind tunnel and image processing was set up to analyse the drag of tennis balls. It was found that a worn tennis ball had a lower coefficient of drag than a new tennis ball. In the range of Reynolds number studied it was deduced that the flow regime was laminar. Using a trajectory model it was found that, for a typical forehand shot, a worn ball would travel 1m further than a new ball.

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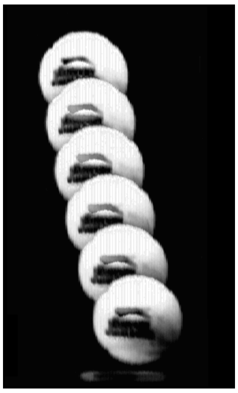

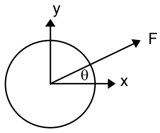

Figure 1. Images of every 2nd frame from a single ball drop captured using a KODAK Motioncorder high speed video camera. The air flow was travelling in the direction of x, with the resulting drag force of magnitude F in the direction θ.

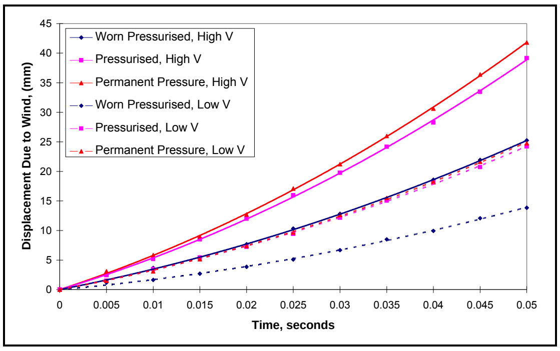

Figure 2. Displacement of the centre of the ball versus time in the direction of the air flow for three different tennis ball types at two different velocities.

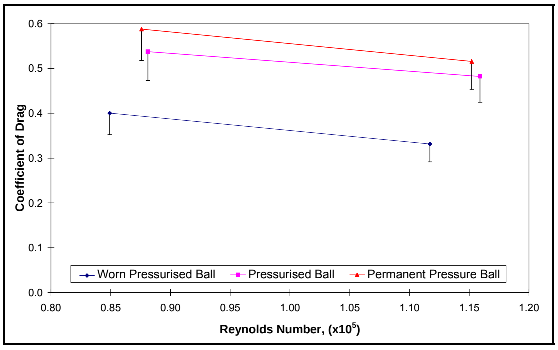

Figure 3. Chart showing the coefficient of drag plotted against Reynolds number for three different tennis ball types.

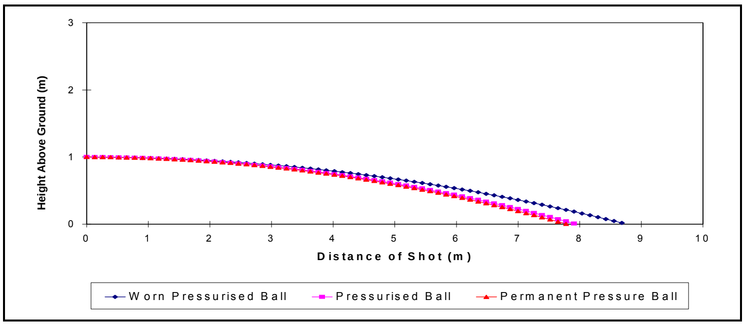

Figure 4. Showing the trajectory estimated for three different ball types using the results from this paper in a computer model.