Physics ATAR - Year 12

Science Inquiry Skills Test 2017

Name:

Mark: / 40
= %

Time Allowed: 50 Minutes

Notes to Students:

1. You must include **all** working to be awarded full marks for a question.
2. Marks will be deducted for incorrect or absent units and answers stated to an incorrect number of significant figures.
3. **No** graphics calculators are permitted – scientific calculators only.

The Aerodynamics of Tennis Balls

The origins of tennis lie in the 12th century when it was played in the courtyards of Europe and was known as *jeu de paume*. This evolved into the game Royal Tennis or Real Tennis. It remained a game for the rich and elite until 1874 when Major Clopton Wingfield invented the game of lawn tennis, which he called ‘sphairistike’ (a Greek term meaning ‘skill in playing at ball’), as shown in Fig. 1. This was helped by the development of the rubber industry in the mid-late 1800s to make the balls. Two hundred years later, Lord Rayleigh (also famous for extracting and identifying the noble gas Argon, for which he won a Nobel prize) used the classical potential flow theory, for flow around a cylinder, to describe the irregular flight of a tennis ball.

Fig 1. Paintings depicting lawn tennis.

Despite its past, significant advances in the research of the mechanics of the game is relatively recent. The work addressed here was sponsored by the International Tennis Federation (ITF), who are the governing body of tennis. Currently the rules of tennis do not specify any technical specifications regarding the outer covering on a tennis ball. The ITF rule simply states that, “The ball shall have a uniform outer surface consisting of a fabric cover and shall be white or yellow in colour”. The results of this study were intended to aid the ITF in deciding whether a new ruling, regarding the aerodynamics of the ball surface, is required to protect the nature of the game and prevent manufacturers from introducing a tennis ball with radically different aerodynamic properties compared to a current tennis ball (but which looked like a regular tennis ball, as shown in Fig. 2).

Fig 2. A regular tennis ball

The trajectory of a tennis ball is determined by the gravitational and aerodynamic forces which act on the ball during its flight. Studies show that measurements of kinematics in a vacuum gives a horizontal range that is 40% longer than the actual range. This means that ignoring air resistance is an assumption that cannot be made if one wishes to model the motion of a sport projectile.

The aerodynamic forces which act on a tennis ball are the **drag** force and the **lift** force. The magnitude of drag force is given by;

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

where; C_D is the drag coefficient,
ρ is air density ($\frac{mass}{volume}$),
A is the projectiles cross sectional area and
v is the projectiles speed.

(a) Determine the units of the drag coefficient (C_D). Show all reasoning below. (3 marks)

Inclusion of drag alone is not enough to accurately model the flight of a ball, we also need to account for spin. A spinning ball sets the air around it in motion in a thin layer near the surface of the ball and causes the air to be asymmetrically whipped down off the backside of the ball. According to Newton's 3rd Law there is then an upward force component on the ball, this is called the lift force, as shown in Fig. 3. This force is called the lift force and it always acts at right angles to the drag force.

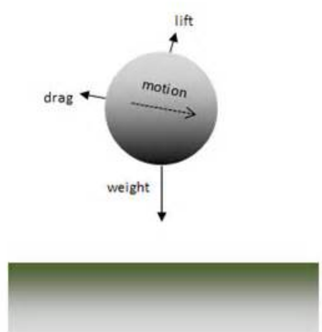

Fig 3. The lift and drag forces acting on a ball

The magnitude of the lift force is given by;

$$F_L = \frac{1}{2} C_L \rho A v^2$$

where; C_L is the lift coefficient,
ρ is air density ($\frac{mass}{volume}$),
A is the projectiles cross sectional area and
v is the projectiles speed.

C_L and C_D are factors that contain the complicated features of the lift force, meaning they may also depend on the projectiles speed, spin rate and surface characteristics.

There are two main methods which can be used to measure the aerodynamic forces acting on a spinning tennis ball. The first involves propelling the ball through the air and measuring the trajectory of the ball. This may involve the ball being propelled through 'still' air using a high-precision cannon, or being dropped into the working section of a wind tunnel. The displacement of the ball is measured and used to calculate the forces on the ball. The main problem associated with this method is that the sampling of the ball displacement is susceptible to large uncertainties. Furthermore it must be assumed that the spin remains constant throughout the test.

An alternative method involves supporting the ball on a rotating force balance (similar to a set of electronic scales) inside the wind tunnel test section, as shown in Fig. 4. The resultant force can then be sampled directly. The main consideration for this type of experiment is to ensure that the ball supports do not interfere with the flow of the air over the ball.

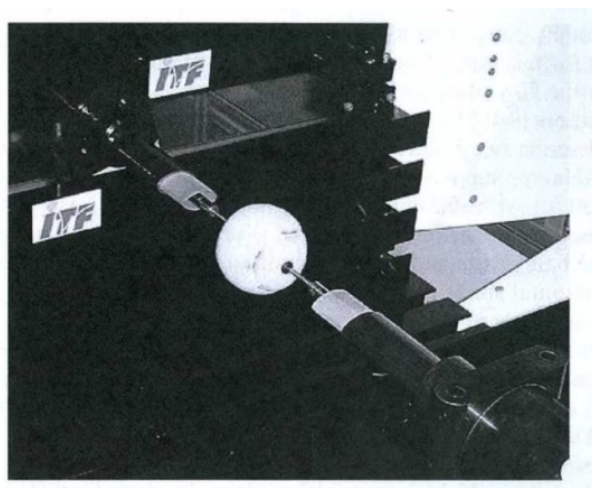

Fig 4. Ball supported in the working section of the wind tunnel.

(b) Explain why these researchers made use of the alternative method.

(2 marks)

The ball was supported in the centre of the test section using two horizontal stings, as shown in Fig. 4 (on the previous page). The stings have a stepped profile to reduce the interference around the ball while maximising the strength of the sting and minimising the vibration of the ball.

The support mechanism allowed the ball to be rotated at a constant velocity while simultaneously measuring drag and lift forces. The motor housing had to be supported by the balances to ensure that the load was transferred correctly. The force balance had been previously calibrated by Aerotech and the calibration was checked prior to the commencement of each test.

A hole was drilled at one pole of the tennis ball and the ball then filled with a polyurethane foam to ensure structural stability of the ball during testing. The diameter of the ball was determined using Vernier calipers, as shown in Fig. 5. The ball was gripped between the calipers and the calipers slowly released. The measurement was recorded when the ball dropped, under its own weight, through the calipers. An average diameter was determined from measurements across several axes through the ball. The repeatability of the measurement was ±0.2 mm.

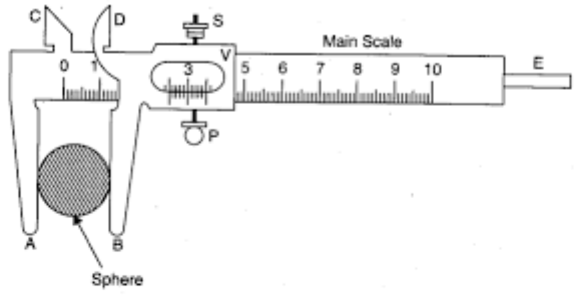

Fig. Vernier callipers—Measuring diameter of a sphere.

Fig. 5 Vernier Callipers – measuring diameter of a sphere

The maximum uncertainty in the wind speed measurement was ±0.1 ms^{-1} at 20 ms^{-1}. The wind speed and force balance signal were sampled at 10 counts per second, for 10 s. Mean values of these two parameters were calculated.

(c) State and explain three ways in which the researchers increased the reliability of their measurements.

(6 marks)

The loading due to the stings is accounted for in the calculation of C_D by the tare loading of the system. The tare ball is placed in the position of the test ball and is supported on a separate vertical string to ensure that the effect on the flow of air due to the presence of the ball is accounted for. It is important to ensure that the tare ball does not touch either of the horizontal stings, so that the load measured by the force balances is solely due to that of drag on the stings.

To verify the accuracy of the force balance and wind speed measurement system another test was conducted with a smooth sphere with a similar diameter as a standard tennis ball. The results compared with data collected by Achenbach (1972) who reported a constant C_D of 0.51 ± 0.01. Achenbach's data was obtained using a sphere that was mounted from the rear to minimise interference. In this study, the smooth sphere exhibited a constant C_D of 0.54 ± 0.01.

(d) State the conclusion that the experimenters would have come to about their experimental setup.

(1 mark)

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(e) Would the use of this equipment still provide valid results? Explain your reasoning.

(3 marks)

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The following results were collected for a tennis ball to determine the value of C_D. These are **not** results obtained by the researchers.

The density of air = 1.225 (units not provided)
The diameter of the tennis ball = 65.4 ± 0.2 mm

F (N) ± 0.020	v (ms^{-1})	
0.044	5.6	
0.072	6.7	
0.185	11.2	
0.215	13.4	
0.485	17.9	
0.850	22.4	

(f) Process the data in the table above so that you are able to plot a linear graph to determine the value of C_D.

(4 marks)

(g) Plot your graph on the graph paper provided including a line of best fit.

(6 marks)

(h) Calculate the gradient of your graph to a precision of 3 sf. Show your working below.
(3 marks)

(i) Calculate the value of C_D including any uncertainty in the final value
(6 marks)

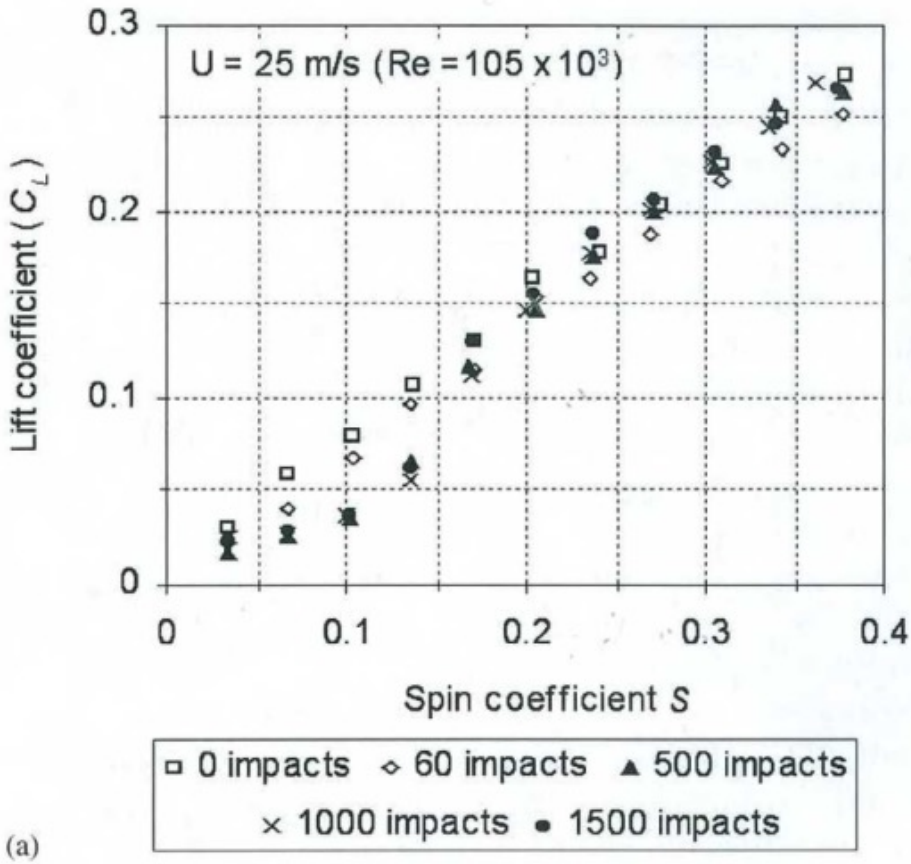
A large selection of tennis balls were tested in the study to cover the wide range of balls used in the game of tennis. A selection of worn tennis balls was also studied. Three balls of each ball type were used and C_D values were obtained for two separate runs for each ball. The repeatability for the three balls of each type was typically ± 0.02. This difference may be due to the random orientation of fluff caused by differences in the handling and storage of balls.

In this study, the wear of a tennis ball was simulated using the 'wear rig' at the ITF laboratory. The ball is projected from an air cannon at a speed of 30 ms^{-1} onto an acrylic surface at an angle of 16˚. The ball then impacted onto a rigid surface which directed it back into the cannon hopper (the loader for the cannon). The process was repeated for the specified number of impacts – 60, 500, 1000 and 1500, to correspond to between 2 and 50 games if only one ball is used in the game.

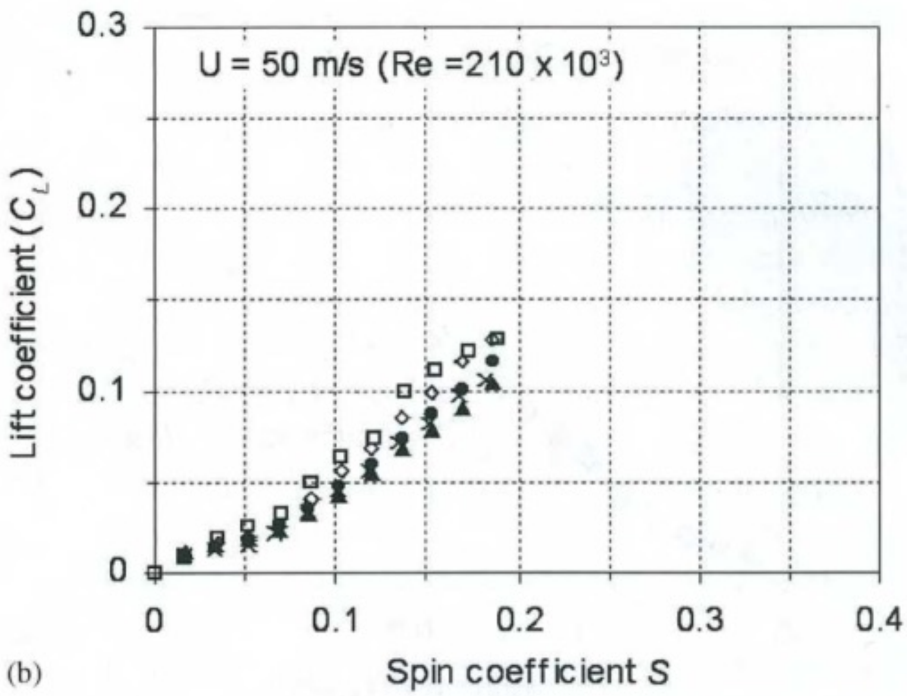
The diameter of the balls was measured before and after wear testing. It was expected that wear might have reduced the measured diameter due to loss of fibres, but this was not noticed, as any differences were smaller than the repeatability of the measurement. It was evident, however, that the balls were less fluffy, see Fig. 6. The surface of a tennis ball is not a rigid object and when caused to rotate, the fluff on the surface will attempt to 'stand up'. This standing up fluff will increase the drag on the ball which in turn increases the lift coefficient. At higher speeds the fluff is forced to lie down

Fig. 6 Fluff on tennis balls

The graphs below show results of C_L obtained for new and worn balls. These are plotted against the Spin Coefficient (S) which is equal to the velocity of the ball (V) divided by the rate of spin (U). The value of spin coefficient is used to make comparisons between different trials.



(a)



(b)

(j) If the spin coefficient in a test has a value of 0.1, state how the velocity of the ball would vary from graph (a) to graph (b).

(1 mark)

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(k) Compare the lift coefficients of the new and worn balls on each graph for the spin coefficient of 0.1. Using the findings from the experiment, explain why this may be the case.

(5 marks)

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The study concluded that there was no significant difference in the drag and lift coefficients of all the new ball brands. However, it was found that the drag and lift coefficients of the spinning worn balls were dependent on the number of impacts that the ball was subjected to. In particular, the study has highlighted that worn tennis balls can exhibit very different properties to those of new tennis balls. Although it is accepted that manufacturers will not sell worn balls, even the most heavily worn ball in this study (1500 impacts) still 'looks and feels' like a tennis ball. Therefor it may be possible for manufacturers to produces a cloth that has the same texture as a worn ball. This would in effect change the nature of the game.

Acknowledgments

Goodwill, S.R., Chin, S.B. & Haake, S. J. (2004). Aerodynamics of spinning and non-spinning tennis balls. *Journal of Wind Engineering and Industrial Aerodynamics,* 92(2004), 935-958. doi: 10.1016/j.jweia.2004.05.004