18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Dip and drift in spin bowling

A. Keith[1], P. Britton[1] and J.-L. Liow[2]

[1]School of Engineering and Physical Sciences
James Cook University, Douglas, Queensland 4814, Australia

[2]School of Engineering and Information Technology
UNSW Canberra @ADFA, Canberra, ACT 2600, Australia

Abstract

The lift force acting on a rotating cricket ball was measured in a wind tunnel. An A grade bowler was videoed and analysed to provide data to ascertain the rotation rates that can be achieved by a bowler. Measurements showed that the bowler could easily achieve a rotation rate of 1800 rpm indicating that test cricket bowlers can provide rapid spin to a cricket ball. Rotation rates of up to 1400 rpm were used and the results showed that a larger lift force is experience by an old cricket ball than a new cricket ball. The lift force measured increased with rotation rates. The reverse Magnus effect was not found for used cricket balls but for a new cricket ball, the lift force reversed its direction twice with increasing Reynolds number for rotation rates below 800 rpm. The possibility of the lift force changing direction with changing Reynolds number and rotation rates makes it difficult for a batsman to predict the flight of a cricket ball and can also make it difficult for a bowler to control the cricket ball precisely.

Introduction

Bowling in cricket

Cricket is a game of immense popularity in countries with a British tradition. The professional cricket matches that run for up to five days per match are called test matches. Throughout most of the 1990s, the Australian Cricket Team has excelled with top rankings in the international arena. However, the team's shock loss of the Ashes Test Series in 2005 to England has changed the perception and currently the Australian Cricket Team is struggling to build back its previous reputation following a 4-0 loss to England earlier this year. One of the bowling action that has been of interest since the 2005 loss is the reverse swing.

In this study, the focus is on the motion of and forces acting on the cricket ball. The bowling action is performed by rotating a straight arm over the body in the direction of the stumps, releasing the ball when the arm is near vertical. Cricket bowlers are categorised into two main type; fast and spin bowlers. Fast bowlers bowl the ball at high speeds (usually over 130 km/hr) while spin bowlers bowl at lower speeds (usually less than 100 km/hr) while imparting spin to the ball. The bowling action often results in lateral (or transverse) movement relative to the initial direction of travel. This sideways movement of the ball in flight is referred to as swing for fast bowlers and drift for spin bowlers.

Spin bowlers attempt to deceive batsman by imparting spin so that the ball trajectory is altered during flight and moves sideways after bouncing. Dip is the reduction in length of a ball's trajectory due to the application of top-spin whereby the ball rotates in an end-over-end fashion. Relative to the ball's centre of gravity, the upper surface is moving forwards while the lower surface is moving backwards. The top-spinning ball experiences a downward force causes it to strike the ground at a shorter distance in flight compared to a ball that is not spinning.

Drift occurs when a ball moves sideways during its flight and it has been found that the ball generally drifts to the side opposite to which the ball will bounce. Drift is useful when there is little bounce on the pitch and bowlers that are able to apply large amounts of spin to the ball are often able to achieve substantial drift of the ball. This occurs even when the spin is applied about an axis parallel to the direction of motion.

The cricket ball

Figure 1. A cricket ball showing the seam and stitching.

A cricket ball consists of a cork core covered with a layer of tightly wound string followed by a leather casing that is traditionally coloured red (Figure 1) and weighs between 5.5 to 5.75 oz (155.9–163.0 g) with a circumference between 8-13/16 and 9 in (224–229 mm). The leather casing is made from four pieces of leather and the equator of the ball is stitched with string to form the seam. The seam along the equator rises above the ball surface by 1–2 mm. To either side of the seam are three rows of stitches (70–90 per row), the closest one has straight stitches of a thinner thread while the two rows of stitches furthest away from the seam have threads that are thicker and the stitches are angled relative to the direction of the row. The region between the two rows of thicker stitches rises about 1 mm above the ball surface. The presence of the seams and the conditions of the ball surface play important roles on the fluid flow around the ball and hence the forces acting on it during flight. During the game, the bowlers usually polish one side of the ball while leaving the other side rougher, which results in different fluid flow behaviour over the two surfaces of the ball during flight.

Previous studies

The development of a lift force on a rotating circular cylinder in a uniform stream, acting normal to the direction of the free stream velocity is called the Magnus effect [1] and its magnitude per unit length is given by

$$F_y = -\rho U \Gamma, \tag{1}$$

where ρ is the air density, U the free stream velocity and Γ is the circulation around the cylinder. However, the lift force on a cricket ball is more complicated and is affected by the surface roughness, the direction of spin, Reynolds number (N_{Re}), and the angular velocity. Maccoll [2] determined lift coefficients for smooth spheres at various N_{Re} and found that the lift coefficient ($C_L=F_y/(0.5\rho U^2 A)$) was negative for value of up to Γ=0.5 with a negative maximum at Γ=0.2. This is known as the reverse

Magnus effect. Tsuji *et al.* [3] results suggested that the reverse Magnus effect only occurs at high N_{Re} and their experiments for $550<N_{Re}<1600$ did not find any reverse Magnus effect. Aschenbach [4, 5] provided data for smooth balls but much of the data so far published are not applicable directly to cricket balls except to provide some guidelines regarding the complexities of the fluid mechanics related to their flight. The swing of the ball in flight has been subjected to a number of theories and investigations. Asymmetric air flow is created by the seam angle and the roughness of the ball. Further complications arise when the ball is spun during bowling and the angular and forward velocities create further variations in the pressure differences around the ball.

Binnie [6] showed that humidity causing condensation shock is unlikely to be a factor in affecting the swing of cricket balls as condensation is only expected to occur at close to 100% humidity, a condition rarely experienced during cricket games. The transition from laminar to turbulent at a N_{Re} of 1.5×10^5 (~32 m/s) for a cricket ball is slightly lower than for a smooth ball [7]. Sayers and Hill [8] found that lift, drag and side forces for a stationary ball was 1.4, 1 and 0.4 N for velocities between 0 to 20 m/s and increased above 20 m/s. The side force was found to reverse at a seam angle of 80° and roughening one side of the ball delayed the reversal to a slightly higher forward velocity. However a constant negative lift force was measured for all forward velocities for a roughened ball when top spun. Sayers [9] showed that inception of reverse lift on a smooth and a rough sphere (roughened with a layer of adhered sand) was highly N_{Re} dependent and reverse swing could be possible with a zero seam angle at lower N_{Re} values than previously known. Sayers and Lelimo [10] studied the forces on spinning cricket balls (2–8 rps) and showed that a topspun ball can have a discontinuous jump in the lift force over certain N_{Re} and a sharp change above N_{Re} of 1.25×10^5. Briggs [11] found that a reverse Magnus effect for a rotating sphere occurred at an air speed of 23 m/s and spin rate of 30 rps, while Sayers and Lelimo [10] suggested that cricket bowlers only had a maximum spin rate of about 15 rps. However there has not been any measured and published data on the actual spin rates of cricket players.

This study was undertaken to find measure actual spin rates. Velocities of cricket balls are easily measured during Test match by Doppler methods and the velocities of the balls do not change significantly during their flight. Wind tunnel test were then carried out to study the effect of the spin on the lift force experienced by cricket balls with different surface conditions to estimate the extend of drift and dip during its flight.

Experimental method

The bowling actions of an A grade cricket player was filmed using a pair of *Redlake Motion Xtra HG-100a* high speed video cameras at a resolution of 1024×1024 pixels at 1500 fps. A view area of 1 m×1 m was used with a 663 μs exposure time whereby any movement slower than 1.5 m/s was frozen to less than 1 pixel of distortion in each frame. The pair of cameras were synchronised so that the second camera started 0.5 s after the first camera and placed along the pitch and separated by about 2 m. The images were downloaded and analysed using the *Motion Central* software. A new two-piece Kookaburra cricket ball was used and it was spray painted white with a black dot placed on it. Details of the filming procedure can be found elsewhere [12].

Wind tunnel tests were carried out on a rotating ball. A small wind tunnel with a maximum speed of 30 m/s and a diameter of 0.54 m was used. The ball was positioned inside the wind tunnel with the aid of an 8 mm diameter shaft mounted on ball bearings. A 50W DC motor was attached to the shaft to rotate the ball and the rotational rate was measured with a tachometer focused on a white strip adhered to the shaft surface (Figure 2). The shaft setup was mounted on a scale that measured mass to the nearest 0.1 g. Four cricket balls were used; balls 1, 2 and 3 were used cricket balls with seam alignments of 0°, 90° and 45° respectively while ball 4 was a new two-piece ball with a 0° seam alignment. A wooden model of the cricket ball was used to test the effect of using a model as a substitute for the actual ball. Wooden ball 1 had a smooth finish obtained by applying several coats of varnish and it had a 0° seam alignment.

Figure 2. View of the wind tunnel setup.

The velocity in the wind tunnel was calibrated with a pitot tube against the frequency of the suction fan which was controlled by a variable frequency drive. The lift force acting on the shaft was measured without the ball and used to correct the lift force reading on the rotating ball. A noticeable bending moment effect due to drag on a stationary ball was observed to be recorded on the scales and this was calibrated for different air velocities and the readings on the scales corrected for this as well. The errors for the force measurements in these experimental was estimated to vary between 5% at low air velocities and gradually rising to a maximum of 20% for the worst case at the highest air velocity.

The drift of the cricket ball was measured by dropping the ball from different heights with rotational rates of 1800 to 2800 rpm past a 2 m diameter wind tunnel at a free stream velocity of 11.5 m/s and measuring the lateral deflection during the fall.

Results and discussion

Bowling speeds

A series of images capturing the ball just after the ball release from the bowler's hand was used to determine the initial velocity and rotational speed. The initial velocity was based on the images where the ball left the hand till it left the view of the first camera. The black dot on the ball relative to the centroid of the ball was determined for each frame and a single revolution was the time for the black dot to return to the same position relative to the centroid of the ball. The initial trajectory angle, the height of the ball at release, and the maximum height reached by the ball were also measured (see Table 1).

Table 1. Ball velocities and rotational speed from bowling film record.

Delivery	Release velocity (m/s)	Release angle (°)	Rotational rate (rpm)	Ball height at release (m)	Maximum ball height (m)
1	19.25	3.0	1667	2.31	2.36
2	18.72	13.5	1731	2.28	3.19
3	18.60	3.8	1836	2.32	2.39
4	21.52	10.2	1922	2.29	3.03
5	20.85	6.7	1711	2.31	2.61

Assuming that the drag is minimal, the maximum height attained by the ball should be solely determined by gravitational pull. Using the release velocity and angle, the maximum heights were calculated (see Table 2). The resolved horizontal bowling speed, the flight distance (distance travelled before hitting the ground) and the calculated vertical impact velocity on the ground are also listed in Table 2. The results showed that there is good agreement between the calculated and measured maximum height reached by the cricket ball confirming that the effect of drag on the ball is minimal over the distance it takes to reach its maximum height.

The bowling speed for the bowler, who is classified as a leg-spin bowler, ranged from 18.2 to 21.2 m/s putting him in the slow bowling regime [10]. The average measured rotational speed of 1773 rpm (29.6 rps) is twice the value indicated by Sayers and Lelimo [10] and comparable to that of baseball players [13]. It can be expected that a professional test cricketer could reach rotational rates above the 1922 rpm recorded in this study, possibly reaching the spin rates of 2100 rpm (35 rps) recorded for baseball pitchers [13].

Table 2. Ball velocities and flight distances

Delivery	Calculated maximum ball height (m)	Initial horizontal velocity (m/s)	Flight distance (m)	Calculated vertical impact velocity (m/s)
1	2.37	19.22	13.33	6.80
2	3.21	18.20	14.68	7.91
3	2.40	18.56	12.90	6.82
4	3.03	21.18	16.59	7.68
5	2.61	20.71	15.10	7.16

Lift force measurments

The roughness of the balls used was roughly estimated by photographing strips of the leather after the experiment through a microscope and comparing the peaks and trough with a ruler. Other measurements were made with a vernier. The ball dimensions are listed in Table 3.

Table 3. Ball dimensions for wind tunnel tests

Ball	Diameter of equator (mm)	Diameter orthogonal to equator (mm)	Height of seam at equator (mm)	Height of stitches (mm)	Roughness (mm)
1	72.1	71.0	1.1	0.1	0.7
2	72.8	71.1	0.5	0.1	1.5
3	72.9	71.2	0.9	0.5	0.5
4	71.9	70.4	1.5	0.8	0.0*

*The roughness was less than 0.1 mm

The rotational rate of the shaft was limited to 1400 rpm for the cricket balls and 1580 rpm for the wooden ball as higher rotational rates resulted in too much vibration. Figure 3 shows the lift force measured for ball 1 (old and 0° seam). The graph shows that the lift force increases with the free stream velocity and increasing rotational speed. Rotating the ball in the opposite direction results in a lift force in the opposite direction and the two sets of results do mirror each other across the x-axis. The lift force is found to scale linearly with the square of the free stream velocity. We did not find the discontinuity of the lift force with increasing free stream velocity as reported by Sayers and Lelimo [10]. The lift force variation with free stream velocity was similar to that of Sayers and Hill [8] for a smooth ball although Sayers and Hill did not find a significant variation in their data over a top spin range of 500–100 rpm, which may be due to the use of too small a range of rotational rates.

Figure 4 shows the lift force measured for ball No.1. The lift force increases with rotational rate similar to the single result of Sayers and Hill [8, Fig. 17 showing 500–1000 rpm rotational speed]. We did not find a lift in the opposite direction at low rotational rates which was suggested by Sayers and Hill [8] and in the C_L plots with spin ratio [1, for $\omega D/2V<0.5$] for smooth spheres. This may be due to the fact that we did not test for very low rotational rates. It was observed that the lift force tends to a constant value above 800 rpm which is in agreement with the results of Watts and Ferrer [14] for baseballs and constant C_L values for spin ratios above 2.5 for smooth spheres [1].

The results for a new cricket ball (No. 4) are shown in Figure 5. At rotational rates above 800 rpm, the lift force increases with the free stream velocity. For rotational rates below 800 rpm, the lift force reverses direction and initially crosses the axis at around 10–15 m/s free stream velocity and then crosses the axis again at a higher free stream velocity. This finding is similar to that of Figure 13 in Sayers and Lelimo [10] where the lift coefficient for rotational rates between 4.2 to 10.8 rps (250–900 rpm) reverse direction twice between N_{Re} of 54000 to 83000 (U=12–18 m/s) for a roughened ball with topspin.

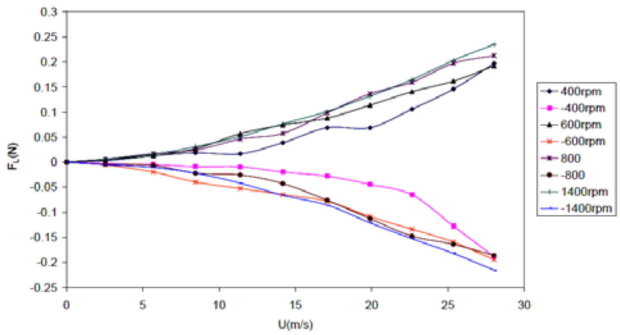

Figure 3. Lift force versus free stream velocity for ball No.1.

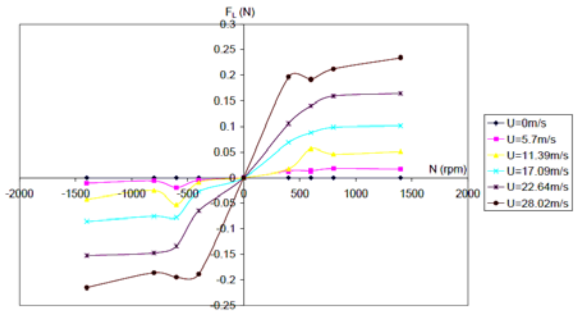

Figure 4. Variation of lift force with rotation rate of the ball No.1.

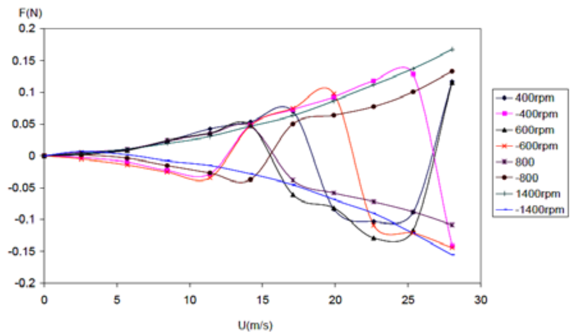

Figure 5. Lift force versus free stream velocity for ball No.4.

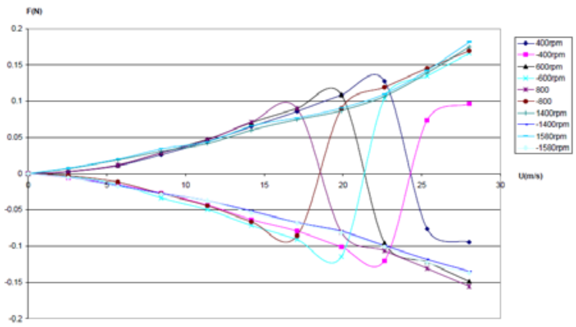

Figure 6. Lift force versus free stream velocity for wooden ball No.W1.

The lift force for the smooth wooden ball (No.WB1) is shown in Figure 6. The lift force reversal appears for the wooden ball but there are a few differences when compared to the new cricket ball. First it appears at a higher free stream velocity compared to the new cricket ball. Second, the lift force reversal only occurs once over the free stream velocity range (0–28 m/s) tested in the wind tunnel. This does not preclude the possibility that a second flow reversal may happen at a higher free stream velocity. Third, a lift force reversal was found for the rotational rate of 1400 rpm, which did not occur with the new cricket ball.

The reverse Magnus effect has been attributed to the possibility that the surface of the ball moving into (and thus against) the wind trips the boundary layer to turbulent flow earlier since it has a higher relative velocity while the surface of the ball moving away from (and thus with) the wind still has a laminar boundary layer since it is at a lower relative velocity. A cricket ball spinning at 30 rps has a rotational velocity of 6.7 m/s on its surface and this is a substantial fraction of ball's forward velocity, hence fairly large difference in the relative velocities of the ball surface to the flow can be expected. The wake is shifted to the side that has the turbulent boundary layer and results in the reverse Magnus effect. At even higher Reynolds number, both sides of the ball have a turbulent boundary layer and the reverse Magnus effect disappears. Similarly Briggs [11] found that the reverse Magnus effect did not occur at high rotational rates.

Drift measurements

Five runs each were made with a new and a used cricket ball which were compared between 0 and 11.5 m/s free-stream velocities. The results showed that the maximum lateral force experienced by the new and used cricket balls were larger when there was a free stream velocity but a lateral force was experienced even without the presence of a free-stream velocity as shown in Figure 7.

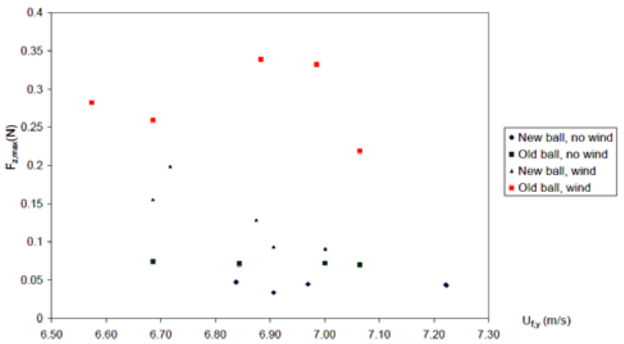

Figure 7. Lateral force versus fall velocity of a new and a used cricket ball with and without the wind tunnel operating.

The magnitude of the lateral force is comparable to that of the lift force and this is of the same magnitude as those measured by Alam *et al.* [15]. The results are for rotational rates varying between 1800 to 2800 rpm but it was found that the influence of the rotational rate on the results was minimal. Alam *et al.* [15] have shown that the lateral force can reverse depending on the free stream velocity and this will be the subject of future investigations into the drift effect of a cricket ball.

Conclusions

A study on the effect of rotation on the forces experienced by a cricket ball has shown that:

- A larger lift force is experienced by an old cricket ball than a new cricket ball.
- The lift force appeared to increase slightly for higher rotation rates.
- The reverse Magnus effect may occur for a new cricket ball at a lower rotation rate and a large Reynolds number when compared to a used cricket ball.
- The reverse Magnus effect may operate only over a particular Reynolds number range with a new ball for a given rotational rate.

The use of a model wooden cricket ball has been shown to be able to reproduce the reverse Magnus effect found with a cricket ball. This may allow larger ball models to be used to extend the Reynolds number range that can be studied.

Acknowledgments

Andrew Kerr and the Saints Cricket Club in Townsville for their assistance in bowling. Scott Anderson for the manufacture of the wooden scale model balls.

References

[1] Munson, B. R. *et al.* "Fundamentals of fluid mechanics," 6th edition, John Wiley, Brisbane.
[2] MacColl, J. "Aerodynamics of a spinning sphere," *J Roy. Aero. Soc*., **20**, 1928, 777–798.
[3] Tsuji, Y., Morikawa, Y. and Mizuno, O. "Experimental measurement of Magnus force on a rotating sphere at low Reynolds numbers," *J of Fluids Engng*., **107**, 1985, 484–488.
[4] Achenbach, E. "Experiments on the flow past spheres at very high Reynolds numbers", *Journal of Fluid Mechanics*, **54**, 1972, 565–575.
[5] Achenbach, E. "The effects of surface and tunnel blockage on the flow past spheres", *Journal of Fluid Mechanics*, **65**, 1974, 113 – 125.
[6] Binnie, A. M. "The effect of humidity on the swing of cricket balls", *Int. J. Mech. Sci*., **18**, 1976, 497–499.
[7] Mehta, R. "Aerodynamics of sports balls", *Ann. Rev. Fluid Mech*., **17**, 1985, 151–189.
[8] Sayers, A. T. and Hill, A. "Aerodynamics of a cricket ball", *J. Wind Engineering and Industrial Aerodynamics*, **79**, 1999, 169–182.
[9] Sayers, A. T. "On the reverse swing of a cricket ball – modelling and measurements", *Proc. Instn. Mech. Engrs. C*, **215**, 2001, 45–55.
[10] Sayers, A. T. and Lelimo, N. J. "Aerodynamic coefficients of stationary and spinning cricket balls", *R & D Journal of the South African Institution of Mechanical Engineering*, **23**, 2007, 25–31.
[11] Briggs, L "Effect of spin and speed on lateral deflection (curve) of a baseball", *American Journal of Physics*, **27**, 1959, 579–586.
[12] Keith, A. "Dip and drift in spin bowling", *B Eng. Thesis*, Mech. Eng., James Cook University, 2005.
[13] Mehta, R. and Pallis, J. "Sports ball aerodynamics: Effects of velocity, spin and surface roughness", *Conference on Materials and Science in Sports*, TMS, 2001, 145. *ed*. Froes, F. H. and Haake, S. J.
[14] Watts, R. and Ferrer, R. "The lateral force on a spinning sphere: Aerodynamics of a curveball", *Am. J. Phys*., **55**, 40–44.
[15] Alam, F. *et al.* "Aerodynamics of used cricket balls", 17th AFMC, 2010, Auckland, New Zealand.