19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Fluid Mechanics of Cricket Ball Swing

R. D. Mehta

Sports Aerodynamics Consultant
Mountain View, CA 94043, USA

Abstract

The ability to make a cricket ball deviate laterally in flight ("swing") has intrigued cricket players and spectators for years, arguably since the advent of the game itself. The basic aerodynamic principles responsible for the swing of a cricket ball were identified decades ago and many papers have been published on the subject. Over the last 35 years or so, several experimental investigations have also been conducted on cricket ball swing, which revealed the amount of attainable swing and identified the parameters that affect it. Those findings are summarized here with updates on phenomena such as late swing and the effects of weather conditions on swing. The concept of "reverse swing" that became popular in the late 1980s and how it can be achieved in practice is also discussed, together with the role of "ball tampering." In particular, the ability of some bowlers to effectively swing an old ball in the conventional, reverse and the relatively newly termed "contrast swing" mode is addressed. The well understood "Magnus" effect on a spinning ball is often used by the slower spin bowlers to make the ball drift through the air. It is discussed here how some fast bowlers can also generate the same effect. Very recently, it has become apparent that bowlers are able to release a cricket ball without any spin imparted to it. This can lead to a very interesting "knuckling" effect, similar to that often seen in baseball.

Introduction

The first published scientific account of cricket ball swing was by Cooke [5], who gave an explanation of why it was possible for fast bowlers to make a new cricket ball "swerve" and why it became more difficult to do this when the shine had worn off the ball. Since then, several articles have been published on the theories of cricket ball swing [7,11,12]. Later on, Barton [1], Bentley *et al*. [2] and Mehta *et al*. [13] described detailed experimental investigations where the magnitude of the side force that produces swing and the factors that affect it were determined; see Mehta [14] for a detailed review of the earlier work. The relatively new concept of "reverse swing," which first became popular in the late 1980s and 1990s, was first explained and discussed by Bown & Mehta [4]. A preliminary analysis of cricket ball swing using computational fluid dynamics was described by Penrose *et al*. [21]. The flow field around a cricket ball was measured and described by Grant *et al*. [6] and Sayers & Hill [22] published some measurements of the aerodynamic forces on a spinning cricket ball. Some of the myths and misconceptions surrounding cricket ball aerodynamics were presented by Mehta [15] and an overview of cricket ball aerodynamics was given in Mehta [16]. A relatively new concept of contrast swing was introduced by Mehta [17] in 2006 and that of "Malinga" swing in 2007 [18]. A detailed and more recent review of sports ball aerodynamics, which includes cricket balls, was given in Mehta [19]. Lock *et al*. [10] presented some surface flow visualization and pressure measurements demonstrating conventional and reverse swing. Recently, Scobie *et al*. [24] proposed an alternative fluid mechanic mechanism for reverse swing. Based on their pressure measurements and surface flow visualization using thermal imaging, they proposed that reverse swing occurs due to the presence of a laminar separation bubble. It is discussed below why this mechanism is not likely to occur in practice. All the measurements shown in this article are taken from the author's own research described by Bentley *et al*. [2].

Aficionados know cricket as a game of infinite subtlety, not only in strategy and tactics, but also in its most basic mechanics. On each delivery, the ball can have a different trajectory, varied by changing the pace (speed), length, line or, most subtly of all, by swinging the ball through the air so that it drifts sideways. The actual construction of a cricket ball and the principle by which the faster bowlers swing the ball is unique to cricket. The outer cover of a cricket ball consists of four or two pieces of leather, which are stitched together. Six rows of prominent stitching along its equator make up the "primary" seam, with typically 60 to 80 stitches in each row. On the four-piece balls, used in all first class and international matches, each hemisphere also has a line of internal stitching forming the "quarter" or "secondary" seam.

Fluid Mechanics of Conventional Swing

Fast bowlers in cricket make the ball swing by a judicious use of the primary seam. The ball is released with the seam at an angle to the initial line of flight. Over a certain Reynolds number (Re) range, the seam trips the laminar boundary layer into turbulence on one side of the ball whereas that on the other (nonseam) side remains laminar (figure. 1). By virtue of its increased energy, the turbulent boundary layer separates later than the laminar layer and so a pressure differential, which results in a side force, is generated on the ball as shown in figure 1.

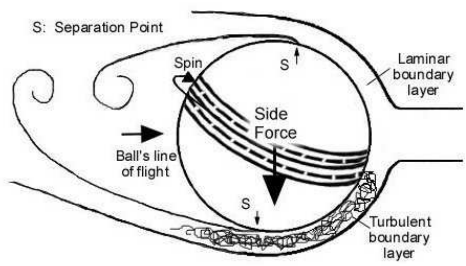

Figure 1. Schematic of flow over a cricket ball for conventional swing.

In order to show that such an asymmetric boundary layer separation can indeed occur on a cricket ball, a ball was mounted in a wind tunnel and smoke was injected into the separated region (wake) behind the ball where it was entrained right up to the separation points (figure 2). The seam has tripped the boundary layer on the lower surface into turbulence, evidenced by the chaotic nature of the smoke edge just downstream of the separation point. On the upper surface, a smooth, clean edge confirms that the separating boundary layer was in a laminar state. Note how the laminar boundary layer on the upper surface has separated relatively early compared to the turbulent layer on the lower surface. The asymmetric separation of the boundary layers is further confirmed by the upwardly deflected wake, which implies that a downward force is acting on the ball.

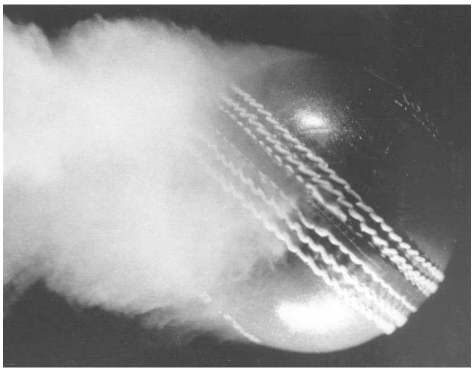

Figure 2. Smoke flow visualization of flow over a cricket ball. Flow is from right to left. Seam angle = 40°, flow speed = 17 m/s, Re = 850,000.

In order to confirm that an asymmetric boundary layer separation on a cricket ball leads to a pressure differential across it, 24 pressure taps were installed on a ball along its equator, in a plane perpendicular to that of the seam (figure 3).

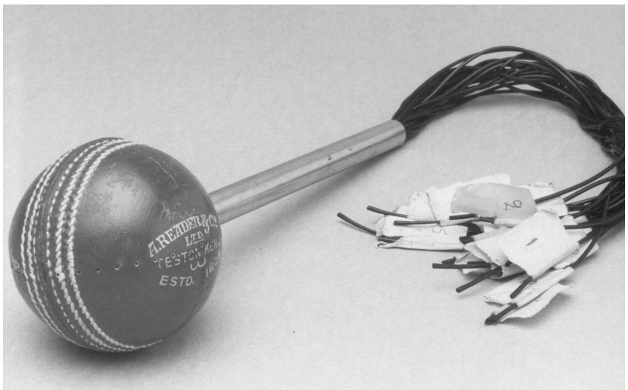

Figure 3. Cricket ball with the core removed and 24 pressure taps (1 mm diameter) installed along the equator.

Figure 4 shows the measured surface pressures on this ball mounted in a wind tunnel with the seam angled at 20° to the oncoming flow. At low values of Re or velocity (U), the pressure distributions on the two hemispheres are equal and symmetric, so there would be no side force. At U = 25 m/s, the pressure dip on the right-hand (seam-side) face of the ball is clearly lower than that on the left-hand (nonseam-side) face, which would result in the ball swinging towards the seam side. The maximum pressure difference between the two sides occurs at U = 29 m/s (65 mph), when the boundary layer on the seam side is fully turbulent while that on the nonseam side is still laminar. Even at the highest velocity achieved in this test (U = 37 m/s, 83 mph), the asymmetry in pressure distributions is still clearly exhibited, although the pressure difference is reduced. The actual (critical) velocities or Re at which the asymmetry appears or disappears were found to be a function of the seam angle, surface roughness, and free-stream turbulence; in practice it also depends on the spin rate of the ball, as shown and discussed below.

In order to measure the forces on spinning cricket balls, balls were rolled along their primary seams down a ramp and projected into a wind tunnel test section through a small opening in the ceiling [2]. The spin rate was varied by changing the starting point along the ramp, and the seam angle was varied by adjusting the alignment of the ramp with the airflow. Once the conditions at the entry to the wind tunnel and the deflection from the datum

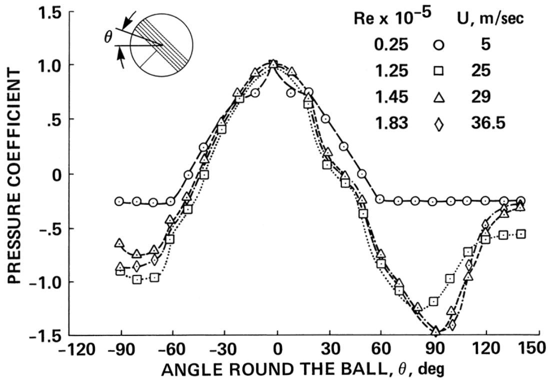

Figure 3. Pressure distributions on a cricket ball held at a seam angle of 20°.

are known, the aerodynamic forces due to the airflow can be easily evaluated. The spin rate and velocity of the ball at the end of the ramp were measured using strobe photography. Figure 4 shows the measured side force (F), normalised by the weight of the ball (mg), and plotted against the ball's velocity; the side force is averaged over five cricket balls that were tested extensively. At nominally zero seam angle (seam straight up, facing the batsman) there is no significant side force, except at high velocities when local roughness, such as an embossment mark, starts to have an effect by inducing transition on one side of the ball. However, when the seam is set at an incidence to the oncoming flow, the side force starts to increase at about U = 15 m/s (34 mph). The normalised side force increases with ball velocity, reaching a maximum of about 0.3 to 0.4 before declining rapidly. The critical velocity at which the side force starts to decrease is about 30 m/s (67 mph). This is the velocity at which the laminar boundary layer on the nonseam side also undergoes transition and becomes turbulent. As a result, the asymmetry between the two sides (difference in the locations of the boundary layer separation points) is reduced and the side force starts to decrease.

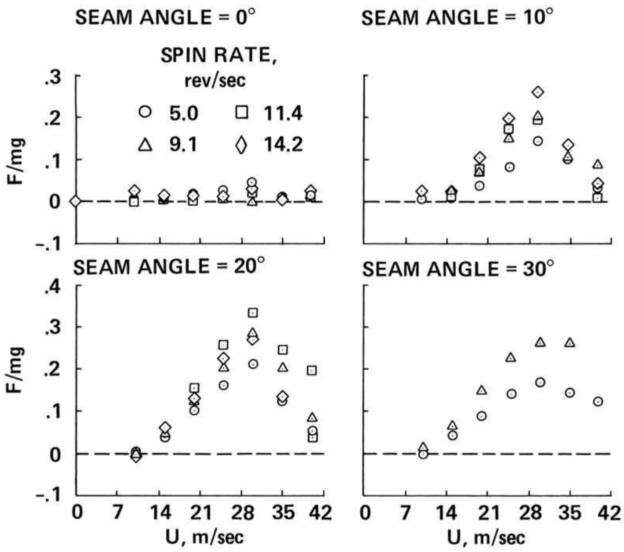

Figure 4. Variation of normalized side force with flow speed; averaged over five balls.

The maximum side force is obtained at a bowling speed of about 30 m/s (67 mph) with the seam angled at 20° and the ball spinning backwards at a rate of 11.4 revs/s. At a seam angle of 20°, the Re based on seam height is about optimal for effective tripping of the laminar boundary layer. At lower speeds, a bowler should select a larger seam angle so that by the time the flow accelerates around to the seam location, the critical speed for efficient tripping has been reached. Of course, releasing a ball spinning along the seam (without much wobble) becomes more difficult as the seam angle is increased. Spin on the ball helps to stabilize the seam orientation. Basically, for stability, the angular momentum associated with the spin should be greater than that caused by the torque about the vertical axis due to the flow asymmetry. Too much spin is also detrimental, since the effect of the ball's surface roughness is increased and the critical Re is achieved sooner on the nonseam side. In order to maximize the amount of conventional swing, the ball surface on the nonseam side should be kept as smooth as possible so that a laminar boundary layer can be maintained.

The actual trajectory of a cricket ball can be computed using the measured forces. Figure 5 shows the computed trajectories at five bowling speeds for the ball exhibiting the best swing properties ($F/mg = 0.4$ at $U = 32$ m/s, seam angle = 20°, spin rate = 14 revs/s). The results illustrate that the flight path is almost independent of speed in the range $24 < U < 32$ m/s ($54 < U < 72$ mph). The trajectories were computed using a simple relation, which assumes that the side force is constant and acts perpendicular to the initial trajectory. This gives a lateral deflection that is proportional to the square of the elapsed time (t^2) and hence a parabolic flight path. In some photographic studies of a swing bowler (Gary Gilmour, who played for Australia in the 1970s), it was confirmed that the trajectories were indeed parabolic [8]. Those studies also confirmed that the final deflections of over 0.8 m predicted here are not unreasonable. One of the photographed sequences was analysed and the actual flight path is also plotted in figure 5. The agreement is rather remarkable considering the simplicity of the image processing and analytical techniques. The data in figure 5 also have a bearing on the phenomenon of the so-called "late swing." There are many theories for late swing, but it turns out that since the flight paths are parabolic, late swing is in fact "built-in," whereby 75% of the lateral deflection occurs over the second half of the flight.

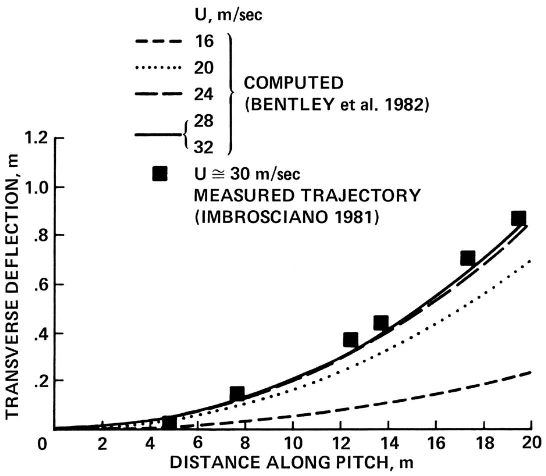

Figure 5. Comparison of computed flight paths using measured forces for the cricket ball with the best swing properties. Seam angle = 20°, spin rate = 14 revs/s.

Fluid Mechanics of Reverse Swing

Since the mid-1980s, there has been a lot of talk in the cricketing world of a supposedly new bowling concept employed by swing bowlers. The new concept or phenomenon is popularly known as "reverse swing" since the ball swings in a direction opposite (or reversed) to that expected based on conventional cricketing wisdom and previously accepted fluid mechanics principles. As discussed above, for conventional swing it is essential to have a smooth polished surface on the nonseam side facing the batsman so that a laminar boundary layer is maintained. At the critical Re, the laminar boundary layer on the nonseam side undergoes transition and the flow asymmetry, and hence side force, starts to decrease. A further increase in Re results in the transition and separation points moving upstream, towards the front of the ball. A zero side force is obtained when the flow fields (boundary layer separation locations) on the two sides of the ball become completely symmetric. In terms of reverse swing, the really interesting flow events start to occur when the Re is increased beyond that for zero side force. As mentioned above, the transition point will continue to move upstream (on both sides now) setting up the flow field shown in figure 6. The transition points on the two sides are symmetrically located, but the turbulent boundary layer on the seam side still has to encounter the seam. In this case, the seam has a "detrimental" effect whereby the boundary layer is thickened and weakened (lower skin friction coefficient), making it more susceptible to separation compared to the thinner turbulent boundary layer on the nonseam side. The turbulent boundary layer on the seam side separates relatively early and an asymmetric flow is set up once again, only now the orientation of the asymmetry is reversed such that the side force, and hence swing, occurs towards the nonseam side, as shown in figure 6; *this is reverse swing*.

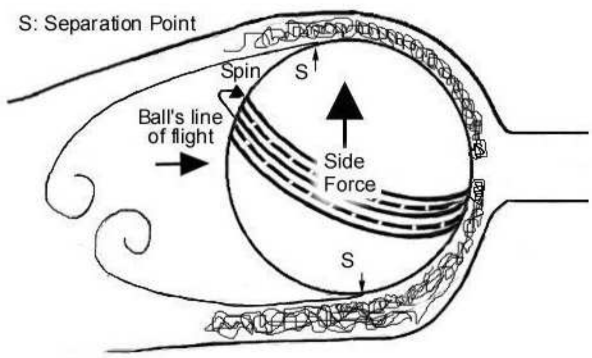

Figure 6. Schematic of flow over a cricket ball for reverse swing.

Needless to say, boundary layer transition is strongly dependent on the condition (roughness) of the ball's surface. This is demonstrated in the side force results for three cricket balls with contrasting surface conditions (figure 7). The new two-piece ball (without the quarter seams) exhibits a higher maximum (positive) side force than the other two balls and the side force does not start to decrease until $U = 36$ m/s (80 mph). This ball will only produce reverse swing for velocities above 45 m/s (100 mph), which is not very useful in practice, although it is worth noting that two-piece cricket balls are generally *not* used in competitive cricket matches. However, the side force measurements for a new four-piece ball (with quarter seams) show that it achieves significant negative side force or reverse swing at velocities above about 36 m/s (80 mph). Note how the magnitude of the negative side force at 40 m/s is not much less than the positive force at 30 m/s. So it seems as though reverse swing can be obtained at realistic, albeit relatively high, bowling velocities. In particular, reverse swing can be clearly obtained *even on a new ball, without any tampering of the surface.*

The "old" ball, with an estimated use of about 100 overs, gives less positive side force compared to the new balls, but it also produces reverse swing at a lower velocity of about 30 m/s (67 mph). The contrasting results for the three balls are directly attributable to the effects of surface roughness on the critical Re.

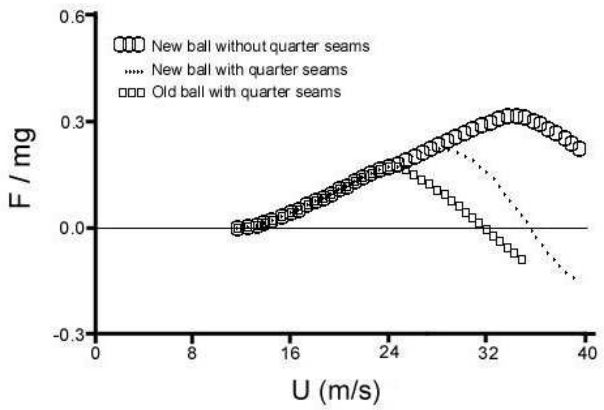

Figure 7. Normalized side force versus ball speed showing reverse swing.

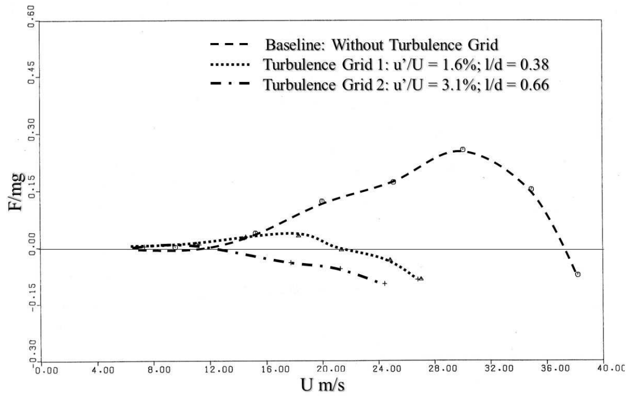

Figure 8. Effects of free-stream turbulence on cricket ball swing. New 4-piece ball, seam angle = 20°, spin rate = 5 revs/s.

Due to the absence of the quarter seams, the new two-piece ball has a smoother surface compared to the new four-piece ball and the critical Re at which transition occurs on the nonseam side is therefore higher. Conversely, the critical Re on the used ball is lower because of the rougher surface. The key to reverse swing is early transition of the boundary layers on the ball's surface and the exact velocity beyond which reverse swing is obtained in practice will decrease with increasing roughness.

Recently, another fluid mechanic mechanism was proposed for reverse swing by Scobie *et al.* [24]. Using a scaled model of a cricket ball, they show using surface pressures and a thermal imaging technique, a separation bubble with laminar separation, transition in the free shear layer and then turbulent reattachment on the nonseam side. As a result, the (turbulent) separation on this side is delayed compared to the seam side and hence the asymmetry required for reverse swing is established. The presence of a separation bubble is well known and understood on a smooth sphere. It typically appears only at the critical Re (point of minimum drag coefficient). It is highly unlikely that this phenomenon would occur on an actual cricket ball (with quarter seams) which is also spinning. The additional roughness from the spinning quarter seam and the fact that transition on a spinning ball occurs in stages (first on the advancing part of the ball that has a higher effective Re) are the main reasons for this conclusion. In fact, to prove that it is indeed early boundary layer transition on the nonseam side that is responsible for reverse swing, Bentley *et al.* [2] introduced free-stream turbulence into the test section using two turbulence generating grids. The two grids (1 and 2) generated turbulence intensity levels of u'/U = 1.6% and 3.1% and length scales (l) equivalent to 0.38 and 0.66 of the ball diameter (d), respectively. Without the addition of the turbulence, reverse swing was only obtained above a flow speed of about 36 m/s (80 mph), as shown in figure 8. However, with the grids, reverse swing was obtained at about 20 m/s (45 mph) for Grid 1, and for Grid 2, reverse swing was obtained right from the start at about 12 m/s (27 mph), without any sign of conventional swing. It is important to note that apart from the increased turbulence levels, a critical parameter is the length scale. Since the length scales here are relatively small (less than the ball diameter), early transition of the laminar boundary layer on the nonseam side is successfully achieved.

Effect of Ball Condition and Contrast Swing

For conventional swing, a prominent primary seam obviously helps the transition process, whereas a smooth polished surface on the nonseam side helps to maintain a laminar boundary layer. So it is wise to polish the new ball right from the start, *but not on both sides*. At the outset, the opening bowler should pick the side on the ball with the smaller or lighter (less rough) embossment and continue to polish only that side during the course of the innings. The other (seam) side of the ball should be allowed to roughen during the course of play to aid the production of reverse swing. As shown above, the exact velocity at which reverse swing occurs, and how much negative side force is generated at a given speed above the critical, is a strong function of the ball's surface roughness. Once the seam side has roughened enough, reverse swing is simply obtained by *turning the ball over* so that the rough side faces the batsman. In general, the production of conventional and reverse swing will not be affected significantly by having a contrasting surface condition on the side facing away from the batsman. So a bowler bowling outswingers will still have the seam pointed towards the slips, but with the rough side facing the batsman, instead of the smooth for conventional swing, and the ball will now behave like an inswinger and swing into the batsman. The whole beauty (and success) of this phenomenon is that a bowler who could only bowl outswingers at the onset (with the new ball) can now bowl inswingers *without any change in the grip or bowling action*. Similarly, a predominantly inswing bowler can now bowl outswingers. Of course, if the contrast in surface roughness on the two sides of a ball is successfully created and maintained, the bowler becomes even more lethal since he can now bowl outswingers and inswingers at will by simply changing the ball orientation. Needless to say, this would make for a highly successful ability since there are not many bowlers who can make the new ball swing both ways using conventional bowling techniques. Moreover, the few that can bowl inswingers and outswingers are generally not equally effective with both types of swing and, of course, cannot do it with the same grip and bowling action. So the key to conventional swing bowling is keeping the nonseam side as smooth as possible, whereas for reverse swing the nonseam side needs to be as rough as possible.

One of the reasons why reverse swing has gained such notoriety is its constant link to accusations of ball tampering [19]. The fact that bowlers started to illegally roughen the ball surface since the early 1980s is now well documented. Oslear & Bannister [20] quote and show several examples and I have also personally examined several balls that were confiscated by umpires due to suspicions of ball tampering. The most popular forms of tampering consisted of gouging the surface and attempting to open up the quarter seam by using either fingernails or foreign objects such as bottle tops. It is rather ironic that a law prohibiting the rubbing of the ball on the ground was introduced in the same year (1980) that I first heard about reverse swing from an old school mate of mine, Imran Khan.

There is another distinct advantage in maintaining a sharp contrast in surface roughness on the two sides or hemispheres of the ball. The primary seam plays a crucial role in both types of swing. It trips the laminar boundary layer into a turbulent state for conventional swing and thickens and weakens the turbulent boundary layer for reverse swing. During the course of play, the primary seam becomes worn and less pronounced and not much can be done about it unless illegal procedures are invoked to restore it, as discussed above. However, a ball with a worn seam can still be swung, as long as a sharp contrast in surface roughness exists between the two sides. In this case, the difference in roughness, rather than the seam, can be used to produce the asymmetric flow. The seam is oriented facing the batsman (straight down the pitch) at zero degrees incidence. The critical Re is lower for the rough side and so, in a certain Re range, the boundary layer on the rough side will become turbulent, while that on the smooth side remains laminar. The laminar boundary layer separates early compared to the turbulent boundary layer, in the same way as for conventional swing, and an asymmetric flow, and hence side force, is produced. The ball in this case will swing towards the rough side (figure 9a). At higher speeds, the boundary layers on both sides are turbulent (figure 9b). However, the layer on the rough side will undergo transition earlier and then develop over the rough surface, thus enhancing boundary layer growth (thickness) and hence reduction in the skin friction coefficient. An asymmetry is developed once again, only this time, the ball will swing towards the smooth side. Note that the 70 mph quoted in figures 9a and 9b is estimated as a nominal "switch over" speed for an old ball when the ball switches from swing towards the rough side to the smooth side. The actual speed, at which the ball swing direction switches, is totally dependent on the condition of the ball surface (on both sides).

This type of swing, which tends to occur when the ball is older and a contrast in surface roughness has been established, is often erroneously referred to as reverse swing. In order to avoid this confusion and distinguish this type of swing from conventional and reverse swing, I gave it the name, "*contrast swing*" [17].

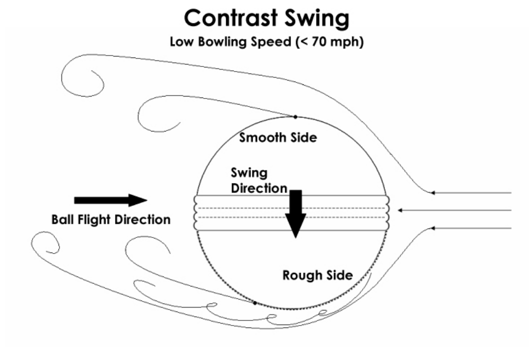

Figure 9a. Schematic for flow over a ball for contrast swing at relatively low bowling speeds.

The most exciting feature about contrast swing is that just about any bowler can implement it in practice. As most cricketers are aware, it is much easier to release the ball (spinning backwards along the seam) with the seam straight up, rather than angled towards the slips or fine leg. Thus, even mere mortals should be able to swing such a ball, and in either direction, since the bowling action is the same for both types of swing, the only difference being the orientation of the ball with regards to the rough and smooth sides. In fact, the medium pace "seam" or "stock" bowlers usually bowl with the seam in this orientation in an attempt to make the ball bounce on its seam so that it may gain sideways movement off the ground. With a contrast in surface roughness, these bowlers could suddenly turn into effective swing bowlers, without any additional effort.

Commentators and players often state that when the ball is reversing, it swings towards the smooth side. They are simply

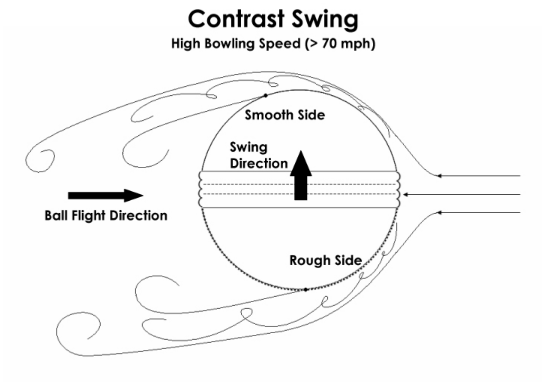

Figure 9b. Schematic for flow over a ball for contrast swing at relatively high bowling speeds.

confusing true reverse swing with contrast swing. More often than not, when the ball swings towards the smooth side, it does so in the contrast swing mode.

Magnus Effect on a Spinning Ball: "Malinga" Swing

When a cricket ball is spun about an axis perpendicular to the line of flight, an asymmetry in the boundary layer separation locations is set up which results in the "Magnus" force. This effect is seen in many sports such as soccer, tennis and baseball, to name a few. As discussed above, the boundary layer cannot negotiate the adverse pressure gradient on the back part of the ball and therefore it tends to separate, somewhere in the vicinity of the ball apex. The exact separation location is determined by the state of the boundary layer. With a spinning ball (figure 10), the extra momentum applied to the boundary layer on the retreating (bottom) side of the ball allows it to negotiate a higher pressure rise before separating and so the separation point moves downstream. The addition of momentum to the boundary layer occurs through viscous diffusion from the rotating surface. The reverse occurs on the advancing (top) side and so the separation point moves upstream, thus generating an asymmetric separation. The upward deflected wake implies a downward Magnus force on this ball.

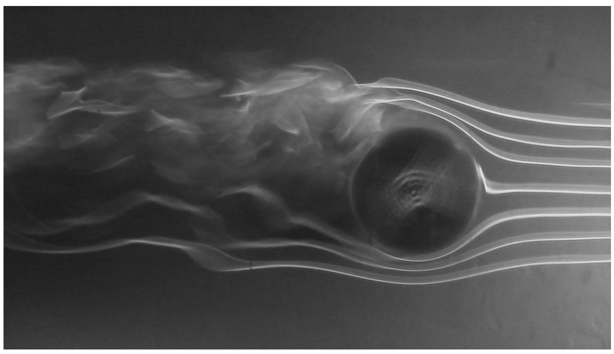

Figure 10. Dye flow visualization over a spinning cricket ball in a water channel. Flow is from right to left and the ball is rotating in a clockwise direction.

In cricket, the slower spin bowlers typically attempt to make the ball "turn" when it comes into contact with the ground. They often vary their pace and amount of spin in order to try and confuse the batsman. However, they also employ the Magnus effect at times by imparting spin about a near vertical axis so that the ball swings sideways through the air before getting additional movement off the ground, as shown in figure 11 and described in Mehta & Wood [12]. With the majority of fast bowlers, the ball

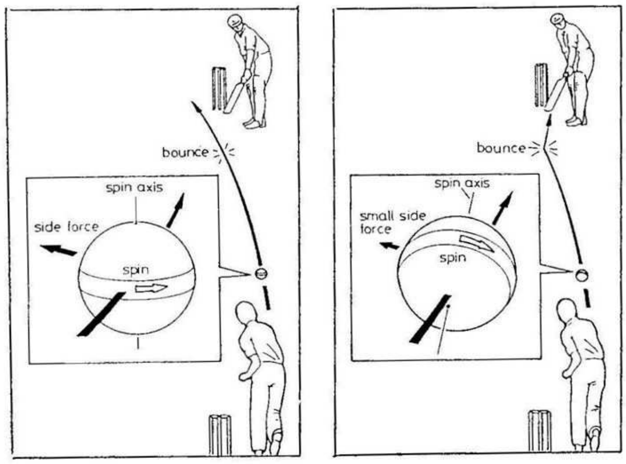

Figure 11. Spin bowlers using the Magnus effect to make the ball swing.

is released with backspin about a near horizontal axis so that there is an upward Magnus force, as shown in the left-hand diagram in figure 12. This opposes the gravitational force experienced by the ball.

However, if the ball is released with the axis of spin inclined (as shown in the right-hand diagram in figure 12), the Magnus force vector is now tilted and there is a lateral component that will make the ball swing sideways. This type of swing is generated by side-arm bowlers such as Lasith Malinga of Sri Lanka.

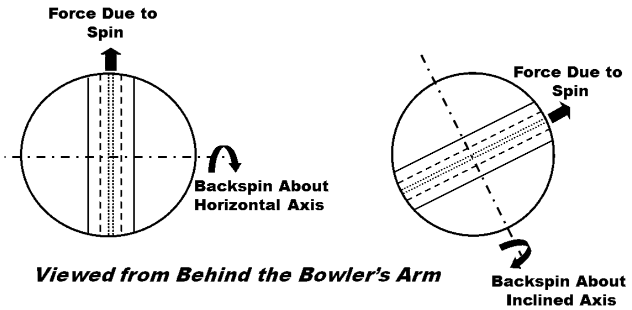

Figure 12. Schematic for spin-induced “Malinga” swing.

I first noticed it in action during the 2007 Cricket World Cup Final and the effect, in terms of the fluid mechanics, was discussed in Mehta [18]. In Malinga’s case, with the side-arm action, the ball swings into the right-hand batsman solely due to the axis of spin. This type of delivery is very effective and it works even when the ball is old with no contrast in surface roughness and a completely “bashed-in” seam. A ball often achieves this state on the Indian sub-continent, where the pitches and the outfield are hard and rough. Once the ball attains this type of condition, the only way for a fast bowler to swing the ball is through “Malinga” swing.

“Knuckling Effect” in Cricket

In baseball, a “knuckleball” is released at relatively low speed (about 30 m/s or 65 mph) and zero or very little spin; the aerodynamics of this pitch are left entirely to random effects of the flow over the ball. It was initially believed that a knuckleball thrown without any spin will be at the mercy of any passing breeze. Thus, the ball “dances” through the air in an unpredictable fashion. However, the real reason for the dance of a knuckleball is the effect of the seam on boundary layer transition and separation. Depending on the ball velocity and seam orientation, the seam can induce boundary layer transition or separation over a part of the ball thus creating a side force. With a baseball rotating very slowly during flight, not only does the magnitude of the force change, but the direction can also change [26]. This is why the ball appears to have a random and erratic flight path. It is important to note that even if the pitcher throws the ball with no rotation, the flow asymmetry will cause the ball to rotate. The flow asymmetry is developed by the unique stitch pattern on a baseball. In figure 13, the ball is not spinning, but it is oriented so that the two seams help in causing transition in the boundary layer on the upper side of the baseball. The boundary layer on the lower surface is seen to separate relatively early in a laminar state. Once again, the downward deflection of the wake confirms the presence of the asymmetric boundary layer separation, which would produce an upwards lift force on this baseball.

Although the seam on a cricket ball is quite different to that on a baseball, similar fluid mechanic effects can be obtained by a slowly rotating seam. Lately in cricket, the slower spin bowlers have added this type of delivery to their arsenal. It is not hard to believe that the spin bowlers, even with the round arm bowling action, can grip the ball with the tips of their fingers and eject it with very little spin imparted to the ball. However, very recently I noticed that even the fast bowlers are now able to achieve this feat. In particular, Zaheer Khan, the Indian fast bowler has a slower delivery (at about 31 m/s or 70 mph) that he very effectively releases with minimal spin imparted to the ball. With the fast bowlers, there is an additional advantage. Since the upwards Magnus force has now been excluded (no backspin on the ball), the ball will tend to drop somewhat faster, thus adding to the batsman’s confusion.

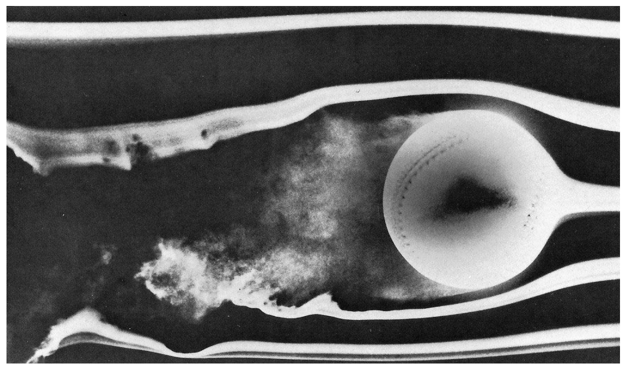

Figure 13. Smoke photograph of flow over a stationary (nonspinning) baseball. Flow is from right to left. Photograph by F.N.M. Brown, University of Notre Dame.

Effects of Weather Conditions on Swing

The effect of weather on swing is by far the most discussed and most controversial topic in cricket, both on and off the field. It is quite fascinating that this topic was discussed in the very first scientific paper on cricket ball swing [5]. The one bit of advice that cricket "Gurus" have consistently passed down over the years is that an overcast or humid/damp day is conducive to swing bowling. However, the correlation between weather conditions and swing has not always been obvious and most of the scientific explanations put forward have also been questionable. Of course, on a day when the ground is soft with green wet grass, the new ball will retain its shine for a longer time, thus helping to maintain a laminar boundary layer on the non-seam side. However, the real question is whether a given ball will swing *more* on an overcast or humid/damp day.

As shown in the previous sections, the flow regime over a cricket ball depends only on the properties of the air and the ball itself. The only properties of the air that may conceivably be influenced by a change in weather conditions are the dynamic viscosity and density. The dynamic viscosity and density both appear in the definition of Re, but small changes in Re are unlikely to affect the side force significantly. However, changes in air density can affect the side force directly since, for a given side force coefficient, the side force is proportional to the density. The air density is higher on a cold day compared to that on a hot day. However, the dependence is not very strong with the air density being only about 4% higher at 15° C compared to that at 25° C. This means that a ball which swings about 60 cm (2 feet) at 25° C will deviate about another 2.5 cm (1 inch) at 15° C. This is obviously not enough to explain what is supposedly observed on a cricket ground, although it does illustrate why it is easier to hit a six on a hot day compared to a cold night (the drag on the ball, which slows it down, is also proportional to the air density). It is rather ironic that humid or damp air is often referred to as constituting a "heavy" atmosphere by cricket commentators, when, in fact, humid air is less dense than dry air.

A popular theory that had circulated for years, especially amongst the scientific community, was that the primary seam swells by absorbing moisture, thus making it a more efficient boundary layer trip. Bentley *et al.* [2] investigated this possibility in detail. Profiles were measured across the primary seam on a new ball before and after a few minutes soaking in water. Even in this extreme example, there was no sign of any change in the seam dimensions (figure 14).

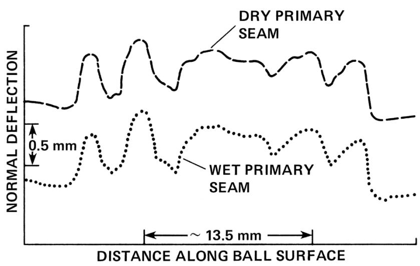

Figure 14. Surface contour plots of the primary seam on a cricket ball to investigate the effects of humidity.

A similar test on a used ball (where the varnish on the seam had worn-off) also showed no swelling of the seam. Rather than soaking the ball in water, a more controlled test was also conducted whereby a ball was left in a humidity chamber (relative humidity of 75%) for 48 hours. Again, no change in the seam dimensions were observed. Recently, James *et al.* [9] used a 3-D laser scanner to measure the surface properties of differently conditioned balls under varying humidity. They also found that humidity had no detectable effect on the ball's geometry.

Bentley *et al.* [2] also performed projection tests on balls with the surface dry, humid and wet and no increase in side force was noted for the humid or wet balls, as shown in figure 15.

Several investigators [1,7,25,27] have confirmed that no change was observed in the pressures or forces when the relative humidity of the air changed by up to 40%. In the past it was suggested that humid days are perhaps associated with general calmness in the air and thus less atmospheric turbulence [25,27]. More recently, James *et al.* [9] proposed a similar hypothesis. They suggest that with bright sunshine, the ground heats up and generates convection currents which make "the air rise off the cricket pitch – that creates turbulence." They go on to theorize that since this effect is absent on an overcast day, a bowler is able to produce more swing. On the other hand, Lyttleton [11] and Horlock [7] conjectured that humid conditions might result in increased atmospheric turbulence. However, there is no real evidence or basis for either of these scenarios, and even if it were the case, the turbulence scales (size of the turbulent eddies) would generally be too large to have any significant effect on the flow regime over the ball. Binnie [3] suggested that the observed

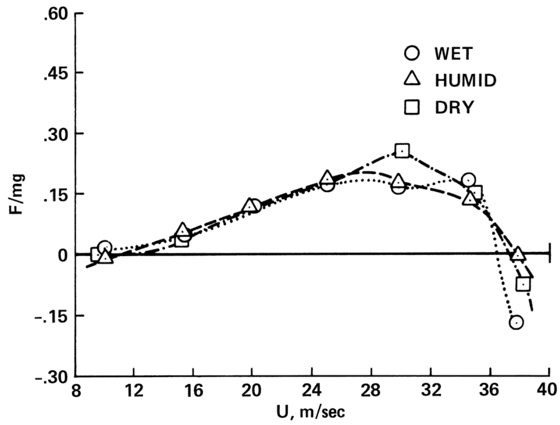

Figure 15. Effect of humidity on the measured side forces on a spinning cricket ball. Seam angle = 20°, spin rate = 5 revs/s.

increase in swing under conditions of high humidity is caused by "condensation shock" which helps to cause transition. However, his calculations showed that this effect could only occur when the relative humidity was nearly 100%. Also, as shown by Bentley et al. [2], the primary seam on almost all new cricket balls is already adequate in tripping the boundary layer in the Reynolds number range of interest.

So there seems to be no (positive) scientific evidence which supports the view that overcast or humid conditions are more conducive to swing. One explanation, which was first proposed by Bentley et al. [2], is that humidity must affect the initial flight conditions of the ball. There is a possibility that the amount of spin imparted to the ball may be affected. The varnish painted on all new balls reacts with moisture to produce a somewhat tacky surface. The tacky surface would ensure a better grip and thus result in more spin as the ball rolls-off the fingers. As shown above in figure 4, an increase in spin rate (at least up to about 11 revs/s) certainly increases the side force. So, perhaps without actually realising it, the bowler may just be imparting more spin on a humid or damp day. This effect has not been investigated independently, and upon further reflection, it may perhaps be somewhat far-fetched. There is one other possibility. Could it be a "placebo" effect? Is it possible that on a day which is supposedly conducive to swing bowling, the bowlers concentrate more on the optimum release for swing (seam angled and the ball spinning steadily along the seam without wobble) rather than trying to bowl too fast or trying to extract that "extra" bounce?

Conclusions

The basic flow physics of conventional swing and the parameters that affect it are now well established and understood. However, some confusion still remains over what reverse swing is, and how it can be achieved on a cricket field. A popular misconception, and one that exists even today, is that when an old ball swings, it must be reverse swing. It is only reverse swing if the ball swings in a direction that is opposed to the one the seam is pointing in so that, for example, a ball released with the seam pointed towards the slip fielders swings *into* the batsman. While it is generally believed (with some justification) that tampering with the ball's surface helps in achieving reverse swing, the exact form of the advantage is still not generally understood. It is shown here that the critical bowling speed at which reverse swing can be achieved is lowered as the ball's surface roughness increases. One of the more important points to note is that ball tampering is not essential in order to achieve reverse swing. Reverse swing can be obtained with a brand new (red) four-piece ball, but only at bowling speeds of more than 36 m/s (80 mph). The whole beauty of reverse swing is that by simply changing the ball orientation, and nothing else, the ball will swing the "wrong" way. With a sharp contrast in surface roughness between the two sides of a cricket ball, contrast swing can be obtained with the seam oriented vertically and pointed straight down the pitch. The main advantage of contrast swing is that it can even be generated with a ball that has the seam completely "bashed in."

It is shown here how late swing is actually built into the flight path of a swinging cricket ball and it is this, rather than some special phenomenon, that is often observed on the cricket field. The question of the effects of weather conditions on cricket ball swing is still not totally resolved, although the balance of evidence seems to suggest that perhaps bowlers pay more attention to the bowling action and ball release when the weather conditions are supposedly conducive to swing. From personal interactions and discussions, I have to come to realize that even professional players and coaches are not all totally convinced that the weather conditions alone can affect cricket ball swing.

Two novel ways of generating ball movement are presented in this paper. With a side arm action, a bowler can generate spin induced "Malinga" swing. This can be achieved even with an old ball with no surface contrast and the seam completely flattened. Recently, both spin bowlers and fast bowlers have started using the "knuckling" effect. As in baseball, the ball is released with zero or very little spin and the movement is produced by asymmetric boundary layer behavior that is generated by the seam. This can result in an unpredictable and erratic flight of the cricket ball and it is proving to be an extremely effective delivery in modern day cricket.

References

[1] Barton, N.G., On the swing of a cricket ball in flight. *Proceedings of the Royal Society London. A,* **379**, 1982, 109-131.

[2] Bentley, K., Varty, P., Proudlove, M. & Mehta, R.D., An experimental study of cricket ball swing. *Imperial College Aero Technical Note 82-106*, 1982.

[3] Binnie, A.M., The effect of humidity on the swing of cricket balls. *International Journal of Mechanical Sciences,* **18**, 1976, 497-9.

[4] Bown, W. & Mehta, R.D., The seamy side of swing bowling. *New Scientist*, **139**, No. 1887, 1993, 21-24.

[5] Cooke, J.C., The boundary layer and seam bowling. *The Mathematical Gazette*, **39**, 1955, 196-199.

[6] Grant, C., Anderson, A. & Anderson, J.M., Cricket ball swing – the Cooke-Lyttleton theory revisited. In: *The Engineering of Sport – Design and Development*. (Haake, S.J., ed.). Blackwell Publishing, Oxford, UK, 1998, 371-378.

[7] Horlock, J.H., The swing of a cricket ball. *ASME Symposium on the Mechanics of Sport*, 1973.

[8] Imbrosciano, A., The swing of a cricket ball. *Project Report*, Newcastle College of Advanced Education, Newcastle, Australia, 1981.

[9] James, D., Macdonald, D.C. & Hart J., The effect of atmospheric conditions on the swing of a cricket ball, *Procedia Engineering,* **34**, 2012, 188–193.

[10] Lock G.D., Edwards S. & Almond D.P. Flow visualization experiments demonstrating the reverse swing of a cricket ball. *Proc IMechE, Part P: J Sports Engineering and Technology,* **224**, 2010, 191–199.

[11] Lyttleton, R.A., The swing of a cricket ball. *Discovery*, **18**, 1957, 186-191.

[12] Mehta, R.D. & Wood, D.H., Aerodynamics of the cricket ball. *New Scientist*, **87**, No. 1213, 1980, 442-447.

[13] Mehta, R.D., Bentley, K., Proudlove, M. & Varty, P., Factors affecting cricket ball swing. *Nature*, **303**, 1983, 787-88.

[14] Mehta, R.D., Aerodynamics of sports balls. *Annual Review of Fluid Mechanics*, **17**, 1985, 151-189.

[15] Mehta, R.D., Cricket ball aerodynamics: myth versus science. In: *The Engineering of Sport. Research, Development and Innovation.* (Subic, A.J. and Haake, S.J., eds.) Blackwell Science, London, 2000, 153-167.

[16] Mehta, R.D., An overview of cricket ball swing," *Sports Engineering,* **8**, No.4, 2005, 181-192.

[17] Mehta, R.D., Swinging it three ways. *The Wisden Cricketer,* **3**, No. 7, 2006, 50-53.

[18] Mehta, R.D. Malinga's unique swing, *The Wisden Cricketer,* **4**, No. 10, 2007, 23.

[19] Mehta, R.D. Sports Ball Aerodynamics, in *Sport Aerodynamics*, (Norstrud, H., ed.) SpringerWienNewYork, 2008, 229-331.

[20] Oslear, D. & Bannister, J., *Tampering with Cricket*, Collins Willow (Harper Collins) Publishers, London, UK, 1996.

[21] Penrose, J.M.T., Hose, D.R. & Trowbridge, E.A., Cricket ball swing: a preliminary analysis using computational fluid dynamics. In: *The Engineering of Sport.* (Haake, S.J., ed.) A.A. Balkema, Rotterdam, Holland, 1996, pp. 11-19.

[22] Sayers, A.T. & Hill, A., Aerodynamics of a cricket ball. *Journal of Wind Engineering and Industrial Aerodynamics,* **79,** 199, 169-182.

[23] Sayers, A.T. & Hill, A., Aerodynamics of a cricket ball. *Journal of Wind Engineering and Industrial Aerodynamics,* **79,** 199, 169-182.

[24] Scobie, J.A., Pickering, S.G., Almond, D.P. & Lock, G.D., Fluid Dynamics of Cricket Ball Swing, *Proceedings of the Institution of Mechanical Engineers Part P Journal of Sports Engineering and Technology,* 227(3), 2013,196-208.

[25] Sherwin, K. & Sproston, J.L., Aerodynamics of a cricket ball. *International Journal of Mechanical Engineering Education*, **10**, 1982, 71-79.

[26] Watts, R.G. & Sawyer, E., Aerodynamics of a knuckleball. *American Journal of Physics*, **43**, 1975, 960-963.

[27] Wilkins, B., *The Bowler's Art*. A&C Black Publishers Ltd., London, UK 1991.