Cricket Ball Aerodynamics: Myth Versus Science

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ABSTRACT: Aerodynamics plays a prominent role in the flight of a cricket ball released by a bowler. The main interest is in the fact that the ball can follow a curved flight path that is not always under the control of the bowler. The basic aerodynamic principles responsible for the nonlinear flight or "swing" of a cricket ball were identified several years ago and many papers have been published on the subject. In the last 20 years or so, several experimental investigations have been conducted on cricket ball swing, which revealed the amount of attainable swing, and the parameters that affect it. A general overview of these findings is presented with emphasis on the concept of late swing and the effects of meteorological conditions on swing. In addition, the relatively new concept of "reverse" swing, how it can be achieved in practice and the role in it of ball "tampering", are discussed in detail. A discussion of the "white" cricket ball used in last year's World Cup, which supposedly possesses different swing properties compared to a conventional red ball, is also presented.

INTRODUCTION

The origins of cricket are obscured and a source of much speculation, but there is some evidence that it was played in England in the1300s. People who do not play cricket (the majority of the human race) know it as a game of childish simplicity. A pleasant game for the beach it seems, but hardly enough to hold the attention of entire nations for days at a stretch. 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, the length, the line or, most subtly of all, by moving or "swinging" the ball through the air so that it drifts sideways. Such movement has always fascinated cricket fans, but seldom do they understand the underlying mechanisms that cause the cricket ball to swing. In fact, more often than not, they have to rely on myth and folklore readily and eagerly spread by the media, rather than the basic principles of science. The physics or aerodynamics of sportsballs has intrigued scientists for years, probably since the evolution of mankind and its invention of ball games.

It was in fact the curved flight of tennis balls that first inspired scientists to comment on the subject (Newton 1672). While this type of "spin-swing" occurs in cricket, there is another type of swing that is perhaps more intriguing. The actual construction of a cricket ball and the principle by which the faster bowlers swing the ball is unique to cricket. A cricket ball has six rows of prominent stitching along its equator, with typically 60-80 stitches in each row, which makes up the "primary" seam. The better quality cricket balls used in competitive cricket are in fact made out of four pieces of leather, so that each hemisphere has a line of internal stitching forming the "quarter" or "secondary" seam. The two quarter seams are traditionally set at right angles to each other. These primary and quarter seams play a critical role in the aerodynamics of a swinging cricket ball. It is said that this type of swing originated around the turn of the century, but there is evidence that it was in existence well before that. Dr. W.G. Grace, often acknowledged as the "father" of modern day cricket, and who played in the late 19th century was apparently an exponent of swing bowling. Bowlers from that era had realised that a perfectly new ball favoured the "peculiar flight", so there is not much doubt that it was this type of swing (and not spin-swing) that the bowlers were referring to.

The first published scientific account of cricket ball swing is that due to Cooke (1955), 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 (Lyttleton 1957, Horlock 1973, Mehta and Wood 1980). More recently, Barton (1982), Bentley et al. (1982) and Mehta et al. (1983) described detailed experimental investigations where the magnitude of the side force that produces the swing and the factors that affect it were determined (see Mehta 1985 for a review). The relatively new concept of "reverse swing", which became popular in the late 1980s and 1990s, was discussed by Bown and Mehta (1993).

ARODYNAMICS 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 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 (Fig. 1). [The Reynolds number is defined as, Re = Ud/v, where U is the ball velocity, d is its diameter, and v is the air kinematic viscosity.] By virtue of its increased energy, the turbulent boundary layer, separates later (further back along the ball surface) compared to the laminar layer and so a pressure differential, which

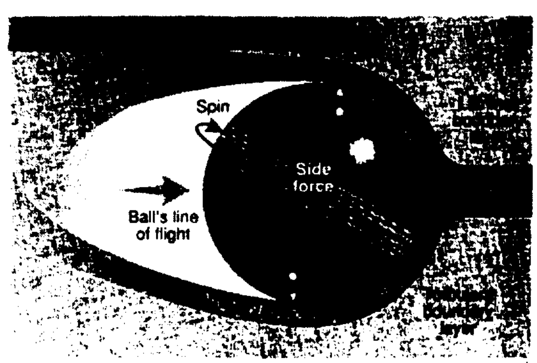

Fig. 1 Flow over a cricket ball for conventional swing.

Fig. 2 Smoke photograph of flow over a cricket ball. Flow is from left to right. Seam angle = 40°, U = 17 m/s (38 mph).

results in a side force, is generated on the ball as shown in Fig. 1. 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 behind the ball, where it was entrained right up to the separation points (Fig. 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 upward deflected wake, which implies that a downward force is acting on the ball.

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 shows the measured pressures on the ball mounted in a wind tunnel with the seam angled at 20° to the oncoming flow. The data shown on the right-hand side in Fig. 3 represent the measurements on the seam side of the ball. At low values of Re or 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 face. This 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), the asymmetry in pressure distributions is still clearly exhibited, although the pressure difference is reduced. The actual (critical) velocities or Reynolds numbers 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.

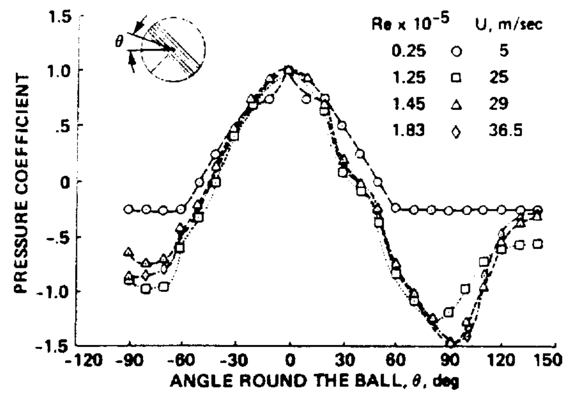

Fig. 3 Pressure distributions on a cricket ball held at a seam angle of 20°.

When a cricket ball is bowled, with a round arm action as the laws insist, there will always be some backspin imparted to it. In simple terms, the ball rolls-off the fingers as it is released. In scientific terms, the spin is necessarily imparted to conserve angular momentum. The ball is usually held along the seam so that the backspin is also imparted along the seam (the ball spins about an axis perpendicular to the seam plane). At least this is what should be attempted, since a "wobbling" seam will not be very efficient at producing the necessary asymmetric orientation, and hence separation. This type of release is obviously not very easy to master and it is the main reason why not every bowler can swing even a brand new cricket ball effectively.

In order to measure the forces on spinning cricket balls, balls were rolled along their seam down a ramp and projected into a wind tunnel through a small opening in the ceiling. 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 are known, the 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, normalized by the weight of the ball, plotted versus the ball's velocity; the side force is averaged over five cricket balls that were tested extensively. At nominally zero seam angle 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 side force increases with ball velocity, reaching a maximum of about 0.3 before falling-off rapidly. The critical velocity at which the side force starts to decrease is about 30 m/s. This is the velocity at which the laminar boundary layer on the nonseam side undergoes transition and becomes turbulent. As a result, the asymmetry between the boundary layer separation points is reduced and the side force starts to decrease. The maximum side force is obtained at a bowling speed of about 30 m/s (67 mph) with the seam angled at 20°

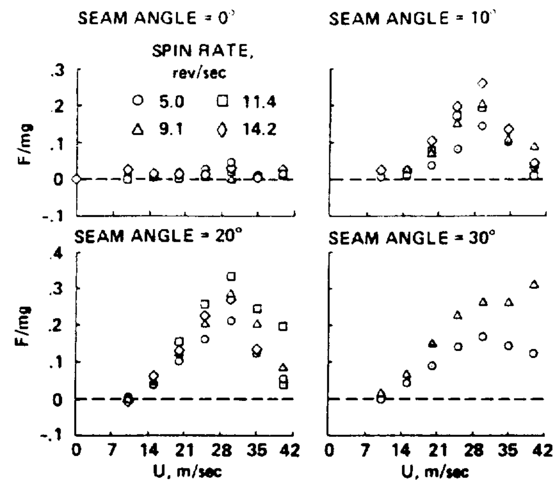

Fig. 4 Variation with flowspeed of the normalized side force (averaged over 5 balls).

and the ball spinning backwards at a rate of 11.4 revs/s. At a seam angle of 20°, the Re based on trip (seam) height is about right 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, 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 of course also detrimental, since the effect of the ball's surface roughness is increased and the critical Re is reached sooner.

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°, backspin = 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 time squared 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 (Imbrosciano 1981). Those studies also confirmed that the final deflections of over 0.8 m predicted here are not unreasonable. One of the photographed sequences was analyzed and the actual flight path is also plotted in Fig. 5. The agreement is excellent considering the simplicity of the experimental and analytical techniques.

The data in Fig. 5 also help to explain the phenomenon of "late" swing. 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 from the bowler to the batsman. A

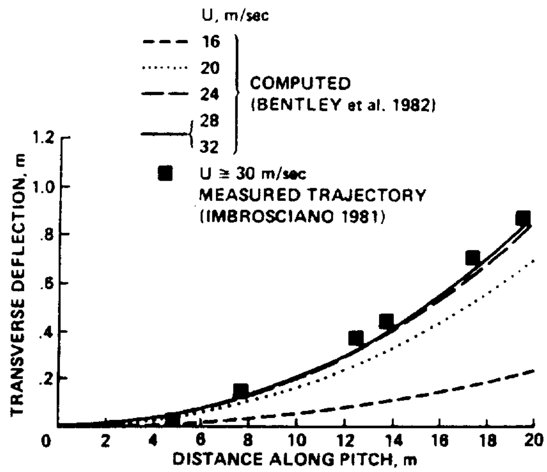

Fig. 5 Computed flight paths using measured forces for the cricket ball with the best swing properties. Seam angle = 20°, spin rate = 14 revs/sec.

couple of theories on late swing are further discussed below in the section on, "Myths and Misconceptions".

AERODYNAMICS OF REVERSE SWING

Since the mid-1980's, 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 accepted aerodynamic principles. This new form of swing bowling was first demonstrated (with astonishing success) by the Pakistani bowlers, in particular Imran Khan, Sarfraz Nawaz, Wasim Akram and Waqar Younis. They produced reverse swing very effectively, and generally using older cricket balls, which obviously added to the intrigue.

Ironically, I first heard about the phenomenon of reverse swing in the summer of 1980 from an old school mate of mine, none other than Imran Khan himself. In talking about some of the issues regarding cricket ball aerodynamics, Imran told me about a curious effect he had observed when bowling. He was predominantly an inswing bowler, but he stated that with the same grip and bowling action, the ball would swing away on the odd occasion. At the time, I honestly did not believe that such a phenomenon could occur since I could not explain it using conventional cricket ball aerodynamics. However, in the following year when we started conducting experiments on cricket ball swing, the whole "mystery" was soon revealed. 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 point moving upstream, towards the front of the ball. A zero side force is obtained when the flow field on the two sides of the ball becomes completely symmetric. In terms of reverse swing, the really interesting flow events start to occur when the Reynolds number 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 Fig. 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, 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 Fig. 6; *this is reverse swing*.

Amongst other factors, transition is strongly dependent on the condition (or roughness) of the ball's surface. This is demonstrated in the side force results for three cricket balls with contrasting surface conditions (Fig 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 drop-off until U = 80 mph. This ball will only produce reverse swing for velocities above 100 mph, 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 80 mph. Note how the magnitude of the negative side force at 90 mph is not much less than the positive force at 60 mph. Of course, the negative sideways deflection will not be as much as the positive deflection since the ball spends less time in the air at the higher velocity. 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*. Some of the fastest bowlers, such as Jeff Thomson (Australia) and Imran Khan from prior years and Shoaib Akhtar (Pakistan) from present times, have been measured bowling in the 90+ mph range and so reverse

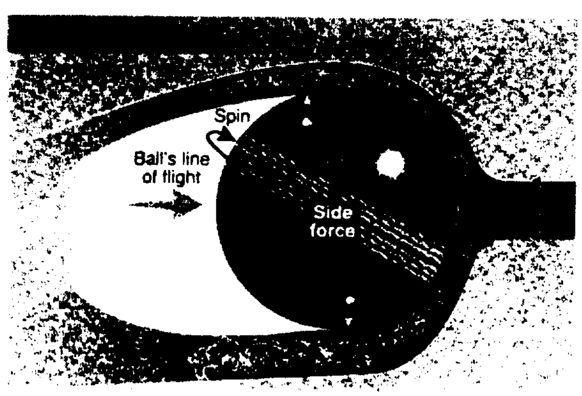

Fig. 6 Flow over a cricket ball for reverse swing.

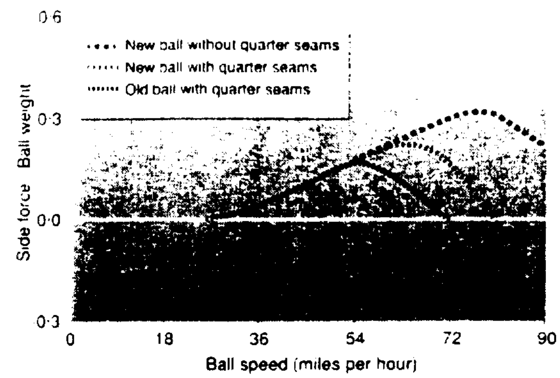

Fig. 7 Normalized side force versus ball speed showing reverse swing.

swing would certainly be achievable by them. Alas, not every bowler can bowl at 90 mph, so what about the mere mortals who would still like to employ this new art? Well, there is hope as shown in Fig. 7. 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 65 mph. The contrasting results for the three balls are directly attributable to the effects of surface roughness on the critical Reynolds number. 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 Reynolds number at which transition occurs on the nonseam side is therefore higher. Conversely, the critical Reynolds number 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.

SWING ON THE CRICKET GROUND AND BALL TAMPERING

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. Historically, bowlers have always paid a lot of attention to these two features of the ball, although the scientific reasons for doing so may not be totally obvious to them. As all true gentlemen cricketers know, only natural substances such as sweat or saliva can be legally used as a polishing agent, although the odd use of "Vaseline" or "Brylcreem" is often at the centre of a ball tampering controversy. Who can forget the infamous "Vaseline incident" in India in 1976, involving the English bowler, John Lever? "Picking" of the primary seam on aging balls is also technically illegal, but bowlers can be often seen running their fingernails over the stitching. I distinctly recall seeing John Snow of England exercise this "art" to near perfection in the 1970s.

Regardless of the chosen "procedure" for polishing, in order to continue obtaining conventional swing from a new ball, 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 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 seam side. 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 a 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 an amazing, not to mention 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 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 to keep the nonseam side as smooth as possible, whereas for reverse swing the nonseam side needs to be as rough as possible.

As Imran Khan stated, it is not difficult to understand why reverse swing is commonly seen in Pakistan since the balls inevitably get roughed up relatively quickly on the hard and dry pitches and grounds, thus resulting in early reverse swing. One of the reasons why reverse swing has gained such notoriety is its constant link to accusations of ball tampering. The fact that bowlers started to illegally roughen the ball surface since the early 1980s is now well documented. Oslear & Bannister (1996) 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 and raise 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 that I first heard about reverse swing (1980). Also, in the following year (1981), the Test and County Cricket Board (TCCB) standardized the balls so that they now had smaller seams. I doubt very much if the cricket authorities were aware of the implications of these changes on what was about to "rock" the cricket scene: *reverse swing*.

SWINGING AN OLD BALL

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 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 there is a sharp contrast in surface roughness 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. At very high bowling speeds, the boundary layers on both surfaces will be turbulent and the ball will swing towards the smooth side, much like in the case of reverse swing.

The most exciting feature about this phenomenon 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, thus confusing not only the batsman, but perhaps themselves as well!

EFFECTS OF METEOROLOGICAL CONDITIONS

The effect of meteorological conditions 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 aerodynamics (Cooke 1955). The one bit of advice that cricket "Gurus" have consistently passed down over the years is that a humid or damp day is conducive to swing bowling. However, the correlation between humid conditions and swing has not always been obvious and most of the scientific explanations put forward have also been somewhat "far-fetched". 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 a damp or humid 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 property of air that may conceivably be influenced by a change in meteorological conditions is the Re through a change in the air viscosity or density. However, Bentley et al. (1982) showed that the average changes in temperature and pressure encountered in a whole day would not change the air density and viscosity, and hence Re, by more than about 2%. Incidentally, although humid or damp air is often referred to as constituting a "heavy" atmosphere by cricket commentators, humid air is in fact less dense than dry air.

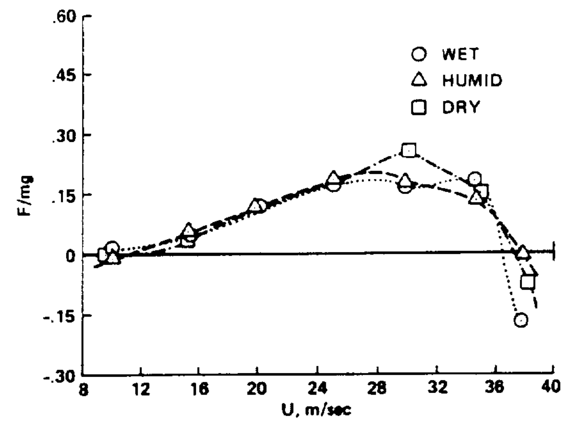

Fig. 8 Effect of humidity on the measured side forces on a spinning cricket ball. Seam angle = 20°, spin rate = 5 revs/sec.

A popular theory that has circulated for years, especially amongst the scientific community, is that the primary seam swells by absorbing moisture, hence making it a more efficient boundary layer trip. Bentley et al. (1982) 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. A similar test on a used ball (where the varnish on the seam had come-off) 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. The projection test was performed on these 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 Fig. 8.

Several investigators (Horlock 1973, Barton 1982, Sherwin & Sproston 1982, Wilkins 1992) have confirmed that no change was observed in the pressures or forces when the relative humidity of the air changed by up to 40%. It has been suggested that humid days are perhaps associated with general calmness in the air and thus less atmospheric turbulence (Sherwin & Sproston 1982, Wilkins 1992). On the other hand, Lyttleton (1957) and Horlock (1973) 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 eddies) would generally be too large to have any significant effect on the flow regime over the ball. Binnie (1976) suggested that the observed 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. (1982), the primary seam on almost all new cricket balls is adequate in tripping the boundary layer in the Reynolds number range of interest.

To my knowledge, there is only one published paper which claims that the positive effects of increased humidity on swing were observed in a wind tunnel test (Bowen 1995). Only two data points were presented which showed that the side force coefficient was higher and the drag coefficient lower for a relative humidity of 54% compared to those at 36%. However, the shapes of the curves and the proposed explanation, that humidity increases the surface roughness on the ball are both hard to believe. One would need to see a lot more evidence and better explanations before such an important result can be accepted for the first time. In my opinion, there is no (positive) scientific evidence which supports the view that humid conditions are more conducive to swing. However, from personal observations and experience, I always have and still do believe in the effect. The only possibility I have come up with is that humidity must affect the actual bowling procedure. There is a possibility that the amount of spin imparted to the ball may be affected. We found that 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, and as shown above in Fig. 4, an increase in spin rate (at least up to 11 revs/sec) certainly increases the side force. So, perhaps actually without realising it, the bowler may just be imparting more spin on a humid or damp day. I first proposed this hypothesis in 1982 (Bentley et al. 1982) and, while it has not been positively confirmed, it should hold until a better scientific explanation is offered.

MYTHS AND MISCONCEPTIONS

One of the popular theories for late swing suggests that a ball released at a speed just above the critical (with the boundary layers on both sides or hemispheres turbulent) may slow down enough during flight so that the boundary layer on the nonseam side reverts to a laminar state, thus creating a late movement of the ball. However, it turns out that a ball released at postcritical Re slows down by less than 5% in flight, and from the shapes of the curves in Fig. 4, it does not seem likely that this effect would occur in practice. Another theory relies on a change in the ball orientation (through the gyroscopic precession effect), but from our test results this is not a significant effect. The suggestion that sudden changes in wind direction can lead to late swing (through a change in the seam angle) is also not very likely to occur in practice (Wilkins 1991). So late swing is most likely a natural (built-in) part of conventional (or reverse) swing, rather than an artifact of some new, unknown phenomenon.

Contrary to popular belief, based largely on comments initially made by Imran Khan and Sarfraz Nawaz, the cricket ball does not have to be wet on one side to produce reverse swing. The notion that this makes the ball heavier on this side and the ball would therefore swing in that direction has no aerodynamic basis to it whatsoever. However, there are some possible advantages to wetting the ball (Wilkins 1991). For one thing, it makes it easier to gouge the softer leather with the fingernails. Also, it is possible that the quarter seam may become rougher by absorbing water underneath the exposed stitches and making the ridges more pronounced. As discussed above, additional roughness reduces the bowling speed at which reverse swing can be obtained. The disadvantage of a wet ball is that it is heavier and it will therefore swing less.

It is also hard to believe, as some newspaper articles have suggested, that the Pakistani bowlers obtain *more* swing from old balls, and that some of them actually prefer to bowl with an older ball. Any bona fide swing bowler should be able to, and to my knowledge does, swing a new ball under any conditions. Apart from the aerodynamic benefits, a new ball is also preferred because it is harder and will, therefore, bounce more off the pitch. Also, with a prominent seam on a new ball, more movement can be obtained "off the pitch" if the ball bounces on the seam. As discussed above, an old ball with a sharp contrast in surface roughness can have some advantages. The main question is how to make the best aerodynamic use of an aging ball and this is what the Pakistani bowlers have seemingly mastered.

During the last World Cup, there was a lot of discussion about the swing properties of the white ball used in the tournament. The white ball was introduced since it was apparently easier to see both for the players on the field and for television viewers. The main contention was that the white ball swung significantly more than the conventional red ball. According to the manufacturer of the white ball (Dilip Jajodia of British Cricket Balls Ltd.), the only difference between the two balls is in the coating. With the conventional red ball, the leather is dyed red, greased and polished with a shellac topcoat. This final polish disappears very quickly during play and it is the grease in the leather that produces the shine when polished by the bowler. The finish applied to the white ball is somewhat different. The leather is sprayed with a polyurethane white paint-like fluid and then heat-treated so that it bonds to the leather like a hard skin. As a final treatment, one coat of clear polyurethane-based topcoat is applied to further protect the white surface so that it does not get dirty easily. As far as the aerodynamics is concerned, the additional topcoat covers up the quarter seam and the effective roughness due to it is therefore reduced. As a consequence, a new white ball should swing more, especially at the higher bowling speeds since a laminar boundary layer is more readily maintained on the smoother surface. Also, the harder surface stays smooth for a longer time; it does not scuff up easily like the red ball and so conventional swing can be obtained for a longer playing time. Another consequence of this is that reverse swing will occur at higher bowling speeds with a new white ball and later in the innings at more reasonable bowling speeds. Also, in theory, it should be more difficult to tamper with the harder white surface. I noted during the last World Cup that the ball often became dirty during the later stages of an innings, leading the batsmen to ask for a ball change. This implies that the hard outer coating did eventually wear out, thus making reverse swing easier to achieve. And indeed, I was able to observe several instances where reverse swing was produced. On the whole, from what I observed during the World Cup, the white ball did not appear to possess swing properties that were significantly different from those of a conventional red ball. Some of the bowlers and so-called "experts" seemed only too eager to blame the excessive number of wide balls on the white ball, rather than on stricter enforcement of the law by the umpires and, perhaps more importantly, on lousy bowling tactics!

CONCLUSIONS

The basic scientific principles of conventional swing are now well established and understood. However, some confusion still remains as to what reverse swing is, and how it can be achieved on a cricket field. 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. Perhaps the biggest misconception is that one must tamper with the ball to achieve reverse swing and this is certainly not the case. Reverse swing can be obtained with a brand new (red) four-piece ball, but only at bowling speeds of more than 80 mph. 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 humidity is still open, in my opinion. While I have personally experienced the effect several times, there is not enough laboratory evidence to explain how the amount of swing may be increased in humid conditions. The introduction of the new white ball with its unique outer cover finish has started a new controversy on how its swing properties differ from those of a conventional red ball. Needless to say, cricket ball aerodynamics would not be such a fascinating subject if all the mysteries and controversies could be readily answered and settled.

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