Effects of Rotation

The rotation of an object in a flow can have a major effect on its trajectory through its effect not only on the drag on the object but also on the lift. Since these effects are interconnected we describe both in this section. We will also subdivide this section by describing the effects of rotation about an axis parallel with the direction of motion and those due to rotation about an axis normal to the direction of motion even though both may be present in any particular context.

The effect of spin about the longitudinal axis of a flying object (the axis parallel with the direction of motion) is very important in some contexts (notably in artillery) and is conveniently described separately from the other effects of rotation. Though the technique of stabilizing the flight of a spinning projectile was known in the days of bows and arrows, the rifling of a gun barrel was first invented in the 15th century in order to impart spin to a bullet that would stabilize its flight. This gyroscopic mechanism is little effected by the flow around the bullet; without it the bullet would begin to yaw and then tumble, greatly reducing the accuracy of the shot (a modern rifle bullet rotates at as much as $300,000 rpm$). However, it is still likely that added rotational component of the surface flow decreases the pressure on the front face of the bullet and therefore decreases the drag.

However, most of the fluid mechanical effects we will describe here come from other contexts and involve other ways in which rotation effects the transition and/or separation of the boundary layer on the object. Consequently the discussion will focus on high Reynolds number flows and, in particular, on Reynolds numbers in the range, 2×10^4 to 4×10^5. As described in sections (Bjg), (Bkk) and (Dcc), the boundary layer on an object in this range of Reynolds numbers may transition before separation (and therefore delay the latter) or it may separate before transitioning. These scenarios can lead to quite different flow patterns and therefore quite different drag coefficients. Moreover the presence of surface roughnesses can induce either transition or separation and this gives rise to another series of possible flow orientations, particularly when separation occurs at one location on one side of the object and at another location on the other side.

Now, it so happens that many of the ball games that we play lie within the range of Reynolds number quoted above, and the possible flow phenomena described above lend a special quality and interest to those games. For example, the games of baseball and cricket use balls that are approximately $7.3cm$ and $7.2cm$ in diameter. A tennis ball is about $6.6cm$ in diameter while a golf ball is about $4.3cm$ in diameter and a soccer ball is about $22cm$ in diameter. The surface roughnesses of baseballs, cricket balls, golf balls and tennis balls all play an important role at least at the professional levels of those sports. The roughness on a baseball consists primarily of an unusual seam, while that on a cricket ball is a broad, raised seam around an equator. A golf ball is covered in circular dimples while a tennis ball has a "furry" surface and a recessed seam. All of these roughnesses play a role in the trajectories of the balls in those games, and in the cases of cricket, tennis and golf play a role in determining how those balls bounce off the ground. It is not clear to the author whether or not the roughnesses on a soccer ball play a role in determining the ball trajectories in that sport but they may do so. The typical ball velocities associated with the professional games are as follows though, obviously ball velocities vary considerably. For convenience we choose the following typical velocities which lead to the quoted Reynolds numbers (using a kinematic viscosity of air of $1.5 \times 10^{-5} m^2/s$):

- *Baseball:* $60 - 90mph$ or $27 - 40m/s$; $Re = 1.3 \times 10^{-5} \; - \; 1.95 \times 10^{-5}$
- *Cricket:* $40 - 90mph$ or $18 - 40m/s$; $Re = 0.86 \times 10^{-5} \; - \; 1.92 \times 10^{-5}$

- *Tennis:* $90 - 130mph$ or $40 - 60m/s$; $Re = 1.76 \times 10^{-5} - 2.64 \times 10^{-5}$
- *Golf:* $150 - 180mph$ or $65 - 80m/s$; $Re = 1.86 \times 10^{-5} - 2.3 \times 10^{-5}$
- *Soccer:* $50 - 70mph$ or $20 - 30m/s$; $Re = 2.93 \times 10^{-5} - 4.4 \times 10^{-5}$

Notice that most of these Reynolds numbers lie within the critical range of Reynolds numbers that lead to the variety of trajectory effects described above. We will describe some specific examples.

We begin with a baseball *curveball* in which the pitcher imparts sufficient spin (see Figure 1) to the ball to

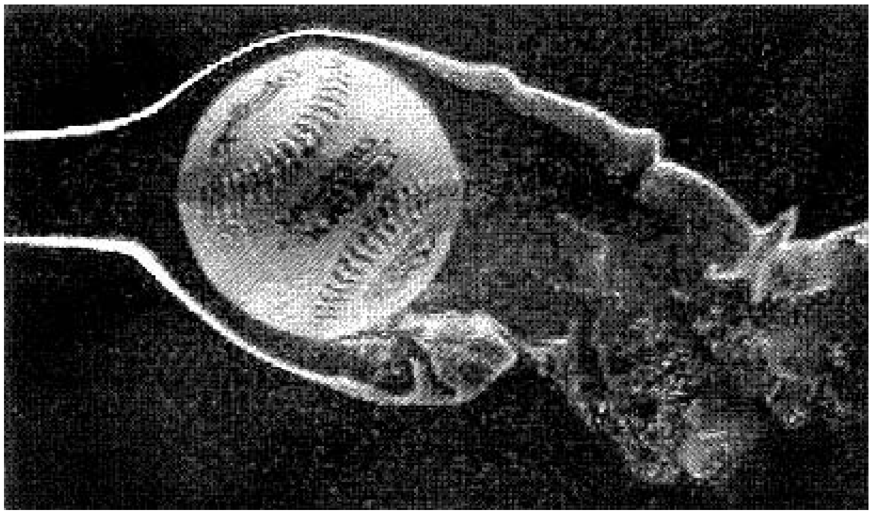

Figure 1: Flow around a spinning baseball at $Re = 3400$ with the ball spinning in a clockwise direction at 0.5 revolutions per second. Photograph by Jim Pallis.

produce a Magnus effect (section (Dcb)) and a trajectory that can curve the ball in a variety of directions. In contrast a *fastball* is thrown with a velocity that exceeds the critical velocity and thus exhibits a reduced drag coefficient that significantly decreases the deceleration on the way to the plate resulting in a much higher arrival velocity. But the pitch known as a *knuckleball* is perhaps unique in sports. It is thrown with almost no spin and the resulting random orientation of the seams relative to the boundary layer development produces separation of the flow on one side of the ball but not on the opposite side. This only occurs because (a) the Reynolds number is at the sensitive value at which the separation point location is very sensitive to small disturbances and (b) the seam happens to be in a location where it may trigger the shift in the flow. The random and varying asymmetry in the flow produces a lateral force that results in a randomly wandering and unpredictable trajectory that is very confusing for the hitter.

Cricket, tennis and golf all have the added feature that the spin imparted to the ball changes the way it rebounds from the ground. Cricket has very similar Reynolds numbers to baseball and a spin bowler utilizes the Magnus effect in the same ways that a curveball pitcher does (Figure 2 shows how the location of the seam alters the position of separation), with the added complication that the spin produces an inclined and often unpredictable rebound when the ball bounces off the ground. In addition a fast bowler utilizes the added velocity to reach a regime of lower drag coefficient that lowers the deceleration of the ball and adds to its arrival velocity. A seam bowler also utilizes the pronounced seam around the equator of a cricket ball to produce a variety of flight patterns and rebound characteristics.

Spin and the Magnus effect also play a substantial role in the games of tennis, golf and soccer (Figures 3, 4 show a spinning golfball and a tennis ball without and with spin). In tennis topspin or backspin are both used not only to effect the flight of the ball but also its rebound characteristics, not only how it bounces off

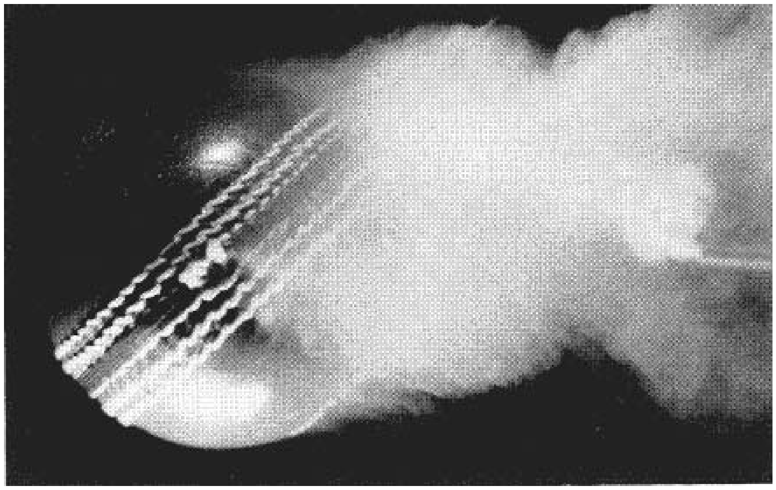

Figure 2: Flow around a cricket ball with $U = 17m/s$, seam angle = 40^o and $Re = 85000$.

the ground but also how it bounces off the opponent's racquet. A well-hit golf drive has spin that produces a very satisfying rising trajectory as the ball disappears down the fairway. The dimples in the surface of a golfball (Figure 3) are intended to increase the frictional contact between the ball and the air). On the other hand an incorrectly hit golfball can have deleterious consequences as the ball deviates to one side or the other in a slice or a pull. With lofted clubs the golfer also uses backspin to effect the way the ball stops on the green (or even rolls backwards) after it lands.

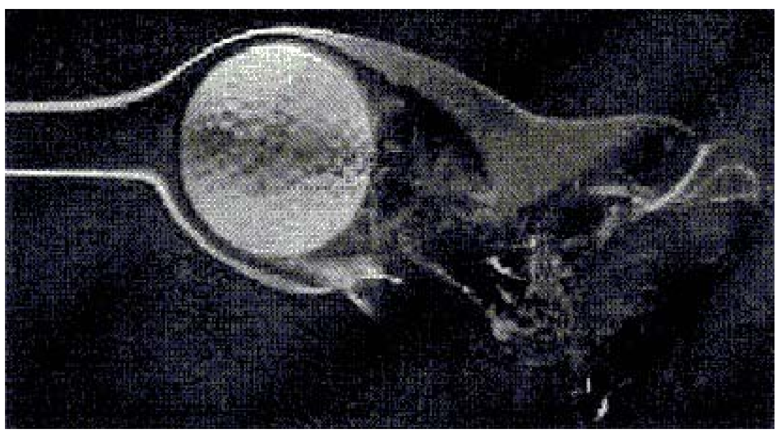

Figure 3: A golf ball at $Re = 1950$ spinning in a clockwise direction.

Soccer players (most famously the English international David Beckham) also use spin to deflect the ball around defenders using the Magnus effect. Such an ability is important in professional soccer where the speeds of flight and Reynolds numbers are high. But a much-less-well-known phenomenon can be observed with smooth soccer-sized beach balls kicked so as to produce a high rate of spin but a low forward velocity. Then there can occur an "anti-Magnus" effect in which the ball trajectory is deflected in the direction opposite to that expected as a result of the Magnus effect. I believe this is due to the location of the laminar separation point being brought forward on the side of the ball where the added surface velocity is directed upstream and the reverse happening on the other side of the ball. Such an asymmetry in the laminar separation location would produce this "anti-Magnus" effect.

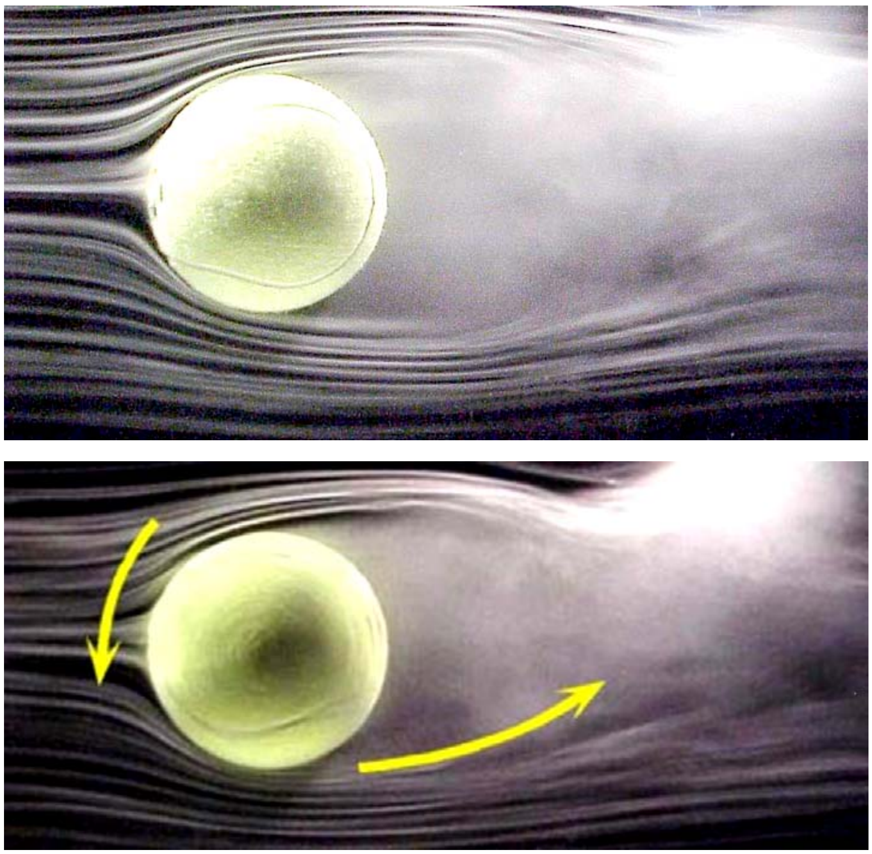

Figure 4: Flows around a non-rotating tennis ball at $Re = 167,000$ (top) and around a tennis ball rotating anticlockwise (bottom).