# Aerodynamics and hydrodynamics in sports

J.M. Pallis
*Cislunar Aerospace, Inc., San Francisco, CA, USA*
R. D. Mehta
*Sports Aerodynamics Consultant, Mountain View, CA, USA*

***ABSTRACT:*** Fluid dynamics, the study of the forces gases and liquids create on a body, has a major impact on sports equipment and athletic performance. From the pattern design of dimples on a golf ball, the latest swimsuits, the curved flight path of a tennis, cricket or baseball, to the planing of a surfboard through water, fluid dynamics affects speed, motion (position and placement) and ultimately athletic performance.

The basic aerodynamic and hydrodynamic principles that govern most sports are identified. In turn, each concept is applied to a wide variety of individual sports, demonstrating how surface textures, form and shape of the equipment or athlete govern speed and motion and how performance can be enhanced. The effects of these specific mechanisms on the behavior and performance of sports equipment are demonstrated. The aerodynamics and hydrodynamics of several different sports are discussed with the help of recent wind tunnel measurements and theoretical analyses.

## SPORTS BALL AERODYNAMICS

Lateral deflection in flight, known as swing, swerve or curve, is well recognized in baseball, golf, tennis, cricket, volleyball and soccer. In most of these sports, the deflection is produced by spinning the ball about an axis perpendicular to the line of flight which generates the *Magnus effect.* It has long been known that the aerodynamics of sports balls is strongly dependent on the detailed development and behavior of the boundary layer on the ball's surface. A side force, which makes a ball swing through the air, can also be generated in the absence of the Magnus effect. In one of the cricket deliveries, the ball is released with the seam angled, which creates the boundary layer asymmetry necessary to produce swing. In baseball, volleyball and soccer there is an interesting variation whereby the ball is released without any spin imparted to it. In this case, depending on the seam or stitch orientation, an asymmetric, and sometimes time-varying, flow field can be generated, thus resulting in an unpredictable flight path. Almost all ball games are played in the Reynolds Number range of between about 40,000 to 400,000. The Reynolds number is defined as, $Re = Ud/\nu$, where U is the ball velocity, d is the ball diameter and $\nu$ is the air kinematic viscosity. It is fascinating that small disturbances on the ball surface, such as the stitching on baseballs and cricket balls, the felt cover on tennis balls and patch-seams on volleyballs and soccer balls, are about the right size to affect boundary layer transition and development in this Re range. A more detailed account of sports ball aerodynamics is given in Mehta and Pallis (2001a).

***BASEBALL AERODYNAMICS***

For a pitch such as the curveball, the ball is released with topspin about the horizontal axis. This results in a Magnus force that makes the ball curve faster towards the ground than it would under the action of gravity alone. In Figure 1, the flow over a spinning baseball is shown in a water channel using dyes at a relatively low Re (3400) and a spin rate parameter (S) of 2.5, where S is defined as the ratio of the equatorial velocity at the edge of the ball (V) to its translation velocity (U). At such a low Re, the flow over the baseball is subcritical, but the asymmetric separation and deflected wake flow are still clearly evident, thus implying an upward Magnus force. The extra momentum applied to the boundary layer on the retreating side of the ball delays separation while the reverse occurs on the advancing side. Note the indentation in the dye filament over the upper surface due to the seam. At higher Re, the rotating seam would produce an effective roughness capable of causing transition of the laminar boundary layer. Spin rates of up to 35 revs/sec and speeds of up to 45 m/s are achieved by pitchers in baseball.

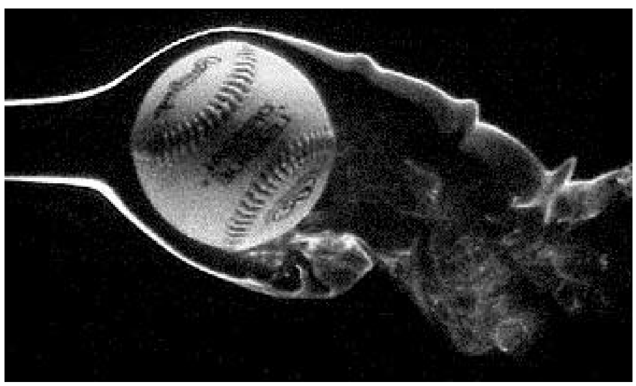

*Fig. 1* Flow visualization of a spinning baseball at Re = 3400 (flow is from left to right and the ball is spinning in a clockwise direction at 0.5 revs/sec). Photograph by Jim Pallis.

In some measurements of the lift force (L) on spinning baseballs, Watts and Ferrer (1987) concluded that the lift force coefficient, $C_L$ [$= L/(0.5\rho U^2 A)$] was a function of the spin parameter only and at most only a weak function of Re. Alaways' (1998) lift measurements were in general agreement, although Alaways also found a dependence of seam orientation with the $C_L$ higher for the 4-seam case compared to the 2-seam. The main significance of the seam orientation is realized when pitching the fastball when pitchers impart backspin to the ball so that there is an upward (lift) force opposing gravity. The fastball would thus drop slower than a ball without spin and the

4-seam pitch will drop even slower compared to the 2-seam. However, even the 4-seam fastball cannot generate enough lift to overcome the weight of the ball, which is what would be needed to create the so-called "rising fastball." The maximum measured lift was equivalent to 48% of the ball's weight, so a truly rising fastball is not likely to occur in practice.

Watts and Sawyer (1975) investigated the flow field around a "knuckleball" and measured relatively large values of the lateral force with large fluctuations for the orientation when the seam coincided with the boundary-layer separation location. This was attributed to the separation location jumping between the front and back of the stitches, thus generating an unsteady flow field. Some interesting flight paths were calculated for pitches where the ball was released with limited rotation. In Figure 2, the baseball data are for a non-spinning baseball and the critical Re is about 155,000. So if the ball was released at about U = 30 m/s there exists a possibility of generating a turbulent boundary layer over parts of the ball and hence a strong separation asymmetry and side force.

### *GOLF BALL AERODYNAMICS*

In golf ball aerodynamics, apart from the lift force, the drag and gravitational forces are also important, since the main objective is to "tailor" the flight path of the ball. The lift force is generated due to the Magnus effect and the role of the dimples is to lower the critical Re, as shown in Figure 2.

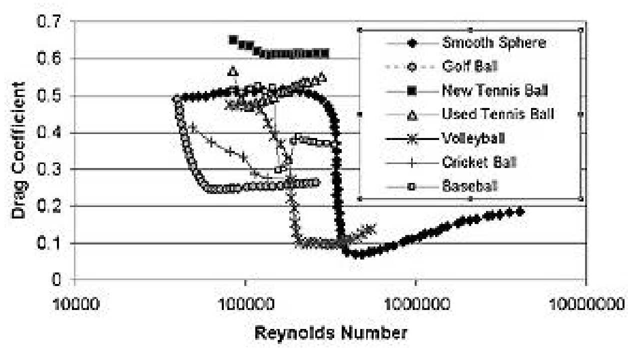


*Fig. 2* Drag coefficient versus Reynolds number for different sports balls.

Bearman and Harvey (1976) conducted a study of golf ball aerodynamics using a large spinning model over a wide range of Re and S. They found that $C_L$ increased monotonically with S (from about 0.08 to 0.25), as one would expect, and that the $C_D$ also started to increase for S > 0.1 (from about 0.27 to 0.32) due to induced drag effects. The trends were found to be independent of Reynolds number for 126,000 < Re < 238,000. More recently, Smits and Smith (1994) made some measurements over the range, 40,000 < Re < 250,000 and 0.04 < S < 1.4. Based on their data, which included measurements of the spin decay rate, they proposed a new aerodynamic model of a golf ball in flight. Their measurements were in broad agreement with those of Bearman and Harvey although a new finding was that for Re > 200,000, a second decrease in $C_D$ was observed, the first being that due to transition of the boundary layer. Smits and Smith proposed that this could be due to compressibility effects since the local Mach number over the ball reached values of up to 0.5.

Over the years, several dimple designs and layouts have been tried to improve the golf ball aerodynamics. Bearman and Harvey (1976) found that hexagonal dimples, instead of the conventional round ones, improved the performance of the ball since the $C_L$ was slightly higher and the $C_D$ lower. In order to try and minimize the amount of sideways deflection on an inadvertently sliced drive, a ball was designed (*Polara*) with regular dimples along a "seam" around the ball and shallower dimples on the sides. The ball is placed on the tee with the seam pointing down the fairway, and if only backspin about the horizontal axis is imparted to it, it will generate roughly the same amount of lift as a conventional ball. However, if the ball is heavily sliced, so that it rotates about a near-vertical axis, the reduced overall roughness increases the critical Re, and hence the sideways deflection is reduced.

### *TENNIS BALL AERODYNAMICS*

Some recent experimental studies of tennis ball aerodynamics have revealed the very important role that the felt cover plays (Mehta and Pallis, 2001b). Figure 3 shows a photograph of the smoke flow visualization over a tennis ball model that is held (non-spinning) in a wind tunnel. The first observation is that the boundary layer over the top and bottom of the ball separates relatively early, thus suggesting a laminar boundary layer separation. However, since the flow field did not change with Re, it was presumed that transition had already occurred and that a turbulent boundary layer separation was obtained over the whole Re range tested, thus putting the ball in the transcritical flow regime. As discussed above, a Magnus force is generated on a spinning tennis ball and the direction and amount of movement is determined by the spin axis and the spin parameter (S).

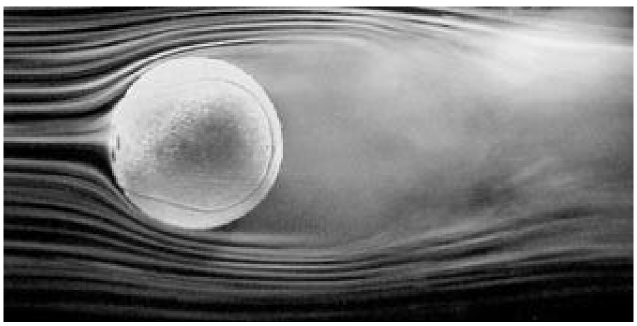

*Fig. 3* Flow visualization of a non-spinning tennis ball (flow is from left to right, Re = 167,000).

Drag measurements on non-spinning tennis balls revealed that the flow over new tennis balls was indeed transcritical, with a relatively high value for the drag coefficient ($C_D \cong 0.6$), higher than any other sports ball data shown in Figure 2. Since almost all of the total drag on a round ball is accounted for by pressure drag, it was proposed that the maximum $C_D$ on a very rough sphere should not exceed 0.5 (Mehta and Pallis, 2001b). However, on a tennis ball, apart from providing a rough surface, the felt cover is also a porous (drag-bearing) coating since the "fuzz" elements themselves experience pressure drag. This additional contribution was thus termed: "fuzz drag." Since the fuzz elements come off as the ball surface becomes worn, the ball $C_D$ should also decrease, and that is precisely what was observed in the data for the used ball (Figure 2). The used ball appears to be in the supercritical regime with a critical Re ≈ 100,000.

### *CRICKET BALL AERODYNAMICS*

Fast bowlers in cricket make the ball swing by a judicious use of the primary seam (six rows of prominent stitching). The ball is released with the seam at an angle to the initial line of flight (Mehta, 2000). 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. The turbulent boundary layer separates later compared to the laminar layer and so a pressure differential, which results in a side force, is generated on the ball. In Figure 4, 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 is in a laminar state. 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.

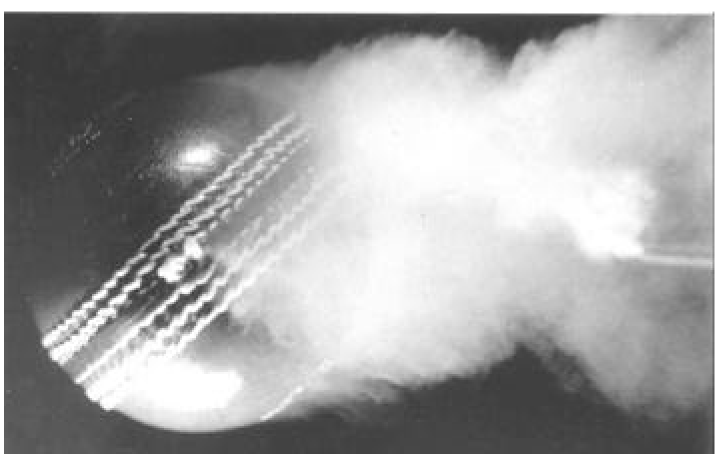

*Fig. 4* Flow visualization over a cricket ball (flow is from left to right, Re = 85,000).

When a cricket ball is bowled, with a round arm action as the laws insist, there will always be some backspin imparted to it as the ball rolls-off the fingers as it is released. Aerodynamic forces measured on spinning cricket balls showed that at nominally zero seam angle there was 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 was set at an incidence to the oncoming flow, the side force started to increase at about U = 15 m/s. The side force increased with ball velocity, reaching a maximum of about 30% of the ball's weight before falling-off rapidly. The critical velocity at which the side force started to decrease was about 30 m/s (Re = 140,000). 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 locations is reduced and the side force starts to decrease.

### *VOLLEYBALL AND SOCCER BALL AERODYNAMICS*

In volleyball, two main types of serves are employed: a relatively fast spinning serve (generally with topspin), which results in a downward Magnus force adding to the gravitational force or the so-called "floater" which is served at a slower pace, but with the palm of the hand so that no spin is imparted to it. The floater has an unpredictable flight path, which makes it harder for the returning team to set up effectively. In soccer, the ball is almost always kicked with spin imparted to it, generally backspin or spin about a near-vertical axis, which makes the ball curve sideways. The latter effect is often employed during free kicks from around the penalty box. A "toe-kick" is also sometimes used in the free kick situations to try and get the "knuckling" effect.

For both these balls, the surface is relatively smooth with small indentations where the "patches" come together, so the critical Re would be expected to be less than that for a smooth sphere, but higher than that for a golf ball. As seen in Figure 2, that is indeed the case for a non-spinning volleyball with a critical Re of about 200,000 (U = 14.5 m/s). The typical serving speeds in volleyball range from about 10 m/s to 30 m/s and so it is quite possible to serve at a speed just above the critical (with turbulent boundary layer separation) and as the ball slows through the critical range, get side forces generated as non-uniform transition starts to occur depending on the locations of the patch-seams. Thus, a serve that starts off on a straight flight path may suddenly develop a sideways motion towards the end of the flight.

## SPORTS HYDRODYNAMICS

Within the broad field of fluid dynamics, the definition of hydrodynamics pertains not only to the flow of liquids but to incompressible flow in general. In most water sports (swimming, rowing, sailing, water skiing, and powerboats), the equipment or the athlete is affected by the dual fluid medium of both water and air simultaneously. In a sport such as skin diving or the analysis of particular watercraft appendages, the body is considered fully submerged and only hydrodynamic (water) forces are of importance. For the majority of water or marine sports the human body or the watercraft/equipment is either planing or surface-piercing and only partially submerged into the water or floating. A "water-line" is formed on the body at the free surface interface between water and air. Effects may be time-dependant: a swimmer's hand and arm may be completely submerged or above water during different portions of a stroke. An oar may be out of or partially submerged in water during rowing.

The forces acting on such objects are similar to those in aerodynamics: thrust, drag, lift, weight with the additional consideration of buoyancy. Fluid mechanisms associated with Reynolds number, boundary layers, flow separation, surface roughness, pressure and skin friction drag also apply to objects placed in water.

In addition to the aerodynamic mechanisms, hydrodynamic forces are affected by: water waves and spray, ventilation (cavitation), fouling (marine growth on an object's surface), planing, the free surface interface and wind shear.

Wave surface deformation occurs for a water surface-piercing body. Water peaks and hollows are formed along the body creating a component of drag called wave drag. This water piling can also form water jets, which shoot into the air creating spray drag.

Planing refers to skimming or gliding over the water surface as opposed to plowing through water as a boat or other water displacement object. Planing is observed in sports such as windsurfing and water skiing.

***SWIMMING***

Hydrodynamics plays a dominant role in the performance of both the human swimmer and the design of the swimming pool and lane dividers. In competition, athletes swim in prescribed lanes. As the swimmers dive into the pool and begin to swim, water waves form. These waves can expand into adjacent lanes, interact with other competitors and reflect off the gutters and sides of the pool. As the athlete turns at one end of the pool, waves are generated in opposing directions, interact, and can cause additional degradation in an athlete's individual performance.

Subsequently, competitive pools are often considered "fast" or "slow"– a fast pool is designed to minimize wave reflection and interaction which allows the athlete an opportunity for a faster race time. Considered the fastest pool in the world, the swimming pool designed for the 2000 Sydney Olympics used a gutterless system. The design resembles "a pool inside a pool" with water spilling over the sides of the pool, to eliminate interaction with gutters and minimize wave reflection.

Floating lane ropes or lines separate the swimming lanes. Floating on the surface of the pool, modern lane rope designs are often rows of spinning wheels used to diffuse the wave and prevent water waves created by one athlete to expand and cross into the path of competitors in adjacent lanes.

Four primary forces act on a swimmer: thrust (propulsive forces), weight, drag and buoyancy. The weight of the swimmer is offset by buoyancy and through the arm stroke and kick. By pressing down on the water, an equal an opposite reaction occurs which lifts the swimmer higher in the water.

In addition to wave drag, the two other major components of drag are pressure drag and skin friction drag. Pressure drag results from water resistance over the swimmer's frontal area and the flow separation which occurs behind the swimmer. Therefore, a swimmer must streamline their body to reduce the amount of separation.

***SAILING***

In competitive sailing, every fraction of a knot counts. Research in aerodynamics and hydrodynamics in sailing, related board (wake board) and power boat sports fills volumes of texts and conference proceedings. There is such great diversity in sizes, shapes and configurations of equipment that generalization is difficult. Researchers and designers often specialize in just one geometric element of analysis: sails, masts, hulls or appendages.

Traditionally, research has been dominated with water channel and on-water design tests (the equipment is built and then sailed against other equipment). More recently, with the surge in available and affordable computational resources Computational Fluid Dynamics (CFD) has been incorporated into some marine sport equipment design.

Aerodynamic and hydrodynamic simulation of marine sports equipment is a tremendous challenge. Realistic results require the modeling of multiple interacting components immersed in air, water or both fluids at the same time, as well as free surface (water wave) effects and wind shear effects.

When a body moves through a free surface, the waves generated by the object play a primary role in the resulting flow and the forces on that object. The wave shapes near the body are determined by the pressure disturbance caused by the moving body. These waves propagated away from (and under) the object after it passes.

Wind shear also affects the velocity profile along the height of a sail. At the water's surface, air motion is affected by friction. Surface wind (the wind from 0 -100 ft.) is different from the winds aloft. Similar to the formation of boundary layers, the wind velocity, influenced by factors such as hull shape, type of weather, and conditions at sea (wind turbulence, water roughness, air temperature) increases from the water surface upward.

**SUMMARY**

The basic mechanisms of aerodynamics and hydrodynamics in sports have been presented. Performance in particular sports, such as sailing, are heavily dependent on both aerodynamics and hydrodynamics and extensive and continuous research has been conducted over a long period. In general, this has not been the case for many other sports, as the authors have presented recent yet basic findings in some ball sports (tennis, baseball). Aerodynamics and hydrodynamics in sports is a wide-open research field. Significant opportunities exist to advance understanding, create innovation and enhance athletic performance through the study and research of aerodynamics and hydrodynamics problems in sports.

***REFERENCES***

Alaways L.W. (1998) *Aerodynamics of the Curve-Ball: An Investigation of the Effects of Angular Velocity on Baseball Trajectories*. Ph.D. dissertation, University of California, Davis, USA.

Bearman P.W. & Harvey J.K. (1976) Golf Ball Aerodynamics. *Aeronautical Quarterly*, 27, pp. 112-122.

Maglischo E. (1982) *Swimming Faster: A Comprehensive Guide to the Science of Swimming*, Mayfield Publishing Co.

Marchaj C (1979) *Aero-hydrodynamics Of Sailing*. Dodd, Mead & Company, New York.

Mehta R. D. (2000) Cricket Ball Aerodynamics: Myth Versus Science. In: *The Engineering of Sport. Research, Development and Innovation* [eds. A. J. Subic and S. J. Haake], pp. 153-167. Blackwell Science Ltd, Oxford.

Mehta R. D. & Pallis J.M. (2001a) Sports Ball Aerodynamics: Effects of Velocity, Spin and Surface roughness. In: *Materials and Science in Sports*. [eds. F. H. Froes and S. J. Haake], pp. 185-197. The Minerals, Metals and Materials Society [TMS], Warrendale, USA.

Mehta R.D. & Pallis J.M. (2001b) The Aerodynamics of a Tennis Ball. *Sports Engineering*, **4**, 177-189.

Pallis J., Banks D. & Okamoto K. (2000) 3D Computational Fluid Dynamics in Competitive Sail, Yacht and Windsurf Design. In: *The Engineering of Sport. Research, Development and Innovation* [eds. A. J. Subic and S. J. Haake], pp. 153-167. Blackwell Science Ltd, Oxford.

Smits A.J. & Smith D.R. (1994) A New Aerodynamic Model of a Golf Ball in Flight. In: *Science and Golf II* (ed. A.J. Cochran), pp. 341-347. E. & F.N. Spon, London.

Watts R.G. & Sawyer E. (1975) Aerodynamics of a Knuckleball. *American Journal of Physics*, **43**, 960-963.

Watts R.G. & Ferrer R. (1987) The Lateral Force on a Spinning Sphere: Aerodynamics of a Curveball. *American Journal of Physics*, **55**, 40-44.

Whidden T. & Levitt M. (1990) *The Art and Science of Sails*. St. Martin's Press, New York.