Sports Ball Dynamics

Trajectory of sports balls (tennis, cricket, soccer, ping-pong, baseball, golf, etc.) complex and counterintuitive, e.g., curve, swing, hook, swerve, slice, etc. Effects spin important.

Cricket Ball

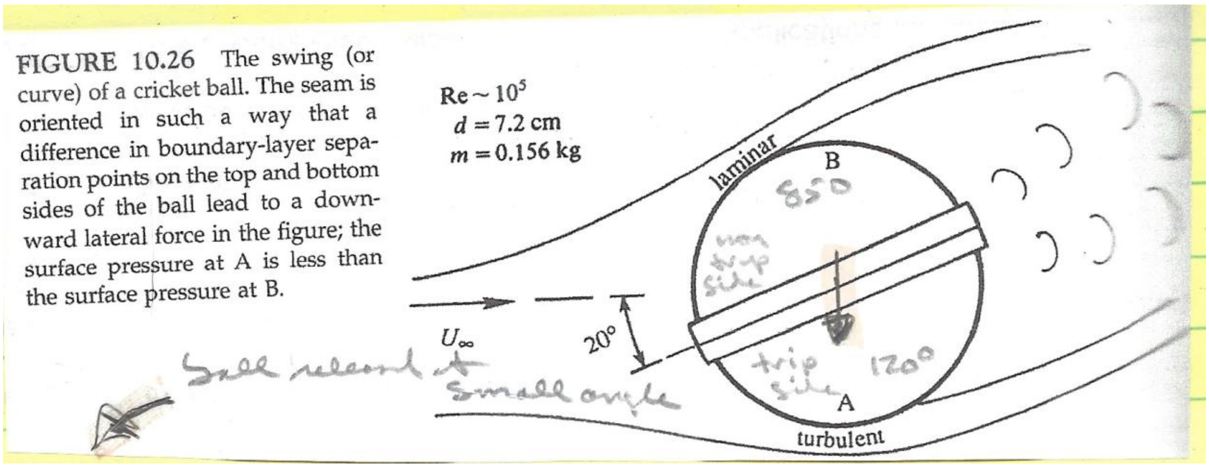


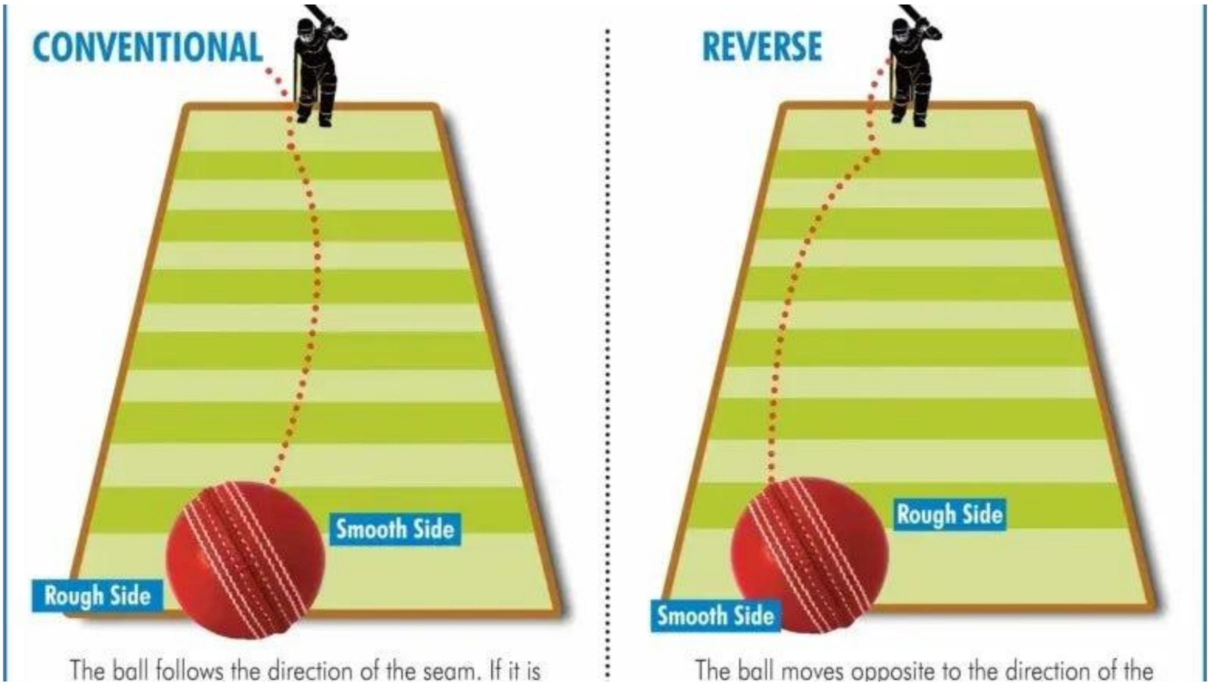
FIGURE 10.26 The swing (or curve) of a cricket ball. The seam is oriented in such a way that a difference in boundary-layer separation points on the top and bottom sides of the ball lead to a downward lateral force in the figure; the surface pressure at A is less than the surface pressure at B.

Looking downward bends to left outswinger vs. inswinger with seam opposite direction and upward force

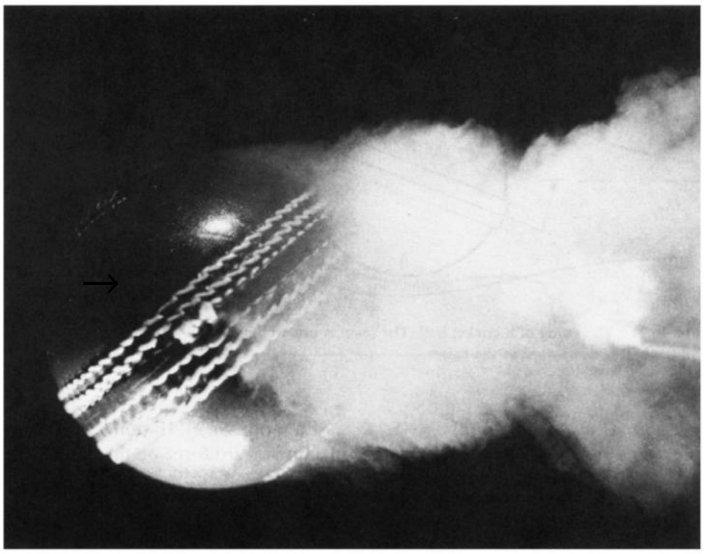
1 mm high seam whose orientation bends flight path for speeds ~ 30 m/s, i.e., $Re \sim 10^5 < Re_{crit} = 5 \times 10^5$ since seam trips lower side BL inducing turbulent flow while upper side remains laminar

A similar potential flow $C_p = 1 - \frac{9}{4}\sin^2\theta\,|_{\pi/2} = -\frac{5}{4}$ vs. B viscous flow higher C_p $\therefore$ downward side force


HOW TO BOWL OUTSWING
SHINY SIDE
OUT-SWING GRIP


CONVENTIONAL
Smooth Side
Rough Side
The ball follows the direction of the seam. If it is
REVERSE
Rough Side
Smooth Side
The ball moves opposite to the direction of the

delayed
separation
seam side



wake deflected
upward

40° release angle

FIGURE 9.24 Smoke photograph of flow over a cricket ball in the same orientation and flow condition as that depicted in Figure 9.23. The flow is from left to right, the seam angle is 40°, the flow speed is 17 m/s, and Re = 0.85 × 10^5. *R. Mehta,* Ann. Rev Fluid Mech. ***17****: 151–189, 1985. Photograph reproduced with permission from the* Annual Review of Fluid Mechanics, *Vol. 17 © 1985 by* Annual Reviews, www.AnnualReviews.org.

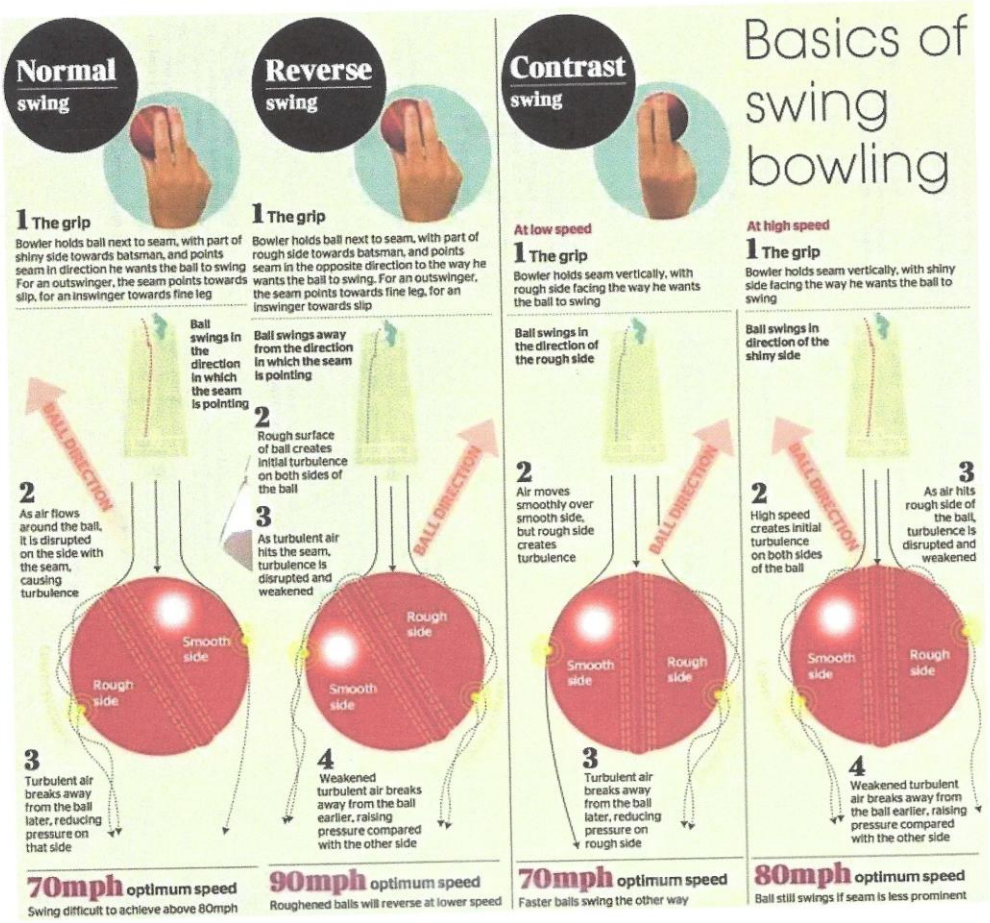
upward force exerted on fluid by ball ⇒ downward force on ball by fluid

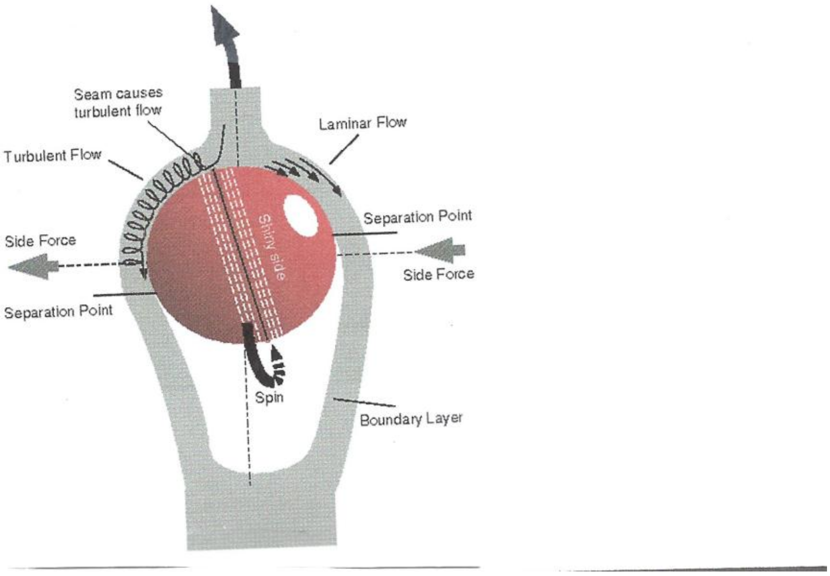
Back spin prevents wobble. Side force 40% weight. Deflection $\propto time^2$ ⇒ parabolic path that bends as much as 0.8 m when reaches batter.

Too slow no bending as seam not effective trip BL

Too fast both sides turbulent also old ball roughness induces turbulence both sides

Effects humidity also causes swing but not yet explained since such effects only change Re by 2% and not enough affect separation.


Basics of swing bowling
Normal swing
1 The grip
Bowler holds ball next to seam, with part of shiny side towards batsman, and points seam in direction he wants the ball to swing. For an outswinger, the seam points towards slip, for an inswinger towards fine leg
Ball swings in the direction in which the seam is pointing
BALL DIRECTION
2
As air flows around the ball, it is disrupted on the side with the seam, causing turbulence
Smooth side
Rough side
3
Turbulent air breaks away from the ball later, reducing pressure on that side
70mph optimum speed
Swing difficult to achieve above 80mph
Reverse swing
1 The grip
Bowler holds ball next to seam, with part of rough side towards batsman, and points seam in the opposite direction to the way he wants the ball to swing. For an outswinger, the seam points towards fine leg, for an inswinger towards slip
Ball swings away from the direction in which the seam is pointing
2
Rough surface of ball creates initial turbulence on both sides of the ball
3
As turbulent air hits the seam, turbulence is disrupted and weakened
BALL DIRECTION
Rough side
Smooth side
4
Weakened turbulent air breaks away from the ball earlier, raising pressure compared with the other side
90mph optimum speed
Roughened balls will reverse at lower speed
Contrast swing
At low speed
1 The grip
Bowler holds seam vertically, with rough side facing the way he wants the ball to swing
Ball swings in the direction of the rough side
2
Air moves smoothly over smooth side, but rough side creates turbulence
BALL DIRECTION
Smooth side
Rough side
3
Turbulent air breaks away from the ball later, reducing pressure on rough side
70mph optimum speed
Faster balls swing the other way
At high speed
1 The grip
Bowler holds seam vertically, with shiny side facing the way he wants the ball to swing
Ball swings in direction of the shiny side
BALL DIRECTION
2
High speed creates initial turbulence on both sides of the ball
3
As air hits rough side of the ball, turbulence is disrupted and weakened
Smooth side
Rough side
4
Weakened turbulent air breaks away from the ball earlier, raising pressure compared with the other side
80mph optimum speed
Ball still swings if seam is less prominent

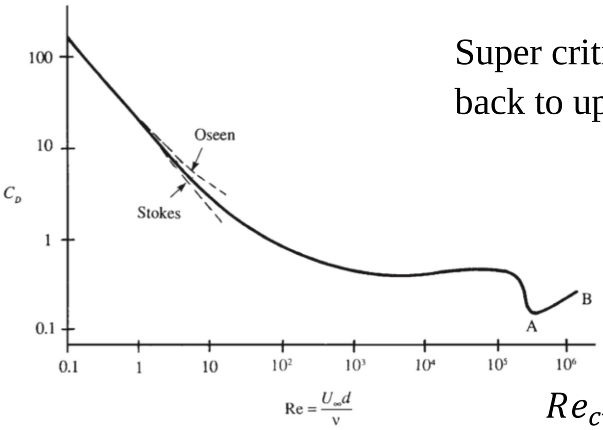

Seam causes turbulent flow
Laminar Flow
Turbulent Flow
Separation Point
Side Force
Shiny side
Side Force
Separation Point
Spin
Boundary Layer

Tennis Ball

Bending due spin: top spin curves downward back spin flatter path. Similar Γ as per cylinder flow with vortex but in this case, differences $Re < Re_{crit}$ (especially for top spin) due asymmetric BL

Separation: deflection rotating sphere called Robins effect

FIGURE 9.22 Measured drag coefficient, C_D, of a smooth sphere vs. $Re = U_\infty d/\nu$. The Stokes solution is $C_D = 24/Re$, and the Oseen solution is $C_D = (24/Re)\quad(1 + 3Re/16)$; these two solutions are discussed at the end of Chapter 8. The increase of drag coefficient in the range A–B has relevance in explaining why the flight paths of sports balls bend in the air.

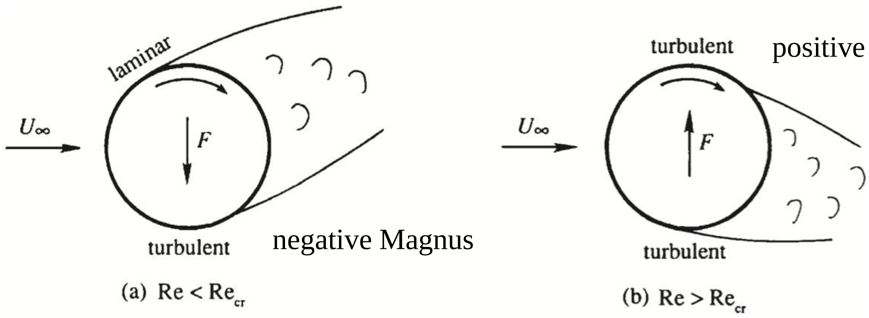


Super critical Re θ_S moves back to upstream

$Re_{crit} = 5 \times 10^5$

Top spin

FIGURE 9.25 Curving flight of rotating spheres, in which F indicates the force exerted by the fluid: (a) negative Magnus effect; and (b) positive Magnus effect. A well-hit tennis ball with spin is likely to display the positive Magnus effect.



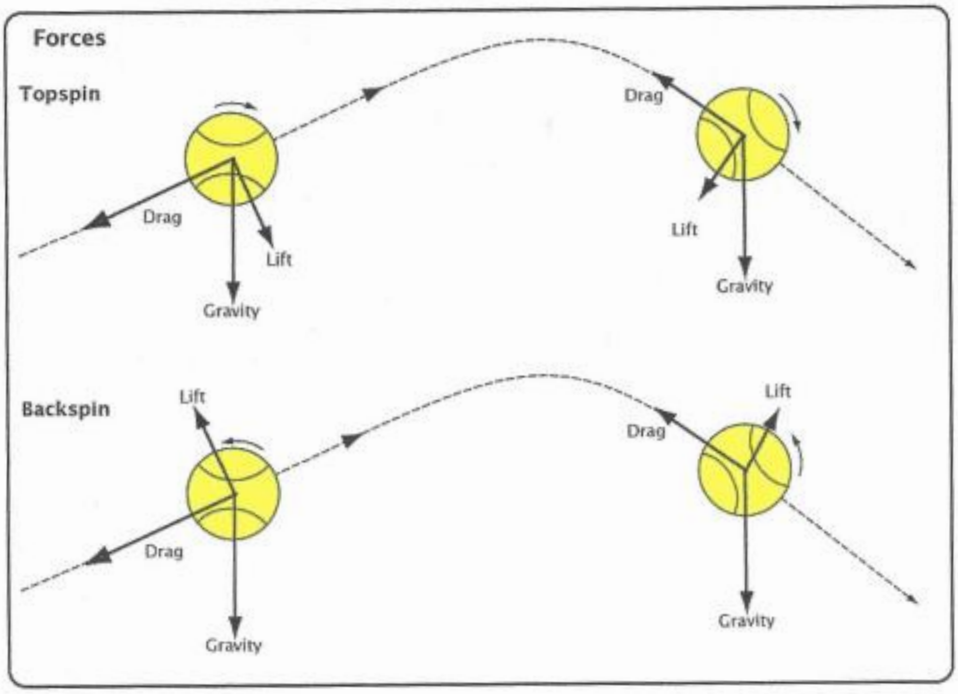
negative Magnus

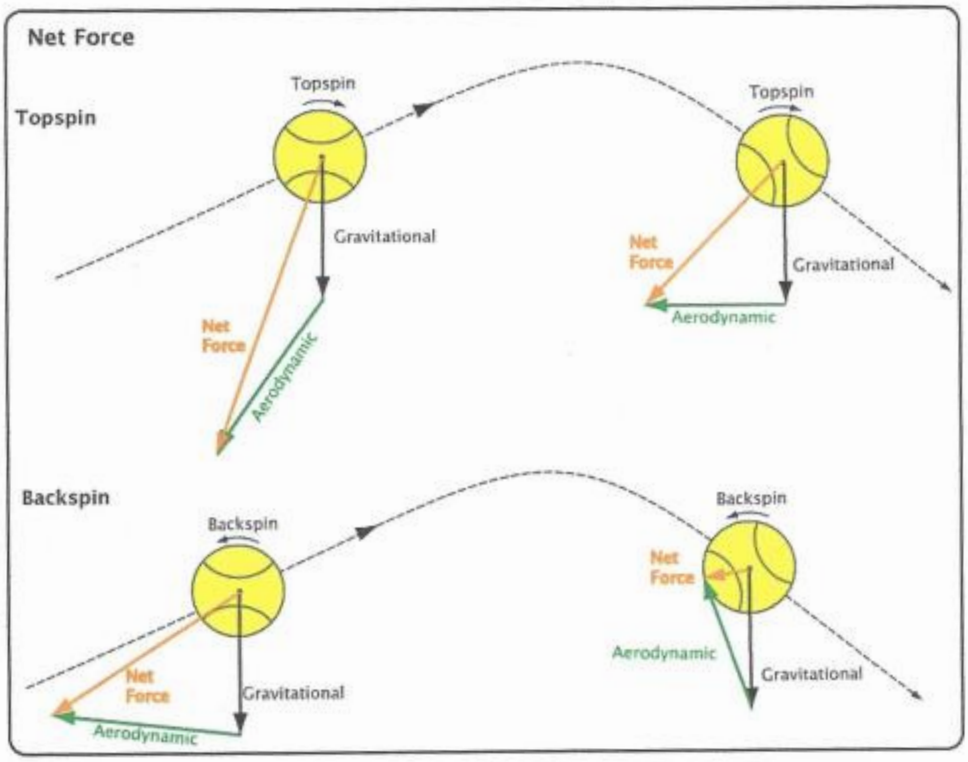
positive Magnus

Larger relative velocity lower side $Re < Re_{crit}$ induces transition lower side, i.e., Re velocity $U_\infty - \omega R$ top vs. $U_\infty + \omega R$ bottom.

$Re < Re_{crit}$: negative Magnus effect, i.e., opposite side force to that with Γ same sense on sphere rotation

$Re > Re_{crit}$: both sides turbulent $\therefore$ positive Magnus effect since even though relative velocity effects same Magnus effect dominates.


Forces
Topspin
Drag
Lift
Gravity
Drag
Lift
Gravity
Backspin
Lift
Drag
Gravity
Lift
Drag
Gravity


Net Force
Topspin
Topspin
Gravitational
Net Force
Aerodynamic
Topspin
Net Force
Gravitational
Aerodynamic
Backspin
Backspin
Net Force
Gravitational
Aerodynamic
Backspin
Net Force
Aerodynamic
Gravitational

Baseball

$Re \sim 1.5 \times 10^5$

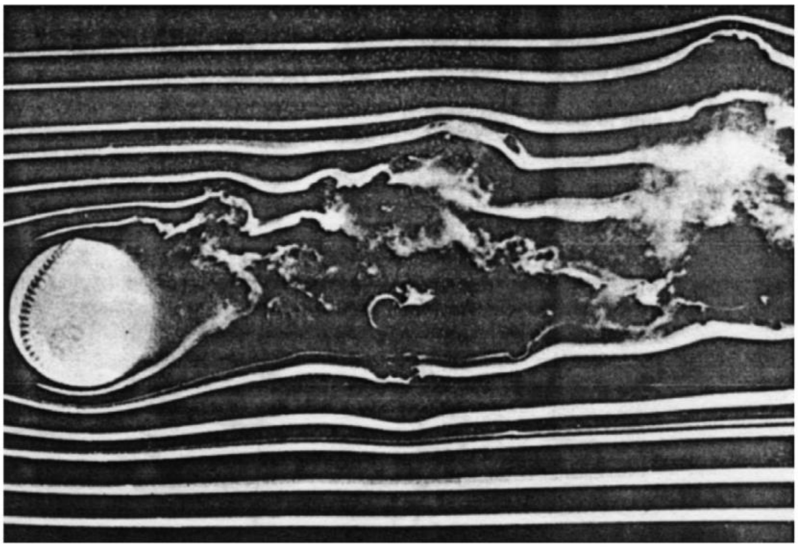
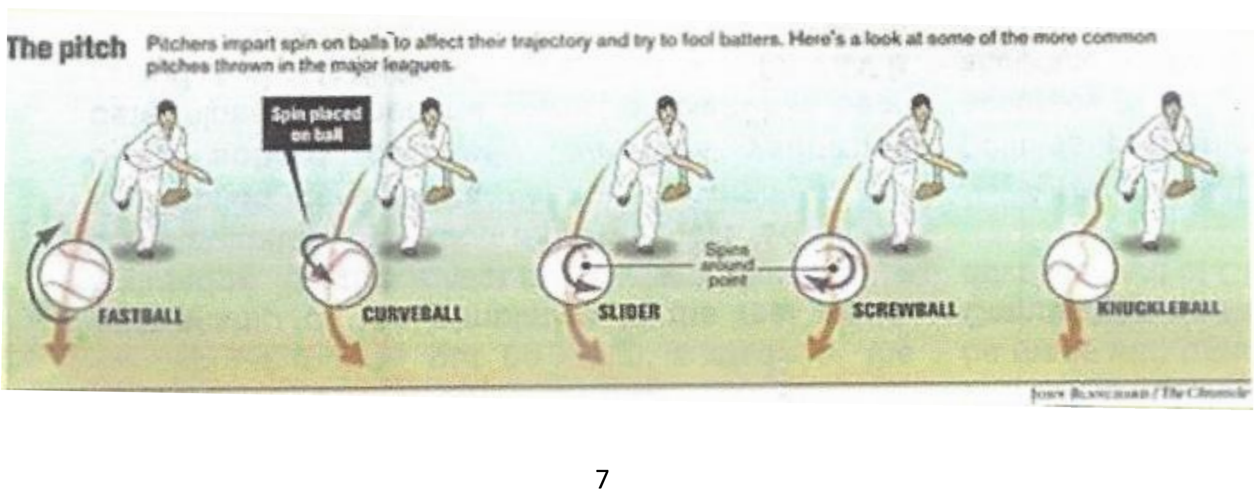


FIGURE 9.26 Smoke photograph of flow around a spinning baseball. Flow is from left to right, flow speed is 21 m/s, and the ball is spinning counterclockwise at 15 rev/s. *[Photograph by F. N. M. Brown, University of Notre Dame.] Photograph reproduced with permission from the* Annual Review of Fluid Mechanics, *Vol. 17 © 1985 by* Annual Reviews, www.AnnualReviews.org.

Curveball: side spin to bend away from throwing arm

Screw ball: opposite

Knuckle ball: no spin and path dependent orientation seam as per cricket ball but in this case irregular trajectory due seam pattern



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AERODYNAMICS OF SPORTS BALLS

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1. INTRODUCTION

Aerodynamics plays a prominent role in almost every sport in which a ball is either struck or thrown through the air. The main interest is in the fact that the ball can be made to deviate from its initial straight path, resulting in a curved flight path. The actual flight path attained by the ball is, to some extent, under the control of the person striking or releasing it. It is particularly fascinating that not all the parameters that affect the flight of a ball are under human influence. Lateral deflection in flight (variously known as *swing*, *swerve*, or *curve*) is well recognized in cricket, baseball, golf, and tennis. In most of these sports, the swing is obtained by spinning the ball about an axis perpendicular to the line of flight, which gives rise to what is commonly known as the *Magnus effect*.

It was this very effect that first inspired scientists to comment on the flight of sports balls. Newton (1672), at the advanced age of 23, had noted how the flight of a tennis ball was affected by spin, and he gave this profound explanation: "For, a circular as well as a progressive motion . . ., its parts on that side, where the motions conspire, must press and beat the contiguous air more violently than on the other, and there excite a reluctancy and reaction of the air proportionably greater." Some 70 years later, in 1742, Robins showed that a transverse aerodynamic force could be detected on a rotating sphere. However, Euler completely rejected this possibility in 1777 (see Barkla & Auchterlonie 1971). The association of this effect with the name of Magnus was due to Rayleigh (1877), who, in his paper on the irregular flight of a tennis ball, credited him with the first "true explanation" of the effect. Magnus had found that a rotating cylinder

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moved sideways when mounted perpendicular to the airflow. Rayleigh also gave a simple analysis for a "frictionless fluid," which showed that the side force was proportional to the free-stream velocity and the rotational speed of the cylinder. Tait (1890, 1891, 1893) used these results to try to explain the forces on a golf ball in flight by observing the trajectory and time of flight. This was all before the introduction of the boundary-layer concept by Prandtl in 1904. Since then, the Magnus effect has been attributed to asymmetric boundary-layer separation. The effect of spin is to delay separation on the retreating side and to enhance it on the advancing side. Clearly, this would only occur at postcritical Reynolds numbers ($Re = Ud/\nu$, where U is the speed of the ball or the flowspeed in a wind tunnel, d is the ball diameter, and ν is the air kinematic viscosity), when transition has occurred on both sides. A smooth sphere rotating slowly can experience a negative Magnus force at precritical Reynolds numbers, when transition occurs first on the advancing side.

Most of the scientific work on sports ball aerodynamics has been experimental in nature and has concentrated on three sports balls: the cricket ball, baseball, and golf ball. Details of these three balls, together with typical operating conditions, are given in Figure 1.

The main aim in cricket and baseball is to deliberately curve the ball through the air in order to deceive the batsman or batter. However, the tools and techniques employed in the two sports are somewhat different, which results in the application of slightly different aerodynamic principles. An interesting comparison of the two sports is given by Brancazio (1983). In golf, on the other hand, the main aim generally is to obtain the maximum distance in flight, which implies maximizing the lift-to-drag ratio. In this article, the more significant research performed on each of the three balls is reviewed in turn, with emphasis on experimental results as well as the techniques used to obtain them. While many research papers and articles were consulted in preparing this review, only those that have made relevant and significant contributions to the subject have been cited. For an overview of the physics of many ball games, see Daish (1972).

2. CRICKET BALL AERODYNAMICS

2.1 *Basic Principles*

The actual construction of a cricket ball and the principle by which the faster bowlers swing the ball is somewhat unique to cricket. A cricket ball has six rows of prominent stitching, with typically 60–80 stitches in each row (primary seam). The stitches lie along the equator holding the two leather hemispheres together. The better quality cricket balls are in fact made out of four pieces of leather, so that each hemisphere has a line of internal stitching forming the "secondary seam." The two secondary seams,