THE FLUID MECHANICS OF SPORTS BALLS

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Abstract.

The objective of this project is to determine what principles of fluid dynamics influence the performance of sports balls. The study was accomplished using a wind tunnel to evaluate lift and drag and produce flow visualization studies of a baseball, cricket, golf, and tennis balls. The findings result from the way the balls' exteriors react with the surrounding fluid (air).

Utilizing a Jet Stream 500 wind tunnel which measures lift and drag, several aerodynamic principles came into play when testing was performed. Bernoulli's theorem explains the production of side and lift forces on sports balls consequent to their surface features. These directional changes are best seen in the knuckle-ball and cricket ball. Aerodynamics of sports balls is strongly dependent on the development and behavior of the boundary layer on the balls' surface.

The critical Reynolds number is the speed at which flow becomes turbulent. Increasing surface roughness decreases the critical Reynolds number, which is best demonstrated in the dimpled golf ball.

Flow visualization studies were utilized to spot flow separation points as related to surface features-allowing comparison of various sports balls.

The fluid mechanics of sports balls directly affect athletic performance. This is vital information for maintaining interest and competitive competency in athletic games. I hope to use this information to design better-performing sports balls which comply with current regulations and enhance athletic performance and popularity.

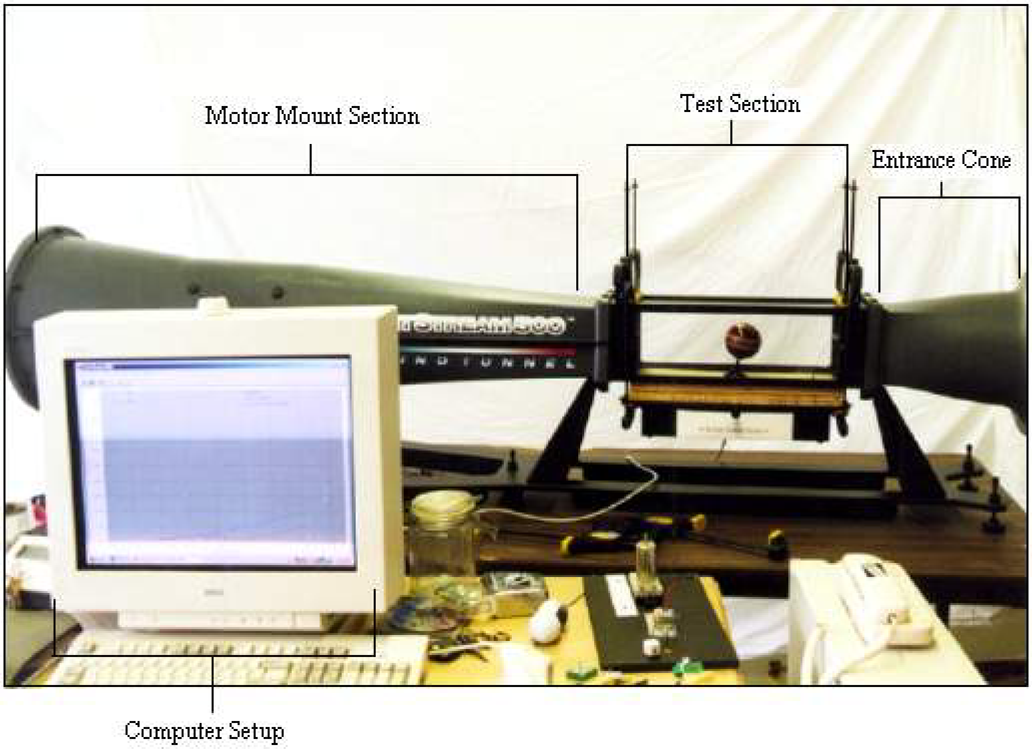
Introduction.

This research was begun after I was invited to the NASA/Ames Research Center, Moffet Field, CA. I was introduced to the idea of testing sports balls after reviewing the ongoing studies of viscous flow around spheres in the fluid dynamics laboratory. I had already constructed a wind tunnel for my previous research on golf balls in flight. However, it was clear that an instrument with greater wind speed capacity was necessary. Fortunately, I was offered the use of a commercially produced unit with available software to measure the lift and drag of the test object.

Procedure.

Wind and flow visualization studies were performed using a Jet Stream 500 wind tunnel manufactured by Interactive Instruments, Inc. (518-347-0955) www.interactiveinstruments.com . In order to test balls of varying diameters in the wind tunnel, a drop down section was constructed out of 1.9cm plywood. This was attached to the top of the test section floor, allowing 3cm more vertical dimension to accommodate the larger sports balls to be tested.

To maintain a constant horizontal flow of air, a “drop down cover” was made by cutting a piece of cardboard to fit around the mount instrumentation.



Customized metal mounts had to be developed to hold the heavier and larger test balls. This was done by cutting a piece of 0.3cm aluminum to fit over the gap of the stock mounting plate. Holes were then drilled into the aluminum to complete the mounting adaptation. This was used for all mounted objects that do not properly fit on the provided mounting plates, which were mounted with sheet metal screws. A small Allen wrench was supplied by Interactive Instrument, Inc., to tighten the Allen screw at the base of the mount.

Using the included software, both lift and drag were measured and recorded for various sports balls as the wind speed was increased from zero to 75mph. The wind tunnel was connected to a DELL computer using the USB port 1.

Testing was ready to begin once the wind tunnel was leveled, and the intake and out take areas are unobstructed. A 1-2 minute warm up period was used prior to actual testing and data gathering.

Testing began with a tare study measuring lift and drag on the empty test chamber. A standard curve was then produced using smooth wooden spheres measuring 1, 1.5, and 2 inches in diameter.

All sports balls were tested five times at varying angles to the horizontal. Mounting was done according to the following positioning protocol:

1. 1. Baseball - placed on the mount similar to position when pitched, as if the ball were lying on the part where two fat ends of the figure eight pattern come nearest and the figure eight was parallel to the line of flight. Also, to achieve the asymmetric boundary layer, the ball must be angled 10° away from the direction of the wind flow.
2. 2. Cricket ball - placed on mount with seams horizontal, perpendicular to the mount, with the rough side facing up. The seam angle is defined as the angle difference between the seam of the ball and the horizontal. Changing the seam angle allows for the measurement of side force on the cricket ball.
3. 3. Tennis ball - the tennis ball was mounted same as the baseball, but the angle of attach stays at 0°. This should really have no affect on the performance of the ball, however, because in flight the fuzz is blown over and covers up the seams of the tennis ball.
4. 4. Golf ball - because the golf ball is perfectly symmetric, the ball is simply mounted on the mount at an angle of attack of 0°.

Carefully following the directions in the Jet Stream 500 manual, all balls were tested a minimum of five trials.

Wind visualization studies were accomplished using dry ice. A cooler containing dry ice was connected to the air intake chamber of the wind tunnel by a hose and soda straws. Six straws were used to create two horizontal rows (three each). This was used to straighten and direct the smoke for photographic purposes. Photographs were made with an EOS III Cannon camera with ASA 200 Kodak color Gold film, using a 2 second shutter speed. Dry ice was placed in a two and a half gallon cooler using thick gloves and goggles. Hot water was placed on the dry ice to create smoke. A copper funnel covered the cooler and was connected to the straws by a plastic tube, and a small florescent strip over the test chamber provided the only light.

Eye protection was worn throughout testing. Gloves were also worn when handling dry ice for flow visualization studies.

Data

Baseball at 65mph	Drag(lbs)	Lift(lbs)
Rough		
Test 1	0.35	0.15
Test 2	0.34	0.15
Test 3	0.34	0.16
Test 4	0.33	0.16
Test 5	0.32	0.16
Average	0.336	0.158
Smooth		
Test 1	0.28	0.02
Test 2	0.28	0.03
Test 3	0.28	0.03
Test 4	0.32	0.02
Test 5	0.3	0.02
Average	0.292	0.024

Table (A-1). Comparison of the difference of drag and lift between a smooth and rough baseball.

Tennis Ball at 70mph	Drag(lbs)	Lift(lbs)
Regular		
Test 1	0.35	0.1
Test 2	0.38	0.1
Test 3	0.39	0.14
Test 4	0.38	0.15
Test 5	0.38	0.15
Average	0.376	0.128
Smooth		
Test 1	0.25	0.1
Test 2	0.25	0.9
Test 3	0.25	0.1
Test 4	0.26	0.1
Test 5	0.25	0.1
Average	0.252	0.26
Fuzzy		
Test 1	0.6	0.01
Test 2	0.59	0.01
Test 3	0.56	0
Test 4	0.57	0
Test 5	0.61	0.03
Average	0.586	0.01

Table (A-2). Comparison of the difference of drag and lift between a regular, smooth and fuzzy tennis ball.

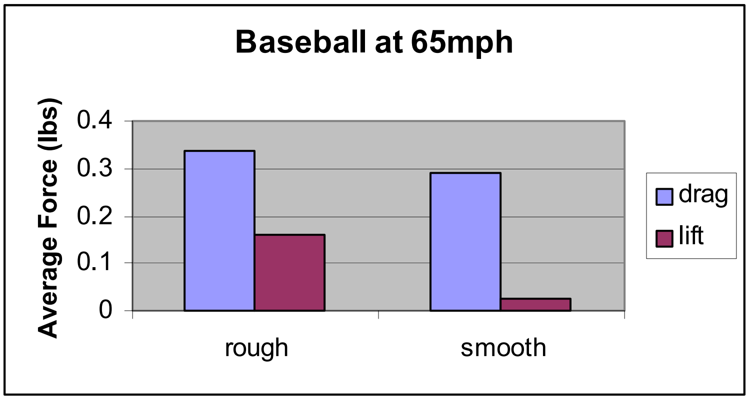
Golf Ball at 75mph	Drag(lbs)	Lift(lbs)
Dimpled		
Test 1	0.13	0.19
Test 2	0.14	0.19
Test 3	0.15	0.19
Test 4	0.14	0.19
Test 5	0.13	0.18
Average	0.138	0.188
Smooth		
Test 1	0.15	0.1
Test 2	0.16	0.11
Test 3	0.15	0.1
Test 4	0.16	0.11
Test 5	0.16	0.11
Average	0.156	0.106

Table (A-3). Comparison of the difference of drag and lift between a dimpled and smooth golf ball.

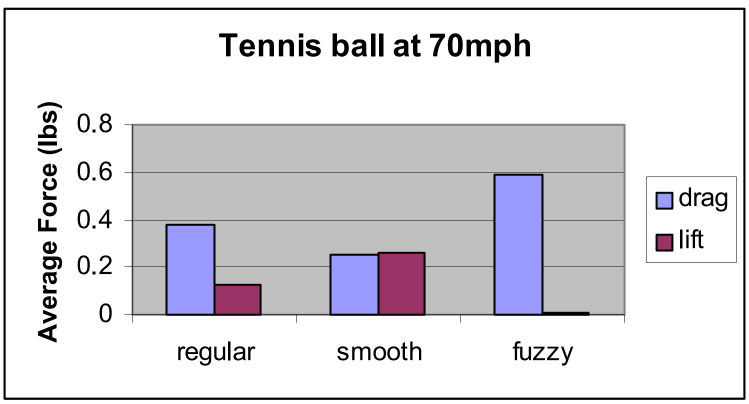
Cricket Ball at 70mph	Drag(lbs)	Lift(lbs)
-10°		
Test 1	0.34	0.36
Test 2	0.34	0.36
Test 3	0.33	0.34
Test 4	0.34	0.35
Test 5	0.35	0.36
Average	0.34	0.354
-20°		
Test 1	0.32	0.45
Test 2	0.32	0.46
Test 3	0.32	0.45
Test 4	0.3	0.45
Test 5	0.3	0.47
Average	0.312	0.456
-30°		
Test 1	0.31	0.39
Test 2	0.31	0.41
Test 3	0.33	0.4
Test 4	0.33	0.4
Test 5	0.33	0.41
Average	0.322	0.402

Table (A-4). Comparison of the difference of drag and lift between cricket balls with seam angles of -10°, -20° and -30°.

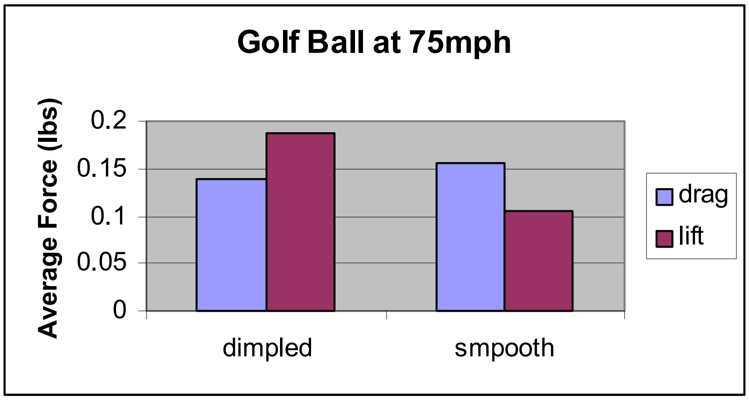
Results.



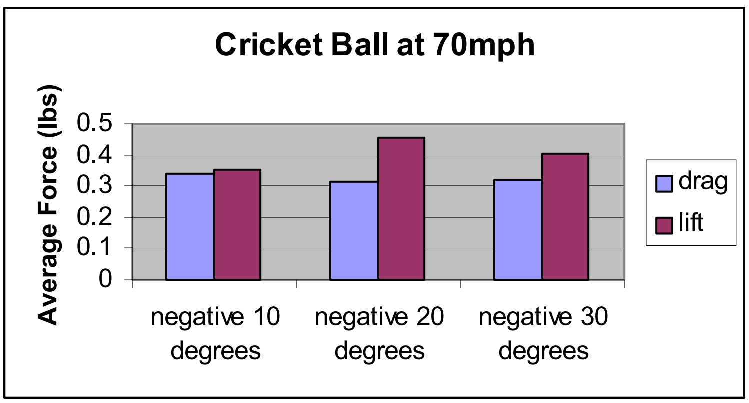
Graph (B-1). Comparison of the difference of drag and lift between a rough and smooth baseball.



Graph (B-2). Comparison of the difference of drag and lift between a regular, smooth and fuzzy tennis ball.



Graph (B-3). Comparison of the difference of drag and lift between a dimpled and smooth golf ball.



Graph (B-4). Comparison of the difference of drag and lift between cricket balls with seam angles of -10°, -20° and -30°.

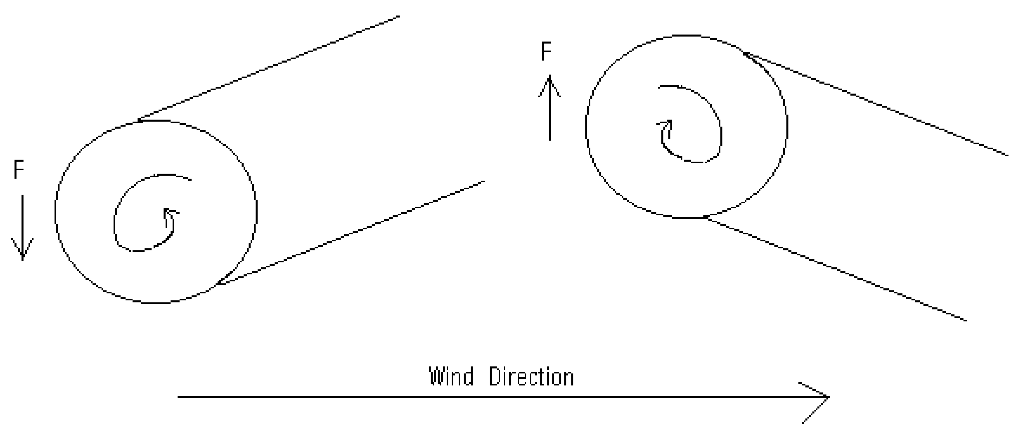
Discussion.

At some point in time, many of us have wondered what puts the curve in Randy Johnson's curve ball, the drop in Venus William's serve, or the flight in Tiger Wood's drive. The answers to these questions all share the common principles of fluid mechanics.

Isaac Newton was the first person to describe the curved flight of a tennis ball. Since that time, other scientists have defined the forces that put the "sport" in sports balls.

The laws of fluid mechanics govern the movement of sports balls as they travel through the air. For proper understanding, a few definitions are necessary. Viscosity is the degree of "stickiness" found in gases and liquids. Friction is the resistance to a ball's flight due to the viscosity of air. The boundary layer is the layer of air on the surface of the ball. It is composed of two regions or states: 1) laminar, with smooth air layers sliding by each other. The inner most layer of stagnant air is known as the Prandtl layer; and 2) turbulent, with the air moving irregularly. This turbulent air sticks to the ball longer, allowing less drag and changing the direction of the ball. The velocity at which this occurs is the transition zone.

Because deviation from a straight line of flight is central to a sport, Gustav Magnus' original explanation of side force is crucial to explaining a ball's seemingly magical movement. He discovered that lateral deflection is produced by spinning the ball about an axis perpendicular to the line of flight. When a ball spins, the boundary layer of air asymmetrically breaks away from its surface thus causing the ball to swerve from a linear path.

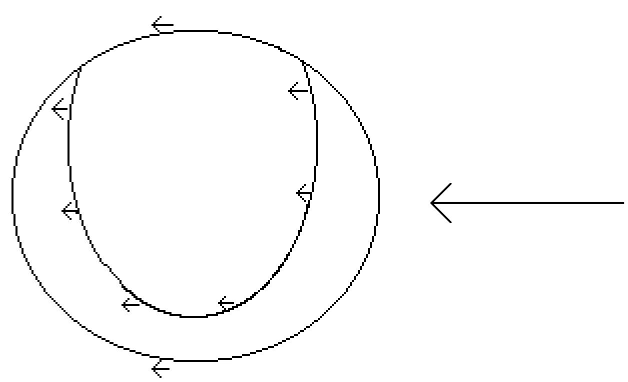


Drag is directly related to both velocity and diameter of the ball; and, inversely, to the viscosity of the fluid. Osborne Reynolds took both of these factors into consideration and derived the Reynolds number (Re), which is a dimensionless value calculated by the product of velocity (**u**) and size of the object (***d***), divided by the air viscosity ($\overline{\sqrt{\ }}$). Through wind tunnel tests, it has been found that as the velocity on a sphere is increased in a fluid (such as air), the boundary layer is tripped from laminar to turbulent. Precritical Re is the term used to define the flow of air on a sphere before the boundary layer has been tripped. After the boundary layer has been tripped, and the drag is greatly decreased, the term postcritical Re is applied.

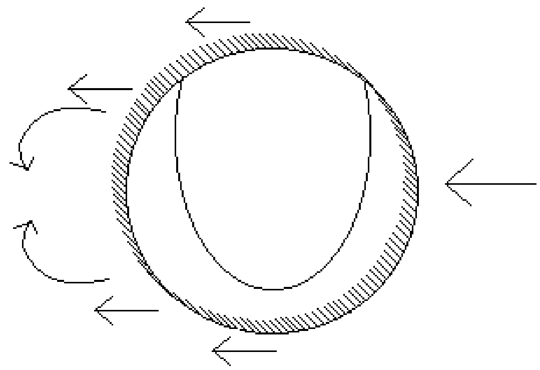
$$Re = \frac{U d}{\nu}$$

All sports balls have surface features that which help produce their characteristic eccentricities of flight. The current study has evaluated the role of these surface features using nonspinning balls. Of greatest curiosity is the fact that the surface features have their greatest influence in the speed range where the individual sports are played. In other words, changing the regulation height or figure eight pattern of baseball stitches would make the new ball virtually useless in the game, as we now know it. Also, significant deepening of the dimples on a golf ball would greatly increase the amount of drag, shortening its flight. Finally, decreasing a tennis ball's fuzz would make it virtually impossible to return a professional's serve because of the ball's decreased drag and increased speed.

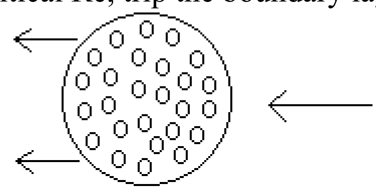
The baseball's raised stitches cause turbulent airflow in an erratic pattern, resulting in the fluttering flight of the non-spinning knuckleball. This was demonstrated in this study by the graphically changing lift and drag measurements of the unspun baseball. Also demonstrated was the effect on lift and drag of a roughened baseball surface. Roughening the surface of a baseball is so effective in altering its flight path, this practice is now illegal. This pattern is caused by the random tripping of the boundary layer by the stitches. As a pitcher delivers a baseball, above 50mph (postcritical Re), the Magnus effect causes the ball to curve. The direction of the curve depends on the angle of delivery from the pitcher's hand. The fastball rises as it nears home plate because of the lift generated by the Magnus effect caused by backspin on the ball as it is released.

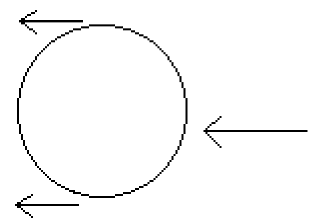


The tennis ball's fuzz greatly increases drag. Flow visualization images in this study demonstrate a fixed turbulent boundary layer is obtained by the tennis ball for the entire Re range. During play it has been proven that the tennis ball looses its fuzz; and, therefore, has decreased drag and travels faster. Unlike the baseball, the seams of a tennis ball are inverted and covered under fuzz that is laid down in flight thus eliminating the seams as an aerodynamic factor. This was confirmed in the current study by a gradually increasing pattern of drag with an increasing wind speed. In addition, the current testing reveals a direct relationship between fuzz height and drag when shaved, regulation, and fluffed tennis balls are compared. Today, with professional player serving speeds becoming overwhelming fast, there is a move to enlarge the size of the official tennis ball, thereby increasing the drag and slowing the ball's speed.



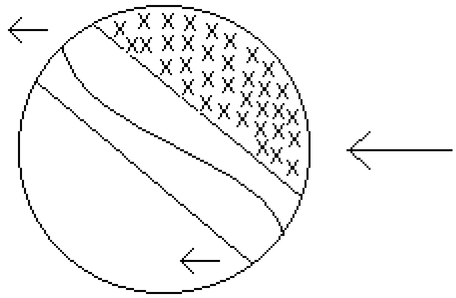
In this investigation, greater drag is measured on a smooth golf ball when compared with a dimpled golf ball. The effect of dimples is to lessen drag, trip the boundary layer, and allow for further flight when hit off the tee. For this reason the dimples act like baseball stitches to cause early boundary layer separation, less drag and greater flight distance. Curiously, the importance of the irregular surface to enhanced flight distance was first realized when 19^{th} century golfers discovered that their heavily used and scared gutta percha balls went further than they did when they were new and smooth. The effect of the dimples is to lower the critical Re, trip the boundary layer and decrease drag.





The cricket ball is another ball that is governed by the Magnus effect. This is not because of spin but because of asymmetric boundary layer separation consequent to the cricket ball's unique design.

The cricket ball has a raised seam around its equator. In a new ball it is 1mm above the surface and composed of six rows of stitches. The ball is thrown spinning on an axis perpendicular to the plane of the seam. It is thrown with the seam angled away from the batter, but at the time of release, the initial force is directed toward the batter. The seam causes an asymmetric boundary layer that which results in side force and causes a nearly parabolic flight path. Also, the bowler (pitcher) is allowed to roughen the surface of the ball. However, to allow asymmetric separation, an experienced bowler only roughens one hemisphere. As also shown for a baseball in this study, the roughness causes the airflow to change from laminar to turbulent. In turn, this causes the air to "stick" to the ball longer, resulting in less drag. In flight, the viscous fluid "sticks" to the rough half of the cricket ball, and does not separate from the ball until it reaches the seam. On the smooth side, the viscous fluid separates earlier from the ball. This asymmetric boundary layer separation causes the side force. Also, the difference in drag between the two hemispheres causes a degree of side force.



Understanding the “sport” in sports balls would not be possible without knowledge of fluid mechanics. In concert with historical evolution and chance, this field of scientific knowledge has allowed us to understand the performance of sports balls we have today and, hopefully, will help us to create better ones for tomorrow.

Conclusion.

My hypothesis is accurate. The principles of fluid mechanics and Newtonian physics determine the performance of all sports balls. The surface features of sports balls affect boundary layer separation, lift, drag and their pattern of flight.

Stitches on a baseball allow it to curve in flight. The fuzz on a tennis ball causes greater drag and increased playability. The dimples on a golf ball provide decreased drag, greater lift and further flight. Finally, the raised seam of a roughened cricket ball causes side forces, which allow for a curved flight path.

Understanding these principles, I hope to develop sports balls with improved performance, providing enhanced enjoyment of the individual sport.

Acknowledgments.

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