Bending a soccer ball with math

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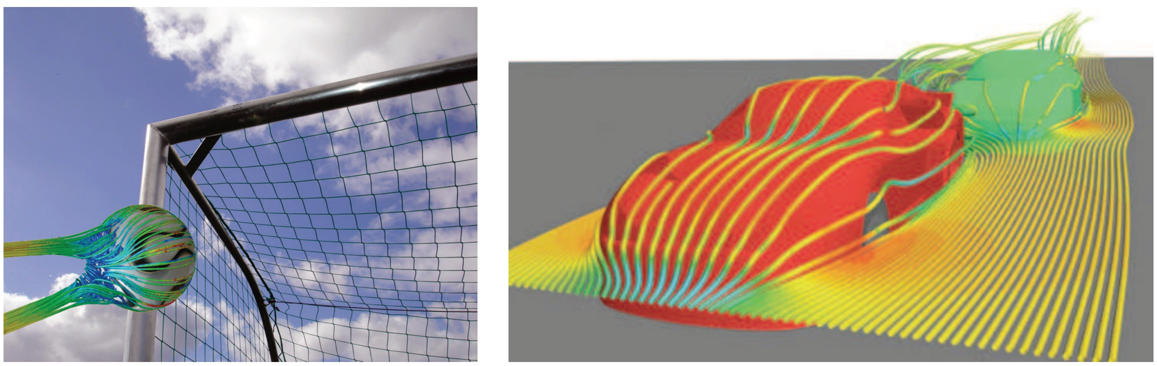
The aerodynamics in sports has been studied ever since Newton commented on the deviation of a tennis ball in his paper *New theory of light and colours* published in 1672. Today, the field of computational fluid dynamics (CFD) studies the affect of aerodynamics in such sports as soccer and NASCAR racing as seen in Figure 1.



(a) (b)

Figure 1: CFD studies aerodynamics in sports. In (a), CFD research predicts the fight of a soccer ball. In (b), a simulation of two NASCAR cars visualizes the streamlines of air produced as a car drafts and is about to pass another.

Soccer matches are filled with complex aerodynamics as evidenced in the way balls curve and swerve through the air in an attempt to confuse goalkeepers and make their way to the back of the net. World class soccer players such as Brazil's Roberto Carlos, Germany's Michael Ballack and England's David Beckham use such behavior to their advantage, especially from a free–kick.

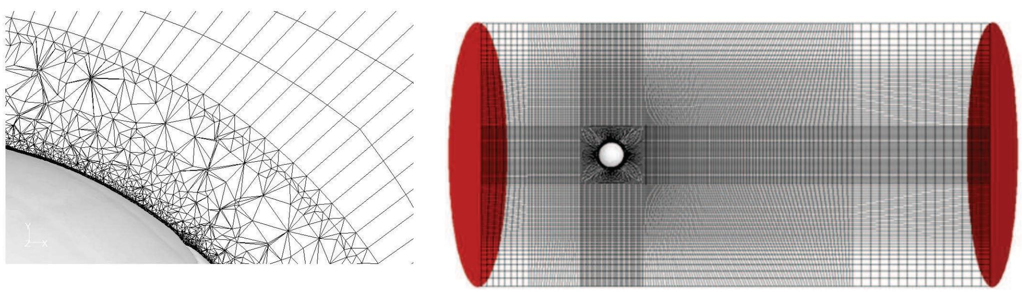
According to research by the University of Sheffield's Sports Engineering Research Group and Fluent Europe, the shape and surface of the soccer ball, as well as its initial orientation, play a fundamental role in the ball's trajectory through the air. In particular, such CFD research has increased the understanding of the "knuckleball" effect sometimes used to confuse an opposing goalkeeper who stands as the last line of defense. The research group focused on shots resulting from "free–kicks" in which the ball is placed on the ground after a foul, for instance.

Calculating the trajectories of objects is a common topic in the calculus curriculum but such problems generally assume the presence of no air resistance. Drag forces play an important role in the path of a soccer ball and can be split into two main types: skin friction drag and pressure drag. Skin friction drag is caused when air molecules adhere to the surface of the ball, which results in friction from the interaction of the two bodies. Pressure drag occurs on a soccer ball when the air reaches the rear portion of the ball. At this moment, a large area opens up for the airflow and since the amount of moving air per unit area must be constant, since we are not adding or removing air, the flow must slow down. This phenomenon is known as flow separation and results in a wake forming behind a body as seen behind moving boats.

A soccer ball has a steep surface which results in a large wake. So, pressure drag dominates. In contrast, the body of the racing car in Figure 1 (b) is streamlined resulting in much smaller amounts of pressure drag. For this case, friction drag dominates.

Laminar flow occurs when the streams of air flow in parallel layers. In contrast, turbulent flow is characterized by chaotic disruption between the layers. Laminar flow is clearly seen in Figure 1 (b) toward the front of the lead car, whereas turbulent flow occurs with the streamlines between the cars. These two flows play an important role on the trajectory of a soccer ball.

A turbulent boundary layer results in the mixing of air flows, which produces more energy close to the soccer ball. As such, the turbulent boundary will have a smaller wake. For soccer balls, a turbulent boundary layer results in a lower total drag than a laminar boundary layer. As such, a transition to laminar airflow will cause a soccer ball to slow down quite suddenly and also potentially drop in the air. The seams of a soccer ball are important as they encourage turbulent flow in comparison to a perfectly smooth sphere with no stitching.



(a) (b)

Figure 2: An important step in CFD simulations is capturing the geometry of a soccer ball with a 3D non-contact laser scanner. The mesh in (a) has approximately 9 million cells. Keep in mind that the air around the ball (b) is meshed as to determine the flow of air throughout a ball's trajectory.

With the surface of an object playing such a critical role, an important step in CFD simulations of soccer balls is capturing the geometry of the ball with a 3D non-contact laser scanner. The resulting mesh digitizes the surface of the ball down to its stitching as seen in Figure 2 (a). Note the refinement near the seams, which is required in order to properly model the path of air in the immediate vicinity of the ball's surface. Since 1970, the official tournament ball of the World Cup has been produced by adidas for the competition, which is held every four years. From this set of tournament balls produced by adidas, four balls with different panel designs were selected to be scanned. Among the digitized balls was the adidas Teamgeist ball used in the 2006 World Cup.

Some free–kicks in soccer have an initial velocity of almost 70 mph. Wind tunnel experiments demonstrated that a soccer ball transitions from laminar to turbulent flow at speeds between 20 and 30 mph, which depended highly on the ball's surface structure and texture.

The techniques developed in Sheffield facilitated detailed analysis of the memorable goal by David Beckham of England versus Greece during the World Cup Qualifiers in 2001. A foul on an English player resulted in a free–kick at a distance of about 29 yards from the goal. A group of defenders, known as the defensive wall, stood side by side on the field between the ball and Greece's goal. Beckham's shot left his foot at about 80 mph. The ball cleared the defensive wall by about one and a half feet while rising over the height of the goal. As it ended its flight, the ball slowed down to 42 mph and dipped into the corner of the net. Calculations showed that the flow around the ball transitioned from turbulent to laminar flow several yards from the goal else it would have missed the net and gone over the goal's crossbar.

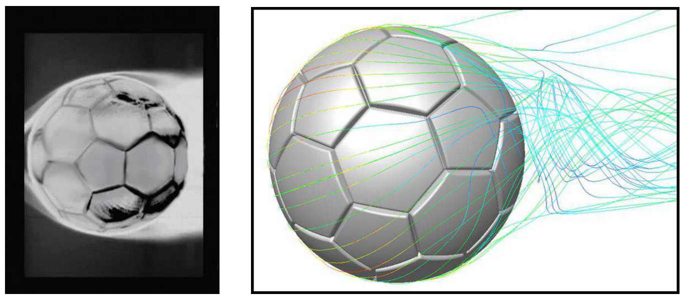


Figure 3: (left) Wind tunnel smoke test of a non-spinning soccer ball. (right) CFD simulation showing wake flow pathlines of a non-spinning soccer ball, air speed of 27 mph.

In a sense, Beckham's kick applied sophisticated physics. Our understanding of these dynamics could affect soccer players from beginner to professional. For instance, ball manufacturers could exploit such work to produce a more consistent or interesting ball that could be tailored to the needs and levels of players. Such work could also impact the training of players. Among the researchers on this project was Sarah Barber who commented, "As a soccer player, I feel this research is invaluable in order for players to be able to optimize their kicking strategies."

To this end, there is a simulation program called Soccer Sim developed at the University of Sheffield. The program predicts the flight of a ball given input conditions, which can be acquired from the CFD and wind tunnel tests, as well as from high speed videoing of players' kicks. The software can then be used to compare the trajectory of a ball given varying initial orientations of the ball or different spins induced by the kick. Moreover, the trajectory can be compared for different soccer balls.

Analyzing aerodynamics in sports can increase the speed of a bicyclist or bobsledder or produce a more effective fastball or free-kick. CFD research allows for such improvement where much of the work is conducted without the presence of an athlete. The impact of the CFD research of soccer balls will be seen over time and may give more insight on how to bend a soccer ball – regardless of and possibly due to its design.

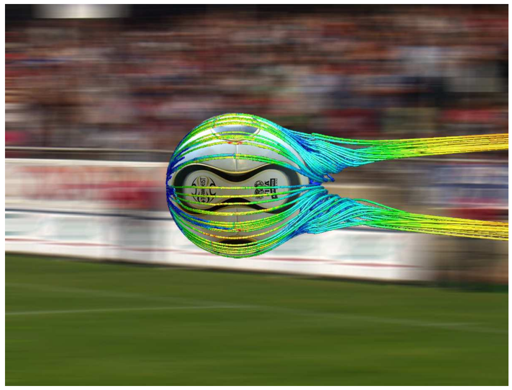


Figure 4: High speed airflow pathlines colored by local velocity over the 2006 Teamgeist soccer ball.

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