

Design of an experiment to test the effect of dimples on the magnitude of the drag force on a golf ball

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ABSTRACT: A subsonic wind tunnel was designed, built and tested using a suspension system, a simple pendulum and a pair of balls to be used in order to test the effects of dimples on the magnitude of the drag force that is exerted on a golf ball during flight. The results of the tests demonstrate that the presence of dimples on a golf ball cause it to experience drag forces that are smaller than those on a smooth ball of the same diameter. These items are being incorporated into the body of experiments that students utilise in the fluid mechanics laboratory at Indiana University-Purdue University Fort Wayne, Fort Wayne, USA, in order to study boundary layers, lift and drag on bluff bodies.

INTRODUCTION

It is well known that the presence of dimples on a golf ball reduces the drag force exerted on it by the surrounding air [1-3]. Indeed, the shape of the dimples, their sizes and the appropriate numbers to be placed on the surface of a given ball continue to be an active area of research because the results thereof affect the claims, sales and performance of different golf balls in the marketplace [4-6].

A typical diagram of experimental results that shows this effect is shown in Figure 1. It can be seen in that diagram that surface roughness reduces the amount of drag on spheres. For golf balls, the reduction is particularly significant when the Reynolds number, based upon the diameter, Re, is in the range of $6\times 10^4 < \mathrm{Re} < 3\times 10^5$.

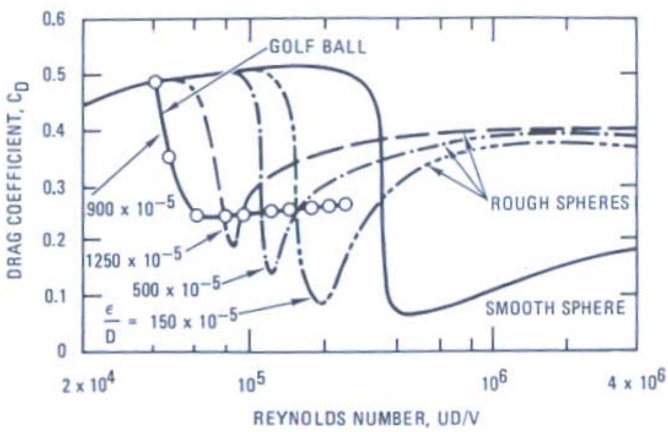

Figure 1: Drag coefficients of smooth or rough spheres [2].

To demonstrate this fascinating phenomenon in a manner that is both accessible and easy to understand, a set of golf balls were purchased, as well as a set of smooth balls of the same dimensions [7-11]. Their weight was altered without changing their surface characteristics. The objective was to measure and compare the drag forces exerted on each ball by a moving air stream in order to assess the effects of dimples on the flight of a golf ball [12].

Each ball was tested in an open-circuit-Eiffel wind tunnel. Wind Tunnel Model 402 B was utilised in this case, which was made by Engineering Laboratory Design (ELD) Inc. and had to be carefully calibrated [9]. The calibration curve obtained is shown in Figure 2.

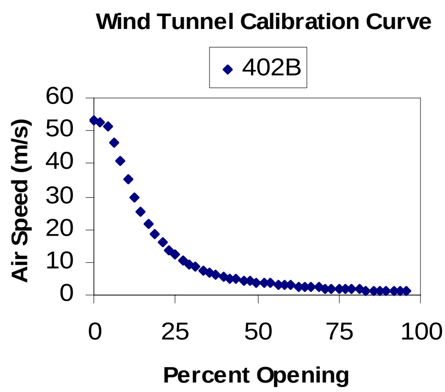

Figure 2: The results of the wind-tunnel calibration.

The air speed could be determined to within ± 0.25 m/s and the angular deflection, θ, could be read to within $\pm 1^0$. For a given trial, the air in the wind tunnel was set to move at a fixed speed. Each ball was then tested at that speed. The speed of the air was changed and the testing protocol was repeated at the new speed. The air speed was increased from 15 m/s (54 km/hr) to 50 m/s (180km/hr) in increments of 5m/s (18 km/hr). This yielded a total of eight different trials for each ball. Test speeds were selected to cover the range for which the

Reynolds number (Re) of each flow was between the following limits: $6 \times 10^4 < \text{Re} < 3 \times 10^5$. As can be seen from Figure 1, this is the flow region for which significant differences in drag performance have been shown to exist between smooth and dimpled spheres [4][13-18]. This region also happens to cover the range of speeds of golf balls during professional competition [1].

THE DESIGN OF BALLS

The objective of this research was to demonstrate to students the effects of dimples by utilising a simple pendulum that would be insertable into the wind tunnel. A golf ball, as well as a smooth ball made of hard rubber, were purchased. The diameter of the smooth ball was 41.73 mm, while that of the golf ball was 41.43 mm. Although the balls had approximately the same diameter, their weights were different due to the differences in their material composition.

A small hole was then drilled into each one and filled with enough lead shots to reach the same target mass of 0.06084 kg that had been set for them. The top of the hole was subsequently sealed and used to attach a small hook onto the ball. The attached hook was used to suspend the ball from the end of a stiff wire of length L, thereby creating a simple pendulum. The free end of the wire was, in turn, connected to a golf-ball suspension system (GBSS), which had been designed for that purpose, as described below.

THE SUSPENSION SYSTEM

The GBSS consisted of a slotted horizontal beam and a vertical plate to which a protractor was attached. The assembly is shown, with ball attached, in Figure 3. When readied for operation, the beam rested on the top of the test section of the wind tunnel. The plate was inserted through the slotted beam and gently lowered into the test section of the wind tunnel until the beam could hold it in equilibrium. The upper end of the wire was loosely hooked onto a smooth pin that was drilled into the vertical plate. The end of the pin projected out of the plate by about 5 mm.

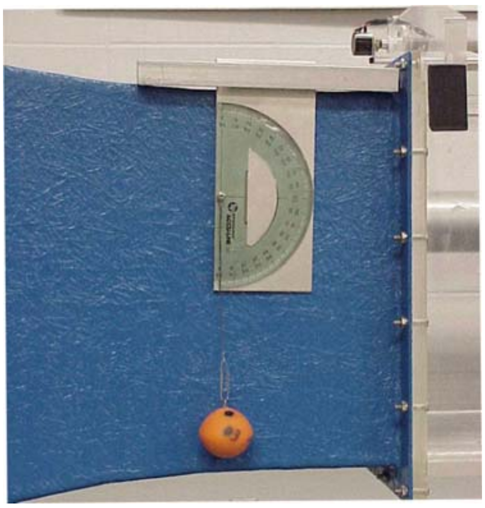

Figure 3: The suspension system with a ball.

A protractor was then attached to the plate in such a way that its centre was occupied by the pin. When at rest, the wire and the ball hung vertically down and the geometric centre of the ball was located at the centre of the test section, as shown in Figure 4.

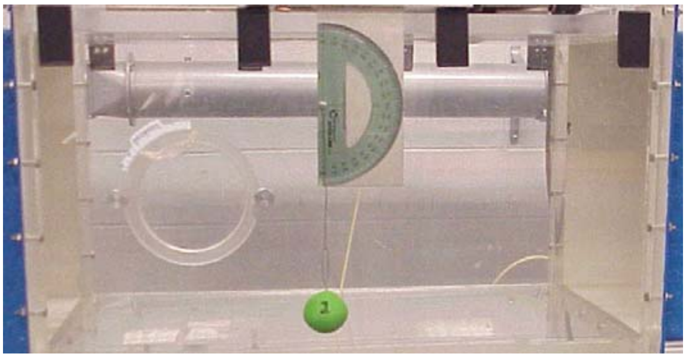

Figure 4: The suspension system in the wind tunnel.

When in operation, wind forces pushed the ball to the right, causing the pendulum to rotate in the vertical plane through an angle θ. In Figure 4, the rotation about the pin was in the counter-clockwise direction. The line formed by the wire against the protractor allowed one to read the equilibrium angle, θ, thereby indicating the amount by which the pendulum had deflected from the vertical.

THE ANALYTICAL MODEL

When each ball was mounted on the suspension system, the ball and the connecting wire moved together as a simple pendulum of length L and of mass m, equal to that of the ball. The mass of the wire and the diameter of the bob were neglected in the analysis. Air blowing through the test section at a steady speed created wind forces that caused the pendulum to swing in the direction of the moving air until a maximum angle of swing θ_{max} was reached.

The force exerted by the moving air on the bob has three components, as follows:

- The horizontal component that is in the direction of air motion is called drag and denoted by F_D;
- The vertical component that tended to raise the ball was called lift and denoted by F_L;
- There was a second horizontal component that was perpendicular to both drag and lift, but this has been neglected in this analysis.

If one assumes that the bob is at rest in the vertical plane at the position of maximum deflection, then applying the equations of equilibrium to the bob leads to the expression for the drag force given by Eq. (1):

$$F_D = \left(1 - \frac{F_L}{mg}\right) mg \tan\theta_{\max} \qquad (1)$$

where F_D is the drag force, F_L is the lift force, m is the mass of the ball, and θ_{max} is the angle that the wire makes with the vertical at equilibrium. Re-arranging Eq. (1) leads to:

$$\frac{F_D}{mg} = \left(1 - \frac{F_L}{mg}\right) \tan\theta_{\max} \qquad (2)$$

If it is assumed that the lift force is much smaller than the weight of each ball, then $\frac{F_L}{mg} << 1$ and Eq. (2) becomes:

$$\frac{F_D}{mg} = \tan\theta_{\max} \qquad (3)$$

It can be seen from Eq. (3) that the drag force increases with the angle that the pendulum makes with the vertical. That force equals the weight when θ_{max} = 45°; it is less than the weight when θ_{max} < 45°; and greater than the weight when θ_{max} > 45°.

If one knows the weight of the ball that is suspended onto the pendulum and can measure the angle that the pendulum makes with the vertical, then, using Eq. (3), one can compute an estimate for the drag force that is exerted on the ball. This implies that the simple pendulum can be utilised as a force transducer. As explained below, Eq. (3) has been used in laboratory exercises in order to determine the effects of dimples on flying golf balls.

TESTING AND RESULTS

A preliminary test was run that was intended to prove the feasibility of the concept. One golf ball and one smooth ball was utilised in a series of trials. For a given trial, the air in the wind tunnel was set to move at a fixed speed. Each ball was then tested at that speed. The speed of the air was changed and the testing protocol was repeated at the new speed. The air speed was varied progressively from 15 m/s (54 km/hr) to 50 m/s (180km/hr) in increments of 5m/s (18 km/hr). This yielded a total of eight different trials for each ball.

The data collected are presented in Figure 5, which presents the average equilibrium angle of each ball versus the air speed in the wind tunnel, using surface roughness as a parameter. One set of data is for the smooth ball and the other for the golf ball. The data showed that the golf ball experienced smaller deflections and, according to Eq. (3), smaller drag forces than the smooth ball across all tested speeds.

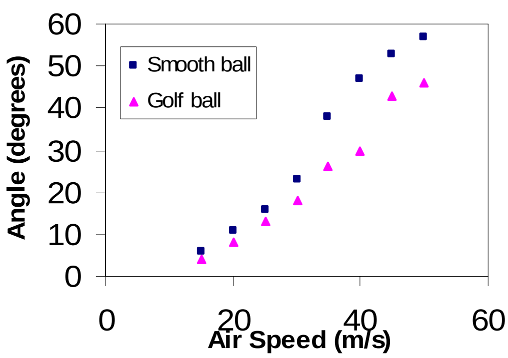

Figure 5: Average angle of the equilibrium of the balls versus air speed.

HOW DIMPLES REDUCE DRAG

The explanation for how dimples reduce drag during the flight of golf balls is found in many books [1][13][19-21], articles [4][5][11][22][23] and Web sites [3][10]. The essence of this explanation is summarised here.

The presence of dimples increases the amounts of energy and linear momentum that are available to those particles of fluid that move in a tiny region near the surface of the ball called the *boundary layer*. The existence and importance of the boundary layer are due to the peculiar behaviour of fluid friction near the surface of a solid body that is in relative motion with the surrounding fluid. In the case of a golf ball, dimples trip air particles that are moving close to them; this disturbance causes the particles to jiggle sideways while they travel forward, instead of staying in *lanes of traffic* that are perfectly parallel to each other at all times, as expected in laminar flow. This jiggling forces particles in adjacent lanes to bump into each other, causing linear momentum to be transferred through bumping. Particles that were moving slowly gain a little more speed; those that were moving fast lose a little speed in the process. Mathematical analyses of the behaviour of flows in this region are called *boundary-layer* theory [7][8][13][24]. Among other results, it indicates two relevant things, namely:

- The changes in velocity noted earlier increase both the kinetic energy and the linear momentum of the whole flow within the boundary layer;
- Turbulent flow has more kinetic energy and more linear momentum than laminar flow. When bumping is vigorous enough, its net result is that the bulk flow of air in the boundary layer becomes turbulent.

Energy and momentum are needed in order to help the moving fluid resist the pressures that oppose its forward motion. It follows that fluid with more linear momentum and more kinetic energy is able to resist adverse pressures over a larger distance along the surface of a round object than fluid with less of both. Eventually, however, adverse pressures succeed in stopping the forward motion of particles along the boundary; this forces later particles to change their paths to avoid getting stuck. Particles change paths by leaving the boundary layer. When this happens, it is said that the fluid has separated itself from the solid boundary. The point at which this occurs is called *the point of separation*. In real flows, the net force due to the pressure that acts on the immersed body as a result of flow upstream of the separation point is always different from that due to the flow downstream from the separation point. The difference between these two forces creates *pressure drag*, which is also called *form drag*. When flow in the boundary layer is turbulent, separation is delayed, meaning that the point of separation is located farther downstream along the body than it would when the flow is laminar. This is illustrated in Figure 6.

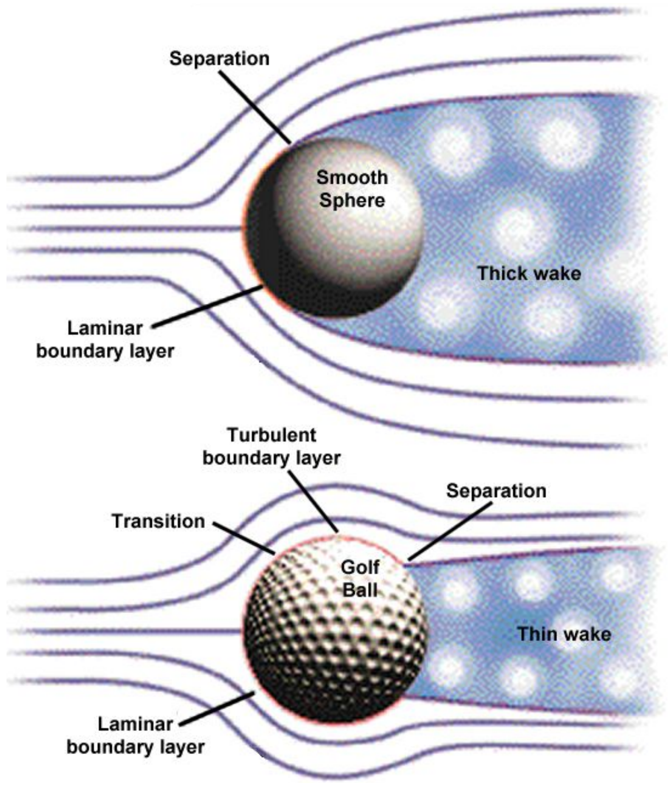

Figure 6: Viscous wake and delayed separation [3].

Therefore, pressure drag is smaller with a turbulent boundary layer than when it is laminar [8-11]. Tangential forces create drag too. However, experiment and analysis show that it is small: less than 5% of the total drag. Thus, when dimples introduce turbulence, separation is delayed, which decreases pressure drag; this, in turn, reduces the magnitude of the total drag on the golf ball relative to what it would be on a smooth ball [1][2].

CONCLUSIONS

An experiment was designed and tested that would utilise the results of Eq. (3) to determine the drag forces on golf balls and smooth balls that are of comparable mass and diameters. A simple pendulum was constructed, test balls obtained and a suspension system built to be used to hold the balls in a wind tunnel. One pair of balls were tested that consisted of a smooth ball and a golf ball of the same diameter and weight across many speeds.

It was found that golf balls experienced drag forces that were smaller than those on smooth balls. This experiment provides a simple way to demonstrate to students the well-known effects of dimples on the flight of a golf ball. This experiment is being expanded by designing five more pairs of balls to be tested; it is also being integrated into the body of hands-on exercises that undergraduate students undertake in the fluid mechanics laboratory.

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