The drag force on an American football

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We have measured the drag coefficient on an American football oriented so that its major axis is pointed directly into the wind. The football was suspended from the top of a wind tunnel by bicycle spokes attached to small bearings. The results are similar to the drag coefficients reported by Rouse (1946) for the case of an ellipsoid with major diameter/minor diameter similar to the length/diameter for the football. The drag coefficient for a spinning football is slightly lower than that for a nonspinning football. Both are in the range of 0.05–0.06, about half the value assumed by Brancazio (1985), about one-third that reported by Rae and Streit (2002) and far smaller than that reported by Cunningham and Dowell (1976).
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INTRODUCTION

Brancazio (1985)[1] stated that it appears that no one has reported information on the drag force on an American football in the open literature. He then performed some computations regarding the flight of a football using drag coefficients for an ellipsoid, which he estimated to be approximately 0.1 when the major axis was pointed into the wind. (The equation defining the drag coefficient is given in the Results section.) The shape of an American football is similar to that of an ellipsoid. A football has more pointed ends, however, and has a rough surface. Rae and Streit (2002)[2] have since reported drag measurements on an American football in a wind tunnel. They found a drag coefficient of approximately 0.15 when the air speed was 60 mph (26.82 m/s). Cunningham and Dowell (1976)[3] earlier reported the effect of air resistance on football trajectories, but instead of reporting drag coefficients they reported the ratio of the actual distance of the trajectory of a kicked football to the theoretical distance of the trajectory with no drag. These results were arrived at by using high-speed photographic analysis of football trajectories of punts by members of the Texas A & M football team. It would be difficult to find the actual drag coefficient from the results reported by Cunningham and Dowell.

However it has been demonstrated by Watts and Bahill (2000)[4] that a baseball travels somewhat less than half the ideal distance when the drag coefficient is 0.5. Thus, we may conclude that the drag coefficient from the data of Cunningham and Dowell was on the order of 0.5, significantly larger than that assumed by Brancazio and that reported by Rae and Streit. We decided to perform drag measurements on a football in the wind tunnel in our Fluid Dynamics Laboratory. We were also interested in determining whether the drag coefficient is different when the ball is spinning on an axis parallel to the flow, since both kicked and thrown footballs do spin. The effect of spin on the drag coefficient of a sphere has been reported by Luthander and Rydberg (1939),[5] who found that the drag coefficient is reduced when the sphere is spinning on an axis parallel to the flow past the sphere.

THE EXPERIMENTAL APPARATUS AND MEASUREMENT METHOD

The test section of our wind tunnel has a cross section of 38×38 cm. If the diameter of an object tested in a wind tunnel is greater than about 1/3 of the lateral dimension of the wind tunnel, the presence of the wall may cause edge effects. In order to reduce edge effects on the drag measurements, we used a football that was somewhat smaller than a standard American college or professional football. We used a foam rubber football (length, 20.8 cm; diameter, 12.7 cm) whose surface roughness and mock strings appeared to be similar to those of a standard football. The length to diameter ratio of the experimental football was 1.64, compared to 1.63 for a National Football League ball. The measurements reported by Rouse[6] were for an ellipsoid with a major to minor diameter ratio of 1.8.

First we drove a 4-mm-diam rod through the ball. Small bearings (1 cm diameter) were placed on the rod snugly against the football as the rod extended from the front and rear of the ball. Very thin wires (guitar strings) were attached to the outer edge of the bearing surfaces with epoxy and bicycle spokes were attached to the wires very close to the bearings so that the ball could swing freely. A schematic drawing of the suspension setup is shown in Fig. 1. The other ends of the bicycle spokes were then affixed to bearings suspended from the top of the wind tunnel in such a way that motion in the downwind direction was unimpeded while sideways drift was prevented (Fig. 2). When the entire apparatus was displaced and then released it was observed to swing freely with very little damping. For the measurements with the ball spinning a tiny (52-g) electric motor was mounted at the rear of the ball. Small wires connected the motor to a variable voltage power supply that rested atop the wind tunnel.

A thrown American football has on average a forward speed of about 20 m/s and a perfect spiral rotates about an axis perpendicular to the forward motion of the ball at about 600 rpm. For a standard football with diameter 17.3 cm, the Reynolds number (defined below) would be 2.16×10^5. With our apparatus we were able to attain Reynolds numbers up to 2.25×10^5 and a rotation rate of 600 rpm. We note that Rae and Streit (2002)[2] used a slightly higher speed (26.82 m/s) in their wind tunnel tests.

First the apparatus was suspended from the top of the wind tunnel without the small electric motor. The wind tunnel was turned on and the wind speed noted from calibration curves.

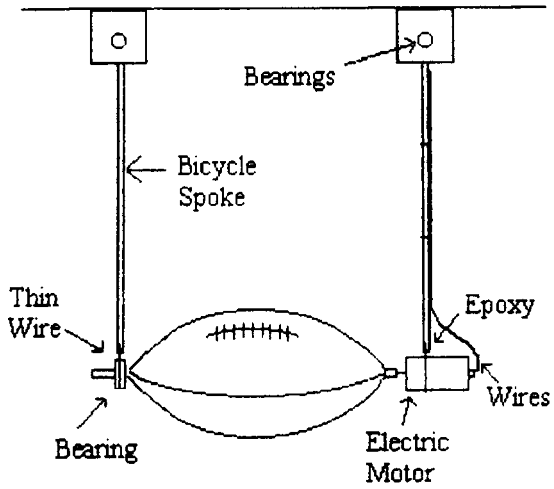

Fig. 1. Schematic of the suspension of the football and the motor.

Table I. Raw data from the experiments.

Speed (m/s)	Angle (stationary)	F_D (N)	Angle (Spinning)	F_D (N)	% decrease
2.8	1.0	0.032	0.3	0.009	73.1
5.5	2.2	0.065	1.8	0.053	18.2
8.4	3.5	0.096	3.2	0.084	12.5
11.3	5.8	0.161	5.5	0.149	7.5
13.9	9.7	0.277	8.8	0.247	11
17	14.3	0.428	13.3	0390	8.8
19.8	19.7	0.610	18.0	0.543	10.9
22.7	25.0	0.810	23.5	0.746	7.9
25.5	29.2	0.969	⋯	⋯	⋯
28.3	35.7	1.271	⋯	⋯	⋯

With the wind tunnel set at a certain speed, the total drag on the apparatus could be calculated from a simple force balance,

$$F_D + 2\, f_D = W \tan(\theta), \tag{1}$$

where F_D is the drag force on the football, $2\, f_D$ is the drag force on the supporting rods, and θ is the angle between the supporting rods and the vertical. W is the weight of the entire apparatus. The supporting rods were cylinders with diameter 1/16 in. (0.00159 m). The drag coefficient on a cylinder has been reported in many textbooks, so that the force f_D could easily be calculated. We chose to measure it using the same method as we used to measure the drag on the football. In order to measure θ, we attached a transparent sheet with lines traced on it to the side of the tunnel. The angle was read visually. The spin rate was measured using a stroboscope.

Data were obtained over a range of ten wind speeds. The procedure was repeated three times for each wind speed and the results averaged for each wind speed. The drag force on the nonspinning ball was nearly identical for the cases where the motor was present and absent. (At equal wind tunnel speeds we could not visually detect a difference between the angle θ with and without the motor. It was certainly less than half a degree.) We then repeated the experimental method for a single supporting rod to obtain f_D.

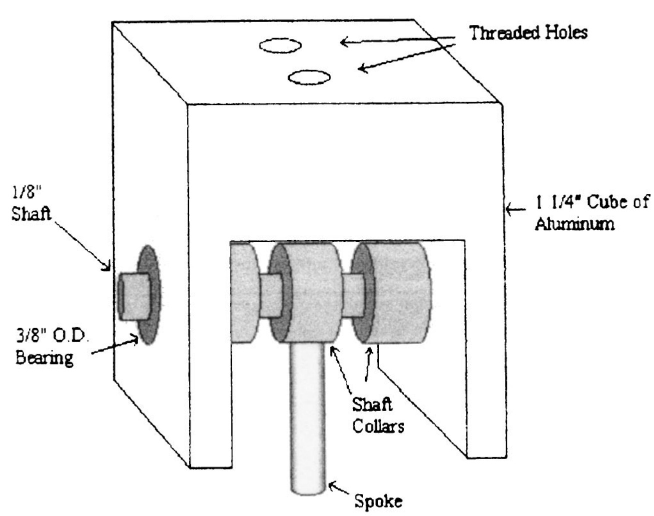

Fig. 2. Bearings in the suspension.

RESULTS

Drag data are normally reported as a drag coefficient $C_D = F_D / 1/2\, V^2\, A$, which is a function of the Reynolds number Re$=V D/$, where V is the wind velocity, is the air density, A is the area normal to the flow, D is the diameter of the football, and is the kinematic viscosity of the air.

Raw data are given in Table I. Note that data for the spinning case were not obtained for the two highest speeds. Unfortunately, the football began to wobble at these speeds. The rotation rate was maintained near 600 rpm.

The drag force is consistently smaller when the ball is spinning. This was quite clear simply by watching the experimental procedure. If the motor was turned off after one of the runs with the ball spinning one could easily detect the angle increasing as the spin rate decreased.

Figure 3 shows three curves. The triangular data points are those that we measured for the nonspinning case. The circular data points are those that we measured with the ball spinning at 600 rpm. The solid line is taken from the textbook by Rouse and represents the drag coefficient for an ellipsoid with major to minor diameter ratio of 1.8 with its major axis toward the wind. Our measurements show that the drag coefficient used by Brancazio was probably slightly too high and those reported by Cunningham and Dowell were far too high for a football whose long axis is parallel to the flow. For

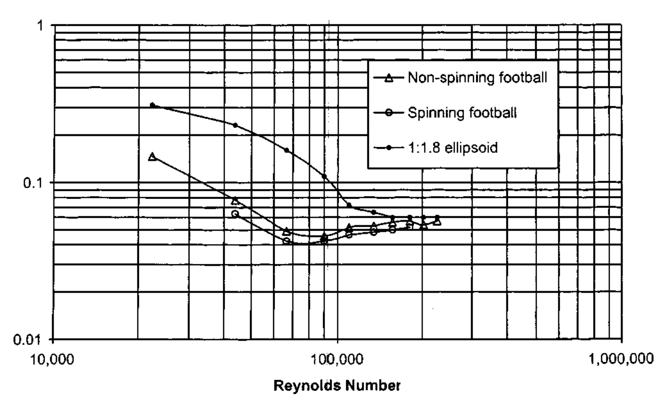

Fig. 3. Football drag coefficients.

forward speeds between 10 and 30 m/s the drag coefficient is in the range of 0.05–0.06. It is smaller by about 10% if the ball is spinning at 600 rpm.

DISCUSSION

The drag force on an object that is moving in a fluid has two components: *viscous drag* and *form drag*. Viscous drag is caused by the viscous force on the surface of the object. Form drag results because flow separation leads to a low pressure wake at the rear of the object. At low speeds (low Reynolds numbers) the viscous drag is the larger of the two. At higher speeds, however, by far the larger of the two drag forces is form drag. One notes, for example, that the drag coefficient show in Fig. 3 is practically independent of Reynolds number when the Reynolds number is greater than 10^5. This is because the area of the wake behind the ball is practically independent of Reynolds number. If the area of the wake decreases (increases) the differential pressure force between the front and real of the ball decreases (increases), decreasing (increasing) the form drag force. Because the motor was mounted near the back of the ball and within the low pressure wake, it would be expected to influence the drag very little, and we found this to be true.

Our measured drag coefficient was much smaller than that inferred from the tests of Cunningham and Dowell. This can be understood by considering the fact that it is very difficult to kick a football in such a way that the major axis is exactly parallel to the direction of motion during its entire trajectory. As shown by Prandtl [reported in Rouse (1946)] the drag coefficient on an ellipsoid with a major to minor axis ratio of 1.00:0.75 with major axis perpendicular to the flow is about 0.6 at a Reynolds number of 10^5, about ten times that of a 1.00:1.18 ellipsoid with major axis aligned with the flow. We can conclude that a small deviation of the major axis from alignment with the flow can have a very large effect on the measured or inferred drag coefficient. The drag coefficient reported by Rae and Streit (2002) was nearly three times as large as the values reported here at high Reynolds numbers. We note that Rae and Streit used a standard size football at a wind speed of 26.82 m/s, which corresponds to a Reynolds number of 2.9×10^5. Figure 3 shows a drag coefficient that is gradually increasing with Reynolds number. However this is not nearly enough to explain the difference between our results and those of Rae and Streit. Rae and Streit commented in their paper that their drag measurements may have been affected by wires connected to an internal motor and other devices that were lead out through a hole in the base of the ball and were fastened to apparatus in such a way that the strain gauge used to measure the axial force may have been affected. On the other hand the football that we used in our experiments was actually a foam rubber ball, and one cannot rule out the possibility that it was smoother than a National Football League game ball.

Why does the drag decrease when the ball is spinning? The wake behind a moving object results when the boundary layer separates from the surface of the ball. For example, in the case of a sphere, separation occurs at an angle of about 110° from the front of the ball when the flow in the boundary layer adjacent to the front of the ball (that is, in the region before separation occurs and the wake forms) is laminar. When the Reynolds number becomes large enough for the flow in this boundary layer to become turbulent, the separation point moves toward the rear of the ball and the wake becomes smaller. When the ball is spinning there is an extra component of the relative speed between the fluid and the surface of the ball. This apparently results in a reduction of the wake area and a subsequent reduction of the drag coefficient on a sphere as reported by Luthander and Rydberg. We suspect that the reduction of the drag coefficient that we measured is caused by this same phenomenon.

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