Aerodynamics of a party balloon

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Abstract. Quantitative experiments are described showing how one can measure the lift and drag coefficients and the buoyant force on a party balloon. A lift coefficient can be used to describe the aerodynamic force that acts on any object when it is spinning.

It is well known that a party balloon can be made to fly erratically across a room, but it can also be used for quantitative measurements of other aspects of aerodynamics. Since a balloon is light and has a large surface area, even relatively weak aerodynamic forces can be readily demonstrated or measured in the classroom. Accurate measurements can be made of drag and buoyant forces, and reasonable estimates can also be made of the Magnus force on a spinning balloon.

The Magnus force acts in a direction perpendicular to both the direction of motion and the spin axis, and plays a dominant role in many ball sports. For example, when a golf ball is launched with backspin, the Magnus force acts vertically upwards on the ball and allows it to travel an even greater distance than it would in a vacuum, at least at the low launch angles used by golfers when driving the ball. In tennis, topspin allows a player to hit the ball almost as hard as he or she likes and still get the ball to land in the opposite court. In that case, the Magnus force acts downwards. When a ball is thrown horizontally and spins about a vertical axis, the Magnus force causes the ball to swerve in a horizontal direction at right angles to the path of the ball. In baseball, a pitcher needs to have a good working knowledge of how the Magnus force can be used to confuse the batter.

Buoyant Force

In the experiments described below, I used a small party balloon inflated to a diameter of 20 cm. It was slightly elliptical, being 25 cm in overall length and with a volume of approximately 0.00557 m^3. Since the density of air at room temperature is 1.21 kg/m^3, the mass of the displaced air was 6.75 gm. Before inflation, the balloon weighed 1.30 gm. For this measurement I used a digital scale costing about \$100 with a resolution and an accuracy of ± 0.01 gm. After inflation, the balloon weighed 1.55 gm. The mass of the inflated balloon was therefore 1.55 + 6.75 = 8.3 gm. On the weighing scale it registered only 1.55 gm since the air exerted a buoyant force lifting it up against the force of gravity. Since the rubber itself had a mass of 1.30 gm, the air inside the balloon had a mass of 7.0 gm. This is slightly larger than the mass of the displaced air since the air inside the balloon was at a proportionally higher pressure.

Drag Force

If a balloon or any other object is falling at speed v through the air, then the air exerts an upwards force on the balloon called the drag force. The formula for the drag force is

$$F_D = C_D \, d \, A \, v^2 / 2$$

where C_D is the drag coefficient, d is the density of the air and A is the cross-sectional area of the balloon. For a balloon of radius R, $A = \pi R^2$. For a circular disk, $C_D = 1.0$. For a sphere, $C_D = 0.5$ at low speeds. For a streamlined object, C_D can be less than 0.1.

In order to get a nice vertical drop I needed to tie a 2.1 gm nut onto the bottom of the balloon using a light cotton thread. Without the nut, the balloon tended to rotate and to veer off to one side. The acceleration of the balloon as it was falling is given by

$$F = ma = mg - F_B - F_D$$

where F_B is the buoyant force (mass of displaced air times g). At the start of the fall where v = 0, the drag force is zero so $a = g - F_B/m$. This works out to be 3.5 m/s^2, which is close to the value 3.8 m/s^2 that I measured. The acceleration was measured by filming the balloon with a video camera at 25 frames/sec, transferring a clip to a computer and measuring the vertical position of a selected point at intervals of 0.04 s. Software was used to fit a fourth order polynomial to the position data, from which I determined the velocity and the acceleration, as shown in Fig. 1.

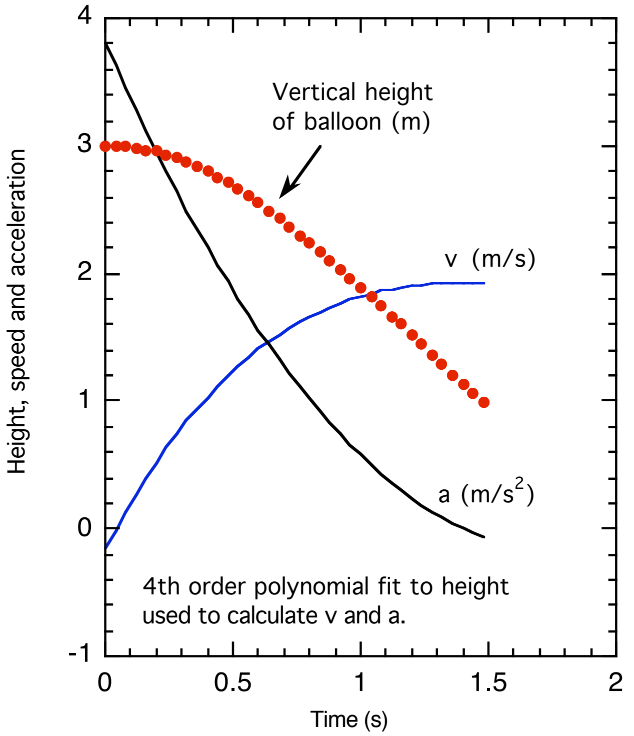

Fig. 1. Results obtained by dropping a balloon from a height of 3 m.

A terminal velocity of 1.95 m/s was reached when a = 0 and then $F_D = mg - F_B$. Using this formula I found that Cd = 0.50, which is the value expected for a slowly moving spherical ball. Part of the reason that a balloon falls slowly is that the drag force slows it down, but the buoyant force also plays a big role. Both of these forces are negligible compared to the force of gravity on say a 145 gm baseball falling through a height of only a few metres, although the drag force is important at the higher ball speeds used in the game of baseball.

Other authors[1, 2] describe similar experiments with a falling balloon but do not quote a measured drag coefficient.

Magnus Force

To investigate the Magnus force on a spinning balloon, I removed the nut at the bottom of the balloon and added a 0.67 gm strip of adhesive tape around the circumference, partly to increase its rotational inertia and partly to stabilise its rotation. Without the tape, the balloon tended to wobble and to twist around as it fell The additional inertia allowed the balloon to spin for a longer time without slowing down so rapidly. The addition of another 2 or 3 gm of string tied around the circumference of the balloon helped to reduce the angular deceleration even further.

The Magnus force F_M acting on a spinning ball travelling at speed V is given by

$$F_M = C_L \, d \, A \, V^2 / 2$$

where C_L is called the lift coefficient, d is the density of the air and A is the cross-sectional area of the ball. The formula is essentially the same as that for the drag force but the lift coefficient is generally smaller than the drag coefficient. The coefficient is called a lift coefficient since the Magnus force is a vertical lift force on say a golf ball moving horizontally with backspin. In fact, the Magnus force acts horizontally on a ball moving vertically, and it acts vertically down on a ball travelling horizontally with topspin. The Magnus force exists only if the ball is spinning and it increases with the rate of spin. The formula here doesn't show the spin effect, but C_L depends on the rate of spin, being roughly proportional to the rate of spin (and is zero when the spin is zero).

The balloon was spun by hand. I found that the best technique was to throw it upwards slightly as I spun it. That way I was able to get the balloon to drop vertically at the start so I could more easily observe and measure the effect of the sideways Magnus force. The Magnus force is proportional to the spin rate and to V squared, so there is only a weak sideways force at the start of the fall since v is low. As the balloon fell towards the floor its spin rate decreased but its speed increased, with the result that the balloon deflected sideways in the expected direction. The Magnus force acts on the whole balloon in the same direction as the direction of rotation of the leading (bottom) edge.

A horizontal deflection of at least 0.5 m is easily obtained after a vertical drop of only about 2 m, as shown in a video film on my sports physics web page[3]. As expected, the direction of the Magnus force reverses when the spin direction reverses. A baseball pitcher achieving a result like this would be worth his weight in gold. While quantitative measurements can be made of the lift coefficient (I found $C_L \sim 0.1$ at 4 rev/sec), I feel that the main value of this experiment is as an excellent classroom demonstration that can also be repeated by a student at home. The horizontal deflection is so large that the net horizontal force can even drop to zero. Since the balloon falls to the floor at an inclined angle, the horizontal component of the drag force (which acts backwards along the balloon’s trajectory) tends to cancel the horizontal component of the Magnus force acting in a direction perpendicular to the trajectory.

References

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