09/24/01

rev. 10/25/02

Experiment 3 – Terminal Velocity and Air Resistance

Objective

In this experiment you will determine the terminal velocity of a falling object. In addition, you will investigate the velocity-dependence of the force of air resistance.

Equipment

- Pasco Scientific Motion Sensor Model CI-6742
- Science Workshop 750 Computer Interface
- Science Workshop Version 2.3.2 Data Acquisition Software for Windows
- Basket-Type Coffee Filters
- Balance

Theory

A common misnomer is that astronauts experience zero g's during space flight. In fact, astronauts experience the g value at their location, which, for missions orbiting the earth, is only slightly less than what we experience here on the surface. Instead, astronauts in orbit around the earth experience free fall motion in the same way that skydivers do. (There is simply no air pushing against them.) Free fall motion provides the sensation called "weightlessness". However, astronauts and skydivers are not actually "weightless".

The difference between skydivers and astronauts can be illustrated by looking at the forces acting upon them. An astronaut orbiting the earth feels only one force, the force of gravitational attraction to the earth. A skydiver, on the other hand, feels two forces: gravitational attraction to the earth and air resistance. Different net forces cause different types of motion. Since an astronaut feels only one force, the net force can not be zero. Newton's Second Law states that this type of situation causes accelerated motion. In this case, the astronaut is accelerating toward the center of the earth with centripetal acceleration (we will have more to say about this situation later on in the course). Because a skydiver feels two forces, the net force may or may not be zero. The value of the net force depends upon the magnitude and direction of each of these forces. Newton's First Law, the Law of Inertia, states that *a net force of zero causes an object to be at rest or in motion with constant velocity.* The purpose of this lab activity is to investigate the second part of this statement.

Air resistance is not a constant force. As you fall through air (or water or oil) a viscous force, air resistance, is generated as you push the molecules out of the way. This force increases with your velocity, the density of the medium and your cross-sectional area. A skydiver, after jumping out of a plane, eventually comes to be in equilibrium when air resistance balances the force of gravity pulling downwards. At this point, the net force is zero and the velocity becomes constant. This constant velocity is known as *terminal* *velocity.* Since our insurance was cancelled after the last class "jump", you will explore this phenomenon using coffee filters.

What does it mean for the net force on an object to equal zero? Many students think that it means there are no forces acting on the object. This is incorrect. The term *net force* is used to symbolize *the sum of all of the individual forces*:

$$\boldsymbol{F}_{net} = \sum_{i=1}^{n} \boldsymbol{F}_i.$$

Since force is a vector quantity, both magnitude and direction must be considered when forces are added. Equilibrium results when these forces effectively "cancel each other out". In other words:

$$\boldsymbol{F}_{net} = 0$$

at equilibrium.

What happens to the motion of an object if the net force on it equals zero? Many students think that the object must be at rest, but this is only true if the object was at rest originally. If the object was in motion originally, then the object remains at constant speed in one direction for as long as the forces are in equilibrium.

Newton's First Law of Motion, although simple to describe, is not intuitive. Understanding it and applying it to different situations can be difficult. Remember that Newton's Laws are the foundation of dynamics, the study of why objects move the way that they do. Relationships between force and motion are one of the central themes of Mechanics.

Procedure

1. Determine the mass of a single coffee filter by placing 10 or 12 (or even 15 or 20!) filters on the balance and measuring the mass of the stack of filters to the nearest 0.05 gram.

Number of filters	
Mass	
Mass of 1 filter	
Weight of 1 filter	

2. Set up Science Workshop to read the data collected by the ultrasonic motion detector. Create graphs of position vs. time and velocity vs. time for display of the data as it is collected. *Before* taking any data, increase the trigger rate of the motion sensor from 20 Hz to 80 Hz.

3. Place the motion detector carefully on the floor, facing upward.* Set the beam so that it takes in a wide view. Practice holding a coffee filter high above the detector so that, when released from rest, it falls and rests upon the detector (or close to it).

4. Record the motion of the falling coffee filter. Several tries may be required to get a reasonably clean data set. It will be easiest if you coordinate with your lab partner: one of you should hold and drop the filter while the other presses the "record" button.

Q1. For a time interval during which the filter is moving at its terminal velocity, what should the plot of position vs. time look like? What should the plot of velocity vs. time look like?

5. Determine the value of the terminal velocity of the coffee filter *from the slope of the position vs. time plot* measured over an appropriate time interval. This is preferable to reading a value directly from the velocity vs. time plot, since the fitted slope can use many position data points. The "canned" velocity plot uses only two position data points per velocity determination.

Q2. Draw a free-body (force) diagram of the coffee filter while it was experiencing terminal velocity.

Q3. Use Newton's First Law to determine the magnitude of the force of air resistance acting on the coffee filter while it was experiencing terminal velocity.

---

* Be sure that the motion detector is far enough away from the edge of the lab table so that the beam doesn't register "see" the lab table instead of the ceiling. If you find that the cord is too short, then put the sensor on the table top instead, and drop the filters while standing on a stool.

6. Record the force of air resistance and terminal velocity for a single coffee filter in the table below. Repeat steps 2–5 for 8 different-sized stacks of coffee filters. Note that as the weight of the stack of filters increases, it will take longer for the falling filters to achieve terminal velocity: be sure to fit the slope to a suitable portion of your plot! Obtain one set of data in which the approach to terminal velocity from rest is readily visible (this works better for the larger stacks). Use the re-sizing controls on the graph display window to get a good view of what is going on. Estimate the length of time required for the filter to reach terminal velocity with the help of the "xy" readout button in the graphing window. Print out two copies (one for you and one for your partner) of your plot showing the fitted line. On your plot, write down the number of coffee filters used, and the estimated length of time required to reach terminal velocity.

# of filters	force of air resistance (N)	terminal velocity (m/s)	square of terminal velocity (m^2/s^2)

Q4. Consider the coffee filter data obtained between the time that it was released and the time that it reached terminal velocity. What evidence is there of acceleration? Does the data suggest that the acceleration of the filter is constant, increasing, or decreasing? Explain.

Q5. Draw a free-body (force) diagram for the filter for each of the following: 1) the moment of release from rest; 2) before reaching terminal velocity; 3) after obtaining terminal velocity. In your sketches estimate the magnitude of the various forces at each of the times.

Q6. According to theory, what is causing the force of air resistance on the coffee filter to change? Is the magnitude of the force of air resistance increasing or decreasing during this time interval? Why?

Q7. Describe how the magnitude and direction of the net force on the coffee filter is changing over this time period.

Q8. Explain why Newton's First Law does not apply to the coffee filter during this time period.

7. The data you have collected shows that the magnitude of air resistance changes as the falling coffee filter gained speed. (The density of air and the cross sectional area were essentially constant throughout the fall.) The question is now more specific and mathematical: exactly how does air resistance change with velocity? There are two mathematical models with which you will compare your results:

$$F_{air} = Bv \qquad \text{and} \qquad F_{air} = Cv^2$$

where B and C are constants. To test the data against these two models, prepare two graphs. The first graph should plot the force of air resistance on the vertical axis and the terminal velocity on the horizontal axis. The second graph should plot the force of air resistance vs. the *square* of the terminal velocity.

NOTE: Since we can safely conclude that the force of air resistance is **zero** when the filters are not moving, you may (should) include the point ($F = 0$, $v = 0$) on both plots. This will help you distinguish which plot looks more like a straight line, since the curve turns out to be very gentle.

Q9. Based on your plots, which model fits the data better? Explain what you did to decide which fit was better.