Lab 1. Free Fall

Goals

- To determine the effect of mass on the motion of a falling object.
- To review the relationship between position, velocity, and acceleration.
- To determine whether the acceleration experienced by a freely falling object is constant and, if so, to calculate the magnitude of the acceleration.
- To calculate the appropriate uncertainties and to understand their significance when analyzing data.

① text goes here

Introduction

When an object is dropped from rest, its speed increases as it falls—that is, it accelerates. In this experiment you will characterize the motion of freely falling objects using an ultrasonic motion sensor. A significant part of the experiment entails understanding the relationship between the acceleration, velocity, and position of an object. You will also employ the concepts of mean (or average) value, standard deviation, and standard deviation of the mean of a measured quantity. An introduction to these concepts is given in the Uncertainty/Graphical Analysis Supplement at the back of the lab manual.

Effect of mass on the motion of a falling object

② At your lab station locate the small yellow plastic ball and a steel ball of the same diameter. After recording the masses of the balls, hold the balls at the same height and drop them together. Note which ball (if either) reaches the floor first. Use the padded catch box to minimize damage to the floor by the steel ball. If the balls strike the floor at different times, consider how accurately you can release the balls at the same time. An experiment with two identical balls can indicate how small differences in release time affect your results.

If you change the height at which the balls are released, does the result change?

Record the conditions and the observed results for each trial that you do. Based on your findings summarize your observations. What can you conclude regarding the effect of the mass on the motion of the falling balls?

Try dropping another object such as a pen or pencil along with the steel ball. How do the motions compare now? What conclusions can you draw from your observations?

Be sure that the notes you make in lab are sufficient for you to repeat the experiment later in the semester if asked to do so.

Characterizing the operation of the motion sensor

③ Consult the Computer Tools Supplement at the back of the lab manual to learn how to connect the "**Motion Sensor II**" to the computer interface box at your lab station. Once the sensor is connected, set up the Capstone software to simultaneously display graphs of position, velocity, and acceleration as functions of time. You may need to change the "sample rate" displayed along the bottom of the Display Area from its default value of 20 Hz in order to obtain enough data for analysis.

Due to electronic limitations, the motion sensor only measures distances greater than 0.25 m (newer version) or 0.40 m (older version). In all your experiments with the motion sensor, make sure that the object of interest is never closer than the minimum value for the sensor you are using. The sensor has two settings. A slider switch on the side can be moved to select a narrow angle (cart pictogram) to a wide angle (stick figure pictogram) operation. For the falling balls, the wide angle version should be used. Note all settings in your lab-notes.

④ Hold a flat object directly beneath the motion sensor and measure its position using a meter stick. Now take some motion sensor data with the flat object at the same position. How are the two position values related? Take another set of motion sensor data with the flat object at another position and compare it with its new position as measured with a meter stick. Analyze the position data to determine the location of the origin ($x = 0$ point) and the $+x$-direction of the coordinate system used by Capstone. Report the results of your measurements, your reasoning, and your conclusions in your lab notebook.

Now take some data while moving the flat object up and down under the motion sensor. Display this position, velocity, and acceleration data in a table. Starting from the position data in this table, determine how Capstone computes the velocity as a function of time. Which position values are used to calculate the velocity at a given time? Repeat this process for the acceleration calculation. Which velocity values are used to calculate the acceleration at a given time? Use this to determine which position values are used to calculate the acceleration at a given time. Show sample velocity and acceleration calculations in your lab notebook, taking care to label the time at which each position value used in the calculation was recorded.

⑤ Use this information to determine how fast the motion sensor can respond to changes in velocity and acceleration. If the velocity of an object suddenly (instantaneously) changes from one value to another, how long will it take the velocity reported by Capstone to reach the new value? How is this change reflected in the value of acceleration reported by Capstone?

If the acceleration of an object instantaneously changes from one value to another, how long will it take the acceleration reported by Capstone to reach the new value?

Characterizing free fall with a motion sensor

Data acquisition

⑥ Hold the basketball under the motion sensor such that the top of the ball is greater than the minimum distance for your sensor. Make sure that hands, feet, stools, backpacks, and such are removed from the target area so the motion sensor "sees" only the basketball. Click on the "Start" button of Capstone to start the data taking process. Wait a few seconds before quickly removing your hand(s) and releasing the ball. Allow it to fall to the floor and bounce twice. Then click the "Stop" button to terminate data acquisition. Expand the graphs to display only the motion during the fall and through the second bounce. Check with your TA to make sure that you have a good set of data. If necessary, repeat the data taking process until satisfactory data is obtained. Print out a copy of the three graphs on a single page in the "landscape" format to include in your notes.

Qualitative analysis

⑦ Observe the acceleration-time graph. Expand the graph vertically so that the acceleration during free fall occupies most of the graph. Ignore the noisy regions during each bounce, when the ball contacts the floor. What conclusions can you make regarding the acceleration of the basketball during the initial fall and between the first and second bounces?

After the first bounce, the ball is moving upward toward the motion sensor and slowing down before it speeds up again and bounces the second time. Explain the sign of the acceleration (negative or positive) during this interval both as the ball slows down while moving upward and speeds up while moving downward.

Is the velocity-time graph consistent with the observed acceleration during each segment of the ball's motion? Compare them using the definition of acceleration in terms of velocity.

Quantitative analysis

⑧ The value of the basketball's acceleration can be found from the position data, from the velocity data, or from the acceleration data. If the kinematic equations describe the path of the basketball, each data set should give the same acceleration.

(1) Use the **position vs. time** graph to determine the average acceleration between the first and second bounce with Capstone's curve fit function. Select the position data between the first and second bounces using the "Highlight range of points in active data" (pencil) tool from the tools along the top of the graph. From the kinematic equation, we expect the position of basketball to be described by an equation of the form $y = At^2 + Bt + C$: the quadratic equation. With the data selected, choose "Quadratic" from the Curve Fit

menu (icon shows red line through blue points) along the top of graph. From your knowledge of the kinematic equations, compute the acceleration of the basketball in free fall from the constant A in the curve fit. Capstone also displays the uncertainty in A. Use this uncertainty to compute the uncertainty in the acceleration. This uncertainty is called the standard error, and is equivalent to the standard deviation of the mean computed for a list of averaged numbers. (If the precision of your acceleration value is less than its standard deviation, ask your TA for assistance in obtaining more significant digits. Always make sure that your printout clearly identifies which data points were used in the curve fit. If Capstone does not make it clear, identify them by hand after you print the data.

(2) Use the **velocity vs. time** graph to determine the average acceleration and its uncertainty between the first and second bounces. From the kinematic equations, we expect the velocity of the basketball during free fall to be described by an equation of the form $v = mt + b$: a linear equation. Select the velocity data between the first and second bounces and choose "Linear" from the curve fit menu to obtain the slope of the velocity-time graph (the constant m). On your printout, identify the data points used to determine the acceleration. The uncertainty in this acceleration measurement is equal to the "standard error" reported by Capstone in the curve fit window.

(3) The **acceleration vs. time** shows the acceleration value direction. One can simply select the data between the first and second bounce and check the mean and standard deviation buttons under the Σ button along the top of the graph. Again, identify the data points used to determine the mean acceleration. The uncertainty in the mean value, is calculated by dividing the standard deviation by the square root of N, where N is the number of data points used to calculate the mean. You will have to count the points by hand. Capstone will compute the uncertainty for you if you use the "User Defined Fit" function in the Curve Fit function, then enter an equation of the form $y = A$ into the Curve Fit in the Tools Palette on the left side bar.

(4) **Compare**: Did the acceleration values determined in this experiment agree with your expectations? Do they agree with each other? Use the quantitative test for consistency described in the "Uncertainty and Graphical Analysis: Using uncertainties to compare measurements or calculations" section of the lab manual. Briefly, we conclude that two measurements, a_1 and a_2, with uncertainties $u(a_1)$ and $u(a_2)$, are consistent if $t' = |a_1 - a_2|/\sqrt{u(a_1)^2 + u(a_2)^2} < 3$. You will need to compare the three accelerations measurements you made from the position, velocity, and acceleration data, respectively. You should also compare these measurements with the "expected" value of $a = g = 9.80 \pm 0.01 m/s^2$.

(5) **Decide and note**: Are some acceleration values "better" (more precise or more accurate) than others? Explain your reasoning.

Conclusion

(9) Discuss what you have discovered about objects in free-fall. What did you expect to find? Did your experiment agree with your expectations? Did the various methods of determining the acceleration of falling objects give the same values? Discuss and explain, using your results for the experiment. You may wish to summarize all your experimental numerical results in a small table here, making it easier to refer to them in this part of your notes. How does the concept of uncertainty assist us in making logical conclusions?

Before you leave the lab please:

Quit all computer applications that you may have open.
Place equipment back in the plastic tray as you found it.
Report any problems or suggest improvements to your TA.