Lab 8: Ballistic Pendulum
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Department of Physics
Physics 182A/195L

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Theory

A ballistic pendulum is a simple system used to measure the speed of a projectile. A projectile is launched with some initial speed, and then collides with the mass at the end of a simple pendulum and is captured. See the left side of Figure 1. The energy left over from this collision causes the pendulum to swing upward until all of its kinetic energy is converted into potential energy. See the right side of Figure 1.

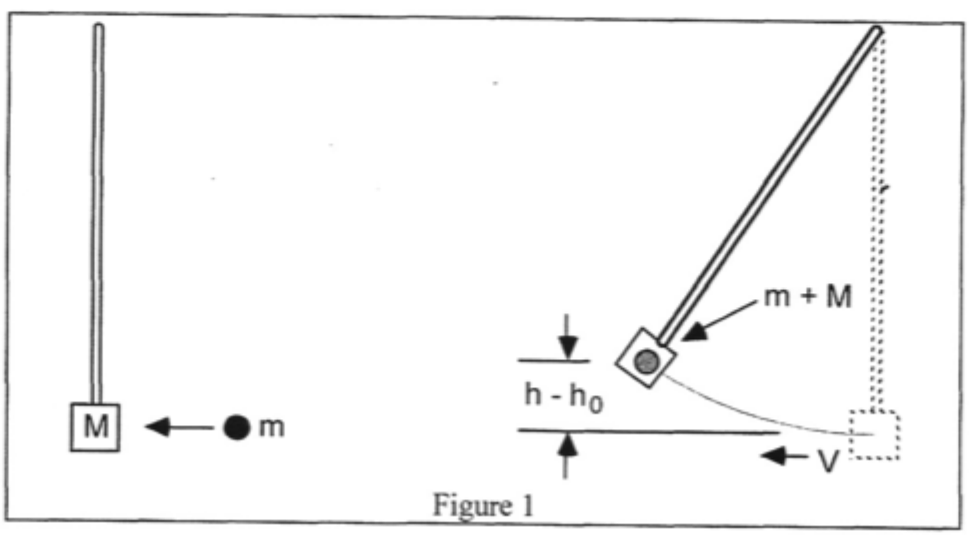


Figure 1: Schematic for the Ballistic Pendulum

In this lab, we will measure the maximum height h that the pendulum mass swings to, and using that information, calculate the speed v_{bi} that the ball had before it collided with the pendulum. You can probably imagine that increasing the speed of the ball will increase how far the pendulum will swing. In the next section we will derive a formula that tells us exactly how these two things are related.

The Collision: conservation of momentum

First let's see what conservation of momentum can tell about the initial speed of the ball.

Let's label the mass of the projectile (a metal ball) as m_b, and the mass of the pendulum m_p. Before the collision, the ball is traveling with some speed v_{bi}. Before the collision, the projectile is traveling with some speed v_{bi}. The pendulum mass is at rest, so its speed is zero, $v_{pi} = 0$. The law of conservation of momentum relates the speeds of the masses before and after the collision:

$$m_b v_{bi} + m_p v_{pi} = m_b v_{bf} + m_p v_{pf}$$

The experimental setup is designed so that the projectile is captured by the pendulum after the collision. Recall from the conservation of momentum lab that this means the collision is perfectly inelastic, and that $v_{bf} = v_{pf}$. Plugging in $v_{pi} = 0$ and $v_{bf} = v_{pf}$, we can write a simplified equation for our system:

$$m_b v_{bi} + m_p(0) = (m_b + m_p) v_{bf}$$

Or, in other words, conservation of momentum relates the speed of the ball before the collision v_{bi} (this is what we want to find), to its speed after the collision v_{bf} :

$$v_{bi} = \frac{(m_b + m_p)}{m_b} v_{bf}.$$

If we can determine v_{bf}, the speed of the ball (and pendulum) right after the collision, then we can find the initial speed of the ball.

The Swing: conservation of energy

Immediately after the collision, the ball is inside of the pendulum, and the pendulum with combined mass $m_p + m_b$ is about to swing upward. Let's see what conservation of energy can tell us about the system. Before the pendulum has swung, it has a kinetic energy ($KE = mv^2/2$) of:

$$KE_{bottom} = \frac{1}{2}(m_b + m_p) v_{bf}^2.$$

If the pendulum is starting from a height of 0, then it has a potential energy ($PE = mgh$) of:

$$PE_{bottom} = 0.$$

At the point where the pendulum swings to its maximum height, let's call that h, the pendulum will momentarily be at rest (just like at the highest point of projectile motion), and so

$$KE_{top} = 0.$$

At that same instant, the pendulum will have a potential energy of:

$$PE_{top} = (m_b + m_p) gh.$$

Conservation of energy tells us that

$$KE_{bottom} + PE_{bottom} = KE_{top} + PE_{top}.$$

Plugging in the values we found above, we have

$$\frac{1}{2}(m_b + m_p)v_{bf}^2 = (m_b + m_p)gh$$

If we solve for v_{bf}, we get:

$$v_{bf} = \sqrt{2gh}.$$

This is the speed of the ball, after the collision, in terms of the maximum height h that the pendulum swings to. We are almost done!

Combining the two systems

From conservation of momentum during the collision of the ball with the pendulum, we found the initial speed of the ball must be

$$v_{bi} = \frac{(m_b + m_p)}{m_b} v_{bf}.$$

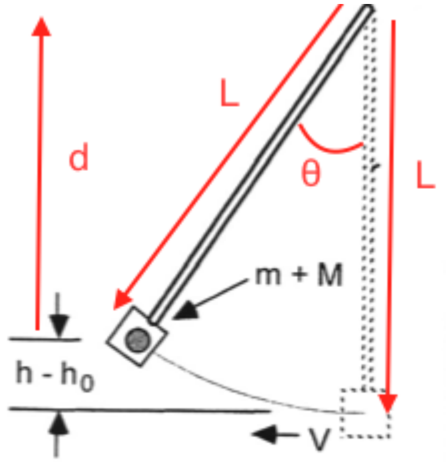
And from conservation of energy during the swing of the pendulum, we found that the speed of the ball after the collision is related to h:

$$v_{bf} = \sqrt{2gh}$$

If we combine these two equations (plug v_{bf} into the first equation):

$$v_{bi} = \frac{m_b + b_p}{m_b}\sqrt{2gh}$$

This is the speed of the ball in terms of the maximum height that the pendulum swings to. For one final convenience, let's try to write this equation in terms of an angle θ that the pendulum arm swings through. This will be useful during the experiment because it's hard to measure the height that the pendulum mass reaches, since it is also moving in the x-direction. But the angle θ it swings to is easy to measure using a protractor built into the ballistic pendulum device.



Looking at the figure above, we can write down a few relations:

$$L = h + d,$$

$$h = L - d$$
$$\cos(\theta) = \frac{d}{L}$$
$$d = L\cos(\theta)$$

Solving for h in terms of θ:

$$h = L(1 - \cos(\theta)).$$

The final result is:

$$\boxed{v_{bi} = \frac{m_b + m_p}{m_b}\sqrt{2gL(1 - \cos\theta)}}$$

Procedure

Part A: Ballistic Pendulum Experiment

Setup

1. Attach the Projectile Launcher to the Ballistic Pendulum and make sure the launcher is level using the thread and bead. Fasten the launcher to the bracket using the two thumb screws through the two holes.
2. Screw in the ballistic pendulum into the pendulum stand using the pendulum screw toward the top of the stand.
3. When the pendulum and projectile launcher are attached properly, the launcher should almost (but not quite) touch the pendulum catcher, shown in **Figure 2**. Again, make sure the launcher is set for a launch angle of zero degrees.
4. Before you use the projectile launcher, make sure the area is clear of others and nothing obstructs the path of the pendulum.

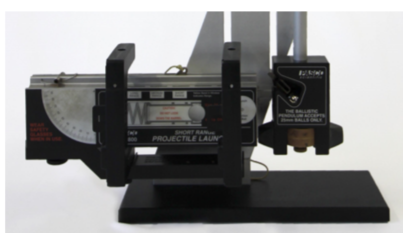


Figure 2: Pendulum and projectile launcher in their initial position.

Five trials

1. To load the launcher, swing the pendulum out of the way, place the ball in the end of the barrel and, using a push rod (not your fingers), push the ball down the barrel until the trigger catches in the second (Medium Range) position.
2. Return the pendulum to its normal hanging position and wait until it stops moving. Make sure to move the angle indicator back to the zero angle position. Note that if the angle

indicator is not at zero degrees when your pendulum is in the normal hanging position that you will need to account for this difference. (See step 4.)

3. Launch the ball so that it is caught in the pendulum. You will notice that the angle measurement scale will have moved to the maximum angle the pendulum reached during its swing.
4. Record the maximum angle in *Table 1*. If your indicator does not start at zero, you must subtract the starting value from the final value!
5. Repeat Steps (3) and (4) five times.
6. Record the average angle in the data input box. Remember to reset the angle indicator each time you launch the ball.

Pendulum Arm Length

1. Remove the pendulum from the pendulum stand, and balance it on a meter stick as shown in **Figure 3**. Note: the ball must be in the pendulum!
2. Find the point at which the catcher is extended as far as possible out over the edge of the meter stick. When properly balanced, the center of mass is directly over the end of the stick.
3. Once balanced, record length in *Table 2*, the distance from the center of mass out to the pivot (screw).
4. Using your value for length, calculate the change in height, Δh. Record the answer in *Table 2*.
5. Measure the mass of the ball + pendulum system. Record your mass in *Table 2*.
6. Measure the mass of just the pendulum. Record your mass in *Table 2*.
7. Calculate the mass of the ball using Steps (5) and (6). Record your mass in *Table 2*.
8. Calculate the launch speed of the ball using the equations from the Theory section. Record your answer in *Table 2*.

Figure 3: Balance the pendulum on a meter stick to find the center of mass.

Part B: Freeflight Experiment

1. Attach Photogates to the launcher using the Photogate Bracket as shown in **Figure 4**. Move the pendulum out of the way and slide the bracket such that Photogate 1 is as close to the end of the launcher as possible. Note: the launcher should not be in the way of Photogate 1, check that the red sensor lights are off to verify.
2. Connect Photogate 1 to *Digital Input 1* and Photogate 2 to *Digital Input 2*.
3. Place the ball in the launcher and compress the spring to the second (medium range) setting as before.
4. Make sure no one is in the way of the ball! Click Record and launch the ball. There is a Stop Condition that should half data recording.
5. The measured speed is shown in the Digits Display. Record this value in *Table 3* and repeat 5 times.

6. Calculate and record your average measured speed in *Table 3*.

Figure 4: Attach the photogates to the launcher stand.

Data

Table 1: Maximum Angle Reached

Trial	Maximum Angle Reached (Degrees)
1	
2	
3	
4	
5	
Average	

Table 2: Pendulum Quantities

Length (m)	Change in Height (m)	Mass: Ball & Pendulum (kg)	Mass: Pendulum (kg)	Mass: Ball (kg)	Launch Velocity (m/s)

Table 3: Launch Velocity Measurements

Trial	Launch Velocity
1	
2	
3	
4	
5	
Average	

Analysis

1. What is the percent difference between your calculated launch velocity from *Table 2* and your average launch velocity from *Table 3*?

2. Which method of finding the launch velocity do you think is more accurate? Why?

3. Calculate the percentage of the total kinetic energy that is lost during the collision with the pendulum. ($100 \times (KE_{total,i} - KE_{total,f})/KE_{total,i}$).

4. Where does the energy go and how is it transferred?

Questions

1. This question is from the Colorado State Driver's license exam: A car at 30 miles per hour skids 40 feet with locked brakes. How far will the car skid with locked brakes at 90 miles per hour? (Hint: Think about Kinetic Energy).

2. Suppose that you and two friends are discussing the design of a roller coaster. One friend says that each summit must be lower than the previous one. Your other friend says this is nonsense, for as long as the first one is the highest it doesn't matter what height the others are. Explain which one is correct and why. (Assume no energy losses due to friction or air resistance).

3. When a jet plane lands on the deck of a carrier, is this an elastic or an inelastic "collision"? In this "collision" the before is just before landing and the after is after the plane has come to a stop.

4. In the measurement of velocity by the free-flight method, what would be the effect on the measurements if (a) the front of the launcher were lower than the rear? (b) the distance between the photogates was long enough to let the ball drop 1 cm between the photogates?