Lab 9. Ballistic Pendulum

Goals

- To determine the launch speed of a steel ball for the short, medium, and long range settings on the projectile launcher apparatus using the equations for projectile motion.
- To use the concepts of gravitational potential energy and conservation of mechanical energy to determine the speed of the ball plus pendulum as it first begins to swing away from the vertical position after the "collision."
- To explore the relationships between the momentum and kinetic energy of the ball as launched and the momentum and kinetic energy of the ball plus pendulum immediately after the ball is caught by the pendulum apparatus.

Introduction

The "ballistic pendulum" carries this name because it provides a simple method of determining the speed of a bullet shot from a gun. To determine the speed of the bullet, a relatively large block of wood is suspended as a pendulum. The bullet is shot into the wooden block so that it does not penetrate clear through it. This is a type of "sticky" collision, where the two masses (bullet and block) stick to one another and move together after the collision. By noting the angle to which the block and bullet swing after the collision, the initial speed can be determined by using conservation of momentum. This observation incorporates some predictions that we can check. In this experiment, the ballistic pendulum apparatus will be used to compare the momentum of the steel ball before the "collision" to the momentum of the ball and pendulum apparatus, equivalent to the wooden block plus the bullet, after the collision. A comparison of the kinetic energy of the ball before the collision with the kinetic energy of the system afterward will also be made.

Figure 9.1 shows a diagram of the ballistic pendulum apparatus. For the ballistic pendulum experiment, the projectile launcher from the projectile motion laboratory is mounted horizontally so that the pendulum can catch the emerging steel ball. The angle indicator can be used to measure the maximum angle reached by the pendulum as it swings after the collision. The angle indicator should read close to zero when the pendulum is hanging in the vertical position. If the reading is measurably different from zero, then take the difference in the angle readings (maximum angle reading minus initial angle reading).

Warning: Never look down the launcher barrel. Wear eye protection until everyone is finished launching projectiles.

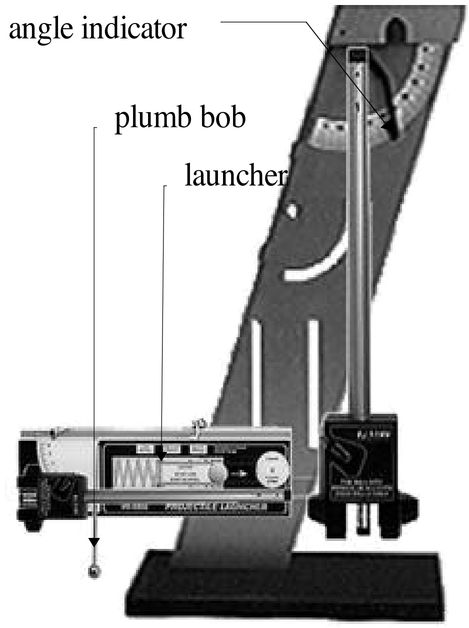

Figure 9.1. Ballistic pendulum apparatus.

Momentum of steel ball before collision

For this part of the experiment, remove the pendulum by gently unscrewing the rod that supports its upper end. Now determine the muzzle velocity of the steel ball by firing it horizontally and measuring the distance traveled horizontally before striking the ground. Do this for the short, medium, and long range settings of the launcher. The momentum of the ball is found by multiplying its mass times its velocity. Quantitatively estimate the uncertainties in these momentum values based on the uncertainties of the measured horizontal distance traveled and the measured vertical height. The momentum of the ball-pendulum system before the ball collides with the pendulum is now known.

Momentum of ball and pendulum after collision

The speed (and from it the momentum) of the ball and pendulum just after the collision is computed by assuming that the kinetic energy of the ball and pendulum just after the collision is totally converted into gravitational potential energy at the top of its swing. This requires that the frictional forces on the ball and pendulum system during the swing are small (negligible). The increase in gravitational potential energy is just the weight of the pendulum times the change in height, and the change in height can be computed from the maximum angle of the pendulum swing and some straightforward trigonometry. Since the pendulum is not a point mass, the change in potential energy is given by the change in height of its center of gravity. The center of gravity can be located by removing it from its support screw at the top and then balancing it on a "knife edge". (A thin ruler works.) While you have the pendulum disassembled, be sure to measure the mass of the pendulum and the distance from the pivot point at the top to the center of gravity.

Mount the pendulum so that it will catch and trap the steel ball before proceeding. Be gentle as you screw in the pendulum support rod; it does not need to be tight. Now launch the ball into the pendulum using the short, medium, and long range settings of the projectile launcher. Repeat each measurement several times and take appropriate averages. (Remember to check the initial angle of the pendulum at rest.)

From your data calculate the speed of the pendulum and ball together just after the collision. Multiply by the appropriate mass to get the momentum. The momentum of the ball-pendulum system just after the collision is now known.

Is momentum conserved?

Compare the initial momentum of the ball and pendulum system before the collision with the final momentum of the same system just after the collision using your calculated velocities and measured masses just before and just after the collision. Is momentum conserved? You cannot answer this question without comparing the difference between the two momenta with the uncertainty of this same difference. If the difference between the momenta is more than three times the uncertainty of the difference, the odds of the difference being due to random variations is small—your data do not support conservation of momentum in this case. If you expect momentum to be conserved, examine your calculations and procedures for errors.

Is kinetic energy conserved?

Since you know the masses and speeds of the objects before and after the collision, you can calculate the kinetic energies of the system before and after the collision. Is kinetic energy conserved? To answer this question, you will need to estimate your experimental uncertainties and compare them with any observed differences, as you did to test conservation of momentum. Assuming that momentum is conserved before and after the collision, find a general symbolic mathematical expression for the ratio of the final kinetic energy over the initial kinetic energy. You may need some help from your TA here. Using the data from your earlier calculations, compare your experimental kinetic energy ratio to that predicted by assuming momentum is conserved. Is it the same ratio? Is overall energy conserved in this collision? If so, what forms of energy would need to be included to satisfy the general energy conservation principle?

Note: A simplification has been made by assuming that the pendulum consists of a point mass on the end of a string whose length is equal to the distance from the pivot point to its center of mass. When the pendulum swings, it necessarily rotates about its center of mass. This suggests that some rotational kinetic energy is imparted to the ball and pendulum system along with its translational kinetic energy ($mv^2/2$). If significant, this would produce a systematic error in the calculated speed of the ball and pendulum system after the collision. Would it make the calculated speed too high or too low? Can you detect any systematic error in your calculated values? Discuss.

Summary

Mechanical energy and momentum are conserved only when certain conditions are met. Qualitatively summarize your results, explaining why the collision between the ball and the pendulum conserves momentum but not mechanical energy. Similarly, explain why the motion of the pendulum during its swing conserves mechanical energy but (apparently) not momentum.

Grading Rubric

	No Effort	Progressing	Expectation	Exemplary
AA Is able to extract the information from representation correctly Labs: 1-12	No visible attempt is made to extract information from the experimental setup.	Information that is extracted contains errors such as labeling quantities incorrectly, mixing up initial and final states, choosing a wrong system, etc. Physical quantities have no subscripts (when those are needed).	Most of the information is extracted correctly, but not all of the information. For example physical quantities are represented with numbers and there are no units. Or directions are missing. Subscripts for physical quantities are either missing or inconsistent.	All necessary information has been extracted correctly, and written in a comprehensible way. Objects, systems, physical quantities, initial and final states, etc. are identified correctly and units are correct. Physical quantities have consistent and informative subscripts.
AB Is able to construct new representations from previous representations Labs: 1-12	No attempt is made to construct a different representation.	Representations are attempted, but omits or uses incorrect information (i.e. labels, variables) or the representation does not agree with the information used.	Representations are constructed with all given (or understood) information and contain no major flaws.	Representations are constructed with all given (or understood) information and offer deeper insight due to choices made in how to represent the information.
AC Is able to evaluate the consistency of different representations and modify them when necessary Labs: 2-10, 12	No representation is made to evaluate the consistency.	At least one representation is made but there are major discrepancies between the constructed representation and the given experimental setup. There is no attempt to explain consistency.	Representations created agree with each other but may have slight discrepancies with the given experimental representation. Or there is inadequate explanation of the consistency.	All representations, both created and given, are in agreement with each other and the explanations of the consistency are provided.
AE Force Diagram Labs: 1-12	No representation is constructed.	Force Diagram is constructed but contains major errors such as mislabeled or not labeled force vectors, length of vectors, wrong direction, extra incorrect vectors are added, or vectors are missing.	Force Diagram contains no errors in vectors but lacks a key feature such as labels of forces with two subscripts vectors are not drawn from single point, or axes are missing.	The diagram contains no errors and each force is labeled so that it is clearly understood what each force represents. Vectors are scaled precisely.

	No Effort	Progressing	Expectation	Exemplary
AF Sketch Labs: 1, 4, 5, 7-9, 11, 12	No representation is constructed.	Sketch is drawn but it is incomplete with no physical quantities labeled, or important information is missing, or it contains wrong information, or coordinate axes are missing.	Sketch has no incorrect information but has either a few missing labels of given quantities. Subscripts are missing or inconsistent. Majority of key items are drawn.	Sketch contains all key items with correct labeling of all physical quantities have consistent subscripts; axes are drawn and labeled correctly.
AG Mathematical Labs: 2-5, 7-12	No representation is constructed.	Mathematical representation lacks the algebraic part (the student plugged the numbers right away) has the wrong concepts being applied, signs are incorrect, or progression is unclear.	No error is found in the reasoning, however they may not have fully completed steps to solve problem or one needs effort to comprehend the progression.	Mathematical representation contains no errors and it is easy to see progression of the first step to the last step in solving the equation. The solver evaluated the mathematical representation with comparison to physical reality.
CA Is able to identify the hypothesis to be tested Labs: 4, 5, 7-9, 12	No mention is made of a hypothesis.	An attempt is made to identify the hypothesis to be tested but is described in a confusing manner.	The hypothesis to be tested is described but there are minor omissions or vague details.	The hypothesis is clearly stated.
CC Is able to make a reasonable prediction based on a hypothesis Labs: 4, 5, 7-9, 12	No prediction is made. The experiment is not treated as a testing experiment.	• A prediction is made but it is identical to the hypothesis OR • Prediction is made based on a source unrelated to hypothesis being tested OR • is completely inconsistent with hypothesis being tested OR • Prediction is unrelated to the context of the designed experiment.	Prediction follows from hypothesis but is flawed because • relevant experimental assumptions are not considered and/or • prediction is incomplete or somewhat inconsistent with hypothesis and/or • prediction is somewhat inconsistent with the experiment.	A prediction is made that • follows from hypothesis, • is distinct from the hypothesis, • accurately describes the expected outcome of the designed experiment, • incorporates relevant assumptions if needed.
CD Is able to identify the assumptions made in making the prediction Labs: 4, 5, 7-9, 12	No attempt is made to identify any assumptions.	An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with the hypothesis.	Relevant assumptions are identified but are not properly evaluated for significance in making the prediction.	Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made.

	No Effort	Progressing	Expectation	Exemplary
CE Is able to determine specifically the way in which assumptions might affect the prediction Labs: 4, 5, 7-9, 12	No attempt is made to determine the effects of assumptions.	The effects of assumptions are mentioned but are described vaguely.	The effects of assumptions are determined, but no attempt is made to validate them.	The effects of the assumptions are determined and the assumptions are validated.
CF Is able to decide whether the prediction and the outcome agree/disagree Labs: 4, 5, 7-9, 124, 5, 7-9, 12	No mention of whether the prediction and outcome agree/disagree.	A decision about the agreement/disagreement is made but is not consistent with the outcome of the experiment.	A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not properly taken into account.	A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account.
CG Is able to make a reasonable judgment about the hypothesis Labs: 4, 5, 7-9, 12	No judgment is made about the hypothesis.	A judgment is made but is not consistent with the outcome of the experiment.	A judgment is made, is consistent with the outcome of the experiment, but assumptions are not taken into account.	A judgment is made, consistent with the experimental outcome, and assumptions are taken into account.
GD Is able to record and represent data in a meaningful way Labs: 1-12	Data are either absent or incomprehensible.	Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly.	All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing.	All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order.
GE Is able to analyze data appropriately Labs: 1-12	No attempt is made to analyze the data.	An attempt is made to analyze the data, but it is either seriously flawed or inappropriate.	The analysis is appropriate but it contains minor errors or omissions.	The analysis is appropriate, complete, and correct.
IA Is able to conduct a unit analysis to test the self-consistency of an equation Labs: 1-12	No meaningful attempt is made to identify the units of each quantity in an equation.	An attempt is made to identify the units of each quantity, but the student does not compare the units of each term to test for self-consistency of the equation.	An attempt is made to check the units of each term in the equation, but the student either mis-remembered a quantity's unit, and/or made an algebraic error in the analysis.	The student correctly conducts a unit analysis to test the self-consistency of the equation.

EXIT TICKET:

☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Report any problems or suggest improvements to your TA.
☐ Have TA validate Exit Ticket Complete.