

Lesson 3 - Understanding Energy (with a Pendulum)

Introduction

This lesson is meant to introduce energy and conservation of energy and is a continuation of the fundamentals of roller coaster engineering.

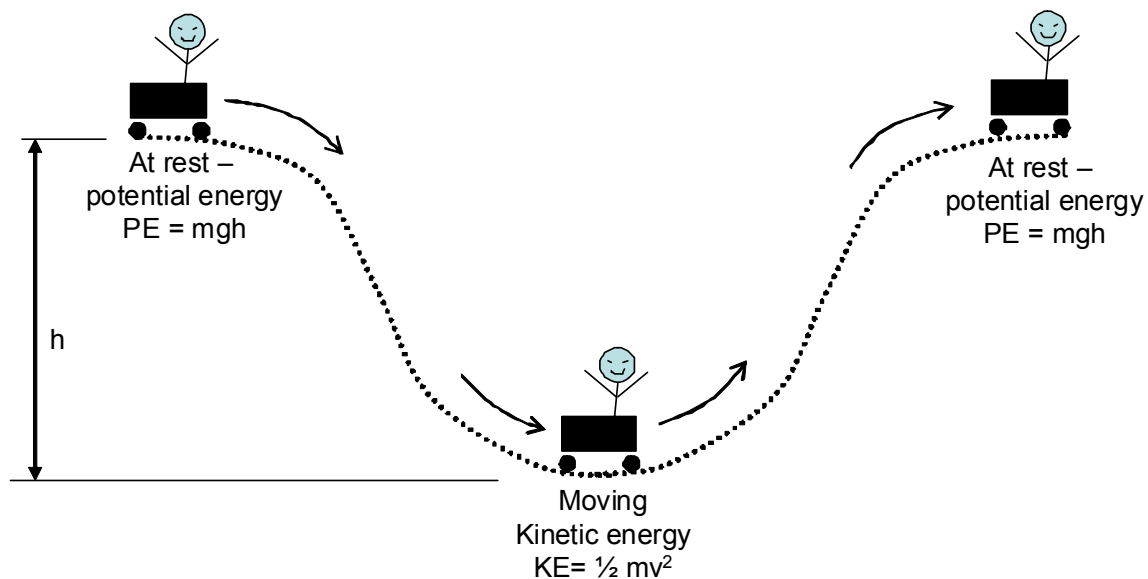


Figure: A roller coaster car moving back and forth between rest and maximum velocity

Purpose

This activity shows the engineering importance of understanding the laws of mechanical energy. It demonstrates how potential energy can be converted to kinetic energy and back again. Given a pendulum height, students calculate and predict how fast the pendulum will swing by using the equations for potential and kinetic energy. The equations will be justified by measuring the speed of the pendulum and comparing theory with experimental.

Similar to the movement of a pendulum, an enormous wrecking ball when held at a height possesses potential energy, and as it falls, its potential energy is converted to kinetic energy. As the wrecking ball makes contact with the structure to be destroyed, it transfers that energy to flatten or take down the structure.

Background

Potential energy (PE) - due to an object's position (height)

Kinetic energy (KE) - due to an object's velocity

Potential energy can be converted to kinetic energy by allowing the object to fall (for example, a roller coaster going down a hill or a book falling off a table). This energy transformation also holds true for a pendulum. As a pendulum swings, its potential energy converts to kinetic and back to potential, as illustrated in the figure above.

In this activity, we will prove that the transformation of energy occurs by calculating the theoretical value of velocity at which a pendulum should swing and comparing it to a measured value. We will also compare the periods (the length of time it takes the pendulum to swing back and forth one time) of the pendulum by allowing it to swing from two different heights.

Four equations will be used in this activity:

$$PE = mgh$$

$$KE = \frac{1}{2}mv_t^2$$

$$v_m = \frac{\Delta d}{\Delta t}$$

$$T = 2\pi\sqrt{l/g}$$

Where,

m is mass (kg)

g is gravity (9.8 m/s²)

Δd is the change in distance (m)

Δt is the change in time (s)

h is height (m)

l is the length of the pendulum (m)

v_t is the calculated velocity (m/s)

v_m is the measured velocity (m/s)

T is the period of the pendulum (s)

Concepts

1. Energy can be transferred from potential energy to kinetic energy. If there are limited other forces acting (friction, drag), then the potential energy equals the kinetic energy ($mgh = \frac{1}{2}mv^2$)

Student Learning Objectives	NYS Standards
Students can:	
define potential and kinetic energy	
Apply concepts of conservation of energy, potential energy, and kinetic energy to simple pendulum experiment	
Relate Kinetic and Potential Energy to real life examples and engineering examples	
Calculate the kinetic and potential energy of a pendulum	

Key Terms

Altitude	Energy	Kinetic Energy
Potential Energy	Conservation of Energy	Pendulum
Mechanical Energy	Mass	Velocity
Turning Point	Drag Force	

Activities

- Bell Ringer (5 min) – Review importance of friction for roller coasters. What would happen to motion if there is no friction? – See picture – if also no air resistance – roller coaster would continue to move back and forth like a pendulum
- Definitions for the day (5 min)

Turning point – point where the cars momentum, forward motion, is overpowered by the friction on the track and the pull of gravity

Energy – Energy is the capacity of a physical system to perform work (work = force X distance)

Kinetic Energy – energy of motion – calculated based on weight (m g) and height above a datum

Altitude – elevation of an object above a known level such as sea level or the earth's surface

Potential Energy – energy stored in an object from being raised to an altitude; it thus has the *potential* for motion. Calculated based on object's mass and velocity

Conservation of energy - the total amount of energy in any closed system remains constant but can change forms (friction turns kinetic energy into heat).

- Provide brief demo of pendulum activity – define goal of the activity – ultimately to help define variables that can make your roller coaster go fast.
- Primary assumption – $PE=KE$ (no friction or drag losses) that enables theoretical calculations of kinetic energy and velocity from PE.
- Break into groups of 3 for the Pendulum Activity– (~25 min)
- How does this relate to roller coasters? (5 min) The cars of a roller coaster reach their maximum kinetic energy when at the bottom of their path. When they start rising, the kinetic energy begins to be converted to gravitational potential energy, but the total amount of energy in the system remains constant. In roller coaster – probably more of other forces also act on roller coaster to slow it down (friction, drag resistance)
- Wrap up and review objectives, teaser for next lesson and collect worksheets (<5 mins)

Supply list (per group)

- stopwatch
- Masking tape
- 10 feet of string or fishing line – attached near ceiling before class would help – the sting needs to be long for the equation for the period of the pendulum equation to be accurate)
- Calculator
- copies of the Swinging Pendulum Activity Sheet
- Mass of known weight (or scale)

Resources

Activity – Pendulum.doc

Worksheet – Pendulum Activity.doc

Worksheet – Pendulum Activity_Answers.doc

Activity – Understanding Energy through a Pendulum

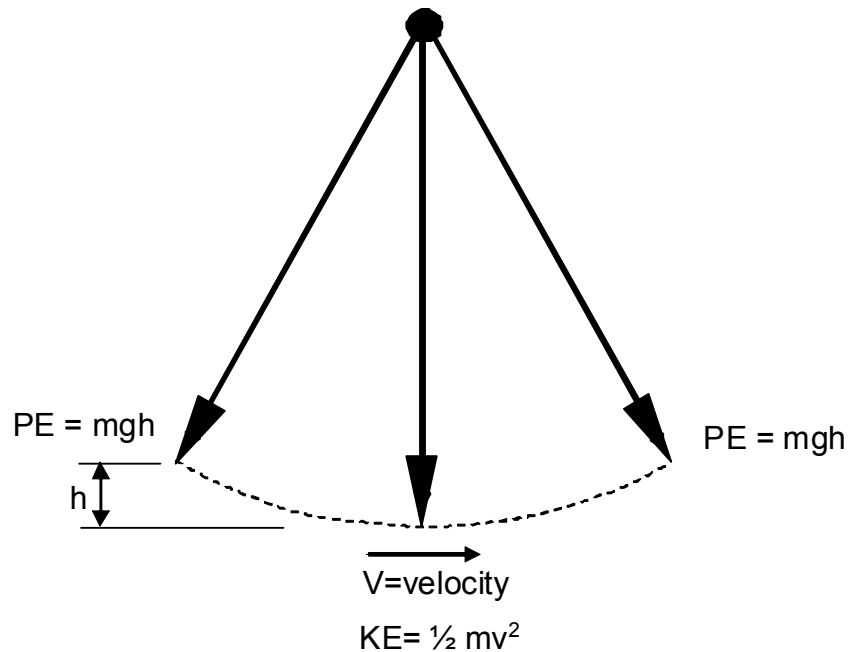


Figure 1: In a swinging pendulum, the potential energy is converted into kinetic energy and back during the course of a swing from left to right.

Introduction

Potential energy (PE) – due to an object's position (height)

Kinetic energy (KE) – due to an object's velocity

Potential energy can be converted to kinetic energy by allowing the object to fall (for example, a roller coaster going down a hill or a book falling off a table). This energy transformation also holds true for a pendulum. As a pendulum swings, its potential energy converts to kinetic and back to potential, as illustrated in the figure above.

In this activity, we will prove that the transformation of energy occurs by calculating the theoretical value of velocity at which a pendulum should swing and comparing it to a measured value. We will also compare the periods (the length of time it takes the pendulum to swing back and forth one time) of the pendulum by allowing it to swing from two different heights.

Four equations will be used in this activity:

$$\text{Potential energy} \quad PE = m g h \quad (1)$$

$$\text{Kinetic energy} \quad KE = \frac{1}{2} m v^2 \quad (2)$$

$$\text{Velocity} \quad v_m = \frac{\Delta d}{\Delta t} \quad (3)$$

$$\text{Period} \quad T = 2\pi \sqrt{\frac{L}{g}} \quad (4)$$

If MKS units (kg, m, s) are used for these calculations, the energy terms are in units of Joules (J)

Where,

m = mass (kg) of the pendulum

g = the acceleration of gravity (9.8 m/s²),

h = height (m) of the pendulum at its starting point above a datum

L = length of the pendulum (m)

v_t = theoretical velocity of pendulum at its lowest point (m/s)

v_m = measured average velocity (m/s) (assuming a straight path between starting and ending point and a constant velocity)

Δd = distance between starting and ending point of the pendulum swing

Δt = time for one swing from left to right (s)

T = period of the pendulum (s) – the time required for a pendulum to swing away and then back to its original position (T = 2t) (Note – this equation is true only for a long pendulum)

Purpose

This activity shows the engineering importance of understanding the laws of mechanical energy. It demonstrates how potential energy can be converted to kinetic energy and back again. Students measure and predict how fast the pendulum will swing by using the equations for potential and kinetic energy. The equations will be justified by measuring the average velocity of the pendulum and comparing theory with experimental. The results of the first part of the experiment will be used to develop a hypothesis for using potential energy to maximize the velocity of a roller coaster.

Hypothesis #1: The potential energy of a pendulum at its starting point is equal to the kinetic energy at its lowest point. Note, this assumes that there are minimal other resistances to motion (friction, air resistance)

$$m g h = \frac{1}{2} m v_t^2 \quad (5)$$

Hypothesis #2 (fill in blanks based on theory above or the results of the first part of your experiment) If a roller coaster behaves like a pendulum, then _____ (increasing / decreasing) the _____ (independent variable) will increase the velocity of the roller coaster.

Independent variables could include the mass, string length, initial height of the pendulum)

Materials for each group of three students:

- Stopwatch
- Masking tape
- ~3 m of light weight string or fishing line
- Calculator
- Meter stick
- Weights

Procedure

Create the pendulum:

1. Measure and record the mass of the weight on the attached data table.
2. Tie the weight to the fishing line and connect the other end to a beam near the ceiling (this can be done by the teacher before class). The weight should be close to the floor when it is hanging straight
3. Place two pieces of tape on the floor on opposite sides of the hanging pendulum so that they are 0.50 m apart with the pendulum at rest in the middle.
4. Measure and record the height of the center of your weight when it is resting at equilibrium and again when it has swung to one of the pieces of tape.

Test Hypothesis #1 by comparing the theoretical kinetic energy of the pendulum (from equation (5)) to the kinetic energy based on the measured average velocity (equations (2) and (3)). This will be done at two different initial heights for verification.

5. Calculate theoretical values
 1. Calculate the potential energy of the pendulum when it is held over one of the pieces of tape. Use the height of the weight at equilibrium (hanging straight down) as the datum. Record values on the data table.
 2. Assuming that Hypothesis #1 is true, calculate the kinetic energy (KE) and theoretical velocity (v_t) at the bottom of the swing.
 3. Calculate the theoretical period of the pendulum.
6. Collect experimental data to compare to the theoretical values:
 1. One group member pulls back the weight until it reaches the edge of one of the pieces of tape.

2. Measure the time for the pendulum to swing to the other tape and back to its original position. Record value. Repeat three more times
3. Use data to calculate the average velocity and kinetic energy.
7. Repeat steps 3-7 but set up the two pieces of tape so they are 0.80-1.0 m apart.
8. Compare the theoretical velocity, kinetic energy and period with your measured values to test your hypothesis and answer discussion question #1

Design your own experiment to test Hypothesis #2. You will use the pendulum as a model for the conversion of potential energy to kinetic energy in a roller coaster. Your goal is to determine what variable can be used to maximize the speed of the roller coaster. Potential independent variables include the length of your pendulum, mass, or height of its initial position. Hint – study equation (5) to help you determine which variable most important.

Independent variable: _____

Explain your choice:

Summarize your experimental plan to test your hypothesis; Create your own data sheet:

Discussion Questions

1. Did the first part of your experiments prove or disprove Hypothesis #1? Explain your answer. If hypothesis #1 was not true, explain what aspects of the theory or your measurements could have contributed to the error.

Swinging Pendulum Worksheet

Name: _____

Part #1 – testing hypothesis #1: kinetic energy = potential energy

first trial (distance = 0.50 m)

1. Experimental Measurements

Mass of Weight (kg) _____

Length of string (m) _____

Height of pendulum from floor when hanging straight (h_1) (m) _____

Height of pendulum from floor when held over tape (h_2) (m) _____

Height above datum ($h = h_2 - h_1$) (m) _____

Table 1: Experimental measurements, $d=50$ cm

Experiment 1: $d=0.50$ m	Trial #1	Trial #2	Trial #3	Trial #4	Average T
Time for one period (T) (s)					

2. Calculations based on theory (show all work and record results in Table 2)

a. Potential energy of pendulum when held over tape (equation 1):

b. Kinetic energy of pendulum at its lowest point (eqn. 5):

c. Velocity of the pendulum at its lowest point (eqn. 2):

d. Time for one period (eqn. 4):

3. Calculations based on measured values (show all work and record results in Table 2):

a. Average velocity (use average time) (eqn. 3)

b. Kinetic energy based on average velocity (eqn. 2)

Experiment 1: d=50 cm	Potential Energy (J)	Kinetic energy (J)	Velocity (m/s)	Period (s)
Theoretical Analysis				
From experimental measurements				
% difference				

Perform the same procedures as before, except adjust the pieces of tape to be 0.80 – 1.0 m apart.

Second trial (distance = _____ m)

4. Experimental Measurements

Mass of Weight (kg) _____

Length of string (m) _____

Height of pendulum from floor when hanging straight (h_1) (m) _____

Height of pendulum from floor when held over tape (h_2) (m) _____

Height above datum ($h = h_2 - h_1$) (m) _____

Table 3: Experimental measurements, d=_____ cm

Experiment 2: d=_____ m	Trial #1	Trial #2	Trial #3	Trial #4	Average T
Time for one period (T) (s)					

5. Calculations based on theory (show all work and record results in Table 4)

a. Potential energy of pendulum when held over tape (equation 1):

b. Kinetic energy of pendulum at its lowest point (eqn. 5):

c. Velocity of the pendulum at its lowest point (eqn. 2):

d. Time for one period (eqn. 4):

6. Calculations based on measured values (show all work and record results in Table 4):

a. Average velocity (use average time) (eqn. 3)

b. Kinetic energy based on average velocity (eqn. 2)

Experiment 2: d=___ m	Potential Energy (J)	Kinetic energy (J)	Velocity (m/s)	Period (s)
Theoretical Analysis				
From experimental measurements				
% difference				