Amusement Park Physics (ME-9426A)

Introduction

The Amusement Park Physics Kit provides material for 16 Vertical Accelerometers and 16 Horizontal Accelerometers. The kit also includes a ball of string that can be marked off in meters for distance measurements, as well as plastic bags for protecting accelerometers, paper, and other supplies from rides which feature spraying water. The only materials you will need that aren't included are scissors, masking tape, pliers, and clear plastic tape.

The accelerometers are designed to be assembled by the students themselves. Instruction sheets for doing so are included with the kits.

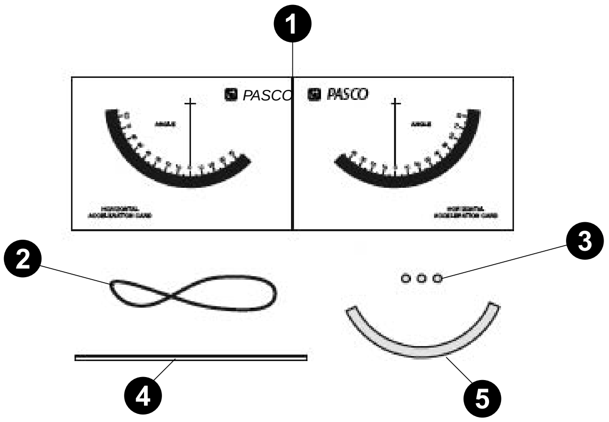
About this manual

This manual includes some basic information on using the accelerometers. It also includes three experiments that can be performed outside of an amusement park: two experiments to be used on playgrounds, and one that requires an elevator.

This manual does not include amusement park experiments for two reasons. First, available rides vary greatly from park to park, so we cannot guarantee that an experiment would work for a particular park. Second, experiments for amusement parks are readily available from other sources, such as the American Association of Physics Teachers (AAPT) *Amusement Park Physics*, a collection of handwritten materials written and circulated by individual teachers and edited by Carole Escobar. It is also possible that an Amusement Park Physics Day is already planned at a park near you, and that materials may be available that are applicable to that particular park. Talk to your local PTRA (Physics Teacher's Resource Agent) for more information.

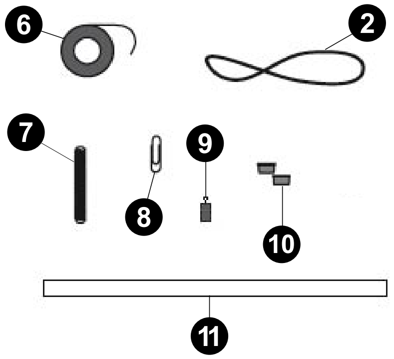
Materials

Materials for building Horizontal Accelerometers:



① Accelerometer card (16×)
② Rubber band (32× total)
③ BBs (60×)
④ Straw (16×)
⑤ Plastic tubing (2.5 m total)

Materials for building Vertical Accelerometers:



② Rubber band (32× total)
⑥ Red tape (3 mm wide)
⑦ Springs (16×)
⑧ #3 Paper clip (17×)
⑨ Weight, 10 g (19×)
⑩ End cap for plastic tube (32×)
⑪ Plastic tube, 30 cm (16×)

Other included equipment:

- Plastic storage bag (16×)
- Accelerometer Construction Sheet (16×)
- String
- Pushpin (5×)
- Bumper sticker (16×)

Additional required equipment:

- Scissors
- Masking tape
- Clear plastic tape
- Pliers

Accelerometers: Theory and operation

The Vertical Accelerometer

Accelerometers measure acceleration indirectly by measuring forces. The Vertical Accelerometer in this kit consists of a cylindrical weight hung from a spring. Its operation can be understood in terms of Hooke's law:

$$F_s = -kx$$

where F_s is the force applied to the weight by the spring, x is the length by which the spring is extended, and k is a constant that depends on the spring. The negative sign indicates that the force is in the direction opposite to the extension. As the force applied to the weight by the string increases, the extension x increases in direct proportion. Thus, the position of the end of the spring indicates the amount of force being applied to the weight by the spring.

Calibration of the device can be in newtons for the spring force, or in the ratio

$$\frac{F_s}{m} = a$$

where *a* is an acceleration, since the mass of the cylinder remains constant for all uses. With the unstretched spring position taken as the zero point, the weight of a single cylinder defines the position corresponding to a restoring force, which has magnitude equal to the weight of the cylinder, or:

$$\frac{F_s}{m} = 9.8\ \mathrm{m/s}^2$$

NOTE: If the device is calibrated in units of *g* instead of $\mathrm{m/s^2}$, it should be pointed out to students that the unit *g* used here is only related to the local acceleration due to gravity in that it has the same magnitude. A reading of 2.0 *g* on an accelerometer does not mean that the gravitational field has increased. Rather, it means that the rider feels a force which is twice the magnitude of the rider's own weight.

When the device is held vertically, the net force on the cylinder is given by:

$$F_{\text{net}} = F_s - mg$$

where *mg* is the weight of the cylinder.

A diagram of the spring and weight are shown in Figure 1. When the accelerometer is held at rest (left), the spring force is equal to the weight but in the opposite direction, so the net acceleration is zero and the scale reads "1g". In other words:

$$F_{\text{net}} = 0 = F_s - mg$$
$$F_s = mg$$

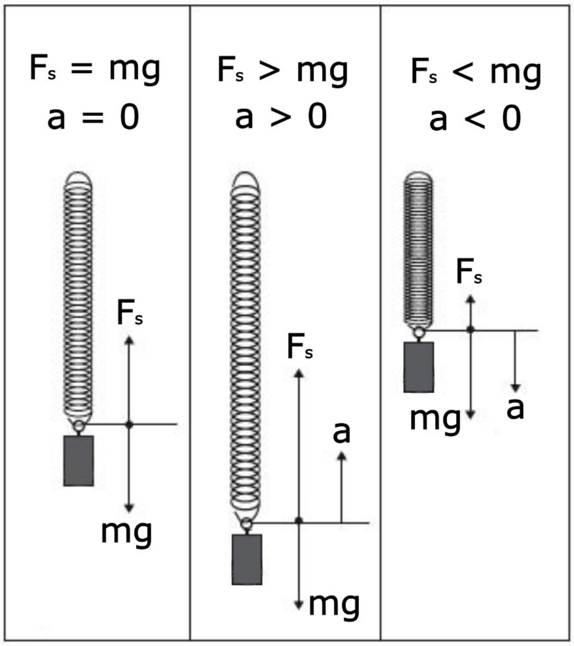


Figure 1. Diagram of the Vertical Accelerometer under no acceleration (left), upward acceleration (middle), and downward acceleration (right).

All the spring is doing is supporting the weight of the cylinder, without accelerating it. This is also true if the device is moving up or down at a constant velocity.

If the weight is accelerating upward, as in the middle panel of Figure 1, the spring must exert not only an upward force equal to the weight, but also enough *additional* upward force to provide the acceleration. With F_s greater than *mg*, the net acceleration will be greater than zero and upward. In this case, the spring will be stretched more than when at rest, and the weight will be below the "1g" position.

If the weight is accelerating downward, as in the right panel of Figure 1, the spring must be applying less force than the cylinder's weight. The spring will be stretched less than when at rest, and the cylinder will be above the "1g" position, with the weight helping to accelerate the mass downward.

The device registers the acceleration as seen in the frame of reference of the rider. Consider the weight of the accelerometer to be a "plumb bob", as its direction response is the same as that of a plumb bob. In this case, the amount of stretch of the spring gives the weight of the cylinder in the combined gravitational and acceleration fields of the ride.

Note that the gravitational field in one direction cannot be distinguished from an acceleration in the opposite direction. This is because you cannot feel the difference between a force due to gravity and a force due to the ride pushing on you. The scale readings display the force experienced in the *local* gravitational field. Since the accelerometer registers the acceleration in the frame of reference of the rider, the readings agree with what the rider "feels" at any given moment.

A negative or downward acceleration occurs after the top of roller coaster hills, when an elevator begins a downward trip, when one begins to slide downhill, or other such scenarios. The sinking feeling riders feel is due to less force being applied upward than they are used to. On some rides, the downward force is partly a push from the safety bar. This downward push produces the feeling that the rider has suddenly become lighter and is rising out of the seat. Sure enough, the accelerometer will read less than "1g" in these scenarios.

Upward or positive accelerations can be felt in elevators as they begin to rise, as well as at the bottom of vertical loops on roller coasters and swings. As the elevator begins to rise, the floor begins to push up with a greater force than the rider's weight. The rider interprets this as an increase in downward force and thus feels heavier. The accelerometer spring stretches to provide the additional force for the weight, registering more than "1g". Both the direction and the magnitude of the readings agree with the rider's feeling of an altered gravitational field.

Upside-down, at the top of a vertical circle like a roller coaster loop or rotating ride, the rider may feel little or no force from the seat, creating a sense of "weightlessness". At the same point, the accelerometer shows little- if any- pull being applied by the spring, so the rider's experience and the reading are again in agreement. At the bottom of the same loop, the strong upward push from the seat feels like a force pushing the rider downward into the seat. This upward force is also applied to the cylinder by the spring, which stretches and yields a large reading, once again agreeing with the rider's experience.

The Horizontal Accelerometer

With Horizontal Accelerometers, unlike Vertical Accelerometers, the relationship between subjective experience and accelerometer reading is less direct. At rest, the BBs in the horizontal accelerometer settle to the bottom of the curved plastic tube. There is no horizontal force applied, and therefore there is no horizontal acceleration.

When the BBs are above the bottom, as shown in Figure 2, the inside of the curved plastic tube applies a force to them. The applied force has a vertical component equal to the mass of the BBs times their horizontal acceleration. The applied force acts along a line that makes an angle θ with the vertical central line of the accelerometer.

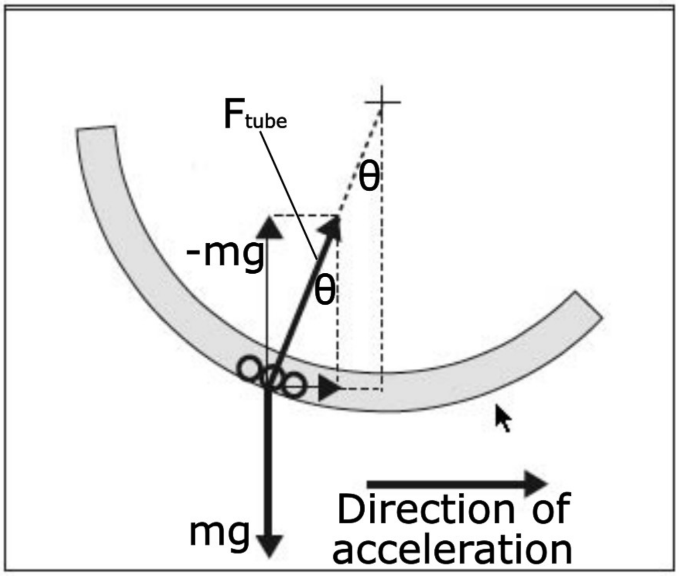


Figure 2. Diagram of a Horizontal Accelerometer. F_{tube} refers to the force exerted by the tubing on the BBs.

Since the components are perpendicular to each other by definition, and the horizontal force *ma* is opposite the angle θ, we find that:

$$tan(\theta) = \frac{ma}{mg}$$

where *a* refers to the horizontal acceleration. This can be rearranged into:

$$ma = mg\tan(\theta)$$

We can divide both sides by the mass *m* of the BBs to obtain our equation:

$$a = g\tan(\theta)$$

where *a* is always directed toward the front of the device.

To measure the horizontal acceleration in the direction you are moving, simply hold the accelerometer level, with the straw pointed in the direction you are moving, and record the angle θ between the center line and the BBs. Use a calculator or the values in Table 1 to find the tangent of the angle, then multiply that value by *g* to obtain the horizontal acceleration.

Table 1. Table of tangents.

Angle (°)	Tangent	Angle (°)	Tangent
0	0.00	45	1.00
5	0.09	50	1.19
10	0.18	55	1.43
15	0.27	60	1.73
20	0.36	65	2.14
25	0.47	70	2.75
30	0.58	75	3.73
35	0.70	80	5.67
40	0.84	85	11.40

To use the Horizontal Accelerometer to measure horizontal *centripetal* accelerations, hold it perpendicular to the direction in which you are traveling, keeping it as level as possible. For example, on the rotor ride at an amusement park, where you are in a rotating cylinder feeling pressed against the wall, hold the accelerometer with the short side pressed to the wall. The accelerometer will be level with the floor and- since you are traveling sideways- perpendicular to the direction of travel.

Before motion begins, the BBs sit motionless in the bottom of the tube, and a centripetal force is needed to make them go in a circle. When the ride begins to rotate, the BBs will ride up the side nearest the wall, as if forced outward. In fact, the tube will be exerting a horizontal force on the BBs, directed inward toward the center of the ride. The BBs will ride up the tube until the angle is large enough to give the necessary horizontal acceleration. In circular motion:

$$a = \frac{v^2}{r}$$

where *v* is the linear speed along the circumference and *r* is the radius of the circle. Therefore, as the ride picks up speed and *v* increases, *a* will also increase and the BBs will travel farther up the curve.

Using the Horizontal Accelerometer as a sextant

The horizontal accelerometer can be used to measure the heights of objects that are too high to measure directly, such as measuring the height from the ground to the top of a tower, as shown in Figure 3. You can measure these distances with reasonable accuracy using just the accelerometer, a piece of string marked out in meters, and a little trigonometry. The procedure is as follows:

1. Using a piece of string marked out in meters, measure the horizontal distance *S* between your position and a point directly below the object of interest.
2. Sight through the straw to the top of the object of interest. Record the angle θ that the center BB rests at for this inclination. *This angle is also equal to the angle between your horizontal line of sight and your line of sight to the top of the object of interest.*

3. Measure h_0, the vertical distance between the base of your height measurement and your observation point. (As long as the ground is level between you and the object of interest, h_0 is just the distance between the ground and your eyes.)
4. Determine the total height H of the tower using the following equation, derived from the fact that tan(θ) = h_1/S:

$$H = h_0 + h_1 = h_0 + S\tan(\theta)$$

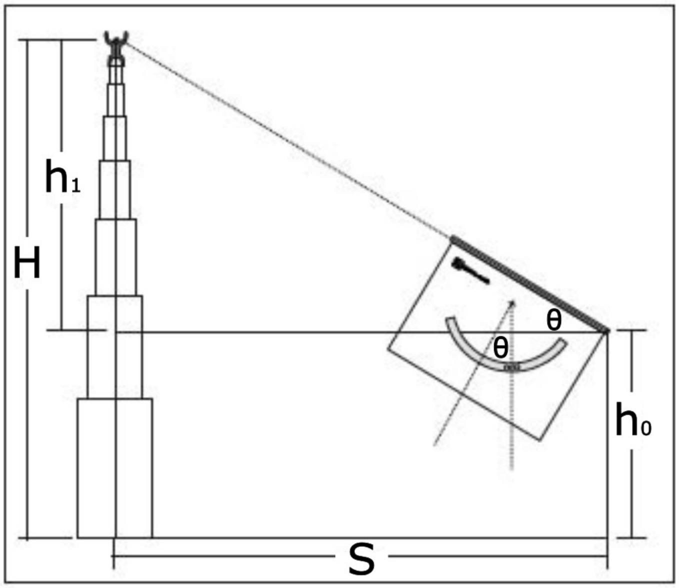


Figure 3. Measuring height with the Horizontal Accelerometer.

Construction tips

Detailed instructions for assembling the Vertical Accelerometer and Horizontal Accelerometer are included with the Amusement Park Physics Kit. Sixteen copies of these instructions are provided, allowing each student to construct their accelerometers at their own pace. When building the accelerometers, advise students to follow the guidelines below.

Vertical Accelerometer

When calibrating the Vertical Accelerometer, employ Hooke's Law and some foresight. In Figure 4, a thin solid wire has been attached to a weight. By hooking the end of the wire onto the lower end of the spring just before lowering it into the tube, one can establish the "2g" point easily. After this, pull the second weight out of the bottom of the tube and remove it, allowing the single weight to rise up to the "1g" point. With these two points determined, it is easy to finish calibrating the accelerometer.

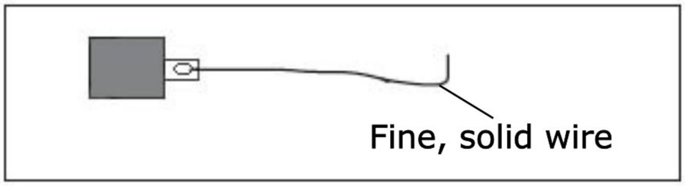


Figure 4. Wire attached to mass. Use to calibrate the Vertical Accelerometer.

Horizontal Accelerometer

One method for constructing the horizontal accelerometer makes use of the rapid set-up time of hot glue. Put the clear tubing in one half of the cardboard and insert the three BBs. Now put hot glue in the places indicated in Figure 5 and press the two halves of the accelerometer together. This will result in a completed accelerometer (except for the straw, which can also be hot glued on) in about 15 seconds.

> **NOTE:** Make sure not to get any hot glue in the end of the tube, as the BBs tend to stick to the glue.

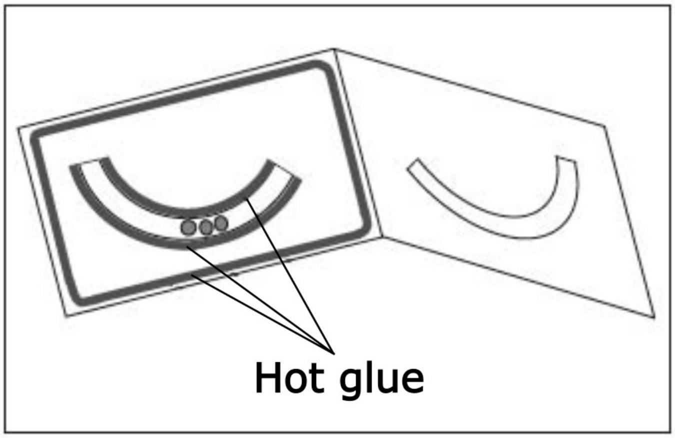


Figure 5. Using hot glue to construct the Horizontal Accelerometer.

For students using simple calculators without trigonometric functions, Table 1 can be printed out and glued to the side of the horizontal accelerometer for reference. Similarly, students should record the length of their pace on the side of the horizontal accelerometer if this length is being used to measure horizontal distances.

Other uses of the accelerometers include:

- Use the vertical accelerometer to measure the acceleration achieved when jumping upwards, or to measure the stopping acceleration when jumping down from a chair seat. This teaches the basic principles of the device before going to the park.
- Accelerometers can be employed to measure motion on mass transit, including buses, light rail, and subway systems.
- The horizontal accelerometer can be used to sight star altitudes.

Experiment 1: Playground Physics - Merry-Go-Round

Objective

In this lab, you will experiment with centripetal accelerations on a playground merry-go-round.

Introduction

While riding a merry-go-round, we experience the sensation of being "thrown" outward. Physics students know that this "force" is actually our own inertia trying to keep us moving in a straight line. However, by exerting the right amount of inward, or *centripetal*, force, we can successfully stay in a circular path and remain on the merry-go-round. This force is usually supplied by friction between our shoes and the ride, as well as friction between our hands and the bars of the merry-go-round. How does this force change with varying distance from the center of the ride? How does it depend on the speed of rotation of the ride?

At least two people are needed to carry out this lab, and three or more are recommended. A stopwatch or digital wristwatch, one or more Horizontal Accelerometers, and a measuring device with a resolution of 0.1 m are required.

Procedure

1. Measure off several distances from the center of rotation. Place the Horizontal Accelerometer at one of these distances, holding it against a bar if necessary to keep it from moving, and making sure it is level. The middle BB should be at 0°. Record *R*, the accelerometer's distance from the center of the merry-go-round, in Table 1.

TIP: Several riders, each with a Horizontal Accelerometer, could be positioned simultaneously at different distances.

2. Push the merry-go-round until it is moving at a steady, relatively slow angular velocity.
3. Measure the time it takes to make one complete rotation at the current speed (or, for more accurate data, find the time to make five full rotations and divide this value by 5) to obtain *T*, the average period of rotation. While the merry-go-round is turning, the person on the ride will measure θ, the angle that the central BB moves to. Record both *T* and θ in Table 1.
4. Repeat Step 3 for at least three different speeds of rotation, holding the accelerometer steady at the same radius. Record the appropriate values on new rows of the data table.
5. Move the accelerometer to a new radius and repeat Steps 3 and 4. Try to match the speeds of the merry-go-round from the first few trials.

Table 1. Collected data

Trial #	*R* (m)	*T* (s)	θ (°)
1			
2			
3			
4			
5			
6			
7			
8			
9			

Analysis

1. For each trial, calculate the tangential speed *v*, the speed at which the accelerometer was traveling around its circular path, using the equation $\mathbf{v = 2\pi R/T}$. Record your calculated values in Table 2.
2. For each trial, calculate the theoretical centripetal acceleration a_c using the equations $\mathbf{a_c = v^2/R}$ or $\mathbf{a_c = 4(\pi)^2R/T^2}$. Record these values in Table 2.
3. For each trial, calculate the *measured* centripetal acceleration from the angle of the BBs, using the equation $\mathbf{a_c = g\ tan(\theta)}$.
4. Compare the calculated and measured acceleration values for each trial.

Table 2. Data values from analysis

Trial #	v (m/s)	Theoretical a_c (m/s^2)	Measured a_c (m/s^2)
1			
2			
3			
4			
5			
6			
7			
8			
9			

Discussion

1. Were the calculated and measured acceleration values for each trial identical? Were they similar? What percentage differences did you get in your results?
2. When the merry-go-round was going at approximately the same speed, how did the measured acceleration vary with the radius? Was the change linear? If not, what was the mathematical relationship?
3. When the accelerometer was held at the same radius, what was the relationship between the measured acceleration and the speed? Was it linear? If not, what was the mathematical relationship?
4. What are some possible sources of error in this experiment?

Experiment 2: Playground Physics - The Swing

Objective

In this lab, you will measure the maximum acceleration on a swing and compare this to a predicted value, determined through the principles of conservation of energy and centripetal force.

Introduction

On a swing, we can observe a number of important physical phenomena in action, including simple harmonic motion, driven harmonic motion, inertia, conservation of energy between gravitational potential and kinetic energy, and centripetal force. In this experiment, we will use the latter two ideas to calculate a theoretical acceleration and then compare the results with the acceleration we actually measure. At least two people, a Vertical Accelerometer, and a Horizontal Accelerometer are needed for this experiment.

Procedure

1. One person (Person A) gets onto the swing with the Vertical Accelerometer and begin swinging. The other person (Person B) takes up a position on the side so that they can see and measure the angle of Person A's motion.
2. Person A on the swing keeps the Vertical Accelerometer pointed upward along the chain or rope of the swing, and will read the maximum value as they pass through the lowest point of the swing's arc. Record this value as a_{max} in Table 3.
3. Person B will use the Horizontal Accelerometer to measure the maximum angle θ that Person A reaches during the swing. To do this, line the straw side of the accelerometer up with the chain when the swing is at its highest point. The angle that is indicated on the accelerometer will be equal to 90° minus θ, as shown in Figure 1. Record the value of θ in Table 3.

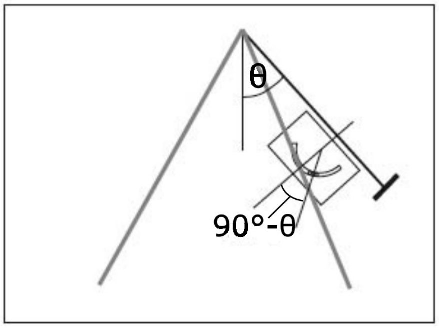


Figure 1. Experiment setup, with relevant angles labeled.

4. Once the observer on the ground has recorded both the angle and the maximum acceleration, repeat Steps 2 and 3 for at least three different maximum angles. Then change places and repeat three more times. Record all data in Table 3.
5. Determine the length of the swing. To do this you can use one person's height and scale up, pace off a horizontal distance and use the Horizontal Accelerometer to determine the height, or use a measuring device. Due to the fact that the person swinging is seated, you can approximate their center of mass as being close to the seat.

Analysis

1. For each trial, use trigonometry to calculate the difference in the height of the swing between the maximum height and the bottom of the arc. (See Figure 2.) Record these values in Table 3.

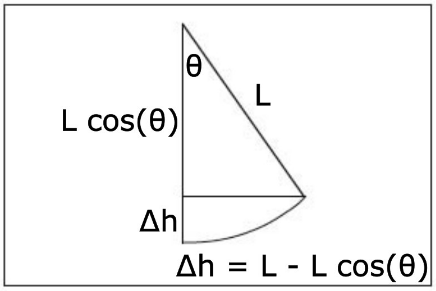


Figure 2. Trigonometric representation of the swing in motion.

NOTE: The difference in height can also be directly measured with a measuring tape by pulling the swing back to the angle determined by Person B.

2. Using conservation of energy between gravitational potential energy and kinetic energy, determine the theoretical maximum velocity v_{max} at the bottom of the swing. Note that the relevant equations combine to yield:

$$mg\Delta h = \frac{1}{2}mv^2$$

   meaning the mass m divides out of both sides and does not need to be measured.

3. The acceleration at the bottom of the swing has two components: gravity and centripetal acceleration. We can show that the centripetal acceleration is equal to $\mathbf{v_{max}^2/L}$, where L is the length of the swing. Calculate this value and convert it to g's by dividing your result by 9.8 m/s^2. Add the 1 g due to gravity to obtain the theoretical net acceleration a_{net}. Record both of these values in Table 3.

L = ________________

Table 3. Collected and calculated data.

Trial #	Measured acceleration a_{max} (g's)	Maximum angle θ (°)	Height difference Δh (m)	Maximum velocity v_{max} (m/s)	Centripetal acceleration a_c (g's)	Theoretical net acceleration a_{net} (g's)
1						
2						
3						
4						
5						
6						
7						
8						
9						

Discussion

1. Compare the acceleration values you calculated and the corresponding values measured on the swing. How well does your prediction reflect reality?
2. Examine the situation and suggest possible sources of error in your measurements and calculations.

Experiment 3: Elevator Physics

Objective

During this lab, you will determine the vertical accelerations in an elevator using an accelerometer and analyze the motion of the elevator.

Introduction

The net force on the mass in the Vertical Accelerometer is given by the relationship:

$$F_s - mg = F_{\text{net}} = ma_{\text{net}}$$

where F_s is the force applied by the spring to the mass and *mg* is the weight of the mass. When the mass is at rest or moving with constant speed upward or downward, the upward pull of the spring equals the magnitude of the downward pull of gravity. In such cases, the net force is zero, meaning the net acceleration of the mass is also zero. Calibrating the accelerometer to read "1g" when at rest recognizes the 1g effect of gravity. A net acceleration of zero can be obtained by subtracting 1g from this reading.

If the mass is accelerating upward, it will be in a position below "1g", meaning the reading is greater than 1g. The net acceleration can again be found by subtracting 1g from the accelerometer reading. In this case the reading will still be above zero (positive), indicating an upward acceleration. If the mass is accelerating downward, it will instead be above the "1g" position, giving a reading of less than 1g. Subtracting 1g from this value will yield a negative net acceleration, in agreement with the downward acceleration of the mass.

Procedure

While riding in an elevator, hold the Vertical Accelerometer upright by pressing it to the elevator wall. Take readings of the acceleration in each of the scenarios listed in Table 5.

Table 4. Accelerometer readings while…

	Trial 1	Trial 2	Trial 3
No vertical motion			
Beginning an ascent			
Middle of an ascent			
As ascent is slowing			
After ascent has stopped			
Beginning a descent			
Middle of a descent			
As descent is slowing			
After descent has stopped			

Questions

1. Are the magnitudes of the accelerations different at the beginning of the ascent than in the middle of the ascent? Explain why or why not.
2. Are the magnitudes of the accelerations different at the middle of the ascent than at the middle of the descent? Explain why or why not.
3. How does the starting acceleration compare with the stopping acceleration? Was this difference (or lack of difference) the same during the ascent as during the descent?
4. Were the acceleration values constant during any of the periods of acceleration, or did they vary? If so, how did they vary? Were they all in the same pattern?
5. How did you feel in each of the situations where you took readings? Compare your sensations with the accelerometer readings.

Mathematical analysis (*Optional*)

If instructed, take a new set of readings. This time, in addition to recording the net acceleration reading during each stage, also record the time it took for that stage to occur and the measured (or estimated) distance over which it took place. (Multiply the value of acceleration in g's by 9.8 to obtain the acceleration in m/s^2.) Record all of these values in Table 5.

Table 5. Data for mathematical analysis

	Time (s)	Distance (m)	Acceleration (m/s^2)
No vertical motion			
Beginning an ascent			
Middle of an ascent			
As ascent is slowing			
After ascent has stopped			
Beginning a descent			
Middle of a descent			
As descent is slowing			
After descent has stopped			

Questions, continued

1. What was the average speed while going up?
2. What was the average speed while going down?
3. Use your acceleration values and times to calculate distances for each of the accelerations. How do these calculated values compare with the ones you measured (or estimated)?
4. What was your average speed during each of the periods where you were moving at a constant speed?
5. Use your data to construct a distance vs. time graph and a velocity vs. time graph.
6. Do these graphs accurately reflect the motion you experienced on the elevator? Explain the sensations you felt at different points in the experience.

Technical support

Need more help? Our knowledgeable and friendly Technical Support staff is ready to answer your questions or walk you through any issues.

Chat	pasco.com
Phone	1-800-772-8700 x1004 (USA) +1 916 462 8384 (outside USA)
Email	support@pasco.com

Regulatory information

Limited warranty

For a description of the product warranty, see the Warranty and Returns page at www.pasco.com/legal.

Copyright

Trademarks