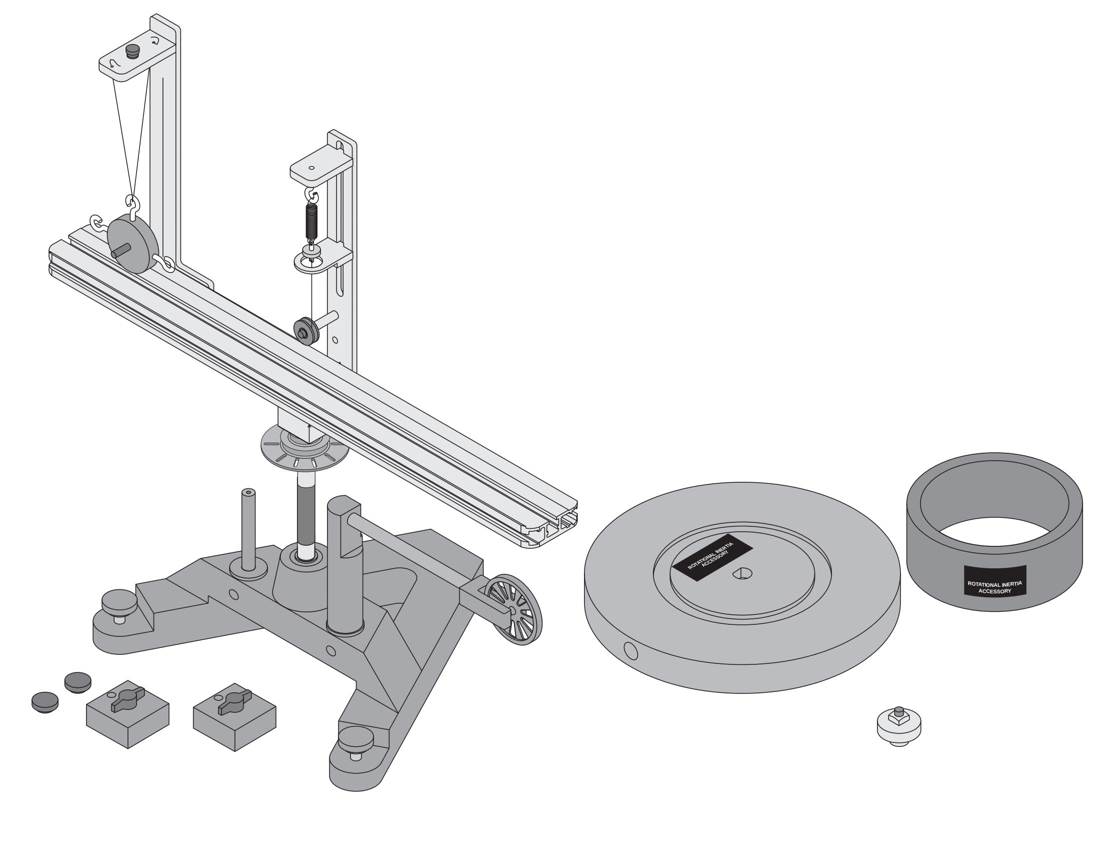
Instruction Manual and Experiment Guide for the PASCO scientific Model ME-8950

012-05293E
8/97

COMPLETE ROTATIONAL SYSTEM



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① The packing carton must be strong enough for the item shipped.

② Make certain there are at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

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Introduction

PASCO's Complete Rotational System provides a full range of experiments in centripetal force and rotational dynamics. The system consists of three separate components:

Description

The ME-8951 Rotating Platform consists of a sturdy 4 kg base with low friction bearings and a rotating arm which serves as a versatile base for rotation experiments. This platform is a general purpose base upon which you may mount anything (having a mass under 3 kg) you wish to rotate. The T-slots in the track supply a convenient way to mount objects to the track using thumbscrews and square nuts. To use the Centripetal Force Accessory (ME-8952) or the Rotational Inertia Accessory (ME-8953), each must be mounted on this base. A photogate/pulley mount and two 300 g masses are also included.

The ME-8952 Centripetal Force Accessory is comprised of two vertical posts which can be mounted to the Rotating Platform with thumbscrews. These posts are adjustable and can be positioned virtually anywhere along the length of the platform. The radius indicator is at the center of the apparatus so it can be clearly seen while the apparatus is rotating. This accessory requires the Rotating Platform (ME-8951) to operate. The PASCO Centripetal Force Accessory can be used to experiment with centripetal force and conservation of angular momentum. For the centripetal force experiments it is possible to vary the mass and radius to see the resulting change in the centripetal force. The force can also be held constant while other quantities are varied. The Centripetal Force Accessory is powered by hand and the rate of rotation can be counted manually or read by a computer. Variable hanging masses are included.

The ME-8953 Rotational Inertia Accessory includes a disk and a metal ring. The disk can be mounted to the rotating base in a variety of positions and at any radius. This accessory requires the Rotating Platform (ME-8951) to operate. The Rotational Inertia Accessory allows you to perform rotational inertia experiments and conservation of angular momentum experiments.

About This Manual

The following Equipment section describes each component in detail and the subsequent Assembly section provides instructions for component assembly and setup.

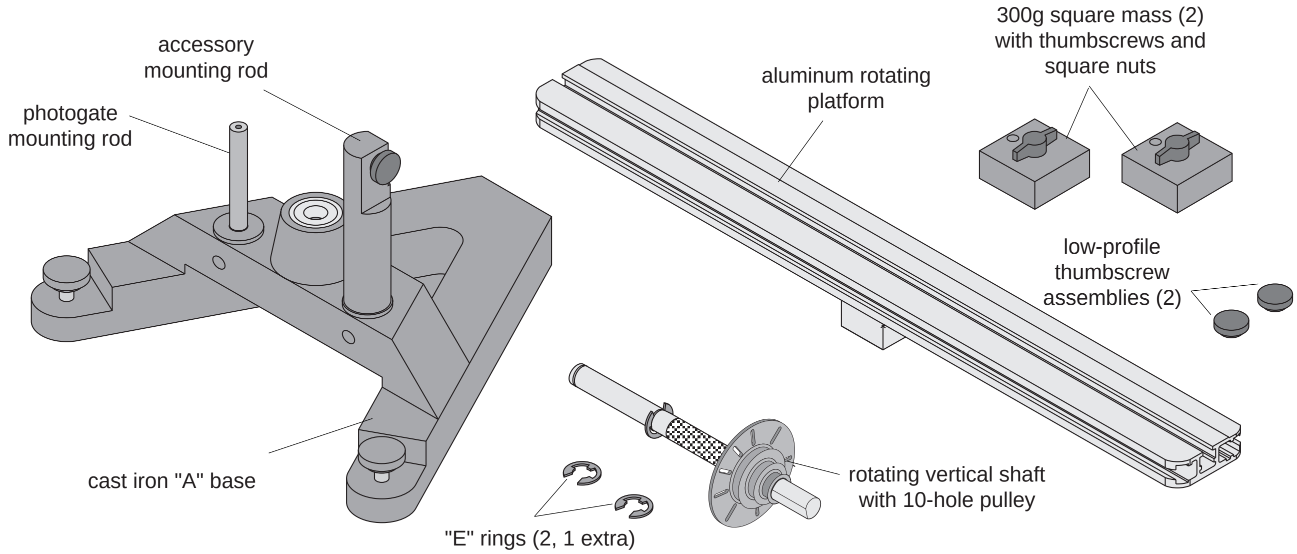
The Experiment section contains several experiments that can illustrate some of the basic theory of centripetal force, rotational inertia, etc.

Computer Timing

You can use a computer with a PASCO Smart Pulley to measure the motion of the apparatus. Some of the experiments describe how to use the MS-DOS version of Smart Pulley Timer. If you are using the Apple II version of Smart Pulley Timer, the procedure for using the program will be similar.

If you are using a computer interface that comes with its own software (such as the Series 6500 Interface for IBM or Apple II, the CI-6550 Computer Interface for Macintosh, or the CI-6700 MacTimer Timing Interface), refer to the interface manuals for instructions on how to use the software with the Smart Pulley.

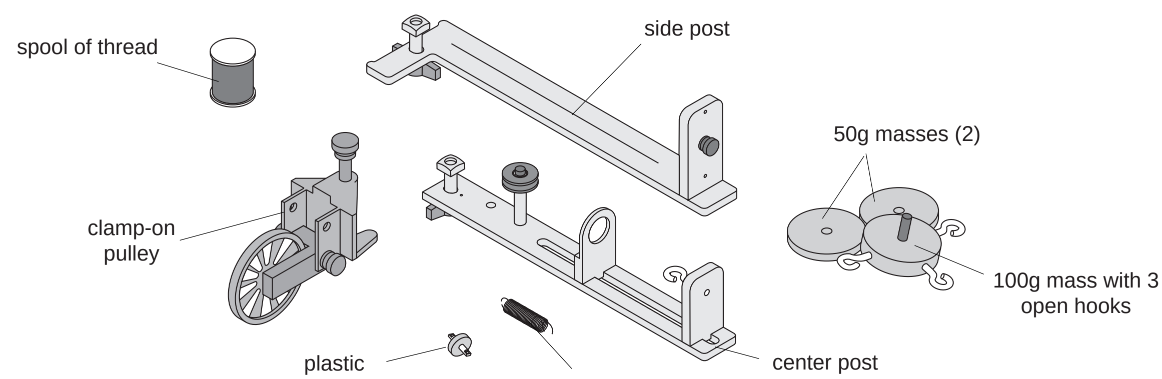
Equipment



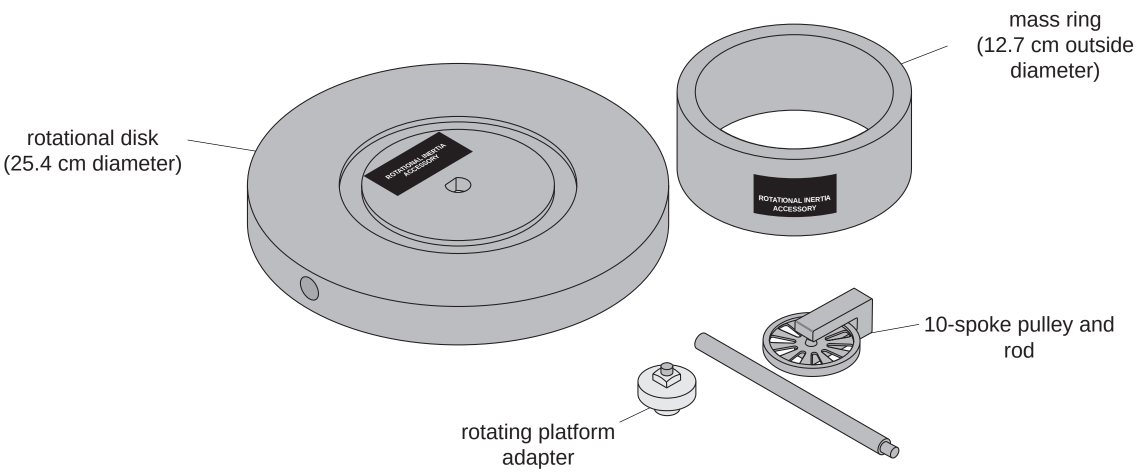
ME-8951 Rotating Platform Equipment

The ME-8951 Rotating Platform Includes the following:

- PASCO cast iron "A" base with rotating shaft and pulley with 10 holes
- aluminum track
- two square masses (about 300 g) with thumb screw and square nut
- two additional low-profile screws and square nuts to act as stops for the square mass in the Conservation of Angular Momentum experiment
- accessory mounting rod for mounting the 10-spoke pulley or the optional Smart Pulley photogate head
- accessory mounting rod for mounting PASCO Photogate (ME-9498A, ME-9402B or later)



- 1 spool of thread
- side post for hanging hooked mass



ME-8953 Rotational Inertia Accessory Equipment

The ME-8953 Rotation Inertia Accessory includes:

- disk with bearings in the center
- ring (12.7 cm diameter)
- adapter to connect disk to platform
- 10-spoke pulley and rod

Other Equipment Needed:

The following is a list of equipment recommended for the experiments described in this manual. See the PASCO catalog for more information.

- Projectile Launcher
- Projectile Collision Accessory
- Smart Pulley (with Smart Pulley Timer software, or a compatible computer interface)
- string
- mass and hanger set
- balance (for measuring mass)
- calipers
- stopwatch

Miscellaneous Supplies:

- meter stick
- graph paper
- carbon paper
- white paper
- rubber bands
- paper clips

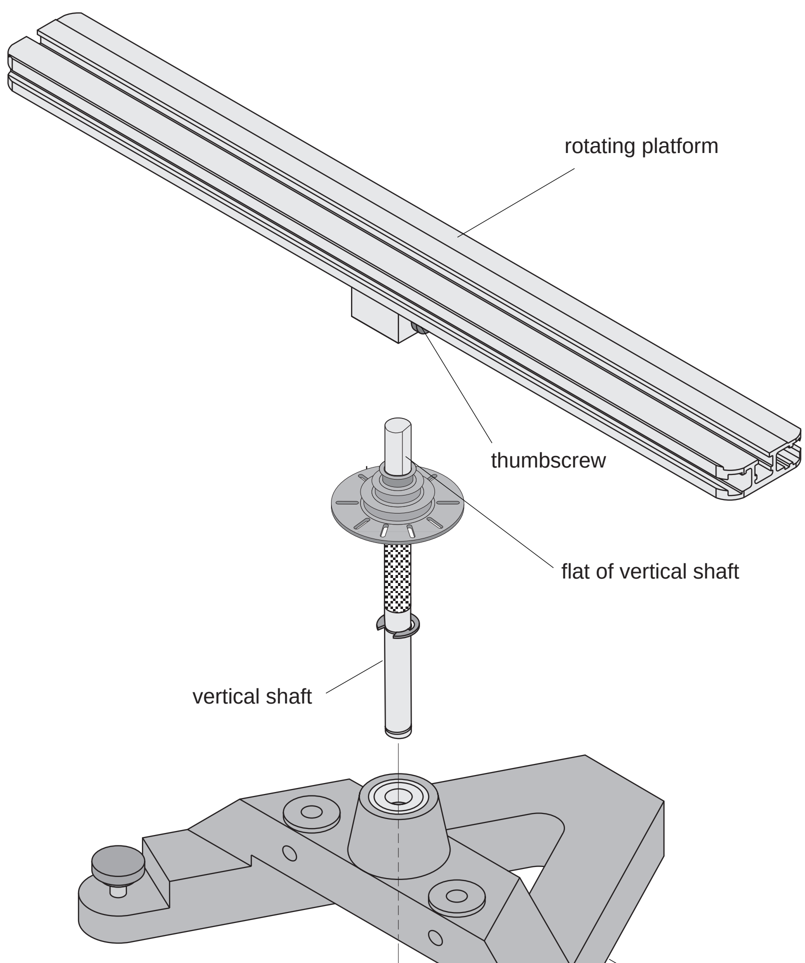
Assembly

ME-8951 Rotating Platform

Assembling the Rotating Platform

① Insert the cylindrical end of the shaft into the bearings on the top-side of the A-shaped iron base. Secure the shaft in place by inserting the "E" ring in the slot at the bottom of the shaft. See Figure 1.

② Mount the track to the shaft and tighten the thumb screw against the flat side of the “D” on the shaft. See Figure 1.



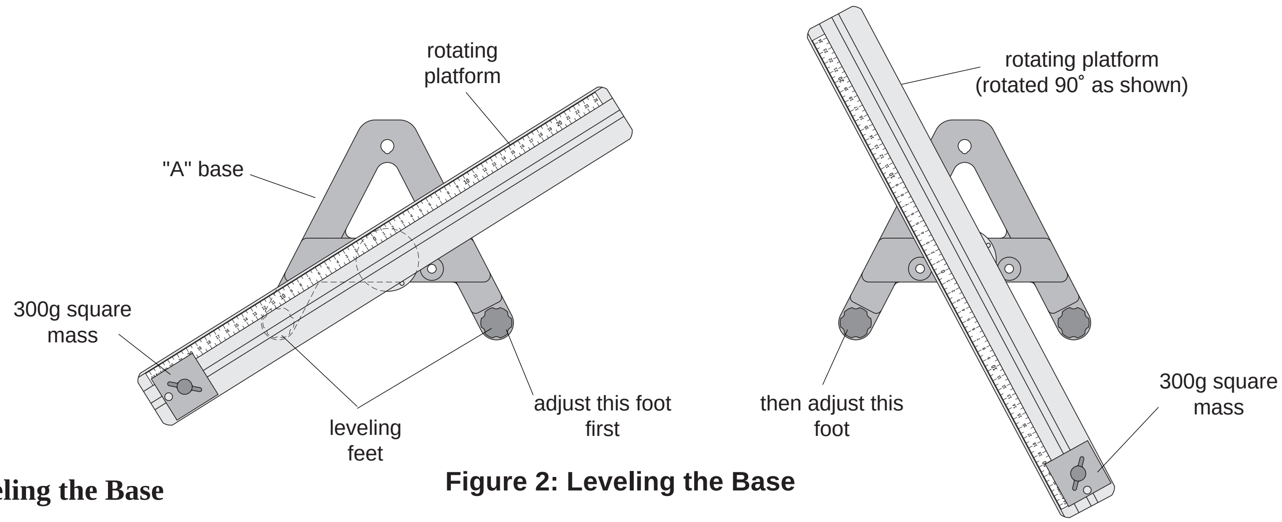


Figure 2: Leveling the Base

Leveling the Base

Some experiments (such as the Centripetal Force experiments) require the apparatus to be extremely level. If the track is not level, the uneven performance will affect the results. To level the base, perform the following steps:

① Purposely make the apparatus unbalanced by attaching the 300 g square mass onto either end of the aluminum track. Tighten the screw so the mass will not slide. If the hooked mass is hanging from the side post in the centripetal force accessory, place the square mass on the same side.

② Adjust the leveling screw on one of the legs of the base until the end of the track with the square mass is aligned over the leveling screw on the other leg of the base. See Figure 2.

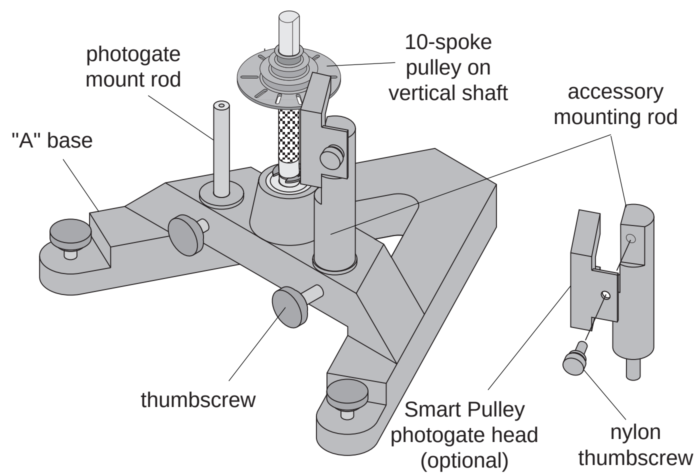
③ Rotate the track 90 degrees so it is parallel to one side of the “A” and adjust the other leveling screw until the track will stay in this position.

④ The track is now level and it should remain at rest regardless of its orientation.

Installing the Optional Smart Pulley Photogate Head

The black plastic rod stand is designed to be used in two ways:

- It can be used to mount a Smart Pulley photogate head to the base in the correct position to use the 10 holes in the pulley on the rotating shaft to measure angular speed.
- It can be used to mount a Smart Pulley (with the pulley and rod) to the base to run a string over the pulley.



To Use the Photogate Head Only:

① To install, first mount the black rod to the base by inserting the rod into either hole adjacent to the

black rod to rotate. Orient the rod and photogate head so the infrared beam passes through the holes

rod in place.

To use the entire Smart Pulley with rod or the Super Pulley with rod:

① Insert the Smart Pulley rod into the hole in the black rod and tighten the set screw against the Smart Pulley rod. See Figure 4.

② Rotate the black rod so the string from the pulley on the center shaft is aligned with the slot on the Smart Pulley.

③ Adjust the position of the base so the string passing over the Smart Pulley will clear the edge of the table.

To mount a PASCO Photogate on "A" base:

① Mount PASCO Photogate on threaded end of rod (rod height may be adjusted with thumbscrew).

② Slide non-threaded end of photogate mount into hole in base, clamp in place with thumbscrew.

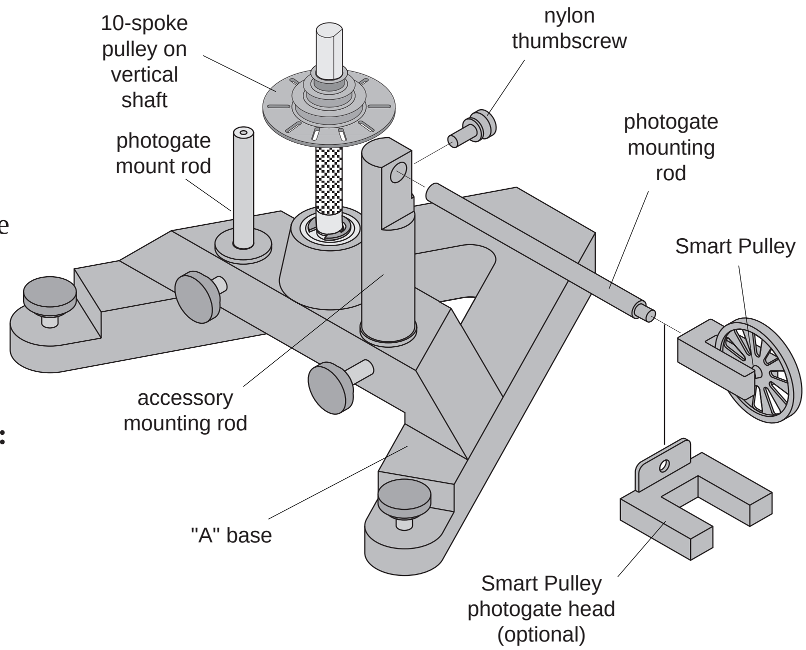


Figure 4: Using the Accessory Mounting Rod With the Photogate Mounting Rod and/or Smart Pulley

ME-8952 Centripetal Force Accessory

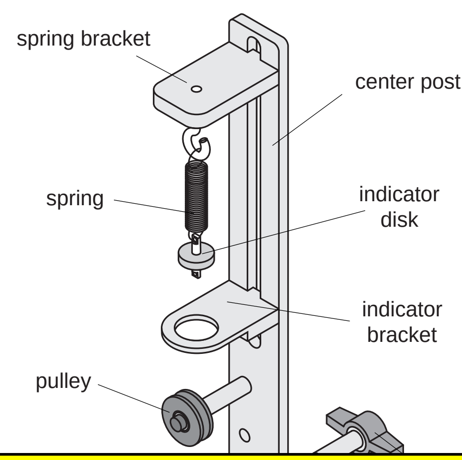
Center Post Assembly

Assemble the center post as shown in Figure 5:

① Attach one end of the spring to the spring bracket and connect the indicator disk to the other end of the spring. Insert the spring bracket into the slot on the center post and tighten the thumb screw.

② Tie one end of a string (about 30 cm long) to the bottom of the indicator disk and tie a loop in the other end of the string.

③ Insert the indicator bracket into the slot on the center post, placing it below the spring bracket.



Side Post Assembly

Assemble the side post as shown in Figure 6:

① Insert the thumb screw at the bottom of the side post and attach the square nut.

② Using a string about 30 cm long, tie the string around the screw head on the top of the side post. Then thread the other end of the string down through one of the holes in the top of the side post and then back up through the other hole. Do not pull the string taut.

③ Loosen the screw on the top of the side post and wrap the loose end of the string around the threads of the screw and tighten the screw.

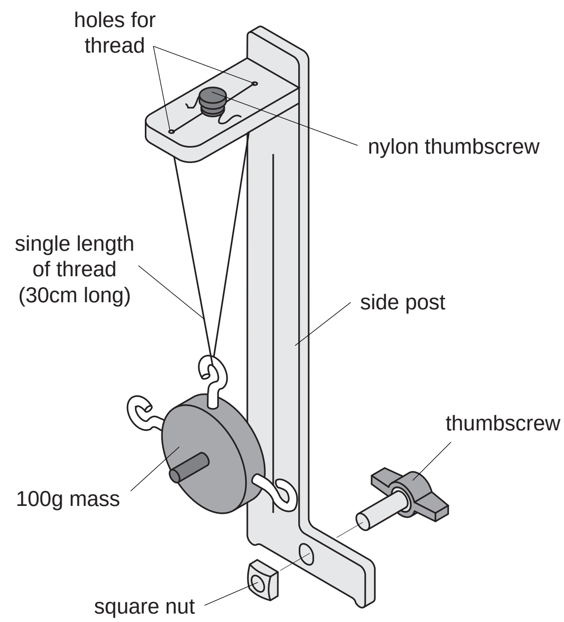
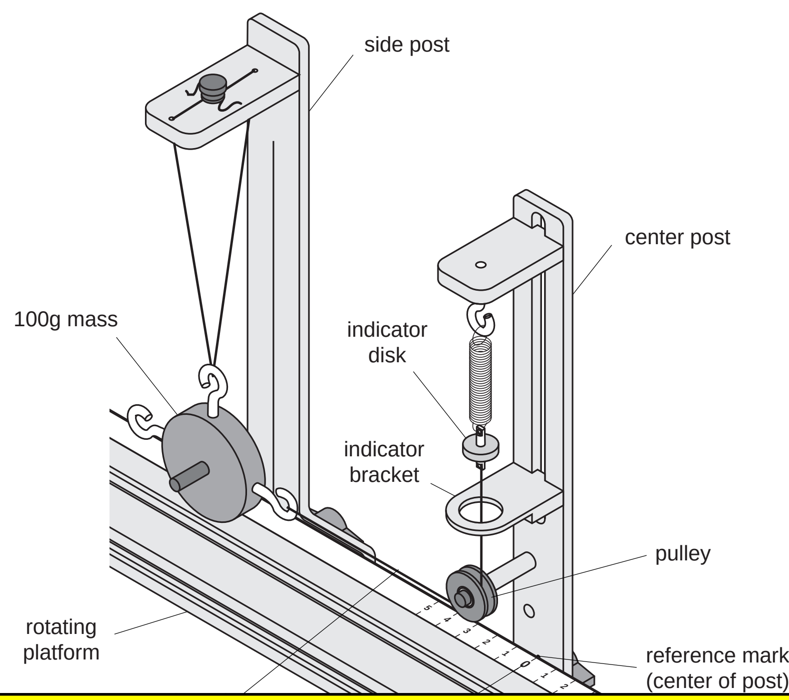


Figure 6: Side Post Assembly

Threading the Centripetal Force Accessory

① Mount the center post in the T-slot on the side of the track that has the rule. Align the line on the center post with the zero mark on the rule and tighten the thumb screw to secure it in place. Then mount the side post on the same side of the track. See Figure 7.

② Hang the object from the string on the side post and adjust the height of the object so the string coming from the center post will be level



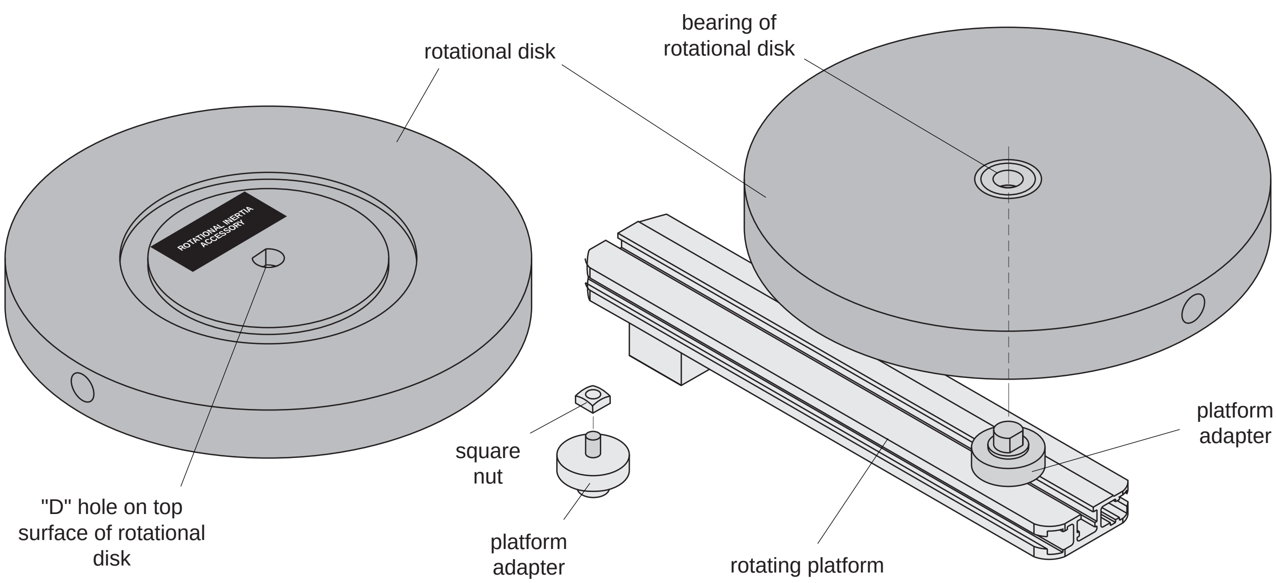


Figure 8: Rotational Inertia Accessory Including Platform Adapter Assembly

ME-8953 Rotational Inertia Accessory

Rotational Inertia Accessory Assembly

Little assembly is required to use the Rotational Inertia Accessory. The rotational disk can be placed directly onto the axle of the rotating base or can be used with the rotating platform via the included platform adapter.

Platform Adapter Assembly

① Attach the square nut (supplied with the Rotational Inertia Accessory) to the platform adapter.

② Position the platform adapter at the desired radius as shown in Figure 8.

③ Grip the knurled edge of the platform adapter and tighten.

The rotating disk can be mounted in a variety of positions using any of the four holes on the rotation disk.

- Two “D” holes exist on the edge of the disk, located at 180˚ from one another.
- One “D” hole is located at the center on the top surface (the surface with the metal ring channel and the PASCO label) of the disk.
- One hole is located at the center on the bottom surface of the disk and is actually the inner race of a bearing. This enables the rotational disk to rotate (in either direction) in addition to other rotating motions applied to your experiment setup.

Experiment 1: Conservation of Angular Momentum: Ball Shot Into Catcher on Rotating Track

EQUIPMENT NEEDED

- Rotating Platform (ME-8951)
- Projectile Launcher (ME-6800)
- Projectile Collision Accessory (ME-6815)
- Smart Pulley Photogate
- Smart Pulley Timer software
- Rubber band
- white paper and carbon paper
- thread
- meter stick
- mass and hanger set

Purpose

The muzzle velocity of the Projectile Launcher can be determined by shooting the ball into the catcher mounted on the track and conserving angular momentum during the collision. This result can be checked by finding the muzzle velocity of the Launcher by shooting the ball horizontally off the table.

Theory

A ball is launched horizontally and embeds in the catcher mounted on the platform. The platform then rotates. See Figure 1.1.

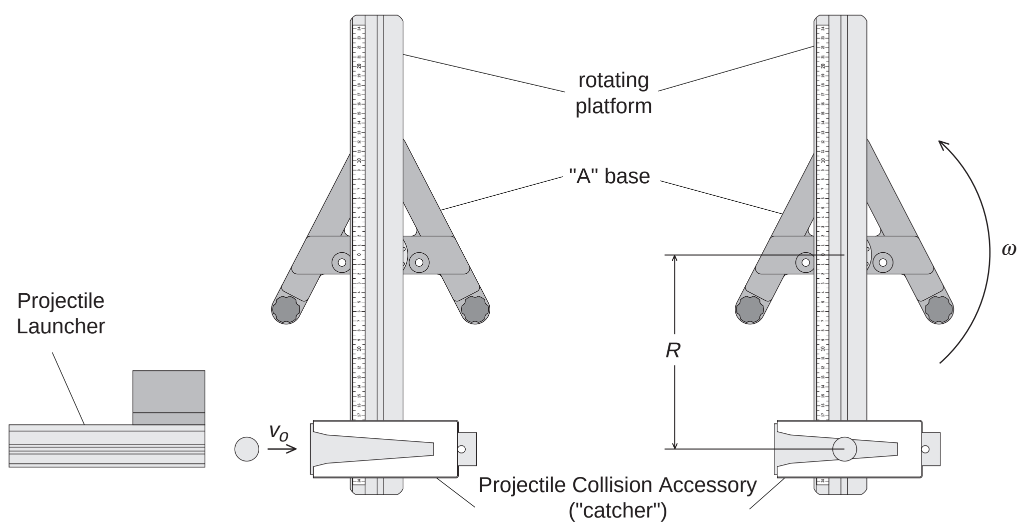


Figure 1.1 Conservation of Angular Momentum

Angular momentum is conserved during the collision but energy is not conserved. The angular

$$v_0 = \frac{I\omega}{m_b R}$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since $\tau = I\alpha$,

$$I = \frac{\tau}{\alpha}$$

where α is the angular acceleration which is equal to a/r and τ is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where r is the radius of the cylinder about which the thread is wound and T is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass, m, gives (See Figure 1.2).

$$\Sigma F = mg - T = ma$$

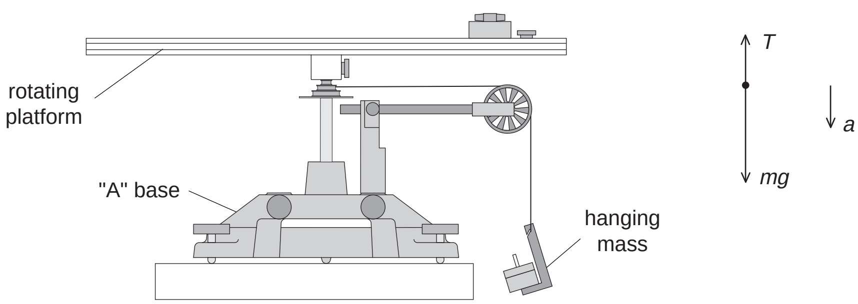


Figure 1.2: Rotational Apparatus and Free-Body Diagram

So, solving for the tension in the thread gives:

$$T = m(g - a)$$

So, once the linear acceleration of the mass (m) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

For comparison, the initial speed (muzzle velocity) of the ball is determined by shooting the ball horizontally off the table onto the floor and measuring the vertical and horizontal distances through which the ball travels.

For a ball shot horizontally off a table with an initial speed, v_o, the horizontal distance traveled by the ball is given by $x = v_o t$, where t is the time the ball is in the air. No air friction is assumed.

The vertical distance the ball drops in time t is given by $y = \frac{1}{2}gt^2$

Part I: Determining the initial velocity of the ball

Setup

① Clamp the Projectile Launcher to a sturdy table near one end of the table.

② Adjust the angle of the Projectile Launcher to zero degrees so the ball will be shot off horizontally. See Figure 1.3.

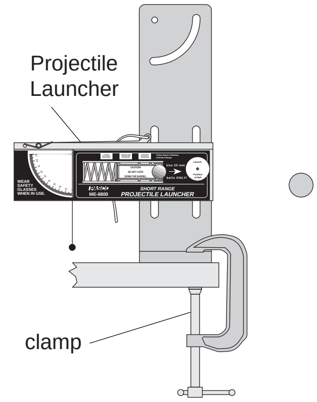


Figure 1.3 Projectile Launcher Setup

Procedure

① Put the ball into the Projectile Launcher and cock it to the long range position. Fire one shot to locate where the ball hits the floor. At this position, tape a piece of white paper to the floor. Place a piece of carbon paper (carbon-side down) on top of this paper and tape it down. When the ball hits the floor, it will leave a mark on the white paper.

② Fire about ten shots.

③ Measure the vertical distance from the bottom of the ball as it leaves the barrel (this position is marked on the side of the barrel) to the floor. Record this distance in Table 1.1.

④ Use a plumb bob to find the point on the floor that is directly beneath the release point on the barrel. Measure the horizontal distance along the floor from the release point to the leading edge of the paper. Record in Table 1.1.

⑤ Measure from the leading edge of the paper to each of the ten dots and record these distances in Table 1.1.

⑥ Find the average of the ten distances and record in Table 1.1.

⑦ Using the vertical distance and the average horizontal distance, calculate the time of flight and the initial velocity of the ball. Record in Table 1.1 and Table 1.4.

Table 1.1 Determining the Initial Velocity

Vertical distance = ____________

Horizontal distance to edge of paper = ____________

Initial velocity = ____________

Trial Number	Distance
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Alternate Method: Determining the

⑧ Run the timing program and set it to measure the time between the ball blocking the two photogates.

④ Shoot the ball three times and take the average of these times. Record in Table 1.2.

⑤ Using that the distance between the photogates is 10 cm, calculate the initial speed and record it in Table 1.2 and Table 1.4.

Table 1.2 Initial Speed Using Photogates

Trial Number	Time
1	
2	
3	
Average Time	
Initial Speed	

Part II: Conservation of Angular Momentum

Setup

① Find the mass of the ball and record it in Table 1.3.

② Attach the ball catcher to the track using a rubber band as shown in Figure 1.4.

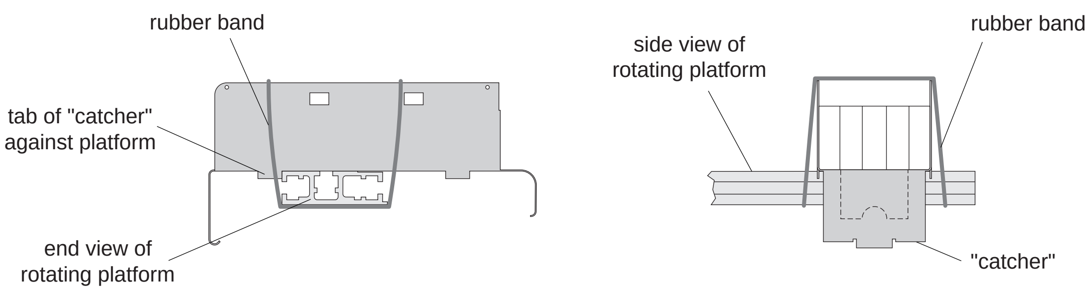


Figure 1.4: Attaching the Catcher to the Track

③ With the Projectile Launcher mounted as it was in Part I, aim the launcher directly down the middle of the ball catcher using the sights inside the projectile launcher. Clamp the launcher to the table.

④ Attach the Smart Pulley photogate to the base, using the black rod. Connect the photogate to a computer and run Smart Pulley Timer.

Procedure

① Load the Launcher with the steel ball on the long range setting.

Table 1.3 Data Mass of Ball

Part III: Determining the Rotational Inertia

Setup

① Attach a Smart Pulley with rod to the base using the black rod.

② Wind a thread around the pulley on the center shaft and pass the thread over the Smart Pulley.

Procedure

Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this "friction mass" will be subtracted from the mass used to accelerate the apparatus.

From the Main Menu select <V>, display velocity

To find the mass required to overcome kinetic friction run "Display Velocity":

① Select <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.

② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures.

③ Press <RETURN> to stop displaying the velocity. Record this friction mass in Table 1.4.

Finding the Acceleration of the Apparatus

To find the acceleration, put about 30 g (Record the exact hanging mass in Table 1.4) over the pulley and run "Motion Timer":

① Select <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.

② Wait for the computer to calculate the times and then press <RETURN>.

To find the acceleration, graph velocity versus time:

③ Choose <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.

④ The graph will now be plotted and the slope = m will be displayed at the top of the graph. This slope is the acceleration. Push <RETURN> and <X> twice to return to the Main Menu.

Measure the Radius

Analysis

① Calculate the average of the angular speeds in Table 1.3 and record the result in Table 1.5.

② Calculate the rotational inertia:

- Subtract the "friction mass" from the hanging mass used to accelerate the apparatus to determine the mass, *m*, to be used in the equations.
- Calculate the experimental value of the rotational inertia and record it in Table 1.5.

③ Using the average angular speed, the rotational inertia, and the distance, *r*, calculate the muzzle velocity of the ball and record it in Table 1.5.

④ Calculate the percent difference between the muzzle velocities found in Parts I and II. Record in Table 1.5.

Table 1.5 Results

Average Angular Speed	
Rotational Inertia	
Calculated Muzzle Velocity, v_0	
Muzzle Velocity	
% Difference	

Questions

① What percentage of the kinetic energy is lost in the collision? Use the masses and velocities to calculate this percentage.

$$\%\ Lost = \frac{KE_{before} - KE_{after}}{KE_{before}}\ X\ 100\%$$

Experiment 2: Rotational Inertia of a Point Mass

EQUIPMENT REQUIRED

- Precision Timer Program
- paper clips (for masses < 1 g)
- triple beam balance
- mass and hanger set
- 10-spoke pulley with photogate head
- calipers

Purpose

The purpose of this experiment is to find the rotational inertia of a point mass experimentally and to verify that this value corresponds to the calculated theoretical value.

Theory

Theoretically, the rotational inertia, I, of a point mass is given by $I = MR^2$, where M is the mass, R is the distance the mass is from the axis of rotation.

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since $\tau = I\alpha$,

$$I = \frac{\tau}{\alpha}$$

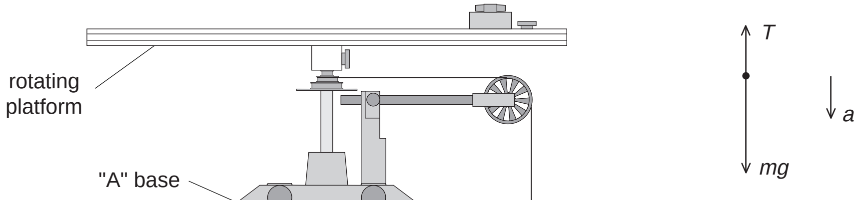
where α is the angular acceleration which is equal to a/r and τ is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where r is the radius of the cylinder about which the thread is wound and T is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass, m, gives (see Figure 2.1).

$$\Sigma F = mg - T = ma$$



Once the linear acceleration of the mass (m) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

Setup

① Attach the square mass (point mass) to the track on the rotating platform at any radius you wish.

② Mount the Smart Pulley to the base and connect it to a computer. See Figure 2.2.

③ Run the Smart Pulley Timer program.

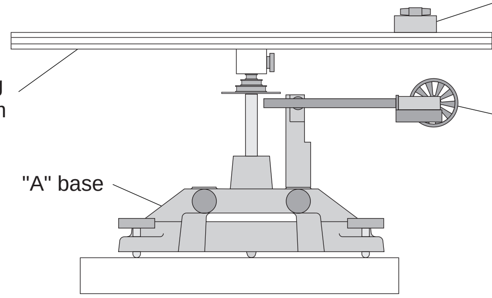


Figure 2.2: Rotational inertia of a point mass

Procedure

Part I: Measurements For the Theoretical Rotational Inertia

① Weigh the square mass to find the mass M and record in Table 2.1.

② Measure the distance from the axis of rotation to the center of the square mass and record this radius in Table 2.1.

Table 2.1: Theoretical Rotational Inertia

Mass	
Radius	

Part II: Measurement For the Experimental Method

Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it

Finding the Acceleration of the Point Mass and Apparatus

① To find the acceleration, put about 50 g over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN> Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.

② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.

③ The graph will now be plotted and the slope = m will be displayed at the top of the graph. This slope is the acceleration. Record it in Table 2.2. Push <RETURN> and <X> twice to return to the Main Menu.

Table 2.2: Rotational Inertia Data

	Point Mass and Apparatus	Apparatus Alone
Friction Mass		
Hanging Mass		
Slope		
Radius		

Measure the Radius

① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 2.2.

Finding the Acceleration of the Apparatus Alone

Since in **Finding the Acceleration of the Point Mass and Apparatus** the apparatus is rotating as well as the point mass, it is necessary to determine the acceleration, and the rotational inertia, of the apparatus by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the point mass.

① Take the point mass off the rotational apparatus and repeat **Finding the Acceleration of the Point Mass and Apparatus** for the apparatus alone.

➤ NOTE: that it will take less “friction mass” to overcome the new kinetic friction and it is only necessary to put about 20 g over the pulley in **Finding the Acceleration of the Point Mass and Apparatus**.

② Record the data in Table 2.2.

⑤ Calculate the experimental value of the rotational inertia of the apparatus alone. Record in Table 2.3.

④ Subtract the rotational inertia of the apparatus from the combined rotational inertia of the point mass and apparatus. This will be the rotational inertia of the point mass alone. Record in Table 2.3.

⑤ Calculate the theoretical value of the rotational inertia of the point mass. Record in Table 2.3.

⑥ Use a percent difference to compare the experimental value to the theoretical value. Record in Table 2.3.

Table 2.3: Results

Rotational Inertia for Point Mass and Apparatus Combined	
Rotational Inertia for Apparatus Alone	
Rotational Inertia for Point Mass (experimental value)	
Rotational Inertia for Point Mass (theoretical value)	
% Difference	

Experiment 3: Centripetal Force

EQUIPMENT NEEDED

- Centripetal Force Accessory (ME-8952)
- stopwatch
- graph paper (2 sheets)
- string
- Rotating Platform (ME-8951)
- balance
- mass and hanger set

Purpose

The purpose of this experiment is to study the effects of varying the mass of the object, the radius of the circle, and the centripetal force on an object rotating in a circular path.

Theory

When an object of mass *m*, attached to a string of length *r*, is rotated in a horizontal circle, the centripetal force on the mass is given by:

$$F = \frac{mv^2}{r} = mr\omega^2$$

where v is the tangential velocity and ω is the angular speed ($v = r\,\omega$). To measure the velocity, the time for one rotation (the period, T) is measured. Then:

$$v = \frac{2\pi r}{T}$$

and the centripetal force is given by:

$$F = \frac{4\pi^2 mr}{T^2}$$

Setup

Level the "A" base and rotating platform as described in the ME-8951 assembly section on page 5.

Procedure

Part I: Vary Radius (constant force and mass)

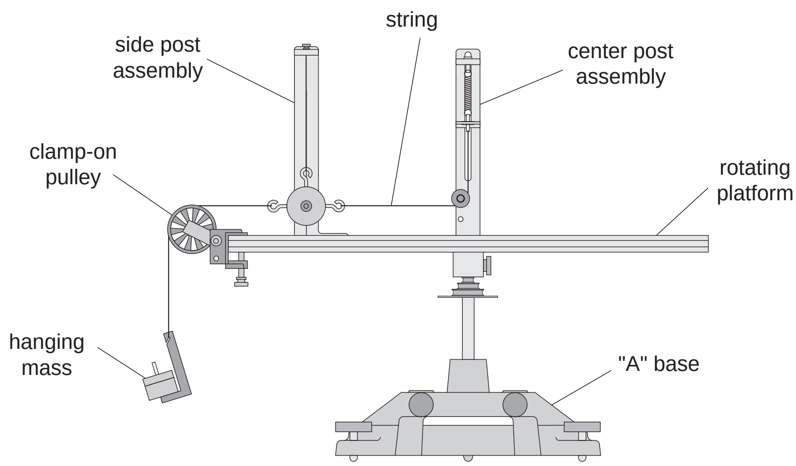


Figure 3.1: Centripetal Force Apparatus

② Attach the clamp-on pulley to the end of the track nearer to the hanging object. Attach a string to the hanging object and hang a known mass over the clamp-on pulley. Record this mass in Table 3.1. This establishes the constant centripetal force.

③ Select a radius by aligning the line on the side post with any desired position on the measuring tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.1.

④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.

⑤ Align the indicator bracket on the center post with the orange indicator.

⑥ Remove the mass that is hanging over the pulley and remove the pulley.

⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once again vertical and thus the hanging object is at the desired radius.

⑧ Maintaining this speed, use a stopwatch to time ten revolutions. Divide the time by ten and record the period in Table 3.1.

Table 3.1: Varying the Radius

Mass of the object = ____________

Mass hanging over the pulley = ____________

Slope from graph = ____________

Radius	Period (T)	T^2

force at the top of Table 3.2.

② Calculate the square of the period for each trial and record this in Table 3.1.

③ Plot the radius versus the square of the period. This will give a straight line since:

$$r = \left(\frac{F}{4\pi^2 m}\right) T^2$$

④ Draw the best-fit line through the data points and measure the slope of the line. Record the slope in Table 3.1.

⑤ Calculate the centripetal force from the slope and record in Table 3.2.

⑥ Calculate the percent difference between the two values found for the centripetal force and record in Table 3.2.

Table 3.2: Results (varying raduis)

Centripetal Force = mg	
Centripetal Force From Slope	
Percent Difference	

Part II: Vary Force (constant radius and mass)

The radius of rotation and the mass of the hanging object will be held constant for this part of the experiment.

① Weigh the object and record its mass in Table 3.3. Hang the object from the side post and connect the string from the spring to the object. The string must pass under the pulley on the center post.

② Attach the clamp-on pulley to the end of the track nearer to the hanging object. Attach a string to the hanging object and hang a known mass over the clamp-on pulley. Record this mass in Table 3.3. This determines the centripetal force.

③ Select a radius by aligning the line on the side post with any desired position on the measuring tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.3.

④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.

⑤ Align the indicator bracket on the center post with the orange indicator.

⑥ Remove the mass that is hanging over the pulley and remove the pulley.

⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once

Table 3.3: Varying the Centripetal Force

Mass of the object = ________________

Radius = ________________

Slope from graph = ________________

Mass Over Pulley	Centripetal Force = mg	Period (T)	$\frac{1}{T^2}$

Analysis

① The weight of the mass hanging over the pulley is equal to the centripetal force applied by the spring. Calculate this force for each trial by multiplying the mass hung over the pulley by "g" and record the results in Table 3.3.

② Calculate the inverse of the square of the period for each trial and record this in Table 3.3.

③ Plot the centripetal force versus the inverse square of the period. This will give a straight line since:

$$F = \frac{4\pi^2 mr}{T^2}$$

④ Draw the best-fit line through the data points and measure the slope of the line. Record the slope in Table 3.3.

⑤ Calculate the mass of the object from the slope and record in Table 3.4.

⑥ Calculate the percent difference between the two values found for the mass of the object and record in Table 3.4.

Table 3.4: Results (varying the centripetal force)

Mass of Object (from scale)	
Mass of Object (from slope)	
Percent Difference	

Part III: Vary Mass (constant radius and force)

The centripetal force and the radius of rotation will be held constant for this part of the experiment.

tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.5.

④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.

⑤ Align the indicator bracket on the center post with the orange indicator.

⑥ Remove the mass that is hanging over the pulley and remove the pulley.

⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once again vertical and thus the hanging object is at the desired radius.

⑧ Maintaining this speed, use a stopwatch to time ten revolutions. Divide the time by ten and record the period in Table 3.5.

⑨ Vary the mass of the object by removing the side masses. Keep the radius constant and measure the new period. Weigh the object again and record the mass and period in Table 3.5.

Table 3.5: Varying the Mass of the Object

Mass hanging over pulley = ________________

Centripetal Force = mg = ________________

Radius = ________________

Mass of Object	Period (T)	Calculated Centripetal Force	% Difference

Analysis

① The weight of the mass hanging over the pulley is equal to the centripetal force applied by the spring. Calculate this force by multiplying the mass hung over the pulley by “g” and record the result at the top of Table 3.5.

② Calculate the centripetal force for each trial using:

$$F = \frac{4\pi^2 mr}{T^2}$$

and record this in Table 3.5.

③ Calculate the percent difference between the calculated centripetal force for each trial and *mg*. Record in Table 3.5.

Notes:

Experiment 4: Conservation of Angular Momentum Using a Point Mass

EQUIPMENT REQUIRED

- Smart Pulley Timer Program
- Rotational Inertia Accessory (ME-8953)
- Rotating Platform (ME-8951)
- Smart Pulley
- balance

Purpose

A mass rotating in a circle is pulled in to a smaller radius and the new angular speed is predicted using conservation of angular momentum.

Theory

Angular momentum is conserved when the radius of the circle is changed.

$$L = I_i \omega_i = I_f \omega_f$$

where I_i is the initial rotational inertia and ω_i is the initial angular speed. So the final rotational speed is given by:

$$\omega_f = \frac{I_i}{I_f} \omega_i$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since $\tau = I\alpha$,

$$I = \frac{\tau}{\alpha}$$

where α is the angular acceleration which is equal to a/r and τ is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where r is the radius of the cylinder about which the thread is wound and T is the tension in the thread when the apparatus is rotating.

Once the linear acceleration of the mass (m) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

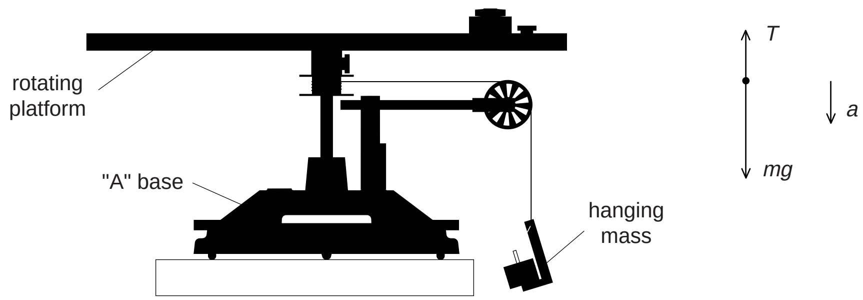


Figure 4.1: Rotational Apparatus and Free-Body Diagram

Part I: Conservation of Angular Momentum

Setup

① Level the apparatus using the square mass on the track as shown in the leveling instructions in the Assembly Section.

② Slide a thumb screw and square nut into the T-slot on the top of the track and tighten it down at about the 5 cm mark. This will act as a stop for the sliding square mass. See Figure 4.2.

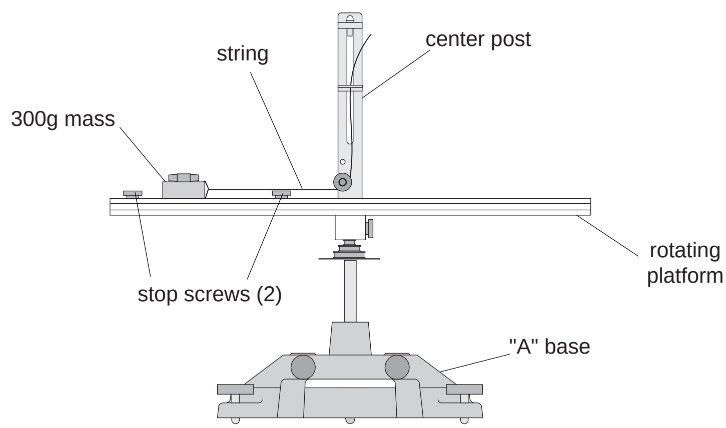


Figure 4.2: Set-up for conservation of angular momentum

③ With the side of the square mass that has the hole oriented toward the center post, slide the square mass onto the track by inserting its square nut into the T-slot, but do not tighten the thumb screw; the square mass should be free to slide in the T-slot.

④ Slide a second thumb screw and square nut into the T-slot and tighten it down at about the 20 cm mark. Now the square mass is free to slide between the two limiting stops.

⑤ Run the Smart Pulley Timer program.

Procedure

① Select <M>-Motion Timer <RETURN>.

② Hold the string just above the center post. With the square mass against the outer stop, give the track a spin using your hand. After about 25 data points have been taken, pull up on the string to cause the square mass to slide from the outer stop to the inner stop.

③ Continue to hold the string up and take about 25 data points after pulling up on the string. Then push <RETURN> to stop the timing.

④ When the computer finishes calculating the times, graph the rotational speed versus time: <A>-Data Analysis Options <RETURN>; <G>-Graph Data <RETURN>; <E>-Rotational Apparatus <RETURN>; <V>-Velocity vs. Time <RETURN>.

⑤ After viewing the graph, press <RETURN> and choose <T> to see the table of the angular velocities. Determine the angular velocity immediately before and immediately after pulling the string. Record these values in Table 4.1.

⑥ Repeat the experiment a total of three times with different initial angular speeds. Record these values in Table 4.1.

Table 4.1: Data

	Angular Speeds	
Trial Number	Initial	Final
1		
2		
3		

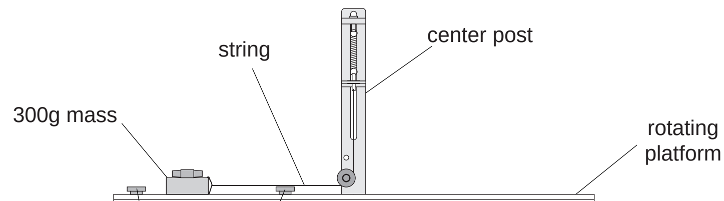
Part II: Determining the Rotational Inertia

Measure the rotational inertia of the apparatus twice: once with the square mass in its initial position and once with it in its final position.

Setup

① Attach a Smart Pulley with rod to the base using the black rod.

② Wind a thread around the pulley on the center shaft and pass the thread over the Smart Pulley. See Figure 4.3.



Procedure

Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the apparatus.

① To find the mass required to overcome kinetic friction run “Display Velocity”: <V>-Display Velocity <RETURN> <A>-Smart Pulley/Linear String <RETURN> <N>-Normal Display <RETURN>.

② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record this friction mass in Table 1.4.

Finding the Acceleration of the Apparatus

① To find the acceleration, put about 30 g (Record the exact hanging mass in Table 1.4) over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.

② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.

③ The graph will now be plotted and the *slope* = *m* will be displayed at the top of the graph. This slope is the acceleration. Push <RETURN> and <X> twice to return to the Main Menu.

Measure Radius

① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record the radius in Table 4.2.

Table 4.2 Rotational Inertia Data

	Mass at Outer Stop	Mass at Inner Stop
Friction Mass		
Hanging Mass		
Slope		
Radius		

Analysis

① Calculate the rotational inertia's:

- Subtract the "friction mass" from the hanging mass used to accelerate the apparatus to determine the mass, *m*, to be used in the equations.
- Calculate the experimental values of the rotational inertia and record it in Table 4.3.

② Calculate the expected (theoretical) values for the final angular velocity and record these values in Table 4.3.

Table 4.3: Results

	Trial #1	Trial #2	Trial #3
Theoretical Angular Speed			
% Difference			

③ For each trial, calculate the percent difference between the experimental and the theoretical values of the final angular velocity and record these in Table 4.3.

Questions

Calculate the rotational kinetic energy $\left(KE_i = \frac{1}{2} I_i \omega_i^2\right)$ before the string was pulled. Then calculate the rotational kinetic energy $\left(KE_f = \frac{1}{2} I_f \omega_f^2\right)$ after the string was pulled.

Which kinetic energy is greater?

Why?

Notes:

Experiment 5: Rotational Inertia of Disk and Ring

EQUIPMENT REQUIRED

- Precision Timer Program
- Rotational Inertia Accessory (ME-9341)
- Smart Pulley
- calipers
- mass and hanger set
- paper clips (for masses < 1 g)
- triple beam balance

Purpose

The purpose of this experiment is to find the rotational inertia of a ring and a disk experimentally and to verify that these values correspond to the calculated theoretical values.

Theory

Theoretically, the rotational inertia, I, of a ring about its center of mass is given by:

$$I = \frac{1}{2}M\left(R_1^{\,2} + R_2^{\,2}\right)$$

where M is the mass of the ring, R_1 is the inner radius of the ring, and R_2 is the outer radius of the ring. See Figure 5.1.

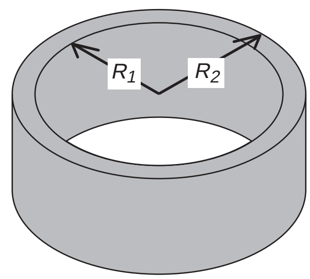


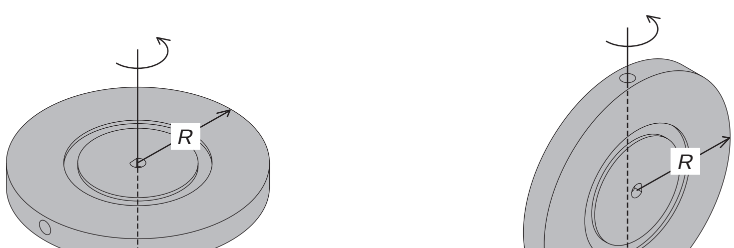
Figure 5.1: Ring

The rotational inertia of a disk about its center of mass is given by:

$$I = \frac{1}{2}MR^2$$

where M is the mass of the disk and R is the radius of the disk. The rotational inertia of a disk about its diameter is given by:

$$I = \frac{1}{4}MR^2$$



$$I = \frac{\tau}{\alpha}$$

where α is the angular acceleration which is equal to a/r and τ is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where r is the radius of the cylinder about which the thread is wound and T is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass, m, gives (See Figure 5.3)

$$\Sigma F = mg - T = ma$$

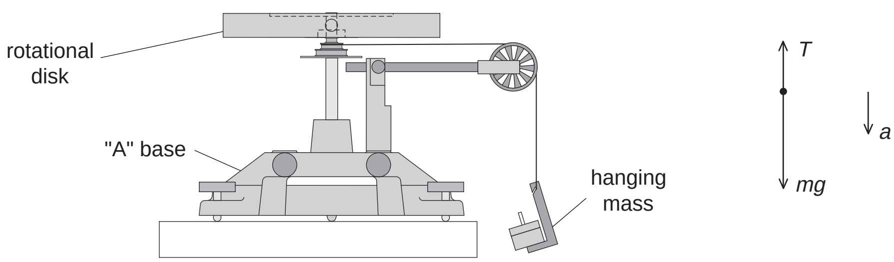


Figure 5.3: Rotational Apparatus and Free-Body Diagram

Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass (m) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

Setup

① Remove the track from the Rotating Platform and place the disk directly on the center shaft as shown in Figure 5.4. The side of the disk that has the indentation for the ring should be up.

② Place the ring on the disk, seating it in this indentation.

③ Mount the Smart Pulley to the base and connect it to a computer.

④ Run the Smart Pulley Timer program.

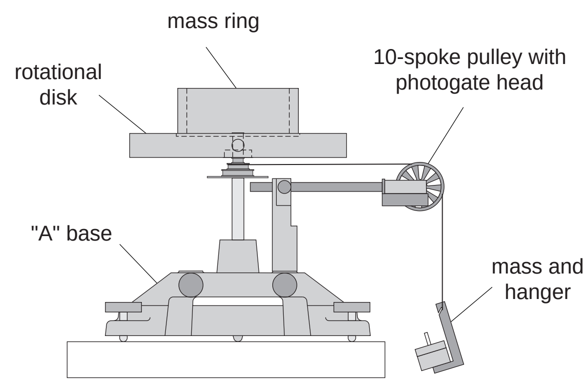


Figure 5.4: Set-up for Disk and Ring

Procedure

Table 5.1: Theoretical Rotational Inertia

Mass of Ring	
Mass of Disk	
Inner Radius of Ring	
Outer Radius of Ring	
Radius of Disk	

Measurements for the Experimental Method

Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this "friction mass" will be subtracted from the mass used to accelerate the ring.

① To find the mass required to overcome kinetic friction run "Display Velocity": <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.

② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record the friction mass in Table 5.2.

Table 5.2: Rotational Inertia Data

	Ring and Disk Combined	Disk Alone	Disk Vertical
Friction Mass			
Hanging Mass			
Slope			
Radius			

Finding the Acceleration of Ring and Disk

① To find the acceleration, put about 50 g over the pulley and run "Motion Timer": <M>-Motion Timer <RETURN> Wind the thread up and let the mass fall from the table to the floor, hitting

④ Push <RETURN> and <X> twice to return to the Main Menu.

Measure the Radius

① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 5.2.

Finding the Acceleration of the Disk Alone

Since in **Finding the Acceleration of Ring and Disk** the disk is rotating as well as the ring, it is necessary to determine the acceleration, and the rotational inertia, of the disk by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the ring.

① To do this, take the ring off the rotational apparatus and repeat **Finding the Acceleration of Ring and Disk** for the disk alone.

➤ **NOTE:** that it will take less “friction mass” to overcome the new kinetic friction and it is only necessary to put about 30 g over the pulley in **Finding the Acceleration of Ring and Disk**.

Disk Rotating on an Axis Through Its Diameter

Remove the disk from the shaft and rotate it up on its side. Mount the disk vertically by inserting the shaft in one of the two “D”-shaped holes on the edge of the disk. See Figure 5.5.

➤ **WARNING!** Never mount the disk vertically using the adapter on the track. The adapter is too short for this purpose and the disk might fall over while being rotated.

Repeat steps **Measure the Radius** and **Finding the Acceleration of the Disk Alone** to determine the rotational inertia of the disk about its diameter. Record the data in Table 5.2.

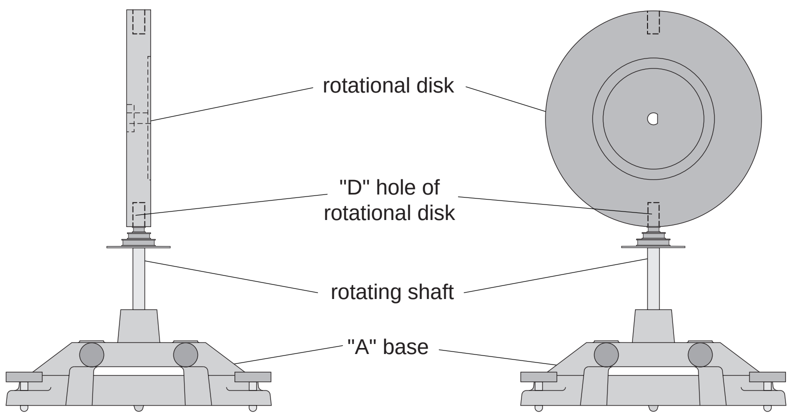


Figure 5.5: Disk mounted vertically

Calculations

This will be the rotational inertia of the ring alone.

⑤ Calculate the experimental value of the rotational inertia of the disk about its diameter.

⑥ Calculate the theoretical value of the rotational inertia of the ring.

⑦ Calculate the theoretical value of the rotational inertia of the disk about its center of mass and about its diameter.

⑧ Use a percent difference to compare the experimental values to the theoretical values.

Table 5.3: Results

Rotational Inertia for Ring and Disk Combined	
Rotational Inertia for Disk Alone (experimental value)	
Rotational Inertia for Ring (experimental value)	
Rotational Inertia for Vertical Disk (experimental value)	
Rotational Inertia for Disk (theoretical value)	
Rotational Inertia for Ring (theoretical value)	
Rotational Inertia for Vertical Disk (theoretical value)	
% Difference for Disk	
% Difference for Ring	
% Difference for Vertical Disk	

Notes:

Experiment 6: Rotational Inertia of Disk Off-Axis (Fixed/Rotating)

EQUIPMENT REQUIRED

- Precision Timer Program
- Rotational Inertia Accessory (ME-8953)
- Smart Pulley
- calipers
- mass and hanger set
- paper clips (for masses < 1 g)
- triple beam balance

Purpose

The purpose of this experiment is to find the rotational inertia of a disk about an axis parallel to the center of mass axis.

Theory

Theoretically, the rotational inertia, I, of a disk about a perpendicular axis through its center of mass is given by:

$$I_{cm} = \frac{1}{2}MR^2$$

where M is the mass of the disk and R is the radius of the disk. The rotational inertia of a disk about an axis parallel to the center of mass axis is given by:

$$I = I_{cm} + Md^2$$

where d is the distance between the two axes.

In one part of this experiment, the disk is mounted on its ball bearing side which allows the disk to freely rotate relative to the track. So as the track is rotated, the disk does not rotate relative to its center of mass. Since the disk is not rotating about its center of mass, it acts as a point mass rather than an extended object and its rotational inertia reduces from:

$$I = I_{cm} + Md^2 \quad \text{to} \quad I = Md^2$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since $\tau = I\alpha$,

$$I = \frac{\tau}{\alpha}$$

Applying Newton's Second Law for the hanging mass, *m*, gives (See Figure 6.1)

$$\Sigma F = mg - T = ma$$

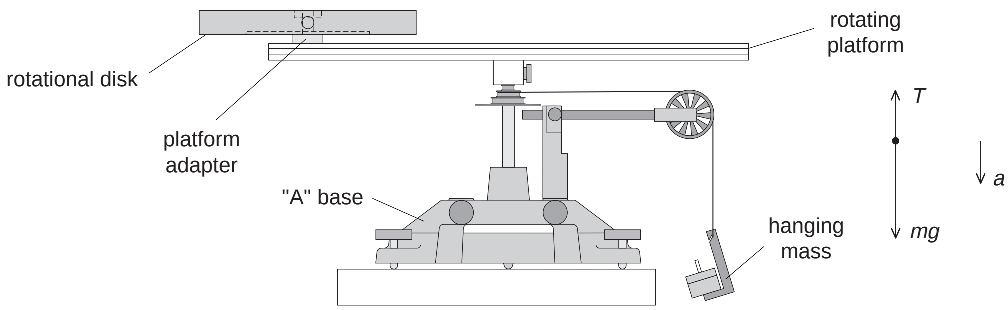


Figure 6.1: Rotational Apparatus and Free-Body Diagram

Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass (*m*) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

Setup

① Set up the Rotational Accessory as shown in Figure 6.2. Mount the disk with its bearing side up. Use the platform adapter to fasten the disk to the track at a large radius.

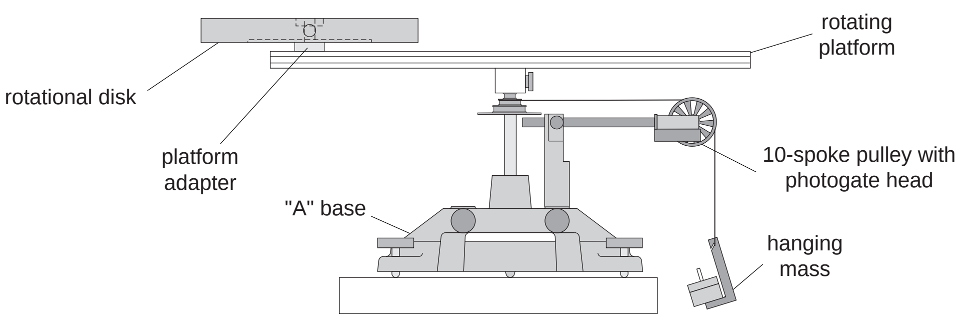


Figure 6.2: Set-up for Disk Off-Axis

② Mount the Smart Pulley to the base and connect it to a computer.

③ Run the Smart Pulley Timer program.

Table 6.1: Theoretical Rotational Inertia

Mass of Disk	
Radius of Disk	
Distance Between Parallel Axis	

Measurements For the Experimental Method

Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this "friction mass" will be subtracted from the mass used to accelerate the ring.

① To find the mass required to overcome kinetic friction run "Display Velocity": <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.

② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record the friction mass in Table 6.2.

Finding the Acceleration of Disk and Track

Table 6.2: Rotational Inertia Data

	Fixed Disk and Track Combined	Track Alone	Rotating Disk and Track Combined
Friction Mass			
Hanging Mass			
Slope			
Radius			

① To find the acceleration, put about 50 g over the pulley and run "Motion Timer": <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.

Measure the Radius

① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 6.2.

Finding the Acceleration of Track Alone

Since in **Finding the Acceleration of Disk and Track** the track is rotating as well as the disk, it is necessary to determine the acceleration, and the rotational inertia, of the track by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the disk.

① To do this, take the disk off the rotational apparatus and repeat **Finding the Acceleration of Disk and Track** for the track alone.

➧ **NOTE:** It will take less "friction mass" to overcome the new kinetic friction and it is only necessary to put about 30 g over the pulley in **Finding the Acceleration of Disk and Track**.

Disk Using Ball Bearings (Free Disk)

Mount the disk upside-down at the same radius as before. Now the ball bearings at the center of the disk will allow the disk to rotate relative to the track. Repeat **Accounting For Friction** and **Finding the Acceleration of Disk and Track** for this case and record the data in Table 6.2.

Calculations

Record the results of the following calculations in Table 6.3.

① Subtract the "friction mass" from the hanging mass used to accelerate the apparatus to determine the mass, m, to be used in the equations.

② Calculate the experimental value of the rotational inertia of the fixed disk and track combined.

③ Calculate the experimental value of the rotational inertia of the track alone.

④ Subtract the rotational inertia of the track from the rotational inertia of the fixed disk and track. This will be the rotational inertia of the fixed disk alone.

⑤ Calculate the experimental value of the rotational inertia of the fixed disk and track combined.

⑥ Subtract the rotational inertia of the track from the rotational inertia of

Table 6.3: Results

Rotational Inertia for Fixed Disk and Track Combined	
Rotational Inertia for Track Alone	
Rotational Inertia for Fixed Disk Off-Axis (experimental value)	
Rotational Inertia for Free Disk and Track Combined	
Rotational Inertia for Free Disk	
% Difference for Free Disk	

⑧ Calculate the theoretical value of a point mass having the mass of the disk.

⑨ Use a percent difference to compare the experimental values to the theoretical values.

Notes:

Experiment 7: Conservation of Angular Momentum

EQUIPMENT REQUIRED

- Smart Pulley Timer Program
- Rotational Inertia Accessory (ME-8953)
- Rotating Platform (ME-8951)
- Smart Pulley Photogate
- balance

Purpose

A non-rotating ring is dropped onto a rotating disk and the final angular speed of the system is compared with the value predicted using conservation of angular momentum.

Theory

When the ring is dropped onto the rotating disk, there is no net torque on the system since the torque on the ring is equal and opposite to the torque on the disk. Therefore, there is no change in angular momentum. Angular momentum is conserved.

$$L = I_i\omega_i = I_f\omega_f$$

where I_i is the initial rotational inertia and ω_i is the initial angular speed. The initial rotational inertia is that of a disk

$$\left(\frac{1}{2}\right) M_1R^2$$

and the final rotational inertia of the combined disk and ring is

$$I_f = \frac{1}{2}M_1\,R^{2 + \frac{1}{2}M_2\left(r_1^{\,2} + r_2^{\,2}\right)}$$

So the final rotational speed is given by

$$\omega_f = \frac{M_1\,R^2}{M_1\,R^{2 + M_2\left(r_1^{\,2} + r_2^{\,2}\right)}}\,\omega_i$$

Setup

① Level the apparatus using the square mass on the track.

Ring onto Disk

Procedure

① Select <M>-Motion Timer <RETURN>.

② Hold the ring just above the center of the disk. Give the disk a spin using your hand. After about 25 data points have been taken, drop the ring onto the spinning disk See Figure 7.2.

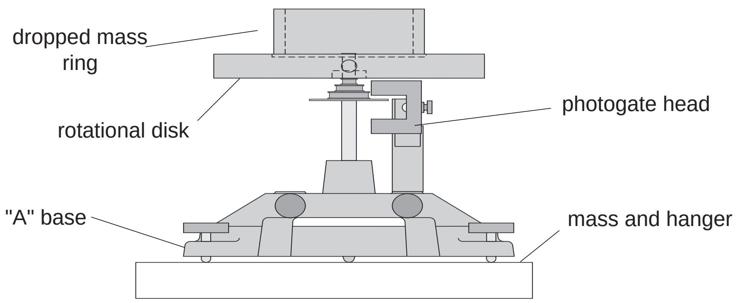


Figure 7.2: Experiment Setup

③ Continue to take data after the collision and then push <RETURN> to stop the timing.

④ When the computer finishes calculating the times, graph the rotational speed versus time. <A>-Data Analysis Options <RETURN> <G>-Graph Data <RETURN> <E>-Rotational Apparatus <RETURN> <V>-Velocity vs. Time <RETURN>

⑤ After viewing the graph, press <RETURN> and choose <T> to see the table of the angular velocities. Determine the angular velocity immediately before and immediately after the collision. Record these values in Table 7.1.

⑥ Weigh the disk and ring and measure the radii. Record these values in Table 7.1.

Analysis

① Calculate the expected (theoretical) value for the final angular velocity and record this value in Table 7.1.

② Calculate the percent difference between the experimental and the theoretical values of the final angular velocity and record in Table 7.1.

Table 7.1: Data and Results

Initial Angular Speed	
Final Angular Speed (experimental value)	
Mass of Disk	
Mass of Ring	
Inner Radius of Ring	
Outer Radius of Ring	

Questions

① Does the experimental result for the angular speed agree with the theory?

② What percentage of the rotational kinetic energy lost during the collision? Calculate this and record the results in Table 7.1.

$$\%KE\ Lost = \frac{\frac{1}{2}I_i\omega_i^2 - \frac{1}{2}I_f\omega_f^2}{\frac{1}{2}I_i\omega_i^2}$$

Notes:

Technical Support

Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

email: techsupp@PASCO.com

Tech support fax: (916) 786-3292

Contacting Technical Support

Before you call the PASCO Technical Support staff it would be helpful to prepare the following information:

- If your problem is computer/software related, note:

  Title and Revision Date of software.

  Type of Computer (Make, Model, Speed).

  Type of external Cables/Peripherals.

- If your problem is with the PASCO apparatus, note:

  Title and Model number (usually listed on the label).

  Approximate age of apparatus.

  A detailed description of the problem/sequence of events. (In case you can't call PASCO right away, you won't lose valuable data.)

  If possible, have the apparatus within reach when calling. This makes descriptions of individual parts much easier.

- If your problem relates to the instruction manual, note:

  Part number and Revision (listed by month and year on the front cover).

  Have the manual at hand to discuss your questions.