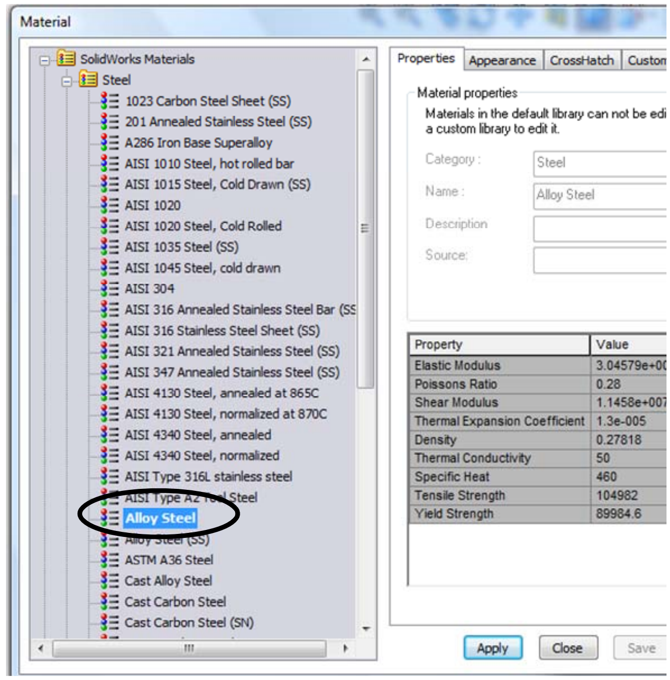
In this tutorial, we will learn the basics of performing motion analysis using SolidWorks Motion. Although the tutorial can be completed by anyone with a basic knowledge of SolidWorks parts and assemblies, we have provided enough detail so that students with an understanding of the physics of mechanics will be able to relate the results to those obtained by hand calculations.




***Begin by creating the six part models detailed on page 2. For each part, define the material by right-clicking "Material" in the FeatureManager and selecting "Edit Material." The Material Editor will appear, as shown here. Select "Alloy Steel" from the list of steels in the SolidWorks materials library. Click Apply and the Close.***

## Rotation of a Wheel

To begin, we will analyze a simple model of a wheel subjected to a torque. From Newton's Second Law, we know that the sum of the forces acting on a body equals the mass of the body times the acceleration of the body, or

$$\sum F = ma$$

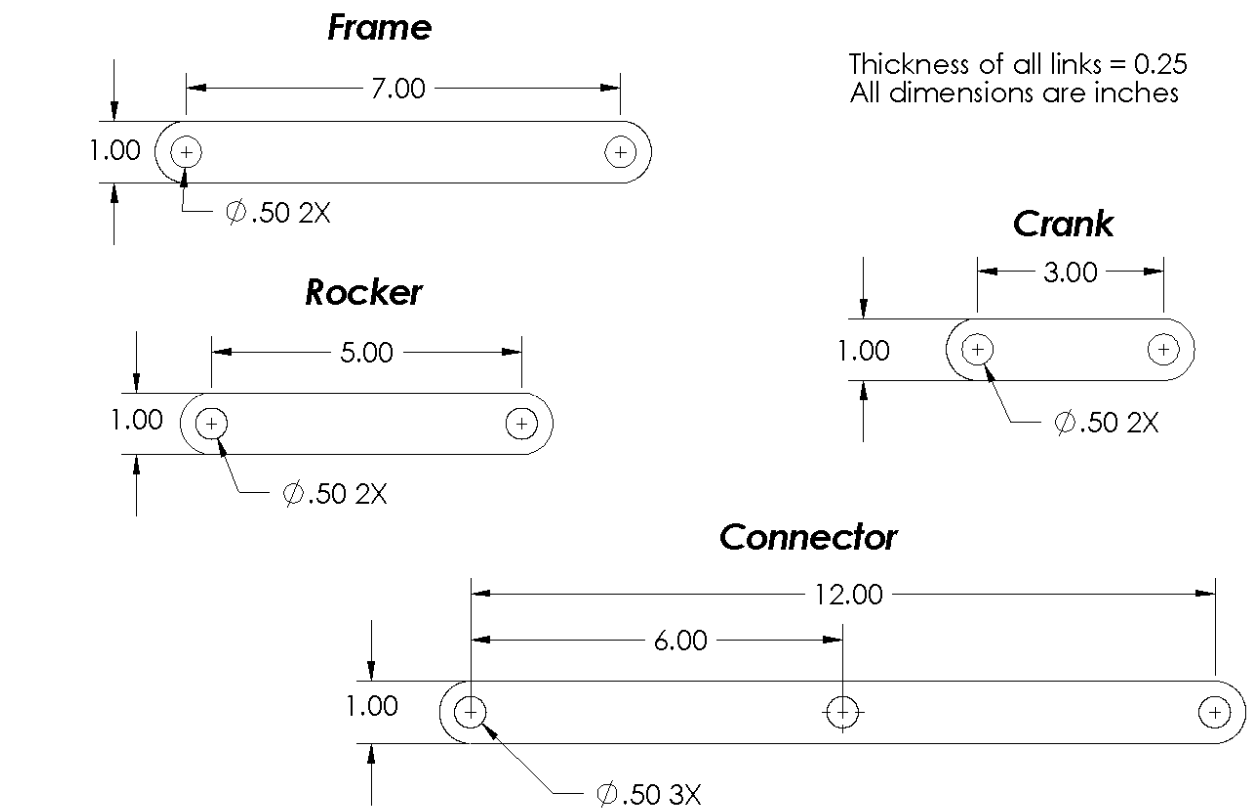
The above equation applies to bodies undergoing linear acceleration. For rotating bodies, Newton's Second Law can be written as:

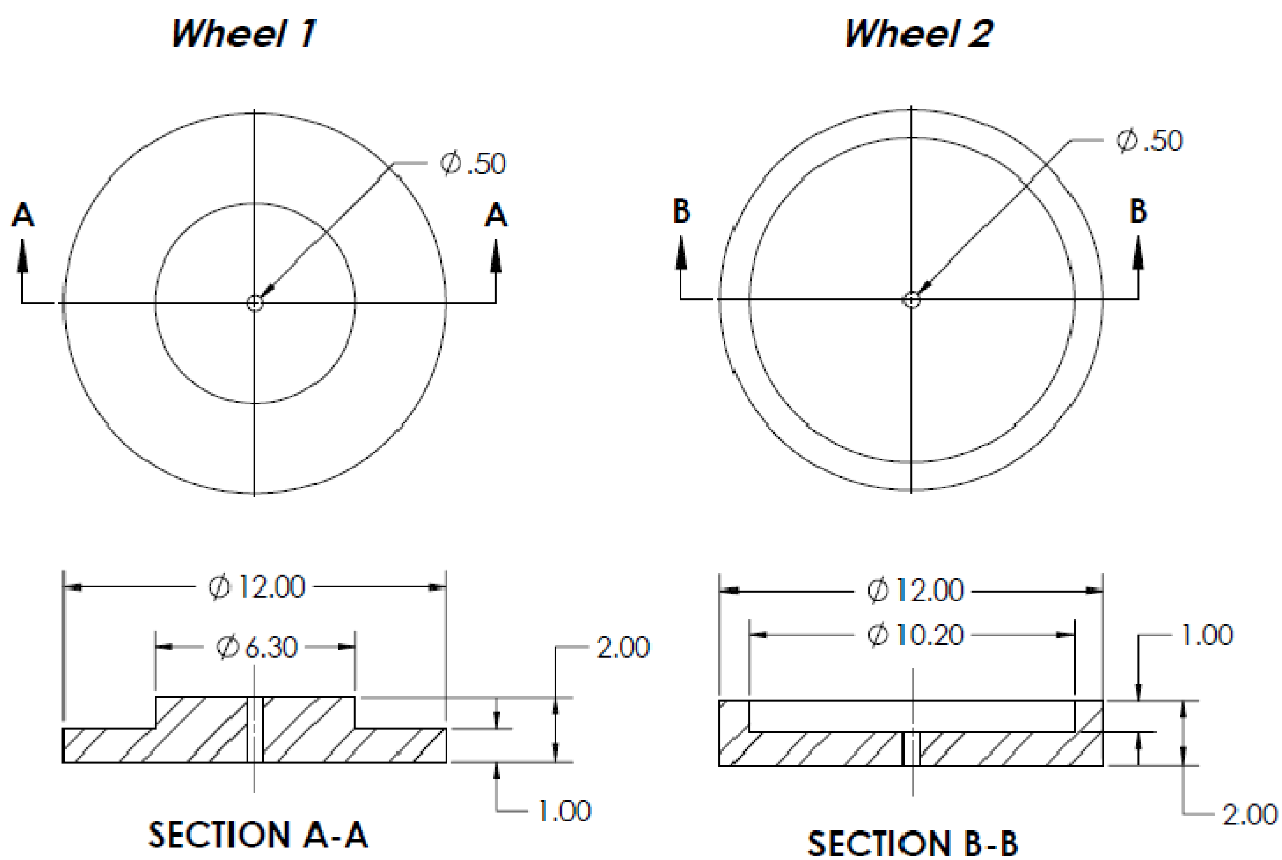
$$\sum M = I\alpha$$

Where $\sum M$ is the sum of the moments about an axis, $I$ is the mass moment of inertia of the body about that axis, and $\alpha$ is the angular acceleration of the body. The moment of inertia about an axis is defined as:

$$I = \int mr^2 dV$$

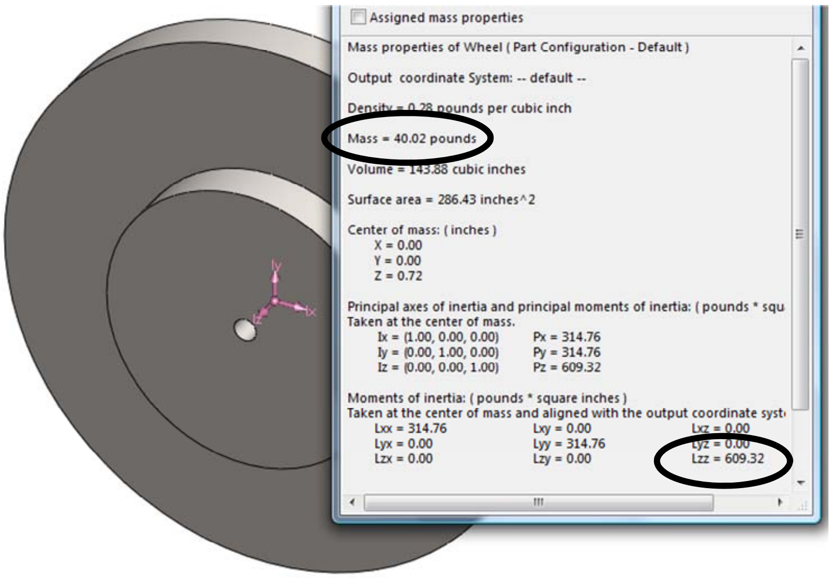
where $r$ is the radial distance from the axis. For simple shapes, the moment of inertia is relatively easy to calculate, as formulas for $I$ of basic shapes are tabulated in many reference books. However, for more complex components, calculation of $I$ can be difficult. SolidWorks allows mass properties, including moments of inertia, to be determined easily.


Frame
7.00
1.00
∅.50 2X
Thickness of all links = 0.25
All dimensions are inches
Rocker
5.00
1.00
∅.50 2X
Crank
3.00
1.00
∅.50 2X
Connector
12.00
6.00
1.00
∅.50 3X


Wheel 1
∅.50
A
A
∅12.00
∅6.30
2.00
1.00
SECTION A-A
Wheel 2
∅.50
B
B
∅12.00
∅10.20
1.00
2.00
SECTION B-B

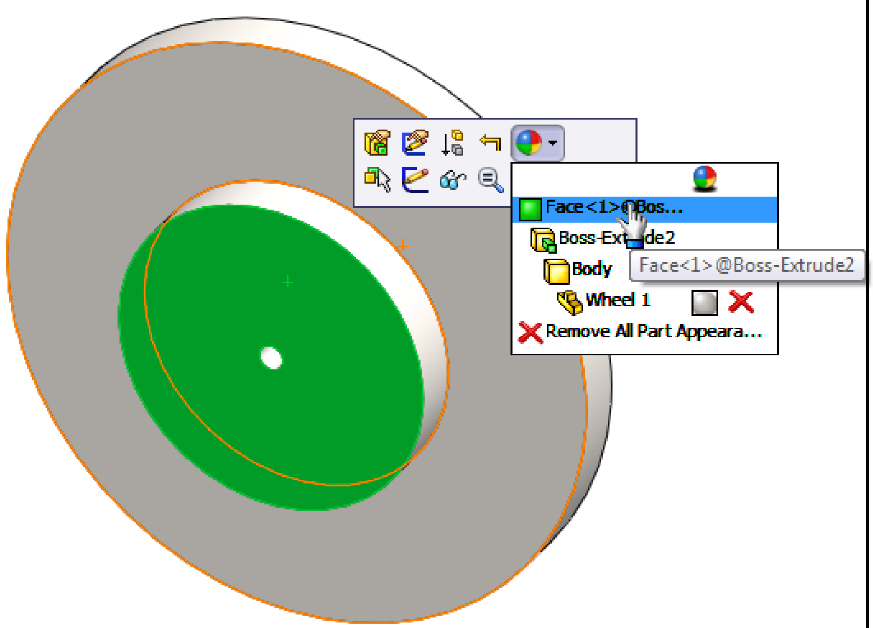
***Open the part "Wheel 1." From the main menu, select Tools: Mass Properties.***

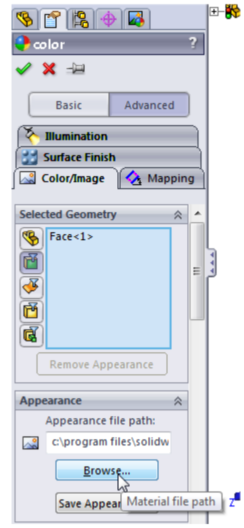
The mass properties of the wheel are reported in the pop-up box. For this part, the weight is 40.02 pounds, and the moment of inertia about the z-axis (labeled as "Lzz" in SolidWorks) is 609.3 lb·in$^2$. Note that if you centered the part about the origin, then the properties, labeled "Taken at the center of mass and aligned with the output coordinate system" will be identical to those labeled "Principal moments... taken at the center of mass."



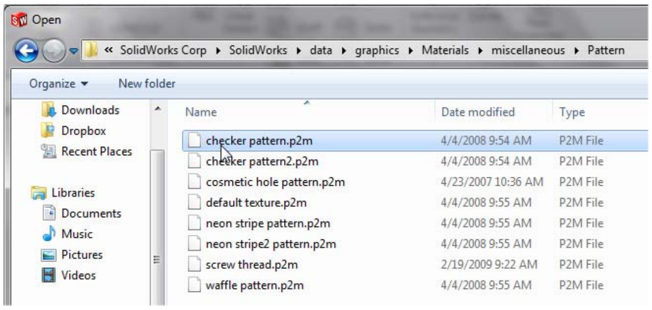

Since the wheel is symmetric about the axis of rotation, it will be difficult to visualize the rotational motion in the model. Adding a non-symmetric pattern to one of the faces of the wheel will be helpful.

***Select the front face of the part, and choose the Appearance Tool from the context toolbar that appears. You can choose to edit the appearance of the face, the feature, the associated solid body, or the entire part. Choose Face, since we will be applying the pattern to the front face only.***

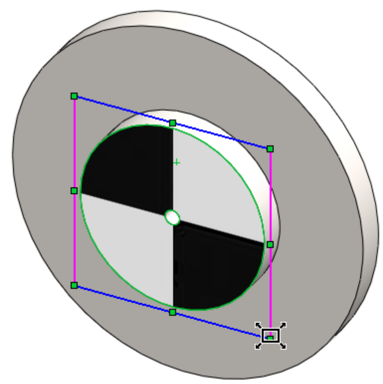




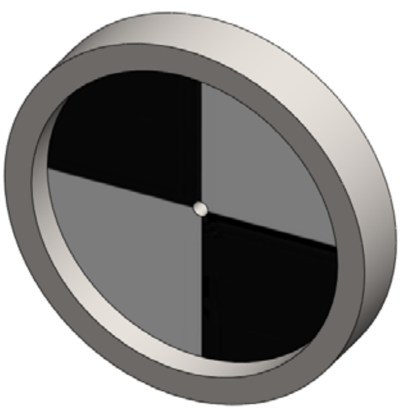

***In the PropertyManager, click the Advanced tab and the Color/Image tab. Under Appearance, select Browse, and select the checker pattern from Materials: miscellaneous: Pattern directory. Click Open to apply the pattern.***




***Click and drag a corner of the pattern, as shown here. Drag the corner outward until the pattern is large enough so the face is divided into four quadrants, and click the check mark in the Property Manager. Save the part file.***



***Open the part "Wheel 2." Find the mass properties, and apply a texture to a face of the model. Save the part file.***

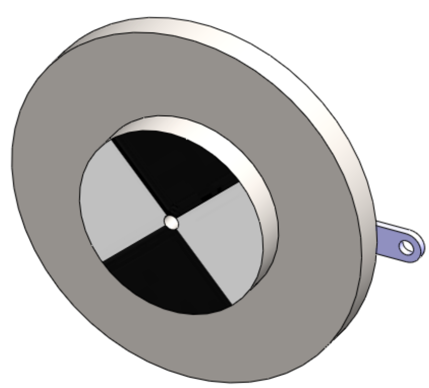


Note that the mass of this part (40.14 lb) is almost identical to that of the other wheel, but the mass moment of inertia (837.0 lb·in$^2$) is about 37% greater. The mass moment of the part depends not only on the part's mass, but also on how that mass is distributed. As more mass is placed at a greater distance away from the axis of the part, then the mass moment of inertia about that axis increases (note the $r^2$ in the equation for $I$ on page 1).

***Open a new assembly. Insert the component "Frame."***

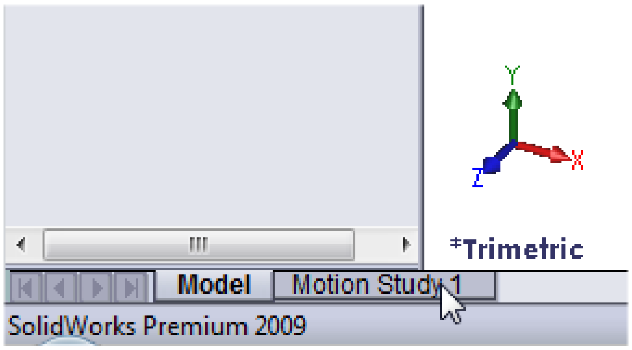
Since the first component inserted into an assembly is fixed, it is logical to insert the component representing the stationary component (the "frame" or "ground" component) first.

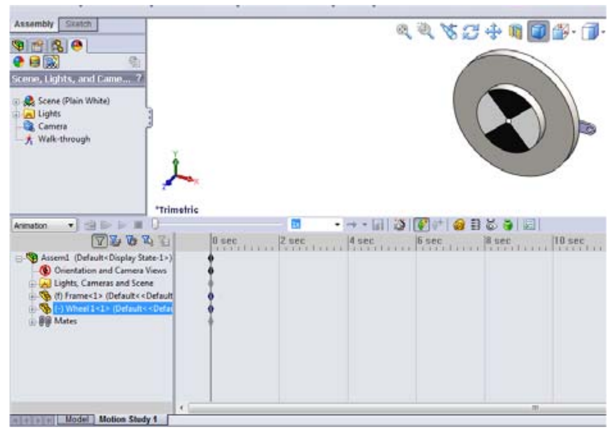
***Insert the part "Wheel 1" into the assembly. Select the Mate Tool. Add a concentric mate between the center hole of the wheel and one of the holes in the frame link. Be sure to select the cylindrical faces for the mate and not edges. Add a coincident mate between the back face of the wheel and the front face of the frame link.***



You should now be able to click and drag the wheel, with rotation about the axis of the mated holes the only motion allowed by the mates. The addition of these two mates has added a *revolute joint* to the assembly.  A revolute joint is similar to a hinge in that it allows only one degree of freedom.

***Click on the "Motion Study 1" tab near the lower left corner, which opens the MotionManager across the lower portion of the screen.***

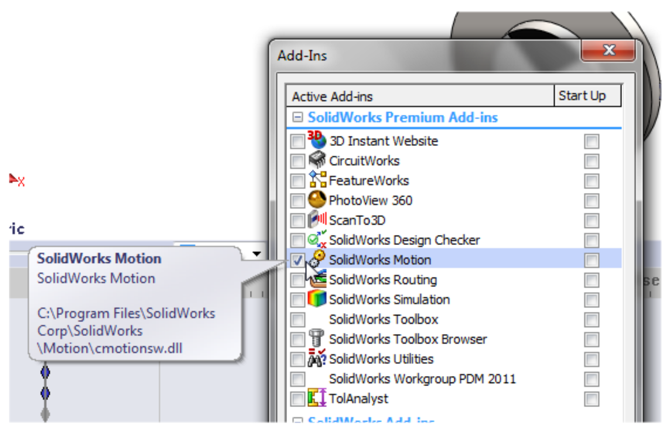



The Motion Manager can be used to create simulations of various complexities:

- *Animation* allows the simulation of the motion when virtual motors are applied to drive one or more of the components at specified velocities,
- *Basic Motion* allows the addition of gravity and springs, as well as contact between components, to the model, and
- *Motion Analysis (SolidWorks Motion)* allows for the calculation of velocities, accelerations, and forces for components during the motion.  It also allows for forces to be applied to the model.

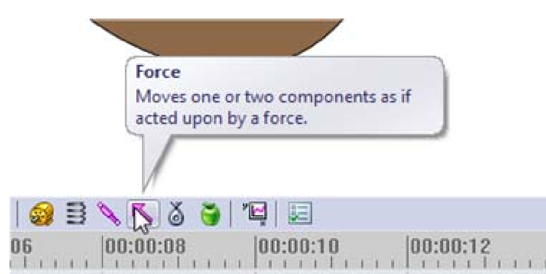
The first two options are always available in SolidWorks.  SolidWorks Motion is an add-in program, and must be activated before it can be used.




***From the main menu, select Tools: Add-Ins. Click the check box to the left of SolidWorks Motion.***

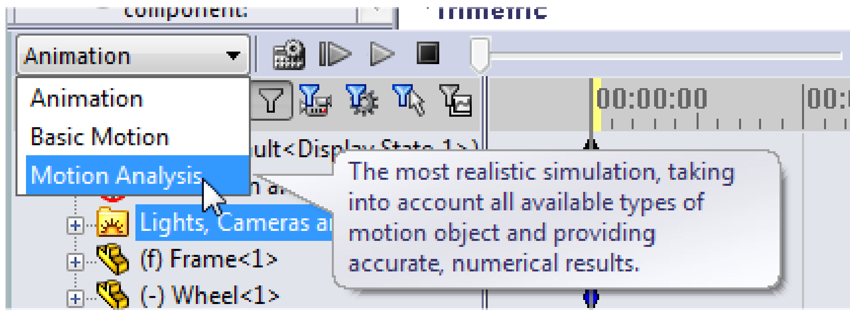
By checking the box to the right of an add-in, you can have that add-in loaded every time you open SolidWorks.

***Select the Force Tool.***



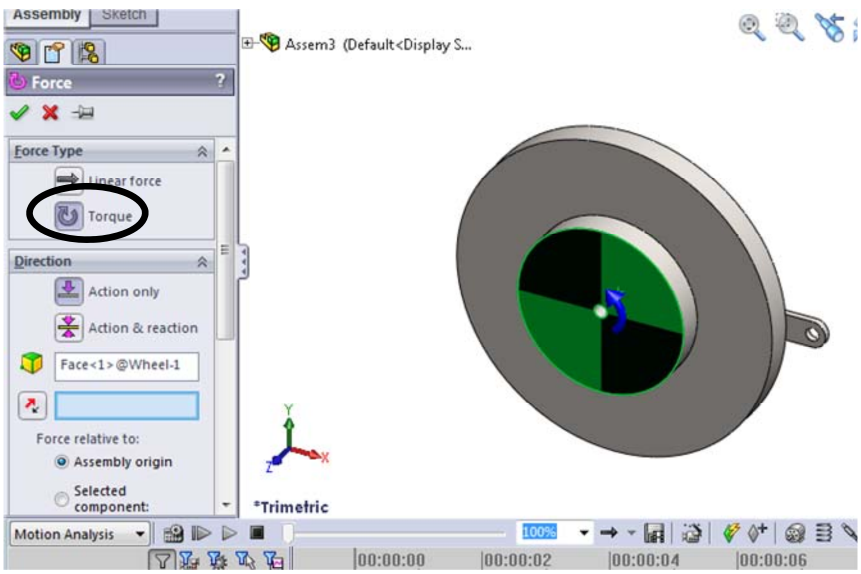

You will see a message displayed that SolidWorks Motion is required in order to add a force to a simulation.

***Select Motion Analysis from the simulation options pull-down menu.***



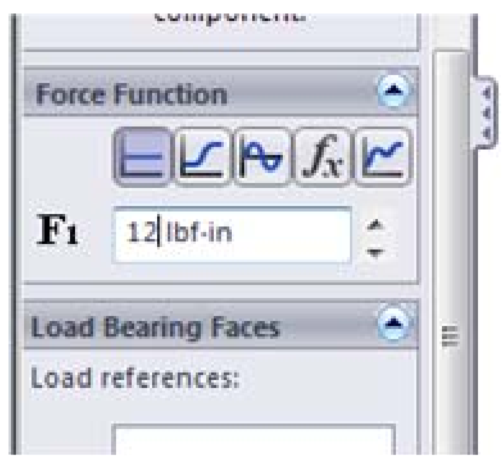

We will apply a torque (moment) to the wheel. We will set the torque to have a constant value of 1 ft·lb (12 in·lb), and will apply it for a duration of eight seconds.

***In the Force PropertyManager, select Torque and then click on the front face of the wheel.***

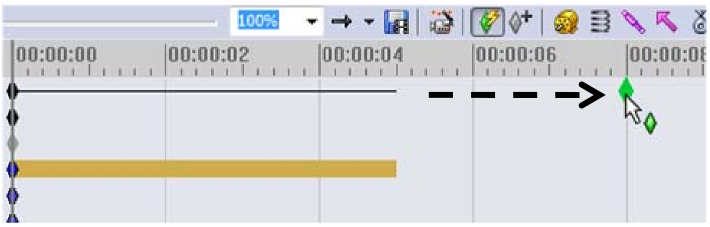


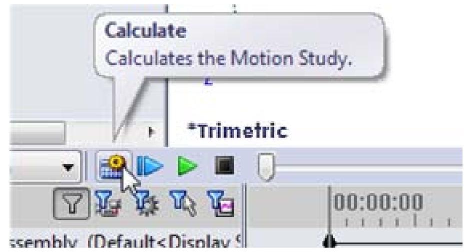

Note that the arrow shows that the torque will be applied in the counterclockwise direction relative to the Z-axis (we say that this torque's direction is +Z). The arrows directly below the face selection box can be used to reverse the direction of the torque, if desired.

***Scroll down in the Force PropertyManager and set the value to 12 in·lb. Scroll back to the top of the PropertyManager and click the check mark to apply the torque.***

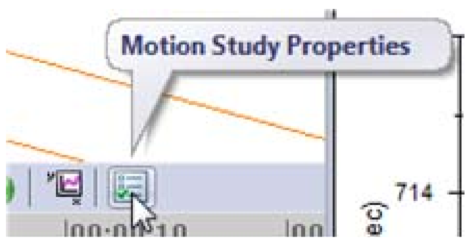
***In the MotionManager, click and drag the diamond-shaped icon (termed a "key" from the default five seconds to the desired eight seconds (00:00:08). Click the Calculator Icon to perform the simulation.***

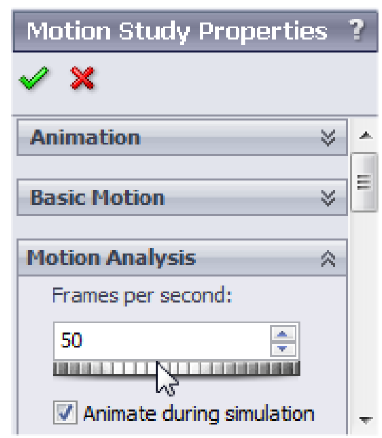



The animation of the simulation can be played back without repeating the calculations by clicking the Play from Start key. The speed of the playback can be controlled from the pull-down menu beside the Play controls.

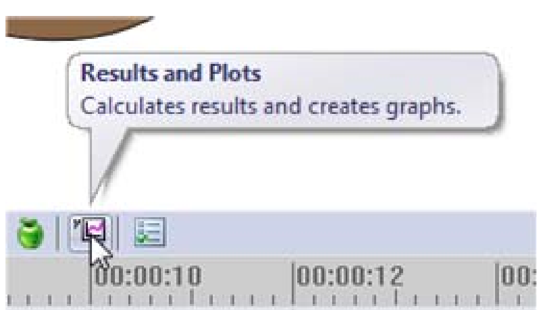

If the playback appears "choppy", then you can repeat the analysis with smaller time increments by selecting Motion Study Properties and setting the frame rate to a higher value. Be careful with setting this rate too high, as the speed of the simulation calculation will be greatly reduced for high frame rates.

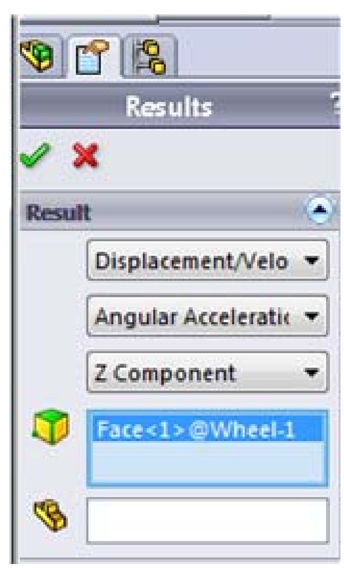


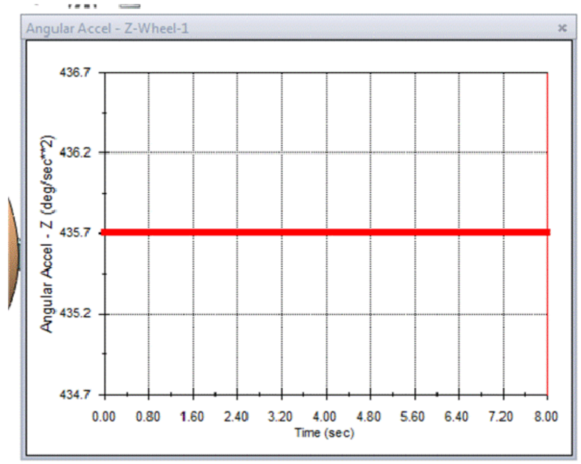




As noted earlier, SolidWorks Motion provides quantitative analysis results in addition to qualitative animations of motion models. We will create plots of the angular acceleration and angular velocity of the wheel.

***Select the Results and Plots Tool. In the PropertyManager, use the pull-down menus to select Displacement/Velocity/Acceleration: Angular Acceleration: Z Component. Click on the front face of the wheel, and click the check mark.***






A plot will be created of the angular acceleration versus time. The plot can be dragged around the screen and resized. It can also be edited by right-clicking the plot entity to be modified, similar to the editing of a Microsoft Excel plot.

We see that the acceleration is a constant value, about 436 degrees per second squared. Since the applied torque is constant, it makes sense that the angular acceleration is also constant. We can check the value with hand calculations. Note that while we can perform very complex analyses with SolidWorks Motion, checking a model by applying simple loads or motions and checking results by hands is good practice and can prevent many errors.

We earlier found the mass moment of inertia to be 609.3 lb·in$^2$. Since the pound is actually a unit of force, not mass, we need to convert weight to mass by dividing by the gravitational acceleration. Since we are using inches as our units of length, we will use a value of 386.1 in/s$^2$:

$$I = \frac{609.3\ \mathrm{lb \cdot in^2}}{386.1\ \frac{\mathrm{in}}{\mathrm{s^2}}} = 1.577\ \mathrm{lb \cdot in \cdot s^2}$$

Since the torque is equal to the mass moment of inertia times the angular acceleration, we can find the angular acceleration as:

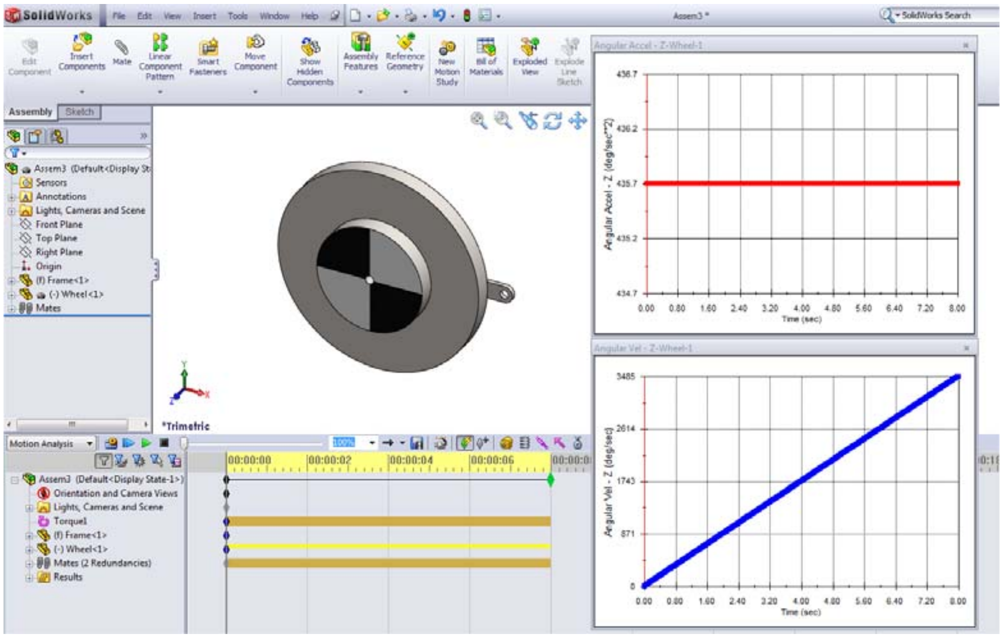
$$\alpha = \frac{T}{I} = \frac{12\ \mathrm{in}}{1.577\mathrm{lb \cdot in \cdot s^2}} = 7.610\ \frac{\mathrm{rad}}{\mathrm{s^2}}$$

Notice that the non-dimension quantity “radians” appears in our answer. Since we want our answer in terms of degrees, we must make one more conversion:

$$\alpha = 7.610\ \frac{\mathrm{rad}}{\mathrm{s^2}}\left(\frac{180\ \mathrm{deg}}{\pi\ \mathrm{rad}}\right) = 436\frac{\mathrm{deg}}{\mathrm{s^2}}$$

This value agrees with our SolidWorks Motion result.

***Select the Results and Plots Tool. In the PropertyManager, use the pull-down menus to select Displacement/Velocity/Acceleration: Angular Velocity: Z Component. Click on the front face of the wheel, and click the check mark. Resize and move the plot so that both plots can be seen, and format the plot as desired.***



As expected, since the acceleration is constant, the velocity increases linearly. The velocity at the end of eight seconds is seen to be about 3485 degrees per second. This result is consistent with a hand calculation:

$$\omega = \alpha t = \left(436 \frac{\text{deg}}{\text{s}^2}\right)(8 \text{ s}) = 3490 \frac{\text{deg}}{\text{s}}$$

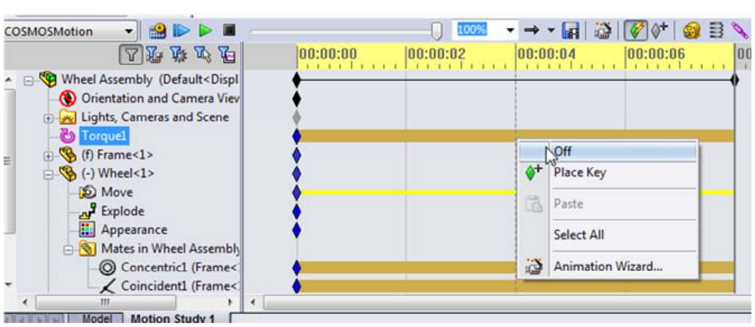
Often, the angular velocity is expressed in revolutions per minute (rpm), commonly denoted by the symbol $N$:

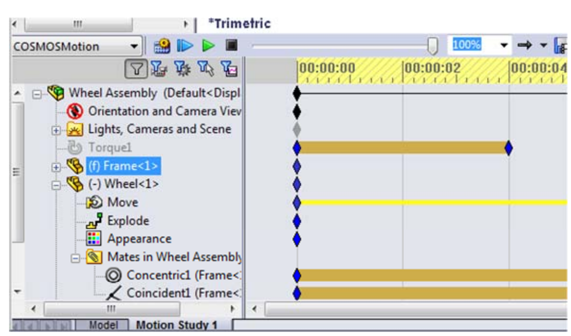
$$N = \left(3490 \frac{\text{deg}}{\text{s}}\right)\left(\frac{1 \text{ rev}}{360 \text{ deg}}\right)\left(\frac{60 \text{ s}}{1 \text{ min}}\right) = 582 \text{ rpm}$$

We will now experiment with variations of the simulation.

***Place the cursor on the line corresponding to the applied torque (Torque1) at the 4-second mark. Right-click and select Off.***

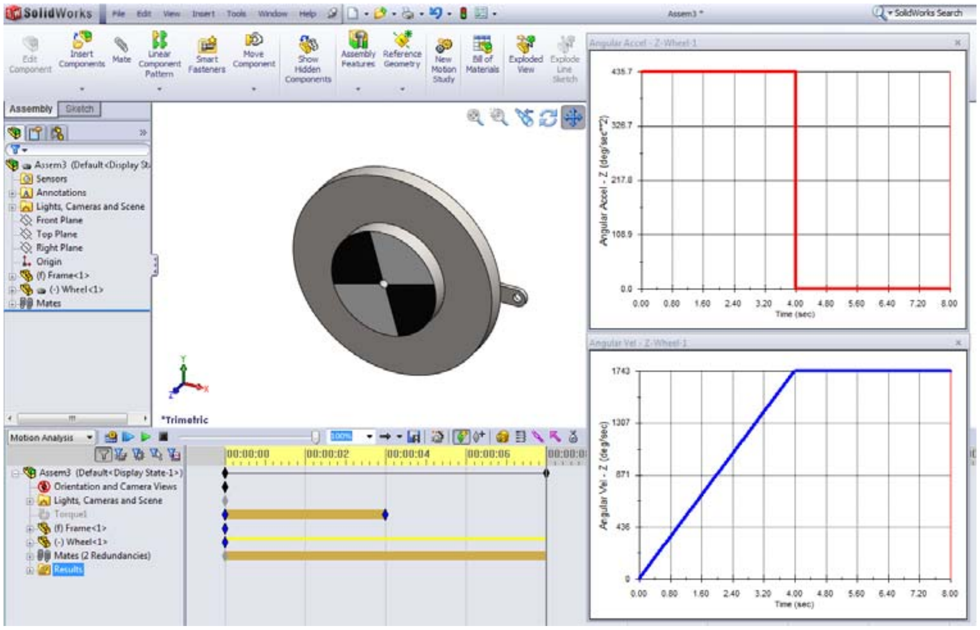
A new key will be placed at that location. The torque will now be applied for four seconds, but the simulation will continue for the full eight seconds.



***Press the Calculator icon to perform the simulation.***

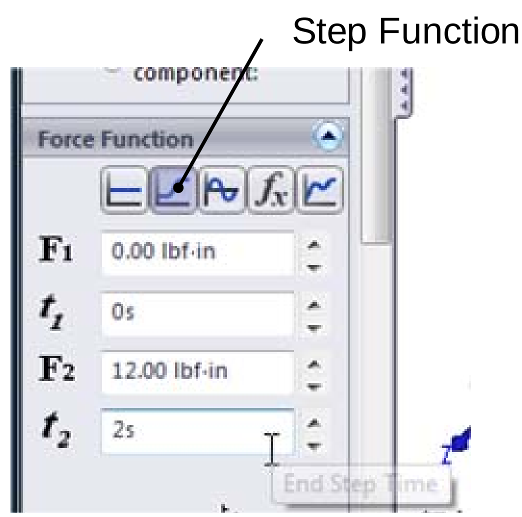
The plots will be automatically updated. Note that the angular acceleration now drops to zero at four seconds, while the angular velocity will be constant after four seconds.

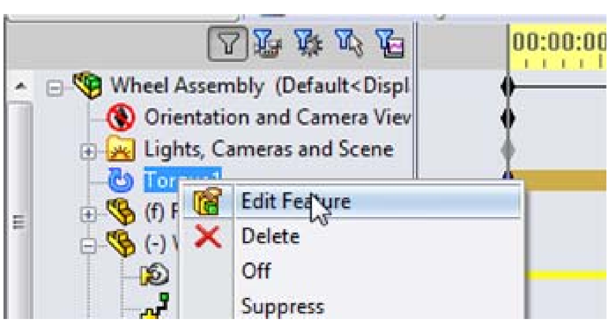


In the previous simulations, the torque was applied as a constant value. That means that the change of the acceleration relative to time (commonly referred to as “jerk”) is infinite at time = 0. A more realistic approximation is to assume that the torque builds up over some period of time. For example, we will assume that it takes two seconds to reach the full value of torque.

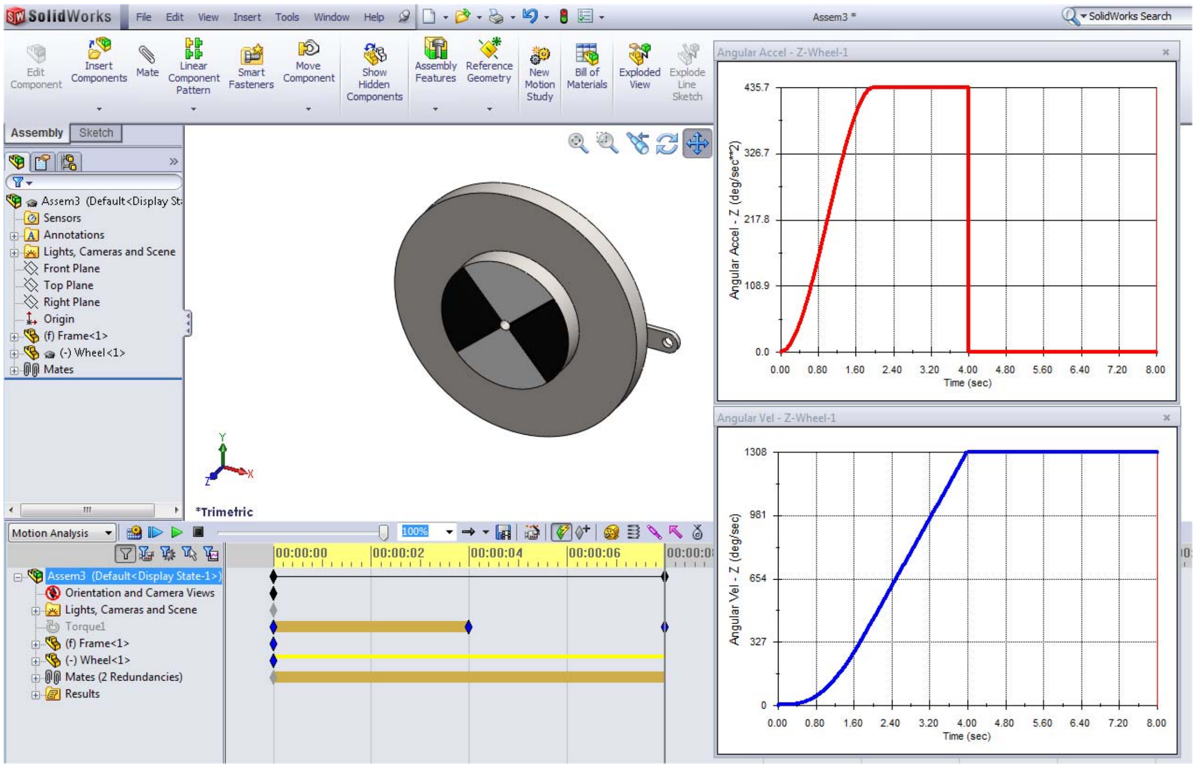
***Move the time bar back to zero. Right-click on Torque1 and select Edit Feature.***

***Scroll down in the PropertyManager, and select Step as the type of Force Function. Set the initial torque to 0 and the final torque to 12 in·lb, and set the end time $t_2$ to 2 seconds. Click the check mark, and run the simulation.***



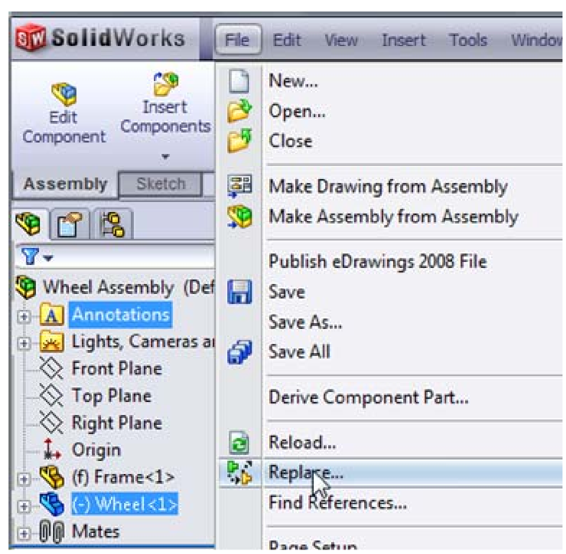

Note that the angular acceleration curve is smooth, and peaks at the same value as before (436 deg/s$^2$). Of course, the final angular velocity is lower than for a constant acceleration. (There is still an infinite change in acceleration at t = 4 seconds. This can be smoothed by adding a second step function which steps the torque from 12 in·lb to zero over a fixed amount of time.)



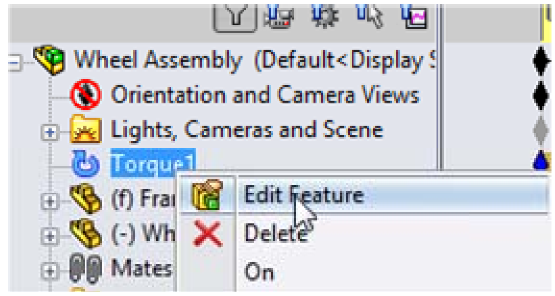

Now let's see the effect of replacing the Wheel 1 component with Wheel 2, which has a higher mass moment of inertia. Of course, we could start with a new assembly, but it is easier to replace the component in the existing assembly. This will allow us to retain most of the simulation entities.

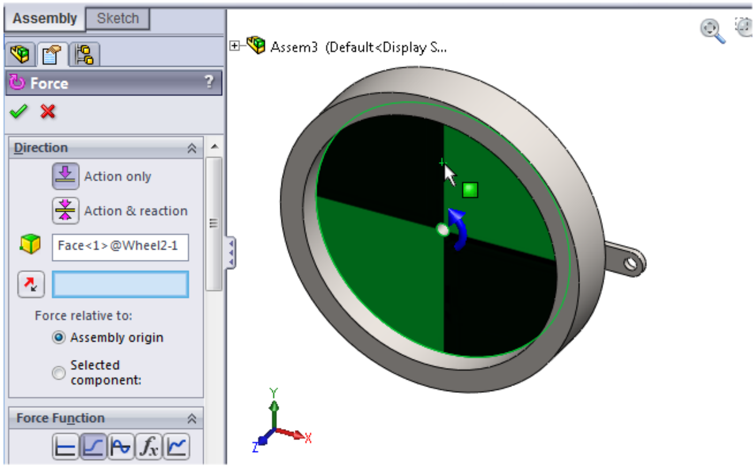
***Select the Model tab. Delete both mates between the Frame and Wheel 1 (otherwise you will receive errors when replacing the wheel, as the mating faces will not be defined). Click on Wheel 1 in the FeatureManager to select it. From the main menu, select File: Replace. Browse to find Wheel 2, and click the check mark to make the replacement.***

***Add new mates between the parts as before (concentric mate between two holes, coincident mate between two faces).***



***Right-click on Torque1 and select Edit Feature. Click on the front face of the new wheel (Wheel 2) to apply the torque. Run the Simulation.***

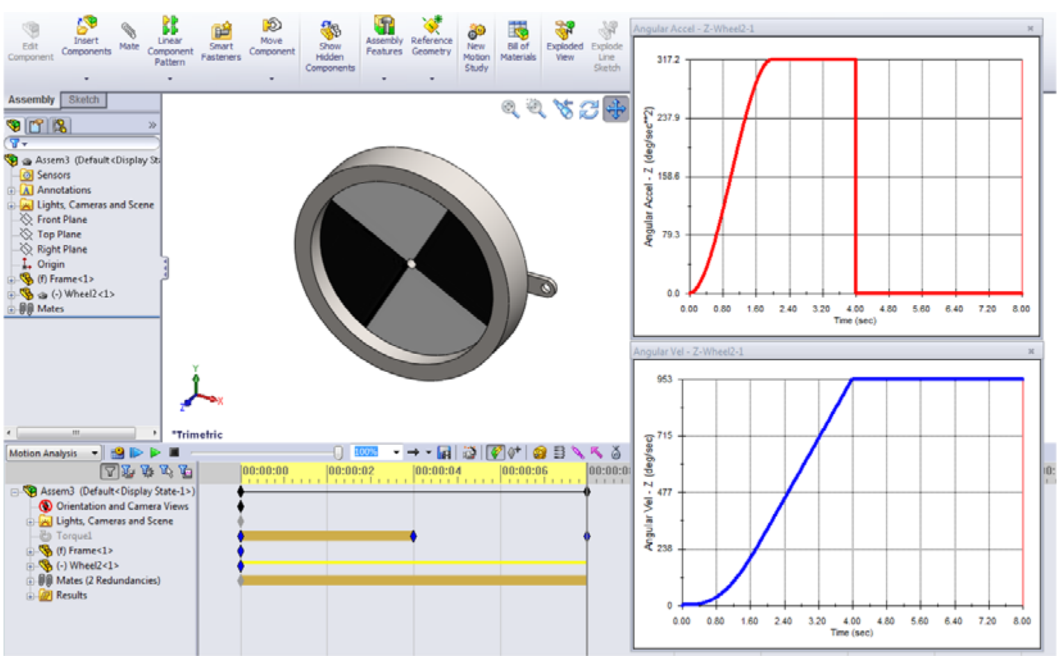



Note that the maximum angular acceleration is about 317 deg/s$^2$, which is significantly less that of the simulation with the earlier Wheel. This value can be verified by repeating the earlier calculations or from the ratio:

$$\frac{\alpha_2}{\alpha_1} = \frac{I_1}{I_2}$$

$$\alpha_2 = \frac{I_1}{I_2}\alpha_1 = \frac{609.3}{837.0}\left(436\ \frac{\text{deg}}{\text{s}^2}\right) = 317\frac{\text{deg}}{\text{s}^2}$$

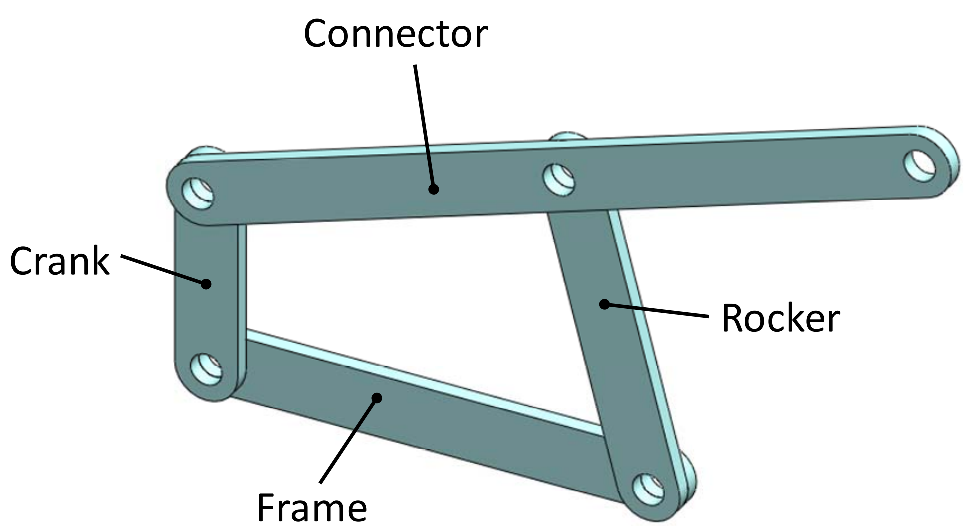


Four-Bar Linkage

In this exercise, we will model a 4-bar linkage similar to that of Chapter 11 of the text. In the text, we were able to qualitatively simulate the motion of the simulation when driven by a constant-speed motor. In this exercise, we will add a force and also explore more of the quantitative analysis tools available with SolidWorks Motion.

***Construct the components of the linkage shown on page 2, and assemble them as detailed in Chapter 11 of the text. The Frame link should be placed in the assembly first, so that it is the fixed link.***

You should be able to click and drag the Crank link around a full 360 degree rotation.

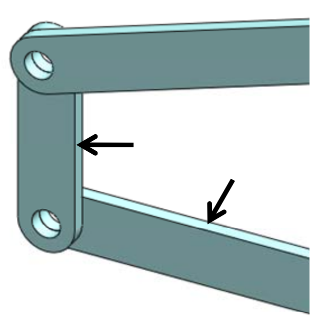


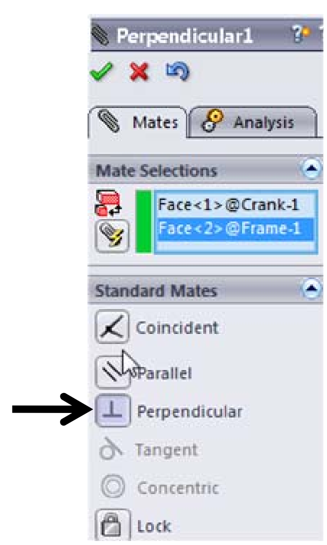

Note that the Connector link has three holes. The motion of the third hole can follow many paths, depending on the geometry of the links and the position of the hole.

Before beginning the simulation, we will set the links to a precise orientation. This will allow us to compare our results to hand calculations more easily.

***Add a perpendicular mate between the two faces shown here.***

***Expand the Mates group of the FeatureManager, and right-click on the perpendicular mate just added. Select Suppress.***

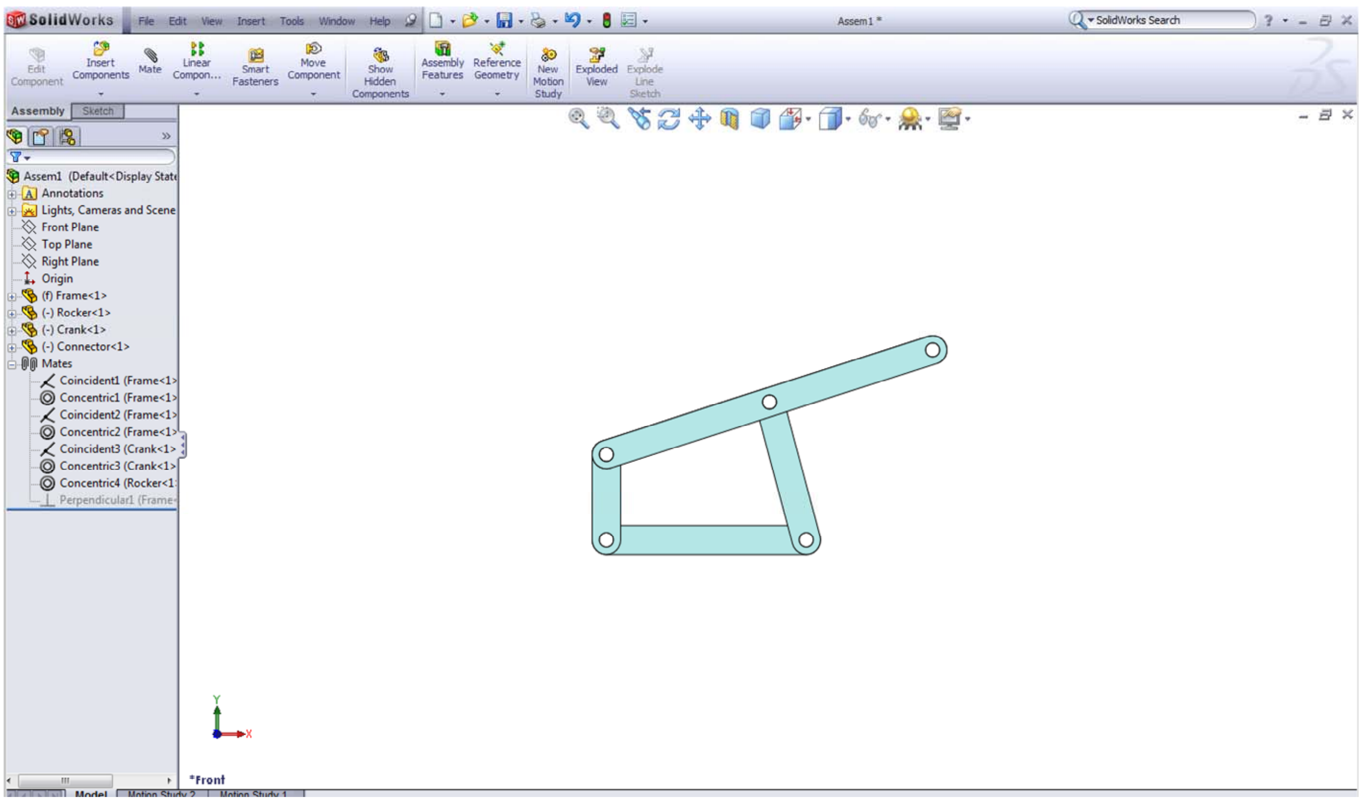




The perpendicular mate aligns the crank link at a precise location. However, we want the crank to be able to rotate, so we have suppressed the mate. We could have deleted the mate, but if we need to re-align the crank later, we can simply unsuppress the mate rather than recreating it.

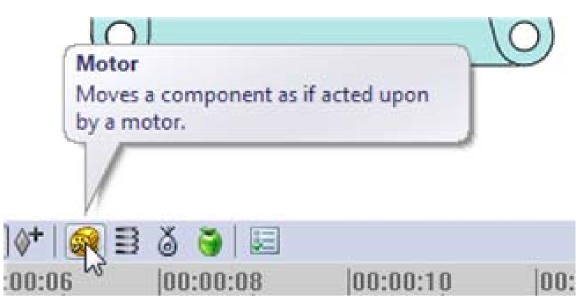
***Switch to the Front View. Zoom out so that the view looks similar to the one shown here.***

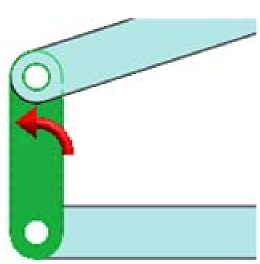
The MotionManager uses the last view/zoom of the model as the starting view for the simulation.

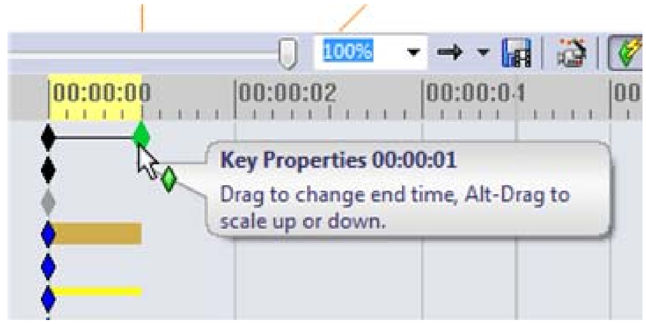


***Make sure that the SolidWorks Motion add-in is active. Click the MotionManager tab.***

***Select the Motor icon. In the PropertyManager, set the velocity to 60 rpm. Click on the front face of the Crank to apply the motor, and click the check mark.***

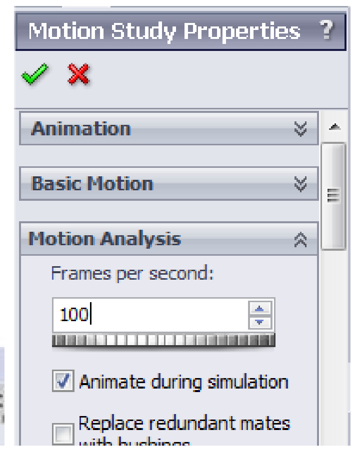




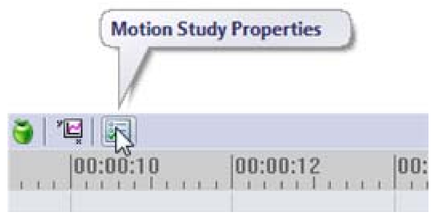

***Click and drag the simulation key from the default five seconds to one second (0:00:01).***

Since we set the motor's velocity to 60 rpm, a one-second simulation will include one full revolution of the Crank.



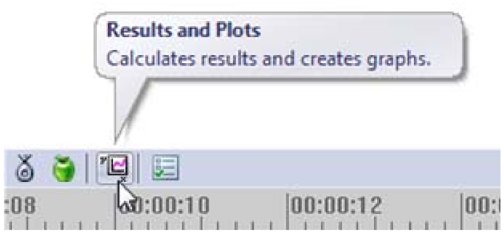

***Click the Motion Study Properties Tool. Under the Motion Analysis tab, set the number of frames to 100 (frames per second), and click the check mark.***

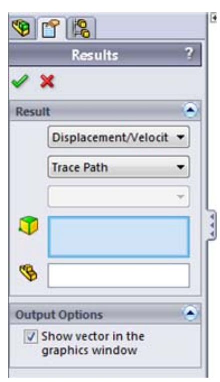
This setting will produce a smooth simulation.

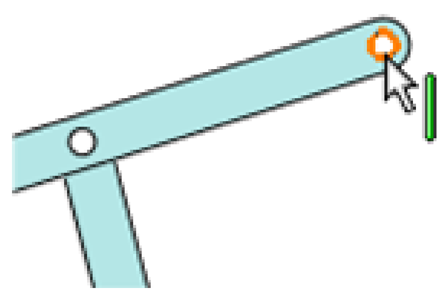



***Choose SolidWorks Motion from the pull-down menu, and press the Calculator icon to run the simulation.***

***Click the Results and Plots Tools. In the PropertyManager, set the type of the result to Displacement/ Velocity/Acceleration: Trace Path. Click on the edge of the open hole of the Connector.***

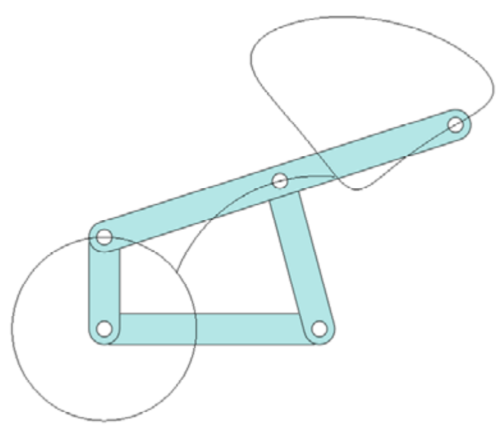


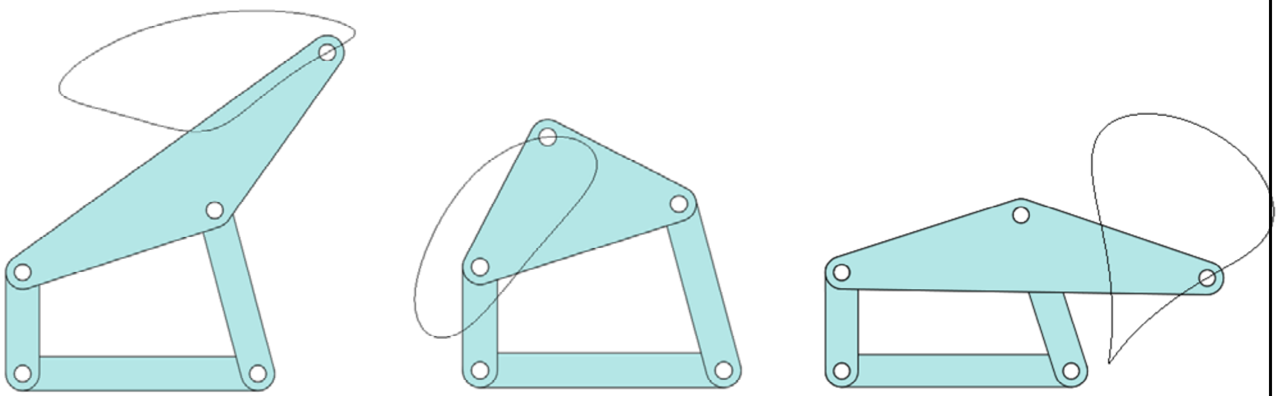



***Play back the simulation to see the open hole's path over the full revolution of the Crank.***

If desired, you can add paths for the other two joints that undergo motion.

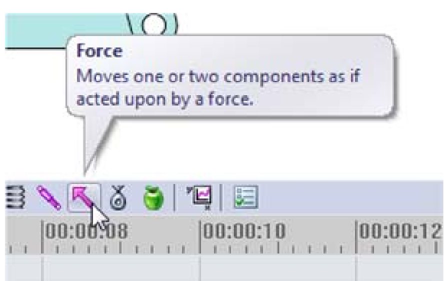


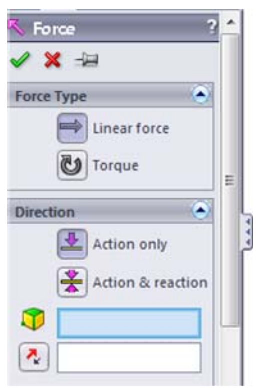
The four bar linkage can be designed to produce a variety of motion paths, as illustrated below.

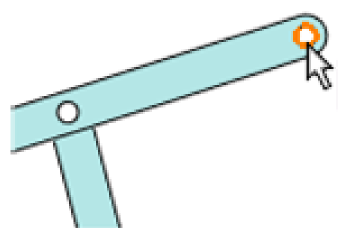


We will now add a force to the open hole.

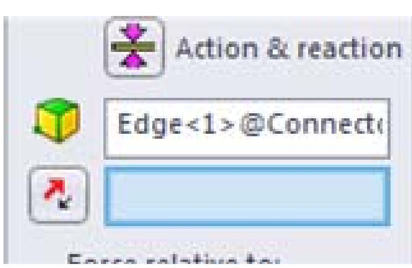
***Move the time bar back to zero. Select the Force Tool. In the PropertyManager, the highlighted box prompts you for the location of the force. Click on the edge of the open hole, and the force will be applied at the center of the hole.***

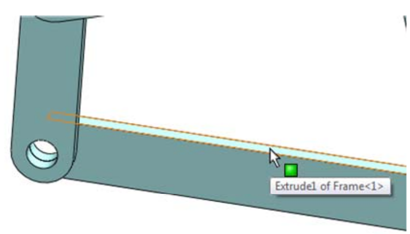


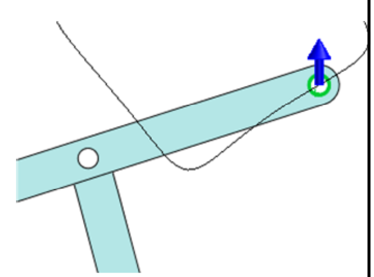



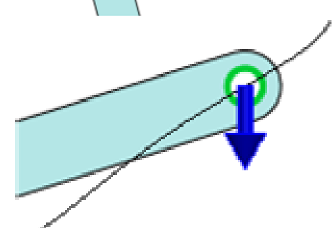
***The direction box is now highlighted. Rotate and zoom in so that you can select the top face of the Frame part. The force will be applied normal to this force. As you can see, the force acts upwards.***



***Click the arrows to reverse the direction of the force.***

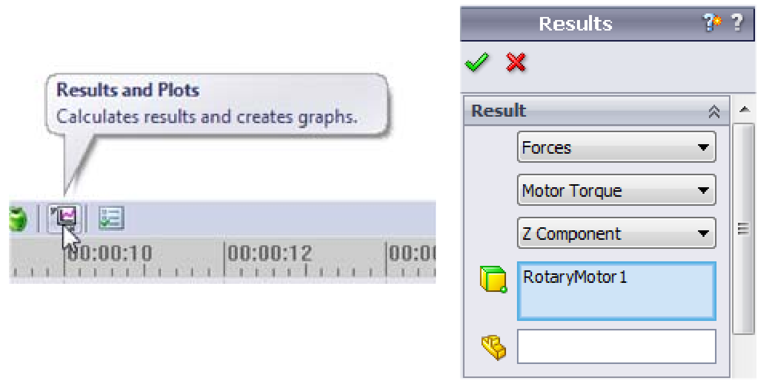



***Scroll down in the PropertyManager and set the magnitude of the force to 20 pounds. Click the check mark to apply the force.***

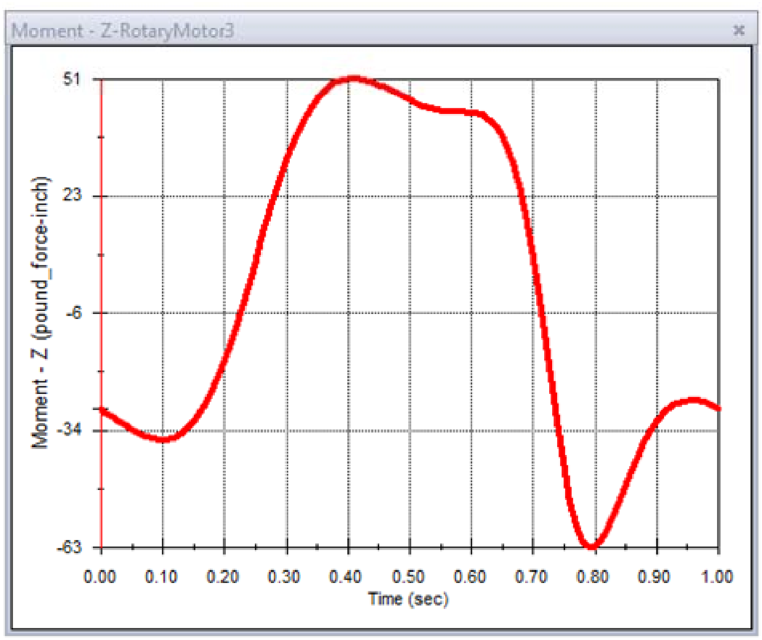

***Run the simulation.***

We will now plot the torque of the motor that is required to produce the 60-rpm motion with the 20-lb load applied.

***Select Results and Plots. In the Property-Manager, specify Forces: Motor Torque: Z Component. Click on the RotaryMotor in the MotionManager to select it, and click the check mark in the PropertyManager.***

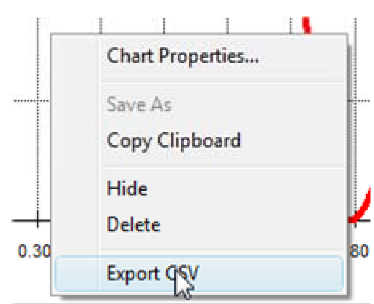



***Format the resulting plot as desired.***




Note that the applied torque peaks at about 51 in·lb. At t = 0, the torque appears to be about -30 in·lb (the negative signs indicates the direction is about the –Z axis, or clockwise when viewed from the Front View). In order to get a more exact value, we can export the numerical values to a CSV (comma-separated values) file that can be read in Word or Excel.

***Right-click in the graph and choose Export CSV. Save the file to a convenient location, and open it in Excel.***



At time = 0, we see that the motor torque is -29.2 in·lb.

Hand calculations for a *static analysis* of the mechanism are attached, which show a value of -29.4 in·lb.

It is important when comparing these values to recognize the assumptions that are present in the hand calculations:

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Moment - Z-RotaryMotor3 | | | |
| 2 | Time (sec) | Moment - Z (pound_force-inch) | | |
| 3 | 0.00 | -29.20 | | |
| 4 | 0.01 | -30.09 | | |
| 5 | 0.02 | -31.05 | | |
| 6 | 0.03 | -32.04 | | |
| 7 | 0.04 | -33.01 | | |
| 8 | 0.05 | -33.95 | | |
| 9 | 0.06 | -34.79 | | |
| 10 | 0.07 | -35.52 | | |
| 11 | 0.08 | -36.09 | | |

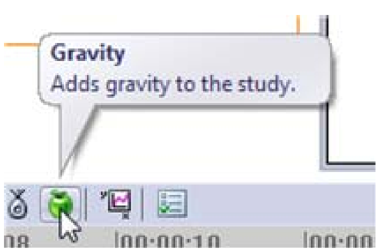
1. The weights of the members were not included in the forces, and
2. The accelerations of the members were neglected.

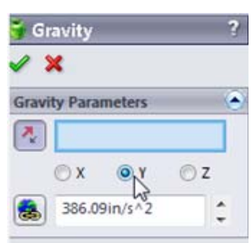
The first assumption is common in machine design, as the weights of the members are usually small in comparison to the applied loads. In civil engineering, this is usually not the case, as the weights of structures such as building and bridges are often greater than the applied forces.

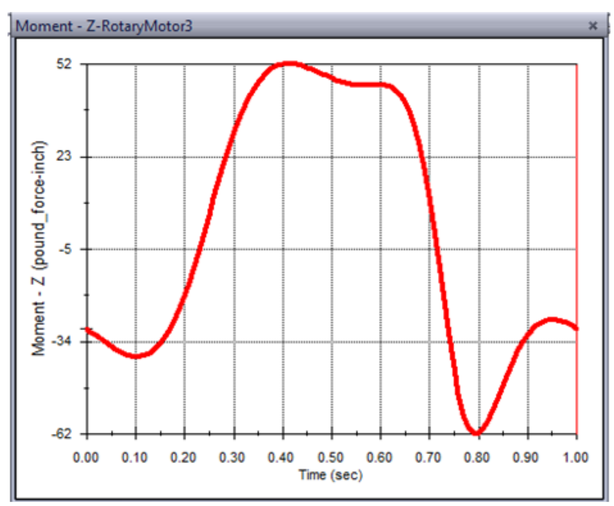
The second assumption will be valid only if the accelerations are relatively low. In our case, the angular velocity of the crank (60 rpm, or one revolution per second) produces accelerations in the members that are small enough to be ignored.

Let's add gravity to the simulation to see its effect.

***Click on the Gravity icon. In the PropertyManager, select Y as the direction. There will be an arrow pointing down in the lower right corner of the graphics area, showing that the direction is correct. Click the check mark. Run the simulation.***



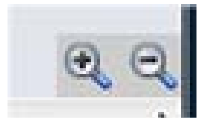



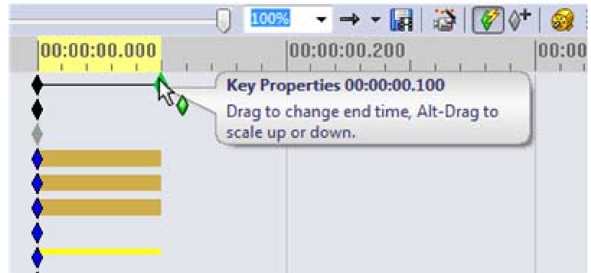




The torque plot is almost unchanged, with the peak torque increasing by only one in·lb. Therefore, omitting gravity had very little effect on the calculations.

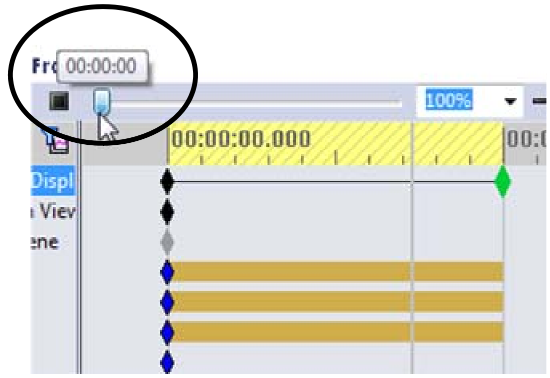
Now we will increase the velocity of the motor to see the effect on the torque.

***Drag the key at the end of the top bar in the MotionManager from 1 second to 0.1 second. Use the Zoom In Tool in the lower right corner of the MotionManager to spread out the time line, if desired.***

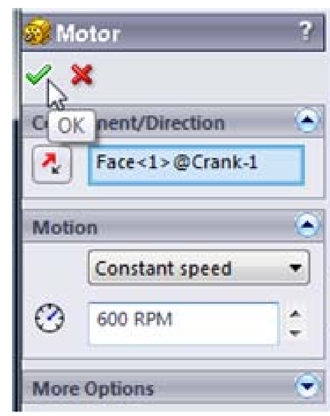





***Drag the slider bar showing the time within the simulation back to zero.***




This is an important step before editing existing model items, as changes can be applied at different time steps. Because we want the motor's speed to be changed from the beginning of the simulation, it is important to set the simulation time at zero.

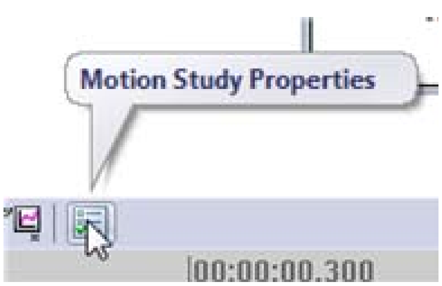


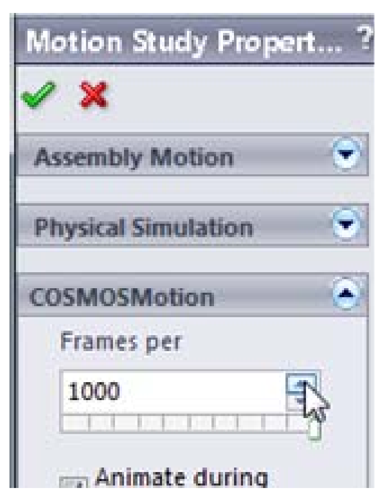

***Right-click on the RotaryMotor in the MotionManager. In the PropertyManager, set the speed to 600 rpm. Click the check mark.***

Since a full revolution will occur in only 0.1 seconds, we need to increase the frame rate of the simulation to achieve a smooth plot.

***Select the Motion Study Properties. In the PropertyManager, set the SolidWorks Motion frame rate to 1000 frames/second. Click the check mark.***

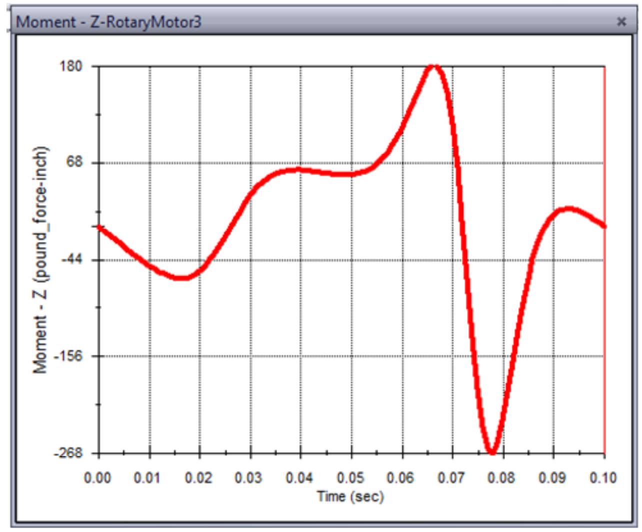
***Run the simulation.***



The peak torque has increased from 51 to 180 in·lb, demonstrating that as the speed is increased, the accelerations of the members are the critical factors affecting the torque.

You can verify this conclusion further by suppressing both gravity and the applied 20-lb load and repeating the simulation. The peak torque is decreased only from 180 to 151 in·lb, even with no external loads applied.




To perform hand calculations with the accelerations included, it is necessary to first perform a kinematic analysis to determine the translational and angular accelerations of the members. You can then draw free body diagrams of the three moving members and apply three equations of motion to each:

$$\Sigma F_x = m a_x \qquad \Sigma F_y = m a_y \qquad \Sigma M_z = I_Z \alpha_Z$$

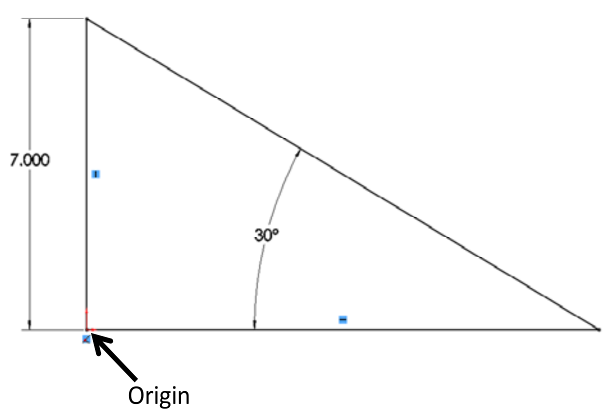
The result is nine equations that must be solved simultaneously to find the nine unknown quantities (the applied torque and the two components of force at each of the four pin joints).

The results apply to only a single point in time. This is a major advantage of using a simulation program such as SolidWorks Motion: since it is not evident at what point in the motion that the forces are maximized, our analysis evaluates the forces over the complete range of the mechanism's motion and allows us to identify the critical configuration.

Roller on a Ramp

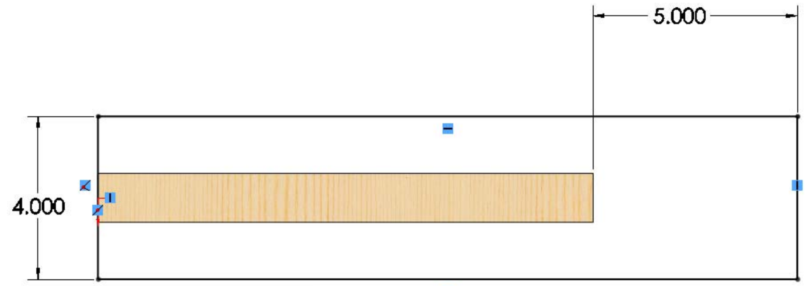
In this exercise, we will add contact between two bodies, and experiment with friction between the bodies. We will begin by creating two new parts – a ramp and a roller.

***Open a new part. In the Front Plane, sketch and dimension the triangle shown here.***

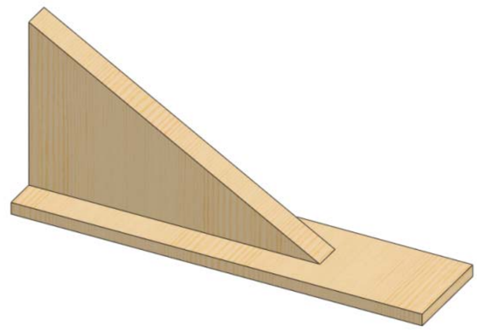


***Extrude the triangle using the midplane option, with a thickness of 1.2 inches.***

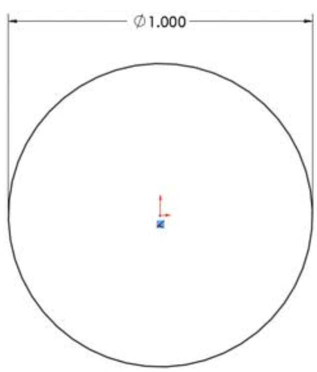
***In the Top Plane, using the Corner Rectangle Tool, draw a rectangle. Add a midpoint relation between the left edge of the rectangle and the origin. Add the two dimensions shown, and extrude the rectangle down 0.5 inches.***

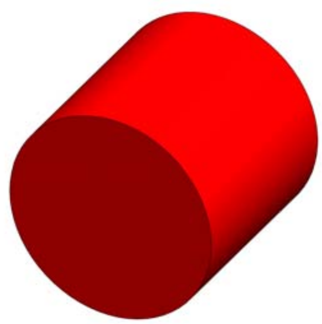



***Modify the material/appearance as desired (shown here as Pine). Save this part with the name "Ramp".***

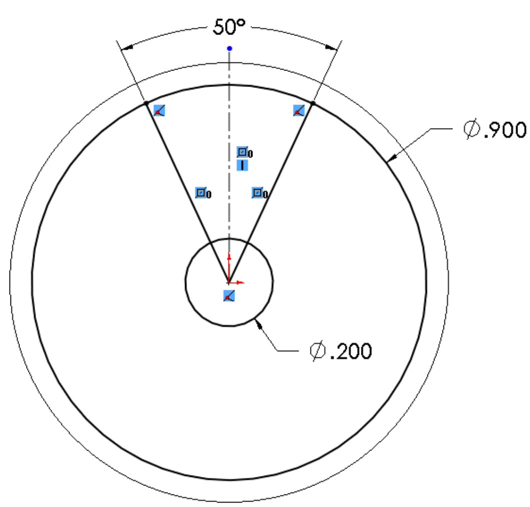


***Open a new part. Sketch and dimension a one-inch diameter circle in the Front Plane. Extrude the circle with the midplane option, to a total thickness of one inch. Set the material of the part as PVC Rigid. Modify the color of the part as desired (overriding the default color of the material selected).***

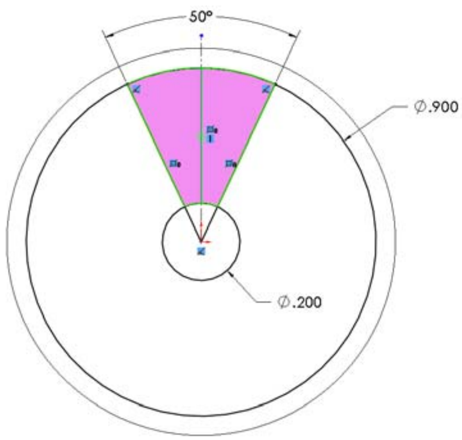


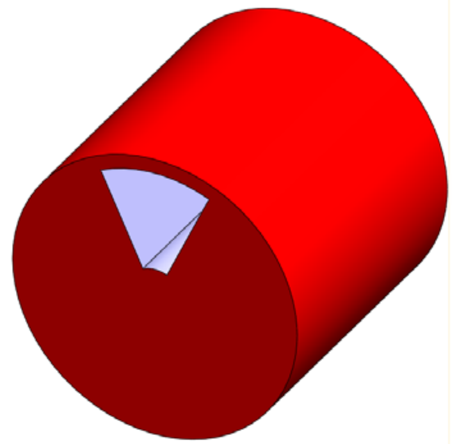



***Open a new sketch on the front face of the cylinder. Add and dimension the circles and lines as shown here (the part is shown in wireframe mode for clarity). The two diagonal lines are symmetric about the vertical centerline.***

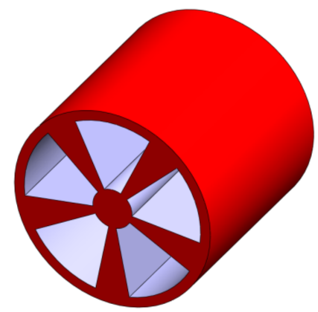


***Extrude a cut with the Through All option, with the sketch contours shown selected. If desired, change the color of the cut feature.***



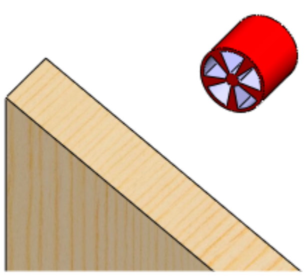



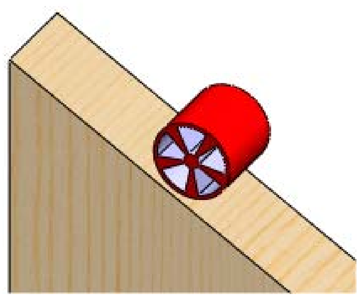
***Create a circular pattern of the extruded cut features, with five equally-spaced cuts. Save the part with the name "Roller".***



***Open a new assembly. Insert the ramp first, and place it at the origin of the assembly. Insert the Roller.***

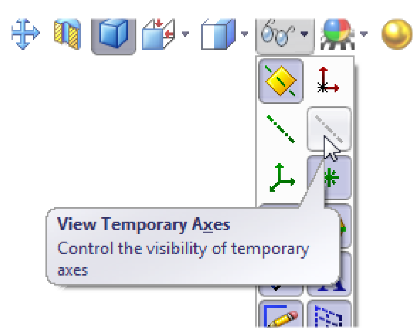
***Add two mates between the ramp and the roller. Mate the Front Planes of both parts, and add a tangent mate between the cylindrical surface of the roller and the surface of the ramp.***





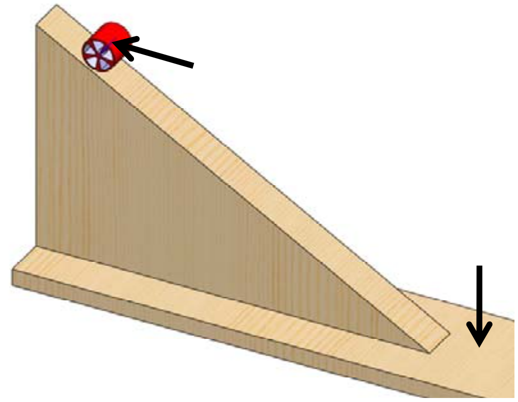
The best way to set the correct height of the roller on the ramp is to add a mate defining the position of the axis of the roller.

***From the Heads-Up View Toolbar, select View: Temporary Axes.***

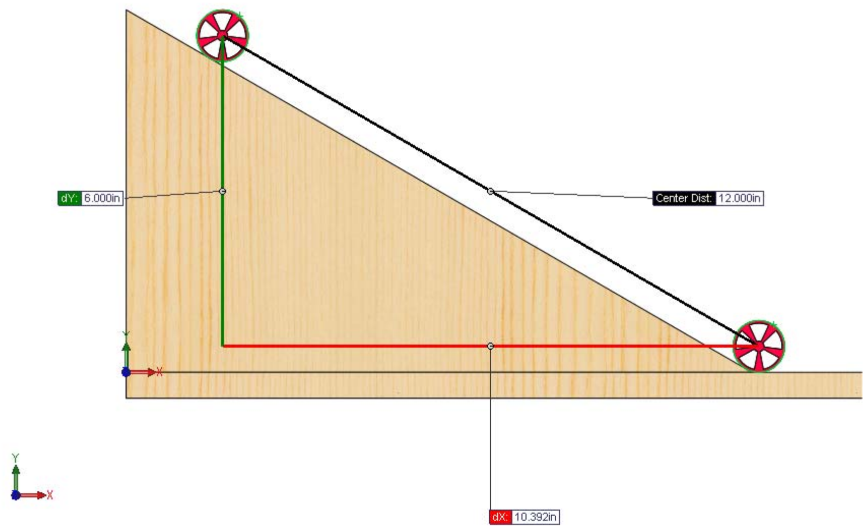



This command turns on the display of axes that are associated with cylindrical features.

***Add a distance mate between the roller's axis and the flat surface at the bottom of the ramp. Set the distance as 6.5 inches.***

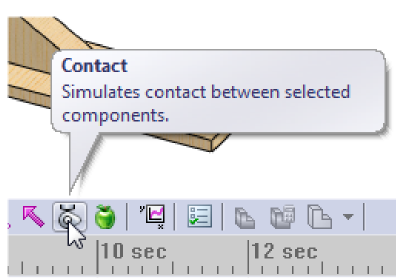


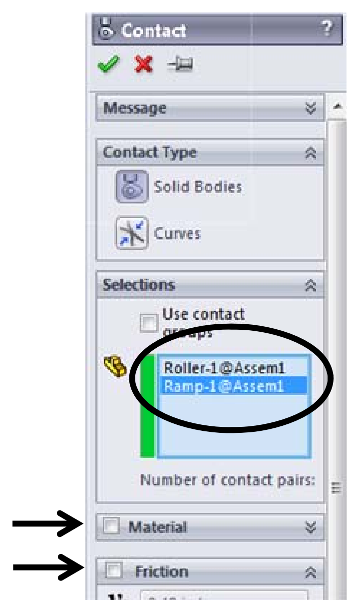
Since the radius of the roller is 0.5 inches, the axis will be 0.5 inches above the flat surface when the surface of the roller contacts that surface. Therefore, the vertical distance traveled by the roller will be 6.0 inches. Also, note that the distance travelled down the ramp will be 12 inches (6 inches divided by the sine of the ramp angle, 30 degrees).




***Turn off the temporary axis display. Switch to the Motion Study. Select Motion Analysis as the type of analysis. Add gravity in the -y-direction.***

***Select the Contact Tool. In the PropertyManager, you will be prompted to select the bodies for which contact can occur. Click on each of the two parts. Clear the check boxes labeled "Material" and "Friction." Leave the other properties as their defaults.***




We will add friction later, but our initial simulation will be easier to verify without friction. In the Elastic Properties section, note that the default is set as "Impact," with several other properties (stiffness, exponent, etc.) specified. At each time step, the program will check for interference between the selected bodies. If there is interference, then the specified parameters define a non-linear spring that acts to push the bodies apart. Contacts add considerable complexity to a simulation. If the time steps are too large, then the contact may not be recognized and the bodies will be allowed to pass through each other, or a numerical error may result.

***Select the Motion Studies Property Tool. Set the frame rate to 500 and check the box labeled "Use Precise Contact." Click the check mark.***

For some simulations, it may be necessary to lower the solution tolerance in order to get the simulation to run. For this example, the default tolerance should be fine.

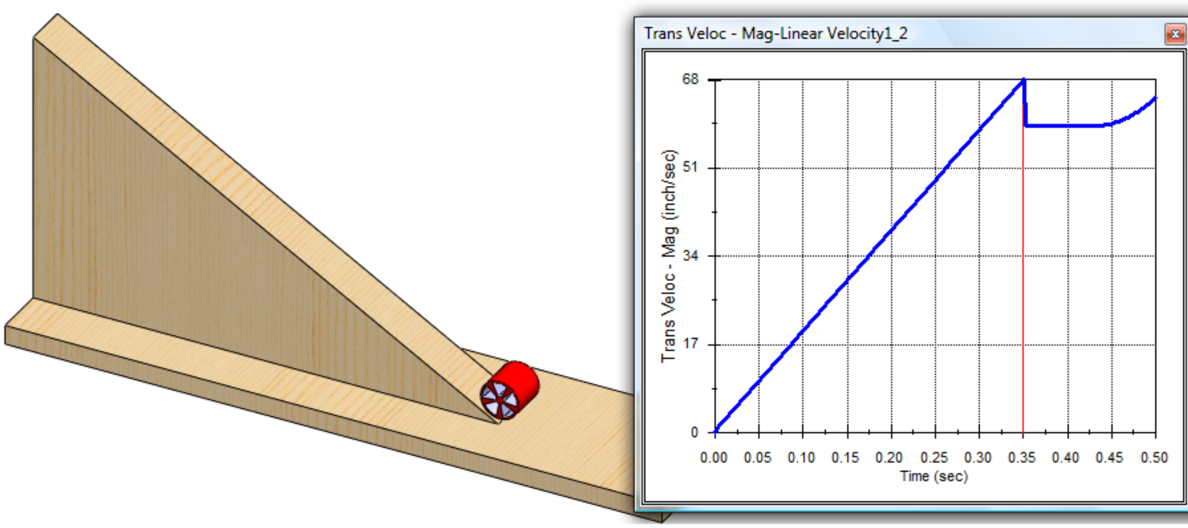
The mates that we added between the parts to precisely locate the roller on the ramp will prevent motion of the roller. Rather than delete these mates, we can suppress them in the MotionManager.

***Right-click on each of the mates in the MotionManager and select Suppress. Run the simulation.***

You will see that the roller reaches the bottom of the ramp quickly.

***Change the duration of the simulation to 0.5 seconds, and run the simulation again. Create a plot of the magnitude of the linear velocity of the roller vs. time.***

The roller reaches the bottom of the ramp in about 0.35 seconds, and the velocity at the bottom of the ramp is about 68 in/s. These values agree with those calculated in the attachment at the end of this document.

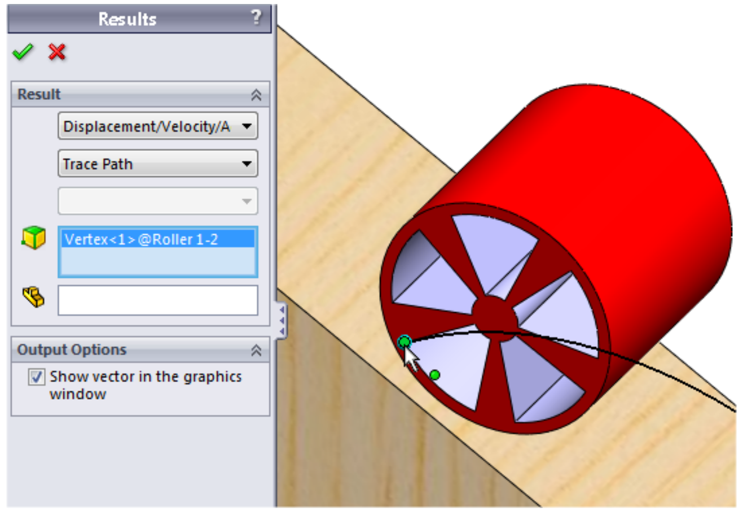



Now let's add friction.

***Move the timeline of the simulation back to zero. Right-click on the contact in the MotionManager tree, and select Edit Feature. Check the "Friction" box, and set the dynamic coefficient of friction to 0.25. (The friction velocity is not critical for this simplified model; it can be set to zero.) Calculate the simulation.***

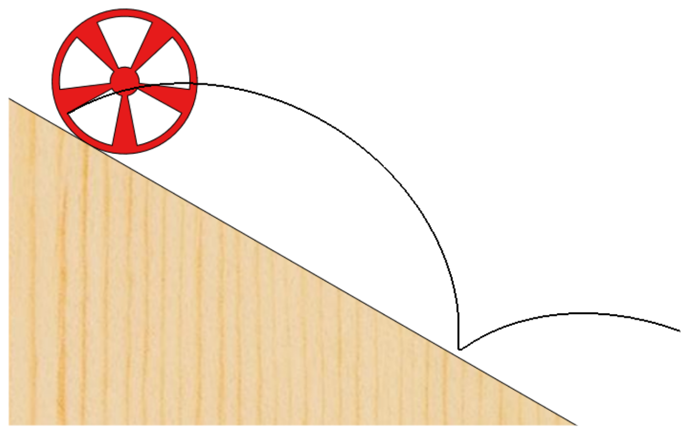
The resulting velocity plot shows the velocity at the bottom of the ramp to be about 54 in/s. This value agrees with that of the calculations shown in the attachment.

To confirm that the roller is not slipping, we can trace the position of a single point on the roller.



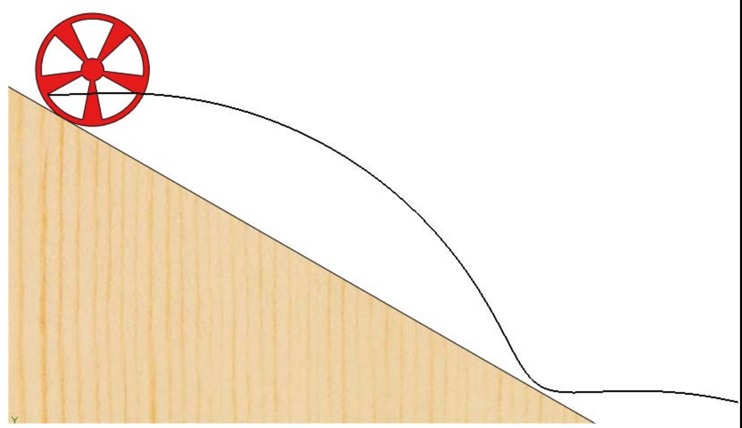

***Select the Results and Plots Tool. Define the plot as Displacement/ Velocity/Acceleration: Trace Path. Click on a point near the outer rim of the roller (not on a face, but on a single point). Click the check mark.***

The trace path shows a sharp cusps where the point's velocity approaches zero (it will not become exactly zero unless the point is on the outer surface of the roller). For comparison, repeat the analysis with a lower friction coefficient.



***Change the friction coefficient to 0.15 and recalculate the simulation.***

This time, the trace paths shows smooth curves when the point is near the ramp's surface, indicating that sliding and rolling are taking place simultaneously.



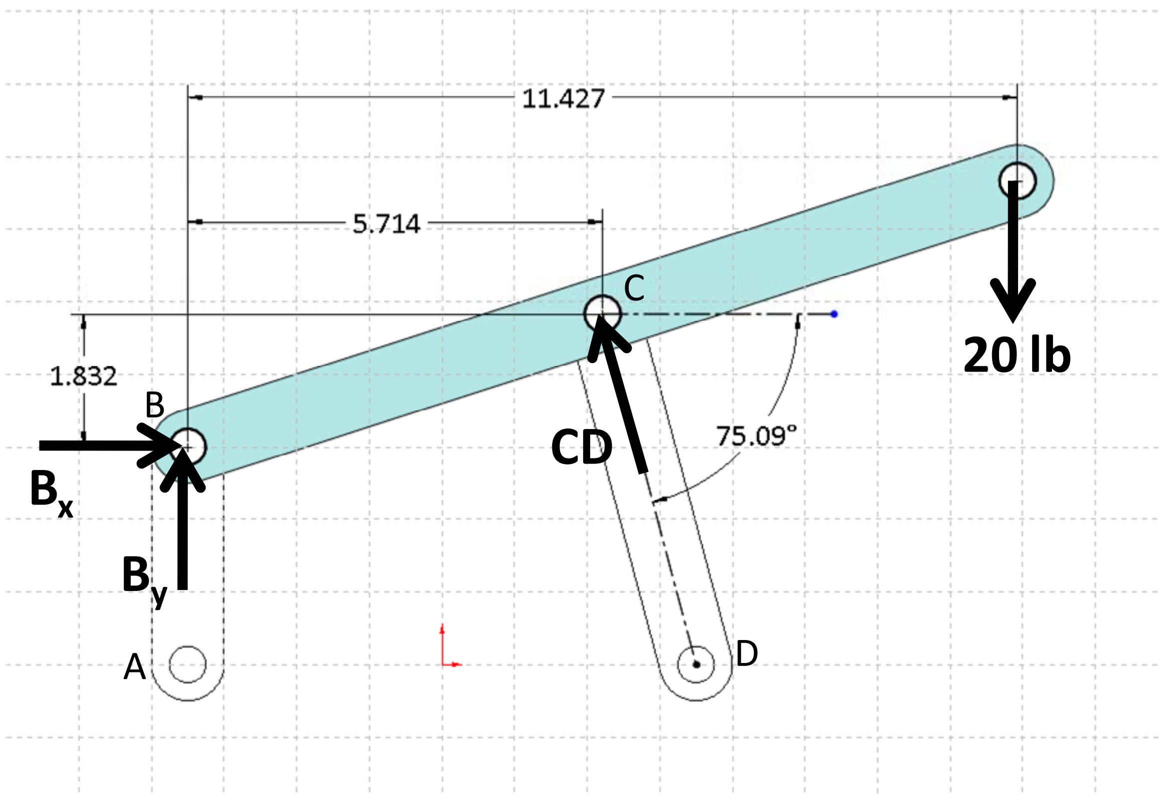
In the attachment, it is shown that the coefficient of friction require to prevent slipping is about 0.21.

It is interesting to note that the friction coefficient to prevent slipping and the time required to reach the bottom of the ramp are both functions of the ratio of the moment of inertia to the mass of the roller. You can confirm this by changing the material of the roller and seeing that the results of the simulation are unchanged. However, if you change the geometry of the roller (the easiest way is by suppressing the cut-out regions), then the results will change.

ATTACHMENT: VERIFICATION CALCULATIONS

STATIC ANALYSIS OF FOUR-BAR LINKAGE SUBJECTED TO 20-LB APPLIED FORCE

Free-body diagram of Connector:




Note that member CD is a 2-force member, and so the force at the end is aligned along the member's axis.

Apply equilibrium equations:

$$\Sigma \mathrm{M_B} = (5.714\ \mathrm{in})\big(CD\ \sin(75.09°)\big) + (1.832\ \mathrm{in})\big(CD\ \cos(75.09°)\big) - (11.427\ \mathrm{in})(20\ \mathrm{lb}) = 0$$

$$(5.522\ \mathrm{in})CD + (0.4714\ \mathrm{in})CD = 228.5\ \mathrm{in \cdot lb}$$

$$(5.993\ \mathrm{in})CD = 228.5\ \mathrm{in \cdot lb}$$

$$CD = \frac{228.5\ \mathrm{in \cdot lb}}{5.993\ \mathrm{in}} = 38.13\ \mathrm{lb}$$

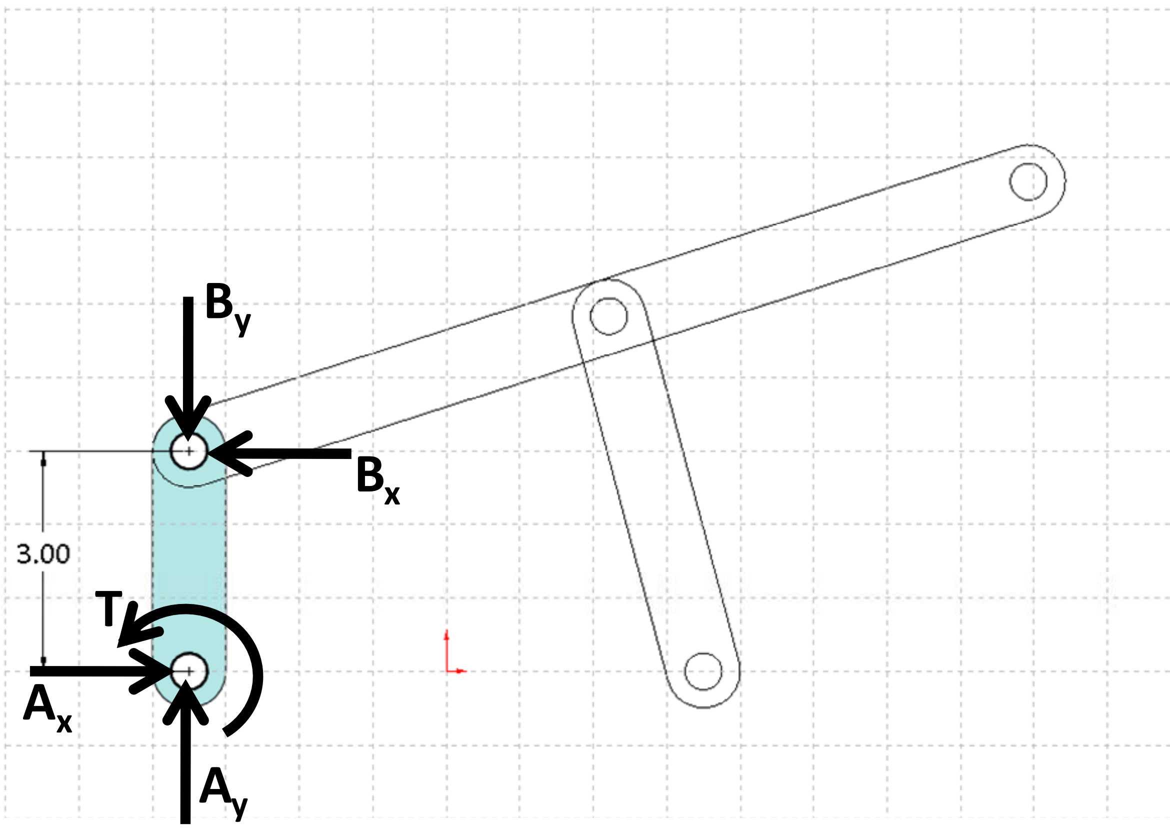
$$\Sigma \mathrm{F_x} = B_x - (38.13\ \mathrm{lb})\cos(75.09°) = 0$$

$$B_x = 9.812\ \mathrm{lb}$$

$$\Sigma F_y = B_y - (38.13 \text{ lb})\sin(75.09°) - 20 \text{ lb} = 0$$

$$B_y = -16.85 \text{ lb}$$

Free body diagram of Crank:




Note that $B_x$ and $B_y$ are shown in opposite directions as in Connector FBD.

Sum moments about A:

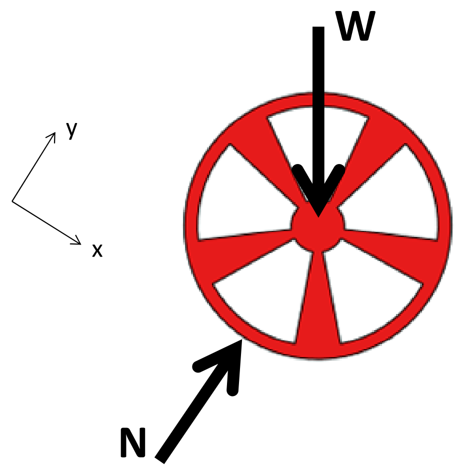
$$\Sigma M_A = T + (3 \text{ in})B_x = 0$$

$$T = -(3 \text{ in})(9.812 \text{ lb}) = \boxed{-29.4 \text{ in} \cdot \text{lb}}$$

ROLLER CALCULATIONS

No Friction:

Free-body diagram:




$$\Sigma F_x = W \sin\beta = m a_x$$

$$\Sigma F_y = N - W\cos\beta = 0$$

Where β is the ramp angle (30 degrees)

Since the weight is equal the mass m times the gravitational acceleration g, the acceleration in the x-direction $a_x$ will be:

$$a_x = g\sin\beta$$

The acceleration is integrated with respect to time to find the velocity in the x-direction:

$$v_x = \int g\sin\beta \; dt = g\sin\beta\, t + v_{xo}$$

Where $v_{xo}$ is the initial velocity in the x-direction. The velocity is integrated to find the distance travelled in the x-direction:

$$x = \int (g\sin\beta\, t + v_{xo})\, dt = \frac{g}{2}\sin\beta\, t^2 + v_{xo}t + x_0$$

Where $x_0$ is the initial position. If we measure x from the starting position, then $x_0$ is zero. If the block is initially at rest, then $v_{xo}$ is also zero. In our simulation, the block will slide a distance of 12 inches before contacting the bottom of the ramp (see the figure on page 23).

Knowing the distance travelled in the x-direction, and entering the numerical values of g as 386.1 in/s$^2$ and of $\sin\beta$ of 0.5 (sin of 30$^o$), we can find the time it takes the block to slide to the bottom:

$$12\text{ in} = \frac{386.1\text{ in/s}^2}{2}(0.5)t^2$$

or

$$t = \boxed{0.353\text{ s}}$$

Substituting this value into Equation 4, we find the velocity at the bottom of the ramp:

$$v_x = 386.1\frac{\text{in}}{\text{s}^2}(0.5)(0.353\text{ s}) = \boxed{68.1\ \frac{\text{in}}{\text{s}}}$$

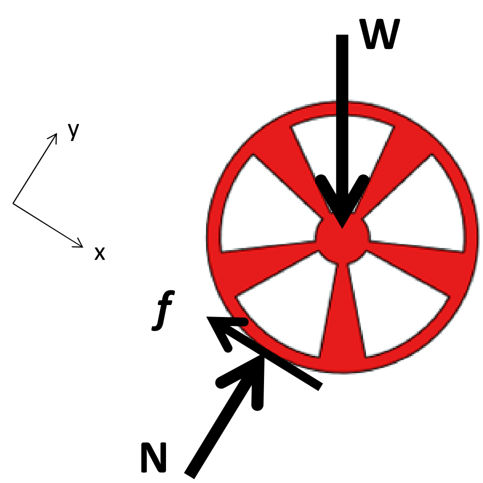
This velocity can also be found by equating the potential energy when the roller is at the top of the ramp (height above the datum equals 6 inches) to the kinetic energy when the roller is at the bottom of the ramp:

$$mgh = \frac{1}{2}mv_x{}^2$$

$$v_x = \sqrt{2gh} = \sqrt{2(386.1\frac{\text{in}}{\text{s}^2})(6\text{ in})} = \quad 68.1\ \frac{\text{in}}{\text{s}} \quad \checkmark$$

Friction Included:

Free-Body Diagram:



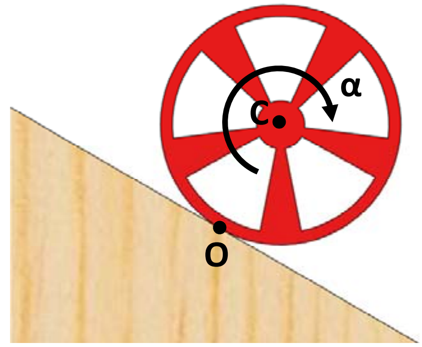

While the roller without friction slides and can be treated as a particle, the roller with friction experiences rigid-body rotation. The equations of equilibrium are:

$$\Sigma F_x = W\sin\beta - f = ma_x$$

$$\Sigma F_y = N - W\cos\beta = 0$$

$$\Sigma M_c = f\,r = I_o\alpha$$

If there is no slipping, then the relative velocity of the roller relative to the ramp is zero at the point where the two bodies are in contact (point O). Since the ramp is stationary, this leads to the observation that the velocity of point O is also zero.




Since point O is the center of rotation of the roller, the tangential acceleration of the center of the roller $(a_x)$ can be written as:

$$a_x = r\alpha$$

Substituting this expression into the first equilibrium equation and solving for the friction force,

$$f = W \sin\beta - mr\alpha$$

Substituting this expression into the third equilibrium equation and solving for the angular acceleration $\alpha$,

$$(W \sin\beta - mr\alpha)\, r = I_o\alpha$$

$$W(\sin\beta)r = I_o\alpha + mr^2\alpha$$

$$\alpha = \frac{W(\sin\beta)r}{I_o + mr^2}$$

The mass and the moment of intertia $I_o$ can be obtained from SolidWorks. For the roller, the values are:

$$m = 0.017163 \text{ lb}$$

$$I_o = 0.002515 \text{ lb} \cdot \text{in}^2$$

Since pounds are units of weight, not mass, they quantities above must be divided by g to obtain the quantities in consistent units:

$$m = \frac{0.017163 \text{ lb}}{386.1 \text{ in/s}^2} = 4.4453 \text{ X } 10^{-5}\ \frac{\text{lb} \cdot \text{s}^2}{\text{in}}$$

$$I_o = \frac{0.002515 \text{ lb} \cdot \text{in}^2}{386.1 \text{ in/s}^2} = 6.5139 \text{ X } 10^{-6}\ \text{lb} \cdot \text{in} \cdot \text{s}^2$$

The value of the angular acceleration can now be found:

$$\alpha = \frac{W(\sin\beta)r}{I_o + mr^2} = \frac{0.017163 \text{ lb}\,(\sin 30^o)(0.5 \text{ in})}{6.5139e-6\ \text{lb} \cdot \text{in} \cdot \text{s}^2 + 4.4453e-5\ \frac{\text{lb} \cdot \text{s}^2}{\text{in}}(0.5 \text{ in})^2} = 243.4\ \frac{\text{rad}}{\text{s}^2}$$

Therefore, the linear acceleration in the x-direction is:

$$a_x = r\alpha = (0.5 \text{ in})\left(243.4 \ \frac{\text{rad}}{\text{s}^2}\right) = 121.7 \frac{\text{in}}{\text{s}^2}$$

Integrating to obtain the velocity and position at any time:

$$v_x = \int a_x \ dt = a_x t + v_{xo} = 121.7 \frac{\text{in}}{\text{s}^2} \ t$$

$$x = \int (a_x t + v_{xo}) \ dt = \frac{1}{2} a_x t^2 + v_{xo} t + x_0 = 60.85 \ \frac{\text{in}}{\text{s}^2} \ t^2$$

For the roller to travel 12 inches in the $x$-direction, the time required is

$$t = \sqrt{\frac{12 \text{ in}}{60.85 \ \text{in/s}^2}} = 0.444 \text{ s}$$

And the velocity at the bottom of the ramp is:

$$v_x = 121.7 \frac{\text{in}}{\text{s}^2} \ (0.444 \text{ s}) = \boxed{54.0 \ \frac{\text{in}}{\text{s}}}$$

We can also calculate the friction force:

$$f = \text{W} \sin \beta - \text{m}r\alpha = 0.017163 \text{ lb}(\sin 30°) - \left(4.4453 \text{ e} - 5 \ \frac{\text{lb} \cdot \text{s}^2}{\text{in}}\right)(0.5 \ in)\left(243.4 \ \frac{\text{rad}}{\text{s}^2}\right)$$
$$= 0.00318 \text{ lb}$$

From the second equilibrium equation, the normal force is:

$$\text{N} = \text{W} \cos \beta = 0.017163 \text{ lb}(\cos 30°) = 0.1486 \text{ lb}$$

Since the maximum friction force is the coefficient of friction $\mu$ times the normal force, the coefficient of friction must be at least:

$$\mu_{\min} = \frac{0.00318 \text{ lb}}{0.1486 \text{ lb}} = \boxed{0.21}$$

This is the minimum coefficient of friction required for the roller to roll without slipping.