The *WORCESTER POLYTECHNIC INSTITUTE*

Grasshopper Engine Model

SUBMITTED BY

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Course Instructor: Professor Stults

Course Number: ES3323

Group 5

Introduction

The following report contains a detailed description and analysis of a model grasshopper engine constructed and assembled utilizing Creo Parametric. The steam engine consists of numerous parts, subassemblies, and sublinkages that have been constructed over the course of several weeks. Each component was created and assembled with specific design specifications intended to accurately model a small scale, fully functioning engine. Kinematic knowledge was applied to each part of the model to ensure correct joints were implemented in order to achieve the proper motion requirements. Upon the completion of the engine, various tests were conducted to measure several kinematic values, interferences, and other relevant data.

Table of Contents

Submission Folder

Location of folder: `\ES3323\A20\submissions\Group5\Final Submission`

Important documents:

- 1_engine_animation.mpg
- 1_master_no_screws_analysis.asm
    - Contains all Kinematic analysis
    - Excess interference removed
- 1_master_screws_no_analysis.asm
    - No analysis
    - All fasteners added
- 1_sublinkage1_colorful.asm
- 1_sublinkage2_colorful.asm

Modeling Strategies

Steam Chest - Angelos

The part to be modeled is shown in Figure 1 to the right. The model is made up of 10 features as shown in the model tree in Figure 2 to the left.

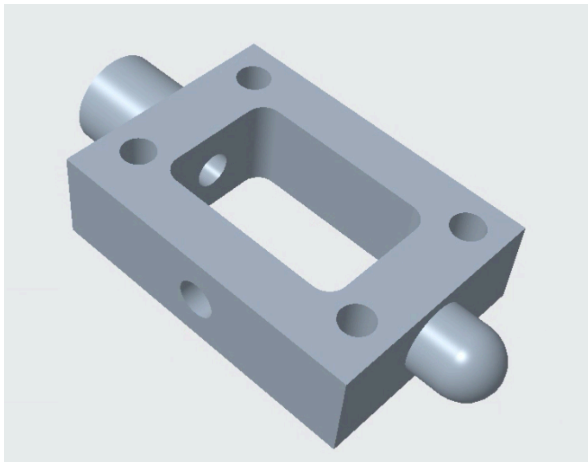


Figure 1. Steam Chest

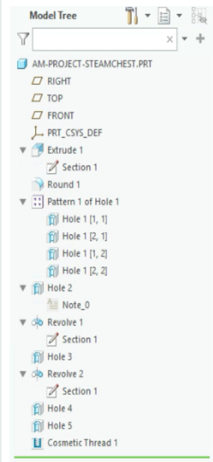


Figure 2. Model Tree

Feature 1: Solid Rectangular Extrusion

Beginning the construction of the first feature on the right plane two rectangles were made to resemble the middle rectangular extrusion of the steam chest. The rectangles were placed in such a way so that the center of them remains the origin. The front face of the part needs to be symmetrical on the right plane thus we chose accordingly when extruding our rectangular sketches. Part of the reasoning in choosing the front plane is to ensure easy alignment when introduced into the large main assembly as the front plane of the engine assembly will be parallel to that of this sub assembly.

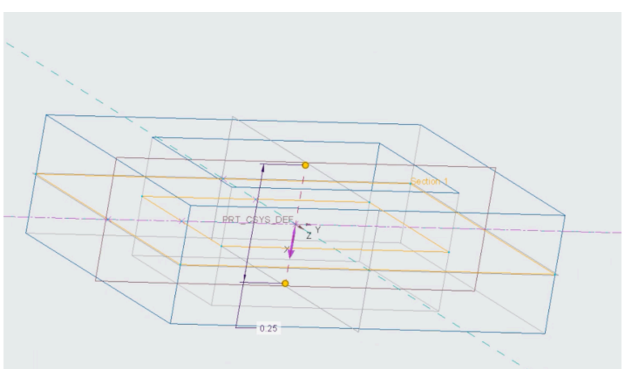


Figure 3. Midplane extrusion feature 1

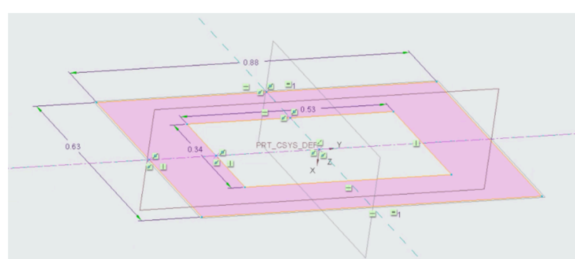


Figure 4. Sketch of rectangular extrusion

Feature 2: Rounds

Rounds were created on every inner edge of the rectangular solid. The purpose of this was to imitate the way the CNC tool will cut the center hole, since it can't create perfect 90 degree angle cuts.

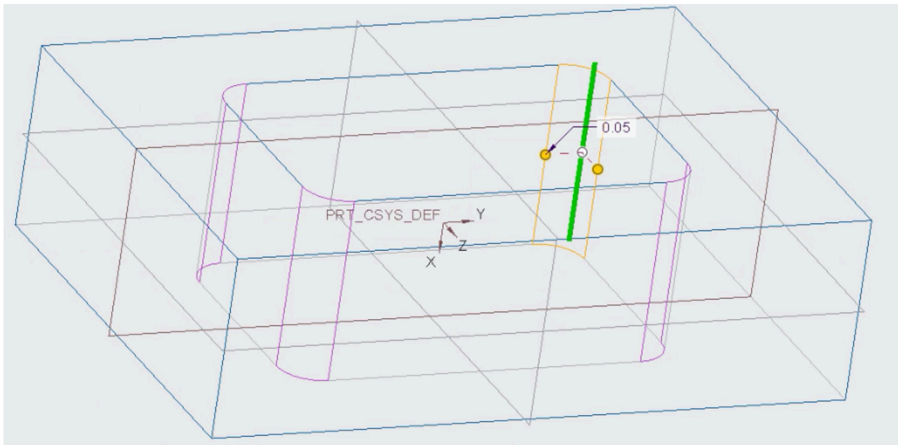


Figure 5. Rounds

Feature 3: Patterned Hole on Solid Extrusion

The third feature is the hole which was created on the rectangular extrusion which was then patterned in all four sides of feature 1, equidistant from the origin, using the given dimensions. Each hole was drilled all the way through so that in case the width of the part changes the hole will still remain a thru hole.

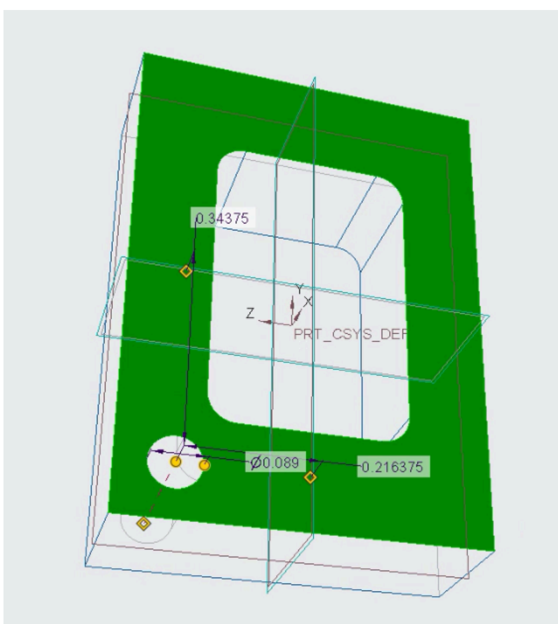


Figure 6. Hole on Feature 1

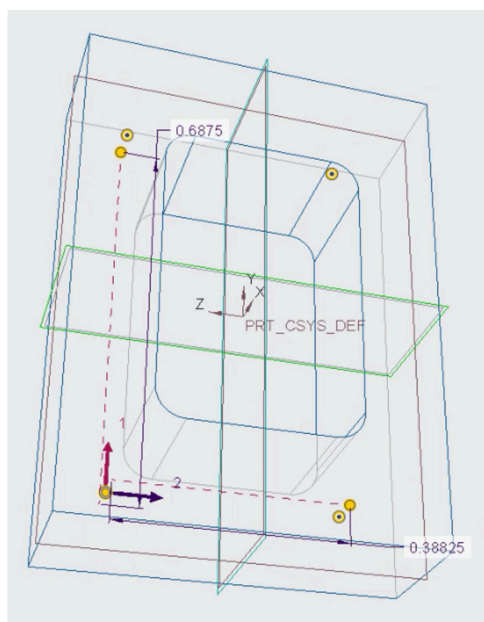


Figure 7. Pattern of Hole

Feature 4: Hole on Back View Solid Extrusion

The fourth feature is the hole that was made on the back view of feature 1. This hole was placed directly at the intersection of the right and top datum planes. The hole was intended for a 5-40 UNC type screw and drilled all the way to the other side, in order to account for any changes in the width of the rectangular prism.

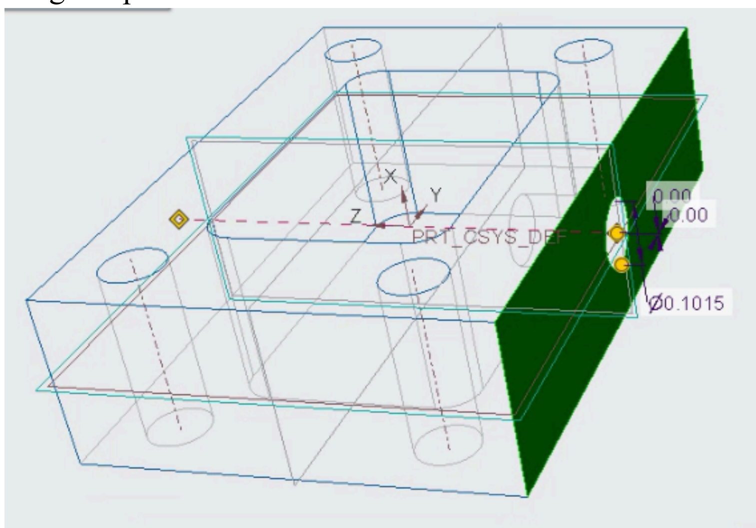


Figure 8. Hole on the back view of feature 1

Feature 5: Circular revolve 1 on right datum plane

The fifth feature for this part included making a revolve at the end of feature 1 and revolving it around the axis created on the right plane as shown in figure 10. The sketch was created on the right plane so that it can always stay in the middle between the two ends of the main solid extrusion. The sketch was made coincident to the solid extrusion to make sure there are no gaps and it all becomes one solid feature.

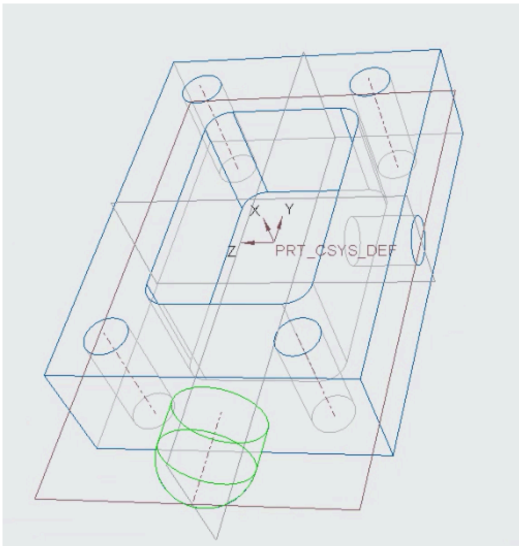


Figure 9. Revolve 1 on Right plane

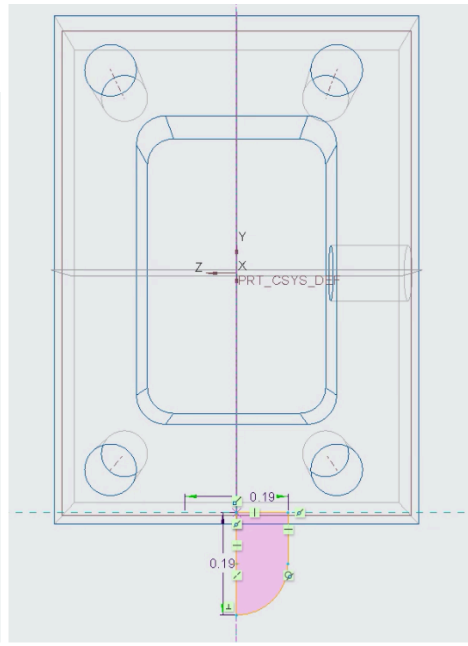


Figure 10. Sketch of revolve

Feature 6: Hole through revolve on right plane

The sixth feature includes the hole that was made intended to go through the solid extrusion and through the center of revolve 1 but not going completely through it as shown in figure 12. The hole was placed in such a way so that it aligns with the center axis of the revolve.

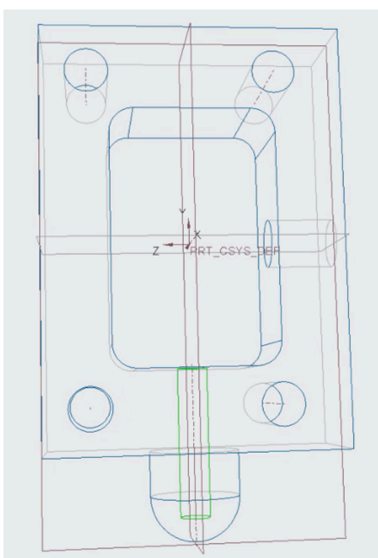


Figure 11. Hole through revolve 1

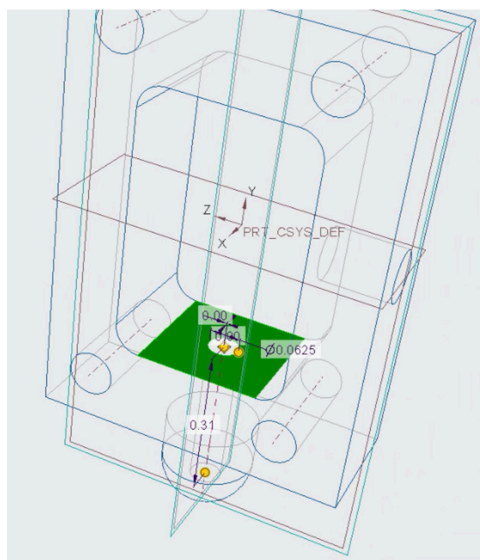


Figure 12. Additional Hole features

Feature 7:

The seventh feature is very similar to feature 5. This is another revolve created on the same plane as the other revolve to maintain symmetry throughout the part.

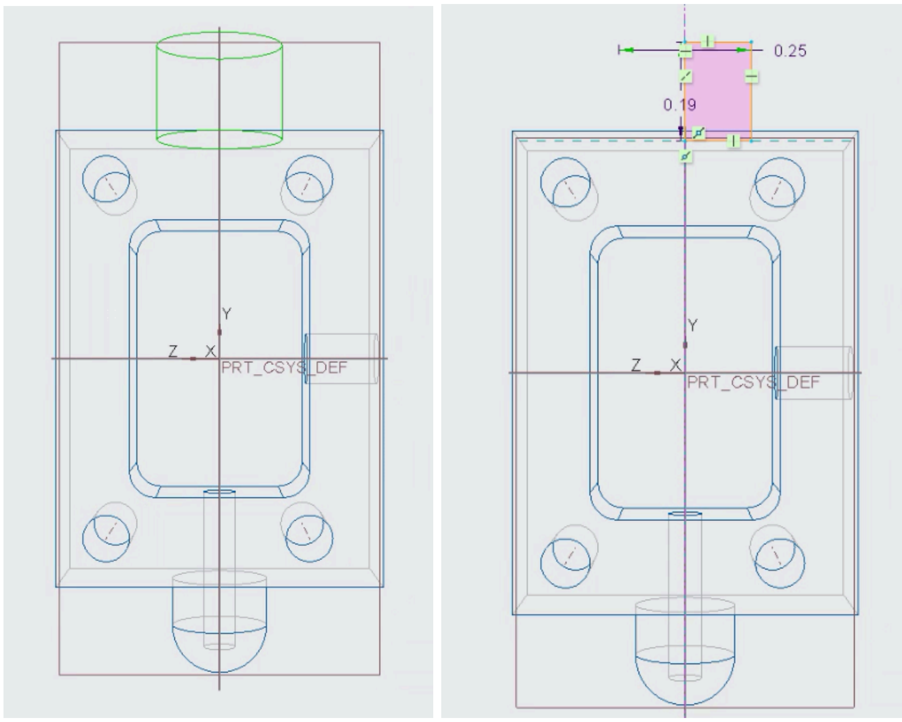


Figure 13. Revolve 2 on right plane

Features 8-10: Variety of holes on revolve 2

Features 8-10 include a series of holes that were all created on the same location with different sizes and depth. Every hole begins at the outer surface of revolve 2 and cut directly on the axis that is the intersection of the front and right plane.

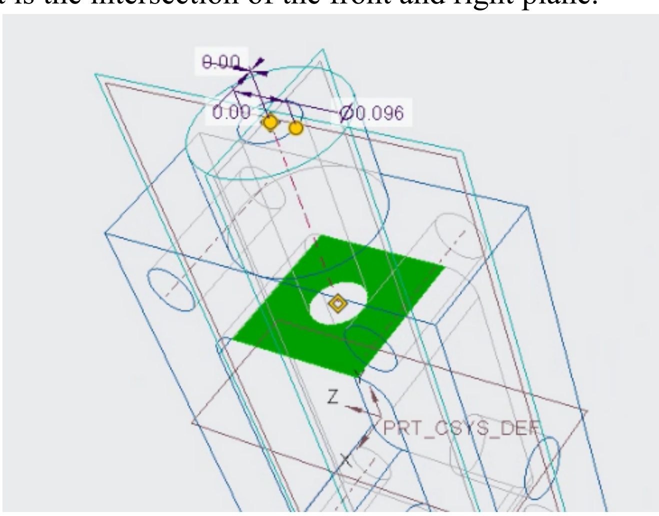


Figure 14. Feature 8 hole

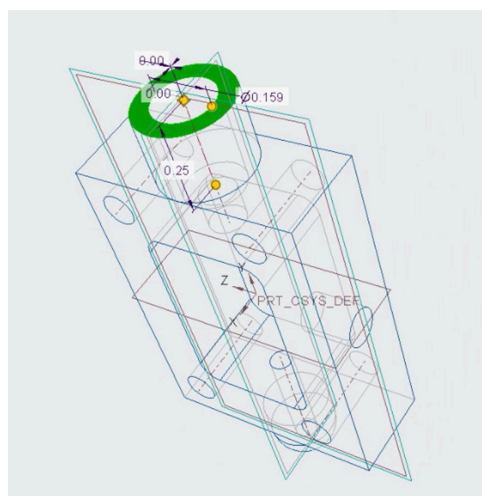


Figure 15. Feature 9 hole

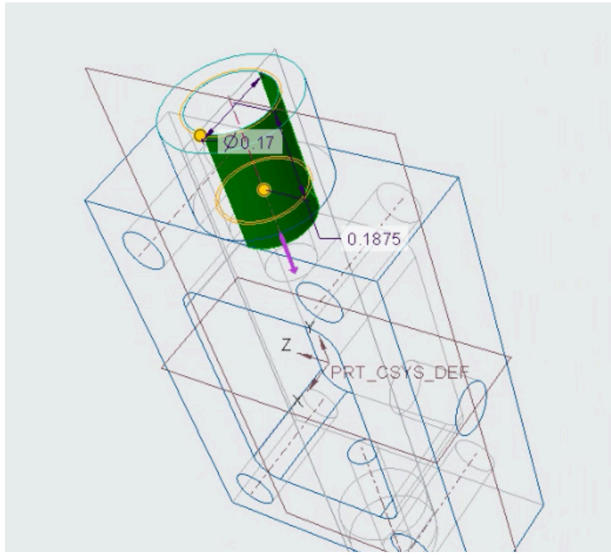


Figure 16. Feature 10 cosmetic threads

Upper Head - Bailey

The part being modeled below in Figure 18 is the upper head or outboard head. The part was created with a singular revolve feature and a series of holes and patterns that can be viewed in the model tree in Figure 19.

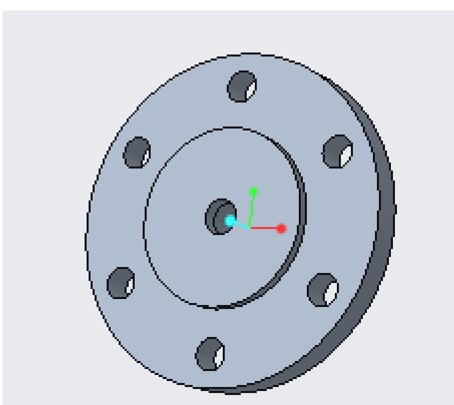


Figure 17. Complete Part

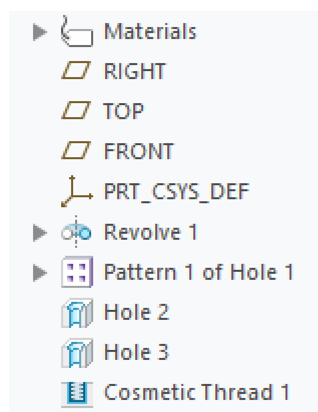


Figure 18. Model Tree

Feature 1. Revolve

The initial feature is a revolve sketched on the right plane. The right plane was chosen as the sketch plane to ensure that when the feature is revolved the front view is the most descriptive view. An image of the initial sketch can be found in Figure 20. Diameter dimensions were used due to the complete circular/cylindrical nature of the part and the dimensions provided in the drawing. Once complete the sketch should be revolved around the X axis.

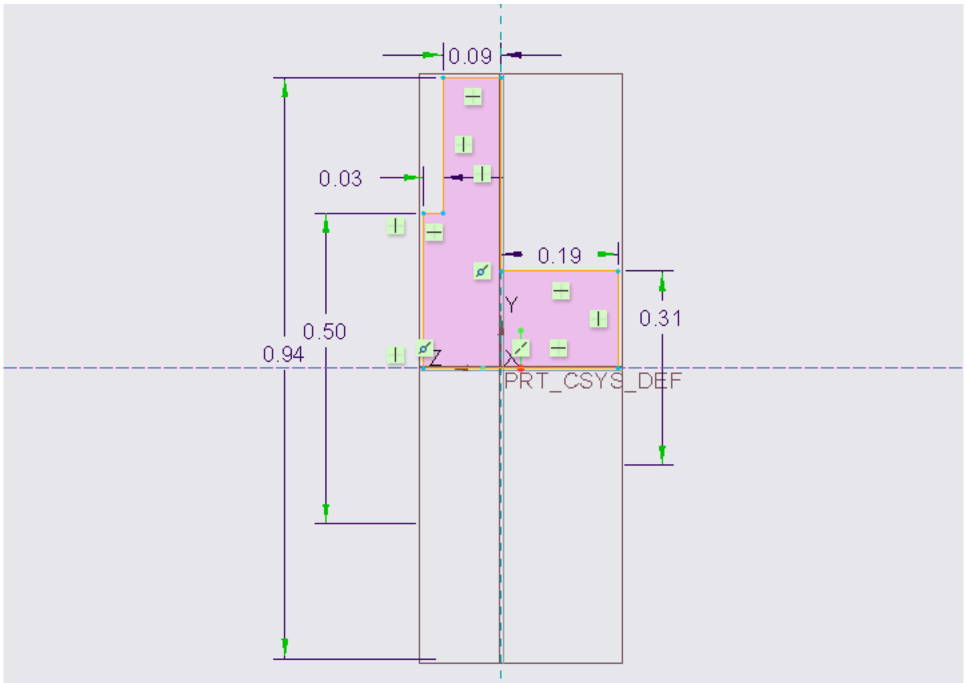


Figure 19. Revolve Sketch

Feature 2. Patterned Hole

The second feature is a hole placed on the front face of the part and patterned around the central axis. The placement of the initial hole was done using a diameter dimension about the central axis and an alignment with the right plane. This placement allows the hole to be centered directly above the central axis and distanced correctly from the part's center. Following the creation of the first hole, an axial pattern was used to form 6 equidistant holes circling the central protrusion. Both the initial hole placement and the pattern description can be seen below in Figures 21 and 22.

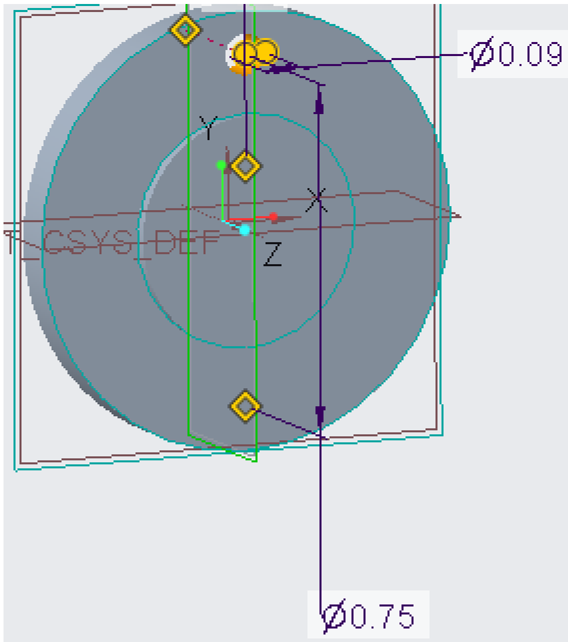


Figure 20. Initial Hole Placement

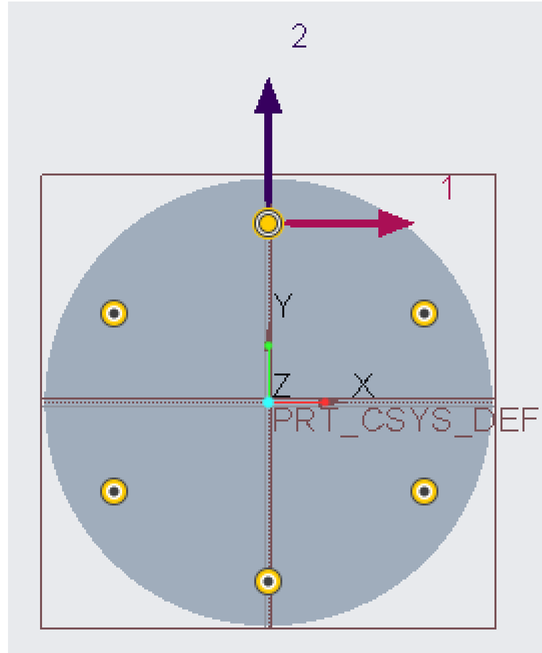


Figure 21. Pattern Description

Feature 3. Central Through Hole

The third feature is a hole through the center of the part aligned with the central or z axis. The back plane was chosen for placement as it would most closely resemble the actual machining process. Figure 23 shows the detailed image of hole placement.

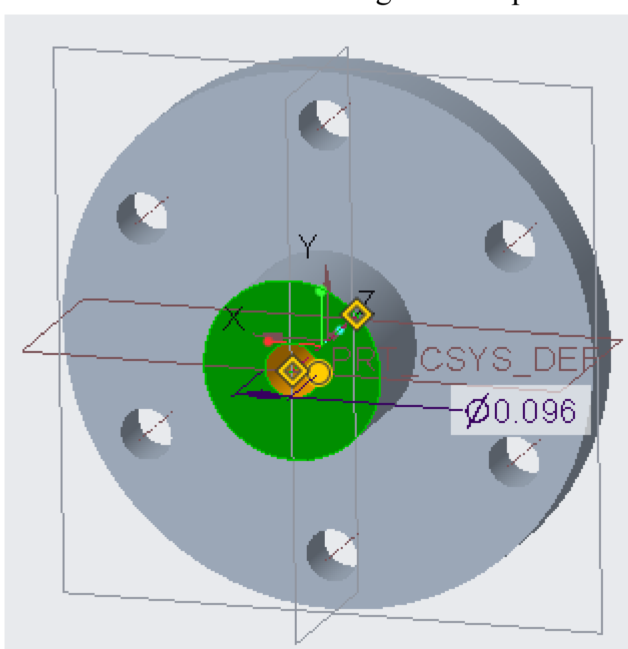


Figure 22. Through hole placement

Feature 4. Partial Central Hole

Again from the back plane we created a hole slightly larger in diameter than Feature 3. This hole, unlike Feature 3, does not go through the entire part but is only cut to a depth of 0.25in from the back plane. For this reason the back face was used for placement and the z axis was used for alignment. By choosing the backface allows for easy placement and dimensioning of the threads in the following feature. Figure 24 shows the placement of this final hole.

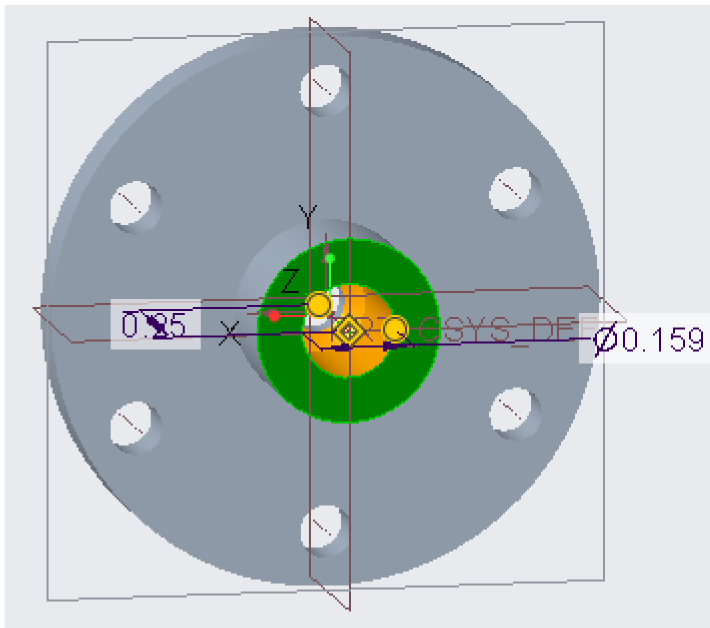


Figure 23. Threaded hole placement

Feature 5. Threads

The final step was to add threads to the inside of Feature 4. The threads were added to a depth of 0.1in as specified in the part drawing. A value of 32 threads per inch was specified in part drawing. Figure 25 shows the placement and property information of the thread feature.

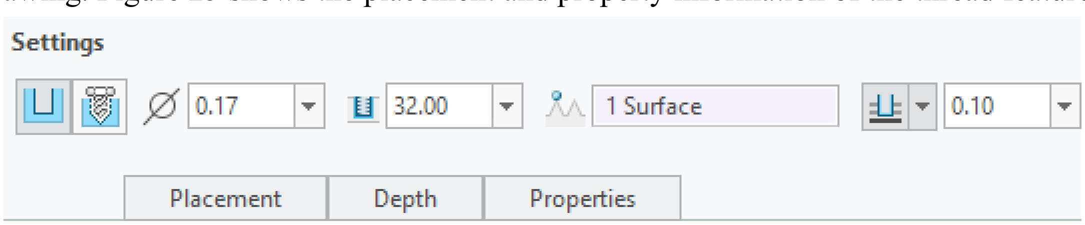
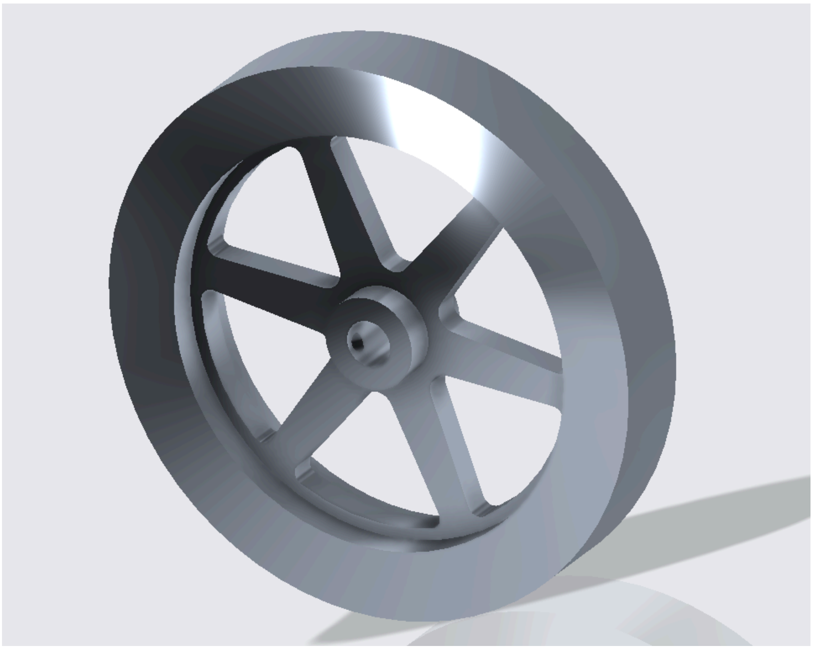


Figure 24. Cosmetic thread placement information

Flywheel - Kohmei

The flywheel is made from a revolve, a patterned triangular cutout, a center axle hole and set-screw hole.



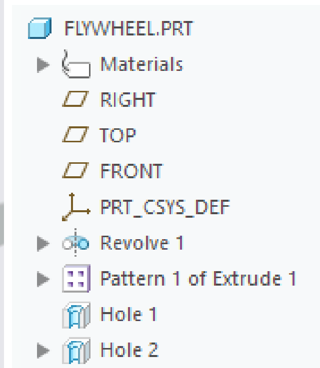


Figure 25. Completed Flywheel

Figure 26. Completed Model Tree

Part 1. Revolved wheel profile

The first revolve profile is sketched on the right place so that the front view of the wheel can show almost all of the features of the flywheel. The origin was chosen to be in the center of the center axle hole so that the revolve can be performed on the axis created from the intersection between the top and right plane. This also helps later when constraining the center axis hole. The origin is also at the midplane between the front and back surface of the flywheel to reflect the symmetry across the front plane.

The revolve is 360 degrees, which allows us to make the full circular shape of the flywheel. Note that the center hole is not created as part of this sketch so that a hole feature can be added there instead of a revolve making a in the part. This was done to more accurately reflect the design intent.

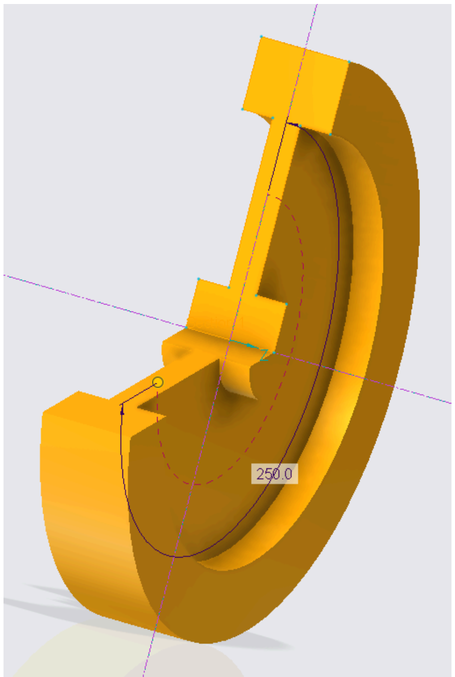


Figure 27. Partially Complete Revolve

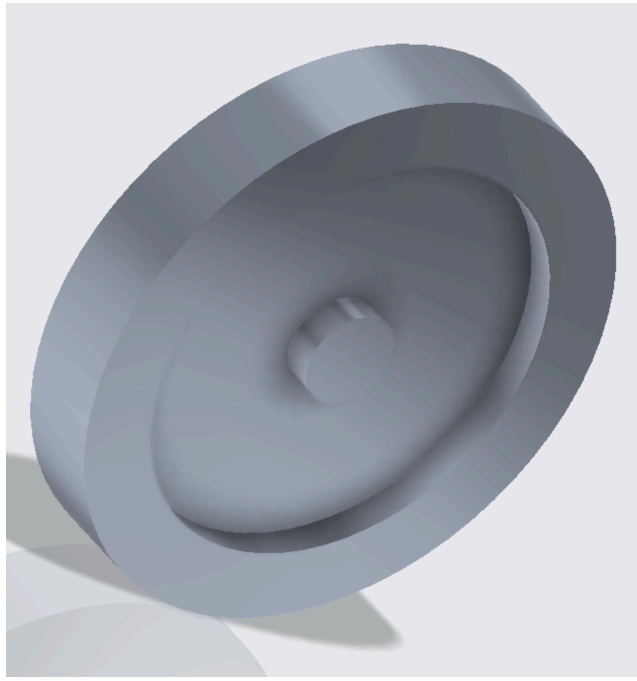


Figure 28. Complete Resolve feature

Part 2. Triangular Cutouts

Drawing on the inset surface of the front of the flywheel, we sketch a single triangular cutout, which is then used to perform a remove material extrusion up to the next surface. The sketch is drawn on the surface of the revolve and not the front plane since this allows us to avoid inputting one parameter by using up-to-next. Up-to-next is used over through all to reflect the design intent while reducing the parameters that need to be imputed.

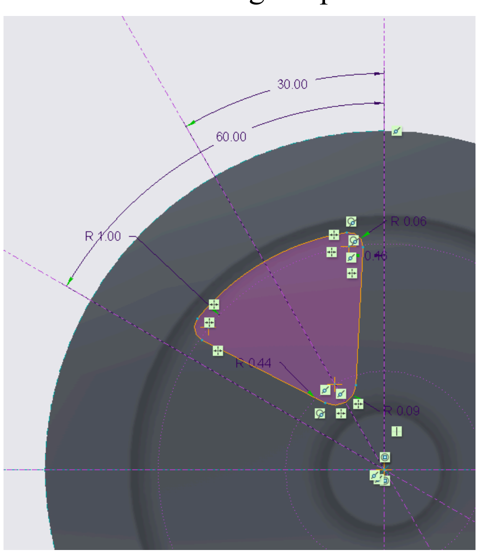


Figure 29. Sketch for triangular cutout

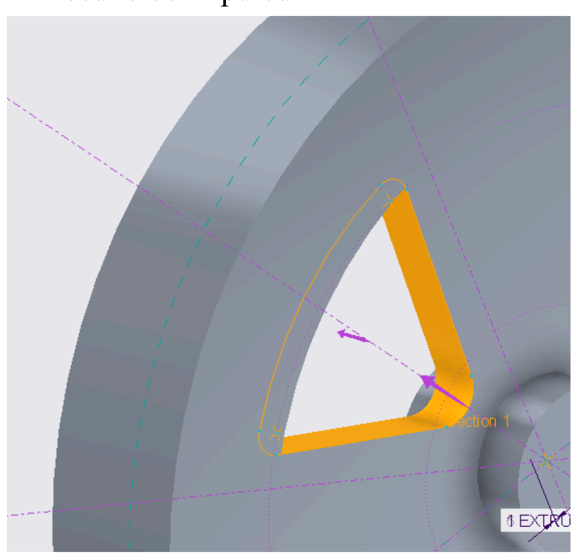


Figure 30. One completed cutout

This cutout is then patterned 6 times over the 360 degree axis that goes into the page.

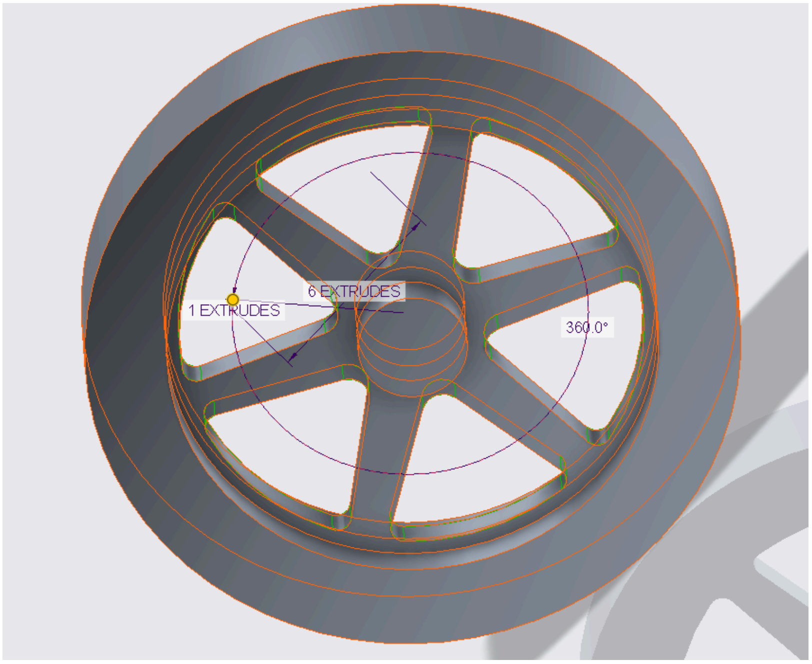


Figure 31. Cutout patterned 6 times over the flywheel

Part 3. Central Hole

Using the aforementioned axis that is defined by the intersection between the top and right plane that goes in and out of the page, we will create a hole feature. The up-to-next-surface termination is used again to reflect design intent while keeping parameters numbers low.

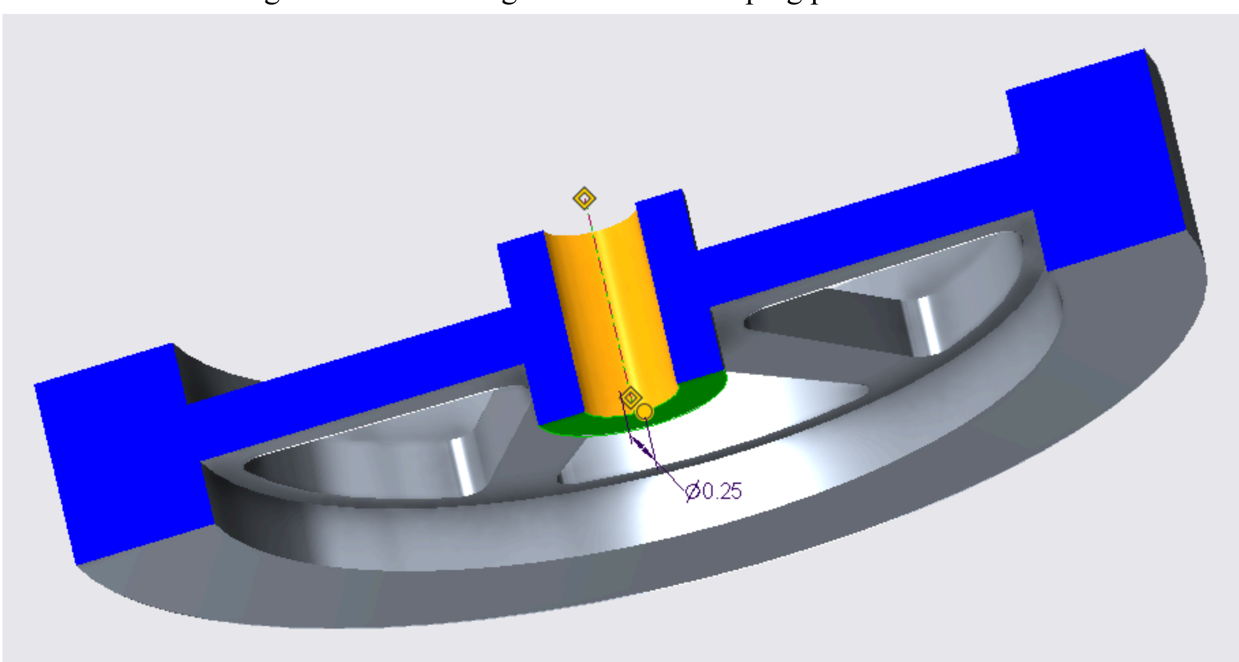


Figure 32. Top section view of central main axis hole

Part 4. Set Screw Hole

Since the set screw does not have exact dimensions the function of the hole was used to extrapolate information about the part. Although when producing this piece, the set screw would be at an angle in the right section view, we decided to reflect the simplest possible design in our model and allow the manufacturer to decide on how to modify this to fit their tools. First a midplane and line was created to define the location of the hole.

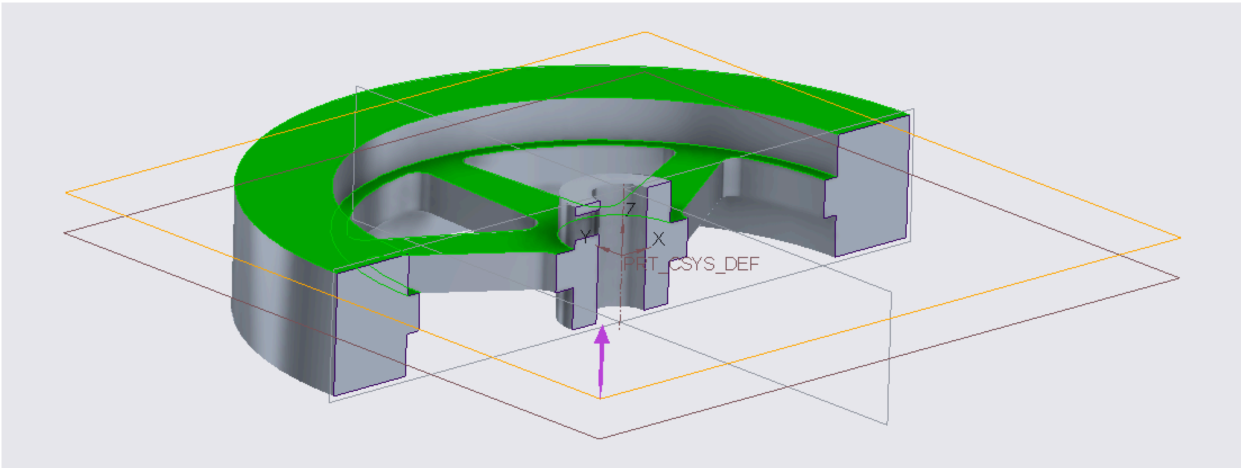


Figure 33. Midplane (orange) and reference planes (green)

The midplane was created between the front of the flywheel and the inset surface of the wheel. The line was created between this plan and the right plane.

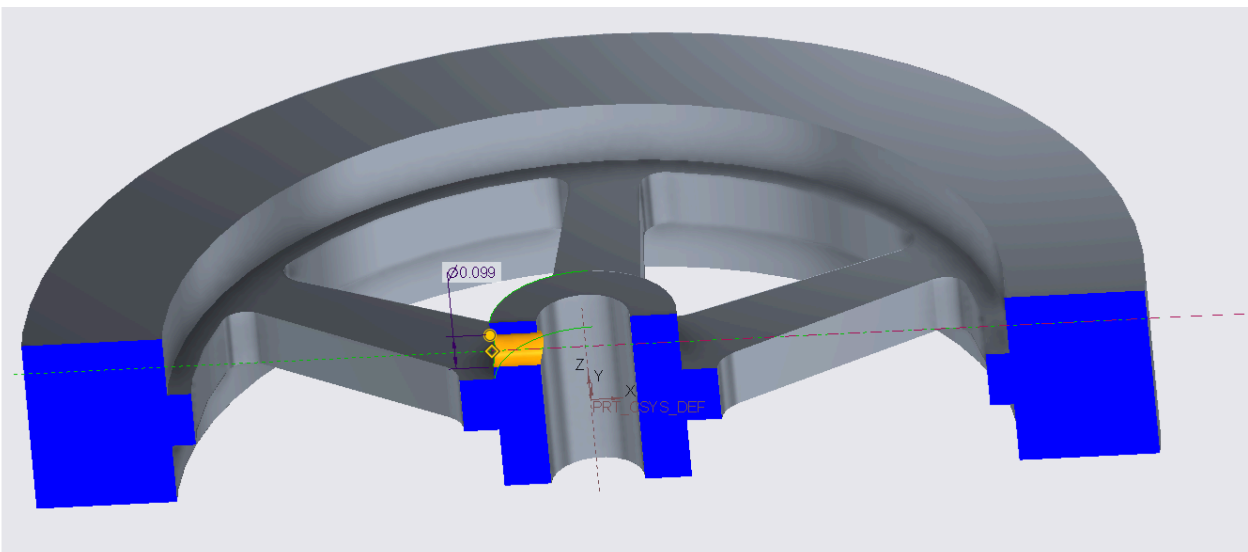


Figure 34. Top section view of completed set screw hole

Then the hole was created, using the line as a reference and up-to-next was used again for the reasons described above.

Expanded Model Tree

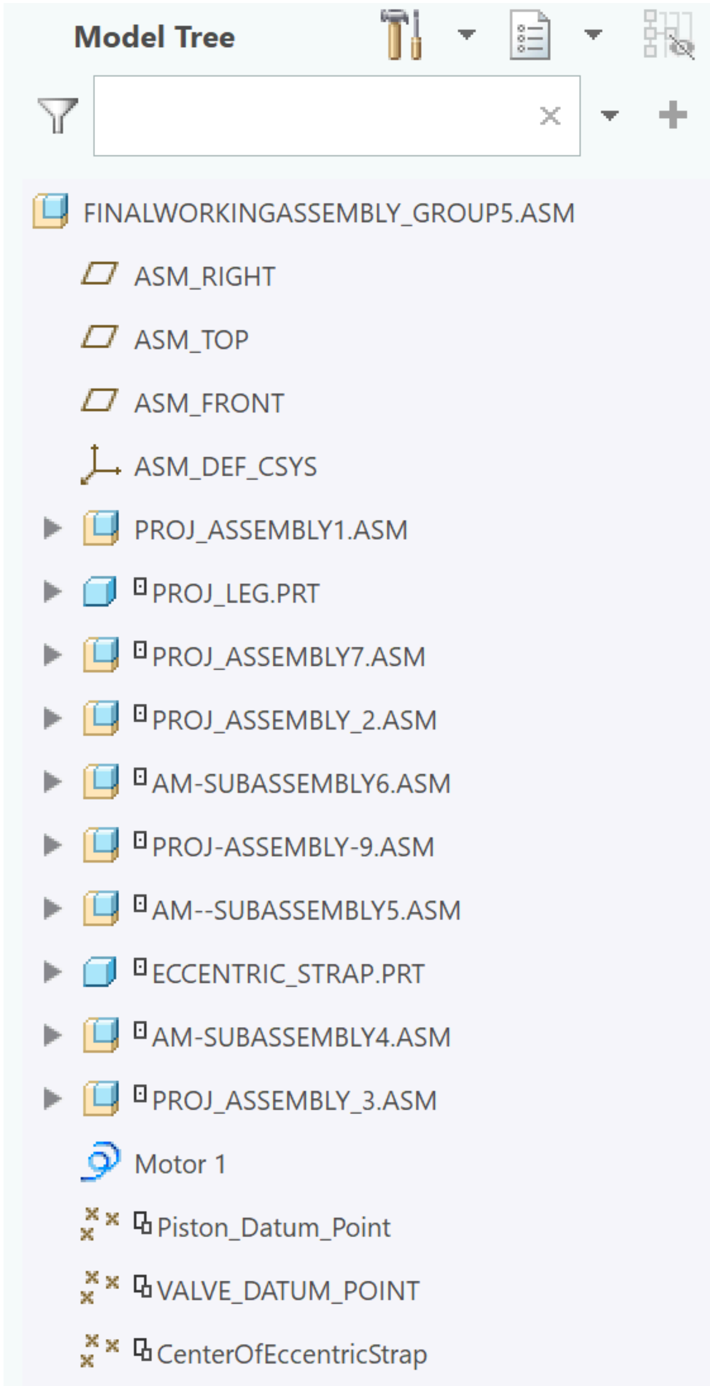


Figure 35. The model tree above displays each of the ten subassemblies/links that make up the complete engine. Additionally we have our motor and three datum points necessary for completion of analyses.

Assembly Constraint Strategy - Project Sub Assembly 3: Valve

Part 1, Valve

The valve was inserted first to the subassembly and was rigidly constrained to ground via various constraints. The three planes of the part were made coincident with the three planes of the subassembly. However, we chose to make the right plane of the subassembly coincident to the front plane of the part and vice versa in order to orient the subassembly in the direction it would face in the final assembly. With the mating of the top planes we were able to establish the vertically sentral plane of the valve as the top plane of the assembly which would prove helpful when orienting the valve to its surroundings within the final assembly.

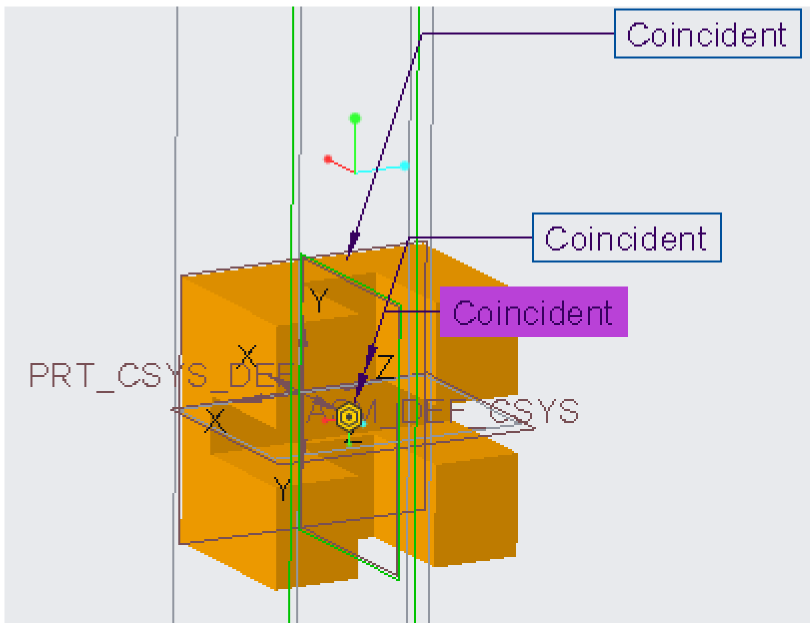


Figure 36. The figure above shows the alignment of the valve datum planes with each of the three assembly planes. Highlighted in green are the right plane of the value and the front plane of the assembly.

Part 2, Nut

The nut was constrained to the valve rigidly by making the top, back, and side faces of the nut coincident with the corresponding inner faces of the valve. This secured all degrees of rotation and translation for the nut while ensuring the nut's central hole remained centralized within the valve. The location of this hole is crucial to ensure the valve rod is aligned both within this subassembly as well as the final assembly.

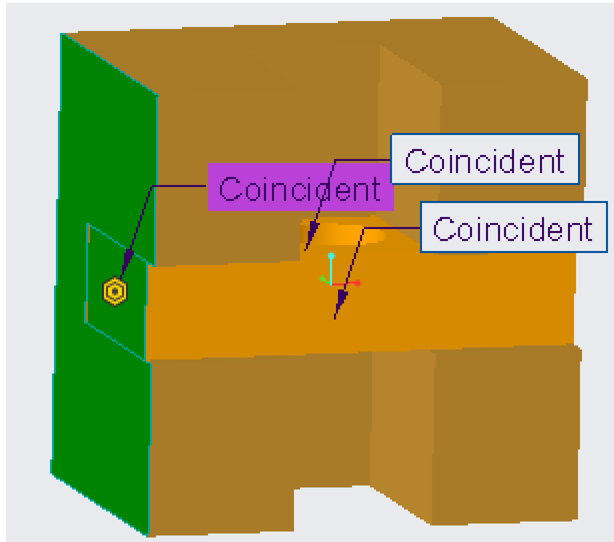


Figure 37. The display above labels each of the three coinciding faces. Highlighted in green are the coinciding side faces that prevent the hole from being able to shift from one side or another within the valve slot.

Part 3, Valve Rod

The third and final part of the subassembly is to be rigidly constrained within the nut hole with the fork-like feature facing up. To ensure the upper portion of the valve rod is facing the correct direction and is not free to rotate within the hole the front plane of the valve rod was made coincident to the right plane of the nut. This ensures that when added to the final assembly the connection between the fork and the valve rod may run normal to the engine's front plane. Establishing the necessary height of this connection relative to the valve and nut is done via a distance measure. This measure was established between the top face of the nut and the bottom edge of the rod portion that exhibits a thicker diameter.

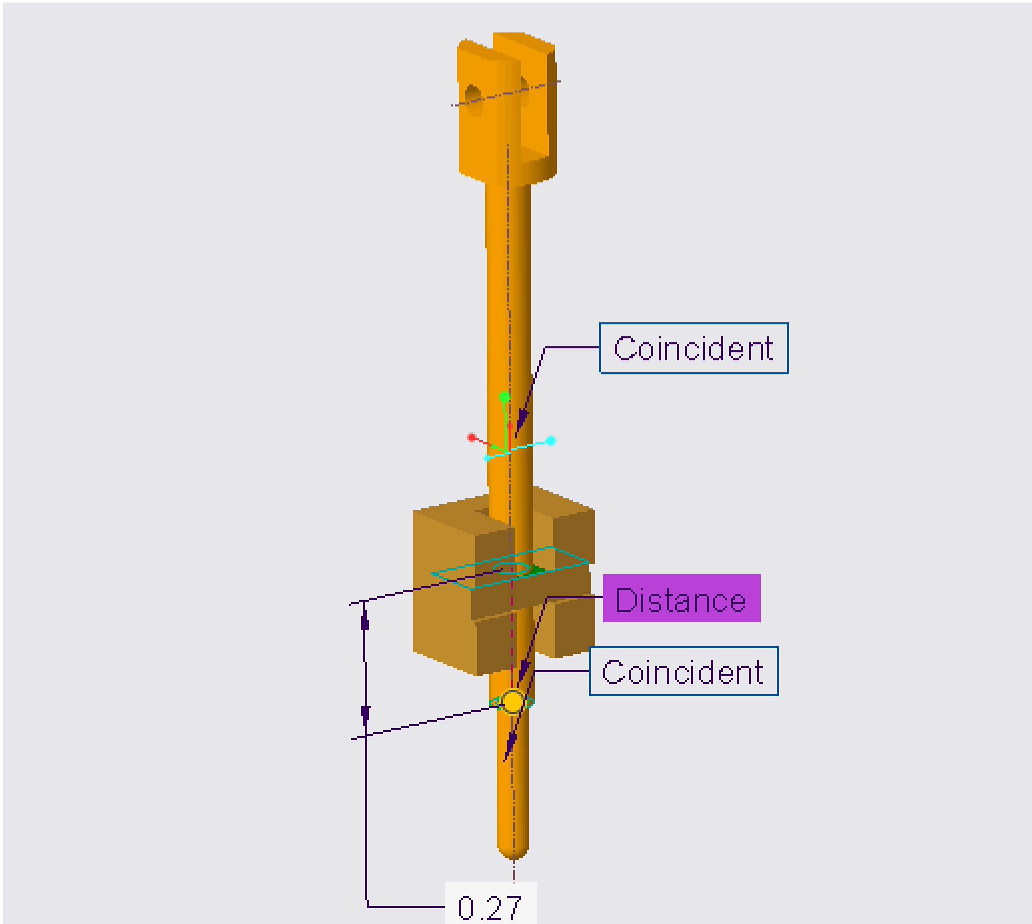


Figure 38. Above is the completed, rigid subassembly with correct orientation of the valve rod. The precise values of the final constraint, the distance measure, is shown.

Mechanism Modeling

Sub Linkage 1

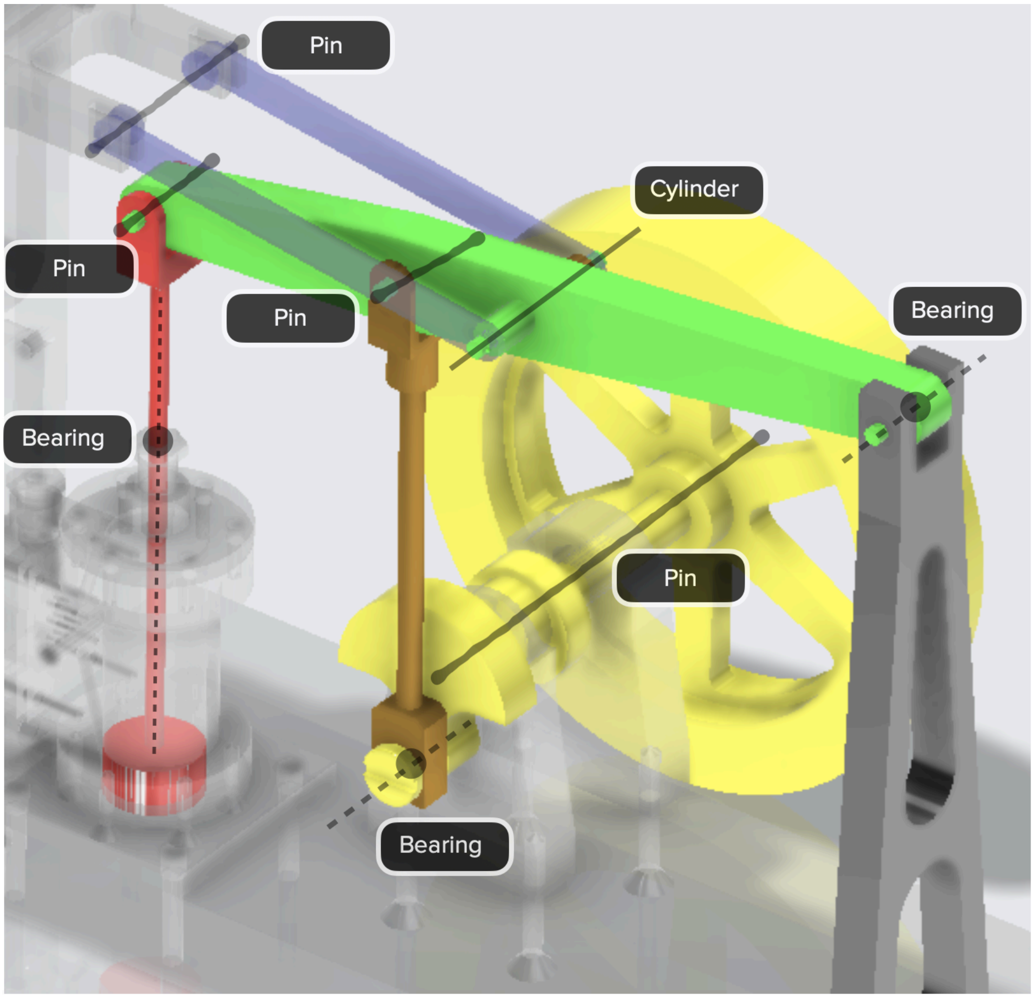


Figure 39. The figure above highlights each of the links within Sublinkage 1 and labels each of the eight connection points.

Sub Linkage 1 consists of a total of 7 links, 6 being smaller sub assemblies and one lone part. The system contains 8 total joints including pin, slider, cylinder, and bearing joints. The base sub assembly is secured to ground and lacks any degrees of freedom. The flywheel subassembly is connected to the base subassembly with a pin joint. The leg is also connected to the base sub assembly via a pin joint. At the top of the leg there is a bearing joint connecting the leg to the beam. Along the beam there are three other connection points with three other subassemblies. The connection between the beam and the links is a cylinder joint and the links are connected to ground on the opposite side with a pin joint. The next connection point between the connecting rod sub assembly and beam is a bearing joint. The bottom of the connecting rod subassembly is a pin joint connecting it to ground. The final component of the sub linkage is the rod/piston assembly which is connected to the beam via a pin joint and connected to ground via a bearing. This accounts for a total of 5 pin joints, 3 bearing joints, and a cylinder joint. Pin joints allow one rotational degree of freedom making them J1 joints. Cylinder joints allow for one axis of rotation and one of translation making them J2 joints. And lastly bearing joints are classified as J4 joints with 3 degrees of rotation and 1 translation. Applying these values to the Kutzbach equation we calculate the degrees of freedom for the system to be 1.

$$\begin{aligned} \textit{Degrees of Freedom} &= 6(L-1) - 5(J_1) - 4(J_2) - 3(J_3) - 2(J_4) - J_5 \\ &= 6(7-1) - 5(5) - 4(1) - 3(0) - 2(3) - 0 \\ &= 1\ DOF \end{aligned}$$

L= 7	J1= 5	J2= 1	J3= 0	J4= 3	J5= 0

Sub Linkage 2

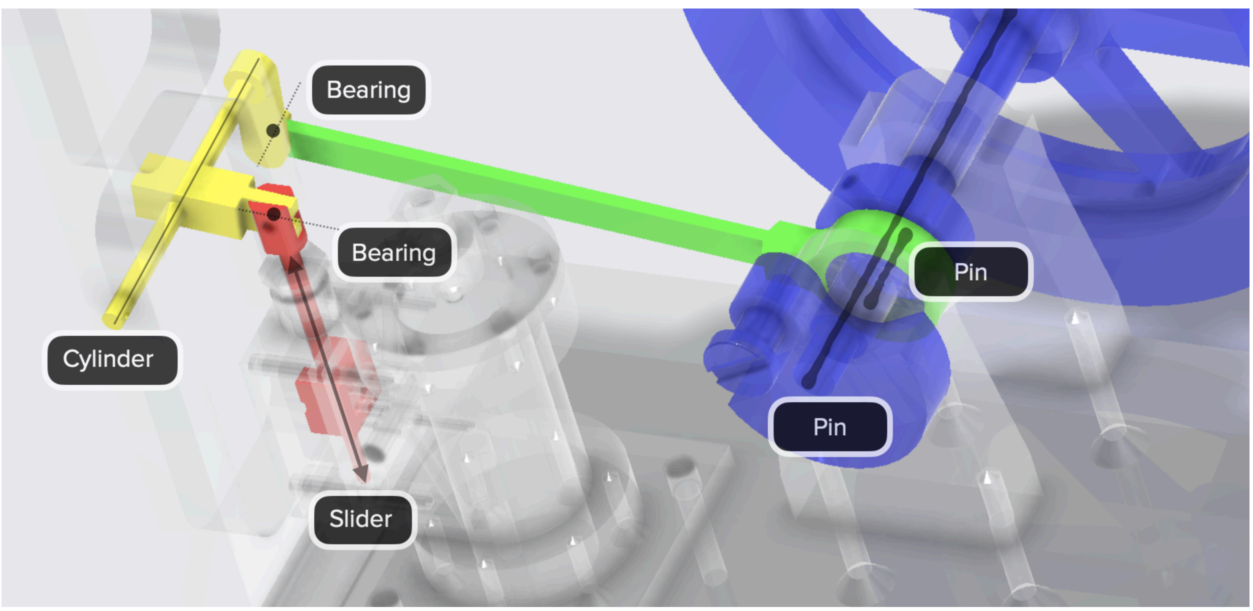


Figure 40. The display above highlights each of the four links connected to the base subassembly (ground). Each of the connection points are drawn and labeled.

Second set of linkages contains five links beginning with the base part fully constrained to ground. The connection between the flywheel subassembly and ground is a pin joint. This is a repeat joint that also exists in Sub Linkage 1 and should be considered in this calculation however must not be double counted when determining DOF for the final assembly. The connecting rod subassembly to flywheel subassembly is also a pin joint. The valve crank subassembly is connected to ground with a cylinder joint and is connected to the eccentric strap via a bearing joint. Lastly, the valve rod subassembly is connected to the valve crank subassembly with a bearing joint and returns to ground with a slider joint. This makes for a total of 2 pin joints, 2 bearing joints, a cylinder joint, and a slider joint. As discussed in the previous sub linkage analysis pin joints are J1, bearings are J4, and cylinders are J2. The slider joint allows for one degree of translational motion making it a J1 joint. The result is 3 J1 joints, a J2 joint, and 2 J4 joints.

$$\begin{aligned} Degrees\ of\ Freedom &= 6(L-1) - 5(J_1) - 4(J_2) - 3(J_3) - 2(J_4) - J_5 \\ &= 6(5-1) - 5(3) - 4(1) - 3(0) - 2(2) - 0 \\ &= 1\ DOF \end{aligned}$$

L= 5	J1= 3	J2= 1	J3= 0	J4= 2	J5= 0

Complete Final Assembly

$$\begin{aligned} Degrees\ of\ Freedom &= 6(L-1) - 5(J_1) - 4(J_2) - 3(J_3) - 2(J_4) - J_5 \\ &= 6(10-1) - 5(7) - 4(2) - 3(0) - 2(4) - 0 \\ &= 1\ DOF \end{aligned}$$

L= 10	J1= 7	J2= 2	J3= 0	J4= 5	J5= 0

Engine Cycle Description

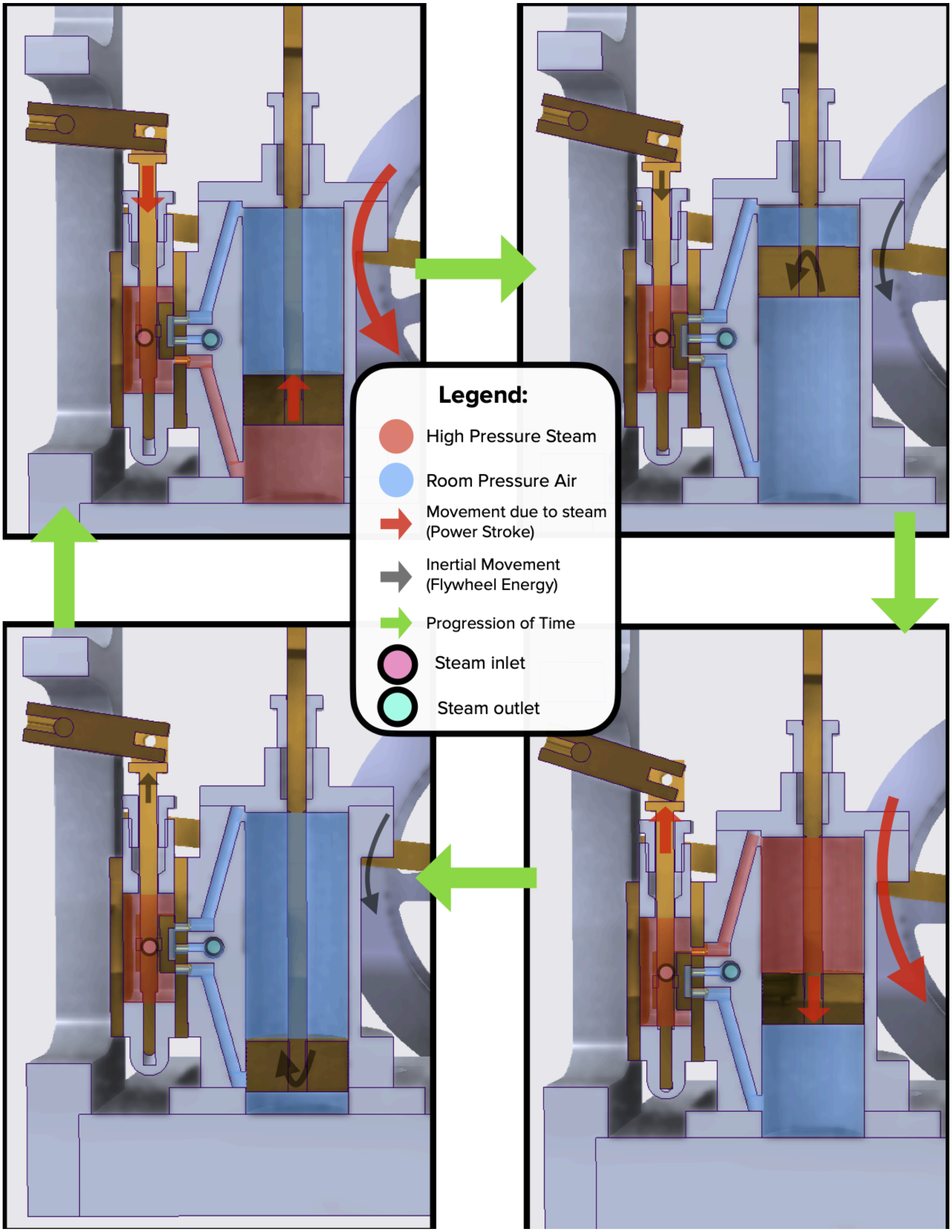


Figure 41. The schematic above illustrates the path that steam takes through the engine. Arrows indicate direction of motion and shaded regions indicate the type of fluid being circulated. See the legend for more detail.

A note on how the engine is set up to run most efficiently:

As the figure 42 shows it is very important to have the correct valve open through the power stroke of the engine in order to convert steam to linear motion, then linear motion to rotational motion. Since both the piston and the valve have a sinusoidal position function when the flywheel is moving at a constant velocity, the valve should be at or very close to its minimum or maximum height when the piston is at it’s midplane. To help explain this, the following table extracts just the important position information from the figure above:

Crank Angle	Left, -90 deg**	Down, -180 deg**	Right, 90 deg**	Up, 0 deg**
Position of Piston*	0	Min (bottom)	0	Max (top)
Position of Valve*	Max (top)	0	Min (bottom)	0
Piston Instantaneous Direction of travel**	Down	Stopped	Up	Stopped
Valve Instantaneous Direction of travel**	Stopped	Down	Stopped	Up

Table 1. Engine cycle analysis, note the 90 degree phase shift between the piston and the valve.

* 0 position is defined as when the midplane between the cylinders is coincident with the midplane of the piston and the valve. Positive is defined as global positive Y (relative directions are listed in the front view)

** The angle is defined as the difference in angle between the crank and the base, which is measured in the global negative z-axis. Instantaneous velocities are assuming a negative angular velocity about a the global z-axis (CCW from the front view)

As you can see from this graph, the positions of piston and the valve are proportional to each other with a 90 degree phase shift. This means that in our initial condition of -90 degree position crank position our piston is in the middle of it's stroke while the valve is at its highest position.

Kinematic Analyses

Part 1: Piston & Valve

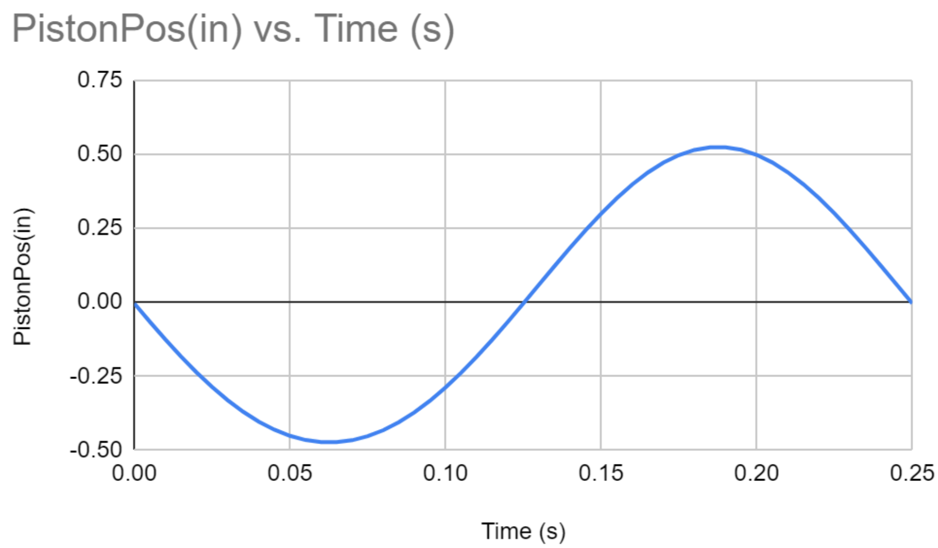


Figure 42. This graph shows the position graph of the piston for one complete revolution of the crank. The piston starts and returns to its initial position in a duration of 0.25s.

In order to get the above graph we defined connection and the motion axis between the piston and the base. The zero position is a result of the midplanes (piston, cylinder) being coincident and this happened at mid stroke (180 degrees). Positive is defined as the global z axis.

Max (inches)	0.5239466094
Min (inches)	-0.473260424
Average	0.01036805452
Best Fit Estimate	-0.5sin(8pi*t)+0.01

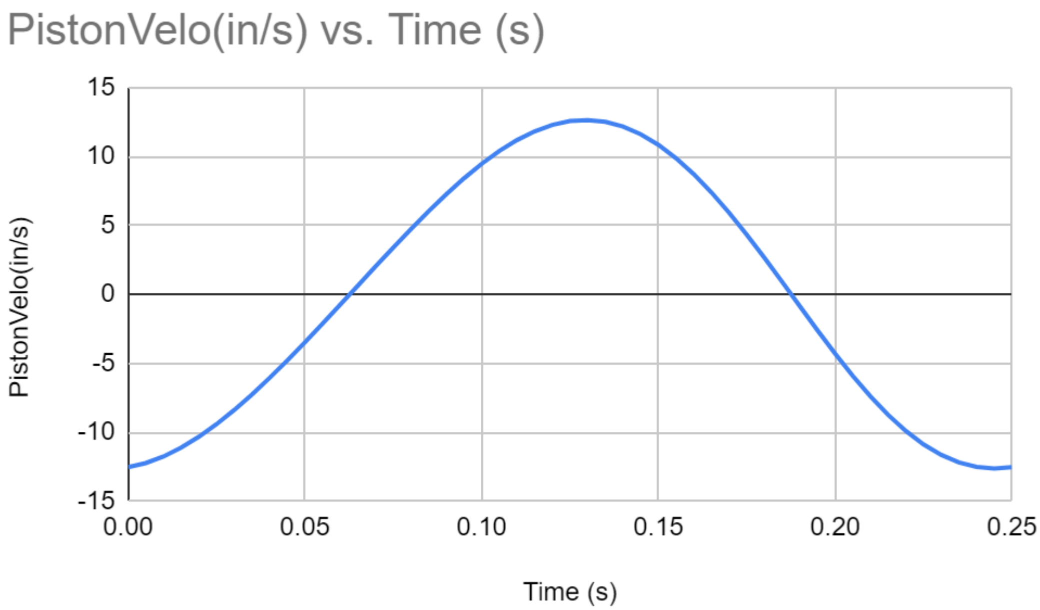
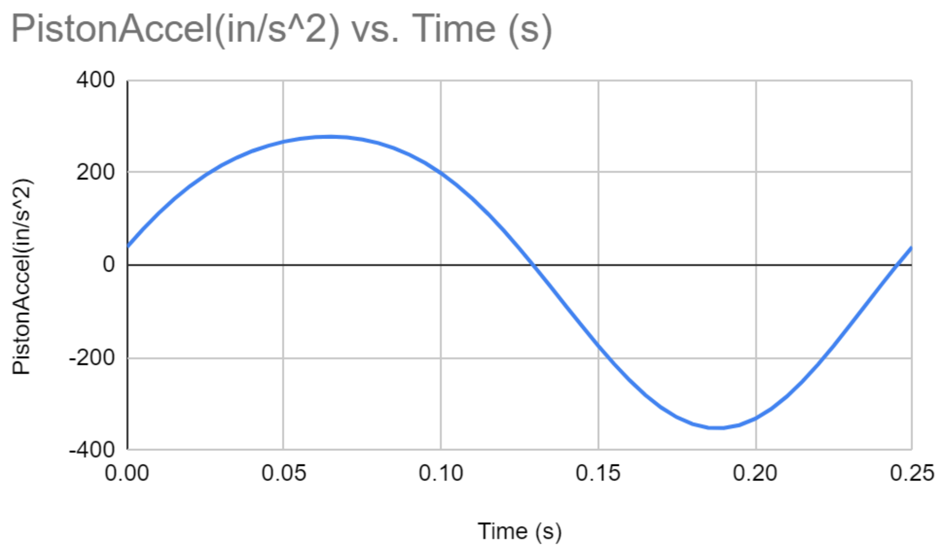


Figure 43. The graph above shows the change in piston velocity over one revolution. The piston's initial position is established at mid stroke therefore the starting and ending points should be nearly equivalent and equal to the piston's maximum velocity.

In order to get the above graph we defined connection and the motion axis between the piston and the base. The velocity is highest (negative/positive) directions when the crank is mid stroke and zero when the crank is at the start of end of the stroke. The engine cycle diagram explains why this process occurs.

Max (inches/s)	12.65103308
Min (inches/s)	-12.63082747
Average	-0.2457506667
Best Fit Estimate	-12.6cos(8pi*t)-0.246



Max (inches/sec^2)	278.2167033
Min (inches/sec^2)	-352.3752123
Average	0.7761907374
Best Fit Estimate	12sin(8pi(t-0.005))+0.776

Figure 44. The graph shown details the acceleration in the y direction of the piston. The acceleration equals zero for a brief moment when the piston crosses its initial position.

In order to get the above graph we defined the connection and the motion axis between the piston and the base. The acceleration is lowest when the crank is mid stroke and highest (negative/positive) when the crank is at the start or end of the stroke. The engine cycle diagram explains why this process occurs.

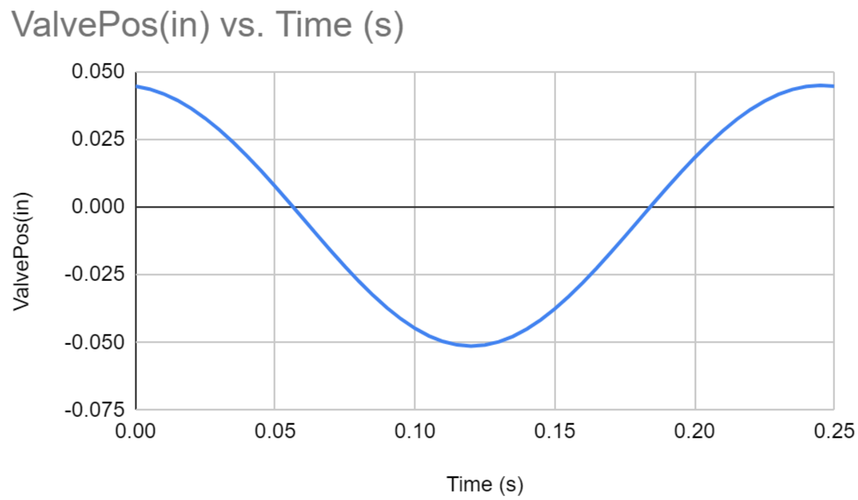


Figure 46. This graph shows the position graph of the valve for one complete revolution of the crank. The valve starts and returns to its initial position in a duration of 0.25s.

In order to get the above graph we defined connection and the motion axis between the valve and the base. The zero position is a result of the midplanes (valve, cylinder) being coincident and this happened at start/end stroke (90,-90 degrees). Positive is defined as the global z axis.

Max (inches)	0.04501219525
Min (inches)	-0.05133483976
Average	-0.001441838334
Best Fit Estimate	0.05cos(8pi*t)-0.0014

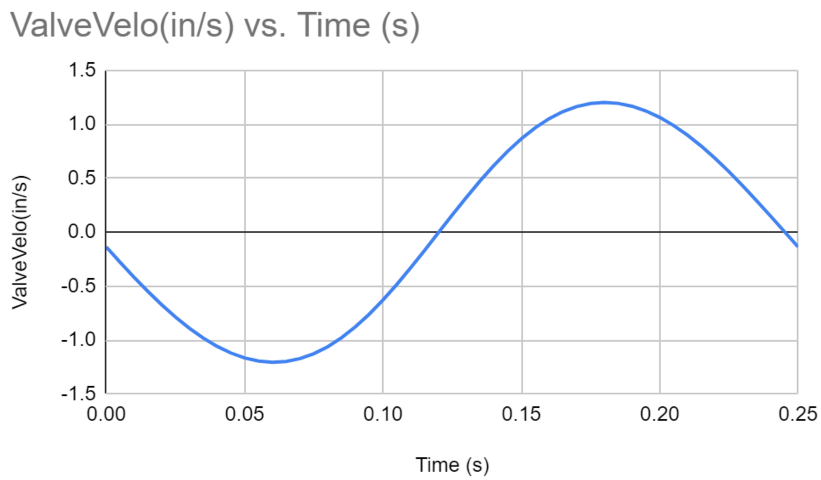


Figure 45. The graph above shows the change in valve velocity over one revolution. The valve's initial position is established at mid stroke therefore the starting and ending points should be nearly equivalent and equal to the valve's maximum velocity.

In order to get the above graph we defined connection and the motion axis between the valve and the base. The velocity is highest (negative/positive) directions when the crank is mid stroke and zero when the crank is at the start or end of the stroke. The engine cycle diagram explains why this process occurs.

Max (inches/sec)	1.202906974
Min (inches/sec)	-1.20562841
Average	-0.002685302146
Best Fit Estimate	-1.2sin(8pi*(t-0.005))-0.003

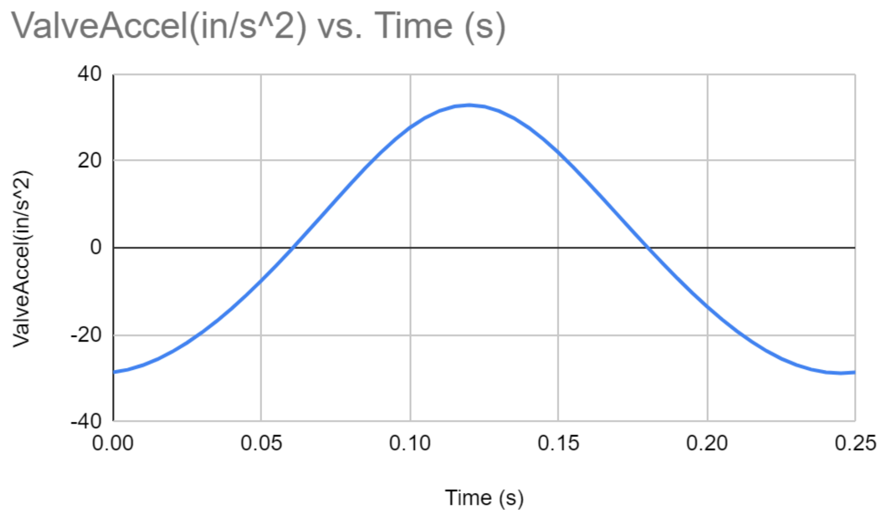


Figure 46. The graph shown details the acceleration in the y direction of the valve. The acceleration equals zero for a brief moment when the valve crosses its initial position.

In order to get the above graph we defined connection and the motion axis between the valve and the base. The acceleration is lowest when the crank is mid stroke and highest (negative/positive) when the crank is at the start or end of the stroke. The engine cycle diagram explains why this process occurs.

Max (inches/sec^2)	32.9304507
Min (inches/sec^2)	32.9304507
Average	-0.5618634984
Best Fit Estimate	-30cos(8pi*t)-0.56

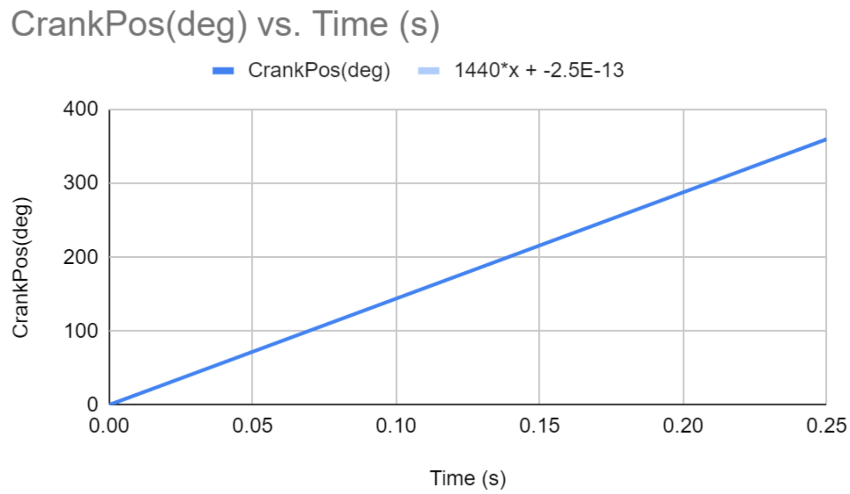


Figure 47. The graph displays the crank angular position over one full revolution. The midstroke was set at zero and thus one revolution leads to 360 end.

In order to get the above graph we defined connection and the motion axis between the crank and the base.

Max (deg)	360
Min (deg)	0
Average	180
Best Fit Estimate	1440t

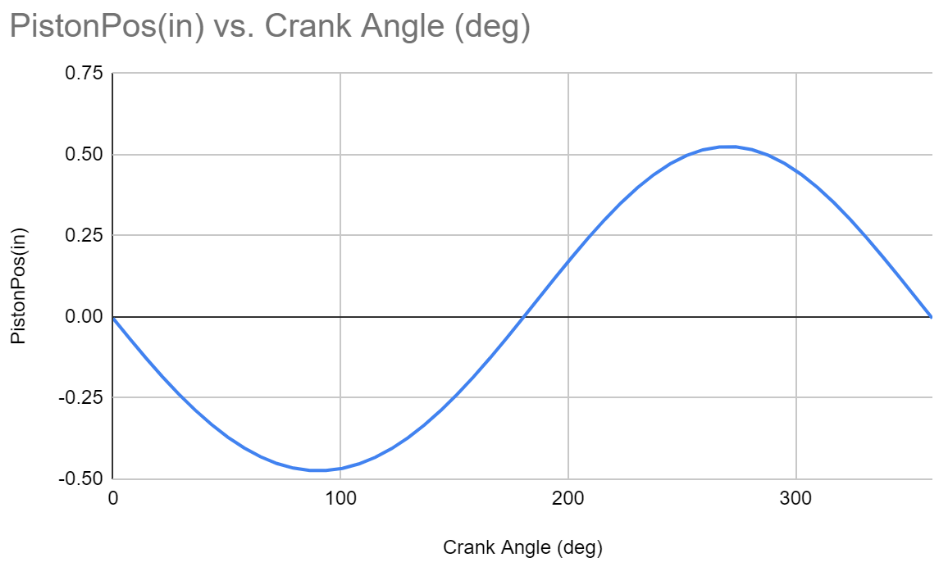


Figure 48. The plot above shows the piston's position with respect to crank angle for a singular revolution.

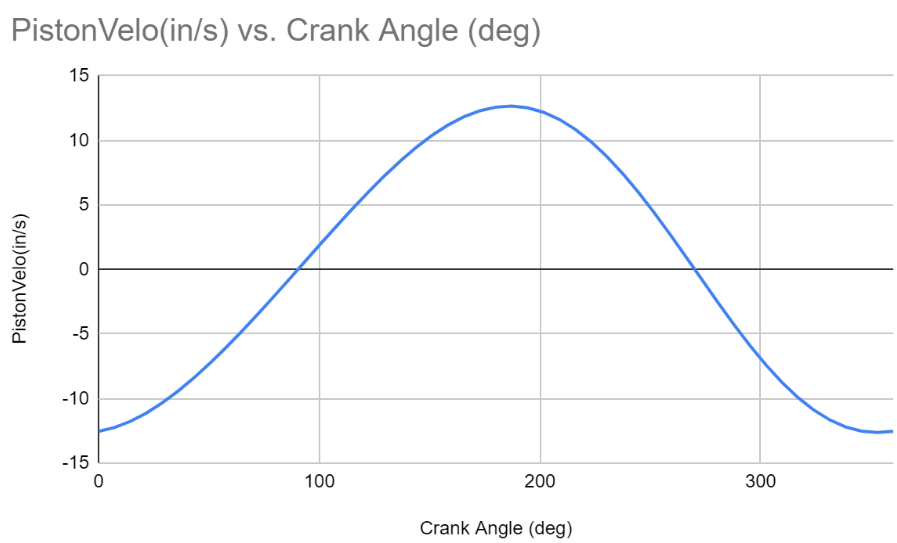


Figure 49. The piston's velocity as a function of crank angle is represented by the plot above.

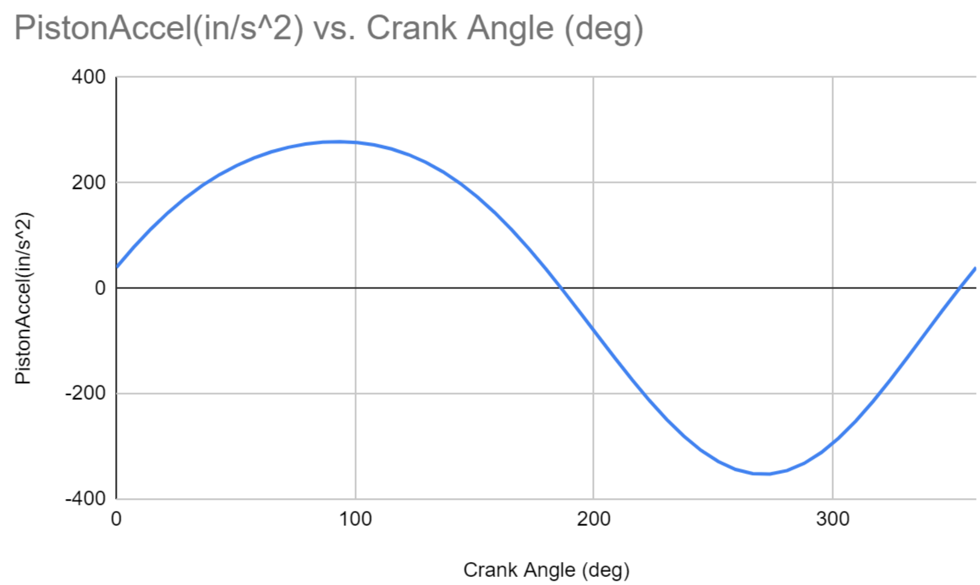


Figure 50. The plot shows the piston's acceleration as it relates to crank angle for one full revolution.

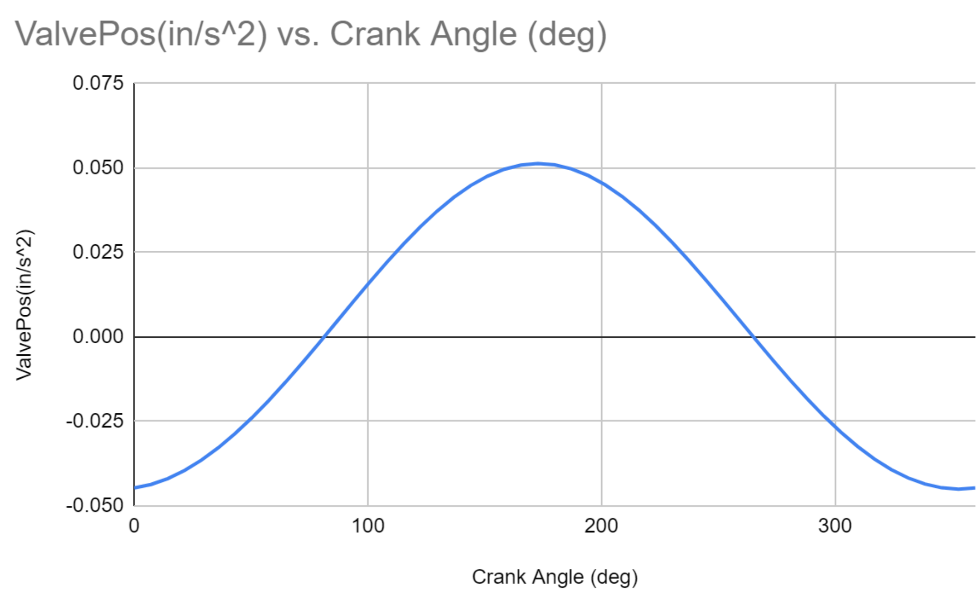


Figure 51. The preceding graph details the change in valve position in the y direction as a function of crank angle.

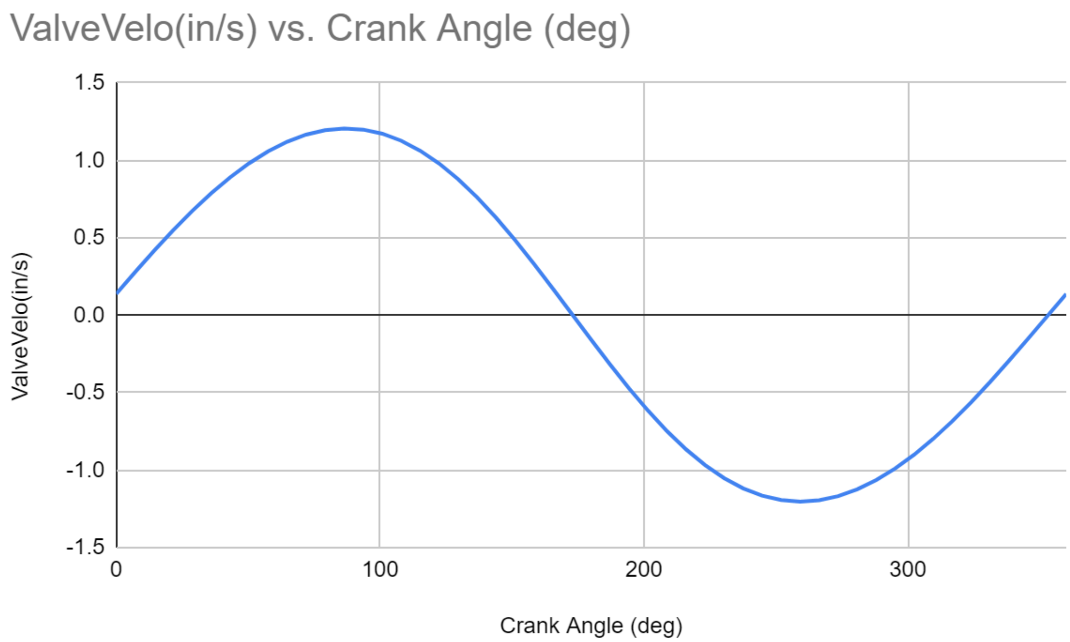


Figure 52. The velocity of the valve is plotted above vs. the angular position of the crank for the complete 0.25s crank revolution.

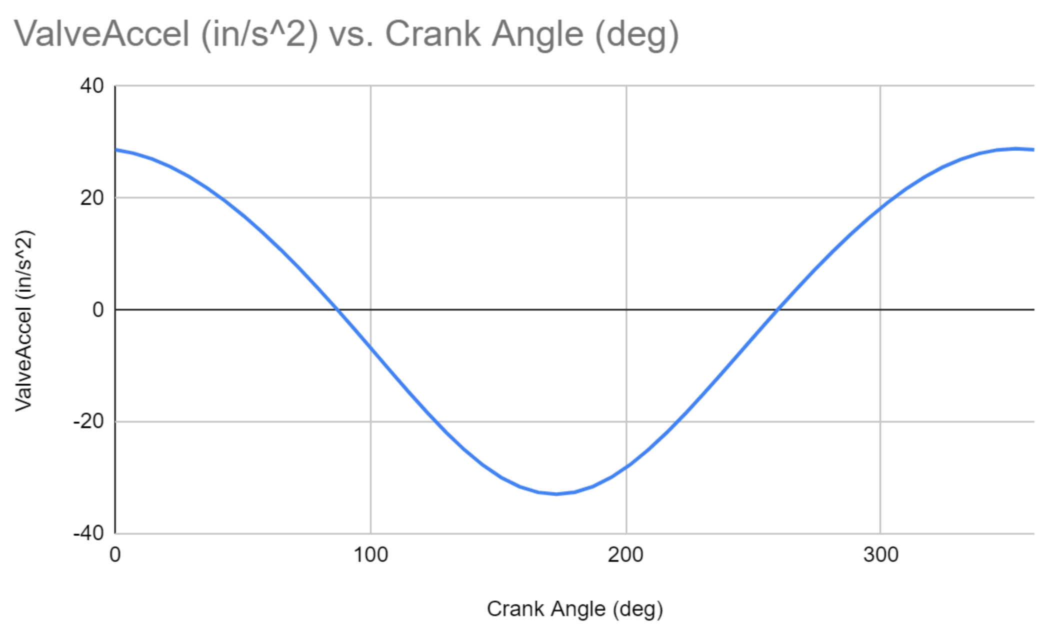


Figure 53. Acceleration of the valve as it relates to crank angle can be seen in the graph above.

Part 2: Leg & Valve Crank

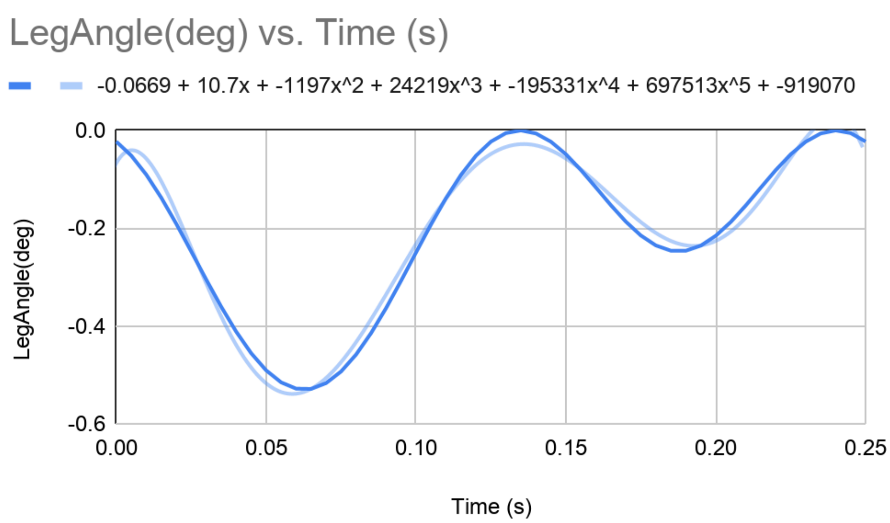


Figure 54. The figure above shows the angular position of the leg with respect to time for one full crank revolution. The zero position was established when the leg was aligned vertically with the right plane of the assembly. The light blue line is the 4th degree polynomial best fit line.

The above graph is measured on the vertical axis, meaning that 0 deg is if the main axis of the leg is vertical. The rotation degrees are defined as into the page and thus this means the positive direction is clockwise in the front view of the assembly. In addition, in the graph above you may notice that the line crosses 0 twice in one cycle and this makes sense because the crank keeps the beam and leg the most flat when it is on either side of the stroke. For example, when the crank is pointing up it pushes the leg out and vice versa.

Max (deg)	-0.00001045021626
Min (deg)	-0.528124336
Average	-0.2016808055

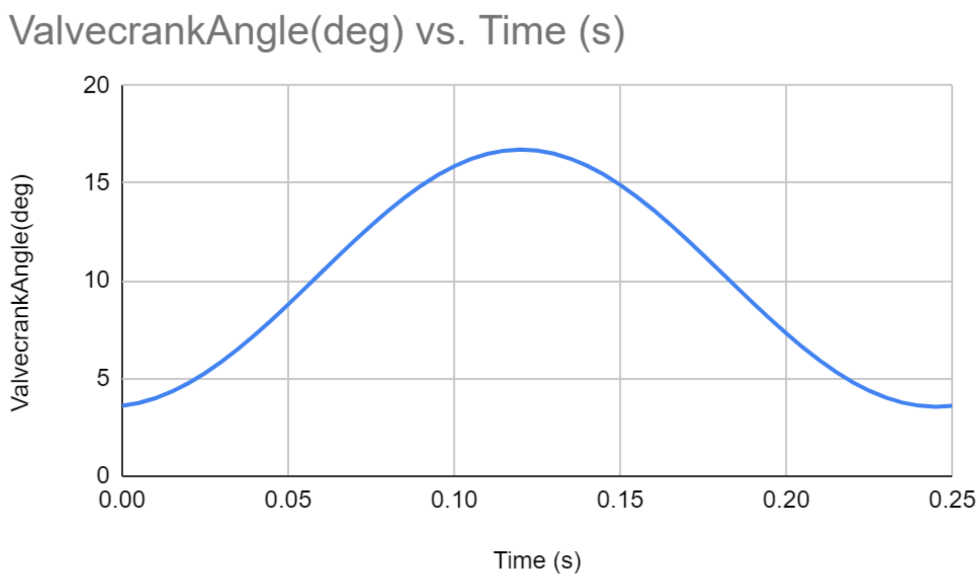


Figure 55. The crank's angular position with respect to time displays a linear correlation corresponding to the angular speed of the motor. The relationship is shown in the figure above.

The above graph is measured on the vertical axis, meaning that 0 deg is if the main axis of the valve crank is vertical. The rotation degrees are defined as into the page and thus this means the positive direction is clockwise in the front view of the assembly. The graph never crosses 0 since the crank does not pass the vertical and it is always on the positive side (left of the column).

Max (deg)	16.70967582
Min (deg)	3.564068425
Average	9.968837987
Best Fit Estimate	-6.568(8pi*t)+9.97

Part 3 - Beam

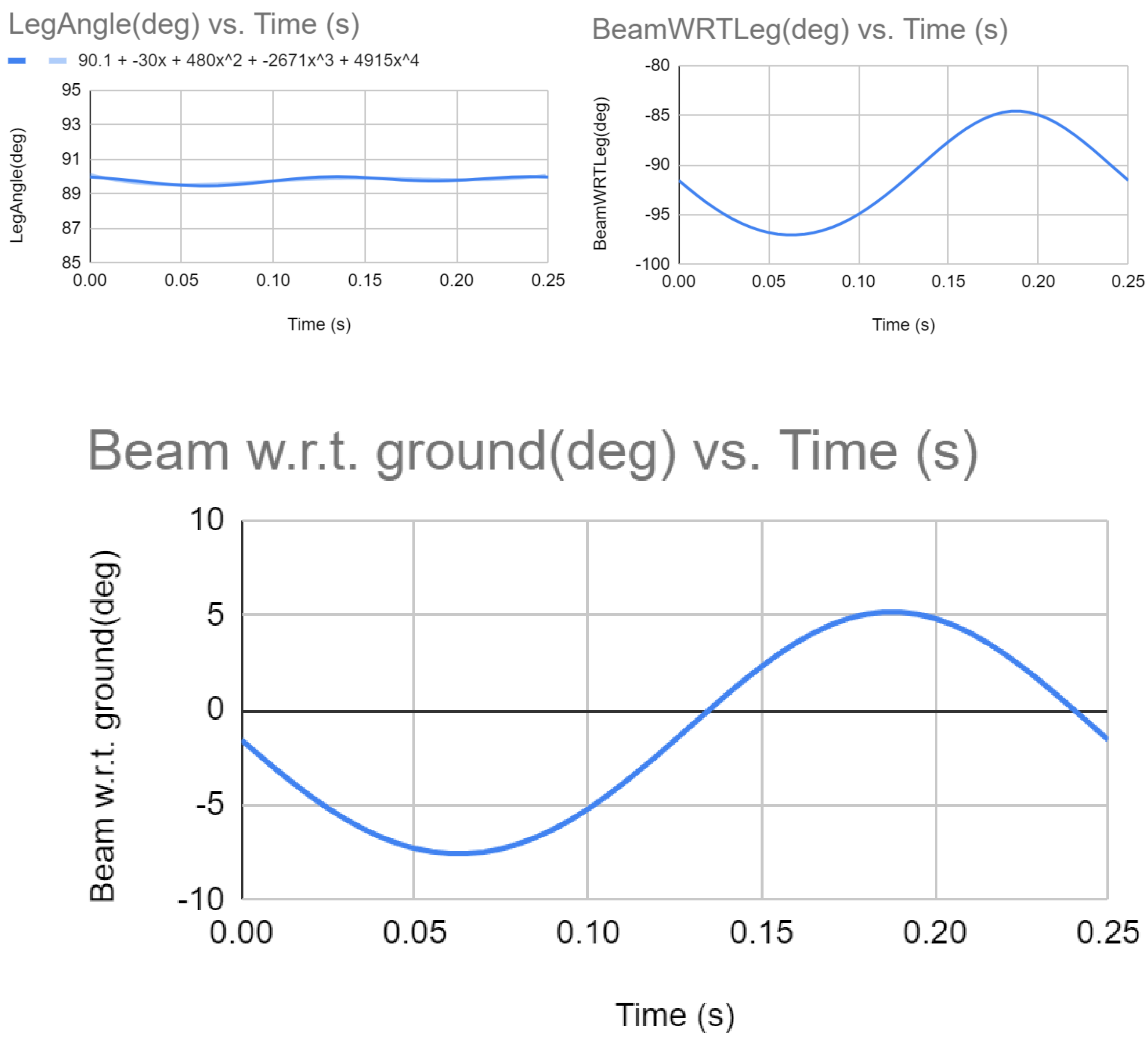


Figure 56. The preceding graphs were created to determine the angle of the beam with respect to ground over the duration of one crank revolution. This required the creation of two plots (top left and right) and the addition of these data values to achieve the desired values as shown in the bottom graph.

In the graphs above it is visible that the angel for the leg and base is insignificant with respect to the motion between the leg and beam. In order to find the angle of the beam with respect to the ground we added the above two graphs to replicate the bottom one.

Max (deg)	5.16063
Min (deg)	-7.56332
Average	-1.389443529
Best Fit Estimate	-6.25sin(8pi(t+0.003))-1.39

Part 4 - Trace Curve

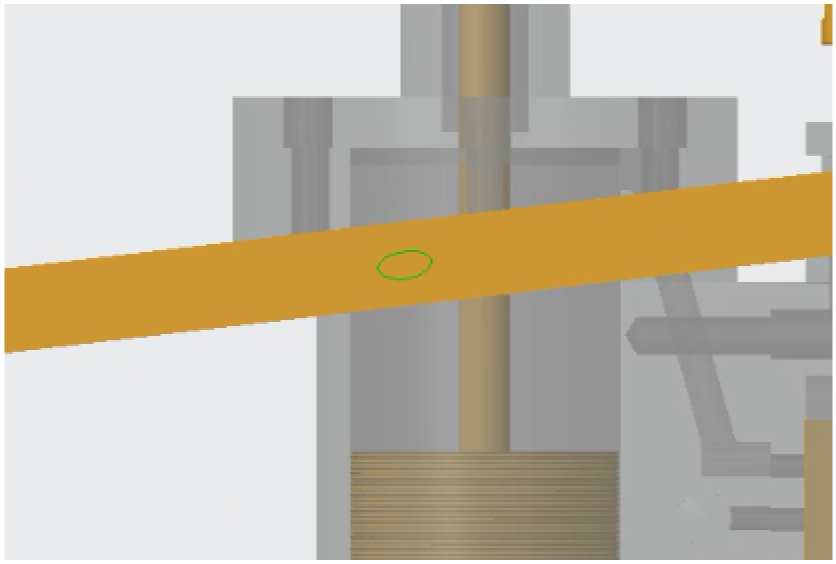
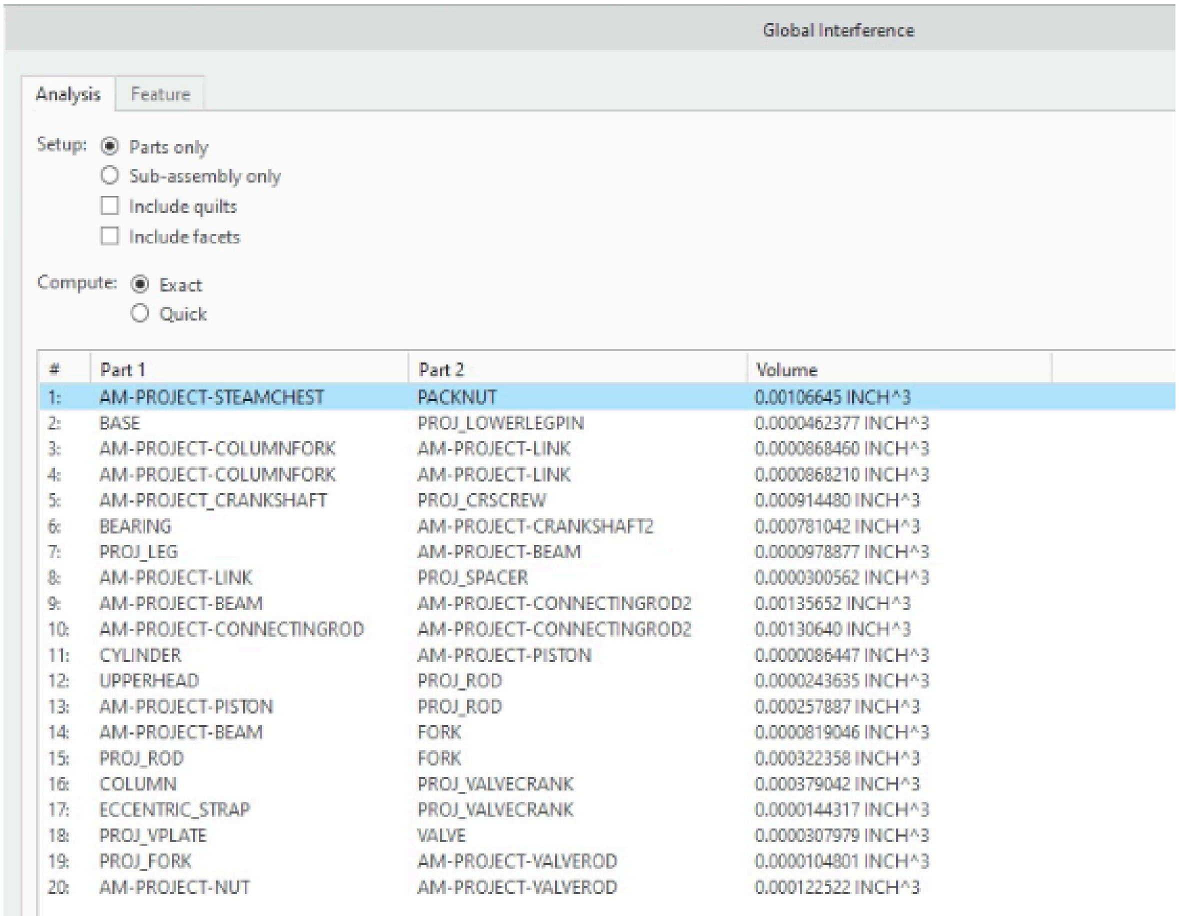


Figure 57. The drawing above highlights and labels a trace curve for the middle of the eccentric strap during engine motion.

Interference Check



#	Part 1	Part 2	Volume
1:	AM-PROJECT-STEAMCHEST	PACKNUT	0.00106645 INCH^3
2:	BASE	PROJ_LOWERLEGPIN	0.0000462377 INCH^3
3:	AM-PROJECT-COLUMNFORK	AM-PROJECT-LINK	0.0000868460 INCH^3
4:	AM-PROJECT-COLUMNFORK	AM-PROJECT-LINK	0.0000868210 INCH^3
5:	AM-PROJECT_CRANKSHAFT	PROJ_CRSCREW	0.000914480 INCH^3
6:	BEARING	AM-PROJECT-CRANKSHAFT2	0.000781042 INCH^3
7:	PROJ_LEG	AM-PROJECT-BEAM	0.0000978877 INCH^3
8:	AM-PROJECT-LINK	PROJ_SPACER	0.0000300562 INCH^3
9:	AM-PROJECT-BEAM	AM-PROJECT-CONNECTINGROD2	0.00135652 INCH^3
10:	AM-PROJECT-CONNECTINGROD	AM-PROJECT-CONNECTINGROD2	0.00130640 INCH^3
11:	CYLINDER	AM-PROJECT-PISTON	0.0000086447 INCH^3
12:	UPPERHEAD	PROJ_ROD	0.0000243635 INCH^3
13:	AM-PROJECT-PISTON	PROJ_ROD	0.000257887 INCH^3
14:	AM-PROJECT-BEAM	FORK	0.0000819046 INCH^3
15:	PROJ_ROD	FORK	0.000322358 INCH^3
16:	COLUMN	PROJ_VALVECRANK	0.000379042 INCH^3
17:	ECCENTRIC_STRAP	PROJ_VALVECRANK	0.0000144317 INCH^3
18:	PROJ_VPLATE	VALVE	0.0000307979 INCH^3
19:	PROJ_FORK	AM-PROJECT-VALVEROD	0.0000104801 INCH^3
20:	AM-PROJECT-NUT	AM-PROJECT-VALVEROD	0.000122522 INCH^3

Figure 58. Initial Global Interference Check

After running the first global interference check we noticed that we had many interferences on the beam and the components that it was connected to. Due to this we decided to re-visit every part file to make sure the dimensions were correct. After making sure that each part and subassembly were modeled correctly, we took each interference scenario and elaborated on it.

We created a table that summarizes whether its interference is expected or unexpected.

Interference	Expected	Unexpected
Steamchest - Packnut	✓	
Base - Lower Leg Pin		✓
Column Fork - Link		✓
Column Fork - Link 2		✓
Crankshaft - Crank Screw	✓	
Bearing - Crankshaft		✓
Leg - Beam		✓
Link - Spacer		✓
Beam - Connecting Rod Fork		✓
Connecting Rod - Connecting Rod Fork	✓	
Cylinder - Piston	✓	
Upperhead - Piston Rod	✓	
Piston - Piston Rod	✓	
Beam - Piston Fork		✓
Piston Rod - Piston Fork	✓	
Column - Valve Crank	✓	✓
Eccentric Strap - Valve Crank	✓	
Valve Plate - Valve	✓	
Valve Fork - Valve Rod	✓	
Valve Nut - Valve Rod	✓	

Table 2. Analysis of Interferences

Interference #1: Steam Chest - Packnut

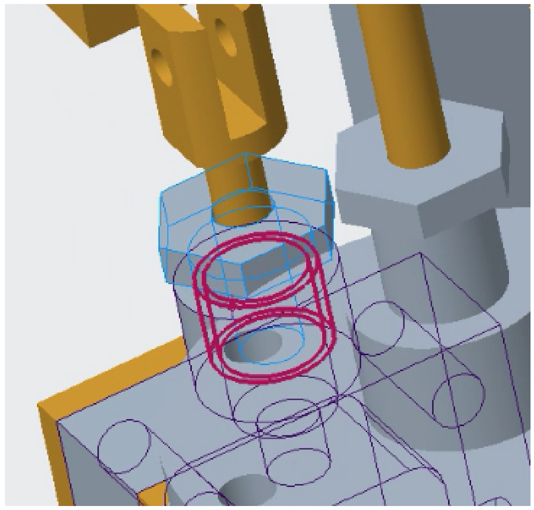


Figure 59. Interference #1

This interference is an assembly connection. The packnut and its threads are interfering with the inner threads of the stem chest. This is something that was expected as the packnut is placed in there so that the valve rod can move inside. Thus, this interference still allows the mechanism to function.

Interference #2: Base - Lower Leg Pin

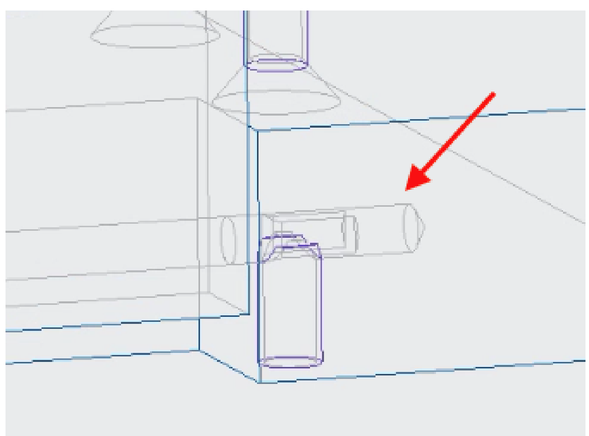


Figure 60. Interference #2

This interference was not expected. The lower leg pin was too long and was interfering with the hole that was created on the base. This was very easy to fix as we increased the depth of the hole and the base and got rid of the interference.

Interference #3/4: Column Fork - Link

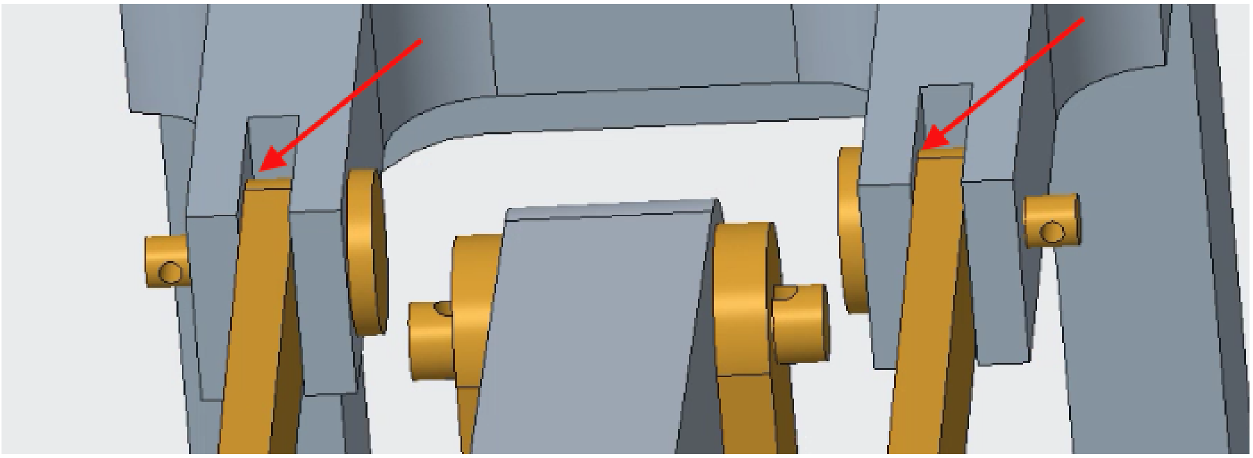


Figure 61. Interference #3/4

This interference was not expected. Both of the links were interfering with the column surface at the locations shown. This was caused due to the constraints at the pin join between the subassembly with the links and the base. There was a wrong plane alignment that was easily changed and resolved the interference.

Interference #5: Crankshaft - Crank Screw

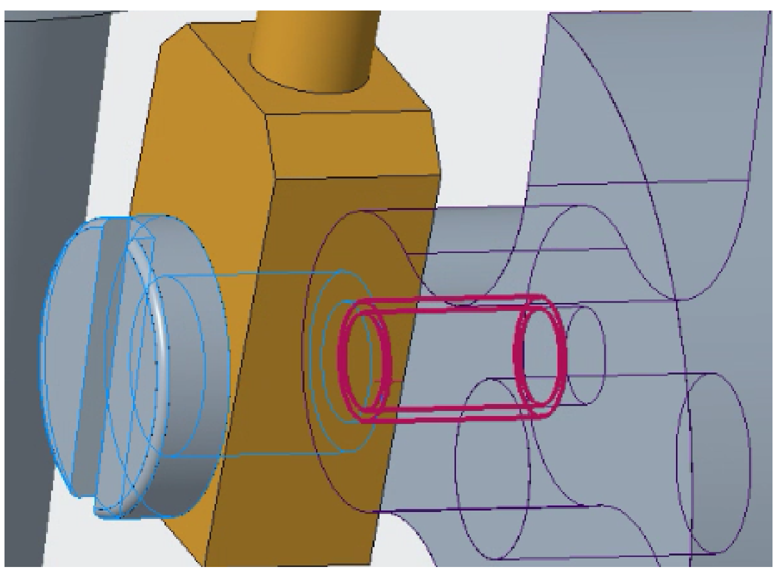


Figure 62. Interference #5

This interference was expected. The crankscrew and its threads are interfering with the inner threads of the crank. The crank screw needs to be fully engaged in that position and thus the connection is obvious.

Interference #6: Bearing - Crankshaft

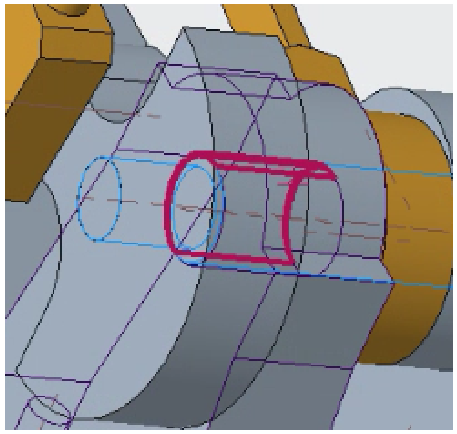


Figure 63. Interference #6

This interference was unexpected. The bearing should not be interfering with only one side of the crankshaft. The reason for this interference was because the pin joint was created by aligning the side of the crankshaft to the bearing. In order to fix this interference the two axes had to be constrained as coincident instead. However, after fixing that the other bearing created a similar interference. After checking the bearing part file it was noticed that instead of the hole being distance 0.375 from the midplane it was centered 0.38. Thus this small displacement error was creating the misalignment issue in the final assembly.

Interference #7: Leg - Beam

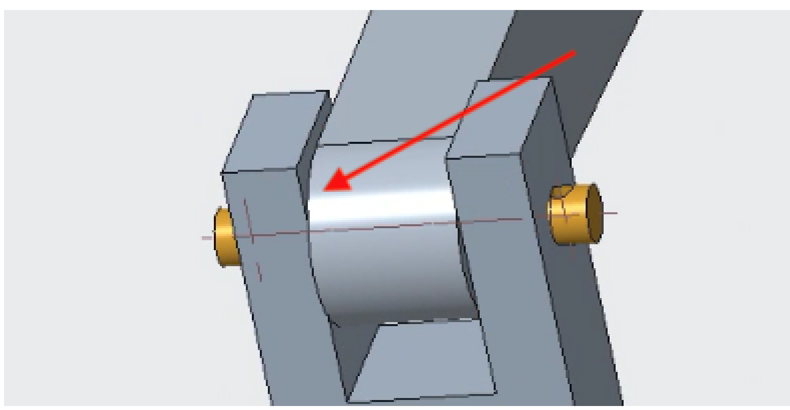


Figure 64. Interference #7

This interference was unexpected. The left surface of the beam was interfering with the inner left surface of the leg. The joint between the two links is a bearing, thus the joint itself could not be manipulated to fix this issue. Instead the pin joint between the beam and the column fork had a distance relationship rather than a coincidence between the two mated planes, thus creating this unnecessary interference.

Interference #8: Link - Spacer

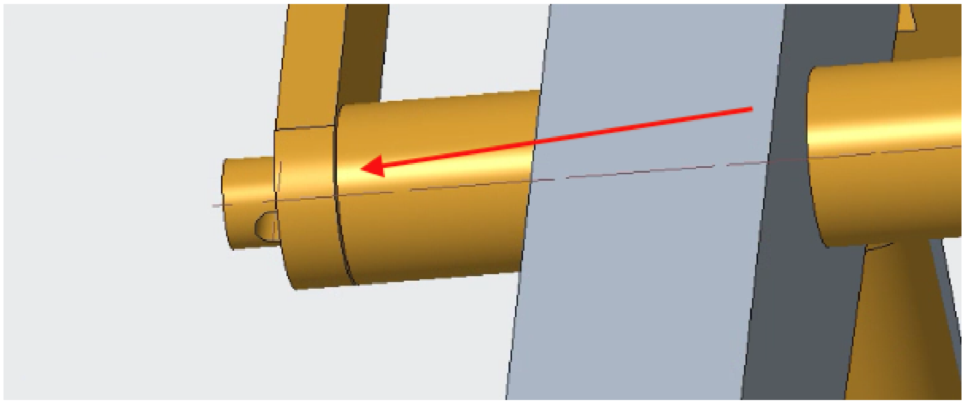


Figure 65. Interference #8

This interference was unexpected. The left surface of the spacer was interfering with the inner left surface of the link. This created for the same issue as interference #7. Similarly, the joint between the two links is a cylinder, thus the joint itself could not be manipulated to fix this issue. Instead the pin joint between the beam and the column fork had a distance relationship rather than a coincidence between the two mated planes, thus creating this unnecessary interference.

Interference #9: Beam - Connecting Rod Fork

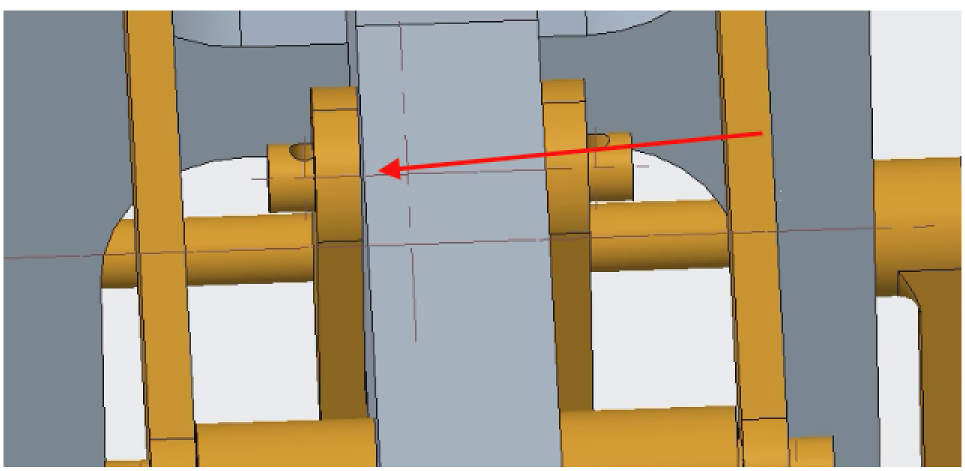


Figure 66. Interference #9

This interference was unexpected. The beam should be centered between the connecting rod fork. After re-visiting the pin joint connection it was noticed that the two midplanes that were selected had a distance factor between them instead of being coincident. This was easily fixed by making the two planes coincident. In turn, this misalignment fixed other interferences on the beam as well.

Interference #10: Connecting Rod - Connecting Rod Fork

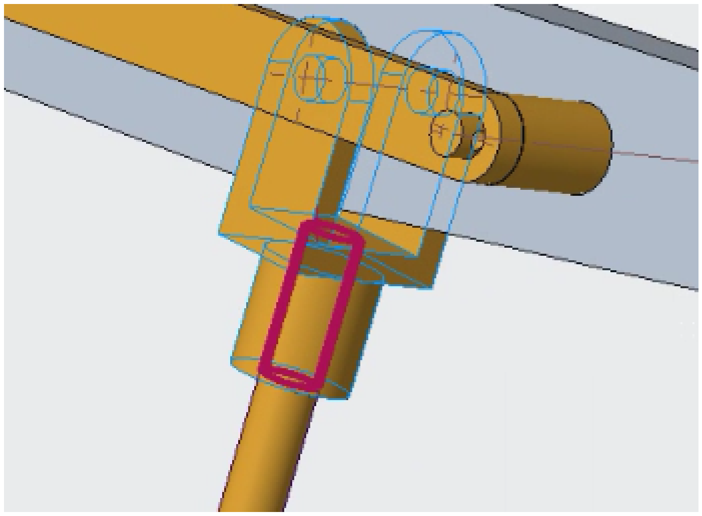


Figure 67. Interference #10

This interference was expected. The rod is supposed to be tightly connected to the fork thus creating an interference. When this apparatus is built in a 3D model those two pieces will be one.

Interference #11: Cylinder - Piston

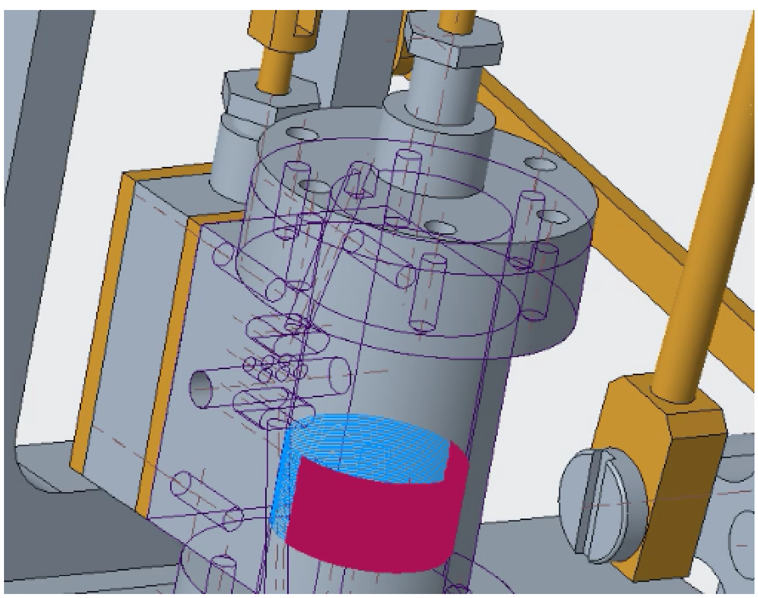


Figure 68. Interference #11

This interference was expected. The piston needs to be touching the inner surface of the cylinder so that no steam is able to escape through the sides.

Interference #12: Upperhead - Piston Rod

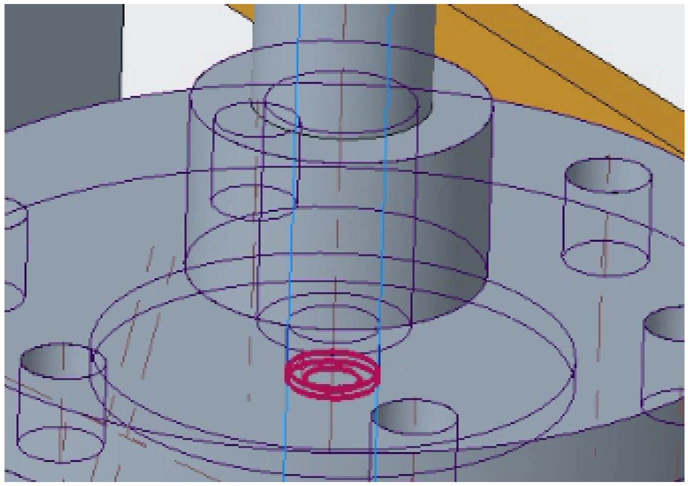


Figure 69. Interference #12

This interference was expected. The piston rod needs to be touching the inner surface of the upperhead hole so that no steam is able to escape through the sides.

Interference #13: Piston - Piston Rod

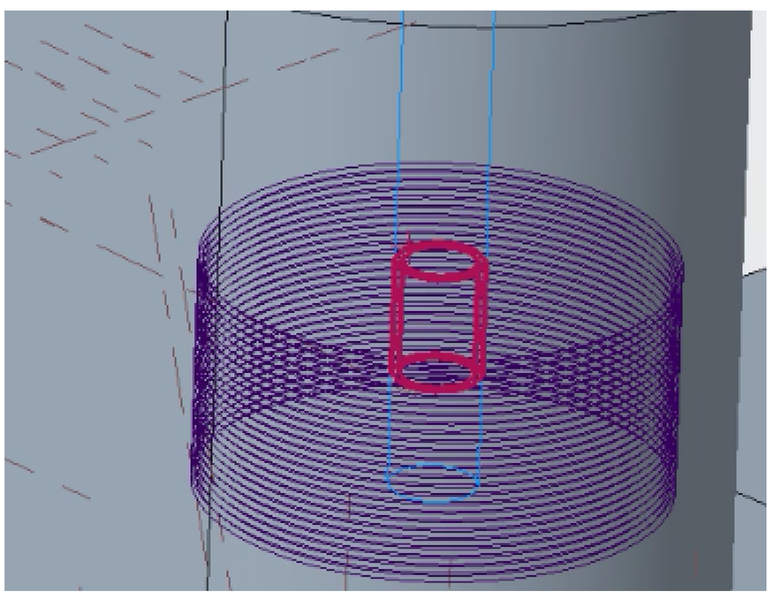


Figure 70. Interference #13

This interference was expected. The piston rod threads need to connect with the threads located in the piston. Thus, when these two parts connect they create a solid uniform structure.

Interference #14: Beam - Piston Fork

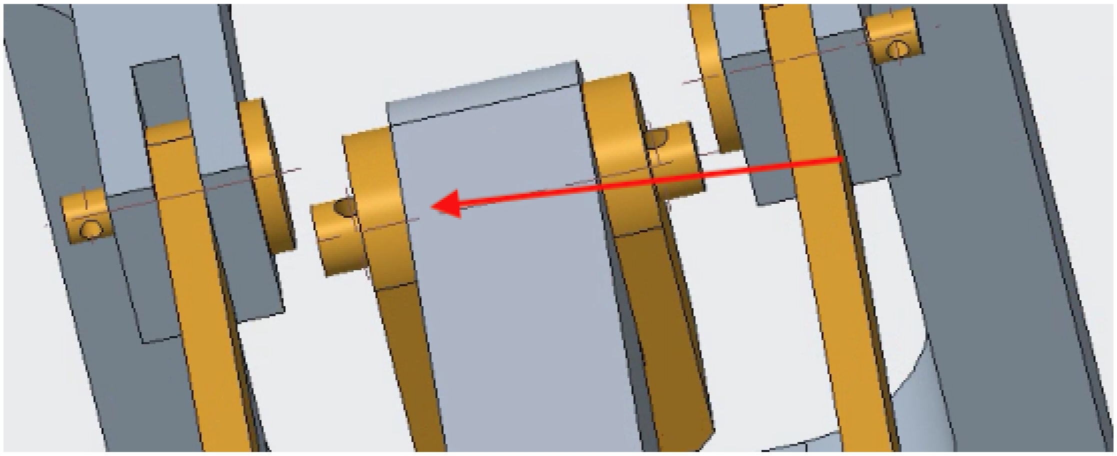


Figure 71. Interference #14

This interference was not expected. The beam outer left surface was interfering with the inner left surface of the piston fork. After re-visiting the pin joint connection it was noticed that the two midplanes that were selected had a distance factor between them instead of being coincident. This was easily fixed by making the two planes coincident. In turn, this misalignment fixed other interferences on the beam as well.

Interference #15: Piston Rod - Piston Fork

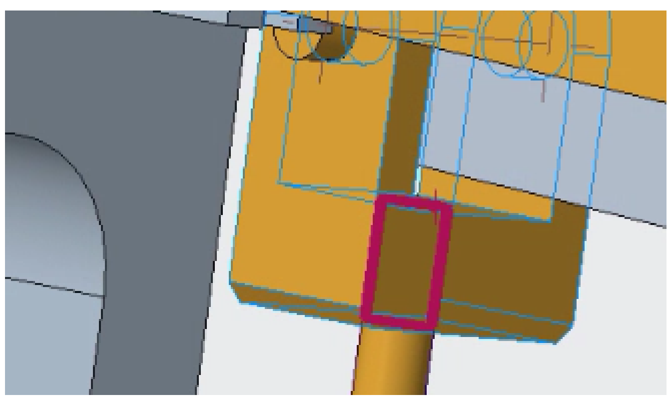


Figure 72. Interference #15

This interference was expected. The rod is supposed to be tightly connected to the fork thus creating an interference. When this apparatus is built in a 3D model those two pieces will be one.

Interference #16: Column - Valve Crank

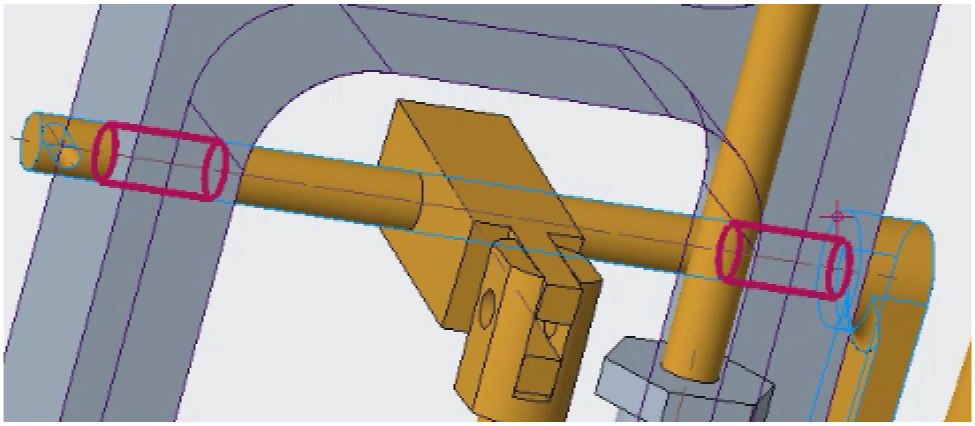


Figure 73. Interference #16

This interference was expected and unexpected at the same time. the two locations where the valve crank is interfering with the inner circles of the column is expected. That is because the valve crank needs to be placed inside the holes tightly. If the user would like to have zero interference then it is very simple to make the holes on the column even larger. The unexpected interference was when the valve crank was intruding inside the column. This was happening because the right datum plane had not been set for the fork to be exactly in the middle, thus resulting in the valve crank being pushed to the image left.

Interference #17: Eccentric Strap - Valve Crank

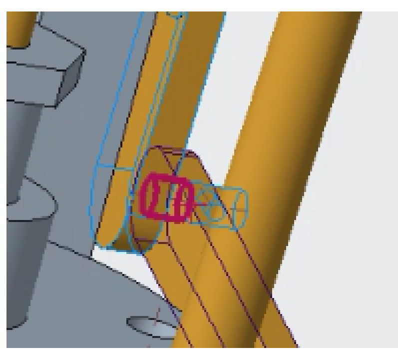


Figure 74. Interference #17

This interference was expected. Once the assembly is complete the valve crank and eccentric need to have a firm connection as they move as one mechanical system.

Interference #18: Valve Plate - Valve

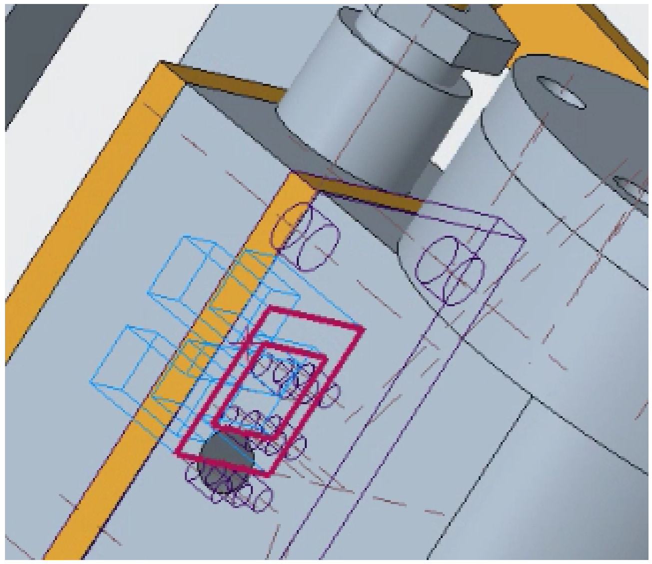


Figure 75. Interference #18

This interference was expected. The valve needs to be very close to the valve plate so that the steam is able to pass at the right times and no steam sneaks through any gaps in the mechanism.

Interference #19: Valve Fork - Valve Rod

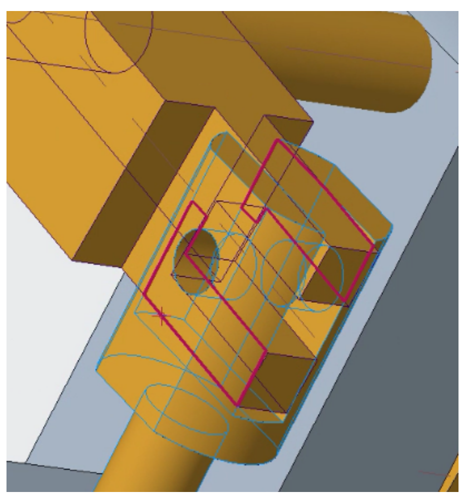


Figure 76. Interference #19

This interference was expected. The valve fork and valve rod fit together like a “glove”. In order for the bearing joint to work properly the two parts need to be coincident with one another.

Interference #20: Valve Nut - Valve Rod

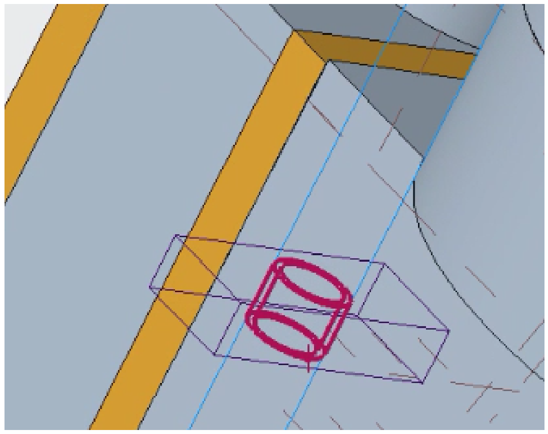
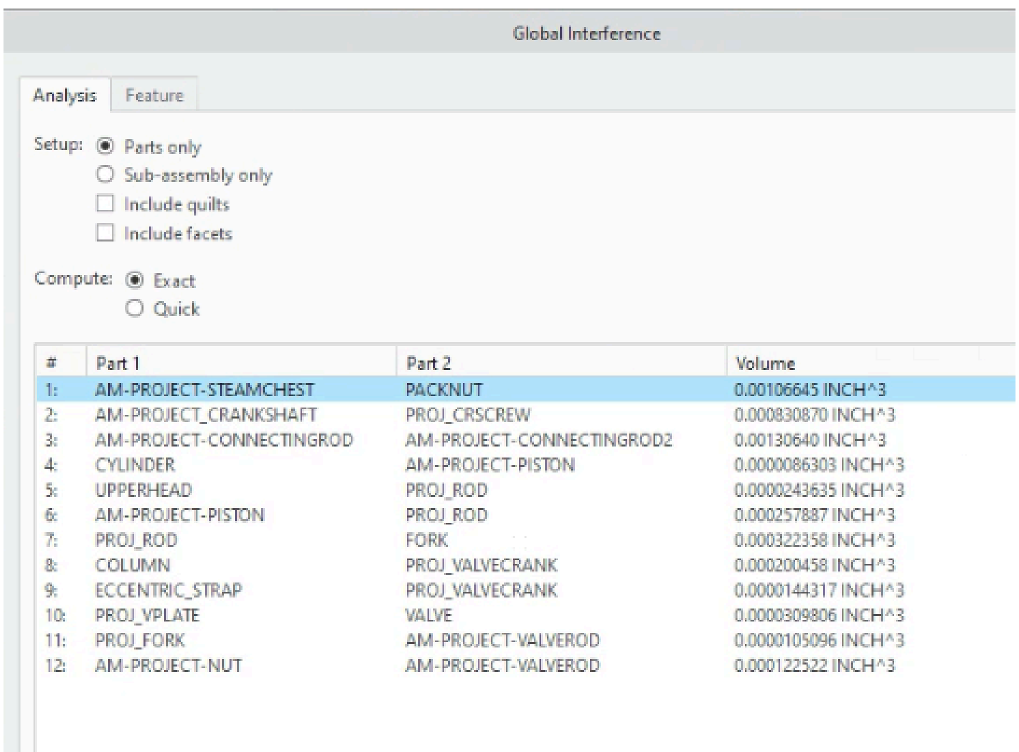


Figure 77. Interference #20

This interference was expected. The valve rod needs to pass through the valve nut and thread onto place, thus creating this necessary interference

After inspecting all the interferences and fixing those that were unnecessary and unexpected we ran another global interference check which now displays only the necessary ones.



#	Part 1	Part 2	Volume
1:	AM-PROJECT-STEAMCHEST	PACKNUT	0.00106645 INCH^3
2:	AM-PROJECT_CRANKSHAFT	PROJ_CRSCREW	0.000830870 INCH^3
3:	AM-PROJECT-CONNECTINGROD	AM-PROJECT-CONNECTINGROD2	0.00130640 INCH^3
4:	CYLINDER	AM-PROJECT-PISTON	0.0000086303 INCH^3
5:	UPPERHEAD	PROJ_ROD	0.0000243635 INCH^3
6:	AM-PROJECT-PISTON	PROJ_ROD	0.000257887 INCH^3
7:	PROJ_ROD	FORK	0.000322358 INCH^3
8:	COLUMN	PROJ_VALVECRANK	0.000200458 INCH^3
9:	ECCENTRIC_STRAP	PROJ_VALVECRANK	0.0000144317 INCH^3
10:	PROJ_VPLATE	VALVE	0.0000309806 INCH^3
11:	PROJ_FORK	AM-PROJECT-VALVEROD	0.0000105096 INCH^3
12:	AM-PROJECT-NUT	AM-PROJECT-VALVEROD	0.000122522 INCH^3

Figure 78. Final Global Interference Check

Discussion of Results

Upon the completion of engine construction we were tasked with monitoring the motion of various components within the system. Using our in depth knowledge of kinematic analyses we applied a motor to the crankshaft of the steam engine that maintained a speed suitable for a model steam engine. We chose an angular velocity of 1,440deg/s in the counterclockwise direction. With this speed we achieve one full crank revolution in a quarter second time interval. After creating an analysis with the motor applied to the system for this duration of time, we were able to collect the motion data necessary for various parts. The starting position for each analysis occurs when the piston is at mid stroke meaning it's midplane is coincident with the right plane of the cylinder.

Piston and Valve Motion with Respect to Time

In order to measure the position, velocity, and acceleration of the piston we applied a datum point to the bottom of the piston face and created three measures referencing this point. The way the piston is constrained within the system it only has one translational degree of freedom in the y direction. Measures were created in accordance with this direction of motion. The resulting position plot exhibits a sinusoidal-like wave following the piston motion from the mid stroke or zero position through a singular periodic motion. The shape of this plot is a result of the nearly uniform motion of the piston from the central plane to either end of the cylinder's central hole. The best fit line corresponding to the plot can be represented by the equation y=-0.5sin(8pi*t)+0.01. As the piston travels within the cylinder it achieves a total stroke length of about 1in placing the zero position at about half this distance. This distance, 0.5in, corresponds to the amplitude of the plot as seen in the best fit equation. The piston achieves this amplitude twice during a singular crank revolution. Taking another look at the best fit equation, we notice the constant 8pi should correspond to the radial degrees covered over the course of one period (8pi=2pi/0.25s). This value will appear in the large majority of best fit lines for the following plot analyses.

The piston's velocity begins at its maximum value due to the chosen starting position; mid stroke. This value was estimated to be an average magnitude 12.64in/sec and is achieved each time the piston crosses its initial position. This graph compliments the position graph and resembles a sinusoidal plot. The best fit line for this plot can be represented by the equation y=-12.6cos(8pi*t)-0.246. The corresponding amplitude in the given equation closely resembles the maximum velocity estimated above. Each amplitude represents the maximum speed and each zero occurs when the piston reaches the beginning or end of its stroke. Acceleration of the piston is displayed with a sinusoidal graph beginning with a small acceleration value. The piston exhibits this small amount of acceleration at the beginning of its motion due to the instantaneous passing of its maximum speed as seen in the velocity plot. This mid stroke acceleration value is estimated to be about 0.776 in/sec^2 whereas the plot's maxima, which occurs at each of the extreme positions of each stroke, varies depending upon the direction of piston motion. The pistons upward stroke, represented by the second half of the function's wavelength, achieves an amplitude with a magnitude that is nearly 100in/sec^2 larger than the initial amplitude. This discrepancy can be explained by the relative motion of the links contributing to piston motion. Because the leg is not fixed rotationally in the x-y plane, it will allow the beam to rotate ever so slightly more than if the leg had been fully constrained. The result is a slightly uneven force applied to the piston on the upwards and downward stroke motion ultimately altering the acceleration.

Similar to the piston, the valve is constrained as to allow for one degree of translation along the y-axis. Each of the three plots were created by collecting this motion data over the course of the 0.25s crank revolution. The resulting position graph appears to resemble a sinusoidal shape with a line of best fit equation y=0.05cos(8pi*t)-0.0014. The valve and piston move in opposition to one another which would explain why their graphs resemble cosine and sine functions respectively. As one reaches the end/beginning of its stroke (or amplitude) the other is passing the mid stroke (or crossing the x-axis). This is crucial for the passage of steam through the system as it will allow for the various steam passages to be open and closed on either side in an alternating fashion. The valve need only cover a total stroke length of about 0.05in substantially smaller than the distance covered by the piston during the same amount of time. As a result, the velocity of the valve during this time period can be estimated by the best fit equation y=-1.2sin(8pi*(t-0.005))-0.003. This exhibits amplitudes of maximum velocity values of nearly 1.2in/s whereas the piston achieves its max values at about 12.6in/s. Much like the velocity and position graphs of the piston, the valve wave functions appear largely uniform for one crank revolution.

Acceleration of the valve is also largely uniform and resembles a sinusoidal wave with maxima in the region of 32.93in/s^2. This differs from the nature of the piston's acceleration graph due the fact that the column, which serves the valve much like the leg serves the piston, is fully constrained. In the case of the piston we said that due to its ability to rotate within the x-y plane it applies an uneven force however in the case of the valve the column's rigidity will contribute to a uniform force on the valve rod for the duration of motion.

Crank

We monitored the angular position of the crank over time for one full revolution. Since the motor is applied directly to the crank with a fixed angular velocity we would expect a linear graph with a slope equivalent to the motor's speed. The plot of our results aligned with our expected values and our line of best fit equation can be represented by the equation y=1440t. Here the slope of 1440 matches with our assigned engine speed of 1440deg/sec and a lack of y intercept indicates the graph originates at the origin of an angular position of zero. This zero position was established to be when the crank lies horizontal, it's top hole and crank screw directly to the left of the center hole and crankshaft.

Piston and Valve Motion with Respect to Crank Angle

The three degrees of motion for both the piston and valve were also graphed with respect to crank angle. These graphs appear very similar in shape as both time and crank angle increase linearly during engine motion. Aside from the values located on the x-axes and their respective ranges, each of the six motion graphs are nearly identical in shape. The domain of 0.25s for the first six motion graphs corresponds to a total crank angle of 360deg respectively. Much like their relationship to time, all plots appear largely uniform in amplitude for both halves of the crank revolution. The only exception to this uniformity being the piston acceleration which differs in amplitude for the two directions of motion for reasons previously discussed.

Leg & Valve Crank

By placing angle measures at the connection points between the leg and the base sub assembly as well as the valve crank and base sub assembly we were able to create two plots. The angular position of the leg with respect to time for one full crank revolution varies ever so slightly at a maximum of above 0.53deg from its zero position. This position was established when the leg is aligned vertically with the right plane of the assembly. The maximum angular displacement from the vertical occurs at the beginning of the revolution and corresponds to the period in time when the piston is located at the very bottom of its stroke. As the piston rises through its initial position the leg vertically aligns itself briefly before decreasing in angular position once again at the top of the piston's stroke. As discussed in the piston motion section this causes the motion graphs for the piston to deviate ever so slightly from a perfectly symmetric wave.

The angular position of the valve crank with respect to the base feature largely follows a cosine wave over the course of one crank revolution. The plot indicates an initial angular offset of about 3.5deg and follows the line of best fit y=-6.568(8pi*t)+9.97 over the course of the crank revolution. This graph appears largely uniform for reasons discussed in the valve motion discussion. The rotation of the valve crank is responsible for valve translation and because the column holds the valve crank in place the piece may rotate with consistency and apply a constant force to the valverod/valve.

Beam

In order to determine the angle of the beam with respect to ground during engine motion we created two separate plots: leg angle with respect to ground and beam angle with respect to leg. The leg angle graph and its effect on piston motion was discussed above. The graph of beam position with respect to the leg mimics a sine wave that begins and ends at an angle just above 90deg. At the crank's initial position, the leg and beam are not perpendicular to one another. The leg is positioned slightly off from its zero (vertical) position and the beam as a result does not lie parallel to the ground. This offset contributes to the nonzero y-intercepts of both plots. The summation of the data for both plots was used to create the resulting graph that is heavily represented by the beam angle with respect to leg graph. This is due to the difference in magnitude of angle change of each of the two measures. The change in angle of the leg is incredibly small, achieving a maximum displacement at 0.53deg, in comparison to the max displacement of the beam which is about 7deg. The final plot representing the complete data set has a line of best fit represented by the equation $y=-6.25\sin(8\pi(t+0.003))-1.39$ and is nearly identical to the plot showing the beam angle with respect to the leg.

Trace Curve

Upon further examination of the trace curve created using a datum point located at the center of the eccentric strap we observe a small ovular shape that is elongated along the length of the eccentric strap. This curve is representative of the path of any point along the eccentric strap during a singular crank revolution. The reason this curve resembles an oval is due to the simultaneous rotation of the shaft about the eccentric as well as the motion of the strap with respect to its connection to the valve crank. The eccentric strap is oriented concentric to the portion of the eccentric that lies off-center from the crankshaft. Therefore, as the crank/crankshaft rotate uniformly the off-center extrusion of the eccentric will trace a large, circular path. This path coupled with the strap's ability to move laterally within the xy plane due to the rotational freedom of the valve crank on its opposing side generate the given trace curve.

Appendix A: Full Engine Model with Fasteners

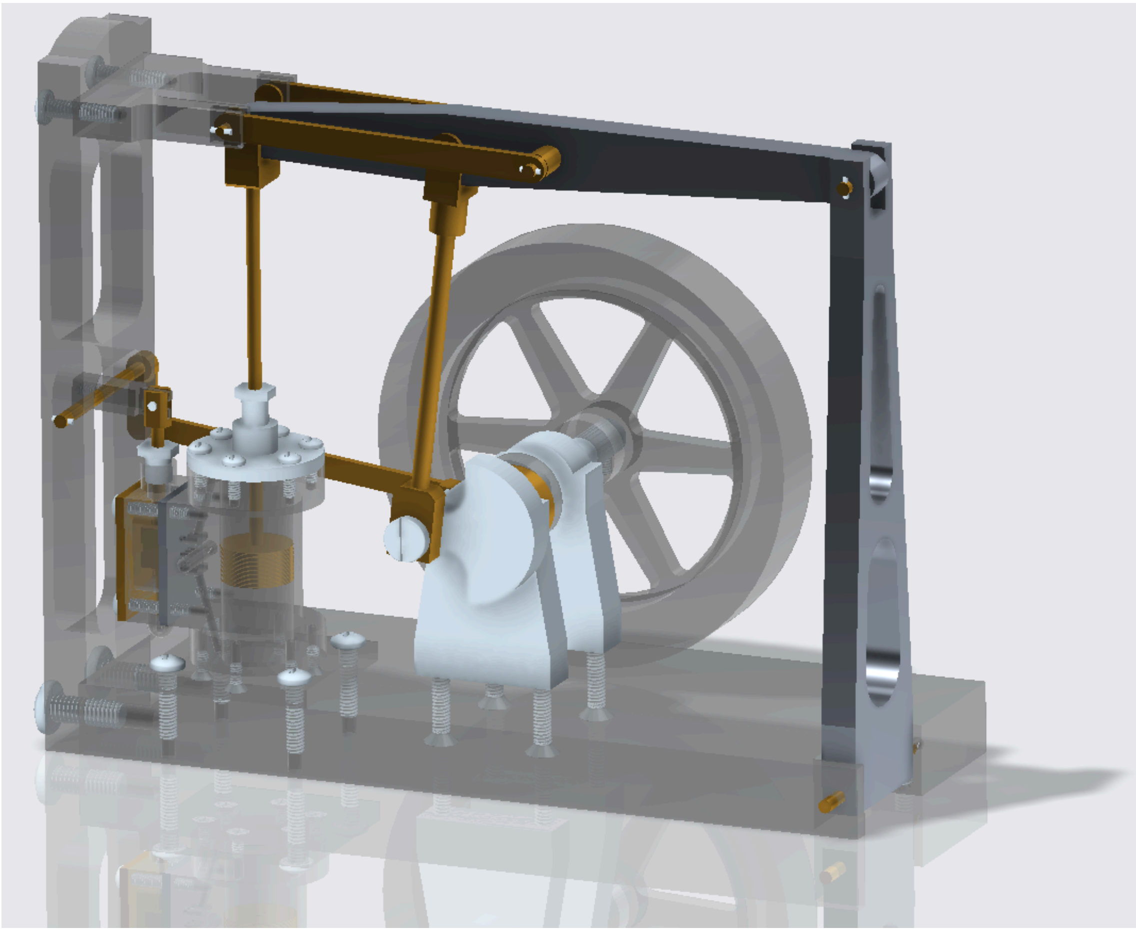


Figure 79. Final working assembly with fasteners is shown above.