ASEN 3113: Experimental Lab 1 - Stirling Lab

ASEN 3113: Thermodynamics and Heat Transfer
University of Colorado at Boulder

Please refer to Canvas and the class schedule for lab groups, due dates and times.

IMPORTANT: Unless otherwise stated, please turn in group reports at **the beginning** of each lab session. There will be **one lab report per group**, where each group member will include a conclusion section of their own that will be submitted individually and separately.

Objectives

- Understand the thermodynamics of the Stirling cycle.
- Describe the thermodynamics of a displacer-type Stirling engine.
- Use thermodynamics to quantitatively analyze power cycles.
- Write a technical lab report. The lab report must be completed in the AIAA format. Please visit the AIAA homepage* for FAQ's regarding this layout.

Experimental Background and Description

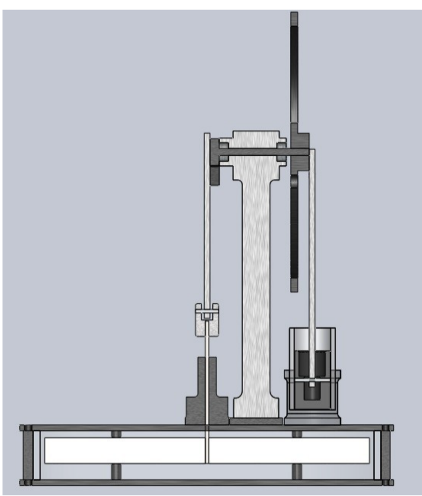


Figure 1: Gamma-type Stirling Engine

Out of the various sub-categories of Stirling engines, the one chosen for this lab is a gamma-type engine (Figure 1). This implies that the power piston is housed in its own cylinder, but both the power and displacer pistons are connected to the same flywheel. The power piston is connected to the displacer piston by the same crankshaft, but their phases are offset. In the engine used for this lab, the displacer piston is made out of an insulating material (Styrofoam) and it does not seal the inside of the large cylinder. The purpose of the displacer piston is to push the working fluid (air) from one thermal reservoir to the other. The air freely flows around the foam displacer to travel from the hot to cold side and vice versa. This displacement of the working fluid creates a forced convective heat transfer and thus creates pressure gradients across the main displacement piston housing which are used to drive the power piston. Stirling engines are classified as an external combustion engine and these engines are ideal for situations that require a very efficient non-internal combustion engine. The ideal example of this situation is providing power to spacecraft sent into deep space where solar cells are impractical.

Stirling engines have been used in many aerospace applications including providing electric power to spacecraft where solar power is not practical, and acting as a cooling system to prevent electric parts from overt-heating. A Stirling engine has the potential to produce the same amount of power as a traditional RTG, while using only one fourth the amount of plutonium (Pu-238). Though Stirling engines are extremely efficient and convenient, they are prohibitively expensive to research and produce. Due to this cost, most Aerospace companies choose to use more conventional means to power their spacecraft.

*AIAA Author's Toolkit; https://www.aiaa.org/techpresenterresources/

Understanding Stirling Engines

The following links may be useful in visualizing and understanding Stirling engines:
http://auto.howstuffworks.com/stirling-engine.htm
http://en.wikipedia.org/wiki/Stirling_engine
http://www.animatedengines.com/ltdstirling.html
http://www.ohio.edu/mechanical/stirling/engines/engines.html

Measurements

- Change in internal pressure (psi)
- Top of top (cold) plate (°C)
- Bottom of top (cold) plate (°C)
- Top of bottom (hot) plate (°C)
- Bottom of bottom (hot) plate (°C)
- Electrical current to the heater (A)

Necessary Data

This is the data that you will need for completing your analysis. The rest of your measurements, such as volume, should come from the CAD model of the engine.

Heater Voltage	48 V
Optical Switch: Logic Gate	0 = Gate obstructed

Required Hardware

- National Instruments CompactDAQ (referred to as cDAQ) (Figure 2)
- Stirling engine (Figure 3)
- Blue BNC cable for pressure transducer to cDAQ connection (Figure 4)
- Stirling engine control box and cables (Figure 5)
- cDAQ power cable
- cDAQ USB data cable

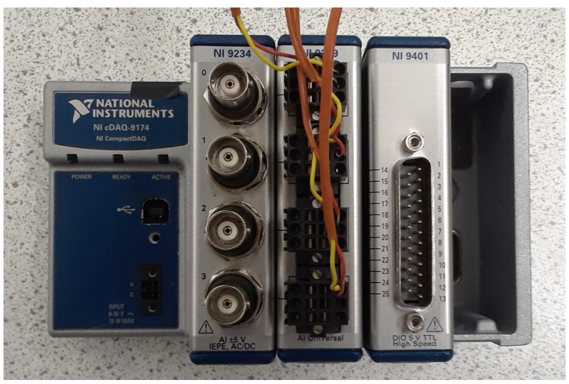


Figure 2: cDAQ

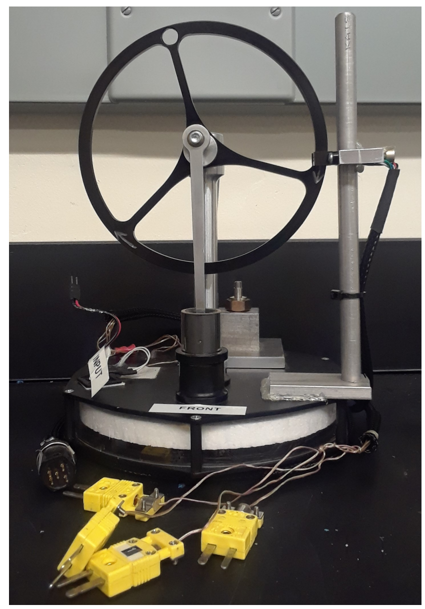


Figure 3: Stirling Engine

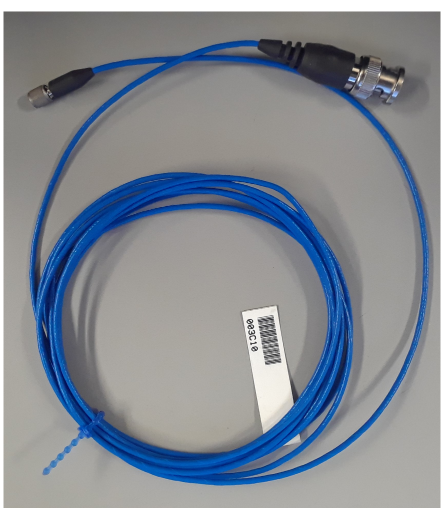


Figure 4: Blue BNC to Pressure Transducer Connection

Figure 5: Control Box

Lab Assistant Setup Procedure

1. Remove the Stirling engine and control box from the storage bin. Verify that the number on the back of the control box matches the number next to the pressure transducer on the Stirling engine. Attach the red and black power cable (small and braided) from the control box to the heater input attached to the Stirling engine. Polarity does not matter.

2. Remove the cDAQ (large piece) and its three units (smaller pieces) from the storage bin. Attach the USB data cable from the cDAQ to the computer in use. Attach the power cable to the cDAQ and then plug the other end into an outlet. Insert each of the cDAQ units into their respective channels as shown above in Figure 2. The NI 9234 unit goes into Slot 1, NI 9219 goes into Slot 2, and the NI 9401 goes into Slot 3.

    (a) Double-check to make sure that the cDAQ is labeled as cDAQ1. To do this open the NI Max program (Start Menu-Data Acquisition-NI Max). Click on the drop-down list on the left under 'Devices and Interfaces' to examine the current devices connected to the computer. Your screen should look something like Figure 6 below.

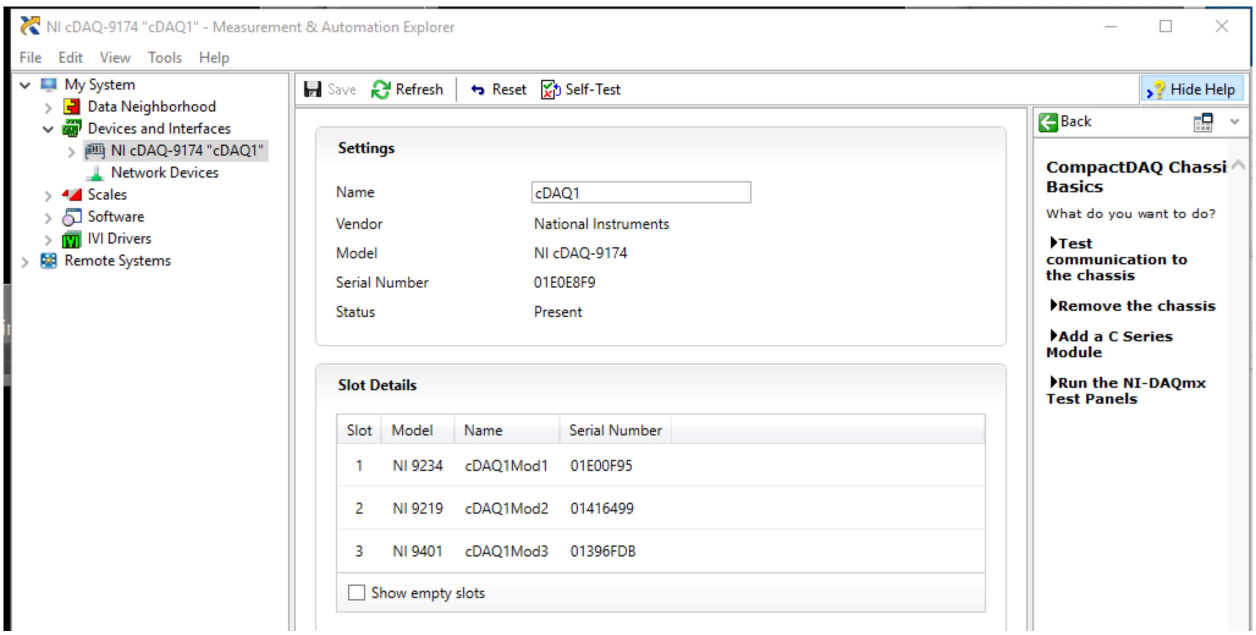


Figure 6: Screen Output from Measurement and Automation Program

3. Plug the thermocouple outputs (yellow prongs) from the Stirling Engine into the corresponding yellow inputs on the NI 9219 unit in the cDAQ. The top thermocouple input on the cDAQ will be labeled 0, for Channel 0. The thermocouples are then stacked in ascending order with the last one being Channel 3. All four thermocouples from the Stirling engine should be labeled. Verify that these thermocouples are matched accordingly.

4. Attach the Blue BNC cable to the top of the pressure transducer on the Stirling Engine. Connect the other end of the Blue BNC to Channel 0 of the NI 9234 DAQ module.

5. Examine the Control Box to ensure all connections to the board are complete. The connections to note are the Optical and DAQ connections. The DAQ connection has grey wiring coming from the cDAQ, whereas the Optical has grey wiring coming from the DB-25 connector.

6. From the control box, attach the DB-25 pin connector to the NI 9401 unit on the cDAQ module. It will only fit one way.

7. Attach the BNC cable labeled “1” from the control box to the Channel 1 input on NI 9234 unit on the cDAQ module with a BNC coupler. This cable is the current measurement.

8. Attach the other BNC cable labeled “2” from the control box to Channel 2 on the same module. This is the optical switch/encoder measurement.

9. The control box requires three separate power cables. The first black cable plugs into a normal AC outlet (DO NOT plug in unless VI is actively running or Stirling Engine could overheat). The second standard wall AC cord powered the cDAQ. The third power connection requires a 5V power supply and no more than 0.15A (We will use the PILOT workstation built-in fixed triple supply). Use the red and black banana connectors for the 5V power source. **Polarity DOES matter here!** Attach 5V power banana cables as shown in figure 7, red banana to 5V port and black banana to black port - GND is not necessary. Turn on the PILOT supply using the push button and notice the button turn on blue.

Figure 7: PILOT Fixed Triple Output Power Supply (5V)

Experimental Procedure

1. Open the file labeled "StirlingEngine" located in the "Courses (Z:)\AES\Software\VIs\ASEN 3113\Lab 1 Stirling Engine\" directory.
2. Before starting the program (VI), make sure that the drop-down box in the VI labeled "Stirling Engine Number" corresponds to the Stirling engine that is being used. This is used to ensure that the proper sensor calibrations are matched with the corresponding engine.
3. Fill in the box labeled "Desired Temp Diff." This is the temperature differential in °C (Celsius) that the automatic controller built into the VI will maintain. You will need to choose a temperature difference $\geq 7°$ C to get good results (MAX of 12° C).
4. Start running the VI by clicking the white arrow in the upper left corner. It will ask you a location to save your data. We recommend you save to your Google "Drive File Stream" since local files are erased.
5. Once the VI successfully begins to run, plug in the 48V power cable and the current to the heaters should immediately spike in the VI meaning proper connection has been made.
6. **NOTE:** If the current does not begin oscillating in a square wave pattern once desired heat difference is reached, then the Mosfet may have been damaged or is not making correct contact on the control board. If this is the case, immediately unplug the 48V power from the wall to avoid damaging the Stirling engine.
7. The engine will take a few minutes to warm-up. Verify that the temperature has reached steady state using the Actual Engine Temp Diff box.
8. Once the engine has exceeded a temperature differential of 7° C, gently spin the flywheel in the direction indicated on it—the engine should begin to run. The direction is clockwise when looking at the power piston side. If it does not maintain rotation, please contact a lab assistant.
9. **IMPORTANT:** Once the engine is running, look at the plot labeled "Pressure." Check that the pressure data is a sine wave with an amplitude of approx. ± 0.03 to ± 0.06 psi. Refer to Figure 8 . If the pressure is lower than this value, please contact a lab assistant.

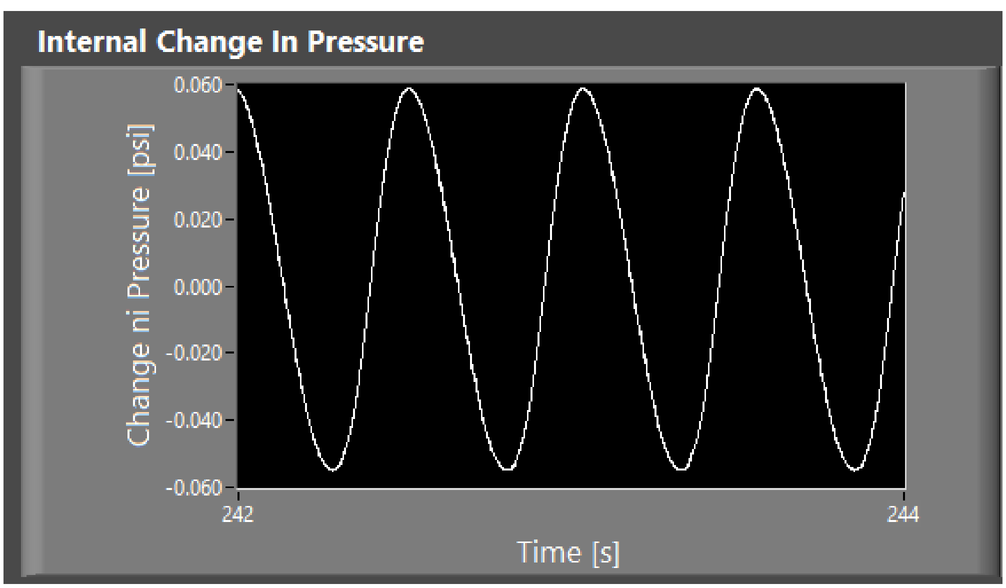


Figure 8: Pressure Plot as Seen in LabView

10. Once the engine has reached the desired temperature differential, **wait** until temperatures Bottom of Bottom and Top of Bottom have become the same (or extremely close, within 1 degree is desirable). The closer to equilibrium these temperatures are, the less heat transfer is going through the bottom plate, therefore, the assumption that all the heat generated by the kapton heater is going into the engine is better held.

11. Let the engine run until it reaches 'steady state' (at least two more minutes). The current plot should also reach a normal duty cycle.

    Common Problem: Make sure that the 5V power supply is turned on. If it's not turned on, you'll see noisy data centered at zero instead of a duty cycle in the heater's amperage plot.

12. Once the temperatures have converged, press the "Stream Data to File" button. Wait for about 5 cycles of the pressure sine wave to complete and then press the button again to stop streaming data. Data collection is now finished! The data file is just a text file (even though it may have an .lvm extension). It records: time (seconds), pressure (psi), top of top thermocouple (Celsius), bottom of top thermocouple (Celsius), top of bottom thermocouple (Celsius), bottom of bottom thermocouple (Celsius), current to the heater (Amps), and the optical switch data (logic 0 or 1).

13. Repeat steps 2-9 twice more at different temperature differentials. You should end up with a total of three data files for three different temperature differentials that you will analyze throughout this lab.

14. Stop the VI (red STOP button in upper right corner) and go to Step 2 and repeat for each desired temperature differential. You must create a different filename for each separate test.

Analysis

NOTE: Each engine runs at a different RPM and efficiency. Do **NOT** mix data from separate engines as this will give you erroneous results.

Pre-Analysis

RPM Analysis

To start you will need to **obtain the RPM and average temperature difference** from the data you collected. Think about which set of data to use for these values: only one sensor measures the rotation state of the flywheel but several measurements can be used to find the temperature differential. State which sensors are used in the calculation of the temperature differential and provide a justification for this decision. *Hint: The RPM values should be roughly 50-180 and should increase as the temperature differential increases.*

After collecting your RPM data, open the provided SolidWorks model (which need not contain the four-spoke flywheel). Using this model, calculate the approximate minimum internal working volume of the engine. Then, follow the included supporting documentation (Appendix D) on how to conduct the initialized motion analysis in SolidWorks. Data from this motion analysis will provide the linear displacement of the pistons as well as the angular displacement of the wheel as a function of time.

When you run the motion analysis, make sure that you simulate enough points to give you a good continuous curve for the displacements of each engine part. Also, note the coordinate directions within the model and the units in which the data is output.

Note that there is a small (about 1mm) hole in the top plate of the engine that allows air to flow between the displacer piston and the power piston. This is so small that it can be neglected as part of the air in the cylinder, and is not included in the CAD model. Finally, assume that when the power piston is at its lowest point, the bottom surface of the power piston touches the upper surface of the top plate.

Also note that the data extracted from the motion analysis will not directly line up with the pressure data, as their sampling rates will be different. These two datasets can be correlated in one of two ways. Either the associated time vectors can be used to interpolate the SolidWorks data for each point in the pressure data, or the SolidWorks data can be fit to the pressure data using the angular state of the flywheel. Finally note that the motion analysis begins when the hole in the flywheel is *directly* in line with the center of the optical sensor (not when the sensor is in line with the edge of the hole).

Please use MATLAB to double check the RPM output from SolidWorks. This will confirm that the motion analysis ran successfully.

Work Integration

To find the work in and out of the system, you are going to need to use numerical integration. The easiest ways to do this is in MATLAB are using either the trapz function or the polyarea function. It is strongly recommended that you read the MATLAB documentation on these two functions to understand how they work. You will also need to understand the following two points not mentioned in the help file:

- If you use the trapz function on a circle, what will the function return as a result?
- If you start the integration at different points within the data vector or split the data vector up into different sections, does this affect your end analysis?

Finally, be sure to remember the rules about integrating over the origin and what this will do to your final results.

Final Analysis

To present your final analysis you will need to answer the following questions within your report. (See the grading rubric for additional requirements). Your final report will need to be in the AIAA conference paper format, but your content will still reflect that of a lab report. To elaborate, you will still need to include sections that you would normally omit if you were truly writing a conference paper. An example of one of these sections is explaining how a Stirling engine works. You are required to do this as you still need to display that you understand the material included within this lab.

1. *What is the maximum (Carnot) thermal efficiency of the engine?*
2. *Derive an expression for the ideal efficiency of a Stirling cycle. (Use the four thermodynamic processes to develop the expression).*
3. *How much work is produced by the engine? Justify the order of magnitude you see for the work within the engine. Include the amount of work and heat flowing into and out of the engine. What is the net work?*
4. *What is the actual thermal efficiency of the engine? (Efficiencies ($= \frac{W_{net}}{Q_{in}}$) are usually less that 0.05%)* ***NOTE:*** *recall Ohm's Law P = IV*
5. *Compare this cycle to other power cycles (Otto, Brayton ...). Is there an advantage to using this kind of cycle? (This is one of the most important questions you will be asked in your career. If your work does not present any advantages to current systems, your financiers will ask why you are doing it.)*
6. *What are the errors and real world components that influence the actual efficiency?*

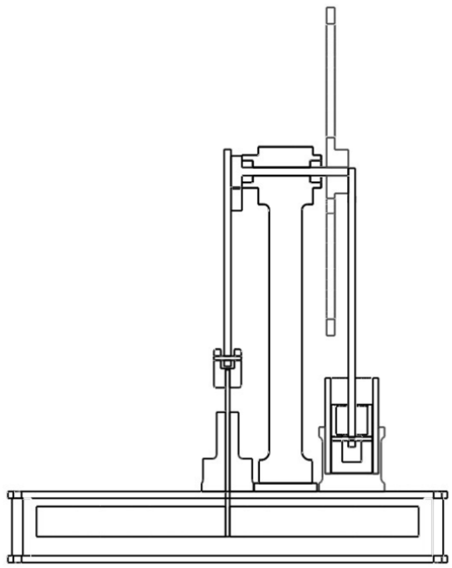
Discussion

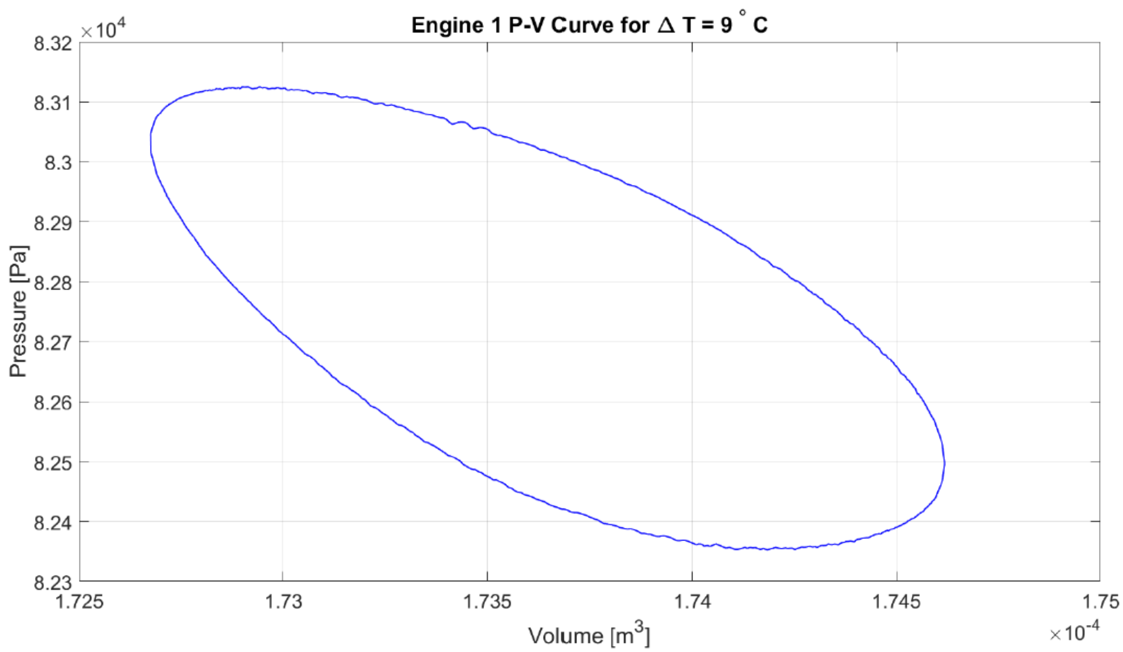
- Overlay one of your P-V diagrams onto an ideal P-V diagram that includes units. As in the prelab, identify each of the thermodynamic processes and discuss the similarities and differences to your data.
- Justify the order of magnitude that your W_{cycle} comes out to be. How close is your W_{cycle} to the theoretical maximum given the same input heat Q_{in}?
- Research and discuss a practical application of Stirling engines as they are used in aerospace engineering. If possible, please note the Carnot efficiency and thermal reservoir temperatures of this application. What are the advantages and disadvantages of the type of Stirling engine chosen for this application? How does this application compare to the Stirling engine used in class? The ASRG project may be used as your research topic.
- Discuss the sources of error within your models and experimental data including why using the W_{out}/Q_{in} ratio is wrong for this experiment.
- Discuss the theory as to why the thermal efficiency of this engine at steady state approaches zero.

Report Rubric

POINTS	DELIVERABLE	SECTION
20	**Pre-Lab**	
5	**Lab Report**	**Abstract** • This should be a concise description of the whole lab that includes important aspects of the experiment, data analysis, and final efficiencies.
15		**Introduction** • Qualitative description of the Stirling engine cycle • Relevance of the Stirling cycle in present day society • Advantages and disadvantages of using this cycle over other cycles in common use today (e.g. Otto, Brayton)
10		**Experimental Procedure** • This should be a high level procedure that outlines the important steps you went through during testing. • Please make a list of steps and not a block of text.
30		**Results** • **P-V diagrams**: Present P-V diagrams for all of your trials, using the volume calculations that were extracted from the engine model. • **Work and Heat Transfer Calculations**: Show the values for the work in/out and the heat transfer in/out of the system. • **Efficiency Results**: Calculate the Carnot, ideal, and actual efficiency for each of your trials. Don't forget to show your work!
20		**Analysis** • **Pre-Analysis**: Complete each of the pre-analysis steps and show your work. This includes RPM and work integration. • **Final Analysis**: This should include discussion of work and Q_in, comparison to other cycles, and calculation of errors.
15		**Discussion** • P-V diagram overlay and discussion • Justify orders of magnitude for W_{cycle} and Q_in • Discussion of research and sources of error
5		**References** • Please reference all sources used when completing research for this lab. You do not need to reference lecture or the textbook.
10	**Individual Conclusions**	• Concluding remarks and suggested improvements. These will be graded on knowledge and insight. • Individual conclusions will be completed by each group member and submitted separately from the report.

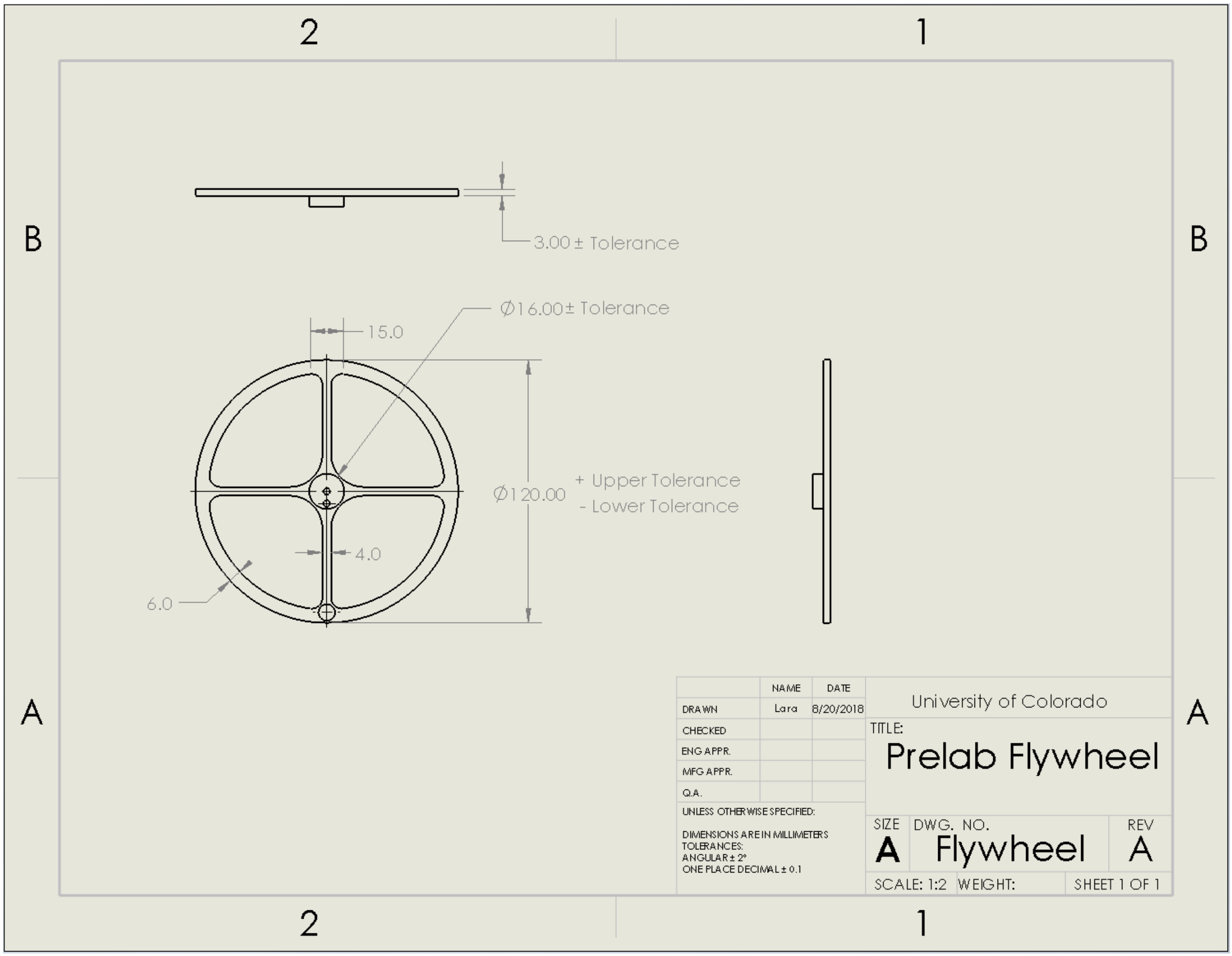
Appendix A





Engine 1 P-V Curve for Δ T = 9 ° C
×10^4
8.32
8.31
8.3
8.29
8.28
8.27
8.26
8.25
8.24
8.23
Pressure [Pa]
1.725
1.73
1.735
1.74
1.745
1.75
×10^-4
Volume [m^3]

Appendix B



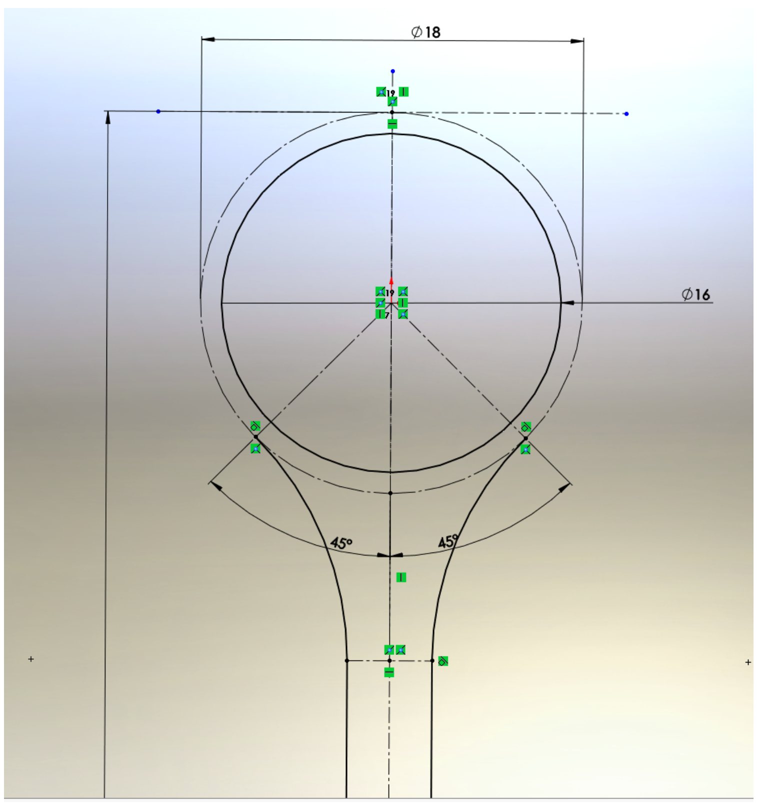
3.00 ± Tolerance
Ø16.00± Tolerance
15.0
Ø120.00
+ Upper Tolerance
- Lower Tolerance
4.0
6.0
NAME
DATE
DRAWN
Lara
8/20/2018
CHECKED
ENG APPR.
MFG APPR.
Q.A.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR ± 2°
ONE PLACE DECIMAL ± 0.1
University of Colorado
TITLE:
Prelab Flywheel
SIZE
A
DWG. NO.
Flywheel
REV
A
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

Appendix C: SolidWorks Flywheel Supporting Documentation

1. Copy the "Flywheel" part from the directory "courses Z:\AES\lab-documents\ASEN 3113\Lab1 Stirling Engine\SolidWorks model". Open the "Flywheel" file, and begin by editing the sketch on "Boss-Extrude 1".

2. With the circumferential encoder hole on the bottom, remove the top two spokes entirely, but leave the spoke adjacent to the encoder hole intact. Remove all curves and construction lines near the center. Create a construction circle in the middle with a 9mm radius. Draw two more lines for construction that are 45°off of the center line. To do this use the smart dimension tool by clicking on both lines to set the angle between them.

3. Using two three point arcs, create fillet between the vertical lines of the spoke and the construction circle that you just made. Constrain the fillets to be tangent to the vertical lines and the construction circle. Make sure (using dimensions, construction lines, or another technique) that the tangent points on the construction circle are symmetric about the spoke and take up 90°of the construction circle:



4. Revolve the spokes by using "Circular Pattern" feature found under Tools ⟩ Sketch Tools. Click on each line you would like to rotate.

5. Exit the sketch.

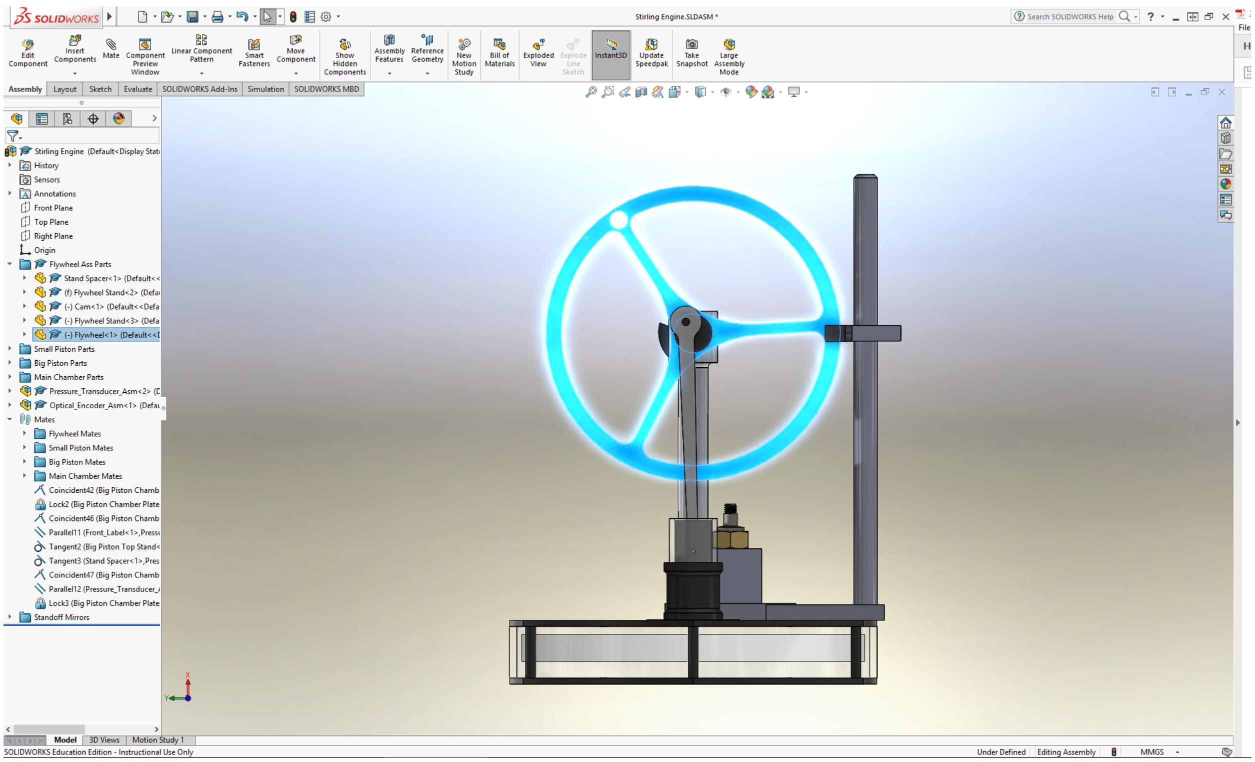
6. **Create the Part Drawing:** Click File: Make drawing from model. Add views consistent with Appendix B. Hint: Uncheck "Only show standard formats" and use "A (ANSI) Landscape".

7. Annotate the part drawings with the necessary dimensions using Smart Dimension. Also indicate tolerances as shown on the drawing in Appendix B.

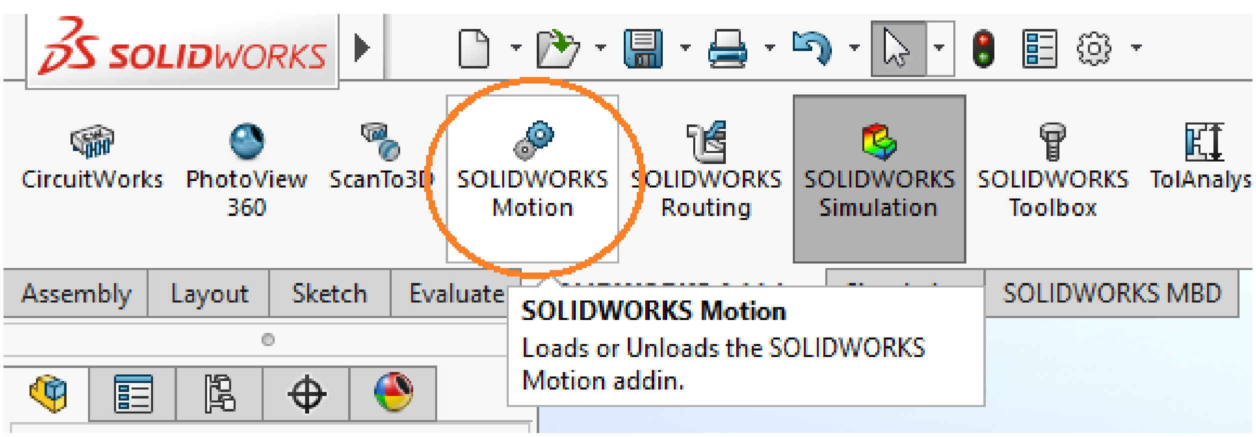
8. Save any necessary changes/files.

Appendix D: SolidWorks Motion Analysis Supporting Documentation

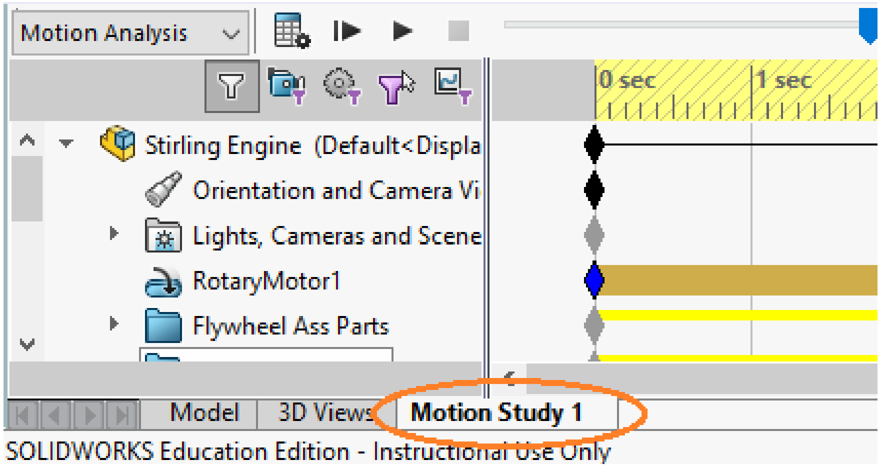
1. Load the ”Stirling Engine” assembly file located in “courses Z:\AES\lab-documents\ASEN 3113\Lab1 Stirling Engine\SolidWorks model”.
2. If you have not done so already, click and drag the flywheel to move the components of the engine. Note the offset of each of the components.



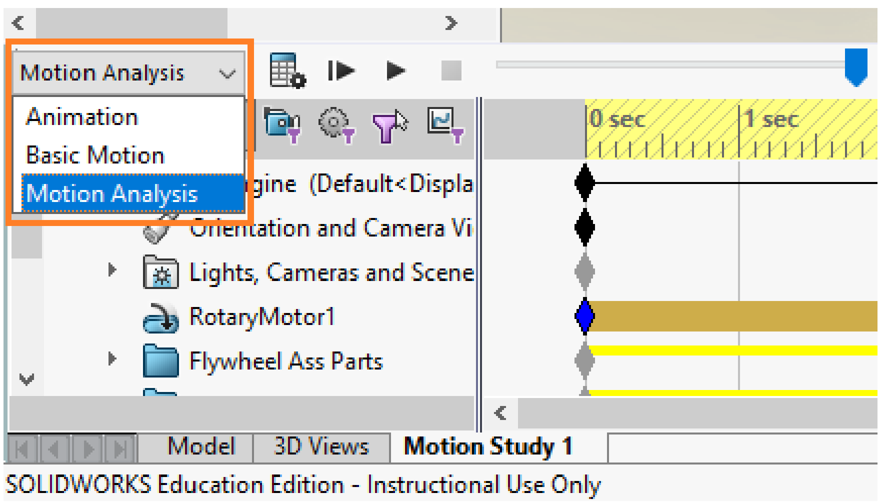
3. Import the SolidWorks Motion module by clicking on the SolidWorks Motion button within the SOLIDWORKS Add-Ins Tab of the Command Manager Toolbar.



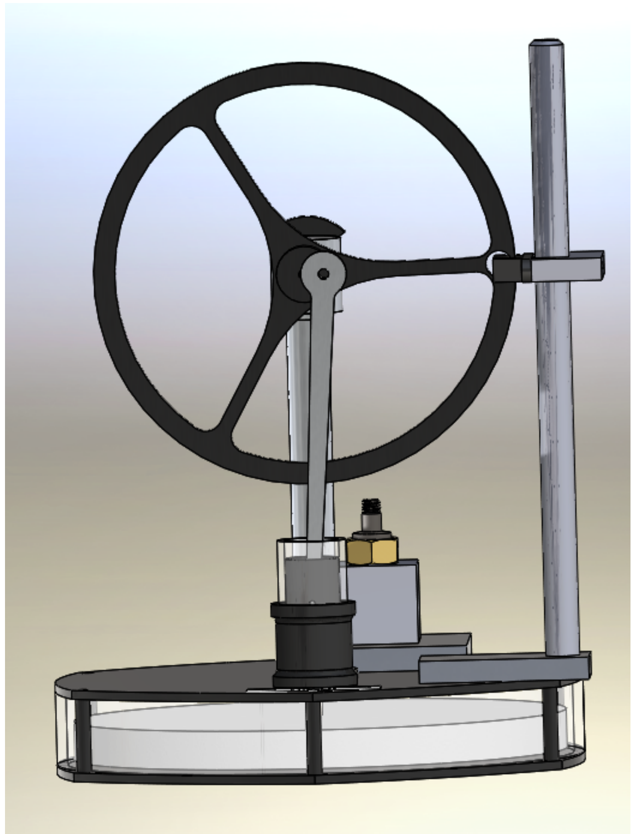
4. Click on the Motion Study tab on the bottom of left corner.



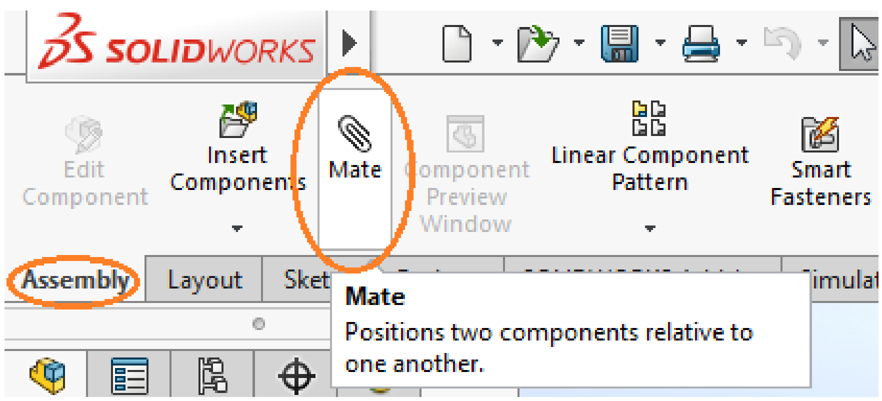
5. Choose Motion Analysis from the drop down menu from the left hand side of the bottom bar that should have appeared after you clicked on the Motion Study tab.



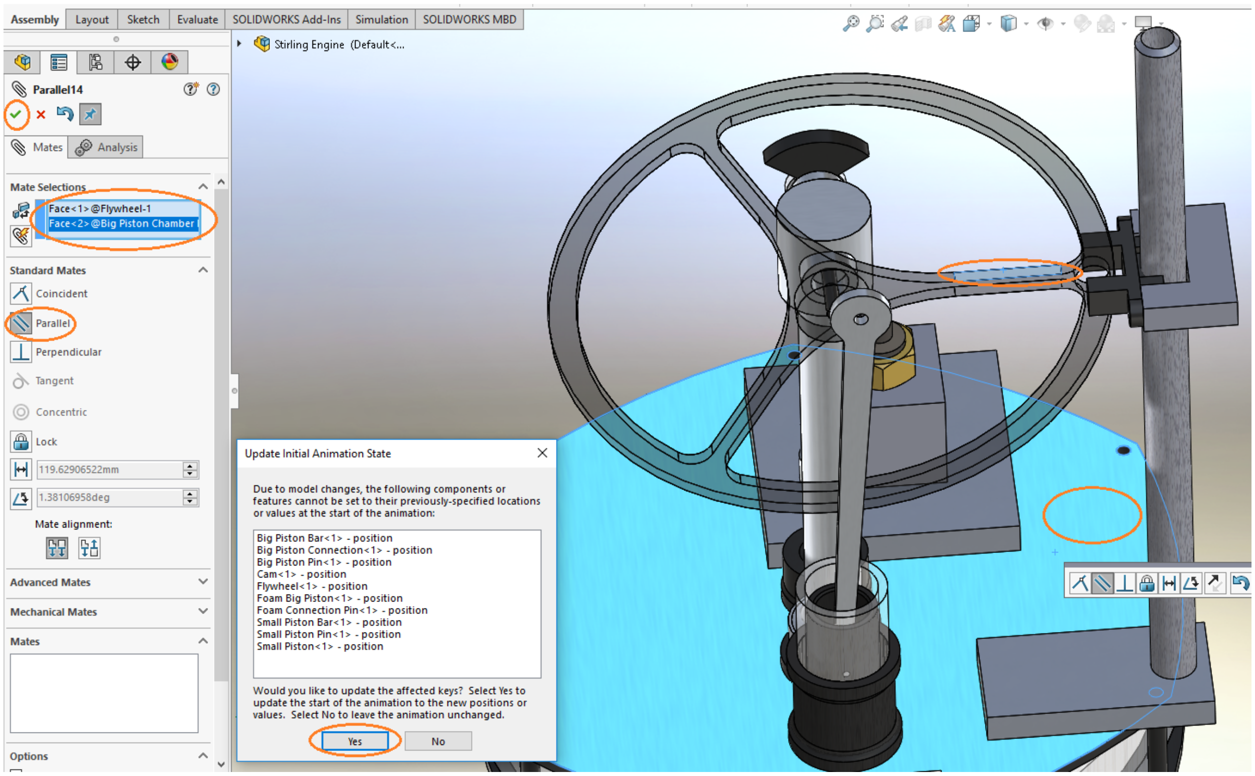
6. **Make sure that your time bar is set at zero for the following two steps.** Visually verify that the hole within the flywheel is aligned with the optical switch. In this position the flywheel arm connected to the hole should be parallel to the top plate of the main cylinder. If this is not the case, the easiest way to set this is to define a parallel mate* between the top plate and the flywheel arm with the hole. After you accept the mate, either suppress or delete it so that the flywheel is free to spin.



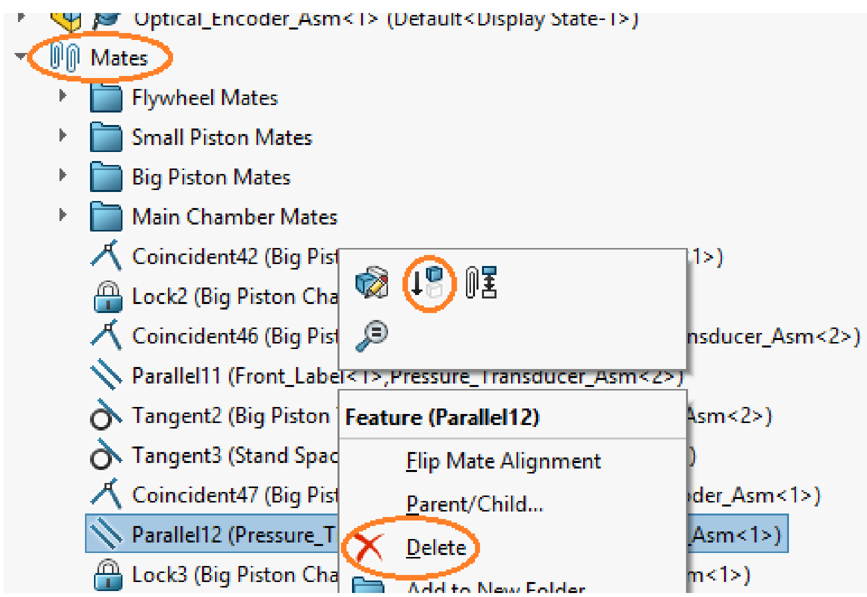
*To define a Mate, click on the Assembly Tab and then select Mate.



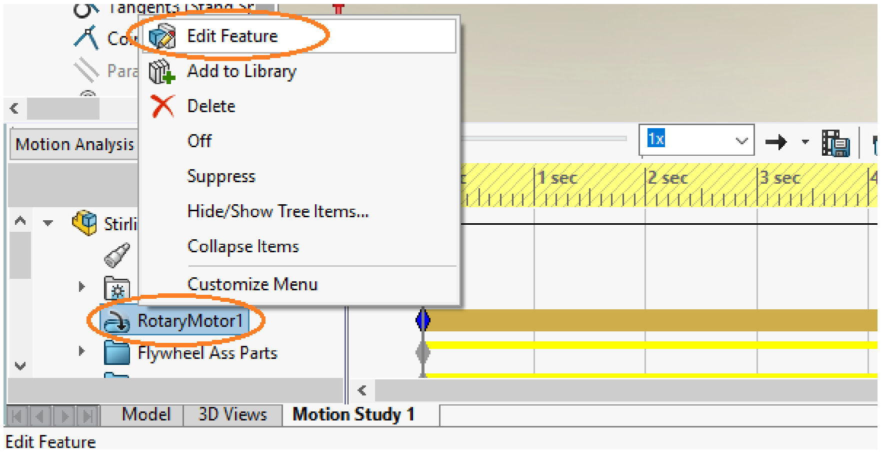
Select Parallel as the type and click on a rectangular face of the flywheel arm with a hole, and then select the top plate to mate them together. You may get a pop-up window to update the animation state – just click "yes". To apply the specified mate click on the green check mark in the upper left hand corner.



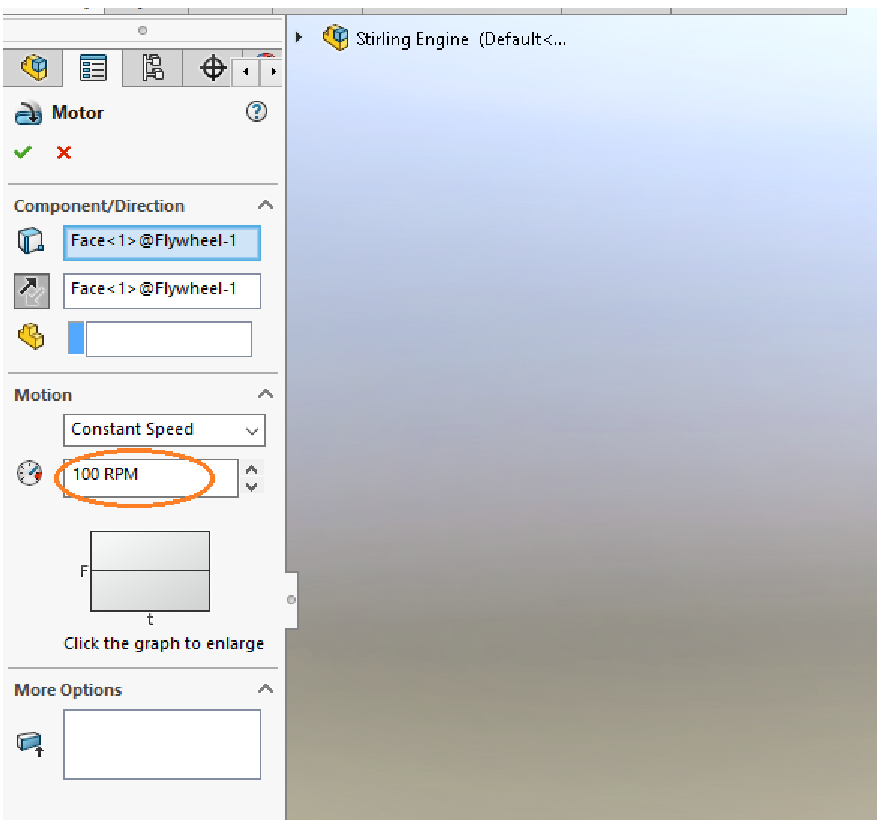
To suppress a Mate, expand the Mates section in the left side bar. Right click on the mate you would like to suppress. You may now delete the mate entirely or simply suppress it.



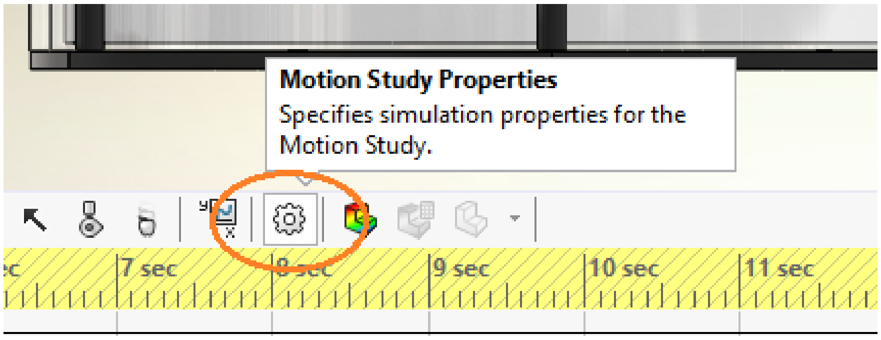
7. Right click on the Rotary Motor1 in the lower scroll bar on the left hand side. Click on edit feature. You will need your calculated RPM for your motor for the next step.



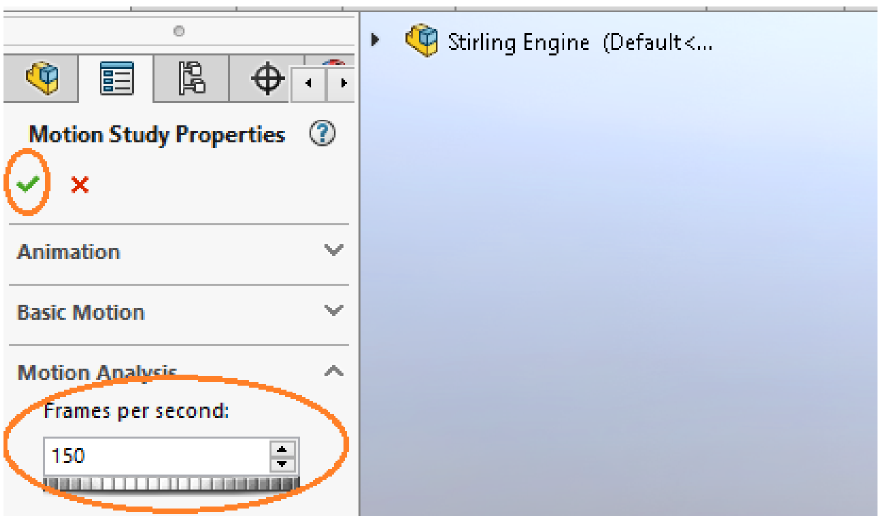
8. Enter your average calculated RPM into the field on the left hand side within the sidebar.



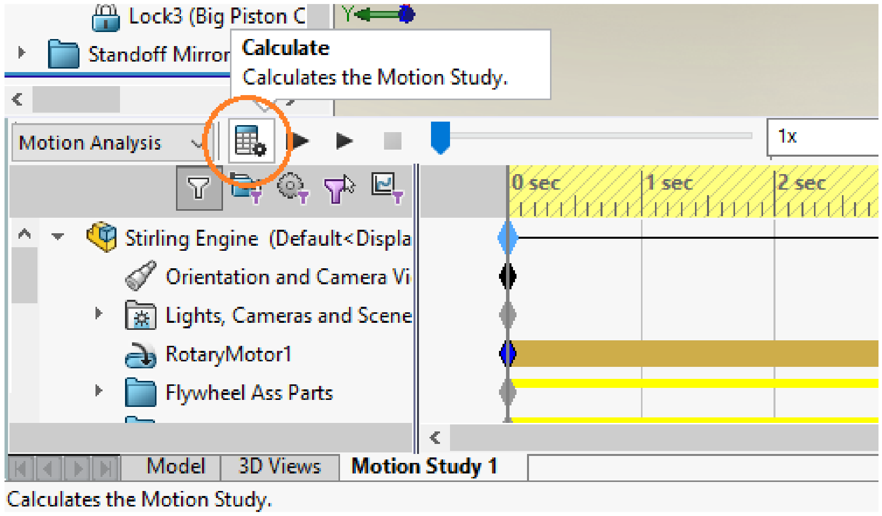
9. After you have entered your calculated RPM, click the check mark at the top of the left side bar. Now click on the properties icon at the top of the bottom motion study bar
Occasionally, this RPM data will not save. Please re-open the RotaryMotor1 feature to verify that your RPM input was saved.



10. In the left side bar under the Motion Analysis tab enter in the amount of frames per second that you want the simulation to calculate. Make sure that this number is large enough to give you a good data set but small enough that you will not drastically slow the simulation. Now click on the check mark in the left side bar.
After completing this motion analysis, double check your RPM and adjust the Frames per Second as needed.

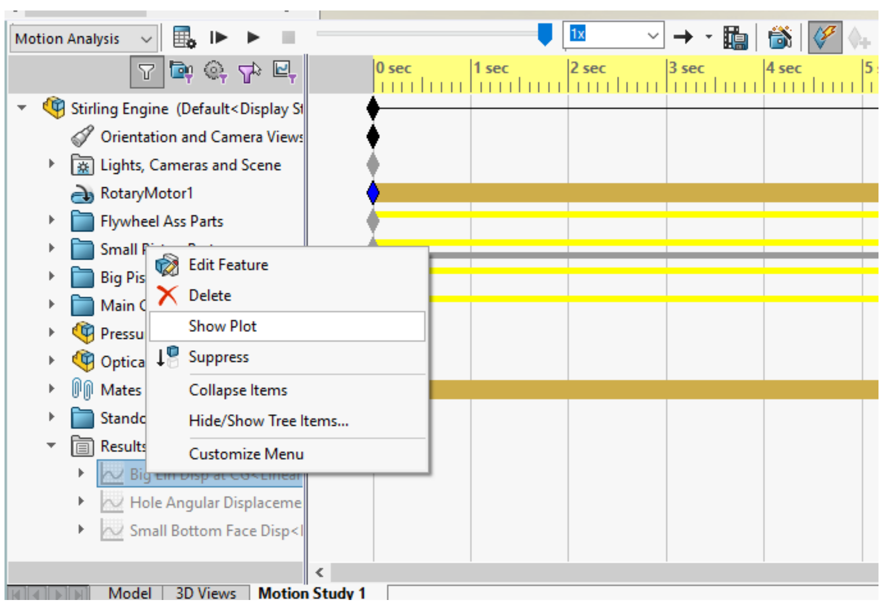


11. Next, run the calculation. To run the calculations, click on the Calculate button on the left hand side at the top of the bottom bar. This will take a couple minutes. Do not run any other programs while the simulation is calculating.

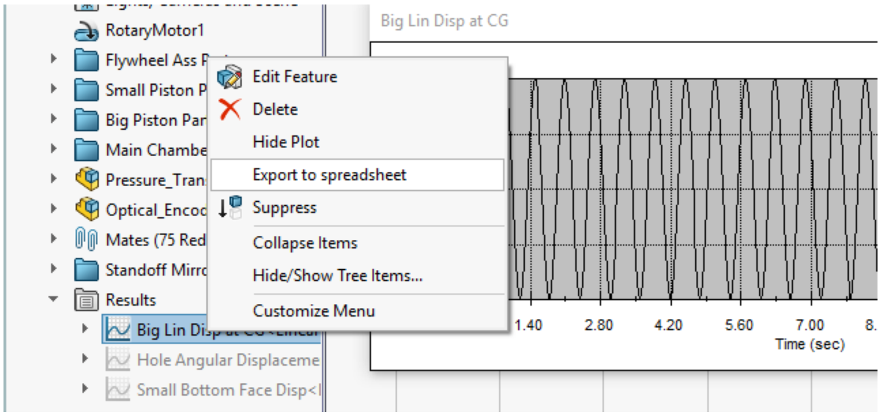


12. Wait for the simulation to finish. You will know when it is finished when in the time bar the orange line reaches the "keys" or the diamond shapes on the right hand side. This is the time limit for the simulation and has been set to guarantee that the simulation will reach steady state for the lower RPM limits that you might experience.

13. Expand the results folder within the bottom left sidebar. Click on each of the plots listed within the folder and click on show plot to view the results from the calculation.



14. Right click on the plot names within the left sidebar again after they appear. Click on the export to spreadsheet to export the data to excel from which you can save the data into a format that you can read into MATLAB. The data labeled Small Bottom Face Displacer shows the position data for the power piston which will provide volume information. (*Note: Make sure that you have selected "show plot" and the plot name is no longer grayed out. If this is not done, export to spreadsheet will not appear as an option.*)
Double check the RPM output from this analysis using MATLAB to verify the motion analysis ran correctly.


RotaryMotor1
Flywheel Ass
Small Piston P
Big Piston Par
Main Chambe
Pressure_Tran
Optical_Encod
Mates (75 Red
Standoff Mirro
Results
Big Lin Disp
Hole Angular Displaceme
Small Bottom Face Disp<
Edit Feature
Delete
Hide Plot
Export to spreadsheet
Suppress
Collapse Items
Hide/Show Tree Items...
Customize Menu
Big Lin Disp at CG
1.40
2.80
4.20
5.60
7.00
Time (sec)