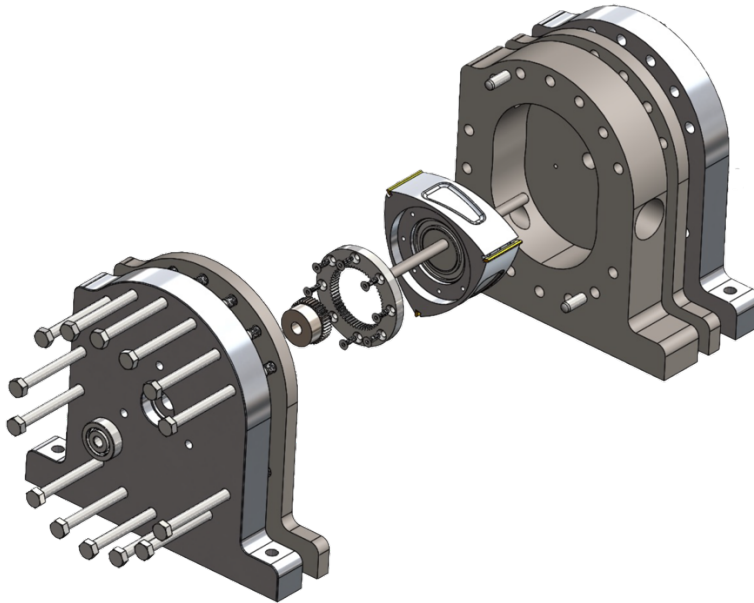# Wankel Rotary Engine

A major qualifying report proposal submitted to the faculty of

Worcester Polytechnic Institute

in partial fulfillment of the partial requirements for
the degree of Bachelor of Science.

April 25, 2024

Authors

Nikki Lam - Giovanni Vecchiarino - Peter Fernholz - Jack O'Neill - Andrew Wirtz - Michael Bragg

Project Advisors:

Professor Selçuk I. Güçeri

Abstract

The objective of this project was to design and fabricate an operational Wankel rotary engine. We researched various rotary engine styles through literature by Kenichi Yamamoto, focusing on the Wankel engine due to its compact design and possession of fewer moving parts. In addition, the team reviewed two past WPI Wankel MQPs, revealing design problems experienced by former groups. Using Yamamoto's equations to form the rotor housing of a Wankel engine and past project experiences, we produced a CAD assembly of a new engine model. Then, as time permitted, we planned to fabricate, construct, and operate our engine to achieve an operating Wankel rotary engine model.

Executive Summary

Project Goal and Objectives

This project aimed to design and fabricate an operational Wankel rotary engine by modifying past MQP engine designs and integrating Mazda design guidelines.

To accomplish this goal, we identified three objectives:

1. Establish Wankel rotary engine geometry in SolidWorks to model a complete Wankel rotary engine assembly.
2. Manufacture Wankel rotary engine components using Washburn Machine Shop facilities at WPI.
3. As time permits, develop simple starting mechanism to test and run final engine model.

For this MQP, our team utilized the Washburn manufacturing facilities at Worcester Polytechnic Institute to machine and assemble this year's Wankel rotary engine.

Design Challenges

For this year's Wankel Rotary Engine, we prioritized the SolidWorks design and manufacturing of the engine over the ignition system. We also received weekly feedback and reading material from professor Güçeri when discussing past MQP and Mazda Wankel engine designs, the disadvantages of the Wankel engine, and possible solutions to our current design. The rotor and rotor housing geometry were the most important components of our design and were based on Mazda's equations when making their own Wankel engine.

Results

Due to delays regarding renovations to the Washburn Machine Shop, we were unable to machine all the engine components, therefore, preventing the assembly and testing of our engine in a timely manner. However, we were able to machine the rotor, rotor housing, and eccentric output shaft for presentation purposes as well as provide a 3D printed model of our engine for a proof of concept.

Recommendations

We recommended future MQP teams to use our SolidWorks model to continue manufacturing all the engine components for final assembly of the engine and testing. Teams should design an ignition system using a CDI magnet sensor that will detect each time the rotor compresses against the engine's sparkplugs. This will allow the sparkplugs to ignite every time the rotor passes so the engine can run consistently. The engine would also benefit from a cooling system since the engine is prone to overheating. Researching and acquiring the optimal fuel delivery system and fuel type may also contribute to an operational Wankel rotary engine. For structural integrity and decreasing overall weight teams can research the potential of a two-layer material housing using steel and aluminum.

Acknowledgements

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1.0   Introduction

The Wankel rotary engine represents a distinct approach to power generation by using the rotation of rotors instead of traditional pistons. Diverging from conventional piston engines, the Wankel engine features a planar and non-reciprocal geometry, replacing the piston with a triangular rotor. This rotor executes a 4-stroke combustion cycle on each of its three faces during every rotation, as illustrated in Figure 1. The innovative design originated in 1954 with German Engineer Felix Wankel (Sherman 2008). For this project, our team based its design on existing models, leveraging intricate geometric calculations refined through successive iterations by Felix Wankel's successors. Our model constitutes a compact engine with a displacement of 25 cubic centimeters, a deliberate choice to minimize material costs, machining time, and facilitate full machining within the Washburn Machine Shops located at Worcester Polytechnic Institute.
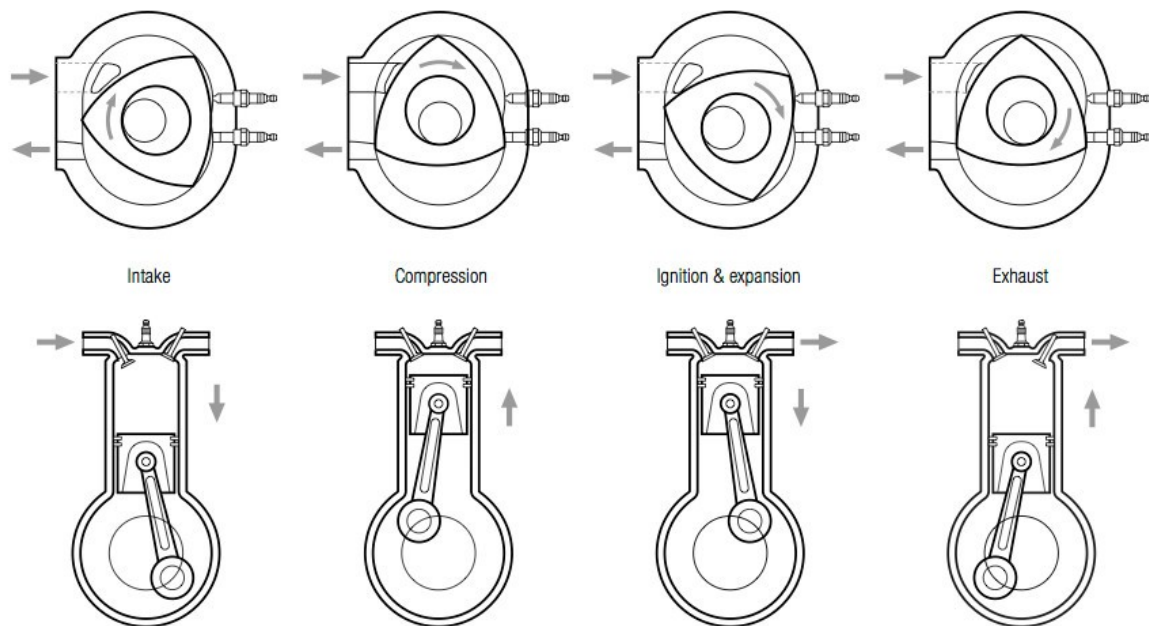

Figure 1: Four stroke combustion cycle of a Rotary Engine (Wikimedia Commons)

2.0   Background

2.1   The Life of Felix Wankel

Born in 1902, Felix Wankel became associated with various political groups, including the National Socialist German Workers Party, commonly known as the Nazi Party, during its early years in the 1920s. Wankel, however, diverged from the predominant ideologies of the Nazi Party, emphasizing his focus on technical advancements, which set him apart from his peers. To convey the importance of technology and education, Wankel secured an audience with Adolf Hitler and other party leaders in 1932. This effort resulted in his expulsion from the Nazi Party due to internal conflicts.

Despite his expulsion, Wankel's fortunes took a turn in 1933 when he was released, thanks to the intervention of Wilhelm Keppler and Adolf Hitler. Subsequently, he was granted state contracts and provided with his own experimental workshop, affording him the opportunity to pursue his engineering projects.

Following the conclusion of World War II, Wankel faced imprisonment by the French, and his workshop was dismantled. However, in 1951, he secured funding to establish a new workshop. While acknowledging Wankel's controversial political associations and condemning his extremist views, it is crucial to note that this new workshop became the birthplace of the initial iterations of the Wankel rotary engine (Sherman 2008).

2.2   What is a Wankel Engine?

The Wankel Rotary engine is a distinctive departure from conventional internal combustion engines, replacing the traditional piston-cylinder configuration with a three-part, planar housing. Each rotor in the engine necessitates its own housing, with these components securely fastened together and separated by a metallic gasket reminiscent of a piston engine's head gasket. The engine features a circular-lobed eccentric output shaft that traverses the entire length of the block, with each rotor containing a lobe, akin to a cam lobe, within its structure. Paired with a ring and pinion gear system, the gear ratio is 3:2, meaning that for every three rotations of the rotor, the eccentric output shaft completes two rotations. This ratio is determined by the unique geometry of the rotor, which takes the form of a three-sided, curvilinear triangular shape.

Figure 2 illustrates the curvilinear nature of the Wankel rotor, showcasing the intricate machining performed by the team. The housing adopts the shape of an epitrochoid, formed by tracing a point on a circle with a diameter ratio of 3:2 to the circle it traces.
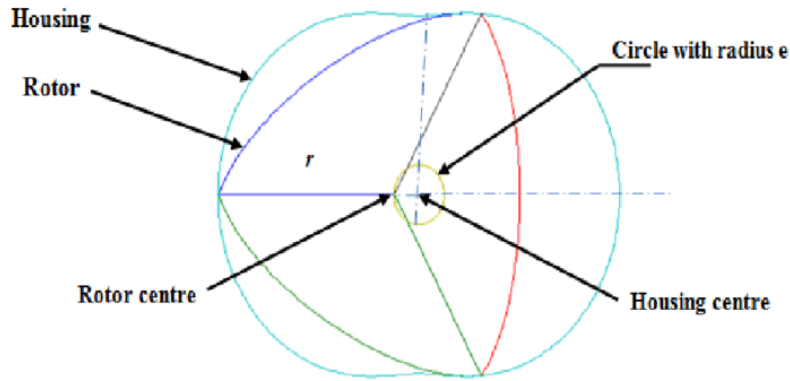
Figure 2: Geometry of the Wankel Rotor and Housing ([(PDF) Development of Rotary Wankel Devices for Power Generation (researchgate.net))](#))

In Figure 3, the image depicts the interaction of the apex seals with the epitrochoid-shaped housing in the team's engine. The eccentricity of the crank lobe, identical in both phasing and diameter, enables each vertex of the rotor to maintain constant contact with the housing. This contact is crucial for sealing and compressing the engine, further enhanced by the incorporation of apex seals. Functionally like piston rings, apex seals in the Wankel engine differ in that each of the three faces is always in separate phases of the combustion cycle. In Figure 4, the labeled strips at each corner of the rotor represent the apex seals, completing the seal between the rotor and the housing wall (both labeled).
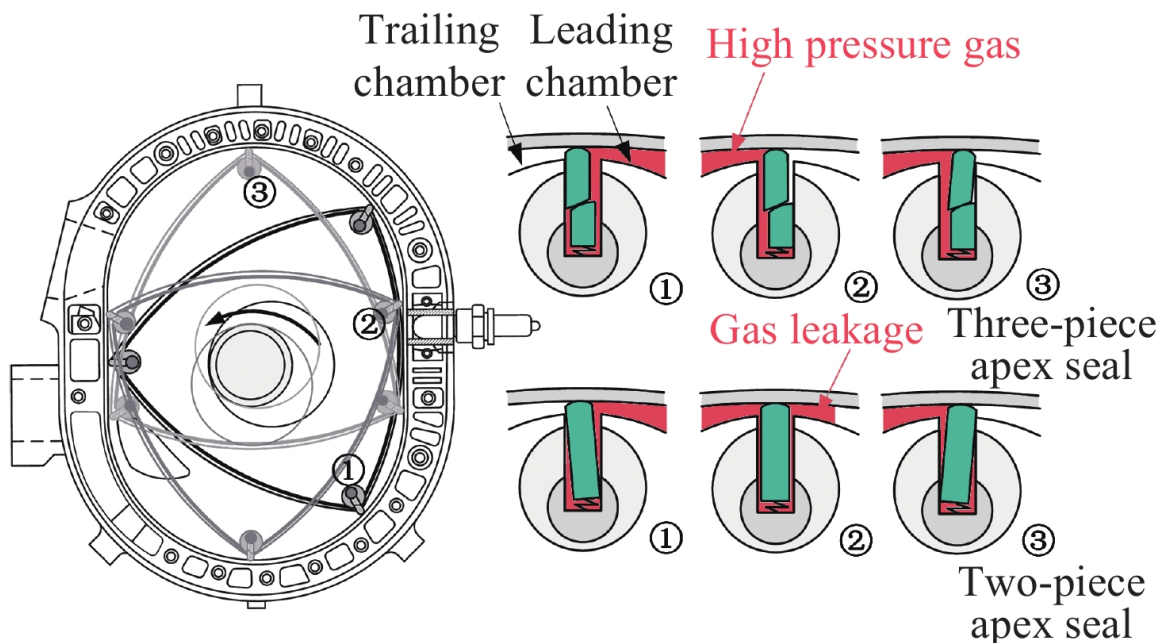
Figure 3: The Interaction of the Apex Seals with the Epitrochoid-Shaped Housing
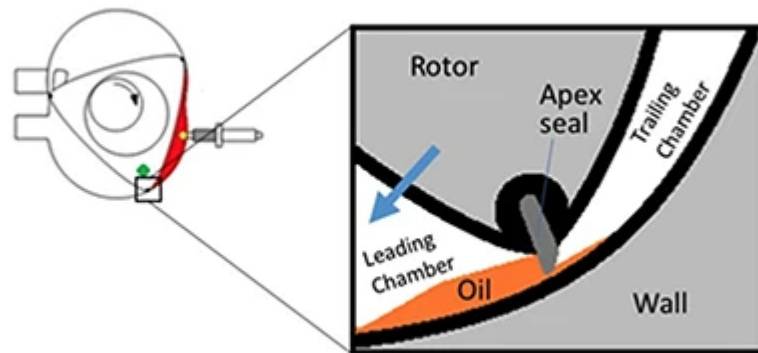
Figure 4: Labeled diagram of the seal between the Apex Seals and the Housing Wall

This design distinguishes the Wankel engine from typical four-stroke engines, allowing all four phases of the cycle to be completed in one full rotor rotation, with each face undergoing a full cycle per rotation. This characteristic minimizes the duration during which each rotor is not generating power, approaching zero power lag. Additionally, Wankel engines operate at significantly higher revolutions per minute compared to piston-cylinder engines.

Mazda, a prominent innovator in Wankel rotary engine technology, showcased its prowess in vehicles such as the Mazda RX-7. Equipped with a 1.3-liter Wankel engine, known as the 13B, this two-rotor configuration produces 300 horsepower and revs up to an impressive 10,000 revolutions per minute. Remarkably lightweight at 330 pounds, the engine achieves a remarkable power-to-weight ratio of 0.9 hp/lb (Thomson, 2020). The ability to operate at elevated speeds enables Wankel engines to achieve high power-to-weight ratios, as the engine output can be geared down to generate more torque at lower output shaft speeds relative to the engine's crankshaft.

2.3   History of Wankel Engines

Felix Wankel, an aspiring engineer without the means for a university education, displayed resilience by embarking on a career in engineering. His initial foray involved the creation of compressors for various applications, including a notable instance where the compressor functioned as a supercharger for a diminutive 0.05L 2-stroke engine. This pioneering application featured an internal triangular rotor, foreshadowing the geometric principles later integral to the Wankel engine. Recognizing the potential for an internal combustion engine, Wankel expanded his design to incorporate intake and exhaust ports, as well as spark plugs.

In 1957, Felix Wankel unveiled the original Wankel engine, named the "Drehkolbenmotor" or DKM. This design involved the simultaneous rotation of both the internal rotor and its housing. The rotor, rotating around its center, and the housing, rotating at a faster speed, maintained a specific angular speed ratio of 2:3. Despite achieving impressive speeds of up to 25,000 rpm, the DKM engine faced challenges, such as distortion of the rotor housing and

difficulties in cooling due to its rotational nature. Nevertheless, the DKM engine marked a significant success, validating Wankel's unconventional design that departed from traditional piston and cylinder configurations for compression and combustion (Hege, 2007).

Addressing the shortcomings of the original DKM engine, Hanns-Dieter Pascheke introduced a modified version known as the "Kreiskolbenmotor" or KKM. In this iteration, the rotor housing remained stationary while the rotor spun within it. This design closely resembles the mass-produced Wankel engines prevalent today. The stationary housing facilitated a simpler cooling mechanism, with coolant passages integrated into the housing. Unlike the DKM, the KKM engine's power transmission occurred through the eccentric shaft, allowing compatibility with conventional automotive transmissions. These advancements, introduced by Pascheke, underscore the evolution and refinement of the Wankel engine design (Hege, 2007).

2.4   Applications of Wankel Engines

The special design of a Wankel engine sets it apart from the piston engine. With the engine itself being so compact it can be used in a tighter space and still produce a similar firepower to the alternative piston engine. This sparked interest in the company Yanmar, which used the Wankel engine for powering basic appliances, such as an outboard boat engine and a chainsaw. As well as even putting a Wankel engine into a motorcycle. In 1960 the IFA/MZ factory created a 175-cc water-cooled motorcycle powered by the rotary engine shown in Figure 5. They replaced the two-stroke engine of the BK 351 design in 1959 with the Wankel engine. It was able to tightly fit into the motorcycle with the Wankel's small compact design and it was even able to produce 24hp which was double that of the previous engine that it had.
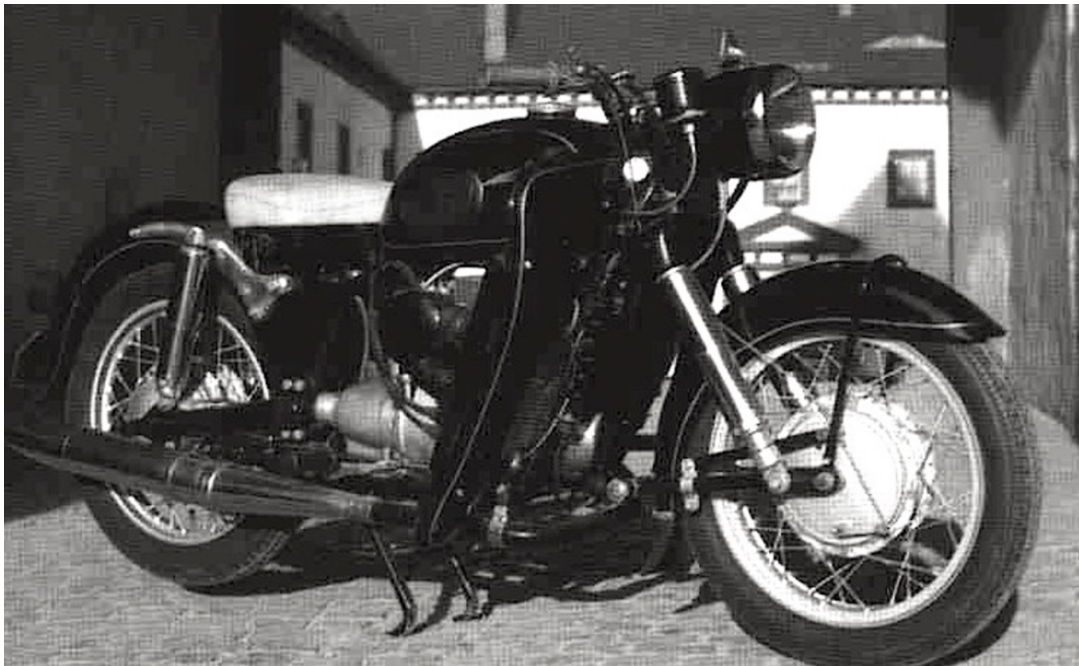
Figure 5: Water-Cooled Motorcycle Powered by Wankel Engine

2.5   Mazda's Use of the Wankel Engine

The most common example of the application of the Wankel engine was Mazda in their cars. The first car that Mazda implemented the Wankel engine, as seen in Figure 6, was the Cosmo Sport production. Debuting on May 30th, 1967, the Cosmo Sort revolutionized the use of the Wankel engine for Mazda.

Figure 6: First Mazda Car with a Wankel Engine

With the implementation of the exhaust gas regulation in 1968, the United States passed the Clean Air Act which "required a reduction of more than 90% in the amount of hydrocarbons contained in the exhaust gas from cars to be brought to market in 1975 and later" (Destefani 2013). This required Mazda to innovate its engine to pass the new act with its engine producing a small amount of nitrogen oxide, but it produced a large amount of hydrocarbons. Mazda developed its new engine in 1973 with the use of a thermal reactor system. The thermal reactor system would essentially use burned hydrocarbon residue in the exhaust gas.

Figure 7: Standard Mazda RX-7

      In 1978 Mazda introduced their breakthrough car the Mazda RX-7 which utilized their new engine that had a fuel efficiency of more than 50% of the last engine that they were using in the Cosmo Sport. Mazda gained most of its popularity as a sports car when it started to debut on the racetrack. With winning its first race in the 24-hour Deytona race it started its racing career for years to come. The next two races the Mazda RX-7 found success in was the British Touring Car Championship winning races in both 1980 and 1981. After seeing the success of Mazda's Wankel engine in the RX-7, it started to catch the eyes of professional teams across the world. The RX-7 found its success in America with the IMSA racing. The RX-7 through 12 years had 100 wins, of which the main car for most of these wins was the Mazda RX-7 GTO which had an incredible horsepower of 640 bhp. The GTO won multiple races in the IMSA racing even making an appearance in Le Mans in 1994.

Figure 8: Mazda RX-7 GTO

Throughout the years Mazda kept up with the production of the RX-7 which sold around 7 million cars up until 1996. They started the design of a new engine that would have a side exhaust but in 2002 Mazda had an economic collapse which had to cancel the design of the new engine. After the stop in production in 2002 the team from Mazda picked it back up in 2003 with a new design that led to the production of Mazda's new model of car the RX-8. The new Mazda RX-8 had the new RENESIS engine, which was similar to the RX-7. With the engine being the same size but heavier the RENESIS engine had more horsepower making it easier to power a bigger car. The other significant upgrade that the RX-8 engine had was that it was the first practical Wankel engine.

Figure 9: Mazda RX-8

Now Mazda has gone above and beyond anything they have done in the past with an innovative Mazda RX-30. Mazda has designed a hybrid engine that will use both gas and electricity to completely change the rotary engine.

2.6   Benefits and Drawbacks

One common benefit of the Wankel engine is the fact that it is compact and small compared to the common piston engine but still produces similar horsepower. However, a lesser-known advantage of the Wankel engine is having less vibration compared to the piston engine. With less vibration being generated from the car's engine it helps the car last longer which is a huge benefit of having the Wankel engine. Compared to the standard piston engine the Wankel lasts longer and requires less maintenance to upkeep. Also, since the Wankel engine is such a simple design it compared to the piston it has fewer moving parts by having only 2 gears rotating. Having fewer moving parts means less that can go wrong and locating issues in the engine has become easier in terms of maintenance as well it is easier to find the issues (Keller 1968).

   With some significant benefits compared to the piston engine, the Wankel does have its drawbacks. One of the main issues is the high heat transfer and the problems with leakage with sealing issues. "The engine's downfalls include high heat transfer (higher surface-to-volume ratios) along with sealing and leakage issues, low efficiency due to smaller compression ratios and poor emissions due to a nonoptimal combustion chamber shape including large crevice volumes, which can cause quenching" (Jaclyn 2020). Trying to solve the efficiency issues of the Wankel is one of the top things companies are looking into to produce a better engine. Another drawback of the Wankel is its cooling application. Trying to cool the orbiting gear is the main concern since it never touches the casing of the engine. It hovers just around it which makes it harder to cool the engine itself. This causes issues when the engine wants to go to higher RPMs, as the engine has a higher RPMs the engine gets hotter and if there is not a good way of cooling the engine down then the engine could fail.

3.0 Methodology

The goal of this project was to design and fabricate an operational Wankel rotary engine. To accomplish this goal, we identified three objectives:

1. Establish and design rotor, rotor housing geometry and all individual engine components using SolidWorks to model a complete Wankel rotary engine assembly.
2. Manufacture the rotor, rotor housing, eccentric output shaft, etc., using Washburn Machine Shop facilities at WPI.
3. As time permits, develop simple starting mechanism to test and run final engine model.

The methods associated with each objective are detailed below.

3.1 Rotor & Rotor Housing Design Components

3.1.2 Rotor Housing

The focus of Objective 1 was to establish the rotor housing geometry using parametric equations given by our advisor, Selçuk Güçeri. Eq.1 was expressed by Kenichi Yamamoto – former supervisor of the Mazda Wankel Engine –in his book *Rotary Engine* when explaining how to produce the trochoid curve that serves as the rotor housing surface.

$$\left. \begin{aligned} x = e * \cos(t) + R * cos(t/3) + a * \cos(t/3) \\ y = e * \sin(t) + R * sin(t/3) + a * \sin(t/3) \end{aligned} \right\}$$

<div align="right">Eq.1 (Yamamoto, 1981)</div>

Where *e:* amount of eccentricity (mm)

      R: Generating Radius (mm)

      t: Angle of rotation of the Internal Gear around the Fixed Spur Gear

      a: Parallel Curve Constant (mm)

Wankel rotary engine requires a gear ratio of 3:2, internal gear: fixed gear. For our engine we used an internal gear with 60 teeth and a spur gear with 40 teeth to meet the 3:2 gear ratio requirement. These two gears were essential to determining our rotor housing shape since the eccentricity, *e*, is determined by the difference between pitch radius of the internal gear and the spur gear, shown in Eq.2.

$$e = q - p$$

<div align="right">Eq.2 (Yamamoto, 1981)</div>

Where *q:* pitch radius of internal gear (mm)

      p: pitch radius of fixed gear (mm)

The pitch radius of the internal gear, q, is 15mm and the pitch radius of the spur gear, p, is 10 mm. Using Eq.2, the eccentricity, e, was calculated to be 5mm. With the calculated eccentricity of 5mm, we were able to determine our R-value using K= R/e, shown in Eq.3.

$$K=R/e \rightarrow R=K*e$$

Eq.3 (Yamamoto, 1981)

Where K: Trochoid Constant

The trochoid constant, K, is usually found to be K=6~8 (Yamamoto, 1981). Our team found that K=7 produced a smoother trochoid curve compared to K=6, which can be seen in Figure 10 and Figure 11. When K = 8 the sides of the curve become flat in Figure 12. By using K=7, we could then calculate R to be 35mm. Because the tips of the rotor would include apex seals, the parallel curve constant, a, would be equal to our apex seal clearance of 0.6mm to create a parallel curve with consideration of the rotor's apex seals.
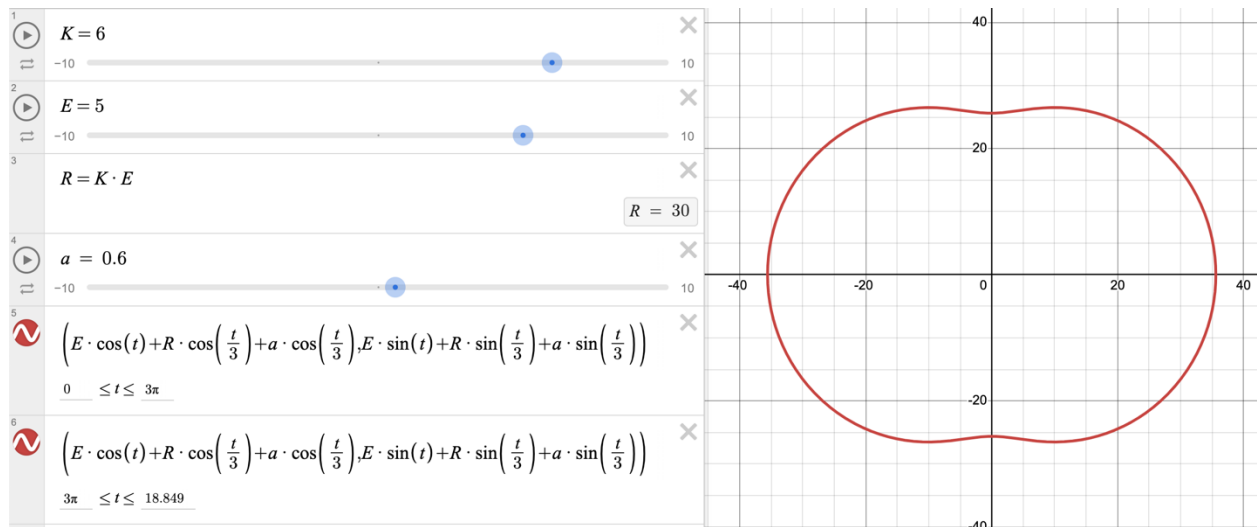
Figure 10: Desmos Trochoid Curve when K=6
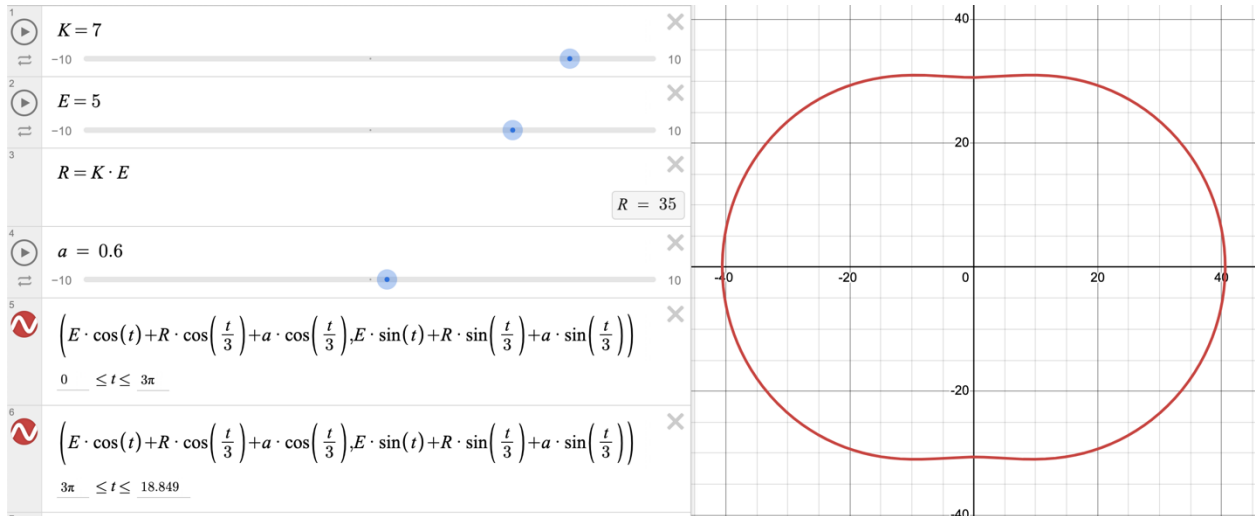
Figure 11: Desmos Trochoid Curve when K=7
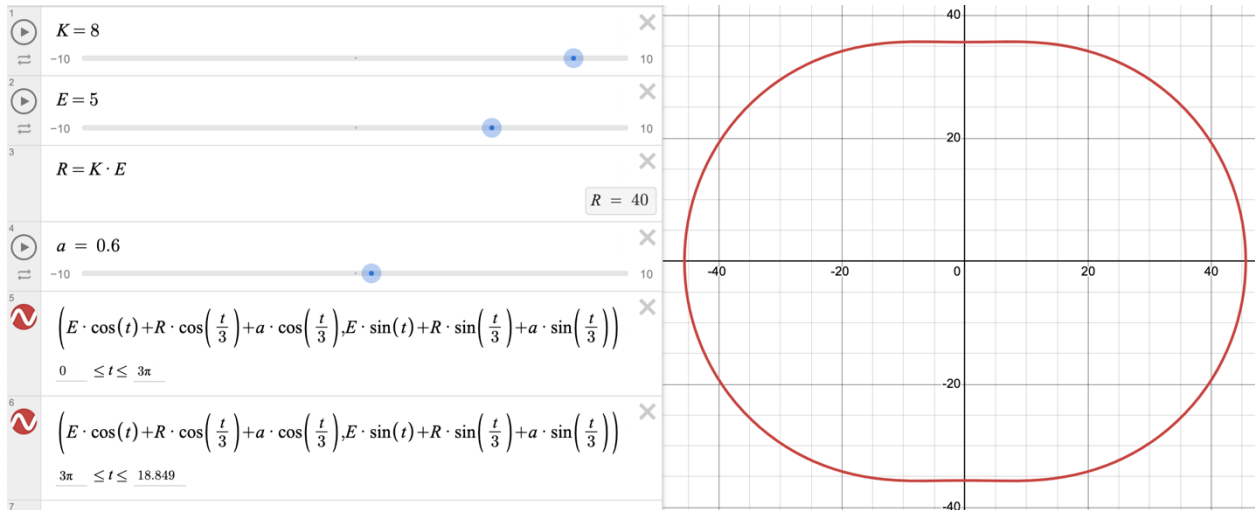
Figure 12: Desmos Trochoid Curve when K=8

The rotor housing equation that was used to model the final rotor housing design can be seen in Eq.4.

$$\left.\begin{array}{l} x = 5mm * \cos{(t)} + 35mm * cos\left(\frac{t}{3}\right) + 0.6mm * \cos\left(\frac{t}{3}\right) \\ y = 5mm * \sin(t) + 35mm * sin\left(\frac{t}{3}\right) + 0.6mm * \sin\left(\frac{t}{3}\right) \end{array}\right\}$$

Eq.4 (Yamamoto, 1981)

Where $e:$ 5mm

$R:$ 35mm

$a:$ 0.6mm

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t: $0 \leq t \leq 6\pi$

After we implemented the parametric rotor housing equation into SolidWorks, the rotor housing curve was produced as a sketch, allowing our design group to create the main rotor housing CAD Model, which can be seen in Figure 13.
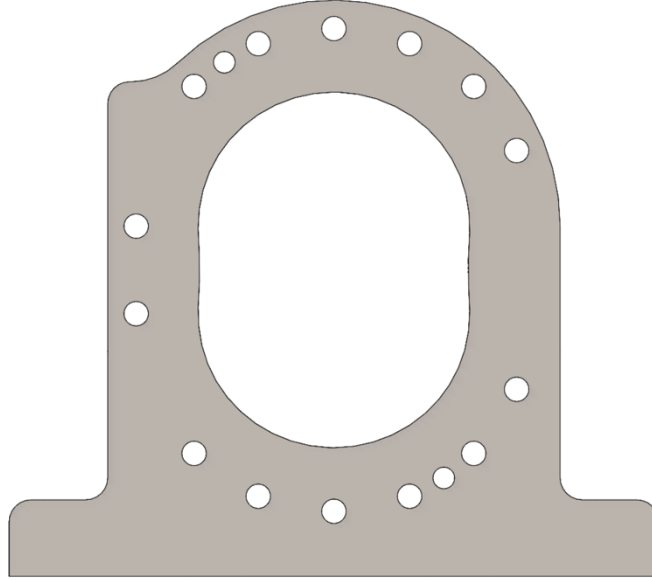
Figure 13: Rotor Housing CAD Model

3.1.2 Rotor

Despite Mazda having their own equation for producing the shape of a rotor, these equations were difficult to implement in SolidWorks due to their complexity. The Mazda rotor equation can be seen in Eq. 5.

$$\left.\begin{array}{l} \boldsymbol{X} = R * \cos(2v) + \dfrac{3e^2}{2R}(\cos(8v) - \cos(4v)) \pm e(1 - \dfrac{9e^2}{R^2} * sin^2(3v))^{\frac{1}{2}} * (\cos(5v) + \cos(v)) \\[3mm] \boldsymbol{Y} = R * \sin(2v) + \dfrac{3e^2}{2R}(\sin(8v) - \sin(4v)) \pm e(1 - \dfrac{9e^2}{R^2} * sin^2(3v))^{\frac{1}{2}} * (\sin(5v) - \sin(v)) \end{array}\right\}$$

<div align="right">Eq.5 (Yamamoto, 1981)</div>

Where $v = \frac{1}{6}\pi \sim \frac{1}{2}\pi, \frac{5}{6}\pi \sim \frac{7}{6}\pi, \frac{3}{2}\pi \sim \frac{11}{6}\pi$

Eq. 5 contains cyclic functions with the period of 2π (Yamamoto,1981). This equation produces an inner envelope that corresponds to the shape of the rotor. However, for our design, we utilized our rotor housing in SolidWorks and placed three coincident points on the housing curve, which would represent as the three corners of the rotor. Next, we connected these points by sketching lines of equal length, resulting in an equilateral triangle that served as the base shape for the rotor design. To ensure constant contact between the rotor and the rotor housing,

we cut a 2mm wide gap at each corner of the rotor to allow our apex seals, shown in Figure 14, to be situated. Under these apex seals will be three slots where three springs will be placed into. These springs will apply pressure against the apex seals to ensure constant contact with the housing surface, especially when the rotor is rotating. The final rotor design can be seen in Figure 15.
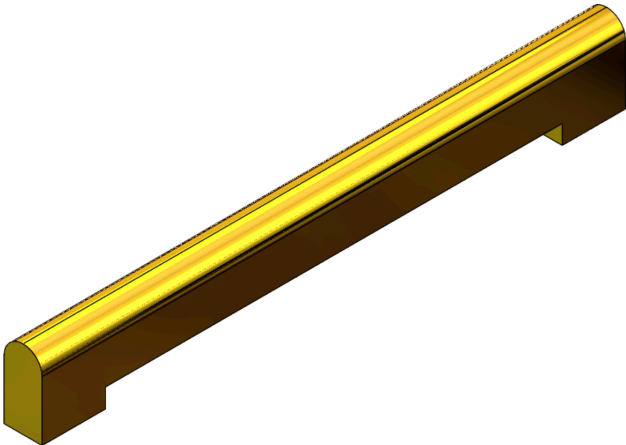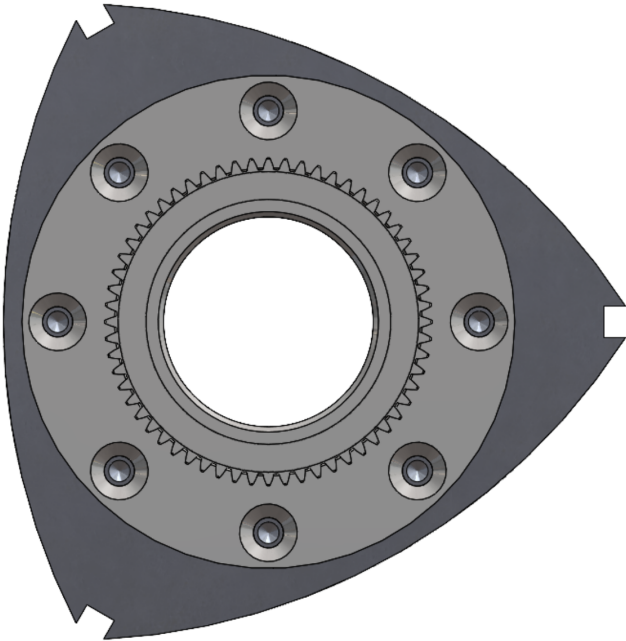

Figure 14: Apex Seal CAD Model

Figure 15: Rotor CAD Model

3.2   Manufacturing Engine Components

3.2.1 Material Selection

For the engine housing, we had five parts in total, two aluminum outer-side housings, two steel inner-side housings, and the central steel housing. The steel was A36 heat-treated steel, so the inner-side housings and central housing could handle high temperatures when the engine would run. A36 steel has a melting point of 2,590°F -2,670°F and a running rotary engine at full throttle and high RPM can reach up to around 1,700°F -2,000°F. In addition, we decided to use 6061 aluminum for the outer-side housings due to its lightweight and ease of use when machining. Another reason for choosing aluminum is that aluminum has a high capability of dissipating heat from a system. 6061 aluminum's melting point would not be suitable for the inner-side housings, but the outer-side housings were further away from the engine's combustion, making it undergo less heat while helping to cool the system. For the eccentric shaft, we used 1018 cold-rolled steel since 1018 cold-rolled bars have a higher tensile and yield strength compared to hot-rolled bars. 1018 is a low-carbon steel with good case hardening qualities.

After finalizing our material selection, the next step was to machine the parts we modeled in SolidWorks. To machine all the parts, we needed to use CNC mills and lathes. Most of the parts were on the mills, and the only part that needed the lathe was the lobes for the eccentric shaft. To program the mills and the lathes, a "G-Code" was needed to tell the mill what was happening in the operation.

To create the G code, our team used Fusion to program the operations that would be done on these machines. To do that, we took our SolidWorks design and imported the parts into Fusion. Then, we could program each part individually for the machine shop tools with the correct feed and speed rates. This was difficult since we were using different types of metals that required different tools, which also required us to use different feed and speed rates.

The inner steel and outer aluminum housings were easy to machine with simple two-step operations. The two inner steel housings had the same design, so we could use the same G-code for both parts. The aluminum housings were slightly different but relatively the same.

The first housing we machined was the aluminum housing. We started with an 8x8x2 block of aluminum seen in Figure 16, then we machined the first operation on the Mini Mill, where we used a 3/8' endmill to eliminate all the excess material. We also used different drills in the first operation with different sizing and a big drill to drill the center so that for the second operation, we could probe that hole to establish the work offset. Then, the final tool we used was a shell mill to give it a nice finishing pass.

Figure 16: 8x8x2 Aluminum Stock

After the first operation was complete seen in Figure 17, we then turned over the stock and clamped it down in the vice on the outer part of the housing, avoiding the top radius of the housing so there would be no movement of the part while it was being machined which can be seen in Figure 18. The rest of the operation was to take off all the other material attached to the housing. Again, using the ¼" endmill, we got rid of the rest of the metal. Then, we ended with a finishing pass of the shell mill.

Figure 17: End of 1st Op.
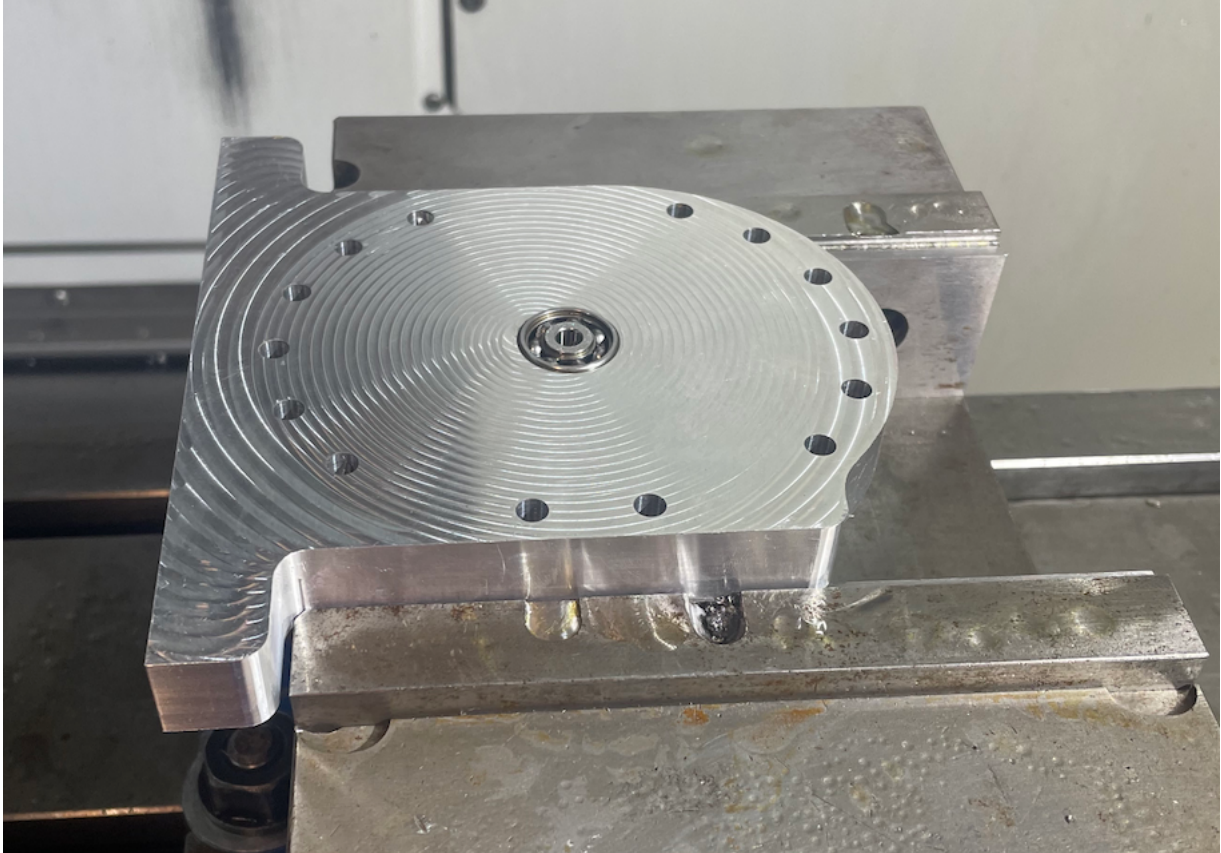
Figure 18: End of Second Op. In Vice

The second Aluminum housing process was the same, but we increased the feed and speed rates because the operation took so long the first time. We then used the ½" endmill to machine the second time, which decreased our operating time by an hour, as seen in Figure 19.

The difference between the inner steel housing and the aluminum housing was the inner steel had four operations. One operation is on the front side, and three are on the back. The extra two operations were to drill the holes needed for the exhaust and the intake, and the other operation was to machine the holes for the glow plugs. We machined the first operation on the VM-2 Mill, which had the same process as the aluminum housing where the housing was outlined during the first operation and removed all the excess metal during the second operation. The difference in this was that we needed different endmills and chamfer mills than we used on the aluminum housing, which can be seen in Figure 19.

Figure 19: ½" Endmill ¼" Endmill and chamfer for Steel Housing

3.2.2 Manufacturing Methods

The rotor and its unique geometrical characteristics required a couple of custom work holding fixtures to machine its complex features. The rotor was machined from a 4"x4"x2" thick block of 6061 Aluminum. In future iterations of this rotor design, 7075 Aluminum could be considered for its higher strength and hardness characteristics compared to 6061. The first operation in the rotor machining was to mill out the outer triangular rotor shape, the bearing bore, the internal gear recess, and tapped gear mounting holes. The fixture in Figure 20 was used to hold the rotor in the vice such that the remaining stock left from the previous operation could be removed and the face opposing to the previously machined rotor face could be milled parallel. Since this fixture jig had very similar geometries to the internal gear, we bought that needed modifications, we added features to the fixture to hold the gear to drill the corresponding holes and reduce the diameter to fit the rotor recess. The rotor gear recess fits tightly over the first cylindrical boss of the fixture to restrict the x and y motion, and bolts clamp the rotor to the fixture from underneath (Figure 21) to restrict rotation and z translation. The minor diameter of the internal gear fits tightly over the top boss on the fixture to restrict the x and y translation. A bolt, washer, and nut clamp on the internal gear teeth through the center clearance hole in the fixture to restrict rotation and z translation (Figure 22)
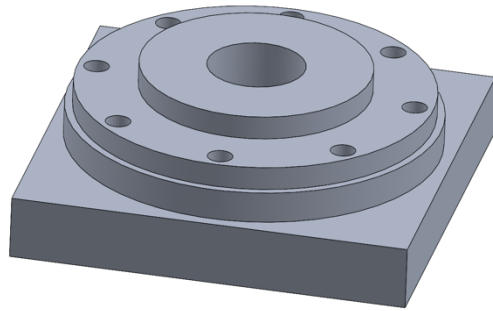
Figure 20: Fixture Jig for Rotor and Internal Gear
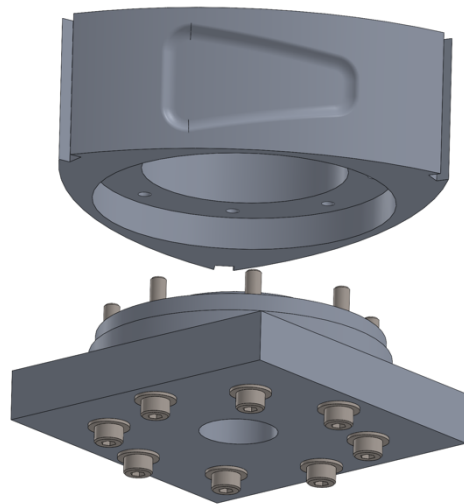
Figure 21: Rotor Fixture Jig Assembly
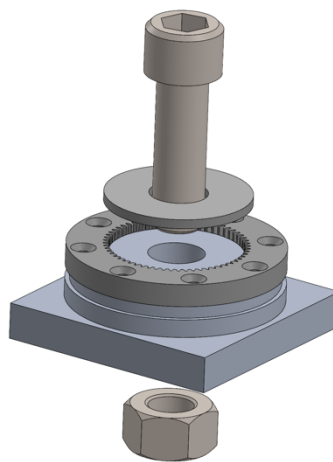
Figure 22: Internal Gear Fixture Jig Assembly Exploded View

The rotor additionally has some radial features that require an additional work-holding fixture to allow precise orientation of the rotor with respect to the machine's axis. If the HAAS mills were fitted with a fourth axis, the rotor could be held by the inner bore with a three-jaw chuck to complete the radial features of the rotor. We designed a dual-purpose soft jaw (Figure 23) that allows the rotor to be oriented vertically with respect to its vertexes as well as its arc surfaces. The pockets on the soft jaw are designed to achieve a tight slip fit with the rotor geometry, and the drilled holes allow corner relief clearance for the vertexes of the rotor. The third rotor operation was to orient the vertexes vertically so that the apex seal slot and spring holes could be milled and drilled (Figure 24). The fourth and final operation was to orient the rotor in the soft jaw such that the arc surfaces were vertical in the mill so the combustion chamber pockets could be milled (Figure 25).
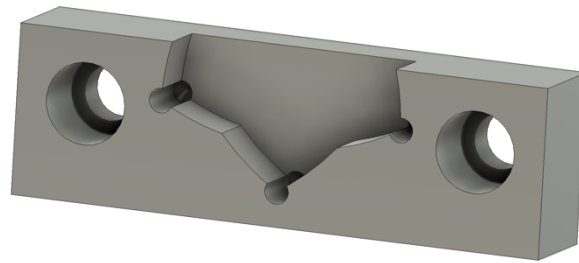
Figure 23: Dual-Purpose Soft Jaw
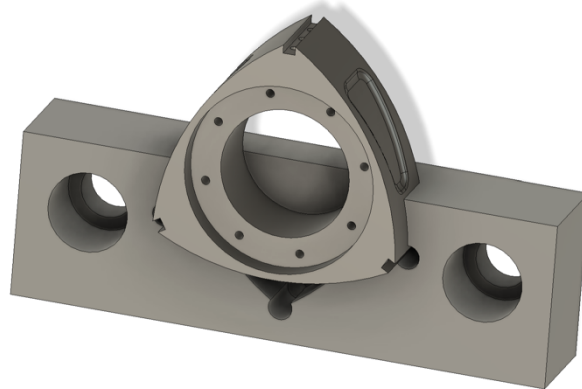
Figure 24: Rotor 3rd Operation Orientation
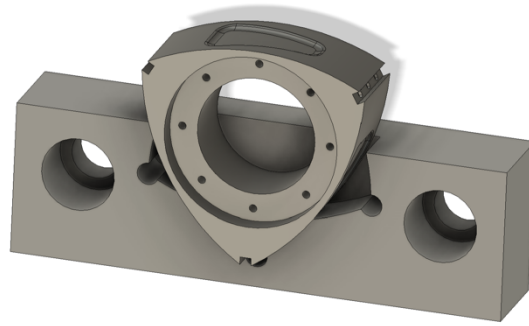
Figure 25: Rotor 4th and 5th Operation Orientation

3.2.3 Manufacturing Issues

When machining, we came across some issues, one main issue we had was the stock size was too big for our design. When we first designed the engine, it was supposed to be 7.88in x 7.03in, but we downsized it later in the design process after we bought the stock. So, when it came to machining, we had to take off a lot more stock than expected. The issue with this was that whenever we had to flip the stock around to do the second operation for the two aluminum housings and the steel housings, they wouldn't be in the middle of the vice. The stock hung over the edge of the vice which can be seen in Figure 26 so when the end mill started to machine the metal down, it created a lot of vibration within the mill. The issue with vibration in mills is that you don't get a clean cut, and you use more friction to get material off rather than the endmill cutting, which affects the tolerances of our parts. Another issue with vibration is that if the spindle load becomes too high due to the vibrations, the machine will get an error code of "Tool imbalance," which stops the program. We had this issue many times for the housings, first in the aluminum housing, to which we then had to manually bump the feed rate down to around 50%, which made the operations take twice as long.
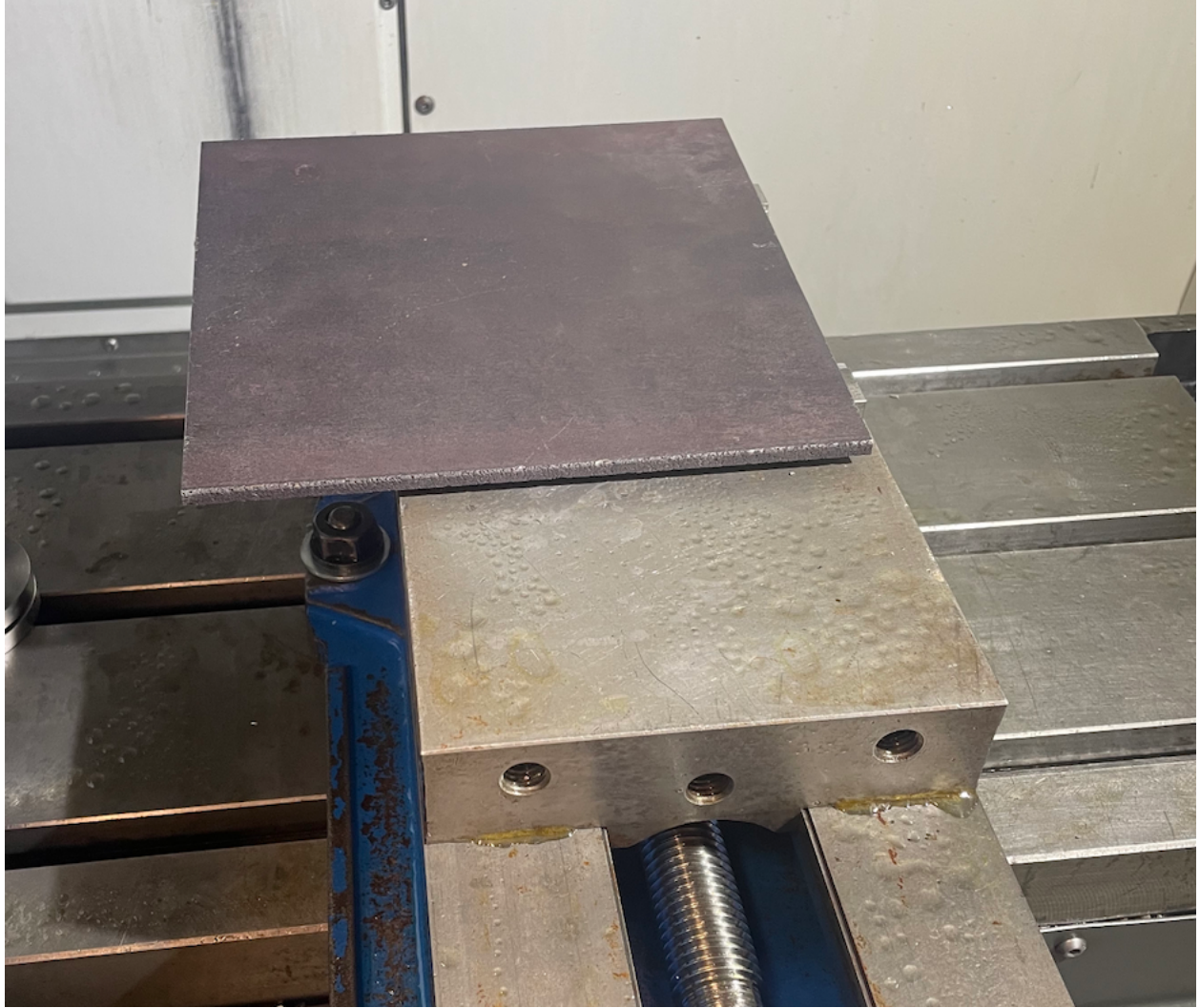
Figure 26: Offset housing in Vice.

Another issue was using the same machines for all the parts. With scheduling time to machine, we could not use the same mill for all our parts. We used five different mills when machining: three different mini mills, a VM-2 mill, and a super mini mill. Different mills were needed to get on a machine to make parts, but the issue is that when machining on so many different machines, the tolerances of the parts will be different. Which would raise an issue when putting all the parts together.

3.3   Engine Starting Mechanism & Testing

For our simple starting mechanism, we planned to use glow plugs to ignite our air-fuel mixture. Our team received a carburetor from our advisor, which allowed for a mixture of air and fuel to enter the engine. Upon activating the ignition sequence, the glow plugs would heat up

within the engine chamber until they reached the ideal temperature for ignition. This preheating process primes the engine for ignition, especially when the engine is placed in colder conditions or when the engine has been inactive for an extended period. After the glow plugs reach their designated temperature, they emit a radiant glow, igniting the fuel mixture upon injection into the combustion chamber. This method not only facilitates a simple, quick, and more reliable method for starting our engine, but it also enhances fuel efficiency by promoting a more direct combustion process. It is essential for there to be two glow plugs, like the spark plugs in Figure 27, to uniformly ignite the combustible gas to force the momentum of the rotor in a clockwise rotation. This process would repeat for the engine to continue running.

Figure 27: Representation of Glow Plug Placement in the Rotor Housing - https://www.howacarworks.com/technology/how-a-rotary-wankel-engine-works

4.0   Results & Recommendations

4.1   Results

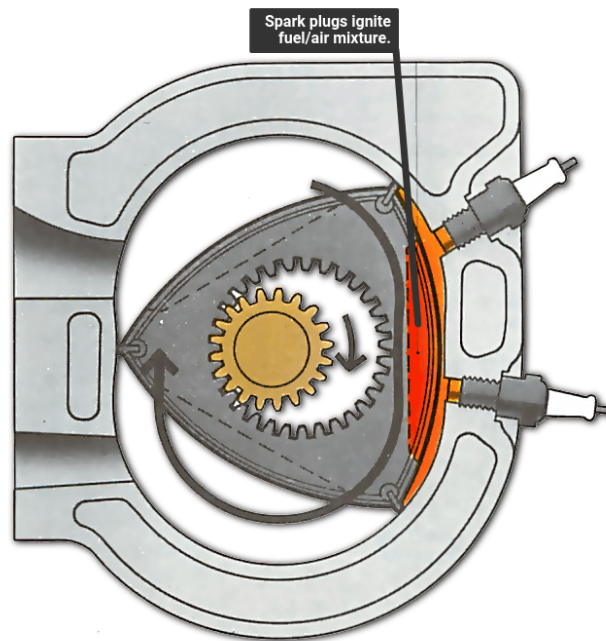Due to delays regarding renovations to the Washburn Machine Shop, we were unable to machine all the engine components, therefore, preventing the assembly and testing of our engine in a timely manner. However, we were able to machine the rotor, rotor housing, and eccentric output shaft for presentation purposes as well as provided a 3D printed model of the engine.

Most of our findings came from our design and manufacturing steps of the project. First, when determining the size of the internal gear and spur gear, we decided to use the same gears that were used in a past Wankel rotary engine MQP. To avoid future material stock shipment delays, general measurements from the past MQP were used to order new stock material. However, when designing our rotor housing using Mazda's equations, the size of the current rotor housing was approximately half the size of the previous MQP rotor housing. This demonstrated that the past MQP group did not follow the Mazda design guidelines when making their engine. Due to the unexpected small size of our rotor housing, the team had possessed more material stock than what was necessary, which led to issues when manufacturing by increasing machining difficulties and manufacturing times of each engine component. With this knowledge, the team has proposed the following recommendations for future MQP groups.

4.2   Recommendations

4.2.1   Purchase Stock Material After Completion of Engine Design

For future groups, we recommend waiting to purchase stock material until after the completion of the engine's design to eliminate potential issues with machining. These issues could stem from last-minute changes in the design, such as the size of the machined pieces, which is one of the problems we encountered. Purchased stock that was larger than the dimensions of the component being machined would need extra material to be cut off, meaning wasted material and manufacturing time, while also being more expensive than a smaller piece of stock. These complications would apply in the case of decreasing the size of the engine, however, conversely, increasing the engine's size could lead to needing to purchase entirely new materials. Ensuring the selected material sizes will not change before purchasing will also void the aforementioned issues.

4.2.2 Ignition System using CDI Magnet Sensor

We initially planned to use an ignition system using spark plugs and a CDI magnet sensor to aid with the timing. However, due to delays regarding manufacturing, we did not have enough time to achieve this system. An ideal topic of work for future groups would be to research and design an ignition system using spark plugs that ignite based on the CDI magnet sensor. This sensor would detect each compression of the motor so that the spark plugs can ignite at the optimal air-fuel mixture in the chamber. This would amend the issues of any possible misfires when using glow plugs and would allow the timing of the ignition to be manually programmed for a more consistent timing for ignition.

4.2.3 Cooling System

Future teams need to add a cooling system for the engine to run to its full potential. A cooling system is necessary due to the excess heat produced during combustion. In addition, the cooling system will keep the engine at an ideal temperature. If the engine overheats, substantial damage could occur to its function. The cooling system we recommend designing is a heat exchanger system. In this system, a coolant would be propelled back and forth through the housing by a water pump. There would be a water jacket in the housing, which would be a hollowed-out area for the coolant to flow through. An example of such a housing is shown below in Figure 28. After flowing through the housing and absorbing some of the heat produced during combustion, the coolant will flow to a radiator, which will act as a heat exchanger, releasing heat from the coolant into the air. The coolant will then continue to circulate through the engine, repeating the process.

Many cooling systems also utilize a thermostat to regulate the flow of coolant. If the engine is sufficiently cooled, the thermostat will close off, stopping the release of coolant, but as soon the engine reaches a set temperature, it will once again begin releasing coolant. Other cooling systems include an overflow tank. For this method, the coolant would absorb the heat, causing pressure to increase and the coolant to expand. The overflow tank gives the coolant a place to exit once it expands, and it will empty as the temperature decreases. A series of tubes will connect the components in the system. It is essential the tubes are fully intact and sealed to ensure adequate cooling of the engine.
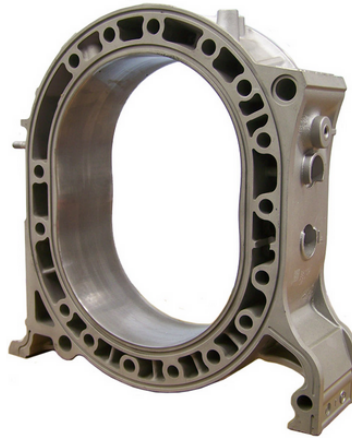
Figure 28: Rotor Housing with Coolant Jacket –
GENUINE MAZDA 13B ROTARY ENGINE ROTOR HOUSING RX8 RX-8 SE3P 2004~2008 OEM | JDM Planet
(jdm-planet.com)

4.2.4   Research Optimal Fuel Delivery System & Fuel Type

Through our research, we have explored several options for fuel mixtures and injection systems. On the injection system front we have looked at several systems ranging from the more typical direct injection system to a multi-port injection system, eventually deciding on direct injection as the most practical due to its increased control over fuel input. While this would require precise timing, the timing would coincide with the ignition timing allowing the timing of one system to be calculated from the other without immense additional work. As for the delivery system, we purchased a 25-cc carburetor based on the size of our engine. However, this could change depending on the size of the engine future groups choose to fabricate. Our research into the fuel mixtures led to 2 main recommendations: either Aviation gas, specifically UL91 or 100UL, as is used in many small-scale engines, or unleaded gasoline with an octane rating above 87. The gas must be unleaded as it can damage the apex seals and clog up the rotors- although this will happen over an extended period of use. Both recommendations seemed to be viable options, although we couldn't run physical tests. Unleaded gasoline is likely more practical due to the difficulty in acquiring aviation gas in smaller quantities.

4.2.5   Suggestions for Researching Material Selection

Our engine used A36 steel, 6061 aluminum, and 1018 cold-rolled steel because of their individual strengths as materials. However, we propose doing more research regarding the strength, temperature resistance, and machinability of the materials used for constructing a Wankel engine. With the limitations of Washburn Labs, it isn't optimal to machine steel or hard materials because it takes longer, and future teams might have to do supplementary tests to be able to machine. Moreover, we most likely over-engineered the eccentric shaft using a harder

material than necessary, but that was just in case we wanted to attach something to it in the future. We suggest the possibility of using 4041 steel and 6061-T6 aluminum since they are the easiest to machine, and that was one of the main drawbacks of our project. Furthermore, teams should prioritize the machinability, weight, and structural integrity of the engine when researching materials.

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5.0 Appendix

Appendix A – Machines Used for Constructing Wankel Rotary Engine
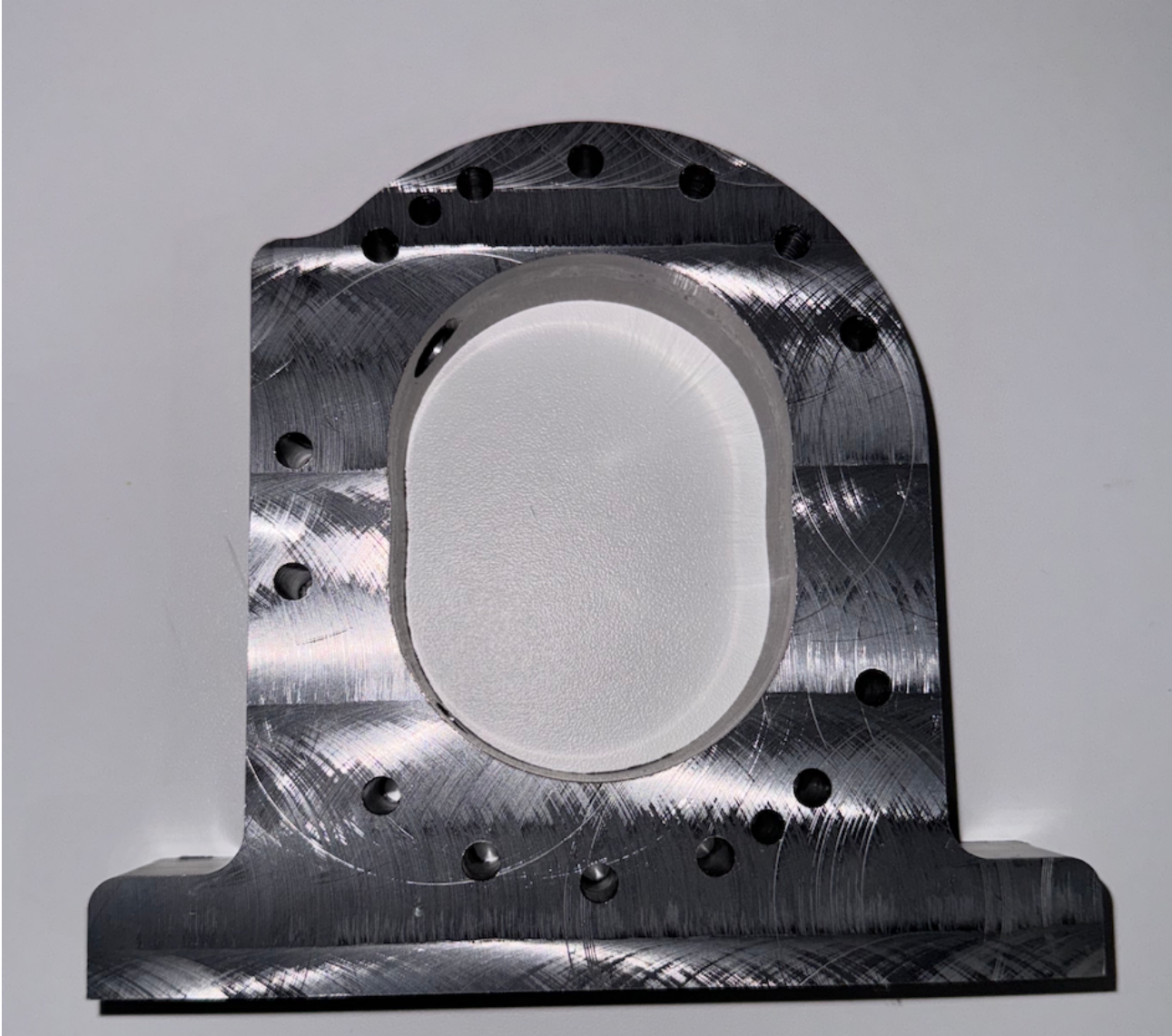

VM-2 Mill

Lathe: ST-10

Super Mini Mill

Mini Mill

Appendix B – Inner Steel Housing

Inner Steel Housing

Appendix C – Purchased Parts List

COMPONENT	QTY REQUIRED	QTY TO BE PURCHASED	COST PER PACK	# OF PACKS	TOTAL COST	WHERE TO PURCHASE
7/16-20 X 1 1/4" Long Socket Head Cap Screw	1	5	$5.64	1	$5.64	https://www.mcmaster.com/92196A380/
7/16 Washer	2	5	$11.25	1	$11.25	https://www.mcmaster.com/98026A114/
M2.5 X 25mm Socket Head Countersunk Screws	8	25	$18.00	1	$18.00	https://www.mcmaster.com/91294A540/
1/4" carbide Spot Drill	1	1	$30.89	1	$30.89	https://www.mcmaster.com/2911A636/
M2.5 hex nuts	8	100	$2.22	1	$2.22	https://www.mcmaster.com/90591A270/
7/64" Stubby Drill Bit	1	2	$1.87	2	$3.74	https://www.mcmaster.com/8947A114/
15/32" Drill Bit	1	1	$10.53	1	$10.53	https://www.mcmaster.com/8870A43/
1/8" Drill Bit	1	2	$1.51	2	$3.02	https://www.mcmaster.com/8870A18/
5mm X 50mm dowel pin	2	10	$8.23	1	$8.23	https://www.mcmaster.com/91595A392/
.196" reamer	1	1	$29.33	1	$29.33	https://www.mcmaster.com/product/8930A21
M5X80mm Housing Bolts	14	20	$16.50	2	$33.00	https://www.mcmaster.com/91287A711/ (PACK OF 10)
M5 Hex Nuts	14	100	$4.76	1	$4.76	https://www.mcmaster.com/90592A095/ (PACK OF 100)
M5 Washers	28	100	$4.00	1	$4.00	https://www.mcmaster.com/98689A114/ (PACK OF 100)
40 Tooth Spur Gear	1	2	$23.41	2	$46.82	https://www.mcmaster.com/2664N323/ (PACK OF 1)
60 Tooth Internal Gear	1	2	$57.74	2	$115.48	https://www.mcmaster.com/2696N16/ (PACK OF 1)
M2.5 x .45 x 8mm LG Flat Head Screw	8	25	$7.80	1	$7.80	https://www.mcmaster.com/91294A016/ (PACK OF 25)
Housing Ball Bearing	2	2	$17.48	2	$34.96	https://www.mcmaster.com/5972K197/ (PACK OF 1)
Rotor Ultra Thin Ball Bearing	1	1	$32.64	1	$32.64	https://www.mcmaster.com/6658K203/ (PACK OF 1)
5mm Dia X 50mm LG Dowel Pin	2	10	$8.23	1	$8.23	https://www.mcmaster.com/91595A392/ (PACK OF 10)
Tube Fitting	6	6	$5.60	6	$33.60	https://www.mcmaster.com/
5-40 X 3/8 long flat head screw	1	1	$12.21	1	$12.21	https://www.mcmaster.com/
.01" shim stock	2	2	$18.33	2	$36.66	https://www.mcmaster.com/
3mm - 4 Flute TiCN End Mill	1	1	$14.04	1	$14.04	https://www.mcmaster.com/
.1975" Reamer	1	1	$24.52	1	$24.52	https://www.mcmaster.com/
Aluminum stock for soft jaws	1	1	$38.70	1	$38.70	https://www.mcmaster.com/
1045 Steel Rod	1	1	$12.48	1	$12.48	https://www.mcmaster.com/
4mm tubing	1 (10 ft)	2 (10 ft)	$32.60	2 (10 ft)	$32.60	https://www.mcmaster.com/
T-Shape 4mm tube fitting	8	8	$0.58	8	$4.64	https://www.mcmaster.com/
7/16-20 X 1 1/4" Long Socket Head Cap Screw	1	1	$5.64	1	$5.64	https://www.mcmaster.com/
7/16 Washer	1	1	$11.25	1	$11.25	https://www.mcmaster.com/
M2.5 X 25mm Socket Head Countersunk Screws	1	1	$18.00	1	$18.00	https://www.mcmaster.com/
1/4" carbide Spot Drill	1	1	$30.89	1	$30.89	https://www.mcmaster.com/
M2.5 hex nuts	1	1	$2.22	1	$2.22	https://www.mcmaster.com/
7/64" Stubby Drill Bit	2	2	$1.87	2	$3.74	https://www.mcmaster.com/
15/32" Drill Bit	1	1	$10.53	1	$10.53	https://www.mcmaster.com/
1/8" Drill Bit	2	2	$1.51	2	$3.02	https://www.mcmaster.com/
5mm X 50mm dowel pin	1	1	$8.23	1	$8.23	https://www.mcmaster.com/
.196" reamer	1	1	$29.33	1	$29.33	https://www.mcmaster.com/
M5X80mm Housing Bolts	2	2	$16.50	2	$33.00	https://www.mcmaster.com/
M5 Hex Nuts	1	1	$4.76	1	$4.76	https://www.mcmaster.com/
M5 Washers	1	1	$4.00	1	$4.00	https://www.mcmaster.com/
M2.5 x .45 x 8mm LG Flat Head Screw	1	1	$7.80	1	$7.80	https://www.mcmaster.com/
Housing Ball Bearing	2	2	$17.48	2	$34.96	https://www.mcmaster.com/
Rotor Ultra Thin Ball Bearing	1	1	$32.64	1	$32.64	https://www.mcmaster.com/
5mm Dia X 50mm LG Dowel Pin	1	1	$8.23	1	$8.23	https://www.mcmaster.com/
Tube Fitting	6	6	$5.60	6	$33.60	https://www.mcmaster.com/
7/16-20 X 1/2" LG Cap Screw	1	1	$7.24	1	$7.24	https://www.mcmaster.com/
Washer for 7/16" screw	1	1	$17.66	1	$17.66	https://www.mcmaster.com/
Fixture Stock (Aluminum)	1	1	$17.64	1	$17.64	https://www.mcmaster.com/
1018 Cold Roll Steel Round Bar (D: 2, W: 2, L: 8)	1	1	$16.87	1	$16.87	https://www.mcmaster.com/
6061 Aluminium Plate 1-3/4 (Width: 8, Length: 8)	2	2	$90.14	2	$180.28	https://www.mcmaster.com/
6061 Aluminum Plate 2 (Width: 4, Length: 4)	1	1	$33.73	1	$33.73	https://www.mcmaster.com/
A36 Steel Plate 1/2 (Width: 8, Length: 8)	2	2	$39.65	2	$79.30	https://www.mcmaster.com/
A36 Steel Plate 2 (Width: 8, Length: 8)	1	1	$152.59	1	$152.59	https://www.mcmaster.com/
Total			$1,043.09		$1,407.14	

PART	QUANTITY
Internal Gear Screw	8
Hex Nuts	12
Washers	32
Bolts	14
Bearing	1
Housing Bearings	2
Tube Fittings	6
Dowel Pins	2
Rotor	1
Front Rotor Housing (Aluminum)	1
Front Rotor Housing (Steel)	1
Rear Rotor Housing (Aluminum)	1
Rear Rotor Housing (Steel)	1
Spur Gear	1
Eccentric Shaft	1
Internal Gear	1
Apex Seals	3

Appendix D – Table of Machined Components and Designated Machines Used

Part:	Machine Used:
Aluminum Housing Front Side	Mini Mill
Aluminum Housing Rear Side	Super Mini Mill
Middle Steel Housing 1st Op	VM-2 Mill
Middle Steel Housing 2nd, 3rd, 4th Op	Super Mini Mill
Outer Steel Housing (Not Complete)	Mini Mill
Lobes 1st Op	Lathe: St-10
Lobes 2nd Op	Mini Mill
Soft Jaws	Mini Mill
Rotor	Mini Mill

Table of Machined Components and Designated Machines Used