Band Motor Crankshaft for Hydrogen Combustion Engine

Final Design Review

Prepared for

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Abstract

This report outlines the steps in which a group of four mechanical engineers at California Polytechnic State University California, San Luis Obispo, addressed an issue brought up by Professor Roger Benham from the Materials Department. The task included developing an automated and modular testing platform for a revolutionary concept crankshaft prototype – meant for a hydrogen combustion engine - developed and produced by the sponsor: Roger Benham. A testing platform is necessary to measure the performance of the shaft design created to eventually implement this subsystem into a complete hydrogen engine design. Values being tested include geometric validation, maximum static loading, maximum dynamic loading, and fatigue testing – these values are calculated via a physical strain gauge on the shaft and a separate Microsoft Excel calculator for validation. Throughout this process, we have implemented the standard engineering design process along with its corresponding reports alongside other specific techniques such as finite element analysis and material design analysis. Overall, the team was able to successfully build an automated test platform that loaded the crankshaft but fell short on the load requirements. Although desired motion was achieved, our system fell short of all load requirements. The system did not put enough torque onto the shaft for our strain gauges to pick up any deflection or torsion. Consequently, no stress values were able to be read. In summary, our team was able to successfully implement an automated and modular design that adequately simulates the desired motion of the crankshaft but fails to output stress values due to lack of torque.
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1. Introduction

Our sponsor, Professor Benham, is a professor at California Polytechnic State University Materials Engineering. He has tasked our team to develop a testing platform that measures the performance characteristics for his band motor crankshaft, which he also refers to as a “journal-less crankshaft”. Our team of four mechanical engineers have designed a mechanism that allows Mr. Benham to measure the torque, speed, and power output of the shaft in Mr. Benham’s engine as well as the relationship between the piston position to crank-angle. This will help him further develop his band motor crankshaft for future production and testing, see Figure 1 for the working band motor prototype.

![Figure 1. Outside View of Professor Benham’s Prototype.](image)

*Figure 1 displays the inside of the prototype exposing the components of the prototype. As presented in our critical design review (CDR), our team worked to manufacture and assemble the testing mechanism to measure the performance of Mr. Benham’s prototype. This report presents the project’s design overview as well as the physical development of our testing platform. We then present our testing procedure necessary to test the specifications we outlined as part of our project’s goals.*

Our projects consist of two important components, the physical testing platform and the computer-based calculator. The calculator outputs the theoretical performance outputs and the physical testing platform outputs the actual performance outputs.

The component of our physical design includes strain gauges sensors, a safety enclosure, and an oscillating pulling mechanism meant to emulate piston motion. The motion of our linkage system will load the crankshaft and will provide measurements via our strain gauges that confirm the calculator outputs.

In this report we present the complete overview of our project. Included in this report are four main parts. In the following sections we list and describe each part.
Part I: Scope of Work.

This report presents the problem and scope of our project. It is a professional agreement between our team and our sponsor which specifies the criteria we must fulfill determined based on Professors Benham’s specifications. It presents our thorough research and process organization needed to successfully complete the project with the given timeline.

Part II: Preliminary Design Review.

This report describes the selected concept design we developed from our concept generation. Each concept design is justified through various techniques, including computer aided analysis, hand calculations for estimated outcomes, and safety plans. The overall goal of this report was to obtain our sponsor’s approval to move forward with our selected design.

Part III. Critical Design Review.

This report presents the full details of our final project. We focus on the concept prototype, a rough prototype of our design, to showcase the function and the manufacturing processes. We also presented a list of the parts needed, both purchased and manufactured. We also presented our planned tests and safety plans for our final prototype.

Part IV. Final Design Review.

This report presents design updates from CDR. This includes changes in the design of our project and changes made during testing. We also present details about the verification prototype (VP), the final design in physical form. We discuss the manufacturing processes, including the challenges and fixes we made as we developed our VP. We discuss the results of testing, and we evaluate the design by comparing the results to our specifications. Finally, we present recommendations to improve the design of our VP as well as the testing procedures.

2. Design Overview

In this section, a brief description of the final design as well as changes the team made to the design since CDR are included. Further discussion of the reasoning for the design changes is also included.

2.1 Design Description

In Figure 2, the complete test platform with automated operation is shown. In this design, the motor drives the linkage system. The speed of the motor is controlled with a voltage regulator. The oscillating linkage system simulates a piston motion and pulls the drive wire, which rotates the crankshaft, providing automated operation. The instrumentation system measures the strain in the shaft so that torque can be calculated. The lubrication system is placed in an optimal location for maintenance and removal. An in-depth guide to safe and effective usage of the platform can be found in Appendix A in the User Manual. The safety enclosure keeps the user safe from pinch
points in the high-speed rotating linkage. A full analysis of the safety of the platform can be found in Appendix B in the Risk Assessment.

2.2 Design Changes Since CDR

A new motor was selected for the verification prototype. We previously planned to purchase a 3000 W brushless DC motor for fans. To safely test Benham’s prototype, we needed a motor with a lower rpm. We determined a motor closer to a shaft speed of 1000 rpm was ideal for testing. The new motor selected offered a smaller rpm and required lower input power. The new motor selected is a two-speed evaporative cooling motor with a ½ hp input power. The separately purchased variable speed controller allows us to vary the speed from 0 RPM to 1725 RPM for the new motor selection.
Additionally, since CDR, the geometry of the safety enclosure has been refined to cover all of the moving parts outside of the test platform itself. This allows for safe operation but also easy access to the motor for maintenance.

3. Implementation

In this chapter, the procurement, manufacturing, and assembly of all subcomponents and subsystems is discussed. The final assembled prototype can be seen in Figure 3. This is the prototype that was initially used for testing.

![Initial assembled prototype for testing.](image)

**Figure 3. Initial assembled prototype for testing.**

3.1 Procurement

The first step in the manufacturing process is procuring the necessary parts and materials to make the prototype. In this section, the procurement of parts and materials for each system is discussed.
Four-Bar Linkage
For the four-bar linkage, the 0.25” aluminum stock was purchased from B&B steel in Santa Maria. The bearings, hardware and spacers were purchased from McMaster-Carr.

Strain Gauges
The strain gauges were purchased online from OMEGA, a retailer for sensing and control technologies. Soldering tools, including wires and shrinking wrap, were donated by the Cal Poly IEEE student branch collaboration laboratory.

Strain Gauge Indicator
The strain gauge indicator was purchased online through eBay. The strain gauge indicator is used but in good condition. We then purchased the 20-pin connector and power cable through Daytronic online. Soldering equipment was provided by the Cal Poly IEEE lab.

Motor and Variable Speed Controller
All parts were purchased in San Luis Obispo. The evaporative cooling motor was brought at Lowe’s. The 16 14-gauge female flag disconnect was purchased at AutoZone. The power cord and motor stand were purchased from Ace’s Hardware. We borrowed the ratcheting crimper from the Cal Poly EE Department. The variable speed controller was donated by the Cal Poly EE department.

Slip Ring
The slip ring was purchased through Amazon online. Acetone and sandpaper were donated by the Cal Poly machine shop.

Lubrication system
The materials for the lubrication system were obtained through online retailers like Amazon, which included the procurement of the reservoir and plastic coolant. Additionally, materials for the oil collector were acquired from Home Depot. Notably, as there was an ample amount of remaining stock from the linkage component, we decided to utilize this surplus for the safety field and lubrication stand. A detailed breakdown of these expenses can be found in Appendix C, specifically in the "Budget" section. The manufacturing process took place in Mustang 60 at Cal Poly SLO, where all necessary tools, such as a drill, finger brake, and water jet, were externally provided.

Safety Shield
The polycarbonate for the safety shield was purchased from Home Depot along with the epoxy used to bond it together.

3.2 Manufacturing
Once all of the necessary parts and materials were obtained, the team could begin manufacturing parts from scratch and modifying purchased parts as necessary. In this section, a brief overview of the manufacturing process for each system is discussed.
Four-Bar-Linkage
The links were cut on the waterjet out of the 0.25” aluminum stock. The links were then post-processed on the manual mill. The ¼” holes were drilled out to 15/32”, and then reamed to 0.499”. This allowed the 0.5” bearings to be pressed into the links. Two bearings were used per hole to fill the width of the links. A final post-processed link can be seen in Figure 4. The drive link required minor filing to allow the D shape hole to fit onto the motor shaft.

![Figure 4. Post-processed link with bearings pressed in](image)

With the links post-processed, the only other modification needed was on the motor stand. The 1/8” hole was drilled out to a #8 so that the spacing link could be connected.

Motor Connections
The evaporative cooler motor requires ½ HP and it is a 2-speed motor. The high-speed runs at 1,725 rpm and the low-speed runs at 1,140 rpm. The input voltage is 115 V, and it is a single-phase motor. To connect our motor to a power source, we purchased a single speed motor power cord; this cord is a three-prong power cord ideal for wall outlet connections. By using a single speed power cord for a two-speed motor, we were limited to high speed only. As part of our goal with senior project, we determined that varying speeds were ideal for testing. We attached a variable speed controller that allowed us to change the voltage input resulting in adjustable speed.

We connected the wires according to the schematic in the motor manual. One of the difficulties that we had was the crimp connectors. The crimp connectors we brought did not allow for the wire to bend so that it would be enclosed in the motor chassis, as seen in Figure 5. To solve this problem, we purchased 16 14-gauge female flag disconnects angled at 90 degrees which allowed the wires to bend.

![Figure 5. Female Connector](image)
Another problem that arose was the cord insulator thickness; it did not fit within the motor chassis because the chassis has a strain relief bent profile. To fit the power cord, we used a precision cutting knife to carefully take off the cord insulator, which allowed us to fit the power cord cables inside the motor chassis, as seen in Figure 6.

![Figure 6. The trimmed wire insulation.](image)

**Sensor Gauges**
To connect the strain gauges in a Wheatstone configuration, we soldered the tabs of the strain gauges to wires. In Figure 7, we have an image of the set up used to solder strain gauges.

![Figure 7. Soldering set up for strain gauge soldering.](image)

The strain gauges are small, 9.8 mm long, which made it difficult to solder. A magnifying glass and magnetic weights were used to hold down and solder the strain gauge, as seen in Figure 8 for the setup. To mitigate this problem, we used a fine tip soldering gun.
The strain gauges also came with a thin layer of Kapton tape; Kapton tape has a temperature rating of about 400° C. We initially tried setting the soldering gun at that temperature, but it did not melt the 60/40 Rosin-Core solder (0.062 in). We had to increase the temperature of the soldering gun to 480 C. Increasing the temperature helped secure the connection between the strain gauge pad and the wires. The wires we used were too thick which caused strain on the soldered strain gauge. This strain often desoldered the wires; we used flush cutters to hold the wires together relieving the strain in the soldered area. An example of a final strain gauge with wires soldered is seen in Figure 9.

Strain Gauge Indicator
In Figure 10, there is the wiring configuration for the strain gauges to the strain gauge indicator. There are four nodes that connect to the slip ring then to the strain gauge indicator.
Figure 10. Wiring Configuration for strain gauge indicator.

It was assumed that the top row of the 20-pin connector are numbers (1, 2, 3, …) and the bottom row are letters (A, B, C, …). We carefully shorted 1 and A and connected it to node +EXE - this process was followed for all 4 nodes, see Figure 11 for the completed wiring.

Figure 11. Wired 20-pin connector.

Lubrication system
In the manufacturing process, a single hole was necessary for the oil reservoir. We opted for a 1/2-inch drill bit suitable for penetrating High-Density Polyethylene (HDPE) bottle. The desired hole's location on the HDPE bottle was indicated with a permanent marker, positioning it on the lower side of the bottle for valve attachment. With the drill bit aligned to the marked spot, we carefully drilled through the material. Following the hole creation, we smoothed out any protruding edges or imperfections with sandpaper. We then affixed the rubber washer to the HDPE bottle using Gorilla glue and securely held it in place with a vise for an hour. To complete the assembly, plumber's tape was wrapped around the threaded section of the plastic coolant and inserted into the drilled hole. The final lubrication system after manufacturing was completed can be seen in Figure 12.
To create the collector, we began with a rectangular piece of galvanized steel sheet. Using a marker, we marked the sheet and then cut it with sheet cutters. Next, we employed a finger press to shape the sheet metal into the form of a container. However, the finger press did not yield a sharp bend, so we had to trim down the tops of the container to ensure it would fit beneath the prototype. To securely join the flaps, we will utilize JB Weld steel epoxy, and for user safety, we will apply Flex Seal tape to cover the top of the container, safeguarding against any sharp edges. The final collector can be seen in Figure 13.

The last element of the lubrication system consisted of the 14” x 3” stand, intended to be securely fastened to the prototype. Given that the prototype had existing 1/2" holes, we designated four specific hole locations for the stand. We designed the stand using SolidWorks and planned to have
it fabricated from the 0.25” aluminum stock using a water jet cutting process. After being waterjet, the stand did not require any post-processing and was ready to go.

**Safety Shield**
The crankshaft system is completely surrounded by metal on all sides, with the exception of the top. Consequently, when designing the safety enclosure, our focus is solely on the top part. To achieve this, we opted to cut a straightforward rectangle from 0.25” aluminum stock, with dimensions measuring 12” by 15.50”, which was also cut using the waterjet. A drawing of this part can be seen in *Figure 14.*

![Figure 14. Drawing of Safety Shield](image)

The manufacturing of both the lubrication stand and the safety shield experienced delays because priority was given to other components, all of which originate from the same stock.

**Linkage Enclosure**
The enclosure surrounding the four-bar linkage is made of acrylic and underwent a series of measurements and cuts. We measured a box that measured 8” x 11” x 10” (L x W x H) and was cut using a miter saw. Next, we marked the position of the holes we would have to bore into the acrylic including holes for the linkage supports, motor shaft, and mating holes to secure the safety shield onto the face of the prototype. After we made sure all holes aligned and the pieces fit, we sanded and sanitized the mating surfaces of the panels and applied Loctite adhesive to them and secured them overnight with clamps.

### 3.3 Assembly

With all the parts manufactured and purchased parts modified, the team was ready to begin assembly. Assembly began on the individual system level first. Once this was completed, all of the systems were integrated with the final test platform.

**Four-Bar Linkage**
The linkage was assembled with the completed links and the hardware. Aluminum spacers were used to prevent interference between the links. The drive wire was also attached, and the drive link was connected to the motor, as seen in *Figure 15.*
Strain Gauge Sensors
The strain gauges are applied over the shaft to measure torque. It was necessary to clean the surface of the shaft; we used acetone, alcohol, sandpaper, and tape to remove dust and corrosion prior to applying strain gauges. We used a thin layer of super glue to apply the strain gauges over the shaft. Maintaining a thin layer is necessary to allow for torque reading for shaft. The strain gauge wires are soldered to the slip ring wires, as seen in Figure 16.

Figure 15. Assembled and integrated linkage.

Figure 16. Solder set up for strain gauge connection to slip ring.

Slip Ring
The slip ring proves the connection between the rotary device and the stationary device. Since the strain gauges are rotating with the shaft, it is connected to the rotary side of the slip ring. The outer surface of the slip ring is fixed; this prevents rotation of the other side of the slip ring. The stationary device is the strain gauge indicator. Soldering was required to connect the slip ring to the 20-pin connector of the strain gauge indicator. Acetone and sandpaper were used to clean the
surface of the shaft to then mount the slip ring over the shaft. The final assembled slip ring can be seen in Figure 17.

![Figure 17. Slip ring assembled on crankshaft.](image1)

**Motor**
The motor was easily connected to the variable speed controller. The variable AC speed controller allows for a voltage input of 0 V to 110 V. The connected motor and speed controller can be seen in Figure 18.

![Figure 18. Motor (left) connected to speed controller (right).](image2)

**Lubrication system**
To complete the assembly of the lubrication system, we followed a step-by-step procedure. Initially, we fastened the lubrication stand to the prototype's enclosure using bolts. Then, we attached the reservoir to the stand using hose clamps. The collector was positioned beneath the prototype enclosure. After the initial testing, we assessed if any areas required lubrication. Subsequently, based on the test results, we made any needed adjustments to the assembly, which
involved altering the length of the plastic coolant. The final assembled lubrication system can be seen in Figure 19.

Figure 19. The lubrication system assembled onto the test platform.

Safety Shield
The safety shield was positioned on top of the prototype. Initially, we planned to secure it in place using corner clamps but found that it was a tight enough fit that clamps were not required, as seen in Figure 20.

Figure 20. Safety Shield positioned on top of enclosure.

Linkage Enclosure
The linkage enclosure was placed over the linkage and bolted to the test platform. As seen in Figure 21, we were able to make a shield that integrates into our linkage assembly, adequately protects users, and is an efficient use of space and materials.
In addition to the physical parts that were manufactured and assembled, this project also involved a software product as well. The only software that was produced by the team was the Excel Calculator. The Excel calculator included two separate calculators.

**Calculator**

The first Excel calculator verifies the geometry of the linkage system to ensure that the 4-bar linkage achieves the desired “crank-rocker” motion so that the movement simulates our expectations. This is done by simply inputting the geometric dimensions of each individual link. This will allow us to find the maximum and minimum position coordinates to then find stroke length and the angle where the rocker linkage changes direction – all using geometric relations. Also, we would be able to find the position of every linkage at any angle. In the same calculator is a static load calculator that uses power and angular speed in order to calculate max torque values. These values had to be chosen based on the motor specifications that we purchased as well as the voltage that we were running at the time.

The second calculator included more positioning data given a crank angle of the crank and exhaust band. In this crankshaft design, there would be a separate exhaust band with different timing that would be responsible for releasing exhaust gases – the final step in a traditional 4-stroke engine. The timing of both the exhaust band and crank band are crucial to investigate as these two should be timed and sized accordingly – meaning they do not interfere with each other by converging at the same crank angle position. Both calculators can be found in Appendix D.
4. Design Verification

To verify that the final prototype met the original specifications given by the sponsor, the prototype was tested, and results were recorded. In this chapter, the specifications, testing, and results are discussed. Additionally, during testing, improvements were made to the prototype.

4.1 Specifications

In *Table 1*, the four specifications that were evaluated through testing are shown with what was measured during testing, the acceptable criteria, results, and notes on for each test completed.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Metric</th>
<th>Acceptance Criteria</th>
<th>Result</th>
<th>Pass/Fail</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accurate dynamic load measuring</td>
<td>Torque</td>
<td>+/- 25 lbf-ft</td>
<td>No torque measured</td>
<td>Fail</td>
<td>Strain in shaft too small to be measured</td>
</tr>
<tr>
<td>Accurate static load measuring</td>
<td>Torque</td>
<td>+/- 25 lbf-ft</td>
<td>No torque measured</td>
<td>Fail</td>
<td>Strain in shaft too small to be measured</td>
</tr>
<tr>
<td>300,000 cycles of continuous operation</td>
<td>Number of cycles</td>
<td>300,000</td>
<td>105,000 cycles</td>
<td>N/A</td>
<td>Stopped because of time, not failure</td>
</tr>
<tr>
<td>Easy replacement of major component</td>
<td>Time to modify</td>
<td>Maximum of 4 hours</td>
<td>1 hr 43 min to replace link</td>
<td>Pass</td>
<td>Includes time to manufacture</td>
</tr>
</tbody>
</table>

4.2 Testing and Results

The testing aimed to assess the conformity of our design with the established criteria. In Appendix E we have tabulated the Design Verification Plan and Report (DVPR) which presents our test plan to verify the functionality of our design. This documentation is essential for users of the testing platform to comprehend the procedures and limitations inherent in our band motor testing system. All testing occurred at Cal Poly in the High Bay, with any necessary equipment other than 115 V power source, being acquired from Mustang ‘60 shop. Other than our team, credit is due to the shop techs at Mustang ‘60 for providing necessary equipment and recommendations. Credit is also due to Sarah Harding for guiding us through the testing process. The initial platform used for testing can be seen in *Figure 22*. 
4.2.1 Dynamic Load testing

Dynamic load testing is imperative for a journal-less crankshaft in a hydrogen combustion engine due to the absence of traditional bearing journals for lubrication. This specialized testing assesses the crankshaft’s ability to withstand the dynamic and fluctuating forces encountered during high-temperature and high-pressure operations typical in hydrogen engines. The process aids in refining material selection, design optimization, and overall performance to ensure the crankshaft’s durability and reliability in the challenging conditions of hydrogen combustion.

The dynamic load testing involved the utilization of a strain gauge integrated into the system to assess its capability in accurately measuring torque under varying operational conditions. A two-speed evaporative cooler motor with a low speed of 1140 and high-speed of 1725 RPM was employed, utilizing its maximum speed of 1725 RPM for this test. To test a variety of speeds, we
utilized a variable speed controller to vary the shaft speed of the motor from 0 rpm to 1725 rpm. Strain gauges sensors were placed on one end of the shaft to easily connect the wires to the strain gauge indicator. Strain gauge sensors were intended to capture real-time data reflecting the dynamic forces applied during testing. However, the challenge emerged when the strain gauges registered a strain on the shaft that was too minute for accurate torque detection. The Excel calculator, utilizing specific formulas (refer to Appendix D), projected stall torque to occur at 15 lbf-ft. The dynamic load calculator is currently incomplete and undergoing further developments.

In the initial dynamic testing, the motor and linkage were not fixed to the wooden base plate. The weight of the motor was relied upon to keep the system in place, as seen in Figure 23. However, when the top speed of 1725 rpm was reached, the high speed and load caused the motor to shift, which resulted in the linkage colliding with the safety enclosure. The safety enclosure failed. After this incident, the team fixed the linkage and motor to the wooden base plate with self-tapping wood screws and metal straps, as seen in Figure 24. Additionally, shaft collars were used to fix the drive link on the motor shaft. After these improvements were made, the platform has no issues running at high speed.

To address minimal shaft strain detection, considerations of strain gauge sensitivity have been raised, prompting potential solutions such as incorporating an amplifier for enhanced sensitivity or exploring alternative methods for dynamic load measurements. To detect minute torque variations accurately, specifications and features such as gauge factor, Wheatstone bridge configuration, resistance, amongst other aspects must be considered. The gauge factor of our strain gauge is 2.07±0.5% at 24° C. The gauge factor represents the sensitivity of the strain gauge. It is defined as the ratio of the fractional change in the electrical resistance to the fractional change in length. Higher gauge factors contribute to better sensitivity in detecting small strains. The strain gauge nominal resistance was 350 ohms. Further research is necessary concerning strain gauge calibration to resolve this issue. The current strain gauge configuration can be seen in Figure 25.
The testing process underscored the need for refinement of the strain gauge system to align the design specifications, emphasizing the importance of understanding sensor capabilities and potential design enhancements to achieve precise torque measurement.

4.2.2 Static Load testing

Similar to dynamic load testing, static load testing is indispensable for a journal-less crankshaft in a hydrogen combustion engine due to the absence of traditional bearing journals. This testing is vital to assess the crankshaft’s structural integrity under constant loads, ensuring it can endure the unique and demanding conditions of hydrogen combustion without failure.

The static load testing encompassed an evaluation of the structural integrity and performance of the system under stationary or constant load conditions. To validate our recorded measurements, we intended to compare them with theoretical values calculated using the created Excel calculator. The theoretical values are derived from the geometry of the internal pulley system, the input speed, and power of the motor actuating the linkage system. See Appendix D for calculations. Unfortunately, same as dynamic testing, the test proved unsuccessful as the strain gauge failed to detect any variations in the load.

4.2.3 300,000 Cycles

The objective of conducting the 300,000 cycles of continuous operation test was to ensure the structural integrity and robustness of the linkage system, as well as to validate the durability of the strain gauges and the associated equipment (motor, strain gauge reader) for future testing of the journal-less crankshaft prototype for a hydrogen combustion engine.

The test was designed to simulate an extended period of continuous use, assessing the system’s ability to withstand operational stress and potential wear over time. The goal was to ascertain that the linkage system remained intact without mechanical failures, and concurrently, to confirm the resilience of the strain gauges and other associated equipment under prolonged and repetitive cycling. We conducted this test at 1725 RPM, which would translate to requiring 173.91 minutes.
of testing to reach 300,000 cycles. However, due to time constraints, we were only able to test for around an hour, resulting in only 105,000 cycles. Although the test was prematurely concluded at 105,000 cycles due to time constraints, the intention was to establish the reliability and endurance of the entire system in a continuous operational scenario, which was a success, due to all equipment remaining intact.

4.2.4 Replacement of linkages

The assessment of replacing the linkage system encompassed the entire process, including the time required for manufacturing. Prior to testing, we measured the human stopwatch operation uncertainty. To measure the stopwatch uncertainty, we had each four different users start/stop the watch as quickly as possible to measure and quantify the average reaction time. The results of this test are in Appendix F, Test 4. Initially, our testing plan involved incorporating variable lengths of the 4-bar linkage system. However, a decision was made to defer this variation in linkage lengths until after the successful completion of dynamic and static testing. Consequently, this specific test was devised as a reference for future tests, involving varying lengths of the linkages. The modification procedure involved several steps: firstly, removing the existing four-bar linkage system entirely from the overall structure. Next, adjusting the lengths using SOLIDWORKS, utilizing the original files provided. Subsequently, a DXF file was generated for waterjet cutting. Following this, the components were waterjet, post-processing was conducted on a manual mill and the required bearings were installed. Finally, the linkages were installed onto the final system after completing the aforementioned steps. See section 3.3 Assembly, for how the linkages were assembled. It must be noted that this test assumes that all materials and equipment are available for immediate use. Issues such as the unavailability of the waterjet may arise, resulting in delays. Successful replacement of the major component was achieved with the specified modification timeframe. The maximum allowable time for the modification was set at 4 hours, and the actual time required was 1 hour and 43 minutes to complete the replacement of the link. This outcome resulted in passing status for the test.

4.2.5 Other Challenges Faced

Another challenge that we had during testing was the wires movement during the shaft rotation. The strain of the wires caused some soldering to disconnect. Cal Poly professor John Ridgely, an expert with strain gauges, helped us determine a quick method to obtain strain gauges reading without changing wires and strain gauges; we adapted the Wheatstone full-bridge configuration to a half-bridge configuration. Two 350-ohm resistors replaced the strain gauges connected to the +SIG. Figure 26 shows the wire connections for a half-bridge configuration to the connector of the strain indicator. 350-ohm resistors were chosen since they had the same resistance as the strain gauges used in this project. To replace the strain gauges with the resistors, we soldered two resistors to the pins in the connector of the strain gauge indicator. One resistor was connected from pin 1 to pin 2. Another resistor was connected from pin 2 to pin 3. Through this simple change, strain can be measured, but not with as high accuracy as a full-bridge configuration.
The variable speed controller malfunctioned during our operation. Ideally the variable speed controller would allow us to control the speed from 0 RPM to 1725 RPM. Unfortunately, the speed controller malfunctioned so the motor shaft spun at 1725 RPM causing the linkage system to rotate vigorously which resulted in the safety enclosure breaking. The safety enclosure successfully protected us while testing. After this test we were able to quickly rebuild and assemble the safety enclosure. A Variac Autotransformer speed controller, donated by the Cal Poly Electrical Engineering department, was used to vary the shaft speed of the motor which allowed us to continue testing.

5. Discussion & Recommendations

This project was full of successes and failures. Due to the limited time of senior project, not all of these failures could be addressed by the team. In this chapter, these failures are discussed along with the team’s recommended solutions. Additionally, the future use of this prototype is discussed.

5.1 Discussion

Through testing, the team verified that the motor, motor controller, and four-bar linkage provide consistent automated operation of the test platform. Improvements were made during initial testing to improve the stability and reliability of the test platform.

Due to manufacturing challenges and initial failures in testing, the team was left with limited testing time. Because of this, the platform was not able to reach 300,000 cycles, but did run for 105,000 cycles without issue. Based on the full inspection of the platform after 105,000 cycles, the team feels confident that the platform would be able to complete 300,000 continuous cycles.
While the instrumentation to measure the strain on the crankshaft was implemented and electronically verified, the actual strain on the shaft was too small to read during operation, so the accuracy of the measurement system was not able to be verified.

The lubrication system was successfully implemented to be used as necessary, and the safety enclosure proved to prevent a user from hurting themselves while allowing the user to observe operation. Additionally, the calculator was verified to deliver the requested outputs.

5.2 Recommendations and Next Steps

In order to create measurable strain in the shaft to analyze crankshaft performance with the test platform, the team recommends two possibilities: adjusting shaft size or increasing motor power. Decreasing the shaft size will make the shaft less stiff, leading to increased deflection. Increasing the motor power will increase the torque on the shaft, which will lead to increased deflection.

Once either or both of these options are completed, it will be possible to complete verification of accuracy of load measurement. It is important to verify the accuracy of the load measurement in order to draw correct conclusions from further testing. The detailed test procedure for this verification can be found in Appendix F. This testing will be taken on Professor Benham and future students he has working with him.

Once the test platform is in a final testing state, the next steps would be to integrate the new developments made by Roger Benham for continuous ongoing testing. Professor Benham has already approached the team with new designs for the cam-crankshaft that he is interested in exploring. Our test platform will allow Professor Benham to further understand, analyze, and optimize his new crankshaft design.

6. Conclusion

Overall, this design was able to satisfy the simulation of desired motion, automation, and modularity test specifications outlined in our initial goals. The final product can be, and was, repeatedly assembled, disassembled, and resized within a reasonable amount of time. This was achieved through rigorous testing and adjusting how we integrated our subsystems as we built and tested our design. In the end, we fell short on a few test specifications that include the static, dynamic, and fatigue loading values output from our strain gauges. Although we were able to verify that our wires were live and our strain gauges worked, we were not able to sufficiently load the shaft to the point where our strain gauges would pick up a value. Similarly, our Excel calculators were only successful in finding position coordinates and static loading, while falling short on fatigue and dynamic loading calculation. Even though we were not able to validate our loading calculators and gauges, we were able to validate our positioning and geometric calculators due to a mishap during manufacturing: a linkage was cut too short and there was interference with the motion that our calculator predicted.

This Final Design Review document outlines the justification, testing, and results of our prototype design and provides reasoning for each step that we took. The report reiterates this point through thorough explanation and review regarding design verification, manufacturability, safety, and
feasibility. We also highlight our major changes and lessons learned throughout the design process throughout this document. Furthermore, we discuss our testing and results in detail to summarize our conclusions and deliver our product. We were able to conclude that our design has the components to work if either the shaft is downsized to a much smaller diameter, or the motor is sized to deliver more power. In summary, we created an effective design, but at a scale too small an extremely durable shaft like the one in this prototype.
References


Appendix A – User Manual

User Manual: Assembly of Test Platform

Introduction
Welcome to the Learn to Use Test Platform user manual. This guide is designed to help you understand and navigate through the test procedures efficiently and safely.

Purpose
The primary purpose of this manual is for users to learn the proper operation of the testing platform. This includes assembling and disassembling components, ensuring correct connections, and aligning the linkage system accordingly. Additionally, users will be acquainted with potential risks and the proper Personal Protective Equipment (PPE) to be used during testing.

Scope
The scope of this test encompasses the following:
- Time measurement for assembling and disassembling parts.
- Familiarization with risks and safety procedures.
- Verification of correct sensor subsystem wiring.
- Calibration of sensors and alignment of the linkage system.

Equipment
Ensure the availability of the following equipment:

1. Testing Platform System:
   - Sensors
   - Strain Gauge Indicator
   - Motor
   - Linkage System
   - Band motor Engine (Benham’s Prototype)
   - Wooden platform attached to linkage system.
   - Variable Speed Controllers

2. Tools:
   - 9/64 Allen Key
   - 11/32 Socket & Ratchet

Hazards
Be aware of the following hazards:

1. Personal Injury:
   - Rapid motion in linkages can lead to cuts or injuries when operational.

2. Projectile Hazards:
   - Components under tension may become projectiles. This includes linkage components as well as the drive wire.

3. Improper Alignment:
   - Check to make sure that all components are secured in their designated slots and fit the items into the outline traced onto the platform.

4. Electrical Hazard:
   - Ensure the motor power is off before handling wires to prevent electric shock and burns.
   - Check your power source and that it can supply enough power to the system.
PPE Requirements
Wear the following Personal Protective Equipment:

1. **Eye Protection:**
   - Safety Glasses

2. **Foot Protection:**
   - Sturdy, Closed-Toed Shoes

3. **Protective Clothing/Accessories:**
   - No long, loose sleeves
   - Tie back long hair
   - Ensure clothing doesn't lead to tripping

Procedure
Follow these steps to conduct the Learn to Use test:

1. **Ensure a Safe Environment:**
   Clear walkways and provide safety equipment.

2. **Use the Calculator:**
   Insert proper inputs into calculator such as dimensions and material properties.
   Run calculator and observe calculated values versus measured values from strain gauges.

3. **Prepare the Working Surface:**
   Properly align crankshaft prototype to the outlines marked on the wooden platform. The linkage system should already be attached to the wooden platform.

![Figure A 1. The setup for the testing platform](image)

4. **Set Up the Band motor Prototype:**
   We recommend that at least two people are included in the transport of the prototype as it is heavy and has an awkward shape. Place the band motor prototype on a stable surface/table where testing will occur.

5. **Connect the Drive Wire:**
   Ensure proper attachment to each pulley in the engine. The image below illustrates the proper alignment of the drive wire within the prototype.
6. Set Up the Linkage System:
The linkage system will be provided fully assembled, therefore instructions for disassembly are provided below for modification. If the linkage system comes disassembled, you will follow the reverse order of the order listed. Begin the disassembly process by using a socket wrench & Allen key to carefully unscrew the bolts in the prescribed order, ensuring that you place bolts & links aside in a line to maintain their original location upon assembly. This order includes:

a. Disconnect the connector link and oscillating link.

b. Separate the connector link and the drive link.

c. Remove the spacing link, oscillating link, and support link connection.

d. Dismantle the drive link, spacing link and support link connection.

Figure A 2. Proper attachment of the drive wire inside engine.
Thoroughly inspect all the bolts and linkages, making notes in the table provided regarding any signs of wear and tear. If new fasteners are required, they can be purchased at your local Home Depot (See Appendix C for specifications). If necessary, apply lubrication to the components or clean the components to ensure optimal performance.

4. For reassembly, follow the reverse order of disassembly as outlined below:
   
   a. Connect the drive link, spacing link, and support link.
   b. Reattach the spacing link, oscillating link, and support link.
   c. Reconnect the connection link and drive link.
   d. Reassemble the connector link and oscillating link, as well as loop drive wire between the links.

Note: Exercise caution and precision throughout the disassembly and reassembly process to ensure the proper functioning of the part.

Attach the linkage with D shape onto the motor.
7. Attaching Safety Enclosure
Once the linkage system is assembled, put the safety enclosure on top of linkage and secure it by ensuring that all nuts and bolts that are concentric with the shield and tighten nuts and bolts until you there is significant resistance.

8. Check Motor Wiring:
Check all wire connections and ensure wires are not worn down and that solder connections are secure.

Check to verify that strain gauges are attached to shaft, if not, carefully apply strain gauges using transfer tape to align the strain gauge and epoxy glue for a secure attachment. Epoxy glue has a 5-minute work time.

8. Attach Safety Shield:
Put the Safety Shield on top of the band motor prototype. Ensure that it is flush with the band motor prototype. It should not be easy to move once placed.

9. Static Tests:
Adjust variable speed controller to 1725 RPM and turn on motor.
Run 5 static tests to measure torque. See Appendix F, Test 2.

10. Verify with Online Calculator:
Using testing inputs such as power and geometry, compare values outputted from the calculator to the values read by strain gauges.

This concludes the user manual. Always prioritize safety and adhere to the provided instructions during the testing process.
# Appendix B – Risk Assessment

## Designsafe Report

**Application:** Senior Project: Final Prototype  
**Description:** This analysis shows some of the basics of a risk assessment for our senior project design.  
**Product Identifier:** Detailed  
**Assessment Type:** Detailed  
**Limits:** Assuming testing is done in a supervised shop.  
**Sources:** Personnel experiences, ANSI B11 standards, assembly drawings W-Z  
**Risk Scoring System:** ANSI B11.0 Two Factor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Initial Assessment Risk Level</th>
<th>Risk Reduction Methods /Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Final Assessment Risk Level</th>
<th>Status / Responsible /Comments /Reference</th>
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<td>1-1-1</td>
<td>operator normal operation</td>
<td>mechanical : pinch point linkages</td>
<td>Minor Remote</td>
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<td>Safety enclosure secured correctly.</td>
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<td>Negligible</td>
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<td>Obtain transfer cart to eliminate lift.</td>
<td>Moderate Likely</td>
<td>Medium</td>
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<table>
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<th>Initial Assessment Risk Level</th>
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## Appendix C – Final Project Budget

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<td>10/15/23</td>
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<td>121000</td>
<td>140919</td>
<td>Evaporative Cooler Motor</td>
<td>Model 2204, 115 V, 1 phase</td>
<td>$119.00</td>
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<td>10/15/23</td>
<td>Ace Hardware</td>
<td>121200</td>
<td>4514881</td>
<td>3-1/2 in H X 6-1/2 in W</td>
<td>Evaporative Cooler Motor Kit</td>
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<td>Autozone</td>
<td>84171</td>
<td>Female Flag Disconnect</td>
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<td>DONATION</td>
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<td>Micro-</td>
<td>MMF010312</td>
<td>Strain Gauge - 5 pack</td>
<td>350-ohm resistance</td>
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<td>Price</td>
<td>Quantity</td>
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<td>10/15/23</td>
<td>Online</td>
<td>Jacqueline Mendoza</td>
<td>143100</td>
<td>Amazon B07XHQL8NB Slip Ring, 6 wire, 10 A, Inner Hole 25.4 mm</td>
<td>$85.00</td>
<td>1</td>
<td>$85.00</td>
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<td>11/15/23</td>
<td>San Luis Obispo</td>
<td>Jacqueline Mendoza</td>
<td>143200</td>
<td>Micheals 10031026 Wooden Dowel 3/8&quot; 3/8&quot; diameter, 12 in length</td>
<td>$3.50</td>
<td>1</td>
<td>$3.50</td>
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<tr>
<td>10/31/23</td>
<td>DONATION</td>
<td>Jacqueline Mendoza</td>
<td>122000</td>
<td>General Radio Company W5MT3 Variac Autotransformer 115 V</td>
<td>$-</td>
<td>1</td>
<td>$-</td>
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<tr>
<td>10/15/23</td>
<td>Online</td>
<td>Jacqueline Mendoza</td>
<td>122000</td>
<td>Amazon LXSCR00001 Variable Speed Controller 110 V</td>
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<td>Santa Maria</td>
<td>Jacqueline Mendoza</td>
<td>141300</td>
<td>Walmart 1739050 Loctite Super Glue -</td>
<td>$-</td>
<td>1</td>
<td>$-</td>
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<tr>
<td>10/16/23</td>
<td>Visa Gift Card</td>
<td>152000</td>
<td>Home Depot 29206 Everbilt Spring Door Hinge Set, 4 in x 5/8 in Radius</td>
<td>$21.00</td>
<td>1</td>
<td>$21.00</td>
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<td>10/17/23</td>
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<td>Visa Gift Card</td>
<td>132100</td>
<td>GetMetals n/a 1008 Steel Sheet 24&quot;x36&quot;x1/8</td>
<td>$56.54</td>
<td>1</td>
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<tr>
<td>10/18/23</td>
<td>Visa Gift Card</td>
<td>131200</td>
<td>Amazon B094JVDQTD Oil Pipe Hose 1/4&quot; PT Thread</td>
<td>$10.69</td>
<td>1</td>
<td>$10.69</td>
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<td>10/19/23</td>
<td>Online</td>
<td>Visa Gift Card</td>
<td>131100</td>
<td>Amazon n/a Natural Cylinder Bottle 4 pack</td>
<td>$16.31</td>
<td>1</td>
<td>$16.31</td>
<td></td>
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<tr>
<td>10/20/23</td>
<td>Online</td>
<td>Visa Gift Card</td>
<td>131300</td>
<td>Amazon B002R9O4CW Drip Tube End Plug 1/4&quot;, 25 Pack</td>
<td>$2.19</td>
<td>1</td>
<td>$2.19</td>
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<td>10/21/23</td>
<td>Visa Gift Card</td>
<td>131400</td>
<td>Home Depot 780007 Neoprene 'O' Ring 3/8 in OD, 1/4 ID, 1/16 thickness, 12 pack</td>
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<td>1</td>
<td>$4.71</td>
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<td>11/02/23</td>
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<td>Austin Rhee</td>
<td>151000</td>
<td>Home Depot 241929 Polycarbonate Sheet 18&quot;x24&quot;</td>
<td>$34.68</td>
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<td>$69.36</td>
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</table>

**Budget:** $1,500.00  
**Actual expenses:** $1,118.63  
**Remaining balance:** $381.37
Appendix D – Software

The following is a table that shows the inputs and outputs of the geometric constraint calculator. We simply use the linkage lengths to calculate if the geometry is valid for desired “crank-rocker” motion. This is shown in the “Dimension Validation Cell.” The right table shows the corresponding arc lengths and angles where the rocker link switches directions – calculated by an array of geometric relations.

This next calculator finds the stroke length of the piston using the cam-crank offset. Similarly, we use the same method to time the Exhaust Band of the engine to ensure proper timing. Calculations and equations were provided by Roger Benham.

<table>
<thead>
<tr>
<th>CamCrank Off</th>
<th>Exhaust Band Offset</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cam Radius</td>
<td>Exhaust Cam Radius</td>
<td>0.05</td>
</tr>
<tr>
<td>Total Radius</td>
<td>Total Radius</td>
<td>0.05</td>
</tr>
<tr>
<td>Stroke Length</td>
<td>Stroke Length</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crank Angle</th>
<th>Differential Length</th>
<th>Exhaust Band Length</th>
<th>PISTON POSITION</th>
<th>EXHAUST PISTON</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>FALSE</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.00148353</td>
<td>FALSE</td>
<td>0.000959931</td>
<td>0.00148353</td>
</tr>
<tr>
<td>2</td>
<td>0.00296706</td>
<td>FALSE</td>
<td>0.001919862</td>
<td>0.00296706</td>
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<tr>
<td>3</td>
<td>0.00445059</td>
<td>FALSE</td>
<td>0.002879793</td>
<td>0.00445059</td>
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<tr>
<td>4</td>
<td>0.00593419</td>
<td>FALSE</td>
<td>0.003839724</td>
<td>0.00593419</td>
</tr>
<tr>
<td>5</td>
<td>0.007417649</td>
<td>FALSE</td>
<td>0.00479655</td>
<td>0.007417649</td>
</tr>
<tr>
<td>6</td>
<td>0.008901179</td>
<td>FALSE</td>
<td>0.005759587</td>
<td>0.008901179</td>
</tr>
<tr>
<td>7</td>
<td>0.010384709</td>
<td>FALSE</td>
<td>0.006719518</td>
<td>0.010384709</td>
</tr>
<tr>
<td>8</td>
<td>0.011868239</td>
<td>FALSE</td>
<td>0.007679449</td>
<td>0.011868239</td>
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</tbody>
</table>

True and False statements show if the distance traveled is within .005 of the stroke length showing the last position before it returns.

PISTON/EXHAUST POSITION CALCULATOR SUBTRACTS STROKE LENGTH FROM DISTANCE TRAVELED IF ABSOLUTE VALUE OF THE DIFFERENCE IS <=.0025 - SMALL ERROR IN GETTING NEGATIVE VALUES
MATLAB Calculator
The following script was utilized to calculate the appropriate link lengths to achieve a 5in stroke length. The important outputs are “del” which is the stroke length of the oscillating bar, and “freq_rat” which is the ratio of speeds between the motor and the oscillating bar. The plot at the end shows the angle of the oscillating bar with respect to time.

```matlab
clear ; close all ; clc

% When l_1/l_0 = 0.5, del = l_2
% and freq_rat ~= 1
% Bars
l_1 = 2;                       % Length bar a                   [in]
l_2 = 5;                       % Length bar b                   [in]
l_3 = 6;                       % Length bar c                   [in]
l_0 = 2*l_1;                   % Length bar d                   [in]

tF      = 10;                   % Final time                     [s]
step    = 600;                  % Time step                      [s]
time    = linspace(0,tF,step);  % Time                           [s]

% Bar a rotation
w = -2;                         % Angular velocity (motor speed) [rad/s]
th_vet = w*time';

% Definitions
k_1 = -2*l_1*l_3*sin(th_vet);
k_2 = 2*l_3*(l_0-l_1*cos(th_vet));
k_3 = l_0^2 + l_1^2 - l_2^2 + l_3^2 - 2*l_0*l_1*cos(th_vet);

% phi
phi_vet = 2*atan2(-k_1-sqrt(k_1.^2+k_2.^2-k_3.^2),k_3-k_2);

% alpha
alpha_vet = atan2(-l_1*sin(th_vet)+l_3*sin(phi_vet),l_0-l_1*cos(th_vet)+l_3*cos(phi_vet));
```
point_A_x_cum = l_1*cos(th_vet); % Point A cumulative
point_A_y_cum = l_1*sin(th_vet); % Point A cumulative

point_B_x_cum = l_0+l_3*cos(phi_vet); % Point B cumulative
point_B_y_cum = l_3*sin(phi_vet); % Point B cumulative

del = max(point_B_x_cum) - min(point_B_x_cum)
del = 4.9999

[max_phi, max_ind] = max(phi_vet);
t = time';
t1 = t(max_ind)
t1 = 3.6895

phi_2 = max_phi - 0.0002;
ind_2 = find(phi_vet>=phi_2);
ind_3 = ind_2(2,:);
t2 = t(ind_3)
t2 = 0.5509

period = abs(t2-t1);
freq = 1/period
freq = 0.3186

freq1 = w/(2*pi())
freq1 = -0.3183

freq_rat = freq/freq1
freq_rat = -1.0010
## DVP&R - Design Verification Plan (& Report)

**Project:** W22 - Bandmotor  
**Sponsor:** Roger Benham  
**Edit Date:** 12/2/2023

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
<th>DESIGN CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measuring dynamic load accurately</td>
<td>Run test platform at specified speed of 5000 rpm and compare calculated loads to measured loads</td>
<td>Torque +/- 25lbf-ft</td>
<td>None</td>
<td>Test platform</td>
<td>Lincoln</td>
<td>11/6/2023</td>
<td>11/14/2023</td>
<td>No torque measured</td>
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<tr>
<td>2</td>
<td>Measuring static load accurately</td>
<td>Statically load test platform to 4500 lbf and compare calculated loads to measured loads</td>
<td>Torque +/- 25lbf-ft</td>
<td>None</td>
<td>Test platform</td>
<td>Lincoln</td>
<td>11/7/2023</td>
<td>11/14/2023</td>
<td>No torque measured</td>
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<td>3</td>
<td>Fatigue Load - Operate to 300,000 cycles without maintenance</td>
<td>Run test platform for 300,000 cycles</td>
<td>Number of cycles</td>
<td>Minimum of 300,000 cycles</td>
<td>None</td>
<td>Test platform</td>
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<td>11/16/2023</td>
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<tr>
<td>4</td>
<td>Modification time</td>
<td>Replace one major component on the test platform (Link, Pulley, etc…)</td>
<td>Time to complete major modification</td>
<td>Maximum of 4 hours</td>
<td>None</td>
<td>Spare major component to replace</td>
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<td>11/11/2023</td>
<td>11/13/2023</td>
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<tr>
<td>5</td>
<td>Maintenance</td>
<td>Assemble and Disassemble linkage system</td>
<td>Number of disassembled and assembled times</td>
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<td>None</td>
<td>Test platform</td>
<td>Lincoln</td>
<td>10/9/2023</td>
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<tr>
<td>6</td>
<td>Learn to use time</td>
<td>Train a student of Benham's choosing to learn to use the test platform and successfully take measurements</td>
<td>Time to independently take measurement</td>
<td>Maximum of 1 hour</td>
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<td>Test platform</td>
<td>Austin</td>
<td>11/1/2023</td>
<td>12/1/2023</td>
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Appendix F – Test Procedures

Test Procedure for Dynamic Load Test

Test #: 1
Test Name: Dynamic Load Test

Purpose: The purpose of this test is to run the test platform at a specified speed of 1140 rpm and compare it to calculated. Through this test, we will determine the highest speed that the motor can operate for our system to safely operate. We will record the torque of the crankshaft.

Scope: The purpose of this test is to accurately record and compare the torque of the crankshaft. Through this test, we will validate our online calculator. We have set an acceptable criterion of +/- 25 lbf for the variations between the recorded values and the output values from our calculator.

Equipment:
1. Linkage system
2. Motor
3. Strain Gauges Sensors
4. Amplifier
5. Strain Guage Indicator

Hazards:
1. Electrical Hazard
   The strain gauge sensors and motor require wiring. It is critical that the operation is performed in a dry area. It is critical that the operator does not touch the wires and ensures that the wires are secure prior to performing the operation.
2. Projectile hazards
   Components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people.
3. Improper alignment
   It is critical to check for improper alignment of linkages or components; it is necessary to realign prior to testing. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear.
4. Severe heat
   It is necessary to ensure that the lubrication system is working properly to ensure that the mechanical parts won’t overheat due to friction, especially at high operation speeds.
5. Pinch Points/Rope Burn
   The safety enclosure should be put on properly to eliminate the risk of minor pinches and cuts. The safety enclosure should be securely on during testing of the platform.

PPE Requirements:
1. Eye Protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.
4. Gloves – Protective gloves should be used to prevent wire burn.

Facility:
Cal Poly SLO - Bonderson Building (192)
Procedure:
1. Set up the test platform in a dry, controlled environment, ensuring all components are properly aligned.
2. Verify that the safety enclosure is securely in place.
3. Put on the required PPE, including safety goggles, sturdy shoes, protective clothing, and gloves.
4. Ensure that all electrical connections are secure and well-insulated to mitigate electrical hazards.
5. Start the test platform motor and run it at a specified speed of 1140 rpm, monitoring temperature and tension.
6. Simultaneously, record the torque of the crankshaft using the torque measuring instrument.
7. Calculate the expected torque value using the online torque calculator for the same operating conditions.
8. Compare the recorded torque value with the calculated torque value. Calculate the variation and ensure it falls within the acceptable tolerance of +/- 25 lbf.
9. If the recorded torque is within the acceptable tolerance range, consider the test successful. If not, investigate potential issues with the system.
10. Record all relevant data, including the test date, time, personnel involved, and any observations.
11. Safely stop the test platform motor.
12. Inspect the motor, test platform and linkage system to ensure no wear and tear has occurred. Comment on conditions in results.
13. Analyze the data, identify any discrepancies, and report the results.
Data:

*Table F 1. Crankshaft Torque Validation Test Data*

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Operator Name</th>
<th>Test Platform RPM</th>
<th>Recorded Torque (lb-ft)</th>
<th>Calculated Torque (lb-ft)</th>
<th>Variation (lb-ft)</th>
<th>Comments</th>
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<td>-</td>
<td>1725</td>
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</tr>
</tbody>
</table>

**Potential safety issues and responses:**

Test Date(s): 11/06/2023 – 11/14/2023

Test Results:

The dynamic test failed since the strain on the shaft was too small for the strain gauge measurement device to read. One improvement we recommend is making the shaft a smaller diameter, and increasing the torque applied on the shaft to obtain larger strain measurements. Increasing the torque applied can increase safety issues, including overheating and shaft noise. This can be made less severe by including the lubrication system.

Performed By: Lincoln
Test Procedure for Verifying Static Load

Test #: 2
Test Name: Verifying Static Loads
Purpose: Calibrate Excel calculator as well as sensors to output values that are either equal or approximately equal within a reasonable range.

Equipment:
1. Linkage System
   a. With sensors installed
2. Motor
3. Calculator

Hazards:
1. Personal injury
   Testing a motor at stall torques so that we achieve maximum stress at the point of concentration puts all components of the system, linkages, drive wire, and prototype under heavy loads. Any sudden failure in any parts can result in catastrophic failures and personal injury.
2. Projectile hazards
   Components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people. Even with a safety enclosure proper measurement should be taken to ensure that all parts are functioning properly and being used for their dedicated function.
3. Improper alignment
   Rushing through the process may lead to improper alignment of linkages or components. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear. This also increases vibrations and the probability of failure/breakages and jeopardizes the safety enclosure’s ability to contain any projectiles.
4. Severe heat
   It is necessary to ensure that the lubrication system is working properly to ensure that the mechanical parts won’t overheat due to friction, especially at high operation speeds.
5. Pinch Points/Rope Burn
   The safety enclosure should be put on properly to eliminate the risk of minor pinches and cuts. The safety enclosure should be securely on during testing of the platform. Do not operate the machinery without the safety enclosure properly sealed and covering the linkage system.

PPE Requirements:
1. Eye Protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.
4. Gloves – To prevent wire burn.

Facility:
Cal Poly SLO - Bonderson Building (192)
Procedure:
1. Ensure a safe testing environment with clear walkways and safety equipment for personnel.
2. Use the calculator to predict the values based on the parameters being tested. Record values.
3. With equipment turned off, carefully ensure that the wires and motor are connected properly to power as well as the strain gauges.
4. Ensure that all sensors, motors, and controllers are calibrated and functional. Record calibration values for reference.
5. Ensure that the linkage system is properly aligned and secured to a base.
6. Securely attach the safety house to linkage system and crankshaft prototype.
7. Connect the motor and set the appropriate motor speed using the variable motor speed controller (stall torque).
8. Record the values of the torque output by the strain gauge indicator and compare with calculated values.
9. Look for any misalignment of components and evaluate if the system operates within specified tolerances. Examine connections and fasteners and record any signs of loosening or deformation.
10. Adjust the calculator if necessary to bring its value closer to the sensor value.

Repeat and iterate 5 times or until the value is below the desired 15% difference.

Results:
- Calibrate the calculator so that it has a similar output to the measured value, the initial goal is to achieve a 15% difference as an allowable difference.

Figure F 1. Exploded View of Linkage System
Data:

*Table F 2. Calculated Values vs. Sensor Values for Calibration*

<table>
<thead>
<tr>
<th>Test Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculator Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Value Difference</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent of Sensor Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Test Date(s): 11/07/2023 – 11/14/2023**

**Test Results:**

The static test failed since the strain on the shaft was too small for the strain gauge measurement device to read. One improvement we recommend is making the shaft a smaller diameter, and increasing the torque applied on the shaft to obtain larger strain measurements. Increasing the torque applied can increase safety issues, including overheating and shaft noise.

**Performed By: Lincoln Hofer**
Test Procedure for Verifying Fatigue Load

Test #: 3

Test Name: Verifying Fatigue Loads

Purpose: The purpose of this test is to run the test platform for 30000 cycles to determine the life and maintenance needed through fatigue load.

Equipment:
1. Linkage System
   a. With sensors installed
2. Motor
3. Calculator

Hazards:
1. Personal injury
   Testing a motor at high torques so that we achieve maximum stress at the point of concentration puts all components of the system, linkages, drive wire, and prototype under heavy loads. Any sudden failure in any parts can result in catastrophic failures and personal injury.
2. Projectile hazards
   Components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people. Even with a safety enclosure proper measurement should be taken to ensure that all parts are functioning properly and being used for their dedicated function.
3. Improper alignment
   Rushing through the process may lead to improper alignment of linkages or components. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear. This also increases vibrations and the probability of failure/ breakages and jeopardizes the safety enclosure’s ability to contain any projectiles.
4. Severe heat
   It is necessary to ensure that the lubrication system is working properly to ensure that the mechanical parts won’t overheat due to friction, especially at high operation speeds.
5. Pinch Points/Rope Burn
   The safety enclosure should be put on properly to eliminate the risk of minor pinches and cuts. The safety enclosure should be securely on during testing of the platform. Do not operate the machinery without the safety enclosure properly sealed and covering the linkage system.

PPE Requirements:
1. Eye Protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.
4. Gloves – To prevent wire burn.

Facility:
Cal Poly SLO - Bonderson Building (192)
Procedure:
1. Ensure a safe testing environment with clear walkways and safety equipment for personnel.
3. With equipment turned off, carefully ensure that the wires and motor are connected properly to power as well as the strain gauges.
3. Ensure that all sensors, motors, and controllers are calibrated and functional. Record calibration values for reference.
4. Ensure that the linkage system is properly aligned and secured to a base.
5. Securely attach the safety house to linkage system and crankshaft prototype.
6. Connect the motor and set the appropriate motor speed using the variable motor speed controller (stall torque).
7. Record the values of the torque output by the strain gauge indicator and compare with calculated values.
8. Look for any misalignment of components and evaluate if the system operates within specified tolerances. Examine connections and fasteners and record any signs of loosening or deformation.
9. Adjust the calculator if necessary to bring its value closer to the sensor value.
10. During operation, complete a visual and audible test to determine when maintenance is needed.

Results: Calculated vs Sensor Values, Pass Criteria, Fail Criteria, Run subsequent adjustments on calculator to match sensor data with any method.
We have set 30000 cycles as the minimum number of cycles before maintenance is needed in our system.
Data:

<table>
<thead>
<tr>
<th>Test</th>
<th>Minimum 300000</th>
<th>Number of Cycles</th>
<th>Notes</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300000</td>
<td>105,000</td>
<td></td>
<td>65</td>
</tr>
</tbody>
</table>

Test Date(s): 11/07/2023

Test Results:
Due to challenges in the manufacturing processes, our team did not have enough time to complete fatigue testing. The target number of cycles (300,000 cycles) was not reached due to time constraints. The system did not fail during this fatigue test and it showed reliability for many cycles.

Performed By: Lincoln Hofer
Test Procedure for Uncertainty Analysis

Test #: 4
Test Name: Modification Time - Optimal Timing for Link Changes in Linkage System

Purpose:
The purpose of this test procedure is to analyze the modularity of our design. A significant aspect of our design is its adjustability, which allows for the switching of linkage dimensions to accommodate different cam-crank offsets and match the corresponding stroke length. By evaluating this modularity, we aim to assess the design’s flexibility and versatility in adapting to varying operational requirements.

Scope:
In this test, our focus is to measure the time required for replacing a single link in the linkage system. We will conduct two individual test runs, with four different users participating in each run. By timing the users during the link replacement process, we will collect data on the duration of the task. Additionally, we will calculate the average time required for link replacement, taking into account uncertainties and propagating them to ensure accurate and reliable results. This analysis will provide insights into the efficiency and feasibility of changing links within the linkage system.

Equipment:
6. Linkage system
7. Timing device – iPhone stopwatch
8. 9/64 Allen key
9. 11/32 socket & ratchet

Hazards:
1. Personal injury
   Rapidly changing a linkage, such as disconnecting and reconnecting mechanical components, can result in personal injury if not done carefully. Fingers, hands, or other body parts can get cut in the process.
2. Projectile hazards
   With components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people.
3. Improper alignment
   Rushing through the process may lead to improper alignment of linkages or components. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear.

PPE Requirements:
1. Eye Protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.

Facility:
Cal Poly SLO - Bonderson Building (192)

Procedure:
1. Measure human stopwatch operation uncertainty by having each user start/stop the watch as quick as possible and averaging the error in time. Repeat five times for each of the four users and average all twenty measurements to come up with an experimental uncertainty for the stopwatch measurement.
2. User one begins disassembly of the linkage when the timer says “Go” and starts the stopwatch. Any one of the linkages can be chosen for disassembly seen in Figure F 2. The timer stops the stopwatch as soon as the user sets down the tools after the linkage is reassembled. Repeat test for second trial for user one.

![Exploded View of Linkage System](image)

*Figure F 2. Exploded View of Linkage System*

3. Repeat step 2 for all four users.

**Results:** Pass Criteria, Fail Criteria, Number of samples to test, Design analysis equations/spreadsheet with uncertainty. Comment on how Uncertainty Analysis will be completed.

- The average modification time across all users must be under 2 hours.

**Data:**

*Table F 4.* accounts for the variability in reaction time, multiple trials for each test run will be conducted and average time will be calculated. The standard deviation of the measured times across the trials will provide an estimate of the reaction time uncertainty.
Table F 4. Reaction Time Uncertainty Analysis

<table>
<thead>
<tr>
<th>User (Name)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>User Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Lincoln</td>
<td>0.07</td>
<td>0.75</td>
<td>0.54</td>
<td>0.81</td>
<td>0.61</td>
<td>0.56</td>
</tr>
<tr>
<td>2 Roze</td>
<td>1.20</td>
<td>0.80</td>
<td>0.81</td>
<td>0.99</td>
<td>1.87</td>
<td>1.13</td>
</tr>
<tr>
<td>3 Austin</td>
<td>1.33</td>
<td>1.19</td>
<td>0.87</td>
<td>1.00</td>
<td>1.19</td>
<td>1.12</td>
</tr>
<tr>
<td>4 Jackie</td>
<td>1.19</td>
<td>1.07</td>
<td>1.21</td>
<td>1.00</td>
<td>0.74</td>
<td>1.04</td>
</tr>
<tr>
<td>Reading uncertainty – resolution from stopwatch</td>
<td>0.01 seconds</td>
<td>Overall average</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
</tr>
</tbody>
</table>

Table F 5. Provides data on the time each user takes to disassemble and assemble a linkage.

Table F 5. Timing for Link Changes in Linkage System

<table>
<thead>
<tr>
<th>User (Name)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>User Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Lincoln</td>
<td>2 h 2 min</td>
<td>1 h 32 min</td>
<td>1 h 22 min</td>
<td>1 h 15 min</td>
<td>1 h 26 min</td>
<td>1 h 31</td>
</tr>
<tr>
<td>2 Roze</td>
<td>2 h 17 min</td>
<td>1 h 50 min</td>
<td>1 h 37 min</td>
<td>1 h 25 min</td>
<td>1 h 40 min</td>
<td>1 h 45 min</td>
</tr>
<tr>
<td>3 Austin</td>
<td>2 h 15 min</td>
<td>2 h 05 min</td>
<td>1 h 45 min</td>
<td>1 h 32 min</td>
<td>1 h 45 min</td>
<td>1 h 52 min</td>
</tr>
<tr>
<td>4 Jackie</td>
<td>2 h 23 min</td>
<td>2 h 11 min</td>
<td>1 h 57 min</td>
<td>1 h 39 min</td>
<td>1 h 56 min</td>
<td>2 h 1 min</td>
</tr>
<tr>
<td>Reading uncertainty – resolution from stopwatch</td>
<td>0.01 seconds</td>
<td>Overall average</td>
<td>1 h 47 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
</tr>
</tbody>
</table>

Test Date(s): 11/11/2023 – 11/13/2023

Test Results:

The result of each user is analyzed to determine the average reaction time using a stopwatch. This data provides valuable information which helps us determine the stopwatch operation uncertainty. The average reaction time for a sample of four people is 0.96 seconds. Each person performed the reaction time test five times resulting in an individual average with a standard deviation, which can be seen in Figure F3.

Additionally, the average time to modify (manufacture and assemble) a link is 1 hour and 47 minutes.
Figure F 3. Exploded View of Linkage System

Performed By: Austin Rhee, Lincoln Hofer, Roze Raymond, Jacqueline Mendoza
Test Procedure for Linkage Maintenance

Test number: #5
Test Name: Linkage Maintenance

Purpose: The objective of this test is to assess the assembly and disassembly of the linkage system with the aim of identifying any potential maintenance process issues with the number of times the linkage system is assembled and disassembled.

Equipment:
1. Linkage system
2. 9/64 Allen key
3. 11/32 socket & ratchet

Hazards:
1. Personal injury
   Rapidly changing a linkage, such as disconnecting and reconnecting mechanical components, can result in personal injury if not done carefully. Fingers, hands, or other body parts can get cut in the process.
2. Projectile hazards
   Components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people.
3. Improper alignment
   Rushing through the process may lead to improper alignment of linkages or components. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear.

PPE Requirements:
1. Eye protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.

Facility:
Cal Poly SLO - Bonderson Building (192)

Procedure:
1. Begin the disassembly process by using a socket wrench & Allen key to carefully unscrew the bolts in the prescribed order, ensuring that you place bolts & links aside in a line to maintain their original location upon assembly. This order includes:
   a. Disconnect the connector link and oscillating link.
   b. Separate the connector link and the drive link.
   c. Remove the spacing link, oscillating link, and support link connection.
   d. Dismantle the drive link, spacing link and support link connection.
2. Thoroughly inspect all the bolts and linkages, making notes in the table provided regarding any signs of wear and tear. Include a check mark in the table under the components when a specific component has been inspected.
3. If necessary, apply lubrication to the components or clean the components to ensure optimal performance.
4. For reassembly, follow the reverse order of disassembly as outlined below:
   a. Connect the drive link, spacing link, and support link.
   b. Reattach the spacing link, oscillating link, and support link.
   c. Reconnect the connection link and drive link.
   d. Reassemble the connector link and oscillating link.
Note: Exercise caution and precision throughout the disassembly and reassembly process to ensure the proper functioning of the part.
5. The acceptance criteria for measurement is 10, therefore repeat the above steps at least 10 times.

Results: Pass Criteria, Fail Criteria, Number trials accomplished, Design analysis spreadsheet filled. Comments on potential safety issues will be made.
### Data:

*Table F 6. Number of Disassembled and Assembled Times*

<table>
<thead>
<tr>
<th>Test #</th>
<th>Connector link bolt #1</th>
<th>Connector link bolt #2</th>
<th>Spacing link bolt #1</th>
<th>Spacing link bolt #2</th>
<th>Connector Link</th>
<th>Oscillating Link</th>
<th>Drive Link</th>
<th>Spacing Link</th>
<th>Support Links (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>5</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>8</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>19</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

**Potential safety issues and responses:**

Ensure that fasteners are secured tightly.

---

**Test Date(s): 10/09/2023**

**Test Results:**

Locking nuts needs to be replaced every 18 times disassembled and assembled to ensure good performance. This indicates that our linkage design is reliable. Locking nuts are inexpensive and easy to switch. This indicates that our system is low maintenance and reliable.

**Performed By: Lincoln Hofer**
Test number: #6
Test Name: Learn to use

Purpose:
The purpose of this test is to determine the average time that it takes the user to learn how to use the testing platform. This includes learning the process of ensuring that the testing platform is connected correctly, and the alignment of the linkage system is according to the user manual. Part of this testing also includes learning about the risks and the proper PPE used when working with our testing platform.

Scope:
We will measure the time it takes for the user to learn how to assemble and dissemble the parts in our testing system. The user will also learn about the risks and the proper safety procedure. Additionally, they will check for correct sensor subsystem wiring. Sensor calibration and linkage alignment will be addressed as part of this test.

Equipment:
10. Testing platform system
   a. Sensors
   b. Strain Guage Indicator
   c. Motor
   d. Linkage system
   e. Bandmotor engine (Benham’s prototype)
11. Timing device – iPhone stopwatch
12. 9/64 Allen key
13. 11/32 socket & ratchet

Hazards:
1. Personal injury
   Rapidly changing a linkage, such as disconnecting and reconnecting mechanical components, can result in personal injury if not done carefully. Fingers, hands, or other body parts can get cut in the process.
2. Projectile hazards
   With components under tension, such as making sudden changes with the drive wire can release this tension, causing these components to become projectiles that can cause injury or damage to nearby objects or people.
3. Improper alignment
   Rushing through the process may lead to improper alignment of linkages or components. Misaligned linkages can cause malfunctioning, reduced performance, or premature wear and tear.
4. Electrical Hazard
   Prior to running the experiment, the power of the motor must be off. It is necessary to check the wire connection of the sensors on the shaft and the connection to the strain gauge indicator. Incorrect wiring could result in electric shock/burns including fire with faulty installations.

PPE Requirements:
1. Eye Protection – Safety goggles
2. Foot protection – Sturdy, closed-toed shoes
3. Protective clothing/accessories – No long loose sleeves, tie back long hair, ensure clothing doesn’t lead to the possibility of tripping.

4. Rubber Gloves

**Facility:**
Cal Poly SLO - Bonderson Building (192)

**Procedure:**
1. Ensure a safe testing environment with clear walkways and safety equipment for personnel.
2. Use the calculator to predict the values based on the parameters being tested. Record values.
3. Ensure that the motor is not connected and that there is a clean working surface.
4. Set up the bandmotor engine (Benham’s Prototype) on a stable surface/table.
5. Ensure that the drive wire is connected, and properly attached to each pulley in the engine.
6. Set up the linkage system, ensure it is correctly placed and stable on a flat surface. Ensure that the linkage system is stable and secured to the ground. Check that the screws and tighten if needed.
7. Connect the drive wire to the linkage and the engine.
8. Place the safety enclosure over the linkage system to prevent injury due to flying linkage parts.
9. Inspect that the sensor strain gauges are connected and placed correctly on the shaft (look at the part information sheet).
10. Verify that the indicator is connected to the strain gauges.
11. Check that the motor wire is connected correctly (same color wires).
12. Run 5 static tests to measure torque and verify with an online calculator.
13. If not accurate, adjust the online calculator.

**Results:** Number of samples to test, Design analysis equations/spreadsheet with uncertainty. The uncertainty analysis will compare the percent difference between the value output by the static test and the online calculator.
- The test will compare and help adjust the online calculator.

**Data:**

*Table F 7. Timing for Link Changes in Linkage System*

<table>
<thead>
<tr>
<th>User (Name)</th>
<th>Time (seconds)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Not performed</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table F 7. Provides data on the time each user takes to learn to use the prototype.

Table F 8. Uncertainty analysis of the measured torque.

<table>
<thead>
<tr>
<th>User (Name):</th>
<th>Test</th>
<th>Measured Torque</th>
<th>Online Calculator Torque</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Torque Uncertainty

This data will be recorded for every user so that the user can ensure they can measure consistent data. The valid percent difference is set at 15%.

Test Date(s): 11/1/2023 – 12/01/2023

Test Results:

This test was not performed because no results were obtained due to the strain gauge’s inability to sense very low strain from the stiff shaft. Once a more sensitive measurement system is implemented, a test to measure the user average training time is needed.

Performed By: Austin Rhee