

Mechanical Actuation Mechanism Design for Cryogenic Microwave Cavities in Axion Dark Matter Searches

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Abstract

Resonant Microwave Cavities are placed in a strong magnetic field at cryogenic temperatures ($\sim 1\text{K}$) in order to try to convert axions into detectable photons. A major challenge is to tune the cavity to allow no interference with the desired environment used for the experiment, which enables the system to operate near absolute zero and maintain superconductivity, thereby reducing noise as much as possible. My project focuses on developing and testing a low-thermal-conductivity gear reduction system with a 1000:1 ratio for cavity tuning. This gear system could significantly improve the thermal and electromagnetic interference of the tuning mechanism, helping ADMX scan for axions more accurately.

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1 Introduction

1.1 Motivation

Dark matter accounts for the majority of the amount of matter within our universe, but its identity and details about it remain unknown. Over the past several years, many particles have been proposed for this, and the axion emerged as a very plausible candidate. It was introduced originally to propose a solution to the strong CP problem in quantum chromodynamics. Axions serve as an explanation for the absence of CP violation in the strong force and help explain cold dark matter, which shapes galaxies.

Detecting axions requires an effective method, such as using microwave cavity horoscopes, which convert them into microwave photons in the environment of a strong magnetic field. The Axion Dark Matter eXperiment (ADMX) is the leading utilization of this method. ADMX faces a major challenge of applying a continuous and accurate tuning of the microwave cavity to search for possible axion masses at various frequencies. This also serves as a constraint on executing the process without much thermal fluctuations of thermal heat and a stable electromagnetic field. Traditional tuning systems require metal gears and shafts. This introduces unwanted thermal conduction and potentially interferes with the electromagnetism in the cold environment, which can potentially degrade the sensitivity of the detector.

To solve this issue, ADMX has begun investigating alternative materials and mechanical systems that maintain precise actuation without compromising the thermal isolation of the cavity. My project is directly tied to this challenge of designing, prototyping, and testing a gear reduction system made of different types of plastic. In the end, ADMX is using a durable, cryo-compatible plastic. The proposed design aims to achieve a 1000:1 reduction ratio to enable fine

cavity tuning while drastically reducing heat transfer. If successful, this system could enhance ADMX's ability to scan for axions efficiently and reliably. It can bring the experiment closer to a potential discovery.

1.2 ADMX

The ADMX experiment depends on a tunable microwave cavity to search for axions by detecting axions through their conversion into photons under a strong magnetic field. Since the mass of the axion is unknown, the cavity must be adjusted across a wide range of frequencies to identify any possible signal. This is done by altering the position of internal tuning rods, which changes the electromagnetic mode structure of the cavity. The scan typically spans the 0.5 - 2 GHz frequency range, corresponding to axion masses in the micro-electronvolt scale.

This tuning process takes place under strict environmental conditions. The cavity operates inside a superconducting magnet at cryogenic temperatures of roughly .1 kelvin and within a high-vacuum chamber. Because of this, thermal insulation and mechanical durability are essential. Traditional metal gear systems introduce unwanted thermal conduction into the cold volume, which can disturb the electromagnetic field and reduce the sensitivity of the experiment.

To address this problem, ADMX is exploring low-conductivity materials such as PEEK (Poly ether ketone), POM (Polyoxymethane), and Vespel, which are all cryo-compatible plastics capable of maintaining strength and precision at low temperatures. My role in this effort is to develop and test a 1000:1 gear reduction system made from a suitable material. This gearbox is designed to provide the fine control necessary for precise tuning while minimizing thermal load on the cavity. It is intended to interface directly with the rod actuation mechanism

and support long-term and stable scanning.

Before the cavity is used in axion detection, its electromagnetic behavior must be carefully measured and mapped. This is done through a method known as bead perturbation. A small dielectric bead is pulled through the cavity to locally disturb the electric field. This produces a small shift in the resonant frequency. These frequency shifts are recorded using a vector network analyzer and used to create a mode map of the electric field distribution inside the cavity. Coaxial antennas allow for low-noise measurements of signal reflection and transmission known as S-parameters.

This mapping process ensures that the cavity modes are correctly aligned and that the field distribution matches theoretical expectations. My gearbox system supports this process as well as it allows for a precise and smooth movement of the tuning rods or bead mechanism without introducing additional heat or instability. With it, both the tuning and characterization stages of ADMX can be performed more reliably and efficiently.

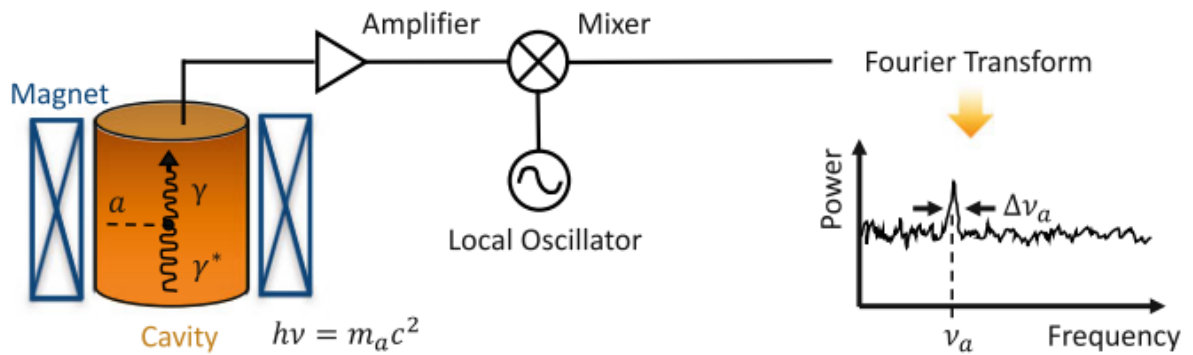


Figure 1.1 Simplified axion detection model of microwave cavity searches.

2 Method

2.1 Material Selection

In designing a gearbox capable of operating inside the ADMX experiment's .1K cryogenic environment, the first concern was material choice. It was going to be made out of. Traditional metal gears introduce too much thermal conduction into the cavity. It risks disrupting the superconducting and electromagnetic conditions required for axion detection. Most importantly, lubricants become unreliable at cryogenic temperatures, which makes conventional lubrication-based gear systems ineffective and produces many thermal and physical problems.

To attack these challenges, an idea was to turn to the aerospace industry, where cryogenic mechanical systems have long been in use. The thesis "*Gears in Space*" provided critical insight into how gear systems are engineered for spacecraft operating in near-zero temperatures and vacuum environments. One of the main takeaways was the consistent shift away from metal-on-metal gears toward high performance engineering plastics.

The thesis discusses how polymer gears such as PEEK and Vespel have been adopted due to their self-lubricating properties, durability, and low thermal conductivity. In cryogenic vacuum tests simulating space conditions, PEEK was shown to be more effective than POM. It showed stable wear rates and low friction coefficients compared to POM. It had reliable performance under moderate load conditions, making it one of the few materials capable of

staying functionable mechanically and thermally.

Most importantly, the document reports that PEEK was successfully tested in multiple NASA mechanisms, including actuator systems and cryogenic filter wheels, where it operated across multiple thermal cycles with minimal wear. These applications were shown relevant to our experiment. They demonstrate that PEEK can withstand not just low temperatures, but the mechanical stress and repeated actuation cycles expected in experiments like ADMX. An extremely important aspect that PEEK performs is having a low and predictable coefficient of thermal expansion. The downside of metals is also their higher thermal contraction and expansion under a thermal extremity. This is critical when tolerances in the gear mesh are tight and stability is essential. Because of these properties, PEEK became our selected material.

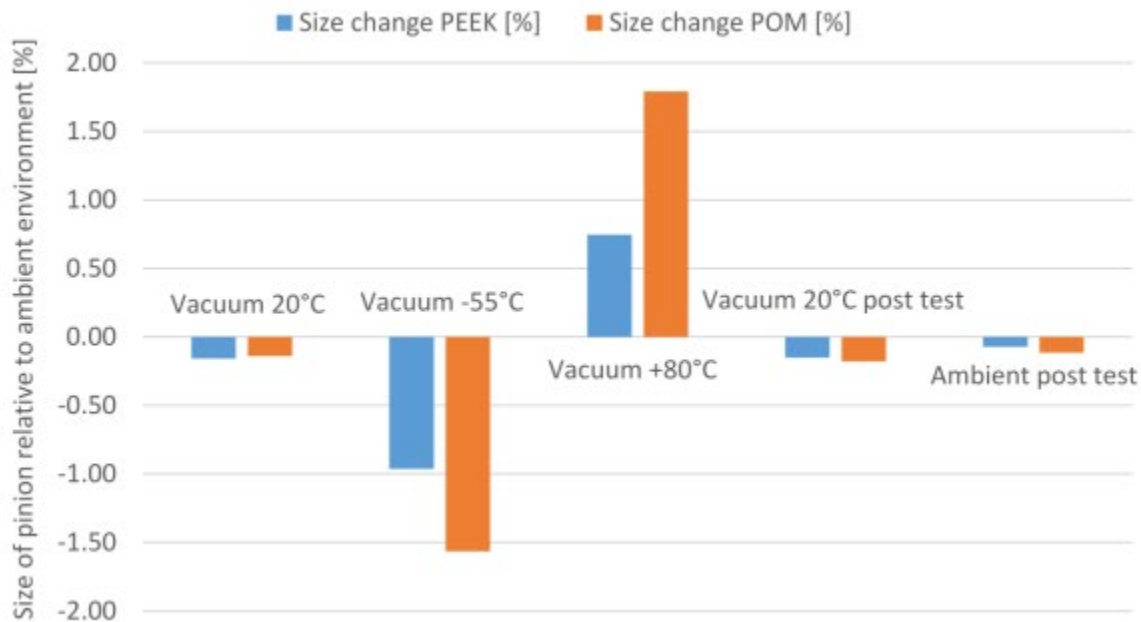


Figure 2.1: Comparison of dimensional stability for PEEK and POM under vacuum conditions at various temperatures. PEEK exhibits lower size change percentages across cryogenic and elevated temperature ranges, indicating more predictable thermal expansion behavior. This supports its suitability for precision gear systems in cryogenic environments like ADMX.

2.2 Model Design

The next stage of the project focused on designing a gear reduction system that could meet the specific mechanical and spatial requirements necessary with the environment for ADMX. The primary objective was to create a compact gearbox with a target gear ratio near 1000:1 while maintaining an overall enclosure diameter size under 40 mm in diameter. Also, the gearbox needed to accommodate a 1/8-inch input and output shafts. Internally, the gearbox should use smaller 2 millimeter shafts to hold the intermediate gears.

The design of the gear system is made through a series of compound gears and spur gears with a modulus of 0.5. Five stages out of the six parts for reduction were accomplished using compound gear pairs with a 3:1 ratio. These stages were arranged to multiply the reduction effect progressively while keeping the overall diameter small enough to fit within the desired limit. The final stage employed a 4:1 simple spur gear, which would complete the overall reduction. This overall system allowed for a detailed level of coordination over the output shaft's position while keeping any gear slippage to a minimum.

All components were designed using SolidWorks, which is a CAD (Computer Aided Design) software that allows detailed modeling for shaft placements and end plates. The gears were able to be placed in a precise and correct clearance with the use of animations and assembly through the whole sequence in SolidWorks. SolidWorks also made it possible to identify points of interference or misalignment before moving forward with producing a prototype, which aided in saving time and ensuring precise production with the cavity system. The final design satisfied all necessary areas of focus, which has resulted in a gear system that is both mechanically sturdy and thermally compatible with the microwave cavity.

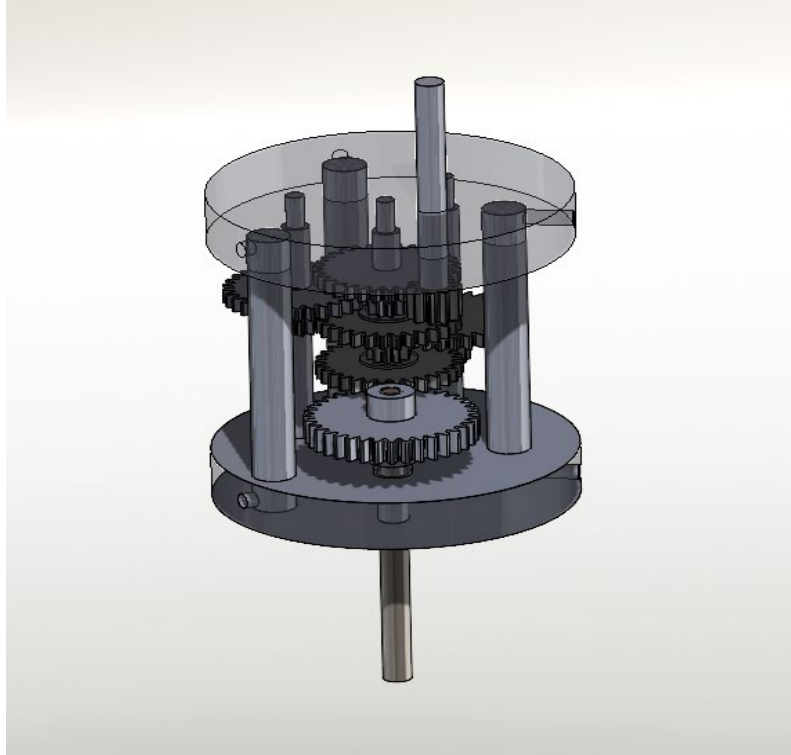


Figure 2.2: CAD model of the 1000:1 gearbox with compound gear stages and spur gear.

2.3 Test

A physical test was conducted to test the whole system together. This phase served as a preliminary check to confirm the CAD modeled system translated into real world components, and it maintains its proper interaction with each through all different conditions. To help verify the design and prepare for prototyping, a physical model of the gearbox was created using 3D-printed parts. These parts were based directly on the SolidWorks design and gave an accurate view of the shape, size, and fit of the full system. Although the printed material does not match the properties of PEEK, it allowed for hands-on testing of the gear layout and motion through all

stages.

To test how well the gearbox worked, a hand drill was used to drive the input shaft. This allowed the system to be run at both high and low speeds. At high speeds, the gears were checked for any skipping or wobbling. At low speeds, the focus was on how smoothly the gears turned, how well they stayed engaged, and whether the output shaft moved as expected.

The test showed that the compound gear stages worked properly. Adequate torque was passed through each stage to the output shaft without major issues. The gears stayed engaged and the shafts remained aligned across different speeds. This physical test verified that the design was functional and ready for further development. It served as a key step in showing the gearbox could perform well physically and not just in simulation, which can potentially disregard an aspect of concern.

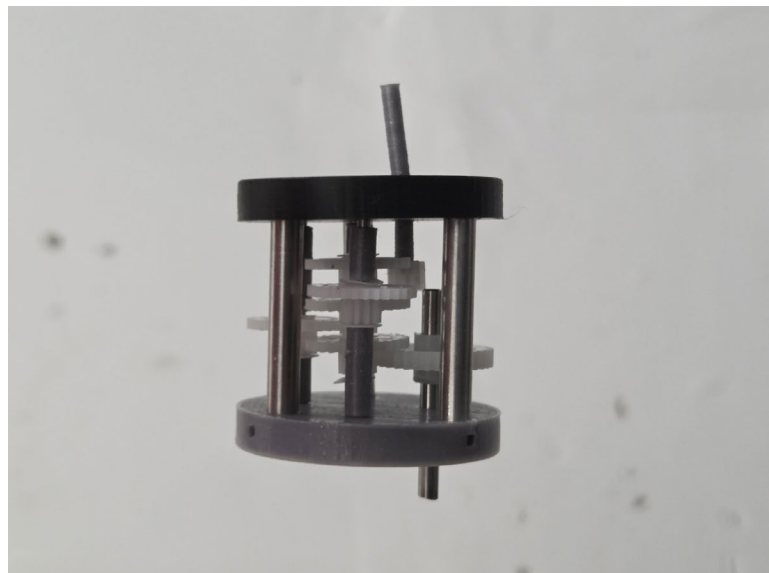


Figure 2.3: 3D-printed prototype of the multi-stage compound gearbox used for physical motion testing. The model is based directly on CAD geometry. The prototype validated the mechanical functionality of the design prior to machining in PEEK.

2.4 Production

After confirming the design through modeling and testing a prototype, the project moved into production. This part focused on making the end plates and bushings. These pieces held the gear shafts in place and helped keep the system aligned. They were important for making sure the gears moved smoothly and stayed in the right position during use.

The first parts made were the end plates. To practice machining and check if the design worked, we used Delrin plastic. Delrin was easier to work with than PEEK and cost less. It gave a way to test the shape and size of the parts before using the final material. Once the parts came out right, we got ready to move forward with PEEK.

The parts were modeled in SolidWorks and then moved to Fusion 360 for manufacturing. In Fusion 360, many different toolpaths were made to guide the milling machine. It was a major focus to alter the speed and depth of the cuts to match what Delrin could handle. After that, we created the G-code and opened it in the Bantam Tools software. This program was used to control the Bantam Tools Desktop Milling Machine.

The milling machine made the parts correctly. The end plates fit the gearbox and matched the design. The holes for the shafts and other features were cut cleanly. No big changes were needed after the cuts. These parts finished the move from design to real hardware. They also showed that the gearbox could be built with the tools and materials we planned to use.

3 Conclusion

This project created a gear system for the ADMX experiment that worked under cryogenic conditions. The design used plastic instead of metal to help reduce heat and keep motion stable. A full gearbox was made with a 1000 to 1 ratio and small enough to fit the space needed. It was tested with 3D printed parts and real machined pieces from Delrin. These tests showed that the system worked like the model and could be built with the tools we had.

If used in ADMX, the gearbox could make tuning the cavity smoother and more exact. It would reduce heat getting into the system and help keep the magnet and cavity stable. This would make scanning faster and more reliable. In a search where control and stability are important, the small changes like this could help the experiment work better and bring us closer to finding the axion.

3.1 Future Work

The next step is to test the gearbox during an actual tuning cycle within the ADMX experiment. This would involve replacing one of the existing tuning drives with the plastic gear system and observing how it performs under cryogenic conditions. These tests will have to observe factors including how well it handles torque stability and how much heat it transfers into the system.

This phase would also test long-term stability and repeatability across multiple runs. If the system shows strong performance without degrading cavity sensitivity, it could be considered for full integration into the detector. Final testing in a live setup will help determine whether the plastic gearbox can meet the precision and thermal demands of ADMX during real axion search operations.

4 Acknowledgements

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5 Appendix

5.1 Appendix A



Figure 5.1: Detailed engineering design of the 1000:1 compound gear reduction system, including front, right, and top views.

5.2 Appendix B

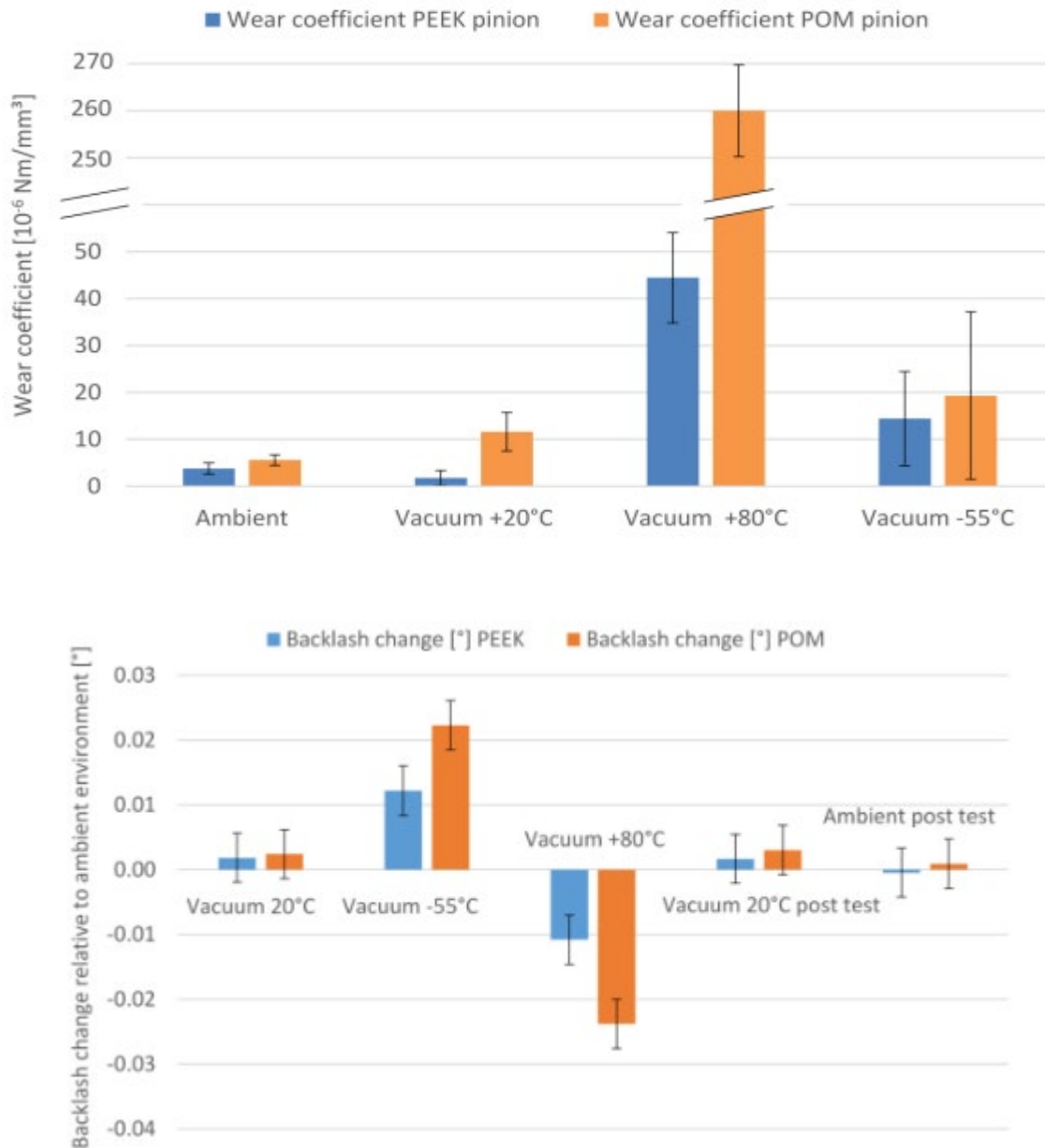


Figure 5.2: Wear coefficient and backlash change comparison of PEEK and POM pinion gears under various environmental conditions. PEEK demonstrates being the best in wear resistance and durability across all test conditions. It is particularly stable performance under vacuum +80°C where POM shows significant degradation (260×10^{-6} mm³/Nm wear coefficient and -0.025 backlash change).

5.3 Appendix C

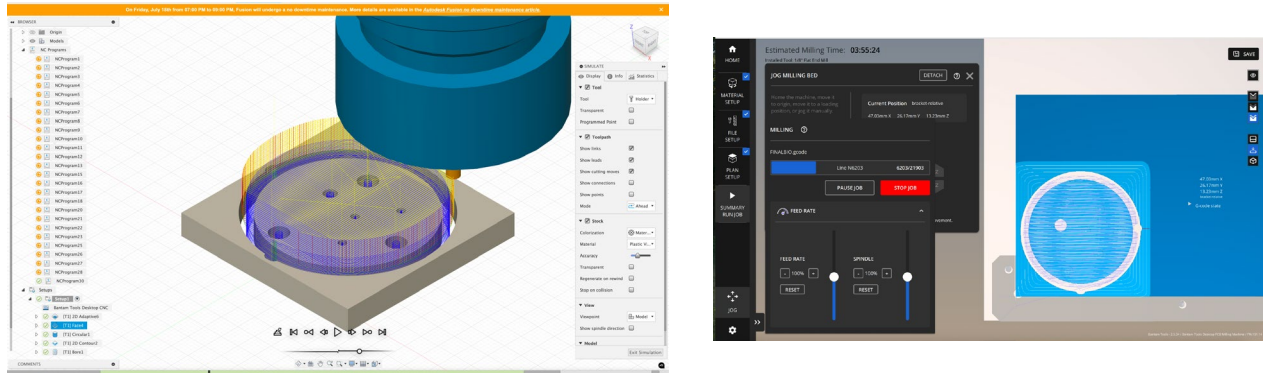


Figure 5.3: CAD modeling and manufacturing workflow showing Fusion 360 CAM programming with generated toolpaths (left) and Bantam Tools milling software (right). The gear components were initially modeled in SolidWorks, then imported into Fusion 360 for toolpath generation and G-code creation. Machining parameters including feed rates and cutting depths were optimized for plastic properties before transfer to Bantam Tools software for CNC milling operations.

5.4 Appendix D



Figure 5.4: Raw material stock used for gear manufacturing showing PEEK rod (gray) and Delrin rod (white) along with a machined test piece for the end plates.

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