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Dynamic Mechanical Analysis Piezoelectric Design

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Dynamic Mechanical Analysis Piezoelectric Design

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Honors Research Project

Submitted to

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Honors Faculty Advisor (signed)

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Dynamic Mechanical Analysis Piezoelectric Design

Letia Bass, Ethan Goodman, Joseph Mazur, Michaela McCrae

Department of Mechanical Engineering

Abstract

This project is a continuation into the design and implementation of a Dynamic Mechanical Analysis (DMA) device that will be used to conduct high frequency testing on tire tread compounds. The design requirements necessary were to design a device that will produce a target frequency of 10 kHz with a 0.05% strain, while being at room temperature. The 3-D model developed by the previous year's students was improved upon and new parts were designed as well. The assemblies (most importantly the connector piece) were 3-D modeled using Creo Parametric and analyzed with COMSOL Multiphysics. A new design involving flexures was also designed to be used in the third year of the project to help increase the overall frequency of the assembly while adding support to keep the assembly in place. Different designs were examined to determine the best design that met all of the design requirements. After the best design was chosen, communication with both local and international companies was done to determine the best method for manufacturing. Communication with companies that could give quotes for glue used to prevent the rubber from shearing off the metal surfaces. The part was then ordered and delivered to the university. The part was then assembled to ensure the parts were manufactured properly and will be tested in the future.

Acknowledgement

We would like to acknowledge our Senior Design Advisor, Dr. Siamak Farhad, and PHD Graduate Student Advisor, Roja Esmaeeli, for their support and encouragement. We would also like to thank CenTiRe (Center for Tire Research) for giving us the opportunity to contribute to the three phase project.

Disclosure

Some of the contents of this project have been removed due to confidentiality of the work previously done be team members during phase one of the project.

Table of Contents

Chapter 1 – Introduction

Background

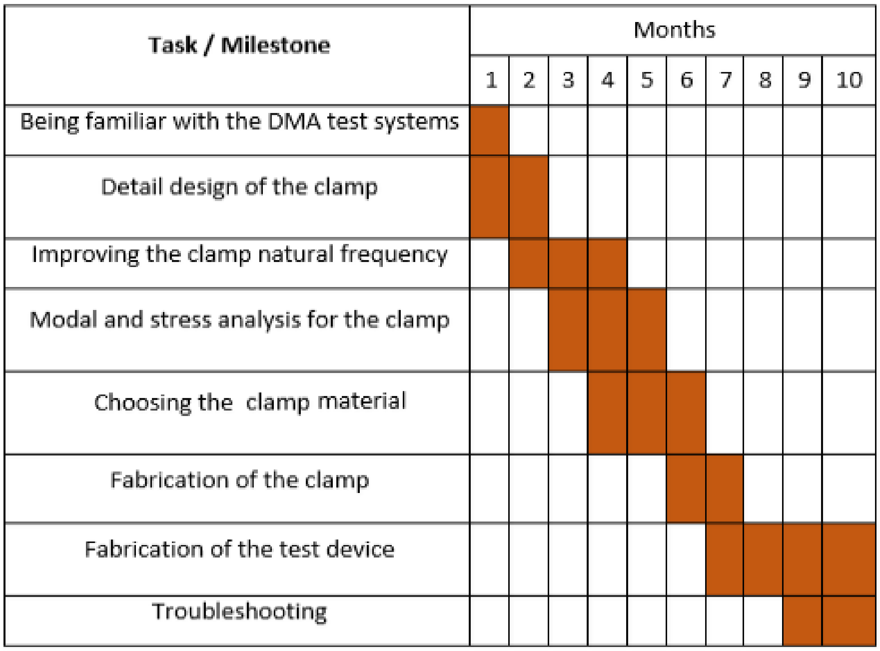
The purpose of this project was to design and test a Dynamic Mechanical Analysis (DMA) Device that would be used to determine the dynamic response of viscoelastic materials for The Center for Tire Research [4]. The device was required to operate at frequencies in the range of 10-1000 kHz because the response of the material in that frequency range helps to determine the material's performance in wet conditions for traction predictions. The other major design criteria was to maintain a target strain of 0.05% at maximum frequency. The University of Akron has a couple of DMA devices, but they are not capable of operating at high enough frequencies to get sufficient results. The current alternative for the DMA device is to run the tests at high temperatures to simulate the required frequency. This yields inaccurate results and causes errors because it is only an estimate. Other DMA devices typically use the Williams–Landel–Ferry (WLF) Equation in their calculations to determine the relationship between stress/strain and temperature. However, the WLF equations assume that the specimen is comprised of pure rubber only and causes additional errors since tire compounds are made from synthetic rubber, carbon black, and other chemical compounds [4].

This project is in year two of a three year plan. The purpose of phase two was to understand the DMA device, optimize the existing design based off of this understanding, manufacture the device, and collect preliminary test data for the design that has the highest frequency. The device uses a piezoelectric actuator that converts electrical energy into linear motion along with clamps to hold the tread specimen in a double-sandwich orientation. The tread is put into shear by the piezo's actuation with the force sensor recording the input from the piezo. A connection piece between the force sensor and piezo was the main design objective focusing on weight, stiffness, Eigen frequency, dynamic force against the piezo, and allowing maximum piezo actuation. There will also be possible testing and data comparison of the system against the existing

University of Akron DMA device. For the design process, we used computer programs to draft and analyze our models. The computer programs that we used were Creo Parametric for the modeling, along with COMSOL Multiphysics for the Eigen frequency and Von Mises stress analysis used to determine the final design.

Product Definition (Design briefs)

During the first year of the project, many components were selected to use in the DMA design. The preloaded piezo actuator that was selected from Physik Instrumente due to the desired frequency of 10 kHz in which it is able to operate. The displacement of the particular piezo is 0.75 micrometers. The force sensor was selected based on which design yielded the highest stiffness and natural frequency from COMSOL Multiphysics analysis. The multi-voltage piezo controller is a component that was selected in the previous phase of the project, along with the piezo and force sensor. The piezo amplifier that was chosen previously is a one channel piezo amplifier module [1][5]. For this year’s phase of the project, the connector piece was the main design focus as seen from the project forecast in Table 1. The connector needs to connect the force sensor and piezo. A gap between the connection and piezo needed to be created for optimal actuator displacement. The goal is for low cost, low weight, high frequency, and the ability to be manufactured. The flexure pieces designed for the third phase of the project should increase the frequency and stiffness even higher optimizing the design further.



Task / Milestone	Months									
	1	2	3	4	5	6	7	8	9	10
Being familiar with the DMA test systems	■									
Detail design of the clamp	■	■								
Improving the clamp natural frequency		■	■	■						
Modal and stress analysis for the clamp			■	■	■					
Choosing the clamp material				■	■	■				
Fabrication of the clamp						■	■			
Fabrication of the test device							■	■	■	■
Troubleshooting									■	■

Table 1: Gantt Chart

Chapter 2 - Conceptual Design

The general process of the design involves the piezoelectric actuator converting electrical energy into mechanical energy, causing the piezo to actuate. The connector joins the piezo to the force sensor. The force sensor has a small part sticking out of it that falls in between the clamp pieces where the rubber specimen will go.

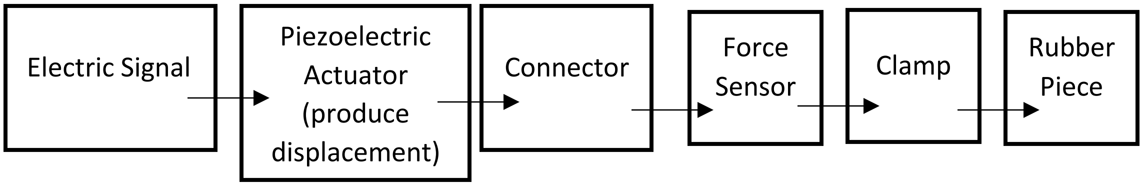


Figure 1: Overall Function Structure Diagrams

The most important decisions that affect the performance of the design were the size and shape of the connector piece since the piezo and force sensor were already chosen. For size, through COMSOL analysis, it was determined that the connector piece being smaller than the force sensor yielded the highest natural frequency. For shape, the more corners and open bottoms caused more problems for deflection, even if the Eigen frequency was higher. Ultimately, a connector piece skinnier and smaller than the force sensor with a cylindrical shape was chosen, as shown in Figure 2

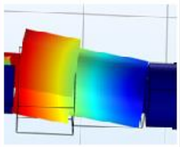
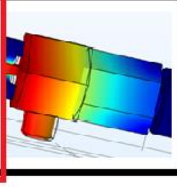
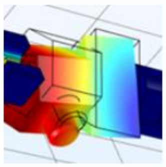
SIZE	**SMALLER THAN THE FORCE SENSOR**	**EQUAL SIZE**	**LARGER THAN THE FORCE SENSOR**
SHAPE			

Figure 2: Morphological Chart

The design requirements for the project were to get the target data we wanted, and design something manufacturable at a low cost and weight. The main priorities would be hitting the target natural frequency, and making sure the design could be manufactured given how tiny the part was. A general overview is shown in Figure 3.

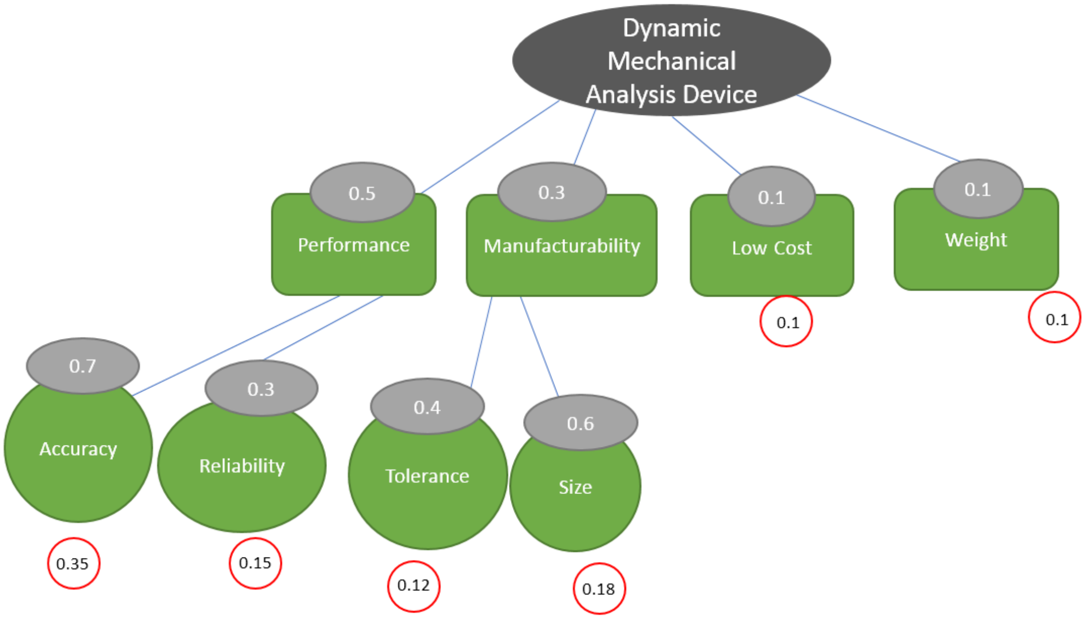


Figure 3: Objective Tree

Different orientations needed to be analyzed in order to find the best overall performance of the DMA device. In phase-one of the project vertical and horizontal orientations were designed to see which would produce the best overall unit stiffness and frequency. Arrangement of the rubber specimens was a large limiting factor on the design leading to a double-sandwich shear test configuration being selected instead of single sample shear test and quadruple block shear test options [2]. A double-sandwich shear test configuration can cause complications and data errors when running over wide temperature ranges due to thermal expansion of the fixture causing the clamping force to largely vary. Thermal analysis of the rubber specimens was completed during phase-one by placing them in the double-sandwich orientation and recording the maximum temperature reached.

Chapter 3 - Embodiment Design

Before the final design was chosen research was done to determine the best overall manufacturing method. Special considerations were made for the scaling of the assembly since all the components would be miniature. The manufacturing methods were narrowed down to those that would be able to machine complex shapes, sharp corners, small sizes, and single unit quantities. The methods were narrowed down to metal 3-D printing and sinker EDM. Through comparison of the two methods it was determined that sinker EDM would be the superior choice meeting all of the desired design requirements. Through extensive research and company recommendations metal 3-D printing was ruled out for it's inability to manufacture the parts on such a small scale as well as not being able to print the threads without requiring additional machining detailed in Table 2 and Table 3 [6][7].

TYPE:	3-D - PRINTING	EDM (SINKER)
PROS:	Lower set-up time	General tolerance: +/- 0.005 inch or 0.127mm
	Reduced labor time	Removal of metal chip issues is superb due to the process taking place in fluid
	General tolerance: +/- 0.5mm	Improved cooling
	Ability to print difficult shapes and hard corners	Ability to print difficult shapes
	Some printers can have the ability to print a 50 micron resolution (AM250 powder bed fusion)	Ability to manufacture smaller parts (Standard tooling cannot)
	Ability to make strong and lightweight parts	Can handle a tolerance as low as 0.00508mm
	Low material waste	Exceptional surface finish and aesthetic
	Reliable manufacturing method	Wider range of materials than 3-D Printing
	Produces accurate and precise parts	Does not have to be attended to during manufacturing
	Titanium is one of the most common and reliable materials to 3-D print	No cutting forces produced, therefore thin materials are possible

Table 2: Manufacturing Methods Comparison (Pros)

TYPE:	3-D - PRINTING	EDM (SINKER)
CONS:	Hard to print on such a small scale (What we need for the project)	Longer set-up and service time
	Threading complications, might be able to print with some companies, but might need to follow through with a tap	Poor visibility during the manufacturing process
	Limited materials offered	Slow material removal rate
	CAD models need to be updated including actual threads	Electrode cost
	Requires initial set-up to begin consistent manufacturing	Difficult to obtain sharp corners due to electrode wear
	Requires some post-machining finishing work (Surface finish may not be sufficient due to layers)	Excessive tool wear during machining
	Able to keep weight down by printing strong internal structure (Higher cost)	High power consumption during manufacturing
	Possibility of internal stresses created by heating and cooling of the metal	
	Possibility of wall failure (0.5 mm thickness minimum)	

Table 3: Manufacturing Methods Comparison (Cons)

A calculated force diagram from phase one was used to determine the glue strength using a factor of safety of 1.5 and a thickness of two millimeters. The force was determined to be 225N shear force. Once this was calculated, a representative from LORD Corporation was contacted to determine what glue was necessary to prevent the rubber from shearing off during actuation as shown in Figure 4 [3].

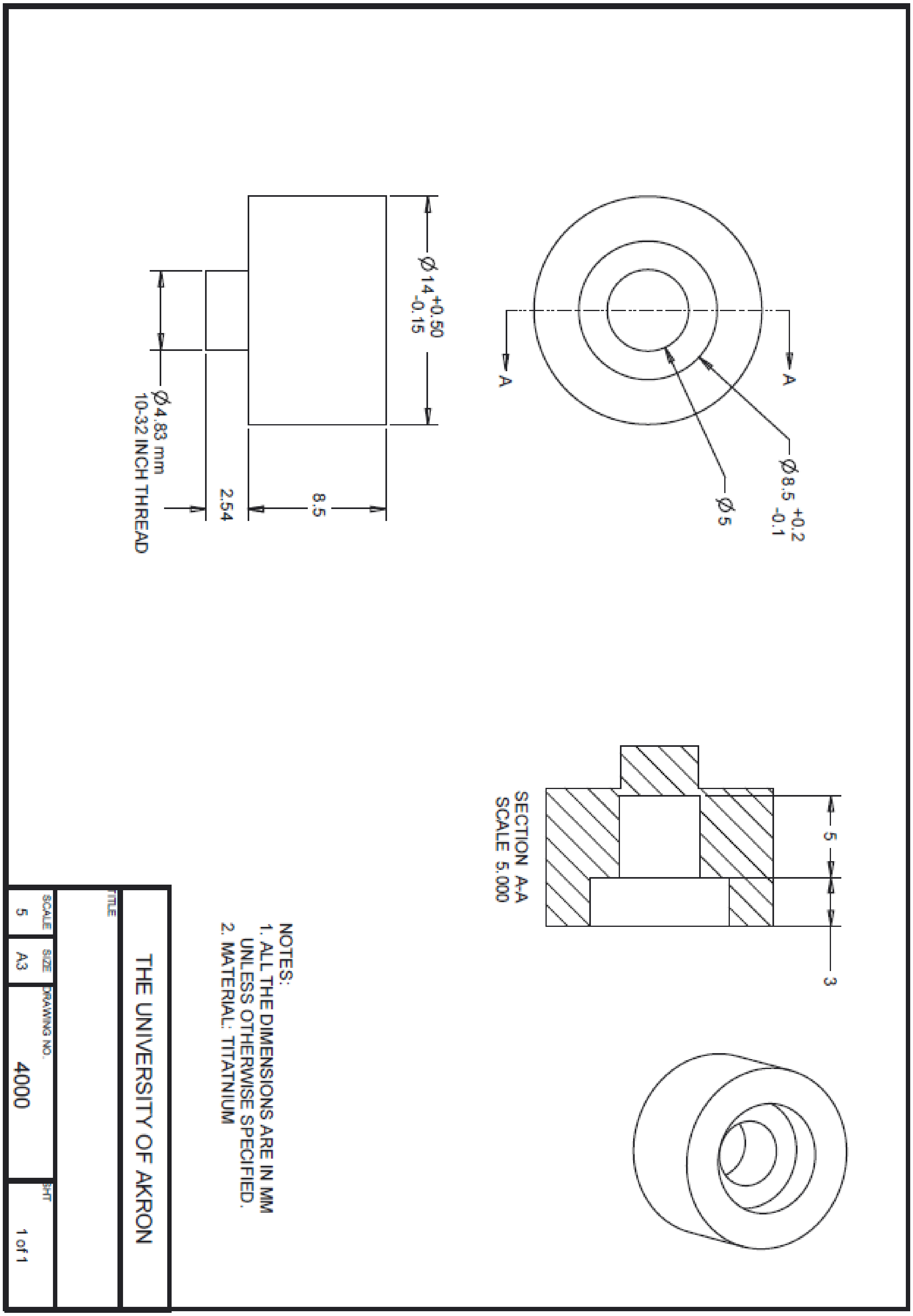
Choosing the glue

- LORD® 7701 Adhesion Enhancer-Surface Modifier
- LORD® 310 Modified Thixotropic Epoxy Adhesive A/B

Figure 4: Selected Glues

Chapter 4 - Detail Design

After multiple design iterations for the connection between the piezoelectric actuator and the force sensor as detailed in Appendix A the final design was chosen to have a high Eigen frequency and low weight. For this the cylinder design was the optimal shape while the size was reduced as much as possible to maintain minimal deflection. The detailed design drawing is shown in Figure 5 below (Confidential – Do not publish).



NOTES:
1. ALL THE DIMENSIONS ARE IN MM UNLESS OTHERWISE SPECIFIED.
2. MATERIAL: TITATNIUM

Figure 5: Part 4000 Connector (Confidential – Do not publish).

Once a final design was decided upon a prototype needed to be created to make sure the parts fit together. The University of Akron's 3-D printing services were utilized to create the prototype out of ABS plastic as seen in Figure 6. Some manufacturing errors were created due to melted plastic, thermal distortion, and tolerance issues from not considering the material thickness. This proved that extra precaution needed to be taken when manufacturing the final part accounting for the tolerance of the chosen method.

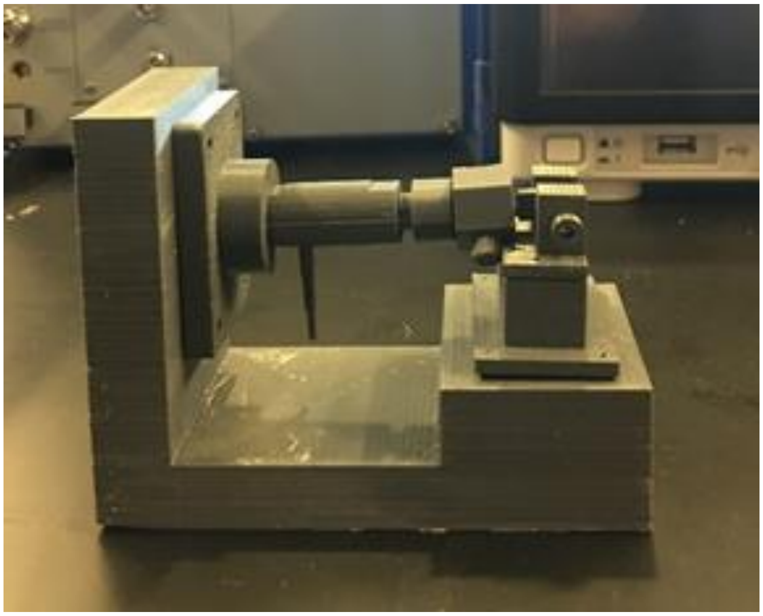


Figure 6: DMA Assembly 3-D Printed Prototype

Chapter 5 - Discussion

The design that selected was manufactured by a company and sent to the university. After receiving many quotes throughout the process, Sinker EDM was chosen for the manufacturing process. Sinker EDM seems to be the best manufacturing method vs the metal 3-D printing option for this application [6]. Cost was one of the factors taken into account when having the parts built and a cost comparison was done between the companies who quoted parts. These companies were all under a thousand dollars with the lead time being less than a month. Many of the American companies that quotes were received from were in the thousands of dollars while the overseas companies were usually less than a thousand. The turnaround time for the overseas companies was significantly less than the American companies. The company that ended up being chosen for the manufacturing process is Nextproto. The grade of steel, cost, and lead time fit our requirements. The parts were received in a timely manner and the parts were of good quality. The next step for the third year of the project is to conduct preliminary testing and compare the data to existing devices. The design that was done during this phase with will have to be thoroughly tested in order to be sure it meets the initial parameters.

Chapter 6 - Conclusions

From this project Solidworks, Creo Parametric, and COMSOL software skills were heavily increased through repetition. Tire industry experience was acquired as well as lab and building experience. For this phase of the project, the initial goal was achieved. We were able to effectively learn about DMA devices and use our knowledge gained to design a device that would test at higher frequencies. After researching the possible manufacturing methods, along with getting quotes, we decided on a method and a manufacturing company. This project was worth doing because of a cumulative interest in the tire industry and the ability to increase student work and research experience. The skills gained with the computer programs, along with increasing manufacturing knowledge, will be able to be applied to our future career. This project will enhance what has already been done for Eigen frequency data and will better the equipment and test results for The University of Akron and tire companies across the nation by working with The Center for Tire Research.

References

[1] Physik Instrumente. (2018). *Piezo Actuator (Motor) Product Line.* Retrieved from http://www.pi-usa.us/index.php

[2] Esmaeeli, Roja & Farhad, Siamak. (2018).*Very High Frequency Testing of Tire Tread Compounds for Improved Prediction of Wet Traction Performance*. [PowerPoint slides]

[3] LORD Corporation. (2018).*Chemlok Adhecives Selector Guide*. [PDF Document]

[4] Esmaeeli, Roja & Farhad, Siamak. (2016). *Very High Frequency Testing of Tire Tread Compounds for Improved Prediction of Wet Traction Performance.* [PDF Document]

[5] Dale, Elisha & JBR, Chiran & Stainer, Megan & Torchilo, Anatoliy. (2017). *Designing a Novel Mechanical Properties Measurement System for Rubbers.* [PDF Document]

[6] (2017, September 10). *Pros and Cons of 3D Printing Metal Components*. Retrieved from https://news.3deo.co/metal-3d-printing/pros-cons-3d-printing-metal-components

[7] Asena Deniz Demirican, Ufuk Okumus, Sema Asik. (2010). *Materials Science and Technology*. [PowerPoint slides]

APPENDIX A - CONNECTION DESIGNS

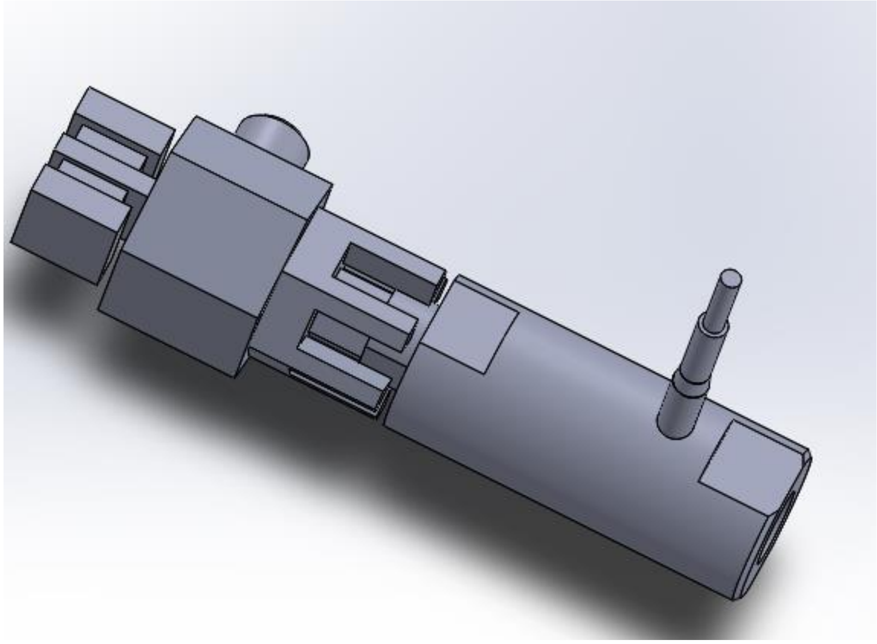


Figure 1: Force sensor and piezoelectric actuator connection design 01, Resulting in an Eigenfrequency = 5.38 kHz from COMSOL analysis by Roja Esmaeeli

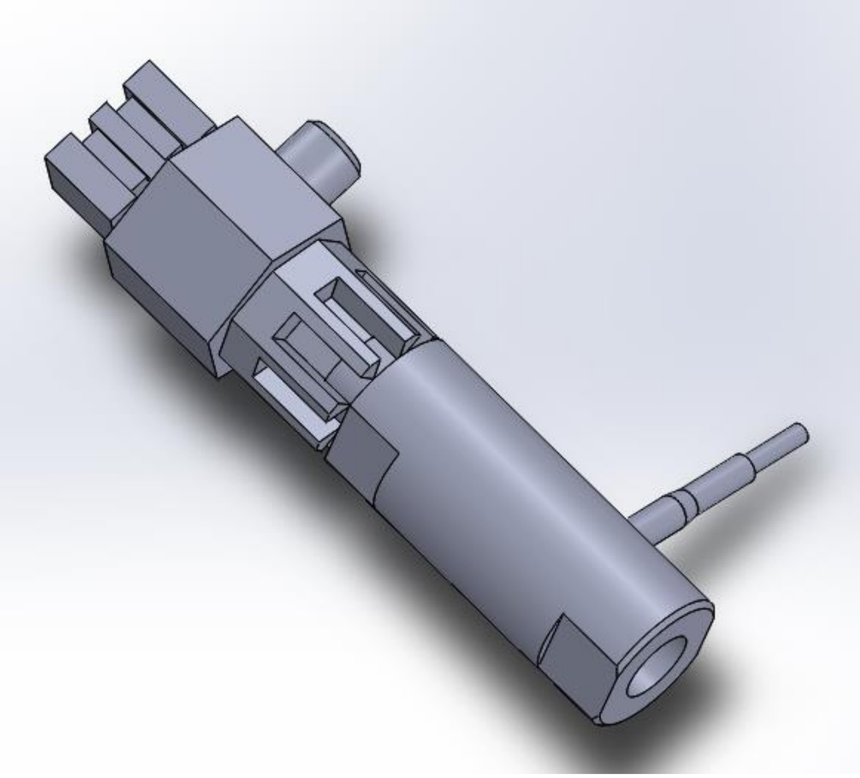


Figure 2: Force sensor and piezoelectric actuator connection design 02, Resulting in an Eigenfrequency = 5.69 kHz from COMSOL analysis by Roja Esmaeeli

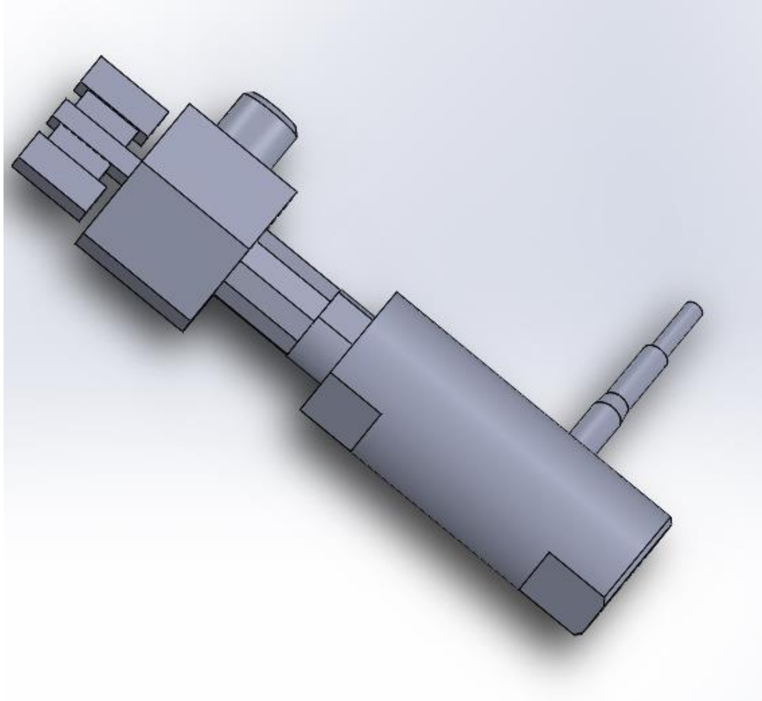


Figure 3: Force sensor and piezoelectric actuator connection design 03, Resulting in an Eigenfrequency = 5.72 kHz from COMSOL analysis by Roja Esmaeeli

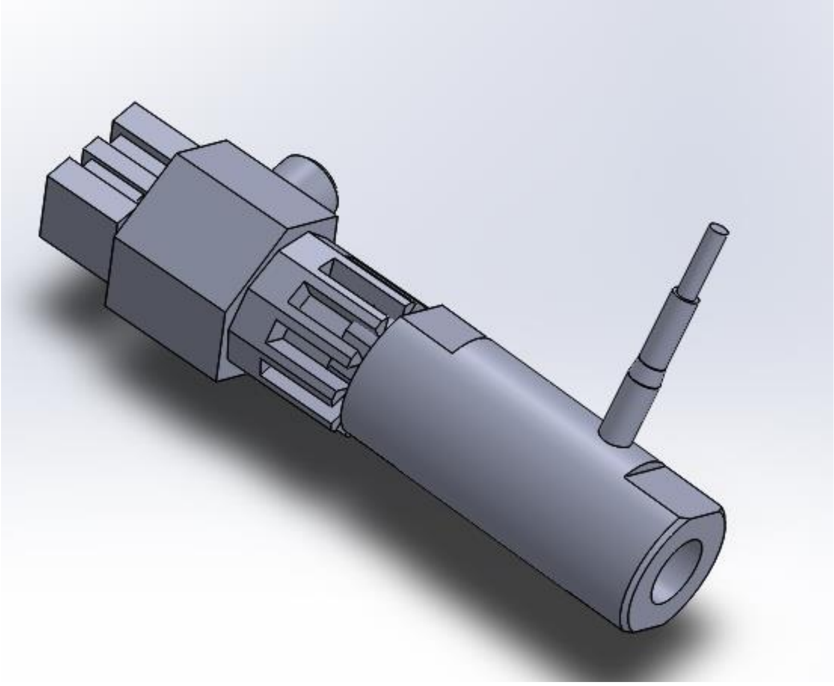


Figure 4: Force sensor and piezoelectric actuator connection design 04, Resulting in an Eigenfrequency = 5.75 kHz from COMSOL analysis by Roja Esmaeeli

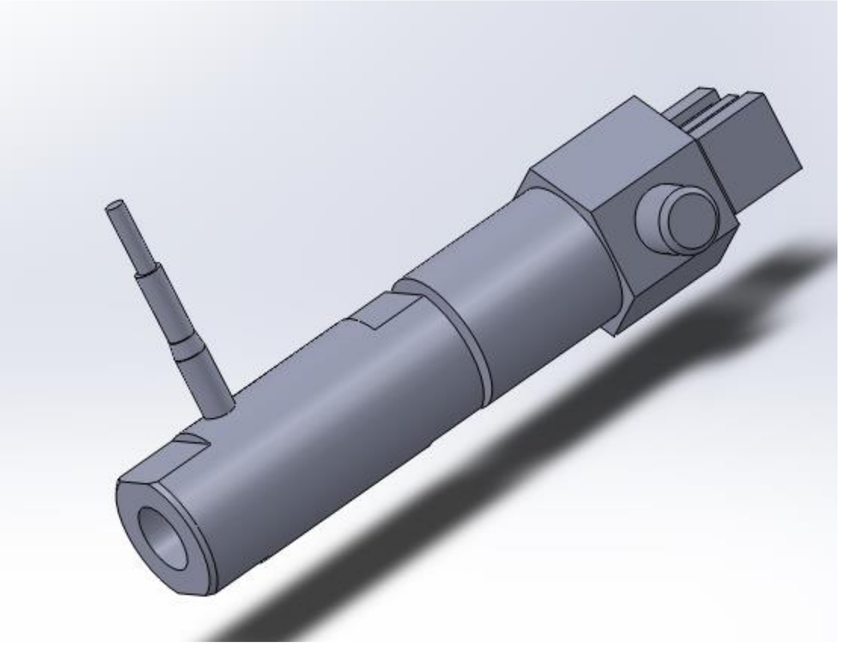


Figure 5: Force sensor and piezoelectric actuator connection design 05, Resulting in an Eigenfrequency = 5.76 kHz from COMSOL analysis by Roja Esmaeeli

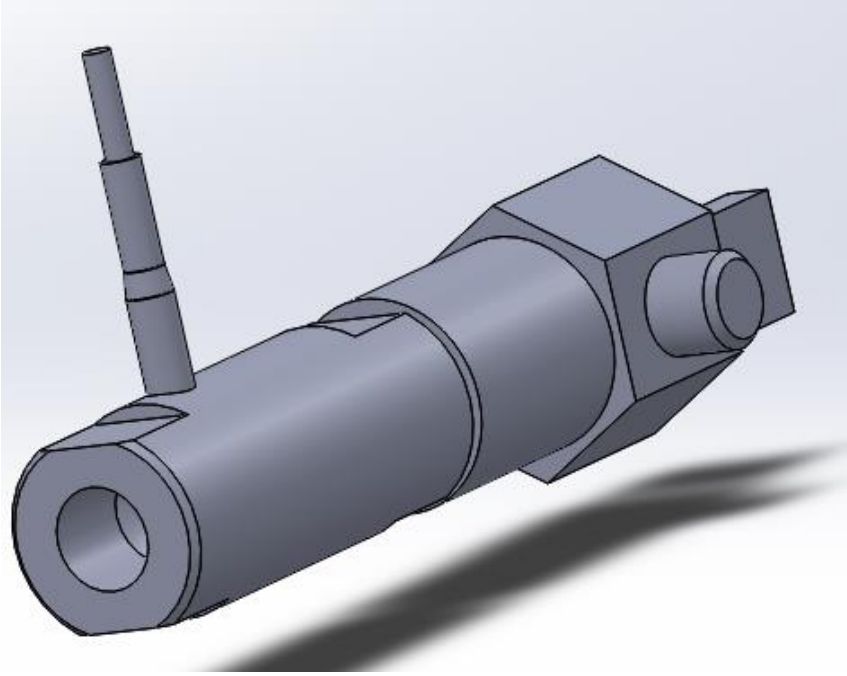


Figure 6: Force sensor and piezoelectric actuator connection design 06, Resulting in an Eigenfrequency = 6.883 kHz from COMSOL analysis by Roja Esmaeeli

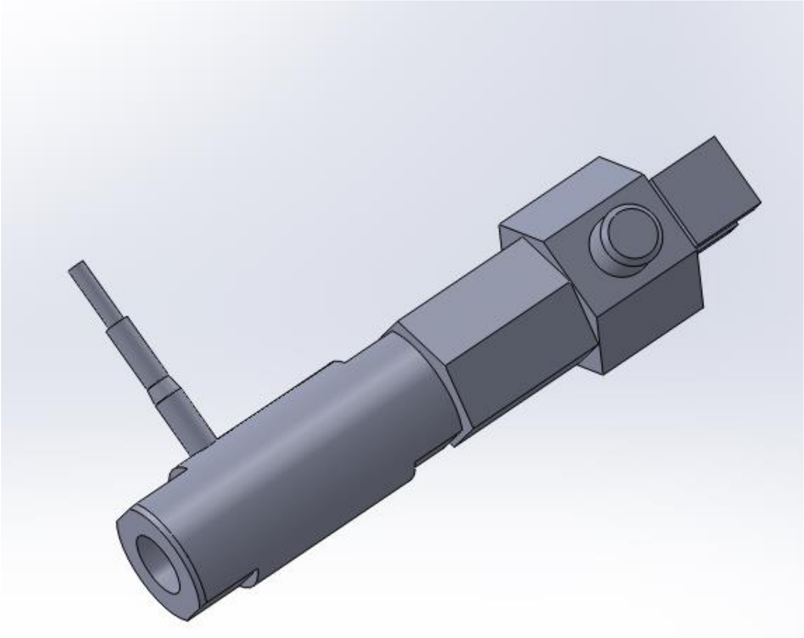


Figure 7: Force sensor and piezoelectric actuator connection design 07, Resulting in an Eigenfrequency = 7.14 kHz from COMSOL analysis by Roja Esmaeeli

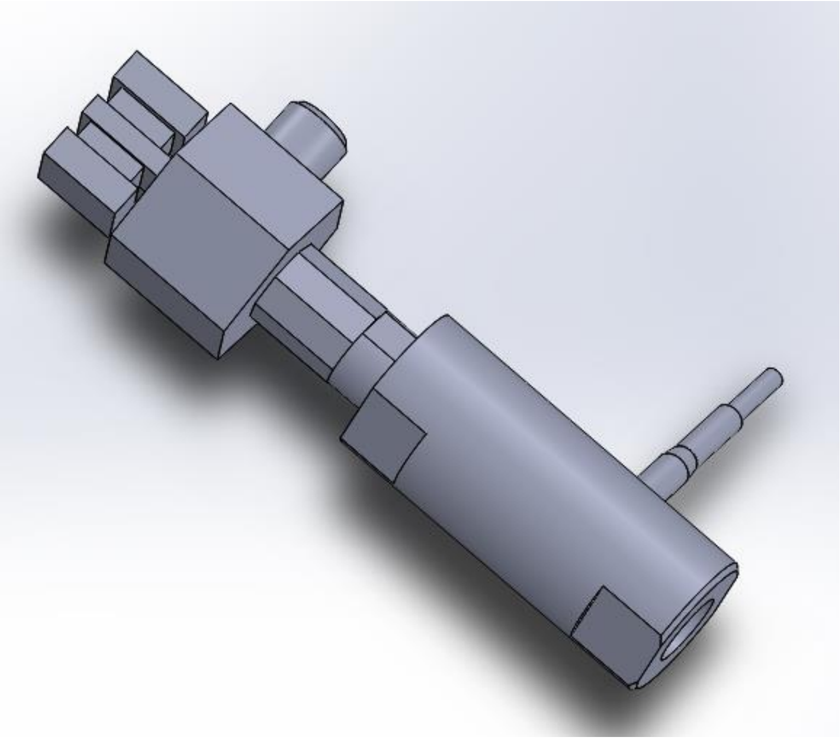


Figure 8: Force sensor and piezoelectric actuator connection design 08, Resulting in an Eigenfrequency = 7.43 kHz from COMSOL analysis by Roja Esmaeeli

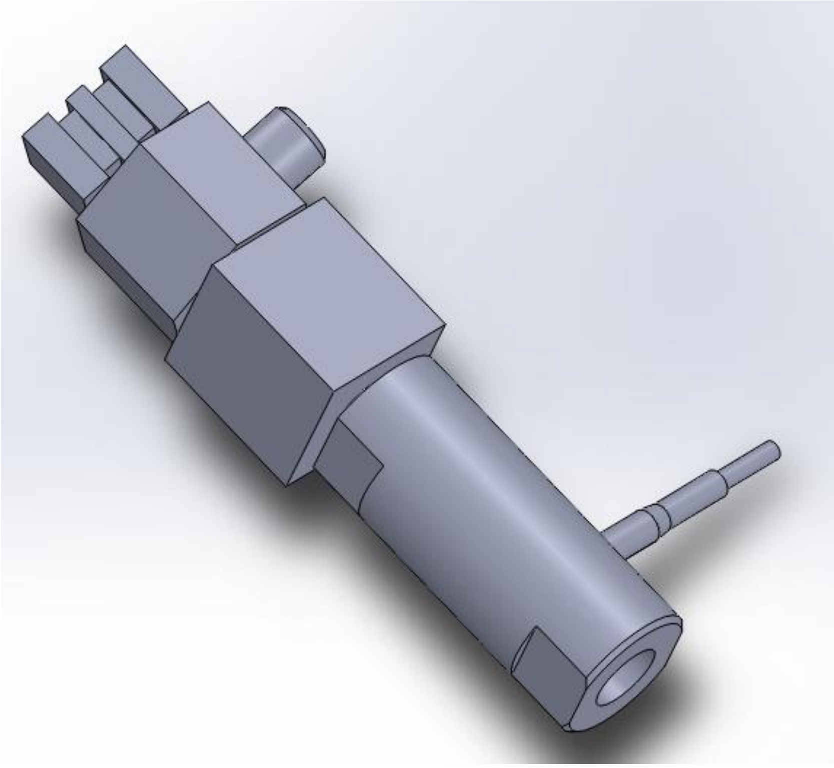


Figure 10: Force sensor and piezoelectric actuator connection design 09, Resulting in an Eigenfrequency = 7.82 kHz from COMSOL analysis by Roja Esmaeeli

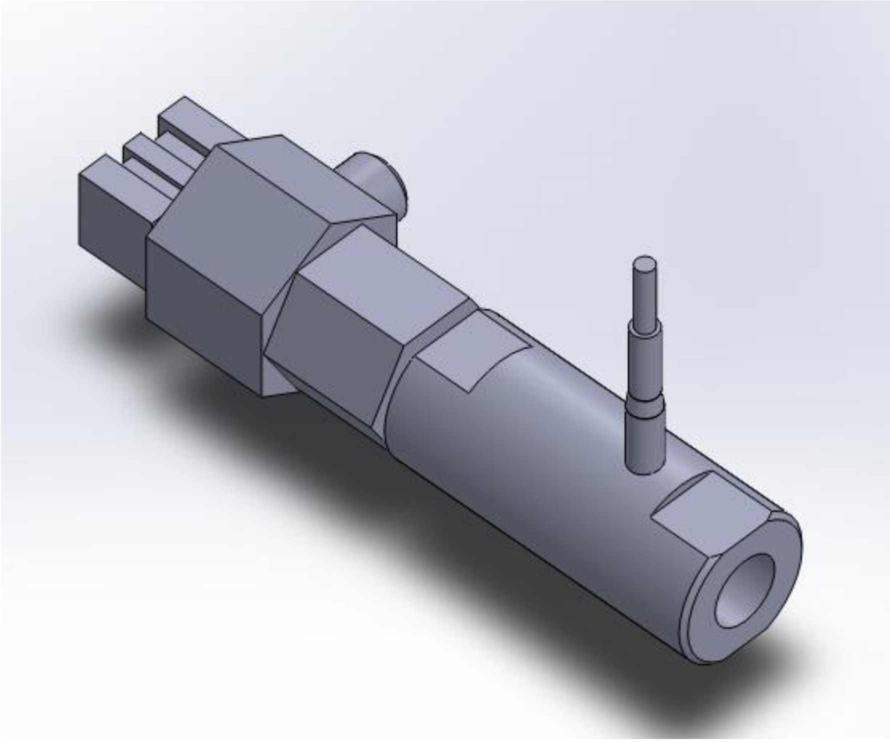


Figure 9: Force sensor and piezoelectric actuator connection design 10, Resulting in an Eigenfrequency = 8.05 kHz from COMSOL analysis by Roja Esmaeeli

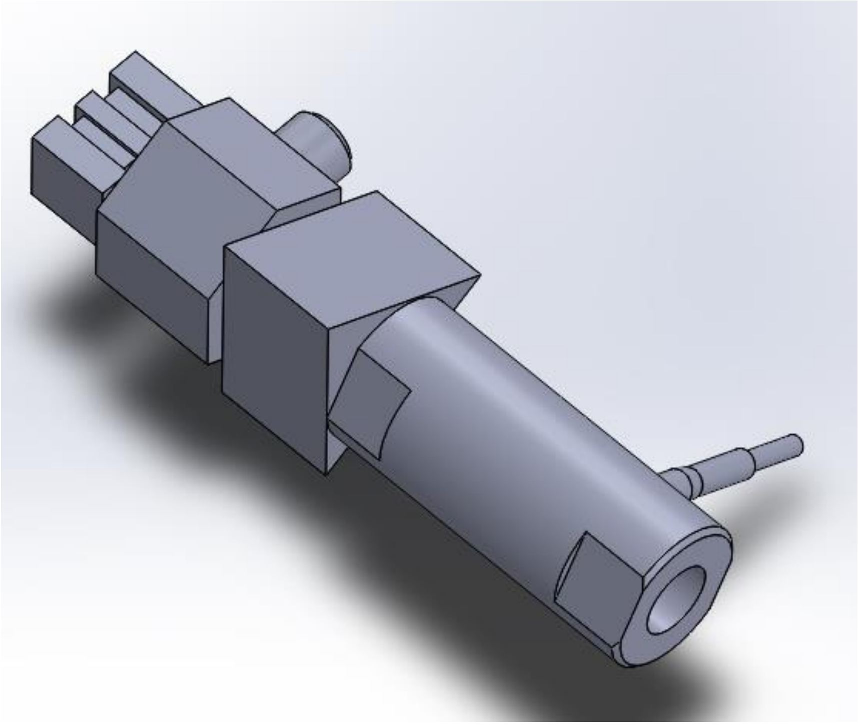


Figure 11: Force sensor and piezoelectric actuator connection design 11, Resulting in an Eigenfrequency = 8.12 kHz from COMSOL analysis by Roja Esmaeeli

APPENDIX B - FLEXURE DESIGNS

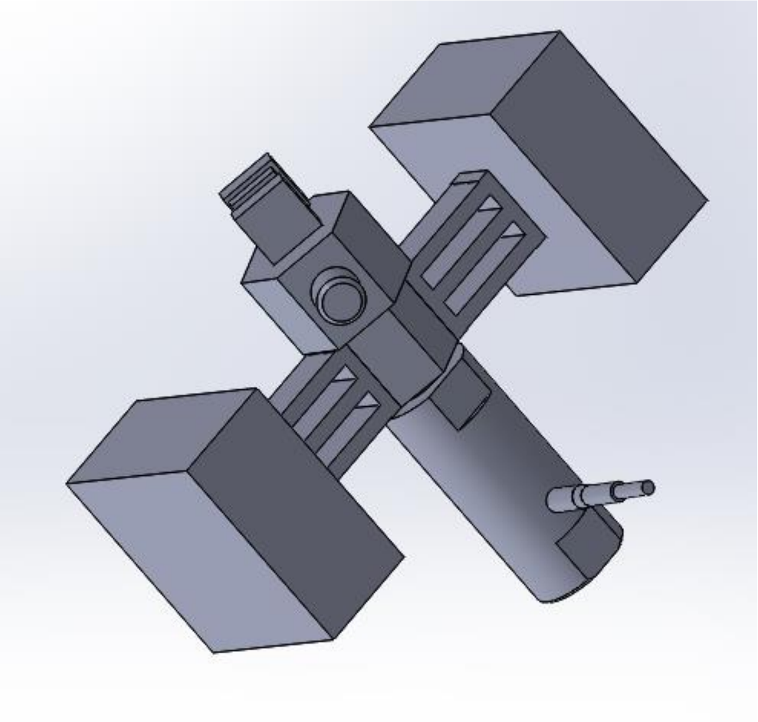


Figure 1: Assembly with flexures design 01, Resulting in an Eigenfrequency = 9.23 kHz from COMSOL analysis by Roja Esmaeeli

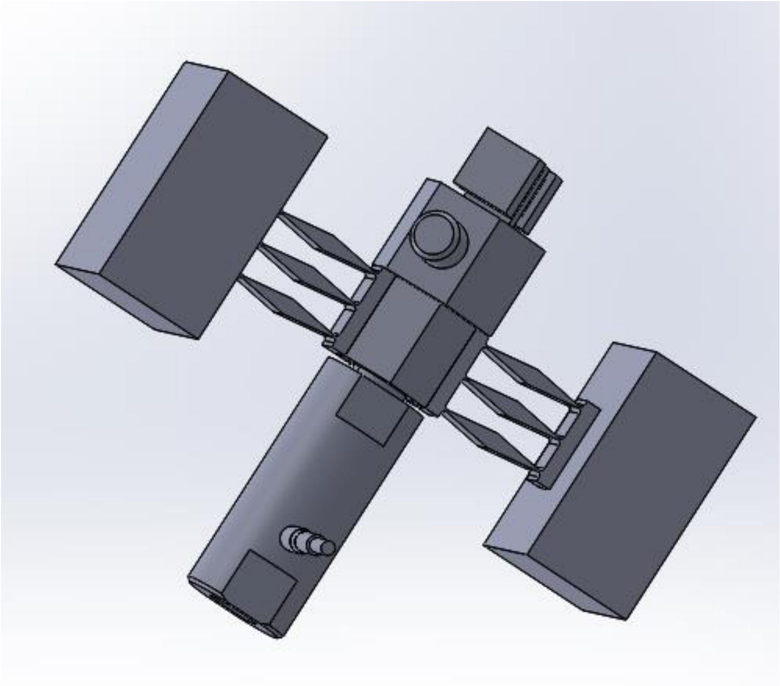


Figure 2: Assembly with flexures design 02, Resulting in an Eigenfrequency = 9.25 kHz from COMSOL analysis by Roja Esmaeeli

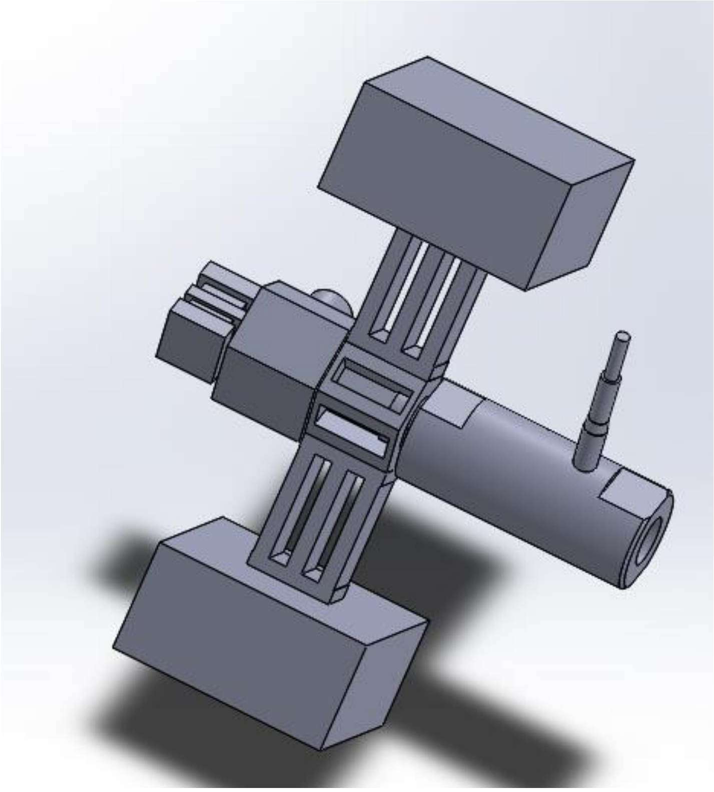


Figure 3: Assembly with flexures design 03, Resulting in an Eigenfrequency = 9.44 kHz from COMSOL analysis by Roja Esmaeeli

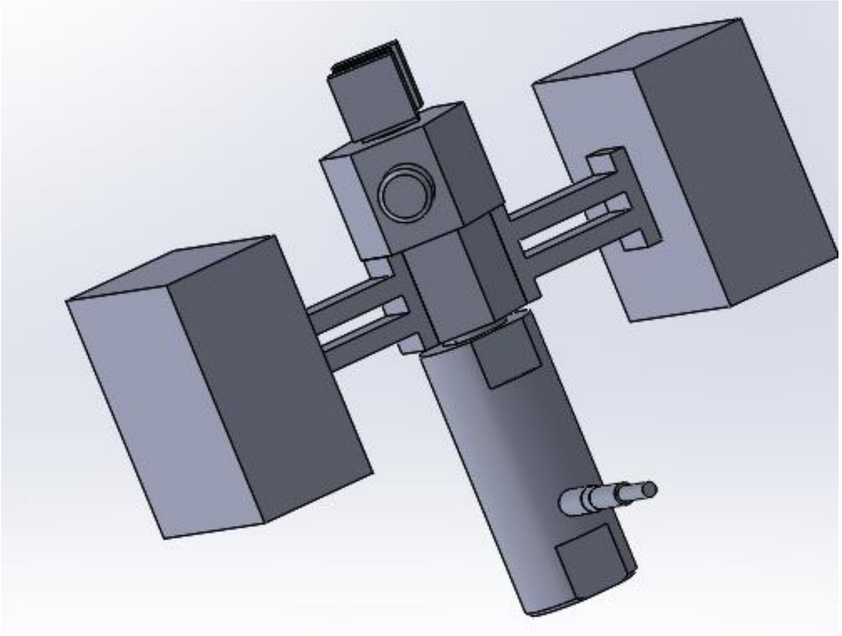


Figure 4: Assembly with flexures design 04, Resulting in an Eigenfrequency = 9.45 kHz from COMSOL analysis by Roja Esmaeeli

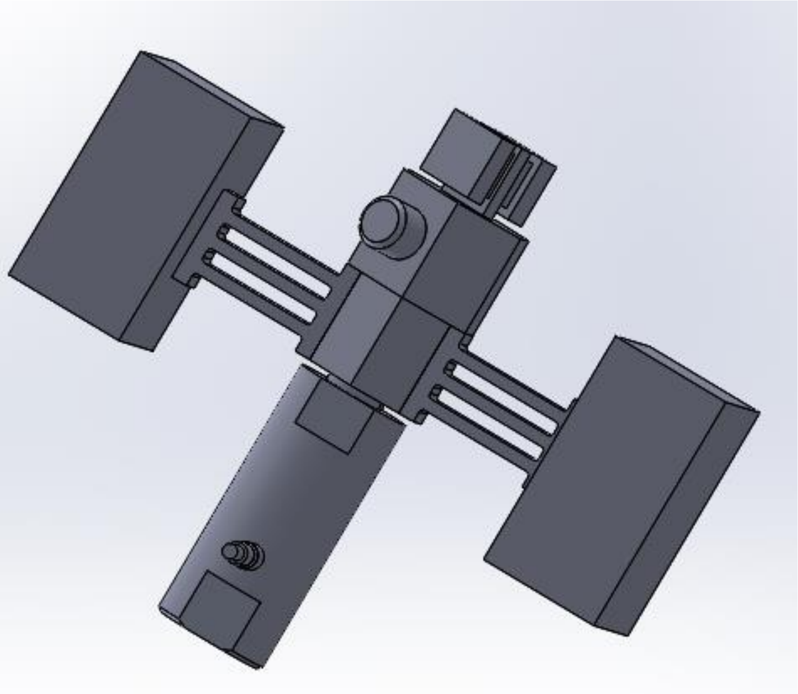


Figure 5: Assembly with flexures design 05, Resulting in an Eigenfrequency = 9.47 kHz from COMSOL analysis by Roja Esmaeeli

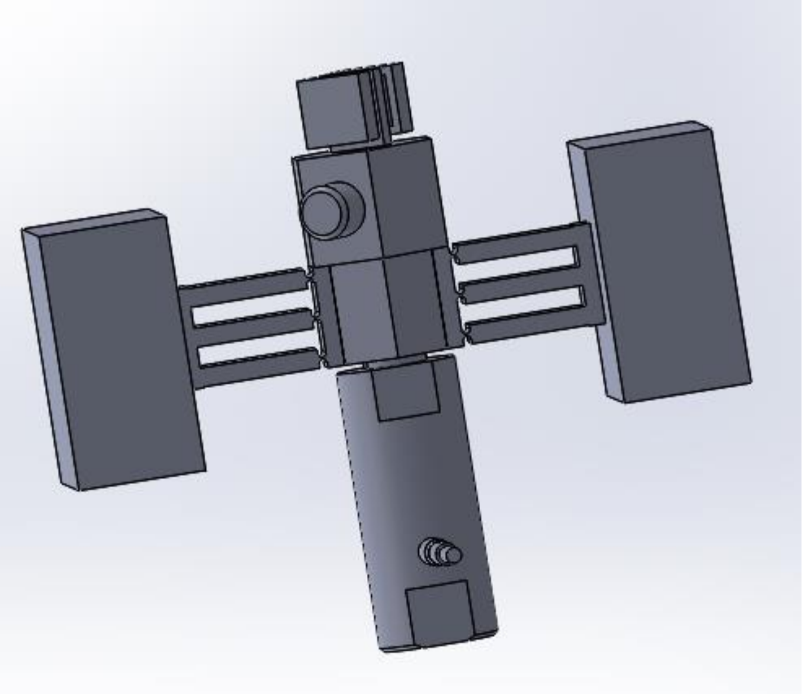


Figure 6: Assembly with flexures design 06, Resulting in an Eigenfrequency = 9.50 kHz from COMSOL analysis by Roja Esmaeeli

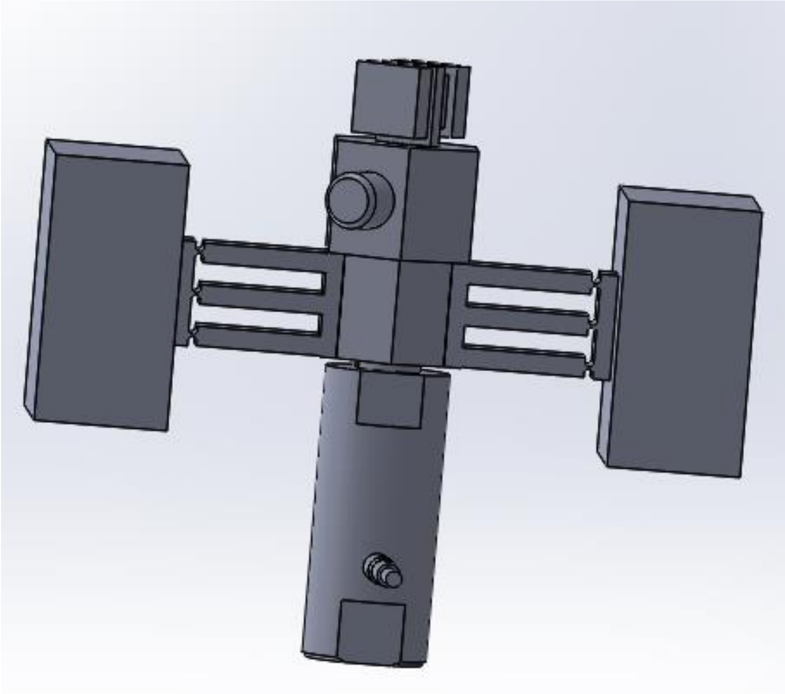


Figure 7: Assembly with flexures design 07, Resulting in an Eigenfrequency = 9.55 kHz from COMSOL analysis by Roja Esmaeeli

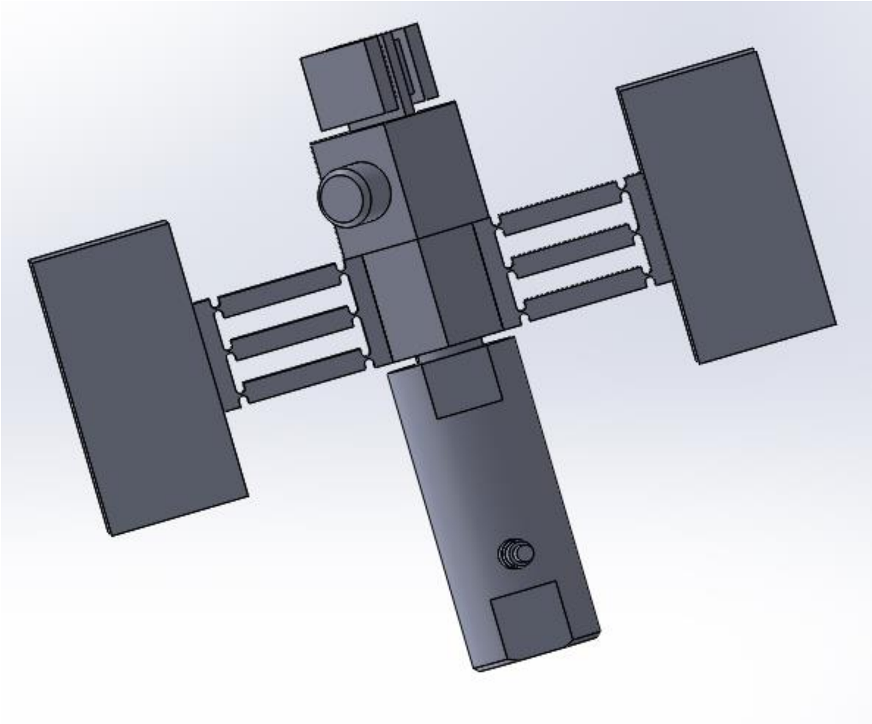


Figure 8: Assembly with flexures design 08, Resulting in an Eigenfrequency = 9.58 kHz from COMSOL analysis by Roja Esmaeeli

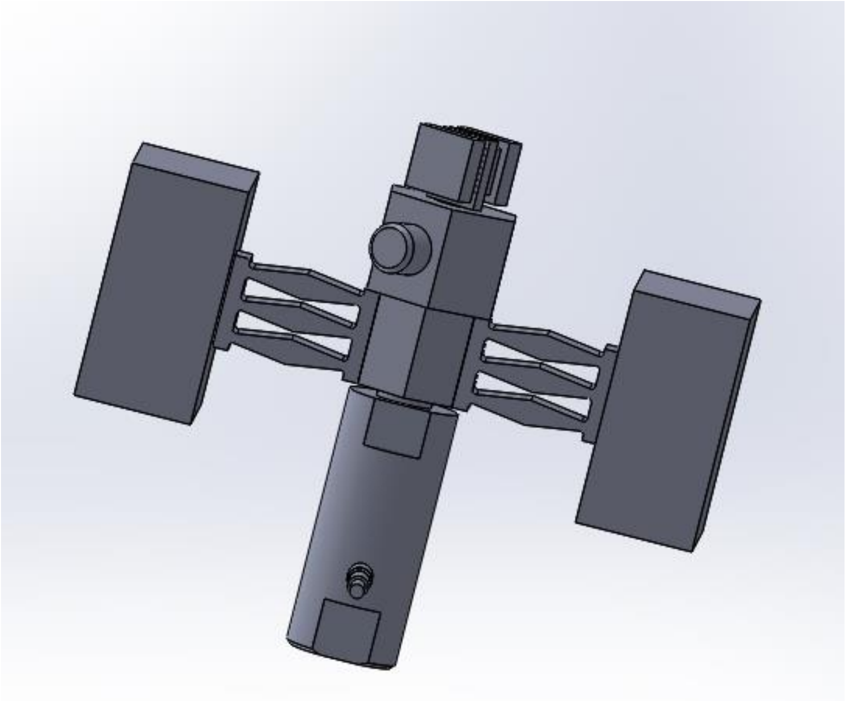


Figure 9: Assembly with flexures design 09, Resulting in an Eigenfrequency = 9.66 kHz from COMSOL analysis by Roja Esmaeeli

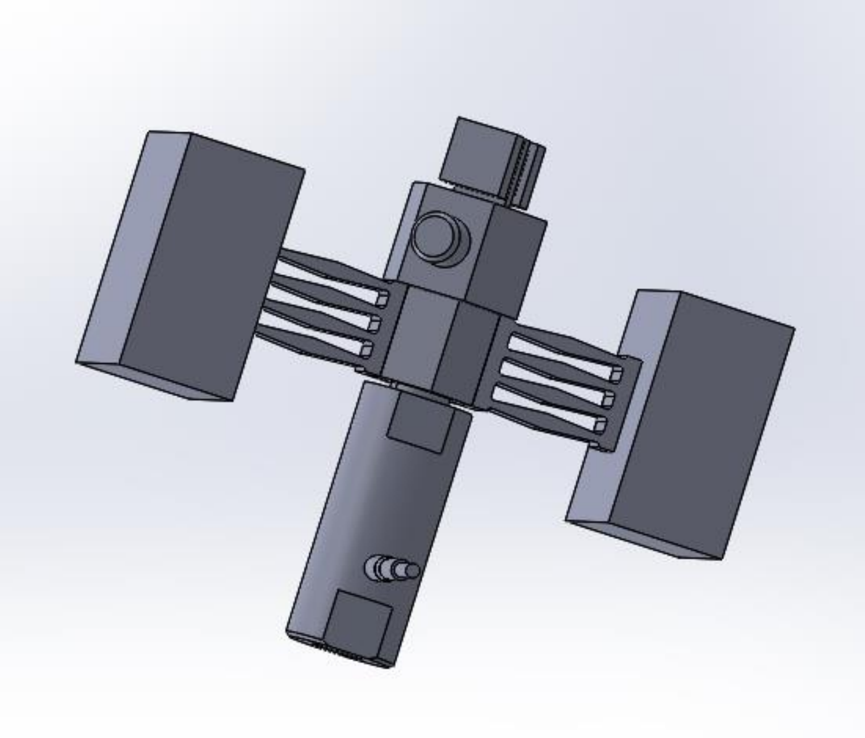


Figure 11: Assembly with flexures design 10, Resulting in an Eigenfrequency = 9.71 kHz from COMSOL analysis by Roja Esmaeeli

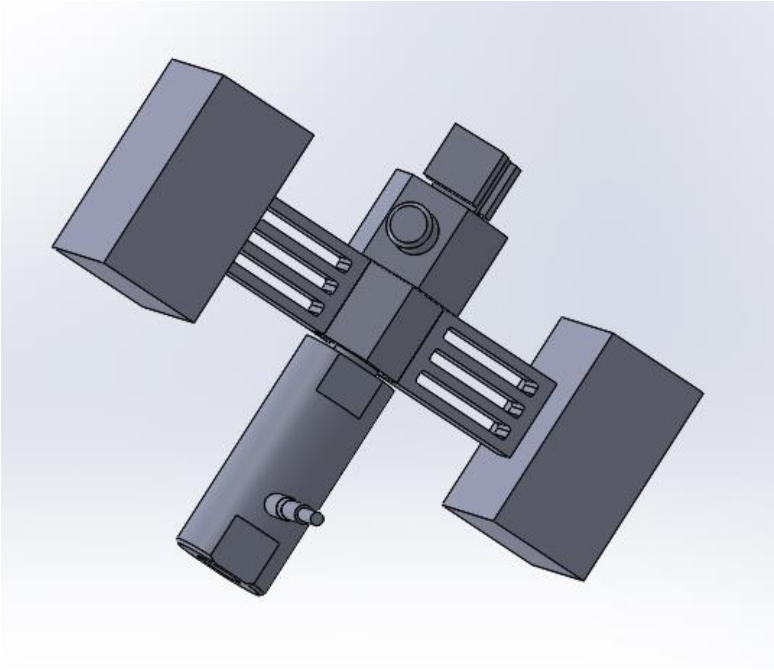


Figure 10: Assembly with flexures design 11, Resulting in an Eigenfrequency = 9.84 kHz from COMSOL analysis by Roja Esmaeeli

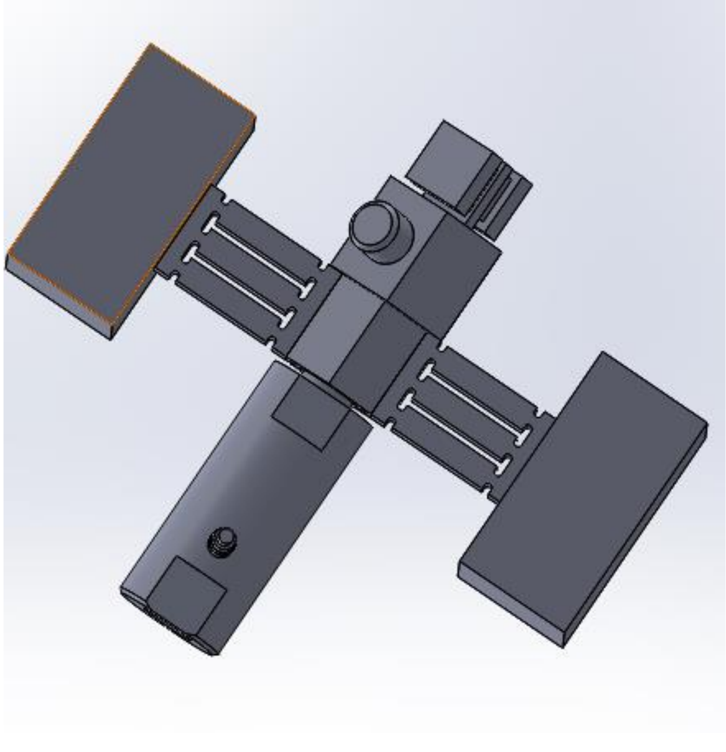


Figure 12: Assembly with flexures design 12, Resulting in an Eigenfrequency = 10.26 kHz from COMSOL analysis by Roja Esmaeeli

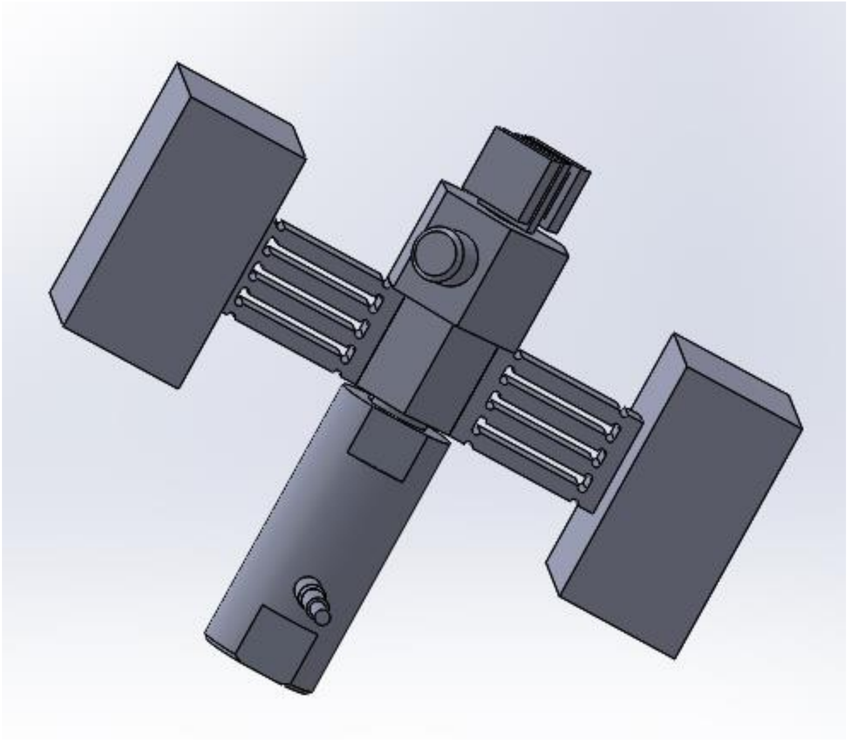


Figure 13: Assembly with flexures design 13, Resulting in an Eigenfrequency = 18.37 kHz from COMSOL analysis by Roja Esmaeeli