Saint Martin's
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Hydraulic Damper for Pulsation Reduction Final Report

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Abstract.

The objective of this project was to design and implement a damper system that effectively reduces pulsations in hydraulic systems, improving operating efficiency and reducing wear and tear on system components. The project implemented a combination of theoretical analysis, computer simulations, and experimental testing to achieve the desired objectives.

The design and optimization of the hydraulic damper are based on the analysis of fluid flow patterns and hydraulic pulsations in the system. Computer simulations will be performed to study the dynamic behavior of the damper under various operating conditions. The experimental testing involves the construction of a prototype damper and its installation in a hydraulic system. Performance measurements are going to be carried out to evaluate the effectiveness of the damper in reducing pulsations. The results should show a significant reduction in pulsations, thereby achieving the objectives of the project.

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1 Introduction

The design of a Hydraulic Damper for Pulsation Reduction has been chosen as our Senior Design Project due to its immense significance in a wide range of engineering applications. In this section, we outline the background information, significance of the project, and problem statement that motivates our work. We then provide a literature review and a market and economic analysis of the potential impact of our project. Following this, we describe our project in detail, including our funding sponsorship, team members and roles, key milestones and activities, and the references we will use for this project. We also present important ideas for presentation and evaluation and discuss strategies for presentation and knowledge dissemination. Finally, we provide a project timeline, risks and mitigation, and a budget estimate.

1.1 Project Background Information:

We have selected the topic of designing a Hydraulic Damper for Pulsation Reduction as our Senior Design Project due to its significance in various engineering applications. Hydraulic systems often suffer from pulsations that can lead to inefficiencies and mechanical wear. Our team is passionate about fluid dynamics and mechanical design, and we believe that this project aligns perfectly with our goals of addressing practical engineering challenges.

1.2 Significance of the Project:

Our project aims to design and develop an innovative hydraulic damper that will effectively reduce pulsations in hydraulic systems. This solution is significant because it can enhance the performance, efficiency, and lifespan of hydraulic machinery. Reducing pulsations also contributes to smoother operations and increased safety in industrial applications.

1.3 Project Problem Statement:

Our Senior Design Project will focus on designing a hydraulic damper specifically for pulsation reduction in hydraulic systems. The problem we aim to solve is the inefficient operation and potential damage caused by hydraulic system pulsations.

1.4 Literature Review:

(1) The sixth paper discussed double-tube hydraulic dampers and analyzed the size, tolerance, and viscosity of the tube and oil respectively. The authors used a MATLAB simulation to create an indicator diagram as well as a speed characteristics diagram. These diagrams were then verified through testing. The team also used ANSYS for parts of their analysis on account of the complexity of the system in question.
(2) The next paper discusses the creation of an electronic testing system for hydraulic dampers using a 32-bit RISC microcontroller to test pumps or valves using virtual instrument technology software. LabVIEW was utilized, using a PID control algorithm.
(3) This eighth paper focuses on methods to negate interference to hydraulic sensor signals. The researchers opted to use a wavelet analysis to achieve this end. The use of an algorithm developed through the wavelet method could then be used to denoise the signal to create more usable data.

(4) One source that will prove to be invaluable is the Chemical Process Dynamics and Controls textbook from the University of Michigan. This textbook has extensive writing on instrumentation and controls. The information included will be incredibly useful for the development of our testing and control system.
(5) Another source that will be useful for gaining additional insight into the fundamental problem of this project will be the Mechanics Map Digital Textbook from Pennsylvania State University. The key part of this will be the section on viscous damped harmonic vibrations. By understanding how harmonic vibrations function, it will be easier to determine how best to dampen said vibrations.
(6) One-dimensional fluid dynamic modeling of a gas bladder hydraulic damper for pump flow pulsation In this paper, a hydraulic bladder damper is discussed. The situation it is addressed towards is given, explaining what the pressure pulsation created by pumps, notably a piston pump, and how the pressure fluctuations aren't desired. The bladder damper, through the provided results, proved to be very effective in significantly reducing the pressure fluctuations. It was also effective in reducing the sound speed, in which it reduced it by a factor of around 6. The construction of the bladder itself is relatively simple, with it being a rubber membrane separating nitrogen and the liquid. There are some other details about its construction, but they are simply optimizations of the construction. (7) Simulation of a Hydraulic Pulsation Dampener Used for Pulsation Reduction Induced by Vibrations in a Hydraulic System This paper discusses an experiment conducted in order to test a potential pulsation damper. The simulation was performed in MATLAB, which is applicable to us as we are able to use MATLAB with decent proficiency. The given simulation can also serve as inspiration for our own simulations when we are workshopping ideas. There are also methods mentioned for analysis that could prove useful for our project.
(8) Modeling and Analysis of Spherical Pulsation Dampeners in Fluid Power Systems This paper discusses the use of computer-aided modeling as opposed to manually made models when it comes to modeling spherical dampers in a fluid system. What's being proposed is a new method, though it was published in 2007 so it is possible that the method proposed is no longer viable or has been adopted. Nonetheless, this will be a resource in modeling our own system for the damper.
(9) Research status, Critical Technologies, and development trends of hydraulic pressure pulsation attenuator - Chinese Journal of Mechanical Engineering This paper addresses pressure pulsations and discusses solutions to them, in addition to being a general update and the current state of research. The applicable dangers of these pulsations in the workplace are also addressed, adding some more context if one is going to explain why this damper is important to those outside of engineering. It also theorizes on the future of pulsation attenuators, which can serve as inspiration and insight for our own project.
(10) Mathematical Modeling of Pulsation Dampeners in Fluid Power Systems This paper discusses modeling through the use of a computer in order to create a resistance-impedance-based model for the fluid system. The point of doing so is to better understand fluid vibrations within the system and model them so that we may better understand them and design for them. It also allows prediction without the use of resources, given the model has been done correctly.
(11) I chose this article because it gives a detailed breakdown of the multibody system in an axial piston pump. It has detailed drawings of a pump system we can use during this project. Also, it has a high-pressure flow rate. We can use this to investigate the nonlinear dynamic system of the pump.
(12) This article also explains in detail a pulsation-dampening system either gas or liquid, with various experiments and calculations that we can use for the purposes of our research. Even though it is a dated source we can still use the methods provided to guide us in designing a dampening system.
(13) This article has various types of pulsation-dampening systems and compares them against each other. We can use this information to compare our test and results with other types of systems, in noise reduction of hydraulic pumps. They also used novel and conventional devices to compare noise reduction. With multiple designs and explanations of how vibration systems work.
(14) The testing device that we can possibly use is the Soloflex whole-body vibration platform. Even though it is not accurate according to other sources, we might be able to use it just for cost purposes. This article can guide us in the formatting and use of this device and help format our tables and data.
(15) This technical article has good drawings of a pulsation dampener that we can possibly use as a starting point for designing our own, also has a lot of different data that we can use to optimize the vibrations in the dampener.

1.5 Market and Economic Analysis:

1.5.1 Target Customers:

This hydraulic damper is initially intended to be used as a research tool for university faculty. As such, we will initially be marketing our system towards educational institutions. The goal of marketing to educational institutions is twofold, to gain a financial foothold in the market as well as to gain invaluable experience in manufacturing this hydraulic damper further to develop the design into a refined production model.

Following this, the plan will be to use the gained reputation and experience from producing for universities to enter the market selling our testing equipment to industrial companies. These companies are primarily going to be research companies as well as the research divisions of manufacturing companies since the hydraulic dampener we are designing is intended for research purposes. This will allow us to easily market it without having to make drastic changes to the design.

1.5.2 Market Size:

The market size for this testing system is admittedly relatively small. There are approximately 400-500 colleges and universities that offer engineering programs. All of these institutions can be potential customers. The variety, size, and type of these universities can be seen below in Figure 1. This data can be used to determine which schools will have the potential need and desire to purchase this product and be used to plan marketing and sales.

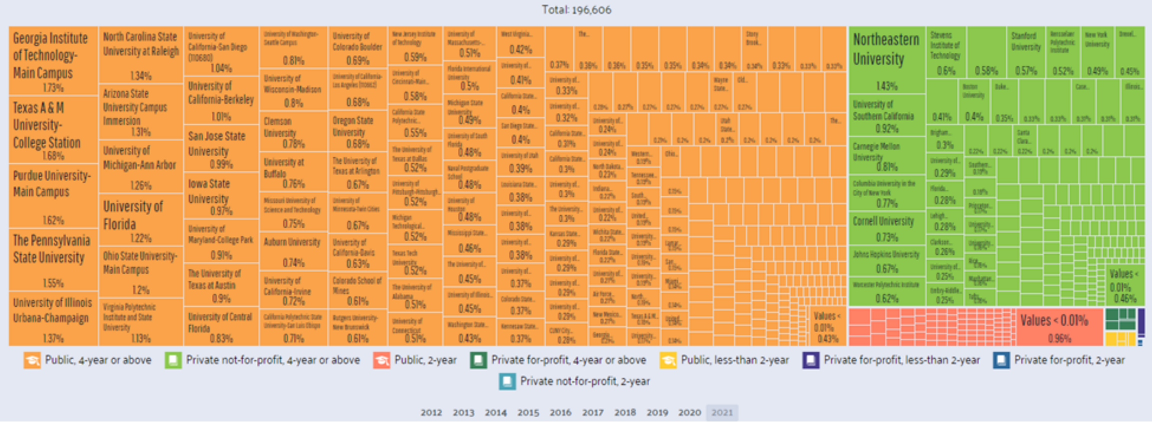

Figure 1: Colleges and universities that offer engineering programs

1.5.3 Market Challenges:

There are several challenges associated with our planned marketing strategy. The first large challenge is that these products maintain a low volume of sales for multiple reasons. The most important reason is that they are what's called durable goods. Durable goods are products that have a long service life, meaning that they will be used for years without replacement. Additionally, durable goods are an economic indicator for recessions, as customers will tend to cease replacing durable goods first as a way of saving money. This must be kept in mind for planning the finances of this venture as it can lead a company into bankruptcy if a recession occurs and the company hasn't accounted for the substantially lower sales.

The next major challenge is the low density of potential customers. With a maximum of 500 educational institutions and even less than that number of companies that this product would be marketed towards spread across the country, we will have a wide distribution network for a relatively small company. Considering that it may be necessary to send a technician to oversee the installation and set up of the product, this could become a substantial cost for the product. This can be seen in Figure 2 on the next page, which shows the number of engineering degrees awarded in the US by county. This is a good representation of the concentrations of potential customers as well as the more removed locations from which we may see patronage.

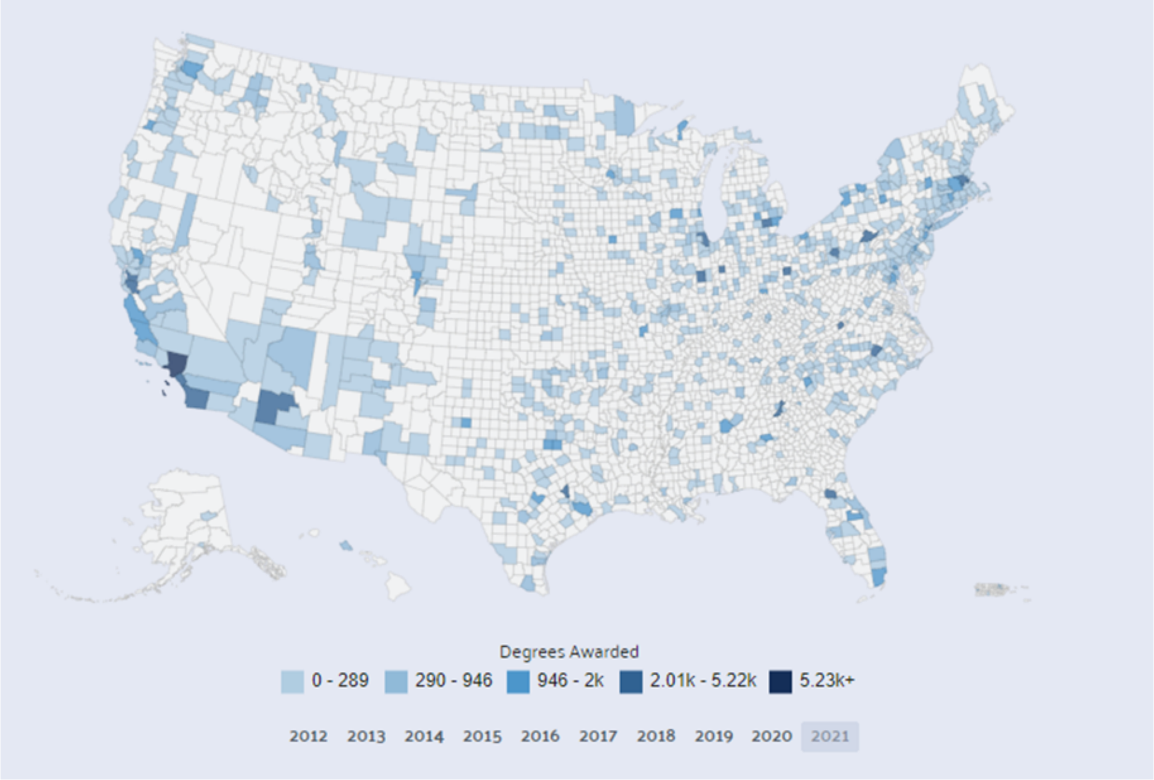

Figure 2: Number of engineering degrees awarded in the US by county.

1.5.4 Cost Savings:

One solution to aid us in keeping the costs down to make our product more competitive in its pricing is to use as many off-the-shelf components as possible. By using off-the-shelf components we reduce the overhead costs of designing and prototyping every component, which allows us to reduce our retail costs as there's a lower startup cost to overcome to get out of debt and begin accruing profits.

1.6 Project Description

Our project will involve the creation of a hydraulic damper system comprising hardware components and control mechanisms. The system will be designed to effectively reduce pulsations in hydraulic fluid flow by absorbing and dissipating energy.

1.7 Funding Sponsorship:

Our intention is to pursue financial backing from research grants, industry affiliates, and institutions invested in hydraulic system enhancement. We are committed to actively seeking collaborations and financial assistance to guarantee the project's successful execution. If external sponsorship is not secured, we will rely on the funding allocated by the school for senior design groups to fulfill the project requirements.

1.8 Team Members and Roles:

Riley Phelps: Team manager as well as modeling and simulation analyst.
Steven Araki: Mechanical controls engineer as well as fluid dynamics specialist.
Stephen Norby: Marketing and communications specialist in addition to project timeline planner.

1.9 Project Key Milestones and Activities:

1. Project initiation and team formation
2. Literature review and research
3. Market analysis and economic feasibility study

4. Hydraulic damper design and prototyping
5. Development and testing
6. Marketing and promotion strategies
7. Seeking funding and sponsorships
8. Final damper integration and testing
9. Project documentation and presentation preparation
10. Project presentation and evaluation

1.10 Important Ideas for Presentation and Evaluation:

During our presentation and evaluation, we will emphasize the following key ideas:

1. The critical need for effective pulsation reduction in hydraulic systems and the potential benefits for industries.
2. The unique features and advantages of our hydraulic damper solution compared to existing dampers.
3. The economic benefits for industrial users and potential cost savings.
4. The significance of our project in improving the efficiency and safety of hydraulic machinery.
5. Our team's expertise in fluid dynamics, mechanical design, vibration theory, and control engineering.

1.11 Presentation and Knowledge Dissemination:

We plan to present our hydraulic damper system and the knowledge gained from this experience through various channels, including:

- A detailed project report and documentation
- Physical demonstrations of the hydraulic damper
- Engaging presentations to industry stakeholders and potential investors
- Participation in relevant engineering conferences and exhibitions
- Publication of research findings in engineering journals and magazines

We are excited about the prospects of our Senior Design Project and look forward to the opportunity to make a meaningful contribution to hydraulic system optimization. Thank you for considering our proposal, and we are eager to begin this exciting journey.

1.12 Project Timeline:

To ensure efficient project management and timely completion, we have developed a preliminary project timeline. This timeline outlines key milestones and activities from project initiation to the final presentation:

- September: Project initiation, team formation, and literature review as well as market analysis and economic feasibility study
- October: Hydraulic damper system design
- November-February: Prototype development and testing
- March: Marketing and promotion strategies, funding sponsorship outreach
- March: Final damper integration and testing, project documentation
- April: Final project presentation and evaluation

1.13 Risks and Mitigation:

We acknowledge potential risks that may affect our project, including technical challenges in damper design, budget constraints, and market fluctuations. To mitigate these risks, we will maintain open communication within our team, seek expert guidance when necessary, and adapt our project plan as needed.

1.14 Budget Total of this Project:

2 Design Methodology & Calculations

In developing our innovative solution, we employed a systematic and iterative design methodology to address the challenges encountered during the process. Our approach seamlessly integrates mechanical, electronic, and control engineering principles to create a robust and efficient solution. This section provides an overview of the preliminary ideas, design approaches, and the evolution of our concept into the final design, emphasizing the safety-centric perspective that guided our decision-making.

Table 1: List of Purchases

Amount	Item	Cost
First Purchase		
1	Pump	$20.91
1	Battery	$24.99
1	Tubing	$7.99
1	Bucket	Donation
1	Switch	$9.99
	Total with tax	$69.63
Second Purchase		
2	Fittings	$21.98
2	Testing Equipment	$33.58
1	Valve fittings	Donation
1	Valve fittings	$7.99
	Total with tax	$69.27
Additional Purchase		
Approx. 10 ft	Filament	$0.51
	Grand total for this project	$139.41

2.1 Preliminary Ideas:

The preliminary design ideas and approaches explored by our team for the development of a Hydraulic Damper for Pulsation Reduction. The project's background, significance, problem statement, and literature review have been previously discussed. We delve into the design options we have considered, including mechatronics diagrams, and other related idea sketches.

2.2 Design Ideas and Approaches:

- Pressure Chamber Hydraulic Damper (Inspired by Reference (6)): Our team explored the idea of a pressure chamber hydraulic damper. This design involves a pressurized air chamber and hydraulic fluid. A mechatronics diagram would illustrate the control system to manage the pressure for effective pulsation reduction. as seen in Figure 3

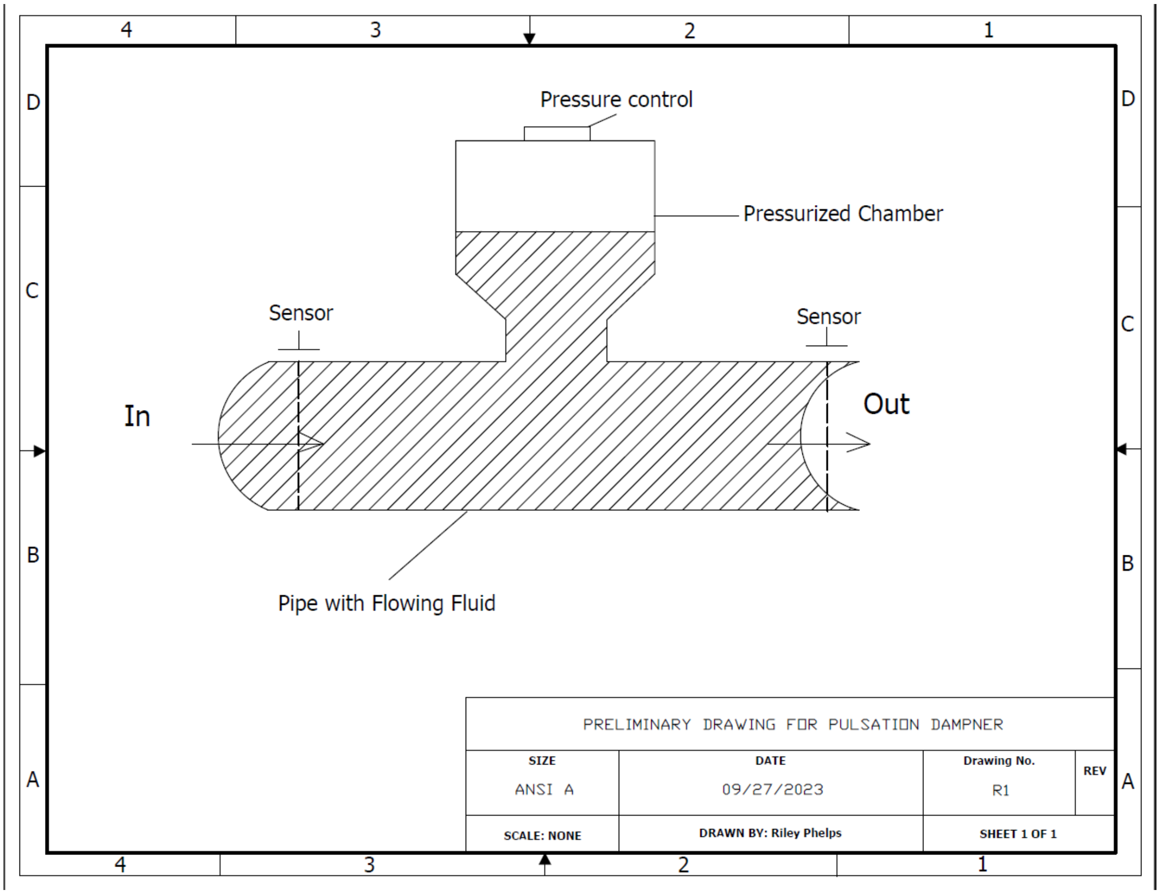

Figure 3: Preliminary Drawing 1

- Simulation-Based Damper (Inspired by Reference (7)): Reference (7) discusses a simulation-based approach for pulsation reduction using MATLAB. We considered implementing a digital simulation model to study various damper configurations. This approach would allow us to experiment with different designs in a cost-effective manner before physical prototyping.
- Spherical Pulsation Dampeners (Inspired by Reference (8)): Reference (8) introduces the concept of spherical pulsation dampeners modeled through computer-aided design. We explored the possibility of utilizing advanced computer-aided modeling tools to design and analyze spherical dampeners. Mechatronics diagrams would depict the electronic control systems necessary for this design. As seen in Figure 4.

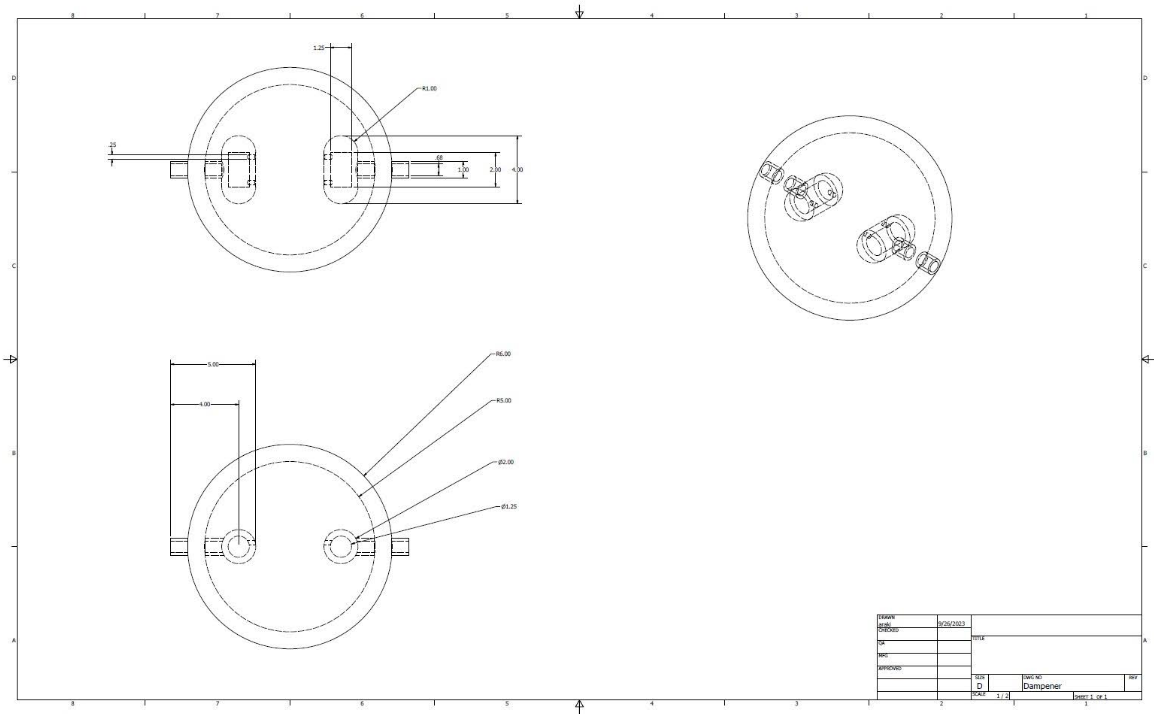

Figure 4: Preliminary Drawing 2

- Innovative Sensor Technologies (Inspired by Reference (3)): Reference (3) discusses the use of wavelet analysis for denoising hydraulic sensor signals. We considered incorporating advanced sensor technologies to improve the accuracy of our damper system. Thermofluids/heat transfer concepts would be applied to optimize sensor placement for efficient data collection.
- Control Algorithms (Inspired by Reference (2)): Reference (2) presents the use of ARM microcontrollers and LabVIEW for hydraulic damper testing. We explored the integration of advanced control algorithms for real-time adjustments to the damper's performance. A mechatronics diagram would showcase the microcontroller setup and control logic.

2.3 Mechatronics Diagrams:

For the design ideas that involve mechatronics components, we would create detailed diagrams to illustrate the interconnection of mechanical and electronic elements. These diagrams would provide a visual representation of how each design would function and be controlled. Mechatronics diagrams are crucial for understanding the control systems necessary for effective pulsation reduction. This is depicted in the Linear Graph below in Figure 5.

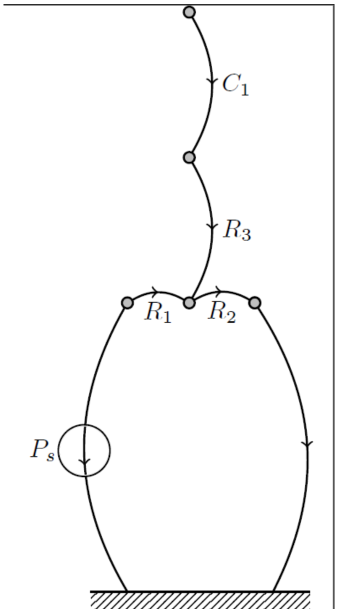

Figure 5: Linear Graph Of System

2.4 Final Idea:

The final design concept chosen for this project is the Pressure Chamber Hydraulic Damper, which was developed by our team to address pulsation reduction in hydraulic systems. The design leverages principles inspired by Reference (6) and aims to provide an innovative solution to enhance the efficiency and safety of hydraulic machinery. Our comprehensive analysis, simulations, and prototyping efforts have culminated in this final design choice.

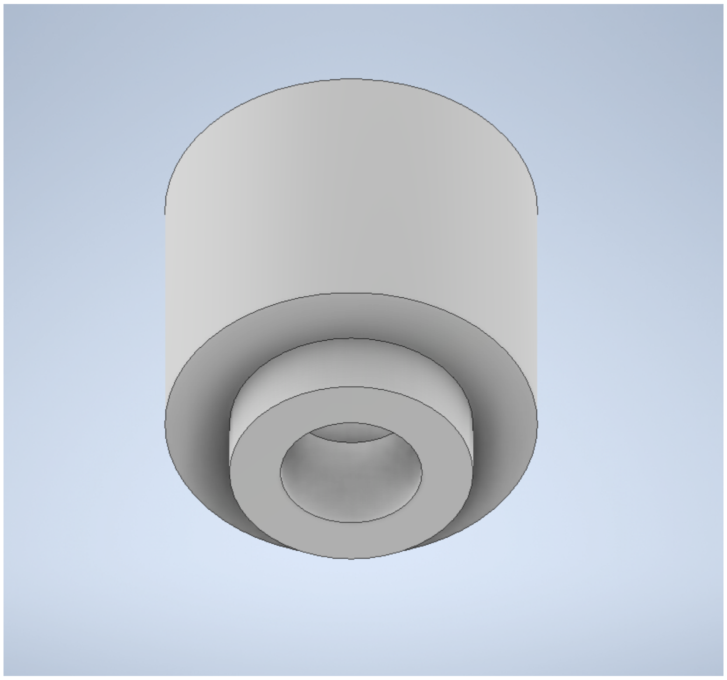

Figure 6: CAD model of final design

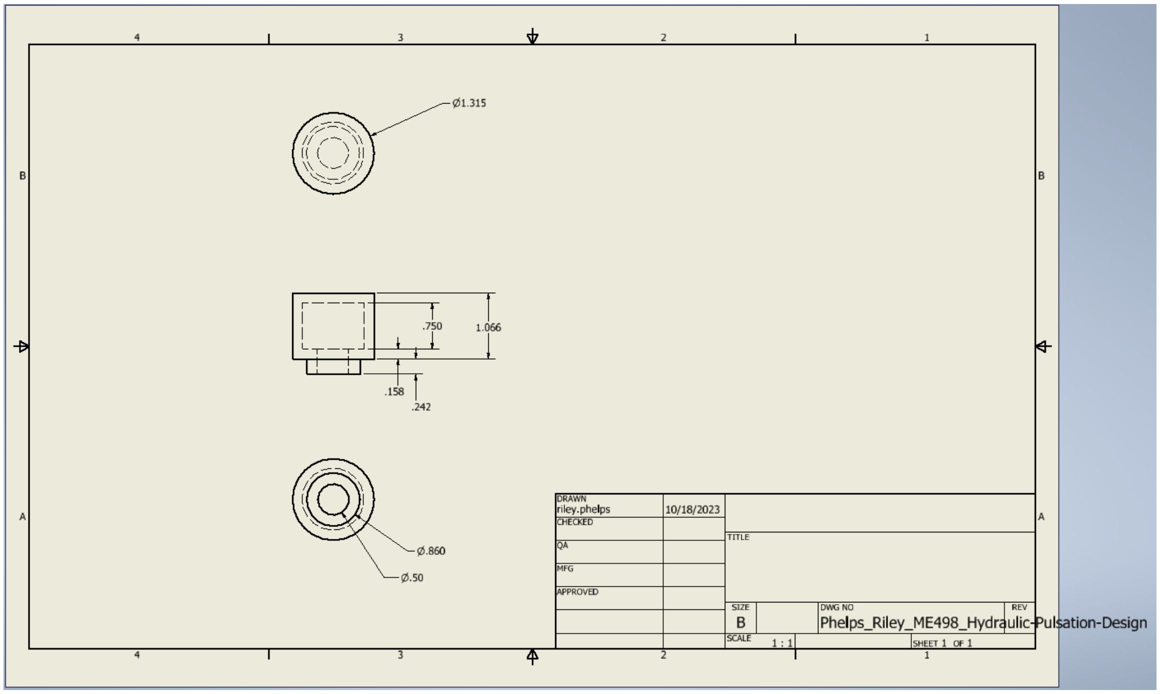

Figure 7: CAD Drawing of final design

2.5 Design Concept: Pressurized Air Chamber Hydraulic Damper

The Pressurized Air Chamber Hydraulic Damper is an innovative solution that uses a section of pressurized air to acts as a spring and equalize the hydraulic fluid. This design has been selected based on its proven effectiveness in reducing pressure fluctuations, as demonstrated in Reference (6). The design concept is explained in detail below:

2.6 Design Components:

Fluid Chamber: This chamber contains the hydraulic fluid which is inline with the system and allows some of the fluid to pass into the chamber, which experiences pressure fluctuations. The primary function of the damper is to reduce these pulsations.
Gas Chamber: The gas chamber is pressurized to 80% of the space inside the damper. The pressure can be controlled to regulate the damping effect.
Pressure Control System: To optimize the damper's performance, a pressure control system is integrated to manage the air chamber's pressure. This system allows real-time adjustments for efficient pulsation reduction.

This is depicted in in Figure 8.

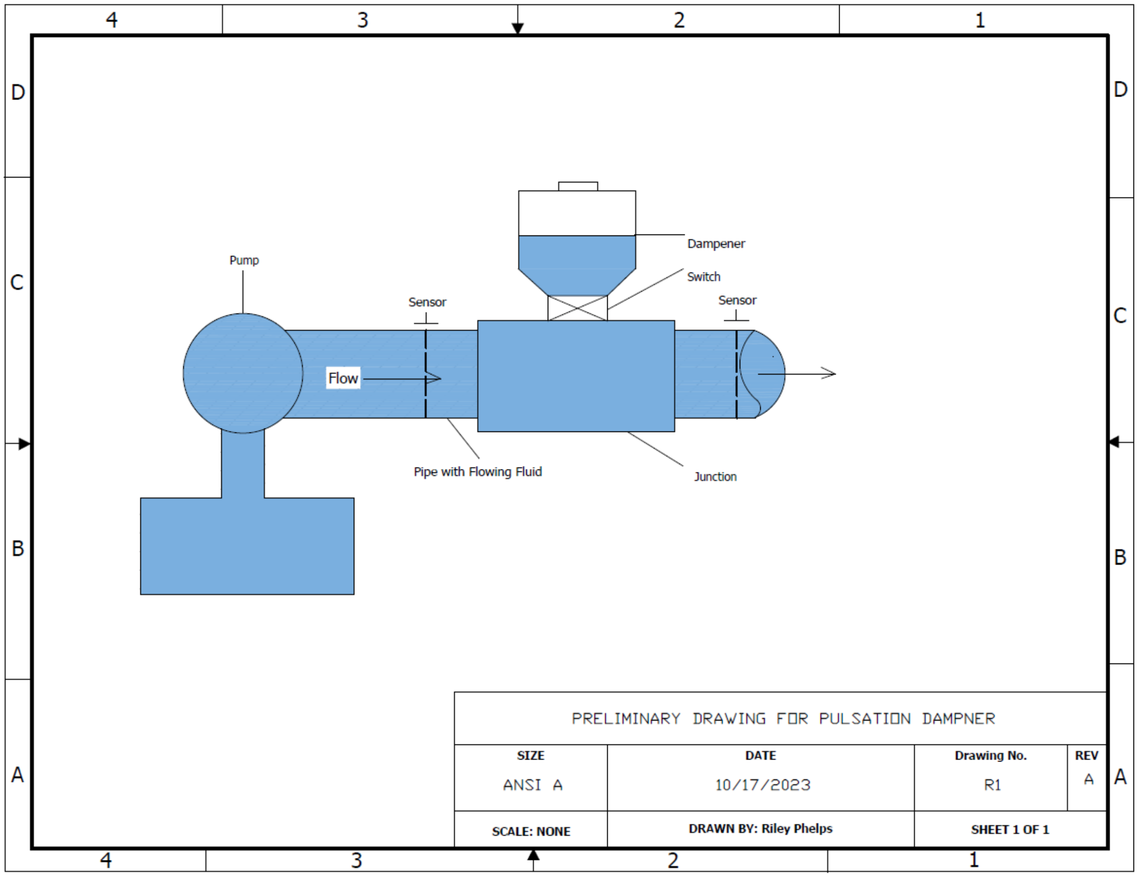

Figure 8: Diagram of Final Design of System

2.7 Working Principle:

The Air-Pressurized Hydraulic Damper operates on the principle that the controlled volume of pressurized air in the air chamber can absorb excess hydraulic pressure. When pressure fluctuations occur in the hydraulic fluid chamber, the air chamber expands or contracts to absorb or release the excess pressure, effectively dampening the pulsations.

2.8 Measuring Performance:

To evaluate the damper's performance, we will use sensors to monitor hydraulic pressure fluctuations before and after the damper. By comparing these data, we can quantify the reduction in pulsations achieved by the damper. In addition to these sensors, we will have theoretical values to compare with, calculated from the Systems Analysis.

2.9 Advantages of the Air-Pressurized Hydraulic Damper:

Simplicity: The design is relatively simple, with no bladder, making it easy to manufacture and maintain.
Cost-Efficiency: By eliminating the need for a flexible bladder, the damper design is cost-effective, aligning with budget constraints and economic feasibility.
Real-time Control: The integration of a pressure control system allows for real-time adjustments to optimize performance under varying conditions.

The Air-Pressurized Hydraulic Damper design has been selected as the final concept for our project. This choice is based on its simplicity, cost-efficiency, real-time control capabilities, and elimination of bladder-related concerns. We are confident that this design will address the issue of pulsation reduction in hydraulic systems and contribute to the enhanced efficiency and safety of hydraulic machinery.

2.10 Safety Factor-Based Design:

For the preliminary design and analysis of the pressurized air chamber in the Air-Pressurized Hydraulic Damper, we will employ a safety factor-based design using failure and fatigue theories. The pressurized air chamber plays a critical role in the damper's performance, and it's essential to ensure its structural integrity. We will also consider mechatronic aspects in the design.

3 Design Analysis

3.1 Material Selection:

To begin, we must select a suitable material for the pressurized air chamber. Given that the safety factor is a primary concern, we need a material that can withstand the anticipated stresses and pressures without failure. Common materials for such applications include high-strength alloys or composite materials. In which the final design would use Polyactic Acid (PLA) filament. This was due to the scale and pressures in the system we could use this material.

3.2 Pressure and Stress Analysis:

The use of Finite Element Analysis (FEA) in the context of the Pressurized Air Chamber Hydraulic Damper is a powerful engineering tool that aids in understanding how the component behaves under various operating conditions. FEA is a numerical simulation method that divides complex structures or components into smaller, manageable elements, allowing for a detailed analysis of stress, strain, and other physical behaviors. The specific focus here is on simulating stress distribution and conducting vibration analysis within the air chamber under different pressure conditions.

3.2.1 Finite Element Analysis (FEA):

Modeling the Geometry: The first step involves creating a digital representation of the air chamber's geometry. This digital model is then divided into small elements, forming a mesh that represents the physical structure.
Material Properties: Assigning material properties to the elements, such as modulus of elasticity and Poisson's ratio, is crucial for accurately simulating the behavior of the material under stress.
Boundary Conditions: Defining how the structure is constrained or supported helps replicate the real-world conditions in the simulation.
Application of Loads: Applying pressure loads to the model allows for the simulation of the effects of hydraulic pressure on the air chamber.

3.2.2 Stress Distribution Analysis:

Simulation Runs: FEA software performs multiple simulation runs, calculating the stress and strain experienced by each element in response to the applied loads and constraints.
Visualization of Results: The analysis results in visual representations of stress distribution, showcasing areas of high and low stress within the air chamber.
Identification of Maximum Stress Points: Engineers analyze the output to identify regions where the stress is concentrated, allowing for a focused examination of potential weak points.

3.2.3 System Dynamics Analysis:

Analysis of Results: Details the intricacies of how each element displayed in Figure 8 interacts with the system as a whole.
Understanding: As the iterative design process will occur, having the information about the system allows for educated and calculated changes.
Constructive: This visualization and formulation of equations allow for integration of the knowledge gleaned into other areas of analysis, allowing for enhanced analysis.

3.2.4 Determining Regions of Concern:

Analysis of Results: Engineers thoroughly analyze the FEA and vibration analysis results to determine the regions of concern.
Iterative Design Improvement: If certain areas exhibit high-stress concentrations or undesirable vibrations, the design can be iteratively refined to address these issues.

3.2.5 Validation and Calibration:

Comparison with Real-World Data: FEA results are validated by comparing them with real-world data obtained through physical testing.
Calibration: If necessary, the simulation model is calibrated based on the validation results, ensuring a high level of accuracy in predicting the air chamber's behavior.

3.2.6 Optimization and Design Refinement:

Optimization Strategies: Using the insights gained from FEA and vibration analysis, engineers can explore design optimizations to enhance the structural performance of the air chamber.
Iterative Refinement: The simulation results inform an iterative refinement process, where the design is adjusted and reanalyzed until an optimal configuration is achieved.

In summary, finite element analysis and systems analysis are powerful tools that provide a comprehensive understanding of how the Pressurized Air Chamber Hydraulic Damper responds to different pressure and vibration conditions. These analyses help identify critical stress points, assess dynamic behavior, and contribute to the iterative design refinement process, ensuring the structural integrity and optimal performance of the air chamber in practical applications.

3.2.7 ANSYS Equivalent Stress and Deformation Results:

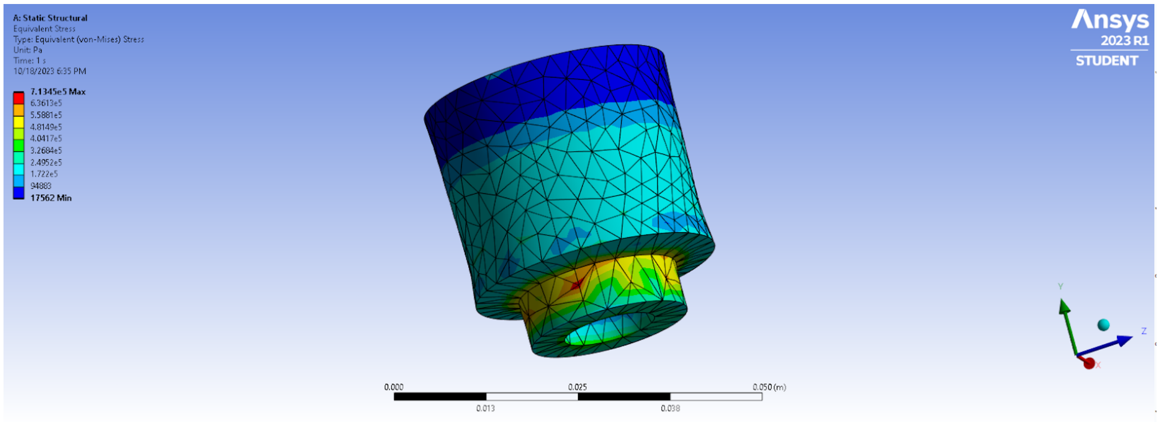

Figure 9: ANSYS Equivalent Stress results

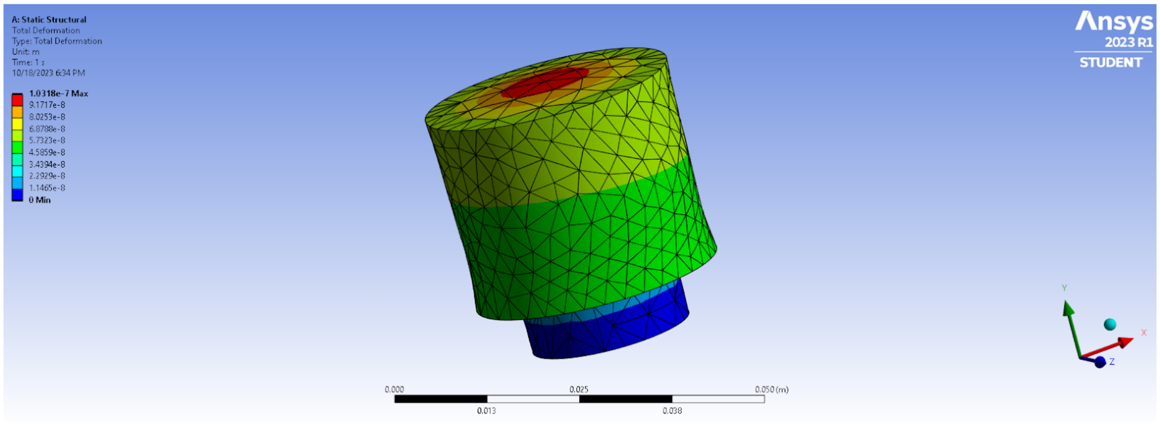

Figure 10: ANSYS Deformation Results

The full report can be found in the Section 9

3.2.8 Elemental Equations:

The following equations are in relation to Figure 5 diagram. Assumptions were made, with the capacitor having a separate pressure source, in addition to R1 and R2 assumed to be the same. As the design for this continues, these assumptions will be ensured to stay true, as the calculations will change if they are not held true.

$$\textbf{Fluid Capacitor:} \quad \frac{dP_C}{dt} = \frac{1}{C} \cdot Q_C \tag{1}$$

$$\textbf{Fluid Resistance (1):} \quad P_{R1} = Q_{R1} \cdot R \tag{2}$$

$$\textbf{Fluid Resistance (2):} \quad P_{R2} = Q_{R2} \cdot R \tag{3}$$

$$\textbf{Fluid Resistance (3):} \quad P_{R3} = Q_{R3} \cdot R_3 \tag{4}$$

$$\textbf{Pressure Input (Pump):} \quad P_s = A_0 \cos(bt - \phi) \tag{5}$$

$$\textbf{Pressure Input (Damper):} \quad P_D = kA_0 \tag{6}$$

A system analysis was then carried out using methods learned in Mechatronics and System Dynamics courses. The capacitor represents our hydraulic damper, as our damper will by definition be a fluid capacitance. The resistances are the pipes, as there will inevitably be internal forces and drag forces from the pipe itself. The generic "R" in fluid resistance 1 and 3 is the assumption that both of these pipes will be identical in all ways possible. Fluid resistance 2 is a different pipe, as for this application it will serve both as a pipe and a switch. The pump pressure input will oscillate due to the nature of a piston pump, hence the cosine. The pressure input for the damper will be a constant value. For future iterations, it may be a sinusoid so that it may serve as an adaptive damper. The result of our analysis yielded the following equation for how pressure will fluctuate within the chamber with known inputs.

The change in pressure of the damper (with respect to time) is given by the equation:

$$\frac{dP_C}{dt} = \frac{P_D - \frac{1}{2}P_S - P_C}{C\left(R_3 + \frac{1}{2}R\right)} \tag{7}$$

With this knowledge, an understanding of how each portion of the system will influence the changing pressure in the capacitor was gained. In addition to this, the damper can be constructed in a way that also reduces internal fluid pressure fluctuations. As this project continues and values for each of the variables are obtained, more systems analysis will be conducted in order to gain proper theoretical values to compare the damper's experimental values.

3.3 Safety Factor Calculation:

Using the maximum calculated stress and the material's ultimate tensile strength, we will calculate the safety factor using the following formula:

$$\text{Safety Factor (SF)} = \frac{\text{Ultimate Tensile Strength}}{\text{Maximum Stress}}$$

Knowing that structural steel has an ultimate tensile strength of 4.6×10^8 Pa and the safety factor being 2, then we can find that the maximum stress allowed is 2.3×10^8 Pa. With the design above, it can withstand a total stress of 7.135×10^5 Pa, which is well below the safety factor.

3.4 Fatigue Analysis:

Fatigue analysis is a critical phase in the engineering and testing process of the Pressurized Air Chamber Hydraulic Damper, aimed at evaluating the durability and structural integrity of the chamber under cyclic loading conditions. Fatigue refers to the phenomenon of material degradation and potential failure that occurs when a component is subjected to repetitive and fluctuating stresses over time. Here's a detailed elaboration on the importance and process of fatigue analysis in the context of the damper:

3.4.1 Understanding Fatigue:

Fatigue failure is particularly relevant in applications involving hydraulic systems, where components often experience cyclic loading due to pressure variations. In the Pressurized Air Chamber Hydraulic Damper, the chamber undergoes repeated expansion and contraction cycles as it responds to hydraulic pressure pulsations.

3.4.2 Objective of Fatigue Analysis:

The primary goal of fatigue analysis is to ensure that the damper can withstand these cyclic loading conditions throughout its operational lifespan. By subjecting the chamber to simulated fatigue tests, engineers aim to identify potential weak points, vulnerable areas, or stress concentrations that could lead to structural failure under cyclic loading.

3.4.3 Simulating Real-World Conditions:

Fatigue tests involve subjecting the damper to loading conditions that mimic the dynamic forces it will encounter during normal operation. These conditions include variations in hydraulic pressure, temperature fluctuations, and other factors that contribute to the cyclic loading experienced by the chamber. **Fatigue Testing Process:**

- **Load Spectrum Definition:** Engineers define a load spectrum that represents the expected range and frequency of pressure fluctuations the damper will experience in real-world applications.
- **Test Setup:** The damper is installed in a controlled testing environment, and instruments such as strain gauges and accelerometers may be used to measure deformations and vibrations.
- **Cyclic Loading:** The damper is subjected to repeated cycles of loading and unloading according to the defined spectrum. This process may continue for an extended duration to simulate the expected lifespan of the damper.
- **Data Collection and Analysis:**
  - **Strain and Deformation Measurements:** Engineers collect data on the strain and deformation responses of the damper throughout the fatigue testing.
  - **Failure Criteria:** Failure criteria, such as fatigue life and stress limits, are established based on material properties and design specifications.
  - **Analysis of Results:** The collected data is analyzed to determine whether the damper meets the required fatigue life and safety margins. Any signs of fatigue-induced damage or failure modes are identified.
- **Iterative Design Improvement:**
  - If fatigue analysis reveals areas of concern, engineers can iterate on the design to strengthen critical points or make material adjustments.
  - The goal is to refine the damper's design to ensure it meets or exceeds the expected fatigue life and safety standards.
- **Safety Mechanisms:**
  - Insights gained from fatigue analysis can inform the incorporation of safety mechanisms, such as pressure relief valves, to prevent catastrophic failure in the event of unexpected stress levels.

The fatigue analysis is a crucial step in validating the structural robustness of the Pressurized Air Chamber Hydraulic Damper. By subjecting the damper to simulated cyclic loading conditions, engineers can confidently ensure its ability to withstand the rigors of real-world hydraulic system operation, contributing to the overall reliability and safety of the damper in practical applications.

3.5 Redundancy and Safety Mechanisms:

To enhance safety, the pressurized air chamber will include redundancy features and safety mechanisms. This includes pressure relief valves and fail-safe mechanisms to prevent over-pressurization. Also to include chamfers along the rigid edges to help ease the pressure in any given corner.

3.6 Mechatronic Design:

The mechatronic design aspect of the Pressurized Air Chamber Hydraulic Damper is a critical component that enhances the functionality and performance of the system. Mechatronics, a synergistic integration of mechanical engineering, electronics, computer science, and control engineering, plays a pivotal role in achieving the real-time adjustability and optimization of the damper's damping performance.

In this context, the mechatronic design specifically involves the integration of advanced sensors and actuators into the air chamber's control system. The sensors, particularly pressure sensors, serve as essential components for gathering real-time data on the chamber's pressure dynamics. These sensors are strategically placed within the damper to continuously monitor the pressure variations experienced during the operation of the hydraulic system.

Pressure sensors operate by converting the mechanical force exerted by the fluid within the chamber into an electrical signal, providing instantaneous feedback on the pressure conditions. The real-time data collected by these sensors serves as a crucial input for the control system, allowing it to make informed and dynamic decisions to optimize the damping performance. Actuators, on the other hand, are responsible for effecting changes in the system based on the information received from the sensors. In the case of the Pressurized Air Chamber Hydraulic Damper, the actuators are employed to adjust the air pressure within the chamber in response to fluctuations detected by the pressure sensors.

The integration of pressure sensors and actuators forms a closed-loop control system, where the feedback from the sensors is continuously used to make adjustments that optimize the damping performance of the damper. When pressure pulsations occur in the hydraulic fluid chamber, the pressure sensors detect these changes, and the control system commands the actuators to modulate the air pressure within the damper accordingly.

This dynamic adjustment of air pressure serves to counteract and absorb excess hydraulic pressure, mitigating pulsations and promoting a smoother fluid flow. The ability to make real-time adjustments based on sensor feedback is a key feature of mechatronics, allowing the Pressurized Air Chamber Hydraulic Damper to adapt to varying operating conditions and provide effective pulsation reduction.

Furthermore, the mechatronic design facilitates the implementation of sophisticated control algorithms that govern the behavior of the damper. These algorithms, often executed by microcontrollers or programmable logic controllers, enable intelligent and adaptive control strategies. For instance, the control system can be programmed to respond differently under different load conditions or in the presence of specific hydraulic system dynamics, optimizing the overall efficiency of the damper.

In summary, the mechatronic design of the Pressurized Air Chamber Hydraulic Damper is a multifaceted integration of sensors and actuators into the control system, allowing for real-time monitoring and dynamic adjustments. This aspect of the design is fundamental to the damper's ability to effectively reduce pulsations in hydraulic systems, contributing to enhanced performance, efficiency, and safety in practical engineering applications

3.7 Circuit Diagram and Control Analysis:

The circuit configuration is straightforward, mandating the pump to operate within a 12V DC circuit, while the sensors operate within a 5V DC environment to detect pressure differentials. The sensors interface with a MyRio device, which in turn connects to a computer where LABView software facilitates the acquisition of voltage fluctuations and records them for subsequent analysis.Figure 11 is the Block Diagram illustrating the setup for Labview to monitor and capture the voltage variations.

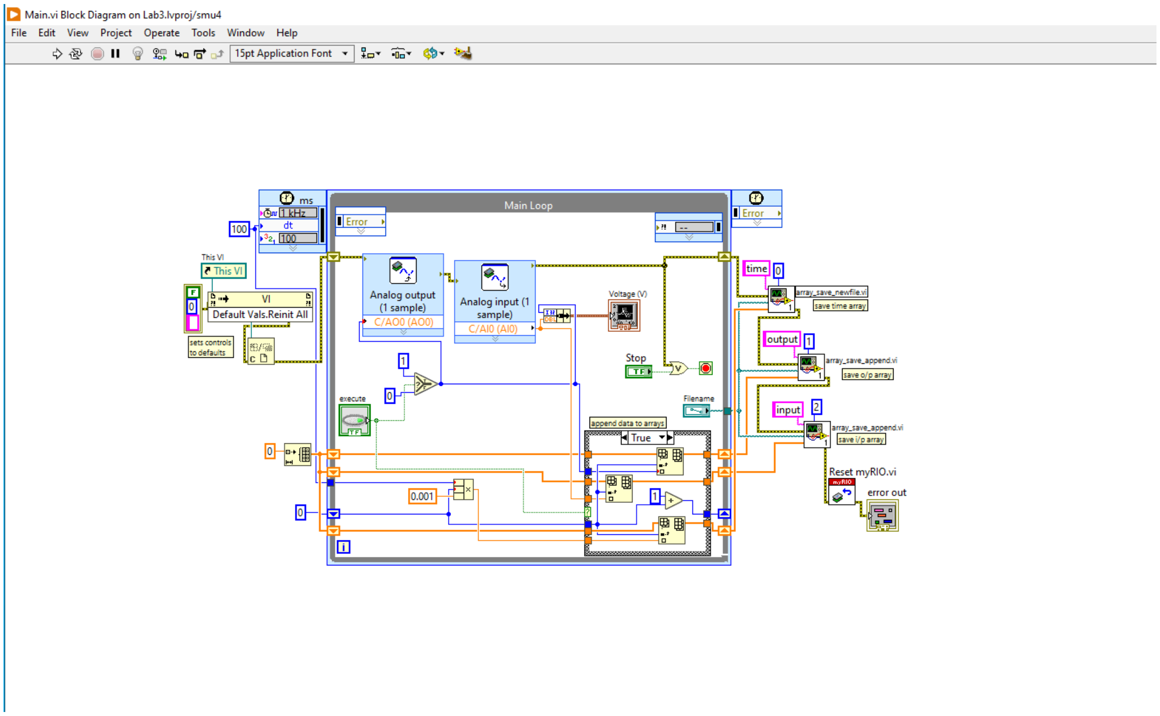

Figure 11: LABView Block Diagram for Analysis and Recording measurements

3.8 Manufacturing Process Design:

The manufacturing process design is a crucial aspect of bringing the Pressurized Air Chamber Hydraulic Damper from conceptualization to reality. This phase involves creating detailed specifications for the fabrication of the pressurized air chamber, ensuring that the manufacturing processes are chosen carefully to meet stringent tolerances and performance requirements. By meticulously addressing the manufacturing process design, the goal is to produce pressurized air chambers that not only meet the specified safety factors and fatigue requirements but also maintain consistency in their performance. The comprehensive approach, as mentioned in the original statement, involves considering not only the design and analysis aspects but also the intricacies of turning that design into a tangible, high-quality component. The integration of mechatronic design principles ensures that the functionality of the damper is maintained through the manufacturing process, leading to a product that is not only structurally sound but also functionally reliable and manufacturable at scale.

3.9 Codes and Standards:

We used all the Fundamental Canons outlined in the Code of Ethics (15). These are the following Codes we used in the development of this project:

3.9.1 Rules of Practice:

1. Engineers shall hold paramount the safety, health, and welfare of the public.
2. Engineers shall perform services only in the areas of their competence.
5. Engineers shall avoid deceptive acts.

3.9.2 Professional Obligations:

1. Engineers shall be guided in all their relations by the highest standards of honesty and integrity.
2. Engineers shall at all times strive to serve the public interest.
9. Engineers shall give credit for engineering work to those to whom credit is due and will recognize the proprietary interests of others.

3.10 Road Blocks:

It is crucial to anticipate and address potential roadblocks and challenges. Identifying these obstacles in advance allows for effective mitigation strategies and contingency plans. The following potential roadblocks are of particular concern in the development of the Air-Pressurized Hydraulic Damper:

3.10.1 Unknown Material Selection (Safety Factor of 2-2.5):

The absence of a pump in the hydraulic system poses a significant challenge in material selection for the Air-Pressurized Hydraulic Damper. A safety factor of 2-2.5 is typically used to ensure the structural integrity of components. However, without precise knowledge of the maximum pressure and stress levels the damper will experience, determining the appropriate materials becomes complex.

3.10.2 Integration of Pressure Control System:

Integrating a pressure control system into the design requires precise calibration and control to optimize the damper's performance. Ensuring that the system can accurately regulate air pressure is essential for effective pulsation reduction.

3.10.3 Budget Constraints and Funding:

Developing and testing the Air-Pressurized Hydraulic Damper may require financial resources that exceed the available budget. Securing adequate funding and sponsorships is crucial for the successful completion of the project.

3.10.4 Regulatory Compliance:

Meeting safety and industry standards is essential for the damper's successful application. Compliance with regulations may require additional time and resources.

3.10.5 Unexpected Design Iterations::

As the project progresses, unforeseen design iterations may be necessary based on the test results and performance data. These potential roadblocks and challenges are acknowledged, and our team is committed to proactive problem-solving and continuous communication. We will prioritize safety, quality, and efficiency while working to overcome these obstacles to complete the Air-Pressurized Hydraulic Damper project.

3.11 Solutions to Road Blocks:

In this section, we outline our strategies to address the potential roadblocks and challenges identified in Section 3.10. Our commitment to safety and project success drives these solutions:

3.11.1 Unknown Material Selection (Safety Factor of 2-2.5):

Solution: Rigorous Testing and Simulation To address the challenge of material selection in the absence of a pump in the system, we will conduct comprehensive simulations and testing. This will help establish the maximum pressure and stress levels the damper will experience, enabling us to make informed material choices. The simulations will involve varying stress scenarios to determine the material's safety factor under different conditions.

3.11.2 Integration of Pressure Control System:

Solution: Rigorous Calibration and Redundancy The integration of the pressure control system requires precise calibration. We will implement rigorous calibration procedures to ensure that the system can accurately regulate air pressure. Redundancy in the pressure control system will be incorporated to address potential control system failures. This will include safety mechanisms that can take over in case of malfunctions.

3.11.3 Budget Constraints and Funding:

Solution: Diversified Funding Sources and Cost-effective Alternatives To mitigate potential budget constraints, we are actively pursuing various funding sources, including research grants, industry partnerships, and sponsorship opportunities. Additionally, we will explore cost-effective alternatives during the design and testing phases, ensuring that the project remains within budget without compromising safety or performance.

3.11.4 Regulatory Compliance:

Solution: Ongoing Communication and Compliance Measures We will maintain open communication with regulatory bodies to ensure that the design aligns with safety and industry standards. Any necessary adjustments will be made promptly to guarantee compliance without affecting the project timeline. Compliance measures will be an integral part of the design and testing processes.

3.11.5 Unexpected Design Iterations::

Solution: Flexible Project Timeline and Regular Reviews To accommodate unexpected design iterations, our project timeline includes flexibility. Regular project reviews will identify and address design changes promptly. The team is prepared to adjust the project plan to ensure that the design meets safety, performance, and market requirements. These solutions represent our proactive approach to overcoming potential roadblocks and challenges. By leveraging testing, redundancy, diversified funding, open communication, adaptability, and flexibility, we aim to ensure the successful completion of the Air-Pressurized Hydraulic Damper project while upholding safety and quality standards.

4 Design Results and Specifications

In the pursuit of optimizing the performance of the hydraulic system, a comprehensive analysis was conducted with a focus on the integration of a pulsation dampener. The primary objective was to mitigate pressure pulsations and enhance the overall stability and efficiency of the system. ANSYS Mechanical Enterprise was employed for detailed finite element analysis, simulating the dynamic behavior of the hydraulic system with and without the pulsation dampener. The analysis encompassed various load conditions, allowing for a robust evaluation of the system's response.

The results of the analysis indicate that the incorporation of the pulsation dampener was successful in achieving its intended purpose. The dampener effectively attenuated pressure fluctuations, leading to a more stable hydraulic system. Key observations include:

Pressure Pulsation Reduction: The pulsation dampener demonstrated efficacy in reducing pressure pulsations within the system. This contributed to smoother fluid flow and a decrease in stress concentrations in critical components.

System Stability: The hydraulic system exhibited enhanced stability, with reduced vibrations and oscillations. This is crucial for ensuring the longevity of system components and minimizing the risk of fatigue failure.

No Critical Failures: The analysis revealed that, under the specified operating conditions, there were no critical failures or structural issues observed in the system. The components maintained structural integrity, and safety margins were within acceptable limits.

While the results of the pulsation dampener analysis were positive, it is important to note that adjustments to the system specifications are warranted to align with the real-world characteristics of the pump and associated components. Recommendations for further refinement include:

System Calibration: Fine-tune the specifications of the hydraulic system components to match the actual performance characteristics of the pump. This involves adjusting parameters such as flow rates, pressures, and material properties.

Real-world Testing: Conduct experimental testing to validate the simulation results and ensure that the hydraulic system performs as expected under practical conditions.

Iterative Design: Consider an iterative design approach, incorporating feedback from real-world testing to refine the specifications and optimize the system for maximum efficiency and reliability.

The pulsation dampener analysis yielded successful results, demonstrating its efficacy in improving the stability of the hydraulic system. However, the need for adjustments to the system specifications highlights the importance of aligning simulation models with real-world conditions for more accurate predictions. The recommendations provided serve as a guide for further refinement, ensuring the hydraulic system's optimal performance in practical applications.

5 Considerations of Physical Prototype

So our objective is to fabricate a physical prototype of the pulsation dampener based on ANSYS simulation results. Our key focus is to get an accurate representation of system behavior, material selection, and validation against simulated data.

5.1 Approach:

Material Selection:

- Identify materials matching ANSYS simulation specifications.
- Consider elastomers, metals, or composite materials based on system requirements.

Component Specifications:

- Align pump specifications with ANSYS-adjusted parameters.
- Establish pump compatibility with the pulsation dampener design.

Dampener Design and Fabrication:

- Develop detailed engineering drawings from ANSYS results.
- Collaborate with a fabrication partner for precision manufacturing.

Instrumentation for Data Collection:

- Integrate pressure sensors and flow meters for real-time data collection.
- Ensure compatibility with data acquisition systems.

Real-world Boundary Conditions:

- Design and implement environmental factors such as temperature and vibration into the prototype testing setup.
- Mimic real-world operating conditions to validate system response.

Testing Scenarios:

- Conduct a series of tests under various load conditions.
- Evaluate the prototype's performance against ANSYS-predicted behavior.

Iterative Testing and Refinement:

- Analyze test results and make iterative improvements.
- Refine the dampener design and component specifications as needed.

Safety and Compliance:

- Adhere to safety standards for materials, pressure vessels, and overall system reliability.
- Engage with regulatory bodies to ensure compliance.

Documentation and Reporting:

- Maintain detailed records of the prototype development process.
- Create a comprehensive report comparing prototype performance to ANSYS simulation results.

Collaboration with Stakeholders:

- Involve engineering teams, designers, and potential end-users in the testing process.
- Gather feedback for continuous improvement.

5.2 Cost Considerations:

Material Costs: Allocate budget for high-quality materials based on ANSYS specifications.
Fabrication Costs: Partner with a reputable fabrication facility with experience in pressure vessel manufacturing.
Instrumentation Costs: Budget for sensors, data acquisition systems, and testing equipment.
Testing and Iteration: Include costs for multiple testing rounds and iterative refinements.
Safety and Compliance: Allocate funds for safety testing and compliance checks.

5.3 Time Considerations (Timelines):

Fabrication: 1-2 months depending on manufacturing flaws
Testing and Iterations: 1-2 months (including refinement periods)
Documentation and Reporting: Ongoing throughout the process

5.4 Monitoring and Contingency:

- Regularly review progress against timelines.
- Allow for contingencies in case of unexpected challenges or design revisions.
- Maintain open communication with stakeholders to address concerns and updates.

5.5 Roadblocks:

Currently, there is one major roadblock in our prototyping process. The roadblock is the need to manufacture the capacitor. To remedy this we have sought additional advice for printing and will be printing the capacitor once we modify the design to account for those recommendations.

5.6 Calculations:

The calculations done were in follow-up to the previous equation given, that is:

$$\frac{dP_C}{dt} = \frac{P_D - \frac{1}{2}P_S - P_C}{C\left(R_3 + \frac{1}{2}R\right)} \tag{8}$$

However, as design considerations were occurring, it became valuable to have an additional metric to measure the success of the damper against, that being the outgoing pressure, or "Pressure in Resistance 2". The following equation factors in previous variables to give the desired pressure:

Outgoing Pressure:

$$P_{R2} = P_D - P_C - P_{R3} \tag{9}$$

Substituting in the previous equation for what P_C is gives this equation:

Outgoing Pressure:

$$P_{R2} = P_D - P_{R3} - \frac{1}{2}P_S - \frac{dP_C}{dt} \cdot C \cdot (R_3 + \frac{1}{2}R) \tag{10}$$

With this equation, we can now set benchmarks of what the desired damping is and set design specs. When entering in a desired sinusoidal function, it will be much easier to tell how much of an effect the inline capacitance will have in the alternating pressure. Now, once values for each of the components are solidified, fabrication of the damper can occur.

5.7 Prototype Photos:

Figure 12: The 3D prototype

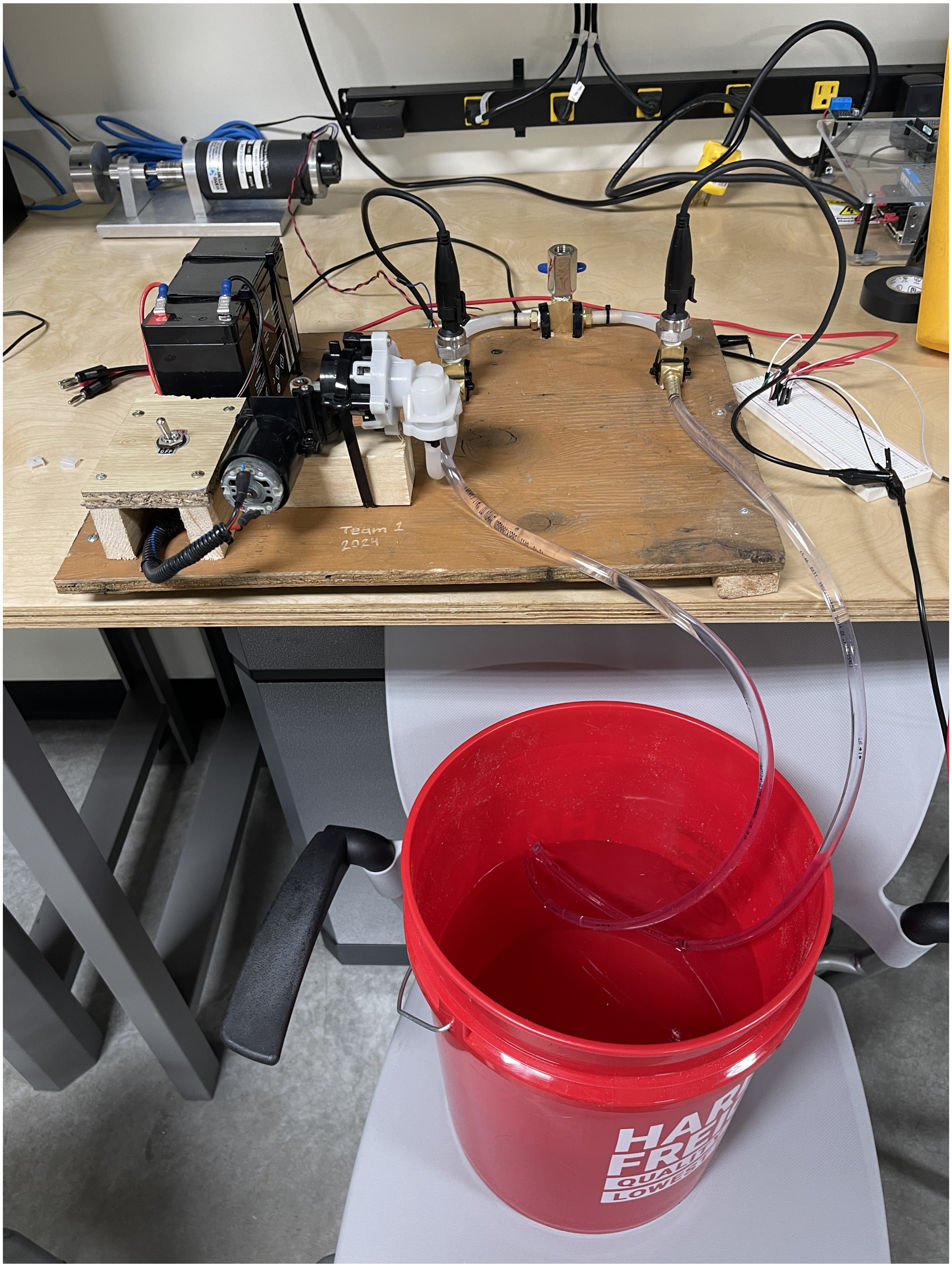

Figure 13: Testing Platform, with all components attached

6 Physical Prototype Manufacturing, Fabrication and Assembly

The physical prototype was meticulously manufactured, fabricated, and assembled to ensure robustness and functionality during testing. Utilizing advanced 3D printing technology facilitated the production of precise and customized components tailored to the system's specific requirements. This approach enabled rapid prototyping and iterative design modifications, thereby accelerating the development process and optimizing component performance. In the assembly process, secure and reliable connections between tubing and fittings were paramount for maintaining system integrity and preventing fluid leaks or pressure losses. To achieve this, high-quality zip ties were employed to provide mechanical support and secure attachment of tubing to fittings, ensuring stability and minimizing movement during operation. Additionally, Teflon tape was applied to threaded connections to create a tight and leak-free seal, enhancing the system's reliability and preventing potential fluid leaks. This sealing method is particularly effective in applications involving fluid dynamics and high-pressure environments, ensuring consistent performance and minimizing maintenance requirements. The assembly involved the systematic integration of 3D-printed components, tubing, and fittings into a cohesive and functional testing system. Careful attention was paid to alignment, orientation, and connection integrity to ensure optimal system performance and reliability. Precise alignment of components was critical to maintaining system coherence and functionality, with alignment fixtures and guides utilized during assembly to ensure accurate positioning and alignment of 3D-printed parts and subsystems. Thorough inspection and testing of connections were conducted to verify secure attachment and sealing effectiveness, ensuring that all connections were leak-free and capable of withstanding operational pressures and dynamic loads. In summary, the integration of advanced 3D printing technology, along with the use of zip ties and Teflon tape for secure tubing and fittings, contributed to the successful realization of a robust and reliable testing system. The meticulous attention to detail in manufacturing, fabrication, and assembly processes ensured the production of a functional prototype capable of meeting the system's design specifications and performance requirements. Future developments will focus on further optimization and refinement of the prototype to enhance performance, reliability, and operational efficiency.

7 Physical Prototype Testing

The pressure irregularities observed in the initial evaluation without the dampener can be attributed to several key factors that influence the hydraulic behavior of the system. First and foremost, the inherent inefficiencies of the pump system lead to non-uniform pressure output, creating variability in the pressure profiles. Additionally, the dynamic variability in head pressure from the source reservoir, influenced by fluid dynamics parameters such as flow rate fluctuations and fluid viscosity, adds complexity to the pressure behavior. Furthermore, transient hydraulic phenomena, including shockwaves and pressure transients induced by rapid valve actuation or abrupt changes in flow conditions, contribute to the observed pressure oscillations.

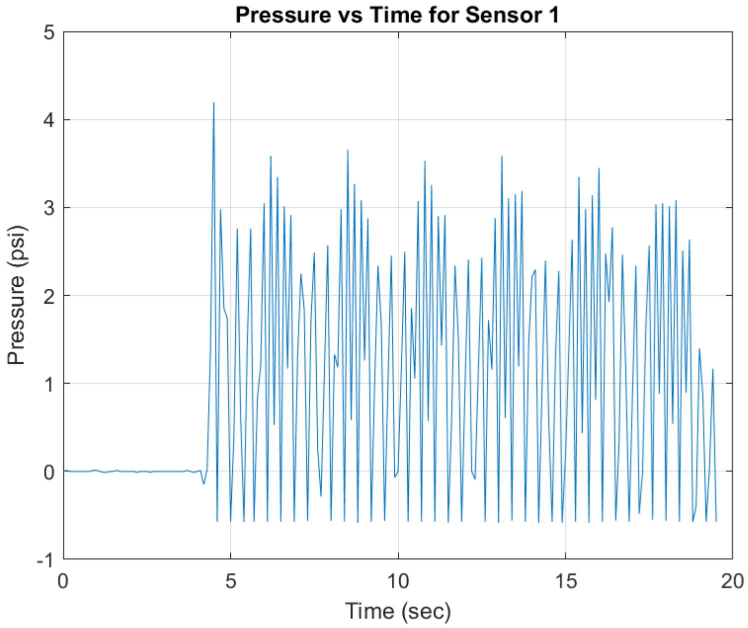

Figure 14: Pressure vs Time for Sensor 1, Baseline Values (Without Dampener).

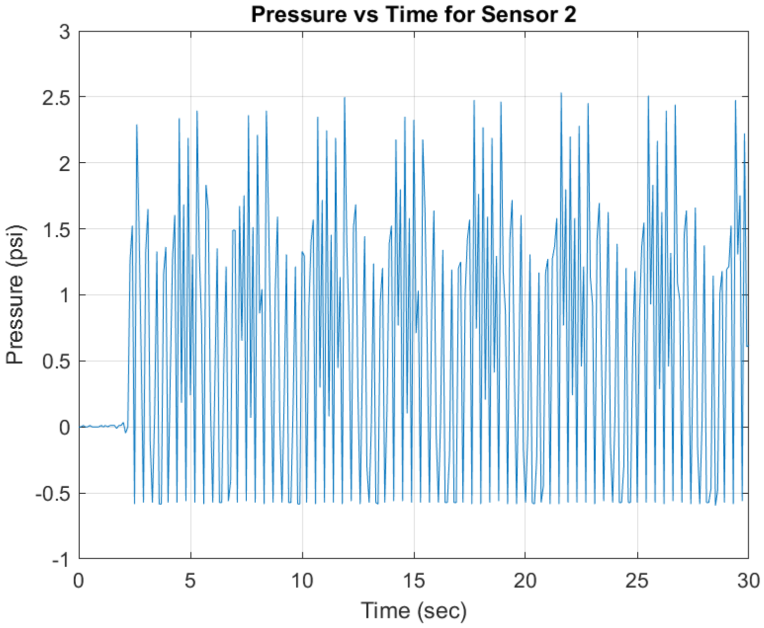

Figure 15: Pressure vs Time for Sensor 2, Baseline Values (Without Dampener).

Figure 14 and Figure 15 illustrate the pressure-time profiles for sensors 1 and 2, respectively, under baseline conditions without the dampener. Figure 15 shows a pronounced pulsatile nature characterized by recurring fluctuations in pressure magnitude over the experimental duration.

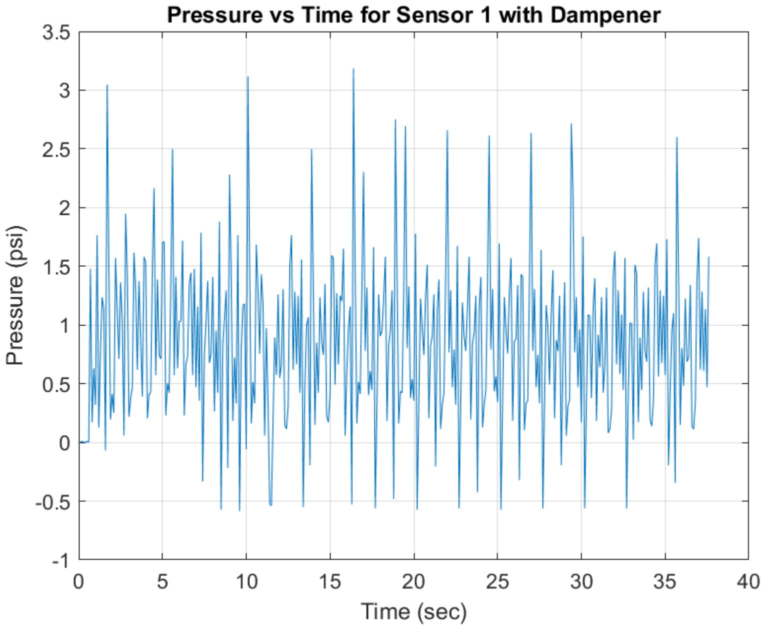

Figure 16: Pressure vs Time for Sensor 1, Values (With Dampener).

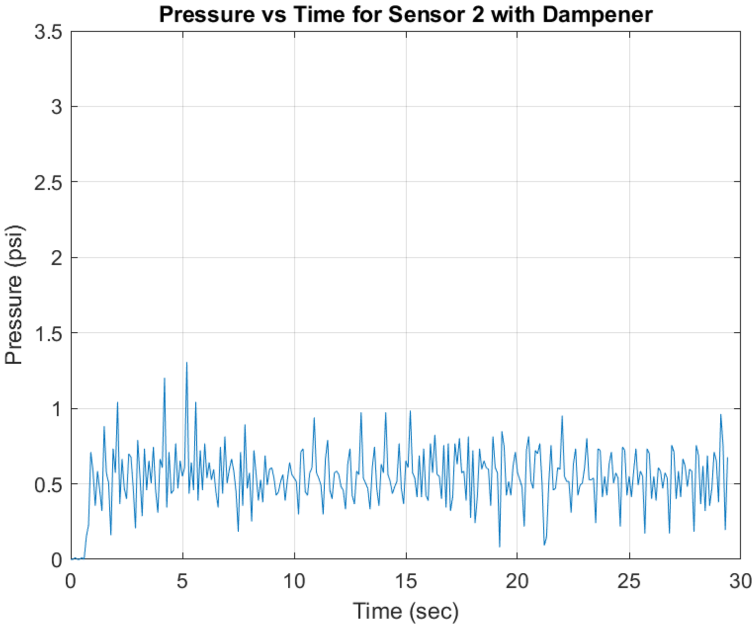

Figure 17: Pressure vs Time for Sensor 2, Values (With Dampener).

In contrast, Figure 16 and Figure 17 present the pressure profiles with the open-air dampener integrated into the system. Figure 17 exhibits a notable transformation, with a flattened pressure curve, indicative of the dampener's efficacy in attenuating pressure fluctuations. This reduction in pressure variability demonstrates the dampener's ability to stabilize the pressure profile by mitigating the effects of the aforementioned factors. A more detailed analysis reveals that the open-air dampener functions by absorbing and dissipating pressure fluctuations, thereby reducing the amplitude of pressure spikes and dips induced by transient hydraulic phenomena. This damping effect is achieved through the dampener's ability to store and release energy, smoothing out the pressure variations and promoting a more consistent pressure output. Moreover, a visual assessment of the system's outlet confirms the transition to laminar flow characteristics in the presence of the dampener, as opposed to the previously observed pulsating flow without the dampener. This transition to laminar flow further corroborates the dampener's effectiveness in stabilizing the system, reducing hydraulic disturbances, and consequently minimizing mechanical stress and wear on equipment.

The integration of the open-air dampener has proven to be instrumental in mitigating pressure fluctuations, stabilizing the pressure profile, and promoting laminar flow characteristics at the system's outlet. These improvements enhance the overall system performance, reliability, and longevity by reducing the adverse effects of pressure oscillations and hydraulic disturbances on machinery components. Future studies will focus on optimizing the dampener's design parameters and exploring additional strategies to further enhance system efficiency and reliability.

8 Conclusion

In conclusion, the development of the Open Atmosphere Hydraulic Damper represents a significant advancement in addressing the challenges associated with pressure pulsations in hydraulic systems. Initially conceptualized with a pressurized design, our team adapted to an open atmosphere dampener configuration to optimize functionality and efficiency based on iterative design evaluations and system performance assessments. The design evolution leveraged principles inspired by existing references, particularly Reference 11, while emphasizing simplicity, cost-efficiency, and real-time control capabilities. Through a combination of theoretical analysis, computer simulations, and experimental testing, the project aimed to design and implement an innovative solution to enhance the efficiency and safety of hydraulic machinery. The final design concept effectively demonstrated its capability to reduce pressure pulsations within the hydraulic system. Finite element analysis results underscored the positive impact on fluid flow, stress concentrations, and overall system stability. Moreover, the integration of advanced 3D printing technology, zip ties, and Teflon tape in the physical prototype manufacturing, fabrication, and assembly processes contributed to the successful realization of a robust and reliable testing system. However, recognizing the need for adjustments to align with real-world conditions, recommendations for system calibration, real-world testing, and an iterative design approach were outlined. The meticulous attention to detail in manufacturing, fabrication, and assembly processes ensured the production of a functional prototype capable of meeting the system's design specifications and performance requirements. Moving forward, the consideration of a physical prototype is a crucial step in validating the simulation results and ensuring the practical applicability of the Open Atmosphere Hydraulic Damper. The proposed approach involves meticulous material selection, alignment of component specifications with adjusted parameters, detailed engineering drawings, and collaboration with stakeholders for testing and refinement. Cost and time considerations, along with a proactive monitoring and contingency plan, will be essential in ensuring the success of the prototype development process. Our commitment to safety, ethical standards, and continuous improvement positions us to overcome potential roadblocks and challenges. By addressing unknowns in material selection, integrating a precise pressure control system, managing budget constraints, ensuring regulatory compliance, and accommodating unexpected design iterations, our team is well-prepared to navigate the complexities of the Open Atmosphere Hydraulic Damper project. In summary, the culmination of theoretical groundwork, simulation, and the proposed physical prototype represents a holistic and proactive approach to solving the problem of hydraulic system pulsations. The project's success hinges on the integration of innovative design, rigorous analysis, and a systematic prototype development process, with a shared goal of enhancing the efficiency and safety of hydraulic machinery.

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9 Appendix

9.1 ANSYS Full Results

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Ansys Mechanical Enterprise Academic Student

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Academic Student 2023 R1


      *****  MAPDL COMMAND LINE ARGUMENTS  *****
 BATCH MODE REQUESTED (-b)    = NOLIST
 INPUT FILE COPY MODE (-c)    = COPY
 SHARED MEMORY PARALLEL REQUESTED
      SINGLE PROCESS WITH   4 THREADS REQUESTED
      TOTAL OF       4 CORES REQUESTED
 INPUT FILE NAME              = C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\
    _ProjectScratch\Scr1984\dummy.dat
 OUTPUT FILE NAME             = C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\
    _ProjectScratch\Scr1984\solve.out
 START-UP FILE MODE           = NOREAD
 STOP FILE MODE               = NOREAD

RELEASE= 2023 R1              BUILD= 23.1      UP20221128    VERSION=WINDOWS x64
```

```
CURRENT JOBNAME=file  18:33:57  OCT 18, 2023 CP=        0.109


 *** WARNING ***                         CP =        0.188   TIME= 18:33:57
 The requested number of CPU cores for shared-memory parallel (100)
 cannot be greater than that specified by the command line option -NP
 (4).  The number of CPU cores used will be left at 4.

PARAMETER _DS_PROGRESS =     999.0000000

 /INPUT FILE= ds.dat  LINE=     0



DO NOT WRITE ELEMENT RESULTS INTO DATABASE

 *GET  _WALLSTRT  FROM  ACTI  ITEM=TIME WALL  VALUE=  18.5658333

 TITLE=
wbnew--Static Structural (A5)

  ACT Extensions:
       LSDYNA, 2023.1
       5f463412-bd3e-484b-87e7-cbc0a665e474, wbex
 /COM,          ANSYSMotion, 2023.1
       20180725-3f81-49eb-9f31-41364844c769, wbex


 SET PARAMETER DIMENSIONS ON  _WB_PROJECTSCRATCH_DIR
  TYPE=STRI  DIMENSIONS=      248        1        1

PARAMETER _WB_PROJECTSCRATCH_DIR(1) = C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2
    \_ProjectScratch\Scr1984\

 SET PARAMETER DIMENSIONS ON  _WB_SOLVERFILES_DIR
  TYPE=STRI  DIMENSIONS=      248        1        1

PARAMETER _WB_SOLVERFILES_DIR(1) = C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\
    wbnew_files\dpo\SYS\MECH\

 SET PARAMETER DIMENSIONS ON  _WB_USERFILES_DIR
  TYPE=STRI  DIMENSIONS=      248        1        1

PARAMETER _WB_USERFILES_DIR(1) = C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\
    wbnew_files\user_files\
--- Data in consistent MKS units. See Solving Units in the help system for more

MKS UNITS SPECIFIED FOR INTERNAL
  LENGTH        (l)  = METER (M)
  MASS          (M)  = KILOGRAM (KG)
  TIME          (t)  = SECOND (SEC)
  TEMPERATURE    (T)  = CELSIUS (C)
  TOFFSET              = 273.0
  CHARGE        (Q)  = COULOMB
  FORCE         (f)  = NEWTON (N) (KG-M/SEC2)
  HEAT                = JOULE (N-M)

  PRESSURE             = PASCAL (NEWTON/M**2)
  ENERGY        (W)  = JOULE (N-M)
```

```
 POWER          (P)   = WATT (N-M/SEC)
 CURRENT        (i)   = AMPERE (COULOMBS/SEC)
 CAPACITANCE     (C)   = FARAD
 INDUCTANCE     (L)   = HENRY
 MAGNETIC FLUX          = WEBER
 RESISTANCE     (R)   = OHM
 ELECTRIC POTENTIAL = VOLT

INPUT  UNITS ARE ALSO SET TO MKS

*** MAPDL - ENGINEERING ANALYSIS SYSTEM  RELEASE 2023 R1          23.1         ***
Ansys Mechanical Enterprise Academic Student
01055371  VERSION=WINDOWS x64   18:33:57  OCT 18, 2023 CP=     0.188

wbnew--Static Structural (A5)



      ***** MAPDL ANALYSIS DEFINITION (PREP7) *****
*********** Nodes for the whole assembly ***********
*********** Elements for Body 1 "Part1-FreeParts|Solid1" ***********
*********** Send User Defined Coordinate System(s) ***********
*********** Set Reference Temperature ***********
*********** Send Materials ***********
*********** Fixed Supports ***********
*********** Define Force Using Surface Effect Elements ***********


***** ROUTINE COMPLETED *****  CP =          0.266


--- Number of total nodes = 5160
--- Number of contact elements = 474
--- Number of spring elements = 0
--- Number of bearing elements = 0
--- Number of solid elements = 2821
--- Number of condensed parts = 0
--- Number of total elements = 3295

*GET  _WALLBSOL  FROM  ACTI  ITEM=TIME WALL  VALUE=  18.5658333
***************************************************************************
*************************        SOLUTION        ********************************
***************************************************************************

*****  MAPDL SOLUTION ROUTINE  *****


PERFORM A STATIC ANALYSIS
 THIS WILL BE A NEW ANALYSIS

PARAMETER _THICKRATIO =      0.000000000

USE SPARSE MATRIX DIRECT SOLVER

CONTACT INFORMATION PRINTOUT LEVEL      1

NLDIAG: Nonlinear diagnostics CONT option is set to ON.
      Writing frequency : each ITERATION.
```

```
DO NOT SAVE ANY RESTART FILES AT ALL
 ****************************************************
 ******************* SOLVE FOR LS 1 OF 1 ****************

SELECT          FOR ITEM=TYPE COMPONENT=
 IN RANGE               2 TO               2 STEP             1

      474  ELEMENTS (OF        3295  DEFINED) SELECTED BY  ESEL  COMMAND.

SELECT          ALL NODES HAVING ANY ELEMENT IN ELEMENT SET.

      1005 NODES (OF           5160  DEFINED) SELECTED FROM
      474 SELECTED ELEMENTS BY NSLE COMMAND.

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS  LKEY =  1   KVAL = 1
      VALUES =     0.0000          0.0000          0.0000        0.0000

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS  LKEY =  2   KVAL = 1
      VALUES =     41116.                41116.          41116.              41116.

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS  LKEY =  3   KVAL = 1
      VALUES =     0.0000          0.0000          0.0000        0.0000

ALL SELECT   FOR ITEM=NODE COMPONENT=
 IN RANGE               1 TO        5160 STEP             1

      5160  NODES (OF          5160  DEFINED) SELECTED BY NSEL  COMMAND.

ALL SELECT   FOR ITEM=ELEM COMPONENT=
 IN RANGE               1 TO     4683 STEP        1

      3295  ELEMENTS (OF       3295  DEFINED) SELECTED BY  ESEL  COMMAND.

PRINTOUT RESUMED BY /GOP

USE             1 SUBSTEPS INITIALLY THIS LOAD STEP FOR ALL  DEGREES OF FREEDOM
FOR AUTOMATIC TIME STEPPING:
  USE           1 SUBSTEPS AS A MAXIMUM
  USE           1 SUBSTEPS AS A MINIMUM

TIME=  1.0000

ERASE THE CURRENT DATABASE OUTPUT CONTROL TABLE.


WRITE ALL  ITEMS TO THE DATABASE WITH A FREQUENCY OF NONE
  FOR ALL APPLICABLE ENTITIES

WRITE NSOL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE RSOL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE EANG ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE ETMP ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES
```

```
WRITE VENG ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE STRS ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE EPEL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE EPPL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

WRITE CONT ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL
  FOR ALL APPLICABLE ENTITIES

*GET  ANSINTER_  FROM  ACTI  ITEM=INT          VALUE=  0.00000000

*IF  ANSINTER_                         ( =    0.00000   )  NE
     0                                 ( =    0.00000   )  THEN

*ENDIF

*****  MAPDL SOLVE    COMMAND  *****

*** WARNING ***                         CP =           0.328   TIME= 18:33:57
Element shape checking is currently inactive.  Issue SHPP,ON or
SHPP,WARN to reactivate, if desired.

*** NOTE ***                            CP =           0.328   TIME= 18:33:57
The model data was checked and warning messages were found.
 Please review output or errors file (
C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\_ProjectScratch\Scr1
1984\file.err ) for these warning messages.

*** SELECTION OF ELEMENT TECHNOLOGIES FOR APPLICABLE ELEMENTS ***
      --- GIVE SUGGESTIONS AND RESET THE KEY OPTIONS ---

ELEMENT TYPE          1 IS SOLID187. IT IS NOT ASSOCIATED WITH FULLY INCOMPRESSIBLE
HYPERELASTIC MATERIALS. NO SUGGESTION IS AVAILABLE AND NO RESETTING IS NEEDED.



*** MAPDL - ENGINEERING ANALYSIS SYSTEM  RELEASE 2023 R1          23.1        ***
Ansys Mechanical Enterprise Academic Student
01055371  VERSION=WINDOWS x64   18:33:57  OCT 18, 2023 CP=     0.328

wbnew--Static Structural (A5)



                    S O L U T I O N   O P T I O N S

  PROBLEM DIMENSIONALITY. . . . . . . . . . . . .3-D
  DEGREES OF FREEDOM. . . . . . UX   UY   UZ
  ANALYSIS TYPE . . . . . . . . . . . . . . . . .STATIC (STEADY-STATE)
  OFFSET TEMPERATURE FROM ABSOLUTE ZERO . . . . .  273.15
  EQUATION SOLVER OPTION. . . . . . . . . . . . .SPARSE
  GLOBALLY ASSEMBLED MATRIX . . . . . . . . . . .SYMMETRIC
```

```
*** WARNING ***                         CP =       0.328   TIME= 18:33:57
Material number 2 (used by element 4210) should normally have at least
one MP or one TB type command associated with it.  Output of energy by
material may not be available.

*** NOTE ***                            CP =       0.328   TIME= 18:33:57
The step data was checked and warning messages were found.
 Please review output or errors file (
C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\_ProjectScratch\Scr1
1984\file.err ) for these warning messages.

*** NOTE ***                            CP =       0.328   TIME= 18:33:57
The conditions for direct assembly have been met.  No .emat or .erot
files will be produced.

                    L O A D   S T E P   O P T I O N S

  LOAD STEP NUMBER. . . . . . . . . . . . . . . .     1
  TIME AT END OF THE LOAD STEP. . . . . . . . . .  1.0000
  NUMBER OF SUBSTEPS. . . . . . . . . . . . . . .     1
  STEP CHANGE BOUNDARY CONDITIONS . . . . . . . .    NO
  PRINT OUTPUT CONTROLS . . . . . . . . . . . . .NO PRINTOUT
  DATABASE OUTPUT CONTROLS
     ITEM     FREQUENCY   COMPONENT
      ALL       NONE
     NSOL        ALL
     RSOL        ALL
     EANG        ALL
     ETMP        ALL
     VENG        ALL
     STRS        ALL
     EPEL        ALL
     EPPL        ALL
     CONT        ALL


SOLUTION MONITORING INFO IS WRITTEN TO FILE= file.mntr



                  ***********  PRECISE MASS SUMMARY  ***********

  TOTAL RIGID BODY MASS MATRIX ABOUT ORIGIN
              Translational mass               |   Coupled translational/rotational mass
       0.11845        0.0000        0.0000     |     0.0000        0.51700E-08   -0.97534
          E-03
       0.0000        0.11845       0.0000     |  -0.51700E-08    0.0000        -0.80750E
          -08
       0.0000        0.0000        0.11845     |   0.97534E-03   0.80750E-08
           0.0000
     ------------------------------------------ |
        ------------------------------------------
                                               |     Rotational mass (inertia)
                                               |     0.30094E-04   -0.54674E-10
                                                  0.78998E-11
                                               |  -0.54674E-10    0.20736E-04     0.12463E
                                                  -10
                                               |     0.78998E-11   0.12463E-10
```

```
                                                  0.30094E-04

   TOTAL MASS = 0.11845
       The mass principal axes coincide with the global Cartesian axes

   CENTER OF MASS (X,Y,Z)=   -0.68175E-07   0.82345E-02   0.43649E-07

   TOTAL INERTIA ABOUT CENTER OF MASS
       0.22062E-04  -0.12117E-09   0.78994E-11
      -0.12117E-09   0.20736E-04   0.55035E-10
       0.78994E-11   0.55035E-10   0.22062E-04
       The inertia principal axes coincide with the global Cartesian axes


  *** MASS SUMMARY BY ELEMENT TYPE ***

  TYPE          MASS
      1   0.118446

 Range of element maximum matrix coefficients in global coordinates
 Maximum = 3.848920078E+09 at element 2814.
 Minimum = 250071320 at element 384.

   *** ELEMENT MATRIX FORMULATION TIMES
       TYPE    NUMBER   ENAME         TOTAL CP  AVE CP

       1       2821  SOLID187     0.844     0.000299
        2       474  SURF154        0.062     0.000132
 Time at end of element matrix formulation CP = 0.765625.

 SPARSE MATRIX DIRECT SOLVER.
  Number of equations =        15138,    Maximum wavefront =      198
  Memory allocated for solver              =    56.939 MB
  Memory required for in-core solution     =    54.700 MB
  Memory required for out-of-core solution =    23.391 MB

 *** NOTE ***                            CP =           1.453   TIME= 18:33:57
 The Sparse Matrix Solver is currently running in the in-core memory
 mode.  This memory mode uses the most amount of memory in order to
 avoid using the hard drive as much as possible, which most often
 results in the fastest solution time.  This mode is recommended if
 enough physical memory is present to accommodate all of the solver
 data.
 curEqn=  15138  totEqn=  15138 Job CP sec=     1.766
       Factor Done= 100% Factor Wall sec=       0.024 rate=      62.8 GFlops
 Sparse solver maximum pivot= 3.863244655E+09 at node 1218 UZ.
 Sparse solver minimum pivot= 103482442 at node 128 UY.
 Sparse solver minimum pivot in absolute value= 103482442 at node 128
UY.

   *** ELEMENT RESULT CALCULATION TIMES
       TYPE    NUMBER   ENAME         TOTAL CP  AVE CP

       1       2821  SOLID187     0.312     0.000111
        2       474  SURF154      0.000     0.000000

   *** NODAL LOAD CALCULATION TIMES
       TYPE    NUMBER   ENAME         TOTAL CP  AVE CP
```

```
      1       2821  SOLID187     0.188     0.000066
       2       474  SURF154      0.062     0.000132
*** LOAD STEP        1   SUBSTEP      1  COMPLETED.   CUM ITER =       1
*** TIME =   1.00000         TIME INC =   1.00000      NEW TRIANG MATRIX


*** MAPDL BINARY FILE STATISTICS
 BUFFER SIZE USED= 16384
      7.375 MB WRITTEN ON ASSEMBLED MATRIX FILE: file.full
      2.125 MB WRITTEN ON RESULTS FILE: file.rst
*************** Write FE CONNECTORS *********

WRITE OUT CONSTRAINT EQUATIONS TO FILE= file.ce
****************************************************
*************** FINISHED SOLVE FOR LS 1 *************

*GET  _WALLASOL  FROM  ACTI  ITEM=TIME WALL  VALUE=  18.5661111

PRINTOUT RESUMED BY /GOP

FINISH SOLUTION PROCESSING


***** ROUTINE COMPLETED *****  CP =         2.266



*** MAPDL - ENGINEERING ANALYSIS SYSTEM  RELEASE 2023 R1          23.1        ***
Ansys Mechanical Enterprise Academic Student
01055371  VERSION=WINDOWS x64    18:33:58  OCT 18, 2023 CP=     2.328

wbnew--Static Structural (A5)



      ***** MAPDL RESULTS INTERPRETATION (POST1) *****

*** NOTE ***                         CP =        2.328   TIME= 18:33:58
Reading results into the database (SET command) will update the current
displacement and force boundary conditions in the database with the
values from the results file for that load set.  Note that any
subsequent solutions will use these values unless action is taken to
either SAVE the current values or not overwrite them (/EXIT,NOSAVE).

Set Encoding of XML File to:ISO-8859-1

Set Output of XML File to:
      PARM,    ,    ,    ,    ,    ,    ,    ,    ,    ,    ,
                ,
       ,    ,    ,    ,    ,    ,    ,

DATABASE WRITTEN ON FILE  parm.xml

EXIT THE MAPDL POST1 DATABASE PROCESSOR


***** ROUTINE COMPLETED *****  CP =         2.328
```

```
 PRINTOUT RESUMED BY /GOP

 *GET  _WALLDONE  FROM  ACTI  ITEM=TIME WALL  VALUE=  18.5661111

 PARAMETER _PREPTIME =      0.000000000

 PARAMETER _SOLVTIME =      1.000000000

 PARAMETER _POSTTIME =      0.000000000

 PARAMETER _TOTALTIM =      1.000000000

 *GET  _DLBRATIO  FROM  ACTI  ITEM=SOLU DLBR  VALUE=  0.00000000

 *GET  _COMBTIME  FROM  ACTI  ITEM=SOLU COMB  VALUE=  0.00000000

 *GET  _SSMODE   FROM  ACTI  ITEM=SOLU SSMM  VALUE=  2.00000000

 *GET  _NDOFS  FROM  ACTI  ITEM=SOLU NDOF  VALUE=  15138.0000
 --- Total number of nodes = 5160
 --- Total number of elements = 3295
 --- Element load balance ratio = 0
 --- Time to combine distributed files = 0
 --- Sparse memory mode = 2
 --- Number of DOF = 15138

 EXIT MAPDL WITHOUT SAVING DATABASE


 NUMBER OF WARNING MESSAGES ENCOUNTERED=          4
 NUMBER OF ERROR   MESSAGES ENCOUNTERED=          0

+--------------------- M A P D L   S T A T I S T I C S ------------------------+

Release: 2023 R1            Build: 23.1     Update: UP20221128   Platform: WINDOWS x64
Date Run: 10/18/2023   Time: 18:33     Process ID: 15628
Operating System: Windows 10  (Build: 19045)

Processor Model: Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz

Compiler: Intel(R) Fortran Compiler Version 19.0.5  (Build: 20190815)
          Intel(R) C/C++ Compiler Version 19.0.5  (Build: 20190815)
          Intel(R) Math Kernel Library Version 2020.0.0 Product Build 20191125
          BLAS Library supplied by Intel(R) MKL

Number of machines requested            :    1
Total number of cores available         :    8
Number of physical cores available      :    4
Number of processes requested           :    1
Number of threads per process requested :    4
Total number of cores requested         :    4 (Shared Memory Parallel)

GPU Acceleration: Not Requested

Job Name: file
Input File: dummy.dat
Working Directory: C:\Users\araki\AppData\Local\Temp\WB_araki_16316_2\_ProjectScratch\
    Scr1984
```

```
Total CPU time for main thread                          :          0.9 seconds
Total CPU time summed for all threads                   :          2.7 seconds

Elapsed time spent obtaining a license                  :          0.4 seconds
Elapsed time spent pre-processing model (/PREP7)        :          0.0 seconds
Elapsed time spent solution - preprocessing             :          0.0 seconds
Elapsed time spent computing solution                   :          0.4 seconds
Elapsed time spent solution - postprocessing            :          0.0 seconds
Elapsed time spent post-processing model (/POST1)       :          0.0 seconds

Equation solver used                                    :          Sparse (symmetric)
Equation solver computational rate                      :     27.0 Gflops
Equation solver effective I/O rate                      :     14.8 GB/sec

Sum of memory used on all processes                     :     150.0 MB
Sum of memory allocated on all processes                :     2112.0 MB
Physical memory available                               :          32 GB

Total amount of I/O written to disk                     :          0.0 GB
Total amount of I/O read from disk                      :          0.0 GB

+------------------ E N D   M A P D L   S T A T I S T I C S -------------------+


 *-----------------------------------------------------------------------------*
 |                                                                             |
 |                                RUN COMPLETED                                |
 |                                                                             |
 |-----------------------------------------------------------------------------|
 |                                                                             |
 |  Ansys MAPDL 2023 R1          Build 23.1         UP20221128    WINDOWS x64   |
 |                                                                             |
 |-----------------------------------------------------------------------------|
 |                                                                             |
 |  Database Requested(-db)  1024 MB     Scratch Memory Requested       1024 MB |
 |  Maximum Database Used       4 MB     Maximum Scratch Memory Used     146 MB |
 |                                                                             |
 |-----------------------------------------------------------------------------|
 |                                                                             |
 |      CP Time          (sec) =          2.672          Time   =  18:33:58    |
 |      Elapsed Time (sec) =          2.000       Date   =  10/18/2023     |
 |                                                                             |
 *-----------------------------------------------------------------------------*
```

9.2 MATLAB Coding for Sensor 1 and 2 Data Analysis

```
clear; clc; close all

%% Sensor 1

% Define the voltage values for Sensor 2
voltage_values_sensor1 = [0.239258
0.244141
0.239258
0.239258
0.239258
0.239258
0.239258
```

```
0.239258
0.239258
0.244141
0.244141
0.239258
0.234375
0.234375
0.239258
0.239258
0.244141
0.239258
0.239258
0.239258
0.239258
0.239258
0.234375
0.239258
0.239258
0.239258
0.234375
0.239258
0.239258
0.239258
0.239258
0.239258
0.239258
0.239258
0.239258
0.239258
0.239258
0.244141
0.239258
0.234375
0.239258
0.244141
0.175781
0.249023
0.834961
2.026367
-0.004883
1.508789
1.030274
0.981445
-0.004883
0.419922
1.416016
0.50293
-0.004883
0.869141
1.416016
-0.004883
0.59082
0.756836
1.538086
-0.004883
1.767578
0.463867
1.665039
-0.004883
```

```
1.523438
0.737305
1.479492
-0.004883
0.791016
1.196289
1.020508
0
0.97168
1.298828
0.351563
0.117188
0.717774
1.333008
0
0.805664
0.742188
1.508789
-0.004883
1.796875
0.488281
1.63086
-0.009766
1.552735
0.776367
1.464844
-0.004883
0.654297
1.235352
0.952149
0
0.673828
1.28418
0.209961
0.239258
0.74707
1.303711
-0.004883
1.030274
0.688477
1.547852
-0.004883
1.743164
0.483398
1.625977
-0.004883
1.47461
0.849609
1.479492
-0.009766
0.493164
1.235352
0.888672
-0.004883
0.649414
1.264649
0.239258
0.200195
0.737305
```

```
1.274414
-0.004883
0.97168
0.732422
1.464844
-0.009766
1.767578
0.498047
1.5625
0
1.582031
0.74707
1.59668
-0.004883
0.854492
1.181641
1.21582
-0.009766
0.644531
1.259766
0.483398
-0.004883
0.791016
1.210938
-0.009766
0.3125
0.830078
1.362305
-0.004883
1.665039
0.424805
1.508789
-0.009766
1.577149
0.585938
1.708985
-0.004883
1.293945
1.05957
1.420899
0
0.375977
1.289063
0.717774
-0.004883
0.615234
1.235352
0.03418
0.234375
0.942383
1.333008
0.004883
1.533203
0.615234
1.538086
0
1.523438
0.46875
1.552735
```

```
-0.004883
1.308594
0.620117
1.362305
-0.004883
0.068359
0.834961
0.610352
-0.004883
0.258789
0.737305
-0.004883
];

% Define minimum and maximum pressure for Sensor 2
min_voltage_sensor1 = 0.239258;  % Voltage at 0 psi
max_voltage_sensor1 = 4.5;      % Maximum voltage at 10 psi
max_pressure_sensor1 = 10;     % Maximum pressure

% Calculate voltage change per psi for Sensor 2
voltage_change_per_psi_sensor1 = (max_voltage_sensor1 - min_voltage_sensor1) / max_pressure_sensor1;

% Convert voltage values to pressure values for Sensor 2
pressure_values_sensor1 = (voltage_values_sensor1 - min_voltage_sensor1) / voltage_change_per_psi_sensor1;

% Display the pressure values for Sensor 2
disp('Pressure values for Sensor 1 (psi):');
disp(pressure_values_sensor1);


%% Sensor 2

% Define the voltage values for Sensor 1
voltage_values_sensor2 = [0.239258
0.239258
0.244141
0.239258
0.239258
0.244141
0.239258
0.239258
0.239258
0.239258
0.244141
0.239258
0.244141
0.239258
0.244141
0.244141
0.244141
0.234375
0.244141
0.244141
0.253906
0.219727
0.239258
0.776367
```

```
0.888672
-0.009766
1.21582
0.888672
0.458984
-0.004883
0.805664
0.942383
0.19043
-0.004883
0.283203
0.805664
-0.009766
-0.009766
0.732422
0.820313
-0.004883
0.410156
0.78125
0.922852
-0.004883
1.235352
0.317383
0.957031
0
1.171875
0.341797
0.795899
-0.004883
1.259766
0.795899
0.576172
-0.009766
1.020508
0.9375
0.307617
-0.004883
0.400391
0.81543
-0.004883
-0.004883
0.454102
0.756836
0
0.063477
0.874024
0.874024
-0.004883
0.952149
0.517578
0.986328
0
1.245117
0.268555
0.883789
-0.004883
1.181641
0.605469
0.683594
```

```
-0.009766
1.259766
0.913086
0.478516
-0.004883
0.683594
0.917969
0.258789
-0.004883
0.336914
0.795899
-0.004883
-0.004883
0.3125
0.756836
-0.009766
-0.009766
0.805664
0.791016
-0.004883
0.615234
0.834961
0.908203
-0.009766
1.240235
0.366211
0.97168
-0.004883
1.196289
0.273438
0.859375
-0.004883
1.171875
0.429688
0.722656
-0.009766
1.303711
0.830078
0.571289
0
0.883789
0.957031
0.34668
-0.009766
0.439453
0.854492
0.112305
-0.004883
0.249023
0.766602
-0.004883
-0.009766
0.644531
0.751953
-0.004883
0.297852
0.830078
0.888672
0
```

```
1.166992
0.566406
1.005859
0
1.240235
0.283203
0.913086
-0.004883
1.230469
0.541992
0.678711
-0.004883
1.166992
0.932617
0.507813
-0.004883
0.625
0.9375
0.219727
-0.004883
0.268555
0.810547
-0.004883
-0.004883
0.151367
0.74707
-0.004883
-0.004883
0.751953
0.771484
-0.004883
0.668945
0.844727
0.908203
-0.009766
1.293945
0.556641
0.991211
-0.009766
1.206055
0.327148
0.917969
-0.004883
1.171875
0.415039
0.791016
0
1.289063
0.742188
0.610352
-0.009766
0.844727
0.97168
0.419922
-0.009766
0.424805
0.922852
0.170898
-0.004883
```

```
0.214844
0.795899
-0.004883
-0.009766
0.136719
0.737305
-0.004883
0.048828
0.737305
0.78125
-0.009766
0.78125
0.820313
0.913086
-0.009766
1.31836
0.566406
1.005859
-0.004883
1.176758
0.341797
0.913086
-0.004883
1.210938
0.43457
0.756836
-0.004883
1.28418
0.722656
0.634766
-0.009766
0.844727
0.961914
0.46875
0
0.483398
0.932617
0.185547
-0.004883
0.263672
0.830078
-0.004883
-0.004883
0.112305
0.751953
-0.004883
-0.004883
0.507813
0.742188
-0.004883
0.595703
0.820313
0.898438
-0.004883
1.308594
0.634766
1.020508
-0.004883
1.162109
```

```
0.361328
0.932617
-0.009766
1.259766
0.43457
0.800781
0
1.279297
0.703125
0.649414
-0.004883
0.859375
0.9375
0.532227
-0.009766
0.473633
0.947266
0.175781
-0.009766
0.249023
0.825195
-0.004883
-0.004883
0.039063
0.727539
-0.014648
0.03418
0.668945
0.742188
-0.004883
0.74707
0.756836
0.888672
-0.009766
1.293945
0.795899
0.986328
0
1.186524
0.498047
0.50293
];

% Define minimum and maximum pressure for Sensor 1
min_voltage_sensor2 = 0.239258;  % Voltage at 0 psi
max_voltage_sensor2 = 4.5;       % Maximum voltage at 300 psi
max_pressure_sensor2 = 10;      % Maximum pressure

% Calculate voltage change per psi for Sensor 1
voltage_change_per_psi_sensor2 = (max_voltage_sensor2 - min_voltage_sensor2) /
    max_pressure_sensor2;

% Convert voltage values to pressure values for Sensor 1
pressure_values_sensor2 = (voltage_values_sensor2 - min_voltage_sensor2) /
    voltage_change_per_psi_sensor2;

% Display the pressure values for Sensor 1
disp('Pressure values for Sensor 2 (psi):');
disp(pressure_values_sensor2)
```

```

%% Graphing sensor 1

% Define time values
timesensor1 = 0:0.1:19.5;

figure

% Plot pressure vs time
plot(timesensor1, pressure_values_sensor1);
xlabel('Time (sec)');
ylabel('Pressure (psi)');
title('Pressure vs Time for Sensor 1');
grid on;

% Save the plot as a PNG file
saveas(gcf, 'pressure_vs_time_sensor1.png');

%% Graphing sensor 2

% Define time values
timesensor2 = 0:0.1:30;

figure

% Plot pressure vs time
plot(timesensor2, pressure_values_sensor2);
xlabel('Time (sec)');
ylabel('Pressure (psi)');
title('Pressure vs Time for Sensor 2');
grid on;

% Save the plot as a PNG file
saveas(gcf, 'pressure_vs_time_sensor2.png');


%% Calculations Sensor 1 with dampener

% Define the voltage values for Sensor 1 with dampener
voltage_values_sensor1_dampener = [0.239258
0.239258
0.244141
0.239258
0.239258
0.244141
0.239258
    0.869141
    0.312500
    0.507813
    0.375977
    0.991211
    0.292969
    0.571289
    0.766602
    0.722656
    0.209961
    1.538086
    0.883789
    0.322266
```

```
0.415039
0.346680
0.908203
0.717774
0.541992
0.820313
0.678711
0.263672
1.069336
0.849609
0.332031
0.400391
0.439453
0.927734
0.795899
0.502930
0.825195
0.610352
0.405273
0.913086
0.893555
0.327148
0.415039
0.419922
0.878906
1.162109
0.483398
0.830078
0.556641
0.541992
0.966797
0.966797
0.336914
0.454102
0.419922
0.820313
1.303711
0.483398
0.839844
0.507813
0.678711
0.678711
0.971680
0.336914
0.522461
0.551758
0.815430
0.854492
0.483398
0.869141
0.439453
0.732422
0.390625
1.000977
0.097656
0.561523
0.673828
0.825195
0.527344
```

```
0.561523
0.839844
0.351563
0.644531
0.419922
1.040039
-0.004883
0.590820
0.688477
0.791016
0.146484
1.210938
0.864258
0.317383
0.546875
0.380859
0.991211
-0.009766
0.576172
0.737305
0.742188
0.214844
1.567383
0.888672
0.307617
0.458984
0.380859
0.957031
0.795899
0.561523
0.849609
0.742188
0.263672
0.654297
0.380859
0.014648
0.009766
0.322266
0.620117
0.483398
0.776367
0.473633
0.522461
0.795899
0.302734
0.288086
0.371094
0.878906
0.991211
0.502930
0.786133
0.522461
0.771484
0.419922
0.903320
0.004883
0.444336
0.664063
0.693359
```

```
0.156250
1.303711
0.825195
0.302734
0.600586
0.419922
0.766602
0.605469
0.556641
0.815430
0.336914
0.312500
0.410156
0.917969
0.908203
0.449219
0.781250
0.522461
0.771484
0.751953
0.942383
0.263672
0.498047
0.654297
0.732422
0.014648
1.596680
0.854492
0.307617
0.458984
0.415039
0.795899
1.220703
0.571289
0.800781
0.410156
0.498047
0.429688
0.947266
0.000000
0.380859
0.776367
0.625000
0.644531
0.761719
0.913086
0.317383
0.590820
0.644531
0.791016
0.034180
1.411133
0.834961
0.307617
0.424805
0.419922
0.786133
1.386719
0.581055
```

```
0.805664
0.400391
0.468750
0.390625
0.996094
-0.004883
0.385742
0.761719
0.654297
0.556641
0.766602
0.883789
0.327148
0.590820
0.625000
0.776367
0.151367
0.717774
0.830078
0.288086
0.375977
0.419922
0.839844
1.372070
0.566406
0.791016
0.439453
0.576172
0.375977
0.952149
0.000000
0.385742
0.747070
0.625000
0.571289
0.727539
0.913086
0.322266
0.595703
0.639649
0.771484
0.058594
0.722656
0.839844
0.292969
0.375977
0.429688
0.815430
1.352539
0.576172
0.795899
0.424805
0.478516
0.385742
0.961914
-0.004883
0.380859
0.766602
0.649414
```

```
0.561523
0.781250
0.908203
0.317383
0.605469
0.615234
0.810547
0.102539
0.849609
0.839844
0.283203
0.380859
0.390625
0.810547
1.362305
0.571289
0.795899
0.439453
0.556641
0.380859
0.937500
0.000000
0.375977
0.737305
0.659180
0.449219
0.708008
0.864258
0.327148
0.610352
0.571289
0.771484
0.156250
0.532227
0.820313
0.263672
0.371094
0.395508
1.396485
1.147461
0.566406
0.766602
0.439453
0.649414
0.312500
0.986328
0.000000
0.375977
0.703125
0.698242
0.400391
0.722656
0.834961
0.317383
0.629883
0.512695
0.766602
0.419922
0.517578
```

```
0.800781
0.273438
0.288086
0.356445
0.844727
0.932617
0.522461
0.791016
0.488281
0.703125
0.429688
0.908203
0.000000
0.419922
0.673828
0.668945
0.249023
0.883789
0.849609
0.312500
0.620117
0.429688
0.786133
0.571289
0.532227
0.800781
0.322266
0.297852
0.390625
0.883789
0.961914
0.478516
0.791016
0.527344
0.771484
0.483398
0.976563
0.156250
0.424805
0.644531
0.708008
0.092773
1.347656
0.854492
0.302734
0.581055
0.444336
0.761719
0.532227
0.546875
0.810547
0.297852
0.288086
0.380859
0.830078
0.981445
0.502930
0.786133
0.498047
```

```
    0.722656
    0.439453
    0.913086
];

% Define minimum and maximum pressure for Sensor 1
min_voltage_sensor1_dampener = 0.239258;  % Voltage at 0 psi
max_voltage_sensor1_dampener = 4.5;      % Maximum voltage at 300 psi
max_pressure_sensor1_dampener = 10;     % Maximum pressure

% Calculate voltage change per psi for Sensor 1
voltage_change_per_psi_sensor1_dampener = (max_voltage_sensor1_dampener -
   min_voltage_sensor1_dampener) / max_pressure_sensor1_dampener;

% Convert voltage values to pressure values for Sensor 1
pressure_values_sensor1_dampener = (voltage_values_sensor1_dampener -
   min_voltage_sensor1_dampener) / voltage_change_per_psi_sensor1_dampener;

% Display the pressure values for Sensor 1
disp('Pressure values for Sensor 1 with Dampener (psi):');
disp(pressure_values_sensor1_dampener)

%% Graphing sensor 1 with Dampener

% Define time values
timesensor1Dampener = 0:0.1:37.6;

figure

% Plot pressure vs time
plot(timesensor1Dampener, pressure_values_sensor1_dampener);
xlabel('Time (sec)');
ylabel('Pressure (psi)');
title('Pressure vs Time for Sensor 1 with Dampener');
grid on;

% Save the plot as a PNG file
saveas(gcf, 'pressure_vs_time_sensor1_dampener.png');


%% Calculations Sensor 2 with dampener

% Define the voltage values for Sensor 2 with dampener
voltage_values_sensor2_dampener = [0.239258
0.239258
0.244141
0.239258
0.239258
0.244141
0.239258
    0.302734
    0.336914
    0.541992
    0.488281
    0.390625
    0.488281
    0.434570
    0.375977
    0.615234
```

```
0.483398
0.454102
0.307617
0.551758
0.483398
0.683594
0.395508
0.522461
0.439453
0.410156
0.537109
0.527344
0.439453
0.327148
0.576172
0.473633
0.361328
0.551758
0.434570
0.517578
0.454102
0.556641
0.434570
0.371094
0.522461
0.498047
0.751953
0.385742
0.541992
0.424805
0.434570
0.566406
0.439453
0.517578
0.473633
0.498047
0.795899
0.424805
0.512695
0.434570
0.683594
0.405273
0.546875
0.434570
0.566406
0.468750
0.512695
0.463867
0.493164
0.429688
0.385742
0.556641
0.424805
0.585938
0.454102
0.493164
0.522461
0.488281
0.429688
```

```
0.317383
0.541992
0.390625
0.620117
0.439453
0.483398
0.346680
0.546875
0.478516
0.405273
0.463867
0.400391
0.532227
0.449219
0.493164
0.498047
0.468750
0.419922
0.429688
0.458984
0.478516
0.405273
0.463867
0.512695
0.478516
0.468750
0.458984
0.366211
0.541992
0.551758
0.429688
0.419922
0.483398
0.498047
0.639649
0.483398
0.468750
0.449219
0.366211
0.522461
0.576172
0.434570
0.410156
0.483398
0.488281
0.478516
0.444336
0.434570
0.380859
0.507813
0.551758
0.419922
0.395508
0.488281
0.478516
0.654297
0.468750
0.454102
0.439453
```

```
0.380859
0.498047
0.556641
0.439453
0.390625
0.507813
0.483398
0.654297
0.478516
0.458984
0.424805
0.444336
0.458984
0.566406
0.439453
0.395508
0.517578
0.498047
0.659180
0.483398
0.468750
0.415039
0.532227
0.415039
0.551758
0.419922
0.405273
0.566406
0.483398
0.590820
0.478516
0.473633
0.410156
0.561523
0.385742
0.566406
0.375977
0.415039
0.566406
0.507813
0.581055
0.483398
0.488281
0.405273
0.585938
0.356445
0.546875
0.341797
0.415039
0.551758
0.493164
0.517578
0.498047
0.493164
0.390625
0.585938
0.498047
0.483398
0.273438
```

```
0.600586
0.556641
0.419922
0.458984
0.419922
0.502930
0.541992
0.483398
0.463867
0.444336
0.332031
0.546875
0.585938
0.458984
0.439453
0.546875
0.537109
0.566406
0.454102
0.278320
0.302734
0.454102
0.561523
0.434570
0.439453
0.498047
0.493164
0.644531
0.473633
0.458984
0.458984
0.371094
0.507813
0.551758
0.419922
0.449219
0.454102
0.498047
0.581055
0.463867
0.463867
0.468750
0.341797
0.551758
0.546875
0.415039
0.473633
0.419922
0.507813
0.541992
0.454102
0.483398
0.468750
0.332031
0.556641
0.546875
0.419922
0.473633
0.415039
```

```
    0.488281
    0.551758
    0.449219
    0.488281
    0.473633
    0.312500
    0.551758
    0.537109
    0.410156
    0.473633
    0.405273
    0.498047
    0.488281
    0.439453
    0.483398
    0.468750
    0.312500
    0.561523
    0.541992
    0.410156
    0.488281
    0.415039
    0.522461
    0.502930
    0.444336
    0.493164
    0.488281
    0.317383
    0.561523
    0.532227
    0.395508
    0.502930
    0.375977
    0.532227
    0.390625
    0.439453
    0.541992
    0.517578
    0.400391
    0.649414
    0.561523
    0.322266
    0.527344
];

% Define minimum and maximum pressure for Sensor 1
min_voltage_sensor2_dampener = 0.239258;  % Voltage at 0 psi
max_voltage_sensor2_dampener = 4.5;      % Maximum voltage at 300 psi
max_pressure_sensor2_dampener = 10;     % Maximum pressure

% Calculate voltage change per psi for Sensor 1
voltage_change_per_psi_sensor2_dampener = (max_voltage_sensor2_dampener -
   min_voltage_sensor2_dampener) / max_pressure_sensor2_dampener;

% Convert voltage values to pressure values for Sensor 1
pressure_values_sensor2_dampener = (voltage_values_sensor2_dampener -
   min_voltage_sensor2_dampener) / voltage_change_per_psi_sensor2_dampener;

% Display the pressure values for Sensor 1
```

```
disp('Pressure values for Sensor 2 with Dampener (psi):');
disp(pressure_values_sensor2_dampener)

%% Graphing sensor 1 with Dampener

% Define time values
timesensor2Dampener = 0:0.1:29.4;

figure

% Plot pressure vs time
plot(timesensor2Dampener, pressure_values_sensor2_dampener);
ylim([0 3.5]);
xlabel('Time (sec)');
ylabel('Pressure (psi)');
title('Pressure vs Time for Sensor 2 with Dampener');
grid on;

% Save the plot as a PNG file
saveas(gcf, 'pressure_vs_time_sensor2_dampener.png');
```

9.3 Values from Sensor 1 and 2 baseline Data

Table 2: Pressure Sensor Readings

Pressure sensor 1			**Pressure sensor 2**		
Seconds	**Voltage (V)**	**psi**	**Time (sec)**	**Voltage (V)**	**Psi**
0.00	0.4979	0.00	0	0.494	0.00
0.27	0.5035	0.42	0.87	0.4948	0.06
0.63	0.5083	0.78	1.63	0.4966	0.19
1.20	0.5126	1.10	1.97	0.4991	0.38
1.67	0.5039	0.45	2.43	0.4962	0.16
2.20	0.5090	0.83	2.93	0.4976	0.27
2.73	0.5137	1.18	3.47	0.4994	0.40
3.27	0.5047	0.51	3.93	0.4965	0.19
3.70	0.5092	0.85	4.43	0.4983	0.32
4.27	0.5138	1.19	4.97	0.5000	0.45
4.73	0.5058	0.59	5.43	0.4960	0.15
5.20	0.5095	0.87	5.93	0.4982	0.31
5.73	0.5143	1.23	6.47	0.5006	0.49
6.20	0.5061	0.61	6.97	0.4943	0.02
7.00	0.5098	0.89	7.63	0.4964	0.18
7.23	0.5145	1.24	7.97	0.4999	0.44
7.67	0.5051	0.54	8.50	0.4959	0.14
8.20	0.5090	0.83	8.97	0.4970	0.22
8.73	0.5137	1.18	9.50	0.5002	0.46
8.33	0.5050	0.53	9.97	0.4979	0.29
9.77	0.5080	0.76	10.50	0.4973	0.25
10.30	0.5130	1.13	11.00	0.4987	0.35
10.70	0.5036	0.43	11.63	0.4986	0.34
11.13	0.5077	0.73	12.03	0.4963	0.17
11.70	0.5118	1.04	12.47	0.4994	0.40
12.40	0.5043	0.48	12.93	0.4998	0.43
12.63	0.5069	0.67	13.47	0.4981	0.31
13.20	0.5110	0.98	13.93	0.4999	0.44
13.63	0.5097	0.88	14.50	0.5007	0.50
14.13	0.5075	0.72	15.00	0.4998	0.43
14.70	0.5111	0.99	15.50	0.5009	0.52
15.13	0.5099	0.90	15.97	0.5038	0.73
15.63	0.5077	0.73	16.50	0.5003	0.47
16.13	0.5092	0.85	17.00	0.5012	0.54
16.70	0.5118	1.04	17.57	0.5011	0.53
17.20	0.5052	0.55	18.03	0.4990	0.37
17.70	0.5100	0.91	18.57	0.5009	0.52
18.13	0.5134	1.16	19.00	0.5027	0.65
18.70	0.5050	0.53	19.53	0.4983	0.32
19.13	0.5089	0.82	19.97	0.4980	0.30
19.67	0.5120	1.06	20.60	0.5000	0.45
20.17	0.5050	0.53	21.00	0.4968	0.21
20.73	0.5068	0.67	21.50	0.5005	0.49
21.17	0.5124	1.09	21.97	0.5037	0.73
21.70	0.5029	0.37	22.50	0.4971	0.23
22.20	0.5071	0.69	22.93	0.4992	0.39
22.70	0.5102	0.92	23.50	0.5033	0.70