MAE 4344 Senior Design

MAE 3723 Lab Project-Final Report

Group: Andy Freberg, Collin Jefferson, Mac McClure, Jordan McKee, Jason Proffitt

Contents

1 Problem Statement

MAE 3723 Systems I has just added a Lab Section where students can have a hands on experience with concepts of system design. The objective of our project is to develop a set of physical systems that can be used in the MAE 3723 Lab Section. The physical systems need to demonstrate important concepts from MAE 3723 Theory Section and have the ability to be concealed from view if desired. Instructors and Lab personnel will also need to be able to reproduce the physical systems.

2 Deliverables

The following is a list of the specific deliverables that were promised to our sponsor:

- Physical Systems
    - Electrical System
    - Mechanical System
    - Fluid/Thermal System
    - Two additional systems of any type
    - Systems must be of varying degrees of complexity
    - Black boxes should be constructed so that systems can be concealed
- MATLAB models of each system
- CAD models of custom parts
- Construction & Design documentation
    - Bill of Materials
    - Procedures on how to build custom parts
    - Procedures on how to assemble physical model
- Operation and Safety documentation
- Optional Deliverables
    - Additional physical systems
    - Suggested lab lessons for systems

3 Final Design

The following is a general description of the final design. The final design consists of five systems that we physically constructed with accompanying MATLAB models. Included with them is a "Construction Document" and "Operations and Safety Document" that detail how to recreate and operate the systems.

3.1 RC & RLC Electrical System

The Electrical System is composed of an RC and an RLC circuit built on breadboards. These circuits demonstrate a first and second order electrical response, respectively. Both circuits have the ability to be hidden in boxes so that a student could be given the option to solve for the component values with given data.

Figure 1: Electrical System-RC Circuit

Figure 2: Electrical System: RLC Circuit

3.2 Fluid/Thermal System - Blowdown Process

The Fluid/Thermal System is done with a Blowdown Process that is composed of a small pressure vessel fitted with a needle valve, pressure transducer, and thermocouple. By doing the blowdown process through the needle valve you can observe a choked flow behavior. Doing the blowdown process through the fill value through a long segment of tubing you can observe laminar flow. Then with the thermocouple that is suspended in the center of the tank you can observe the temperature response for either flow type.

Figure 3: Fluid/Thermal System-Blowdown Tank

3.3 Mechanical System

The Mechanical System is composed of two carts on a track connected to springs and dampers. You have the ability to show a second order response when using only one cart connected to the spring and damper. If you use both carts then there is a fourth order system response. Due to the dampers being returned to sender we were unable to finish constructing this system. Below is a figure that illustrates the mechanical system and a picture of the physical system so far.

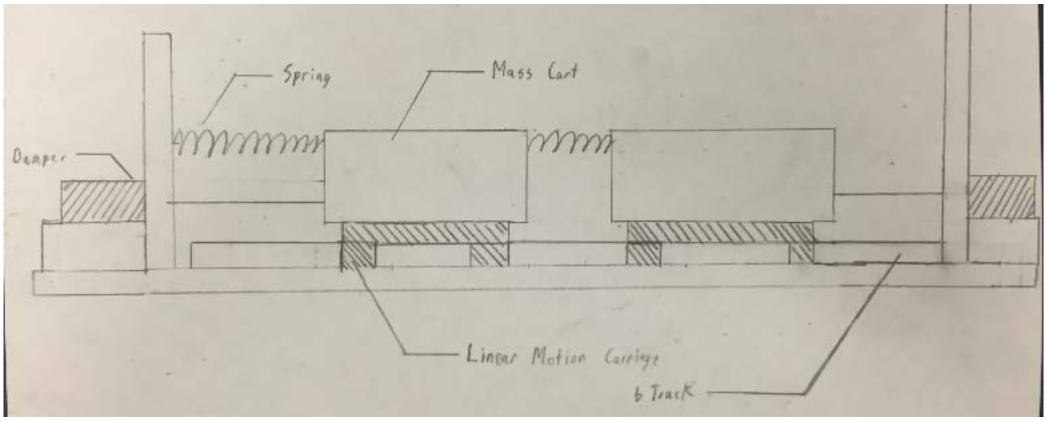


Figure 4: Design for the Mechanical System

Figure 5: Mechanical System So Far

3.4 Electro-Mechanical Speaker System

The Electro-Mechanical system is composed of a speaker, whose displacement is measured by an optical sensor. The system is third order where an electrical input is transferred to a mechanical object.

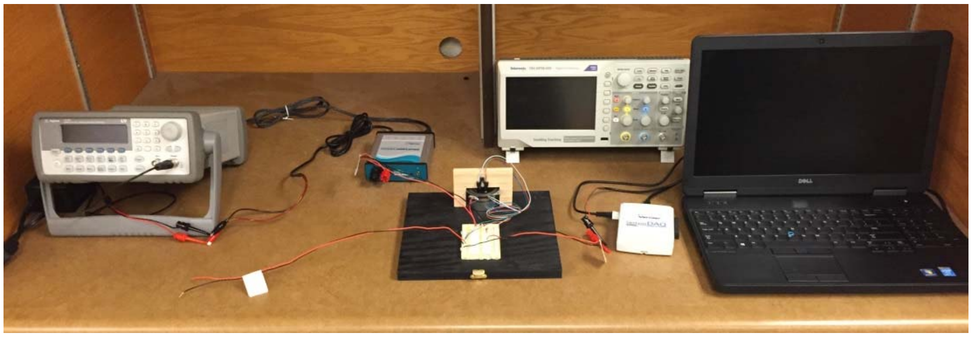


Figure 6: Electro-Mechanical System

3.5 Computer Generated System

The computer generated system consists of an Arduino that has a Runga-Kutta solver run for a given equation. The Arduino can be reprogrammed with different equations for the Runga-Kutta to solve, so you have the ability to simulate any of the other system responses. This makes it so that when concealed in the box a user may not know which system is a real system or which is a simulated one.

Figure 7: Computer Generated System

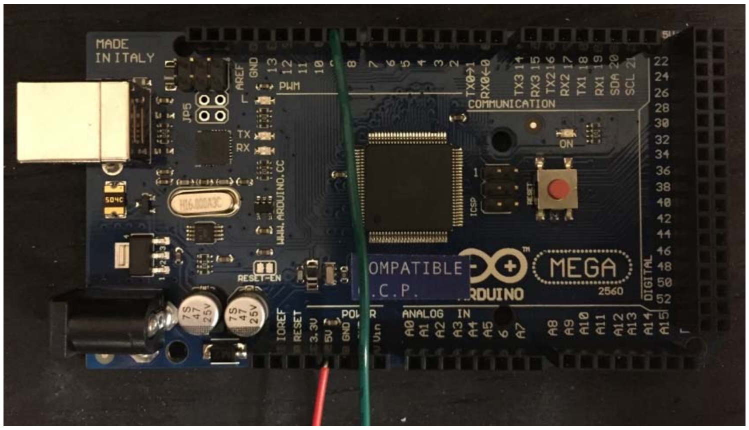


Figure 8: Close up of the Arduino Mega 2560

3.6 Cantilever Beam System

One of our optional systems is a simple cantilever beam that we designed for the Spring 2015 lab session we administered. The setup allows a user to find the natural frequency of a beam.

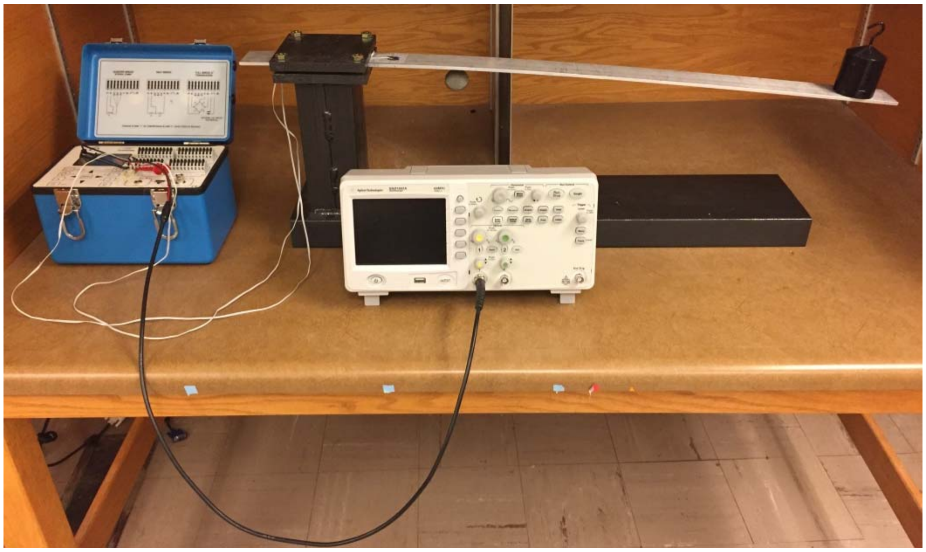


Figure 9:Cantilever Beam System

3.7 Speaker-Spring System

The other optional system for the Spring 2015 lab session was a speaker that is upside down that allows springs to be hung from it. The springs have a mass suspended from them and the speaker is hooked to a function generator. The natural frequency of the springs can be found by tuning the function generator.

Figure 10: Speaker-Spring System

4 Detailed Description of Work Done

4.1 Searching Codes, Safety & Information

This section details the codes and safety related to our project.

4.1.1 Work Done

Our group researched the ASME Pressure Vessel Codes and made sure that we based our designs around its safety criteria. The URL for the codes is listed below.

https://www.asme.org/shop/standards/new-releases/boiler-pressure-vessel-code/pressure-vessels

4.1.2 Reason Done

The fluid/thermal system was to be a blowdown process which requires a pressurized vessel. The major concern is safety when it comes to pressurizing tanks so we needed to be sure that any designs we came up with would be safe. To determine what is "safe" we researched the ASME Pressure Vessel Codes to give use a criteria that must be met by each design we come up with.

4.1.3 Results

The results of our research showed that in order for us to guarantee the safety of our design we needed to use professionally made SAE rated pressure vessels and cannot physically alter them. Physically altering a pressure vessel requires recertification which will cost us more time than is allowed for our project. All our fittings need to be rated for the same or more pressure than the tank as well.

4.1.4 Decisions Made

Our group decided to buy a new professionally made pressure vessel and buy all rated fittings from McMaster-Carr. We also wanted any designs for the fluid/thermal system to incorporate a pop safety valve that is rated for the maximum operating pressure of the tank to ensure it cannot be over filled.

4.2 Creation of Alternative Designs

This section details the designs that were considered for each system, what we learned from the alternative designs, and what decisions we made based on the designs.

The proposed designs for each system evolved over multiple meetings with the sponsor and discussions with advisors. In the following sections the progression of each system design and selection of materials is discussed in detail. The process used for decision making consisted of first creating multiple system design with suggested materials. Then a meeting with the sponsor and advisors was held to present the possible design and researched materials where discussion of the pros and cons lead to a change in design and more guided direction of research. The objective of this back and forth is to ensure that the proposed design and materials is satisfactory with the sponsor and the goals of the project.

4.2.1 Electrical System

4.2.1.1 Work Done

For the electrical system the alternative designs were pretty limited, the sponsor wanted a RLC and RC circuit. We researched the advantages and disadvantages of permanent versus breadboard wiring. We also researched resistor, capacitor, and inductor values available on the market. Preliminary and intermediate sketches of our electrical design are shown in Appendix 9.2 and 9.3.

4.2.1.2 Reason Done

We wanted to ensure the interchangeability of components, such that students or instructors could modify the circuits as needed, but we wanted to make sure that the circuits would not be damaged or rearranged by accident.

4.2.1.3 Results

Our team found that resistors were cheap and were widely ranged, while the choice of inductors was very limited as to affordability and inductance value. Capacitors were, for the most part, were suggested to be kept in the micro-Farad range in order to keep voltage low and for safety reasons. For a base, we found that circuit boards would be fixed, but would not have room for user error. Breadboards, on the other hand, could be customized and altered as needed, but left room for user error.

4.2.1.3 Decisions Made

We decided that our resistors would be the primary interchangeable piece, which would allow for the least user error when adjusting the circuit. Capacitors could also be interchangeable, and they would be kept in the micro-Farad range. For inductors, we determined we would need to find available and affordable models and test their values. Finally, our sponsor agreed that using a breadboard was the most desirable mounting option since it allowed for customization of circuits.

4.2.2 Fluid/Thermal System

4.2.2.1 Work Done

The sponsor expressed preference to the design of a blowdown process be used for the fluid and thermal system. For the fluid/thermal system, we began by researching air tank blowdown processes, including choked flow, laminar flow, and thermal properties. Additionally, we researched isothermal versus adiabatic responses, and looked for thermocouples that could measure adiabatic responses. We also looked for safety requirements for our tank and its requisite fittings. As we worked through the math for the model, Dr. Elbing and Dr. Ghajar were most helpful in reviewing our work and discussing alternate approaches. The preliminary and intermediate designs are shown in Appendix 9.2 and 9.3.

4.2.2.2 Reason Done

Our biggest research driver was finding the proper model for the blowdown process. Many assumptions had to be made in order to simplify the model, and it was these various assumptions that were the topic of much discussion and research. Furthermore, the process would require a sensitive enough thermocouple in order to measure the thermal response, but this thermal couple had to physically compatible with out tank fittings. Finally, this system held our biggest concern for safety, so we needed to determine a safe way to fill the tank and release the air.

4.2.2.3 Results

We were able to successfully model a quick blowdown as an adiabatic choked flow of an ideal gas, and a slow blowdown as an isothermal laminar flow of an ideal gas. We also developed a map of the requisite fittings for the tank. Finally, a thermocouple of a thin probe type, instead of a surface mount, was ideal for proper response time and accurate measurement of air temperature response only.

The idea is that when the blowdown process is executed slowly it can be considered isothermal and give a first order fluid system response. During research on needle valves it was found that in the process of conducting an experiment the rate at which the needle valve opens could affect the response of the process. To correct for this a quick release valve was added between the tank and needle valve so that a specific setting can be applied to the needle valve for an experiment prior to evacuating the system.

The decision to go with a probe type thermocouple was due to the fact that surface mount thermocouples complicate the response due to the heat transfer of the tank. Also the temperature change of the tank may not be drastic enough for surface mount to read effectively due to the lower pressure being used. The issue with probe type thermocouples is the sample rate is generally slow (around 3 seconds). The group has researched thermocouples with faster sample rates to correct for this.

4.2.2.4 Decisions Made

Our sponsor specified that he desired an air blowdown process, and approved our mathematical models. Additionally, we found that a Type T 4-element thermocouple was the best instrument to measure the thermal process, but we would need a special compression fitting in order to insert the thermocouple into the tank. For the other needed fittings, we determined that a needle valve, quick release valve, pressure gage, and pop safety valve were required, in addition to the pressure transducer.

4.2.3 Mechanical System

4.2.3.1 Work Done

While designing the Mechanical system, we considered multiple configurations, including vertical and horizontal orientation, as well as both rotational and translational motion. We also investigated 3D printing in order to generate light components and various ways to reduce friction in the system. Additionally, the team studied various forms of damping mechanisms, and spoke with Airpot sales representatives about their stock of dampers. We had looked into both vertical and horizontal setups, sketches of our designs are shown in Appendix 9.2 and 9.3.

4.2.3.2 Reason Done

Our two main research objectives was to see how gravity and friction affected system parts. Furthermore, a major design goal was to determine what type of damper to use, and whether or not we could by one.

4.2.3.3 Results

Our research yielded evidence that the most friction would be non-linear. Rotational motion was thought to be difficult to model and measure and vertical set-ups would require initial conditions due to gravitational effects. Vertical orientation would also limit the springs and dampers more.

4.2.3.4 Decisions Made

Our sponsor requested that translational motion be done instead of rotational motion. Horizontal motion was also favored in order to maximize spring and damper motion. Finally, a professionally manufactured adjustable damper with minimal stiction was found, and 3D printing was selected as the way to generate light-weight components for the system.

4.2.4 Electro-Mechanical System

4.2.4.1 Work Done

In the beginning design stages of the Electro-Mechanical System, two types were discussed: a flywheel powered by an electrical motor and a speaker. A speaker was decided on and several different speaker models were researched and their specifications examined. Dr. Conner and various sales representatives were also consulted about possible measurement devices. The preliminary and intermediate designs are shown in Appendix 9.2 and 9.3 for the electro-mechanical system.

4.2.4.2 Reason Done

Our client requested that a speaker be used since it is a device students use every day. Furthermore, this system would yield a good model and have good measurement accuracy, and would be easily modeled in both the time and frequency domain. However, we knew that our measurement method would greatly affect the system, as would the size of the speaker.

4.2.4.3 Results

Eventually, an adequate model was found that measure voltage in and linear displacement out. For this model, a large speaker is desired for its large displacement, which would provide greater ease of measurement. However, larger speakers cost more than smaller ones. Additionally, there were many different problems associated with each kind of measurement device that we researched. Some were very accurate but very expensive, while others were not accurate enough or physically changed the system, and therefore the model. It was apparent that a balance between size, price, and accuracy would have to be struck.

4.2.4.4 Decisions Made

Our team decided that an optical sensor was the best measurement device for both accuracy and price. A smaller speaker was selected to use in the short run, with plans to use a large speaker in the future when a larger budget would be available. Noise was found in the measured response as well, but since this is a Systems class and not Measurements, we decided it was not critical to address this.

4.2.5 Computer Generated System

4.2.5.1 Work Done

The computer system was developed to be an ideal black box experiment: simply a CPU that could emulate any type of system desired. In order to simplify the modeling of the system, we used a model from one of our physical systems for the computer to simulate. The Runge-Kutta and Euler methods were researched to approximate the system response, as were analog and digital output methods. The Arduino and Raspberry Pi models of CPU's were considered as the operating platforms. The configuration is pretty simple and is listed in Appendix 9.2.

4.2.5.2 Reason Done

This experiment satisfied our client's desire for a neat experiment to compare with our other systems. Due to its versatility, it can be made to simulate a variety of systems and can also output in several ways.

4.2.5.3 Results

The model we chose hinged on its ability to fit comfortably within a black box. Both operating systems were mostly the same, with Arduino having the most resources available. Additionally, both would need minor wiring in order to work properly.

4.2.5.4 Decisions Made

We chose the Arduino Mega 2650 as our operating system, which will use a Runge-Kutta method to approximate a physical response. The output of the system will be analog and will utilize a low pass filter to make it readable by the DAQ.

4.2.6 Cantilever Beam System

4.2.6.1 Work Done

The Cantilever Beam System was set up primarily for the Spring 2015 demonstration lab. Research was conducted on natural frequency equations for a cantilever beam, and a simplified model created. Additionally, we tested both quarter and half Wheatstone bridge combinations in order to ensure proper output.

4.2.6.2 Reason Done

Our client desired a lab that demonstrated natural frequency, and if not overcomplicated, this lab was a simple way to meet that request. Strain was desired as an output in order to show the natural frequency, and initial trials of this lab set showed that the quarter bridge arrangement was easily saturated.

4.2.6.3 Results

We tested both a distributed mass and point-mass model of the beam, and found that by mathematically “moving” the beam’s mass to the end, the model of the system was greatly simplified. Furthermore, by having students add mass to the end of the beam, we were able to demonstrate that in this situation, the point-mass assumption was more valid. Finally, we were also able to avoid saturation by using a half bridge output.

4.2.6.4 Decisions Made

The final plan for the Cantilever Beam was to use the point mass assumption and a half bridge for the output, as per the results of our laboratory trials.

4.2.7 Speaker-Spring System

4.2.7.1 Work Done

The Speaker-Spring System was set up primarily for the Spring 2015 demonstration lab. Research was conducted on resonant frequency equations for mass-spring systems, and we tested multiple spring-mass combinations.

4.2.7.2 Reason Done

Our client desired a lab that demonstrated resonant frequency and this specialized lab speaker was already available. Effective modeling was needed for this experiment, but could be easily done. Moreover, students would have an optimal lab setup with very simple user interface. Our team also felt that this lab would be one of the most enjoyable.

4.2.7.3 Results

Students were able to use the given equations to calculate the resonant frequency of the system for each spring-mass combination. By adjusting the connected function generator, they would then physically observe the resonant frequency, and determine a percent difference. Additionally, our team found that the point-mass model is preferred for ease of modeling.

4.2.7.4 Decisions Made

We decided that this was a good simple system to make part of our line-up, and the students indicated in their feedback that they really enjoyed this lab. Furthermore, we determined that large masses relative to each spring were the best to ensure the accuracy of the point-mass assumption.

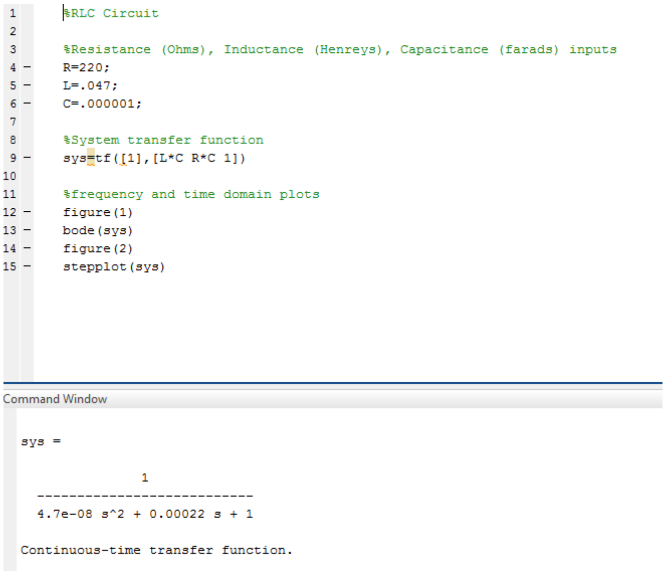
4.3 Calculations and Modeling

4.3.1 Work Done

Our group has created models for each of our systems in MATLAB. These models will simulate the time and/or frequency responses for a step input or sine input depending on which system is being used. For example, the model for the electro-mechanical system shows the time response to a sine input since this is appropriate for this system while the model for the electrical systems shows the time and frequency domain responses for a step input. We have also created a Solidworks model for the mechanical system. Finally, the choked flow pressure response for the blowdown tank was initially modeled in VBA and later moved into MATLAB as well.

By creating these models, our group was able to easily change system parameters and check how the response would act. For example, we extensively used our models for the electrical systems to help us determine what resistors, capacitors, and inductors we should buy to allow us to have a reasonable response time for the students to easily view. This same process was followed for each of our systems to assist us in buying correct parts.

We also researched limitations of each of our systems to help us model the systems correctly. When the physical system varied from the model, we conducted research and brainstormed on what could cause the differences in our model vs. experimental data. Once a solution was found, we corrected the model to match the physical experiment. Below is the RLC circuits MATLAB model which is similar to all the other MATLAB programs with the exception of the inputs. The full MATLAB scripts and graphs for the systems are shown in Appendix 9.4.



```
%RLC Circuit

%Resistance (Ohms), Inductance (Henreys), Capacitance (farads) inputs
R=220;
L=.047;
C=.000001;

%System transfer function
sys=tf([1],[L*C R*C 1])

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
stepplot(sys)
```

```
sys =

                 1
  ----------------------------
  4.7e-08 s^2 + 0.00022 s + 1

Continuous-time transfer function.
```

Figure 11: Example MATLAB Command Window RLC Circuit

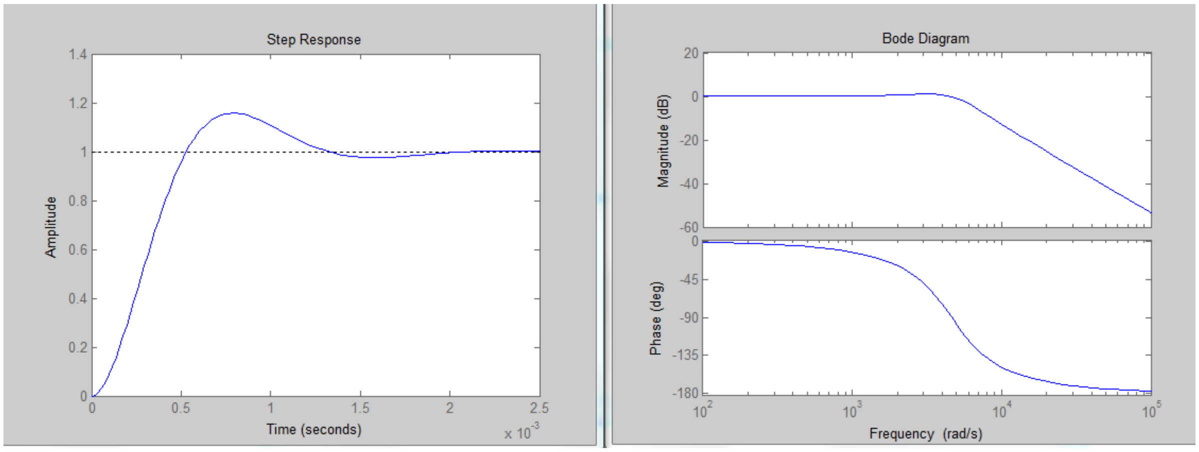


Figure 12: Example MATLAB Figures-Time and Frequency Domain RLC Circuit

4.3.2 Reason Done

The reason behind creating the models (besides the fact that it was stated in our deliverables) was to allow us to change system parameters and easily see how the response of the system “should” change. This is much easier and more effective than buying different parts to change the system. By doing this process, we were able to pick parts that we knew would work for that system and would give us the response we desired.

4.3.3 Results

The results from our research and work on the system modeling has led to a final product that allows students to have user friendly MATLAB models for each system to assist in conducting the future labs. These models accurately simulate the physical systems, and many lab questions can be asked and answered through the use of our models.

4.3.4 Decisions Made

We decided to create models that would accurately simulate the physical systems. Our models also allow for the system parameters to easily be changed for students to observe how the response can vary. Making an array that can be copied to Excel for the time input and amplitude output we also wanted to include so that the data can be easily compared to data from the physical systems.

4.4 CAD Modeling

4.4.1 Work Done

CAD Modeling was done solely for the Mechanical System and the black boxes. Drawings for the black boxes were created, as well as the Mechanical System components. An assembly for the full Mechanical System was also made, and a motion simulation created using that model.

4.4.2 Reason Done

CAD Models were created in order to have clear and accurate documentation on file so that the physical systems could be easily recreated. Additionally, the motion study was an excellent tool to test the response of our mechanical system.

4.4.3 Results

The models of the black boxes were used to dimension the boxes according to overall system sizes. Also, the mechanical system model was used to check coefficients for springs and dampers and preview the response of the system with those values. The full CAD model and its animation can be conducted on the Solidworks files in the project Dropbox.

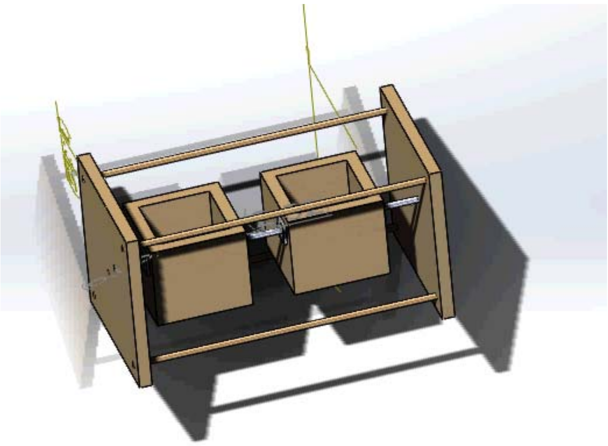


Figure 13: CAD simulation of the Mechanical System

4.4.4 Decisions Made

We determined that we would use the CAD files for the baskets of the mechanical system to 3D print the baskets, saving us time, money, and weight. Additionally, we found that concealment of the systems allowed for instructors to have students find components with given response, and that the box bases would give the systems good stability.

4.5 Experiments to Test Concepts

This section details the preliminary tests we did in VBA, MathCad, MATLAB, and with physical objects to experiment with how well our designs would function prior to creating them.

4.5.1 Work Done

Our group met with Dr. Elbing and Dr. Reid multiple times to debug and make sure that our choked flow assumptions and coefficients were behaving the way we wanted and expected in real life. The fluid/thermal blowdown and mechanical system models required the most debugging and testing to find an efficient way to code MATLAB so that it was user friendly and adjustable.

We ran multiple MATLAB simulations of our systems with varying coefficients to establish a range of values to shop for products. Once we picked out products we conducted multiple runs in MATLAB of coefficients of these products to find a good combination for price efficiency. For the mechanical system the group also used Solidworks to test coefficients.

When building our Labview and LoggerPro interfaces for the systems we tested our RC circuit to make sure that our interface was working correctly and that we could collect data and transport it to Excel in a user friendly way. Below is an image that shows one of the group members testing a system.

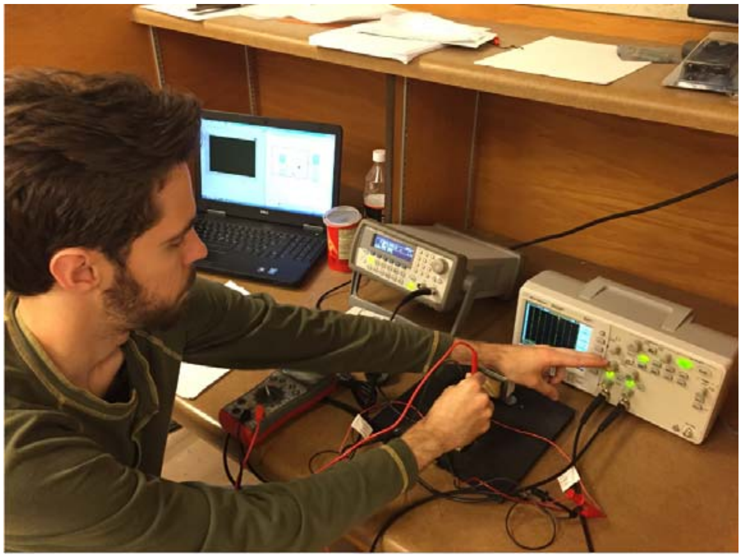


Figure 14: Team Member Testing Components of System

4.5.2 Reason Done

The thermal/fluid blowdown systems had to take into account many coefficients that were dependent on the products we chose. We were surprised on some of the results we were getting from or choked flow model and needed to consult professors to make sure everything was okay.

Our group tested multiple coefficients in MATLAB because we needed to know which ones would give us the response we wanted in real life, which was an under-damped response in second order systems and a long rise time in first order systems. When we found good ranges of values we then could find products matching these specifications.

After we found a range of products we ran MATLAB simulations again to find the most cost efficient combination of products as well as make sure that we were still getting our desired response.

Our group needed to test how our method of data collection in Labview and LoggerPro so that we could create a detailed set of steps and make it as user friendly as possible.

4.5.3 Results

Through our consultation with professors, adjustment of coefficients, and testing of our blowdown tank we were able to make an accurate MATLAB model for Choked Flow and Laminar Flow which is nice because we had only anticipated being able to do Choked Flow at the beginning of the project.

Our range of values for the electrical components based on the products available consisted of resistors from 100 ohm to 1M ohm. The range of capacitors is from 0.1 µF to 2200 µF. The inductor ranges are from 0.3H to 5H. The mechanical system mass can range from 1 kg to 100 kg, springs from 2 lb/in to 19 lb/in, and damper value from 0-40 lb/(in/s).

4.5.4 Decisions Made

We decided to calibrate and tune our MATLAB for the Choked Flow and Laminar Flow by changing coefficients to match line resistance and the fittings we used.

We decided to primarily use LoggerPro for data collection based on it being more user friendly compared to Labview. We decided to keep the Labview method in our Operation Doc because some computers, like the laptops in the Measurements Lab, do not have LoggerPro installed or the correct drivers. Labview is also free on the OSU IT site and LoggerPro is not on the OSU IT site.

We decided to buy a few different electrical system components so that there is a good variety of responses to choose from. We went with an Airpot adjustable damper from 0-5 lb/(in/s) which allows us to use a few different compression spring values on the mechanical system.

4.6 Testing of Overall Design

This section is similar to the Experiments to Test Concepts section except that in this we tested all the final designs and made final changes and tweaks. We were also able to present some of our systems for the Spring 2015 MAE 3723 Lab section where students were able to use our systems and perform experiments and fill out assignments we made.

4.6.1 Work Done

After our Experiments to Test Concepts phase we were able to finalize construction of systems, test the physical system compared to the MATLAB, and create the Operations Doc for each system. We got a chance to test the Blowdown tank, electrical systems, spring speaker system, and the cantilever beam for Spring 2015 MAE 3723 students to observe how well students were able to use our systems. Below is a picture of a group member teaching the Spring 2015 Lab section about the blowdown process particularly the choked and laminar flow.

Figure 15: Team Member Teaching MAE 3723 Lab

4.6.2 Reason Done

The physical systems needed to be solidly attached to the baseplates and boxes we made and permanent wires attached to them so that they can be stored and setup again with ease. Testing the physical systems gave us the chance to compare them to their respective MATLAB models. By doing this we could tweak the MATLAB models to better match our physical systems. Presenting and using our systems to the MAE 3723 lab students was done so that we could make any changes to user friendliness if needed and write good descriptions in the Operations Document.

4.6.3 Results

We found that in Choked and Laminar Flow we needed to adjust coefficients in MATLAB to reflect non-dry air assumptions and that the resistance of the pipe fittings, particularly the turn, needed to adjustment. After making the changes our response in MATLAB and in real life is extremely similar.

4.6.4 Decisions Made

We made the decision to fix all the systems even the blowdown tank to baseplates because it was easy for students to move and mess up the systems while using them. This will give them more structure and weight. We made the decision not to filter our data, but to include larger time steps and acquire more data during a system run because we were told not to go into the Measurements subject too much.

5 Detailed Description of Final Design

This section goes over Section 3 in more detail. Shown are images of the systems and descriptions about how they function, generally how they were built, generally how they are operated, and cost associated with them. These general descriptions are expressed in much more explicit detail in the "Construction Document" and "Operation and Safety Document". The explicit details of these documents are too long to be inserted into this document so refer to the other two documents for that information.

5.1 Electrical System

Figure 16: Electrical System - RC circuit

Figure 17: Electrical System - RLC Circuit

5.1.1 What It Does

The electrical systems consist of an RC experiment and a RLC experiment. The idea is to show high pass and low pass filters with the RC experiment and investigate rise time in first order systems. The other idea is to show under-damped response with the RLC as well as second order response. The final design allows for an individual to change out the resistor, capacitor, and inductor to customize the response. The final design also allows for an individual to conceal the circuit with a box made to go over the baseplate.

5.1.2 Model

The final design has a MATLAB model that can accept different input voltage, resistor, capacitor, and inductor values and create the transfer function and give output data to be exported to Excel. Once in Excel the data can be compared to the physical system data. All of the MATLAB programs look very similar

5.1.3 How to Use It

An extremely detailed description on how to use the system is available in "Operation and Safety Document". In a general description though, the way to use the system is inputting a voltage with a function generator then reading the output though a Vernier SensorDAQ into Labview or LoggerPro. This data can then be moved to Excel and compared to the MATLAB data.

5.1.4 Manufacturing

A 10x10 inch box with a 10x10 inch base was constructed out of 19/32 inch plywood to house the system. A breadboard is attached to the baseplate that allows a user to change out components. The electrical system is constructed on the breadboard with permanent input and output wires leading to the breadboard. An extremely detailed manufacturing description is in our "Construction Document".

5.1.5 Cost to Produce

The cost to reproduce this system is $185.25. The detailed list of materials and cost is in Section 8.1.

5.2 Fluid/Thermal System

Figure 18: Fluid/Thermal System - Blowdown Tank

5.2.1 What Does It Do

The Fluid/Thermal system consist of a Blowdown Tank process. The blowdown tank allows for a user to see a pressure vs. time and temperature vs. time response on one physical system. A total of 3 different experiments can be performed on the blowdown tank, which are choked flow, laminar flow, and thermal response. The choked flow consists of letting air out of a needle valve at a slow rate which will give an isothermal response. The laminar flow consists of letting air out of the fill valve into a long segment of tubing at a high rate. The thermal response can be measured using either choked flow or laminar flow from a thermocouple that is suspended in the middle of the tank.

5.2.2 Model

The final design has a MATLAB model that can accept different coefficients for just about any of the limiting parameters. The main parameters of interest are the resistance of the fittings in the laminar flow model, the discharge coefficient in the choked model, and the initial pressure of the tank. Most other variables are obtained by assuming air at ambient temperature modeled as an ideal gas. For the laminar flow, an isothermal response is assumed, and for the choked flow, an adiabatic model is assumed. The outputs of the models are pressure and temperature.

5.2.3 How to Use It

An extremely detailed description on how to use the system is available in "Operation and Safety Document". In a general description though the way to use the system is to first fill the tank with air up to about 120 psi. Then you can do either the choked flow or laminar flow experiment and measure the voltage output from the Wheatstone bridge and pressure transducer in Vernier SensorDAQ into LoggerPro. This data can then be moved to Excel and compared to the MATLAB data.

5.2.4 Manufacturing

A 24x15 inch baseplate made out of 19/32 inch plywood to stabilize the system. A breadboard is attached to the baseplate that allows for the thermocouple and pressure transducer to be powered. The blowdown tank has a pop safety valve, pressure gage, fill valve, needle valve, and quick release valve that make up its structure. An extremely detailed manufacturing description is in our Construction Document.

5.2.5 Cost to Produce

The cost to reproduce this system is $478.36. The detailed list of materials and cost is below in Section 8.2.

5.3 Mechanical System

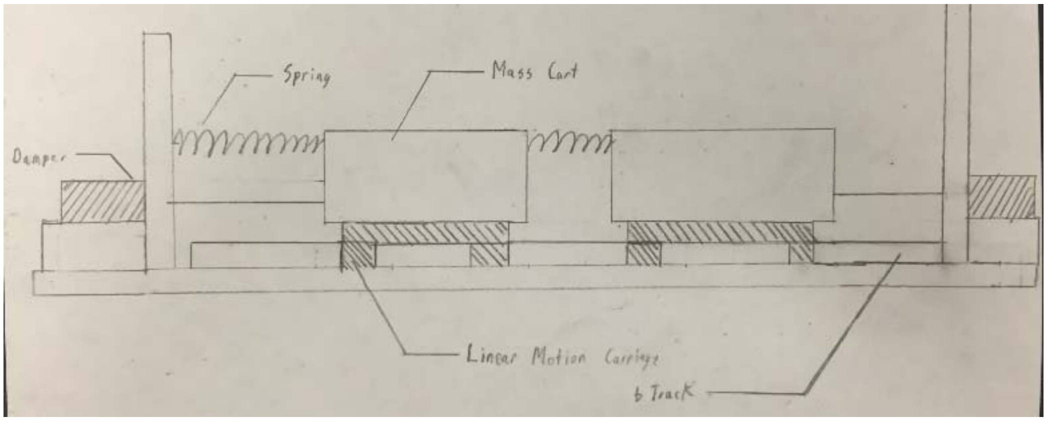


Figure 19: Mechanical System Drawing

Figure 20: Partially Complete Mechanical System

5.3.1 What It Does

The mechanical system consists of a rail with two cars connected by a spring and damper. An input force is applied to one of the carts which then moves the two carts while an accelerometer records their movement. The system has the option to only use one cart for a second order response, while using both carts creates a complex fourth order system. This system can be concealed so that students can be given a set of data and be asked to find coefficients or replicate the results.

5.3.2 Model

The final design has a MATLAB model that can accept different coefficients for mass, damping, and spring constants. The model is for a two-cart fourth order system, but can become a second order system by entering 0s for the second cart coefficients. The output of the model is displacement.

5.3.3 How to Use It

An extremely detailed description on how to use the system is available in "Operation and Safety Document". In a general description though the way to use the system is to first connect or disconnect the second cart as desired. Then a force can be applied to a cart and released. The carts will move back and forth and the accelerometers on them will output a voltage to the Vernier SensorDAQ into LoggerPro. This data can then be moved to Excel and compared to the MATLAB data.

5.3.4 Manufacturing

A 35x10x10 inch box made out of 19/32 inch plywood houses the system. The track is screwed to the baseplate and posts attached to the baseplate hold the spring and dampers horizontal to the carts. The damper screws into a spot on the cart while the springs are held on by a metal clip.

5.3.5 Cost to Produce

The cost to reproduce this system is $521.00. The detailed list of materials and cost is below in Section 8.3.

5.4 Electro-Mechanical System

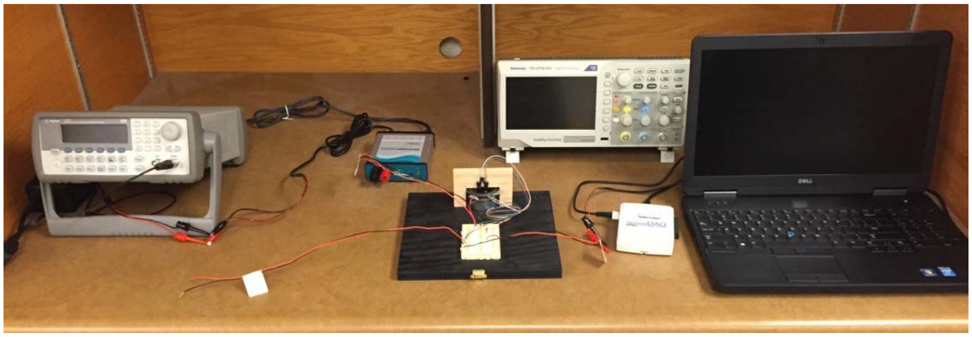


Figure 21: Electro-Mechanical System

5.4.1 What It Does

The electro-mechanical system consists of a breadboard with an RC or RLC circuit that includes a speaker. The speaker’s displacement is measured and outputted as a voltage to the Vernier SensorDAQ. The idea is to show how using a circuit to power a mechanical device responses. This system results in a third order response

5.4.2 Model

The final design has a MATLAB model that can accept different coefficients for a large number of variables that are greatly dependent on the speaker used. These coefficients should be obtained through destructive testing, so whatever speaker is used, at least two speakers should be obtained. The model is constructed using a force balance of the speaker cone and a KVL analysis of the coil around the speaker. These two equations can be combined to obtain a third order transfer function. The output of the model is displacement.

5.4.3 How to Use It

An extremely detailed description on how to use the system is available in "Operation and Safety Document". In a general description though the way to use the system is to connect the function generator to power the circuit with a square wave. This will make the speaker displace which can then be measured by the optical sensor. The optical sensor outputs a voltage to the Vernier SensorDAQ into LoggerPro which is calibrated to show a displacement change. This data can then be moved to Excel and compared to the MATLAB data.

5.4.4 Manufacturing

A 10x12 inch baseplate made of 19/32 inch plywood stabilizes the system. The breadboard houses the RLC or RC circuit while the speaker is under a brace that the displacement sensor is screwed to. The displacement sensor can be moved in order to calibrate and adjust for speaker size. An extremely detailed manufacturing description is in our Construction Document.

5.4.5 Cost to Produce

The cost to reproduce this system is $346.43. The detailed list of materials and cost is below in Section 8.5.

5.5 Computer Generated System

Figure 22: Computer Generated System

5.5.1 What It Does

The computer generated system consists of an Arduino programmable board and a simple low pass filter. The idea with this system is to replicate any of the other physical systems. Since some of the systems may be concealed by the black boxes, it will not be readily apparent that this system is simply a programmable board executing a function rather than the actual system that it is simulating. This board is extremely versatile in that it can output to MATLAB and LoggerPro, the code can be easily changed in order to simulate any of the other systems using the models developed for them, and the inputs can be read either through the code or by the use of potentiometers.

5.5.2 Model

This system allows the use of any of the other models. The main function of this board is to execute the Runge-Kutta method to simulate any of the models the user would like to simulate.

5.5.3 How to Use It

Simply insert the function of choice into the “rungekutta” Arduino program, change the step size, and upload the code to the board. The inputs and outputs can both be read and written in digital and analog form and code exists to facilitate both. Just comment out the input or output method not being used. To use the analog output, a low pass filter is used since the board cannot output in true analog, but instead will output in the form of pulse wave modulation. The low pass filter will change the output into the analog value. This is output to the SensorDAQ and read in by LoggerPro. The digital output will be read by MATLAB. To do this, use the “serialcoms.m” MATLAB file to run the board. Ensure that you have chosen the serial output when doing this.

5.5.4 Manufacturing

Constructing this system is very simple. The code is uploaded to the board and the board will do the rest. The board is powered by 5 volts either through the USB cable when using a serial output to MATLAB or through a 5-12 volt power cable when working with the analog output. The low pass filter consists of a 4.6 kΩ resistor and a 0.1 µF capacitor. Ensure that there is a power source to supply 5 volts to the board and that the wires are connected to the correct pins that can be chosen when entering the code.

5.5.5 Cost to Produce

The cost to produce this system is $77.30. More details for this can be found in Section 8.4.

5.6 Cantilever Beam System

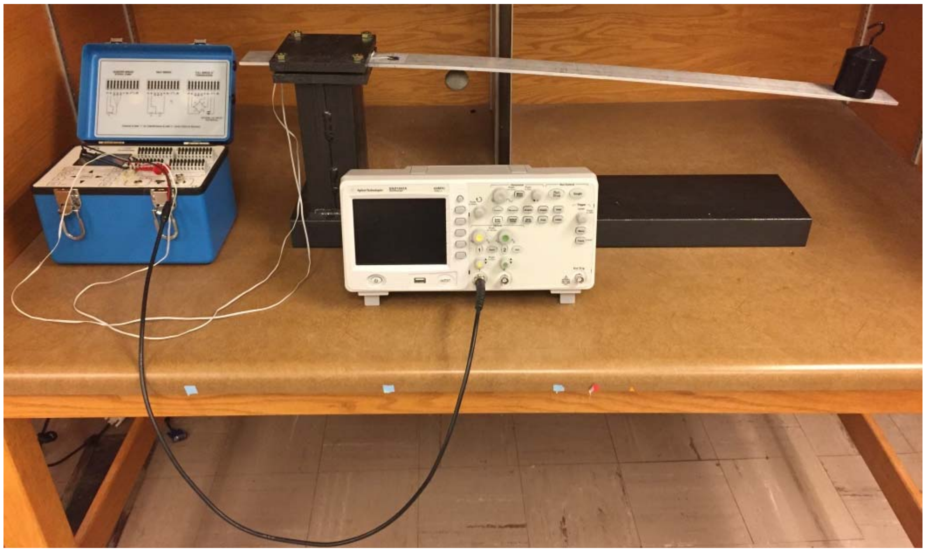


Figure 23: Cantilever Beam

5.6.1 What It Does

The Cantilever Beam system demonstrates the natural frequency of a system, as well as the accuracy of estimations.

5.6.2 Model

The beam’s mass is assumed to be a point-mass at its end. Its behavior is modeled by the following equations:

$$y_m = \frac{WL^3}{3EI} \qquad I = \frac{wt^3}{12} \qquad k = \frac{W}{y} \qquad \omega = \sqrt{\frac{k}{m}} \qquad f = \frac{\omega}{2\pi}$$

5.6.3 How to Use It

A detailed description on how to use the system is available in "Operation and Safety Document". In general, the beam end is displaced and released, and the natural frequency displayed on the oscilloscope recorded. Then, a large mass is placed on the beam end and the same is repeated. This new frequency is recorded and the two natural frequencies compared.

5.6.4 Manufacturing

The strain gauge on the cantilever beam should be wired to the Wheatstone bridge box in a half bridge configuration. The oscilloscope is connected to the Wheatstone bridge box.

5.6.5 Cost to Produce

This system was made from materials available in the Measurements Lab so it did not cost the group anything to make.

5.7 Speaker-Spring System

Figure 24: Speaker-Spring System

5.7.1 What It Does

The speaker-spring system demonstrates the resonate frequency of a mass-spring system by suspending a mass and spring from a vibrating speaker.

5.7.2 Model

A point-mass is assumed and its behavior is modeled by the following equations:

$$k = \frac{mg}{x} \qquad f = \frac{\sqrt{\frac{k}{m}}}{2\pi}$$

5.7.3 How to Use It

A detailed description on how to use the system is available in "Operation and Safety Document". In general, a spring and mass are hung from the speaker. The function generator is then set to the calculated resonate frequency. The user should then adjust the frequency until resonance is observed, and record this experimentally derived frequency.

5.7.4 Manufacturing

The speaker should be connected to a power amplifier, which is connected to a function generator. The speaker is attached upside down to a rod, with the mass and spring hung form a hook on the cone.

5.7.5 Cost to Produce

This system was made from materials available in the Measurements Lab so it did not cost the group anything to make.

6 Evaluation of Final Design

The following is the evaluation of the final design (both the good and the bad), assessing the degree to which each deliverable was completed.

6.1 Physical Systems

6.1.1 Electrical System

Good: The RC and RLC response can be customized via altering the configuration and/or changing the components on the breadboard. Furthermore, these systems are some of our smallest and can be easily concealed.

Bad: Our inductor choices were limited to two at the present, due to size and cost.

6.1.2 Fluid/Thermal System

Good: Choked flow can be modeled, as can laminar flow (by attaching a plastic tube to the discharge). The thermal system can also be modeled via the thermocouple inserted into the tank via the compression fitting.

Bad: Our compression fitting was manufactured with a defect, and some of the wire was compromised. This reduces the number of thermocouples that can be connected from two to one.

6.1.3 Mechanical System

Good: All components have detailed assembly instructions, dimensions, and CAD models. A working SolidWorks simulation has also been created to test spring and damper coefficients.

Bad: The system is currently not fully complete due to difficulty in material acquisition.

6.1.4 Additional System: Arduino

Good: The Arduino board can replicate any of the other systems. It can also output in analog directly into LoggerPro.

Bad: The Boot Bus Bug has been found in most Arduino boards. This bug prevents new code from being written to the chip.

6.1.5 Additional System: Electro-Mechanical System

Good: The displacement and voltage measurement of the system are working well, without significant cost or alteration to the speaker.

Bad: Our current system is a little small. Plans for a system that utilizes a bigger speaker are available.

6.1.6 Additional System: Cantilever Beam

Good: This model is simple, but is still fairly accurate. Unlike the other systems, it does not require complex differential equations.

Bad: The cantilever beam itself may not be as easily available to other labs. It may have to be reproduced.

6.1.7 Additional System: Speaker-Spring

Good: This system is a fun and clear example of the effects of resonant frequency. The model is very simple and the operation of the lab is user friendly.

Bad: Quality springs are currently in short supply. Furthermore, an accurate measurement device for motion is needed to make the lab more quantitative and less qualitative.

6.1.8 Varying Degrees of Complexity

Good: First, second, third, and fourth order systems are all represented. Some non-differential models are also utilized (at least in the observed domain). The Mechanical System with two carts is the most complex, while the cantilever beam is one of the simplest.

6.1.9 Black Boxes

Good: Each system has a black box that can conceal it. Each box latches closed and has holes for wires for the input and output.

6.2 MATLAB Models

Good: Each system has its own mathematical model. In most models, the coefficients can be easily edited to customize the response.

Bad: Sine input for the electro-mechanical and electrical systems result in MATLAB “symsum” issues.

6.3 CAD Models

Good: Black boxes have been dimensioned and documented. The Mechanical System model can be used to test spring and damper response, and can be used to 3D print light-weight carts.

6.4 Construction & Design Documentation

Good: Documents on how to construct black boxes, custom parts, and assembly of systems have been created. Additionally, a detailed bill of materials for each system exists for ease of reproduction.

6.5 Operation and Safety Documentation

Good: Documents for each system detail how to operate each system, collect data, and include videos of how to use the systems as well as to aid in instruction.

6.6 Optional Deliverables

Good: Our team ended up having two more systems than expected. We were also able to conduct a lab with some of our physical systems and their worksheets, at the conclusion of which very positive student feedback was received.

7 Recommendations for Future Work

The following is our team's recommendations for any further work on this project.

7.1 Electrical System

More inductors could be found in order to have more options for the response of the Electrical System. Inductors can be large and expensive, so diligent research is advised to find an economical option.

7.2 Fluid/Thermal System

Our team suggests that adding additional wires (about 6-8) for the compression fitting be considered. This is so that different thermocouples could be used during the same experiment. This would be useful in demonstrating the response of different measurement devices, and comparing the accuracy of each against the mathematical models.

7.3 Mechanical System

In the future, in order to acquire the proper dampers, Airpot should be contacted more than a month in advance. Unfortunately, the working with this company was a slow process for us. Linear bearings are also recommended instead of the sleeve bearings we are currently using, in order to further reduce friction in the system.

7.4 Electro-Mechanical System

Acquiring a large speaker is highly recommended (similar to the one used in the Speaker-Spring System). This will improve the accuracy of the optical sensor, thereby improving experimental correlation with the model.

7.5 Arduino System

It is suggested that more than one Arduino Mega 2560 be purchased in case of part failure. Specifically, there is a bug with the Arduino system that causes the board to become unalterable at some point. If further changes need to be made, another Arduino board would need to be on hand.

7.6 Cantilever Beam System

Since many of the components used for this system belong to the Measurements lab, this system will need to be replicated specifically for the MAE 3723 lab. Our team also suggests using different beam materials so that the natural frequencies of each beam can be compared versus their materials. Also, modeling in the time domain might also be interesting to explore.

7.7 Speaker-Spring System

Since many of the components used for this system belong to the Measurements lab, this system will need to be replicated specifically for the MAE 3723 lab. A larger variety of springs is also recommended for greater lab versatility.

8 Summary of Money Spent

8.1 Electrical System

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
2	$1.49	1	$1.49	100uF 50V 20% Radial-Lead Capacitor	2721044	Radio Shack
3	$7.99	1	$7.99	100-Piece 1/2-watt Carbon-filmed Resistors Assortment	2710306	Radio Shack
4	$39.06	1	$39.06	Hammond 159ZA Choke, 0.3H, 1A Inductor	159ZA	Hammond through Amazon.com
5	$23.80	1	$23.80	Hammond Fixed Inductor D.C. Filter Choke 5H	158Q	Hammond through Amazon.com
6	$8.49	1	$8.49	3 color set 22-gauge single strand wire	2781224	Radio Shack
			Total System Cost			
			$104.80			

8.2 Fluid/Thermal Blowdown System

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$49.99	1	$49.99	Horn-Air Black 2 Gallon 6 Port Air Tank	TA-206H	HornBlasters, Inc.
2	$12.17	1	$12.17	Squeeze-Grip Zinc Alloy Valves, 1/4 NPT Female	6852K11	McMaster-Carr
3	$37.28	1	$37.28	Easy-Set Needle Valves, Brass, 1/4 NPTF Female	46425K12	McMaster-Carr
4	$15.81	1	$15.81	ASME-Code Nickel-Plated Brass Pop-Safety Valve, 1/4 NPT Male, 150 psi	5784T12	McMaster-Carr
5	$1.69	4	$6.76	Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Solid Hex-Head Plug	50785K335	McMaster-Carr
6	$3.69	2	$7.38	Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Pipe Size, Solid Hex-Head Plug	50785K337	McMaster-Carr
7	$153.97	1	$153.97	PRSSR TRNS -1TO9BR 0-5V DIN	1TO9BR	Digikey
8	$135.00	1	$135.00	1/4 Compression Fitting w/Thermocouple	TG24T(T)-A4-T,12"/4"(BW)	Conax
9	$25.00	1	$25.00	T Type Thermocouple, Unsheathed, Diameter: 0.001", Length: 12"	COCO-001	Omega
			Total System Cost			
			$443.36			

8.3 Mechanical System

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$0.08	500	$40.00	500 mm Track	6109K42	McMaster-Carr
2	$64.56	2	$129.12	Linear motion Cart	6109K41	McMaster-Carr
3	$0.89	3	$2.67	3 inch compression springs, various constants		Ace
4	$64.20	2	$128.40	0-5 in/lb*s Damper	2KS120	Airpot
5	$44.95	2	$89.90	9 Piece Hanging Weight Set with Hooks	SS20111	Sci-Supply.com
6	$0.97	4	$3.88	1"x2"x8' Furring Strip board	160954	Home Depot
8	$2.38	6	$14.28	Metal L joint bracket	315683	Home Depot
		Total System Cost				
		$519.00				

8.4 Computer Generated System

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$64.99	1	$64.99	Arduino Mega 2560 Rev3	2760127	Radio Shack
2	$0.99	1	$0.99	5 Volt AA battery pack	2700383	Radio Shack
3	$3.33	1	$3.33	USB Connetor (to computer for readings/writing)	551691278	Wal-mart
4	$7.99	1	$7.99	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$77.30			

8.5 Electro-Mechanical System

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$19.99	1	$19.99	2 Inch Computer Speaker		Wal-mart
2	$3.47	1	$3.47	Optek Displacement Sensor	OPB704WZ	Optek
3	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$47.43			

8.6 Speaker-Spring System

The speaker-spring system used existing materials from the Measurements Lab so we did not have to spend any money on them.

8.7 Cantilever Beam

The cantilever beam system used existing materials from the Measurements Lab so we did not have to spend any money on them.

8.8 Black Boxes

Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$20.27	4'x8' 19/32 unsanded plywood	326135	Home Depot
1	$4.37	1-5/8" Fine tread drywall screws	158CDWS1	Home Depot
3	$11.61	Flat Black Spray Paint	J2853812	Home Depot
	Total System Cost			
	$36.25			

9 Appendix

9.1 Creation of Alternative Designs-Particular System Equations and Info

9.1.1 Fluid System Information

Boiler and Pressure Vessel Code-2015 Edition

Section VIII Pressure Vessels: https://www.asme.org/shop/standards/new-releases/boiler-pressure-vessel-code/pressure-vessels

First Order Fluid System Equation

$$AR\frac{dh}{dt} + gh = Rq_v$$

$$\tau = \frac{AR}{g}$$

9.1.2 Thermal System Information

Boiler and Pressure Vessel Code-2015 Edition

Section IV Heating Boilers and Section VI Care and Operation of Heating Boilers: https://www.asme.org/shop/standards/new-releases/boiler-pressure-vessel-code/heating-boilers

First Order Thermal System Equation

$$mc_pR\frac{dT}{dt} + T = T_b$$

$$\tau = mc_pR$$

Second Order Thermal System Equation

$$R_1C_1\frac{dT}{dt} + T = T_b$$

$$R_1 R_2 C_2 \frac{dT_b}{dt} + (R_1 + R_2)T_b = R_2 T + R_1 T_o$$

Choked Flow Equations

$$\dot{m} = \mathrm{C_d A} \sqrt{\mathrm{k} \frac{\mathrm{m}}{\mathrm{V}} \mathrm{P} (\frac{2}{\mathrm{k}+1})^{\frac{\mathrm{k}+1}{\mathrm{k}-1}}}$$

$$m_{n+1} = \mathrm{m_n} - \left[C_d A \sqrt{\mathrm{k} \frac{\mathrm{m}}{\mathrm{V}} \mathrm{P} (\frac{2}{\mathrm{k}+1})^{\frac{\mathrm{k}+1}{\mathrm{k}-1}}} \right] t_{step}$$

9.1.3 Electrical System Information

Low Pass/High Pass

First-order Equation

$$RC \frac{dv}{dt} + v = v_s$$

RLC Circuit

Second-order system

$$LC \frac{d^2 v}{dt^2} + RC \frac{dv}{dt} + v = v_s$$

9.1.4 Mechanical System Information

Second-order response

$$m \frac{d^2 x}{dt^2} + c \frac{dx}{dt} + kx = f$$

First-order response

$$m \frac{dx}{dt} + kx = f$$

9.2 Creation of Alternative Designs-Preliminary Sketches and Ideas

9.2.1 Fluid System Selection

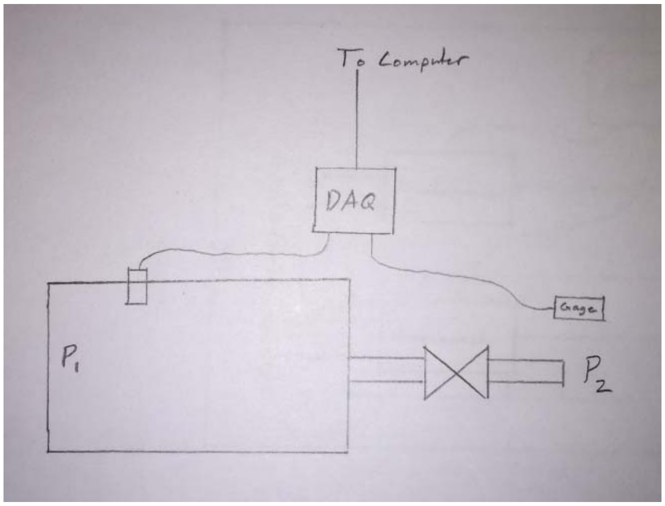


Figure 25: Rough Preliminary Fluid System Blowdown Tank

9.2.2 Thermal System Selection

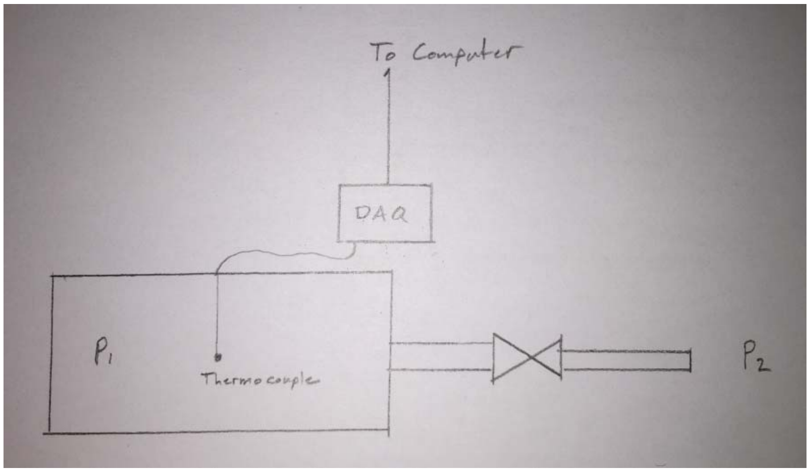


Figure 26: Rough Preliminary Thermal System Blowdown Tank

9.2.3 Mechanical System

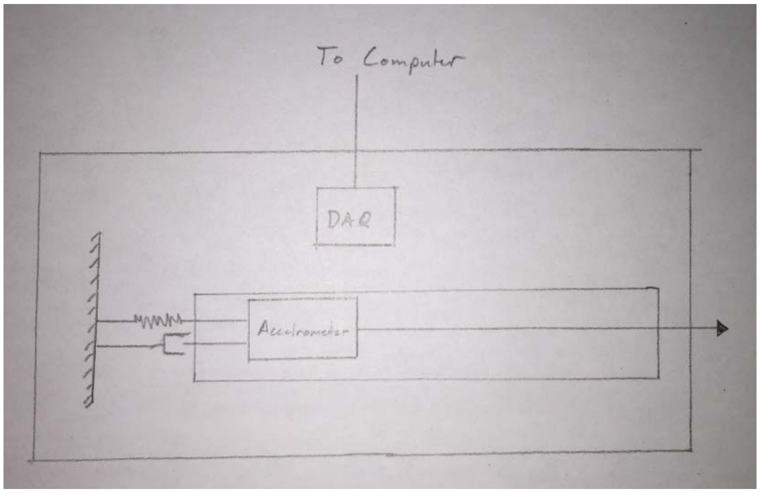


Figure 27: Single Horizontal Cart Configuration

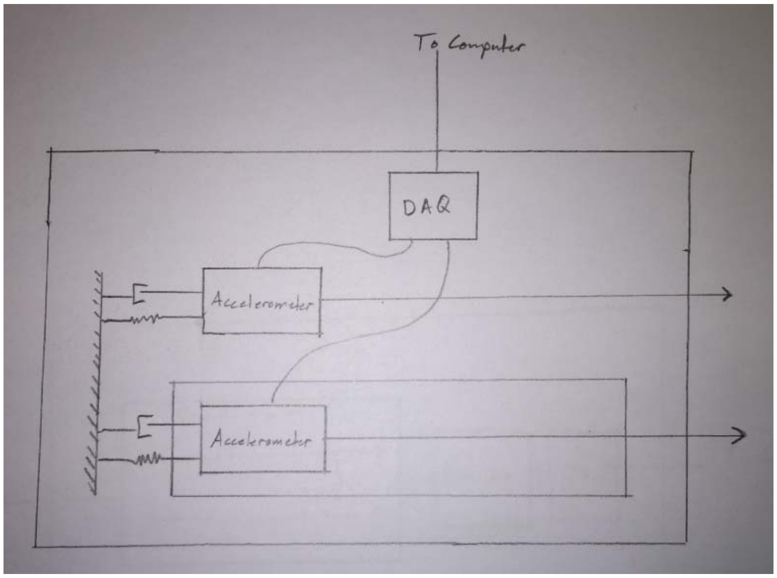


Figure 28: Horizontal Track and Friction Example

9.3 Creation of Alternative Designs-Sketches of Intermediate Designs

9.3.1 Fluid System Configuration

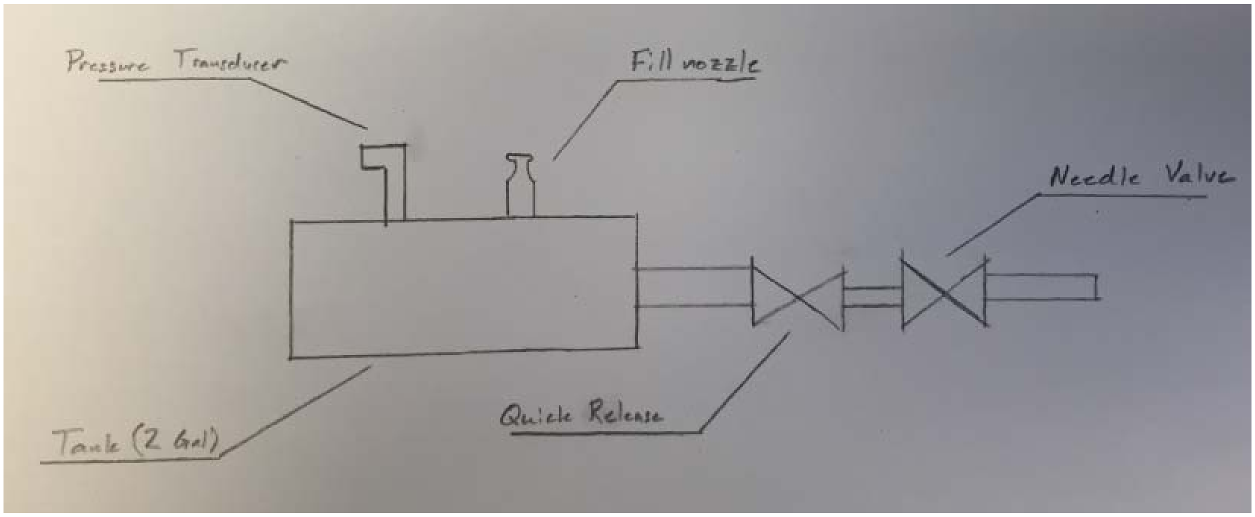


Figure 29: Blowdown Tank Fluid System Configuration

9.3.2 Thermal System Configuration

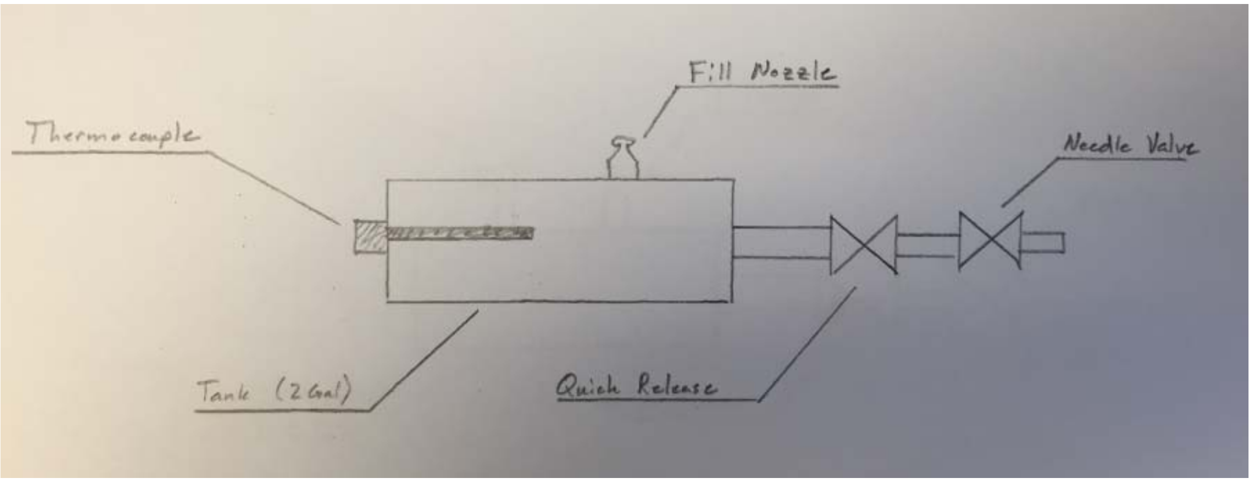


Figure 30: Blowdown Tank Thermal System Configuration

9.3.3 Electrical System Configuration

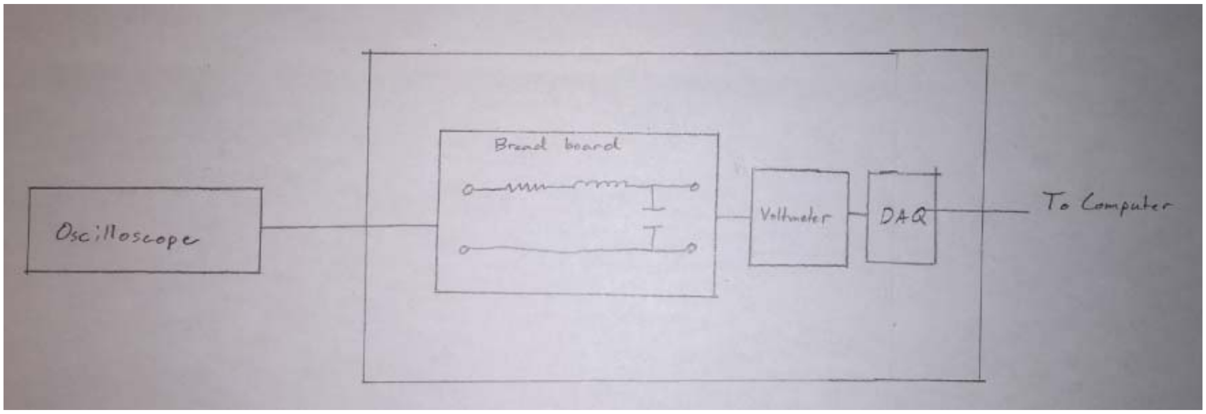


Figure 31: Electrical System RLC Configuration

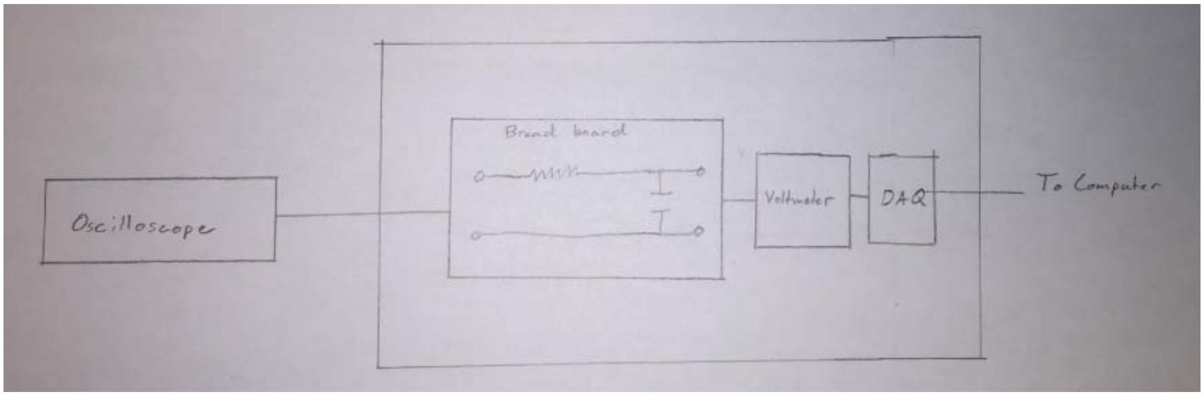


Figure 32: Electrical System Low Pass Configuration

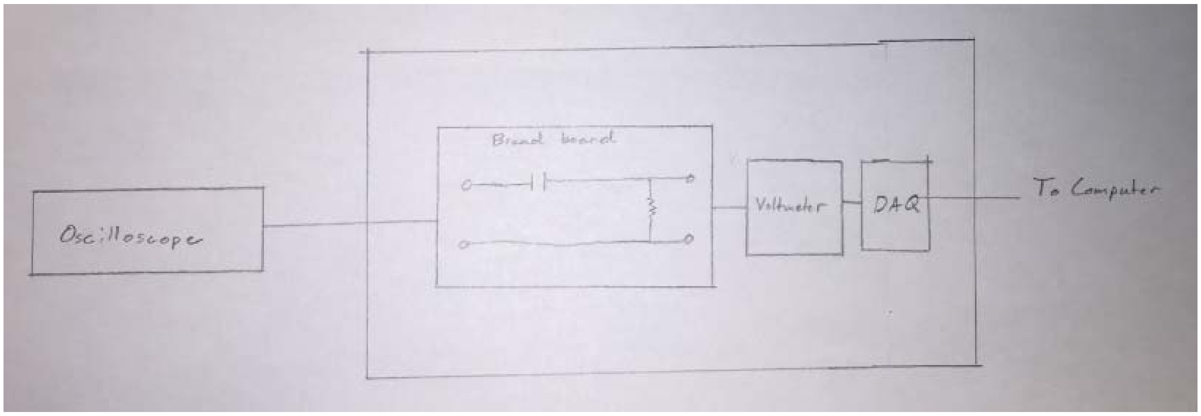


Figure 33: Electrical System High Pass Configuration

9.3.4 Mechanical System Configuration

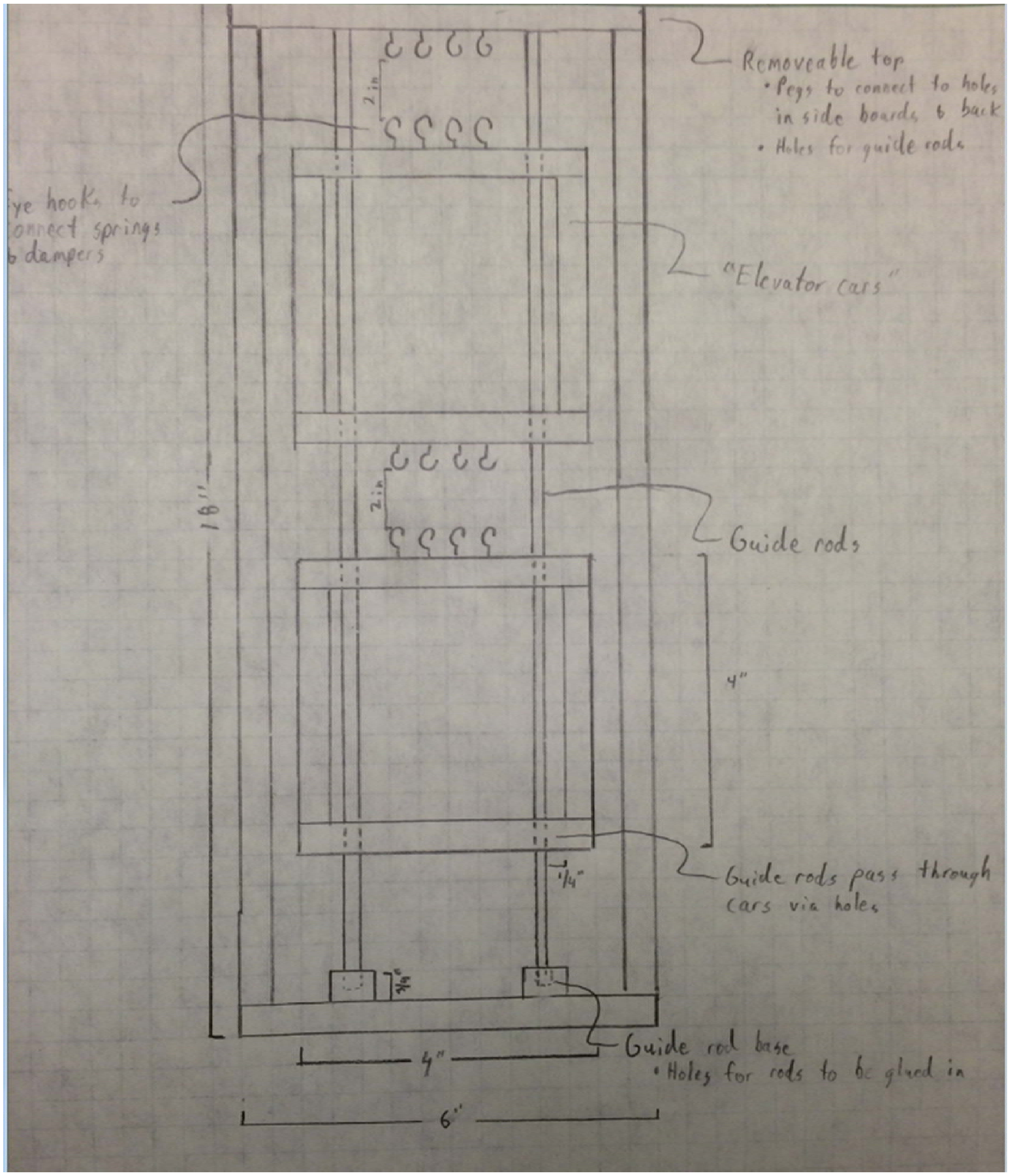


Figure 34: Mechanical System Configuration

9.3.5 Computer Generated System Configuration

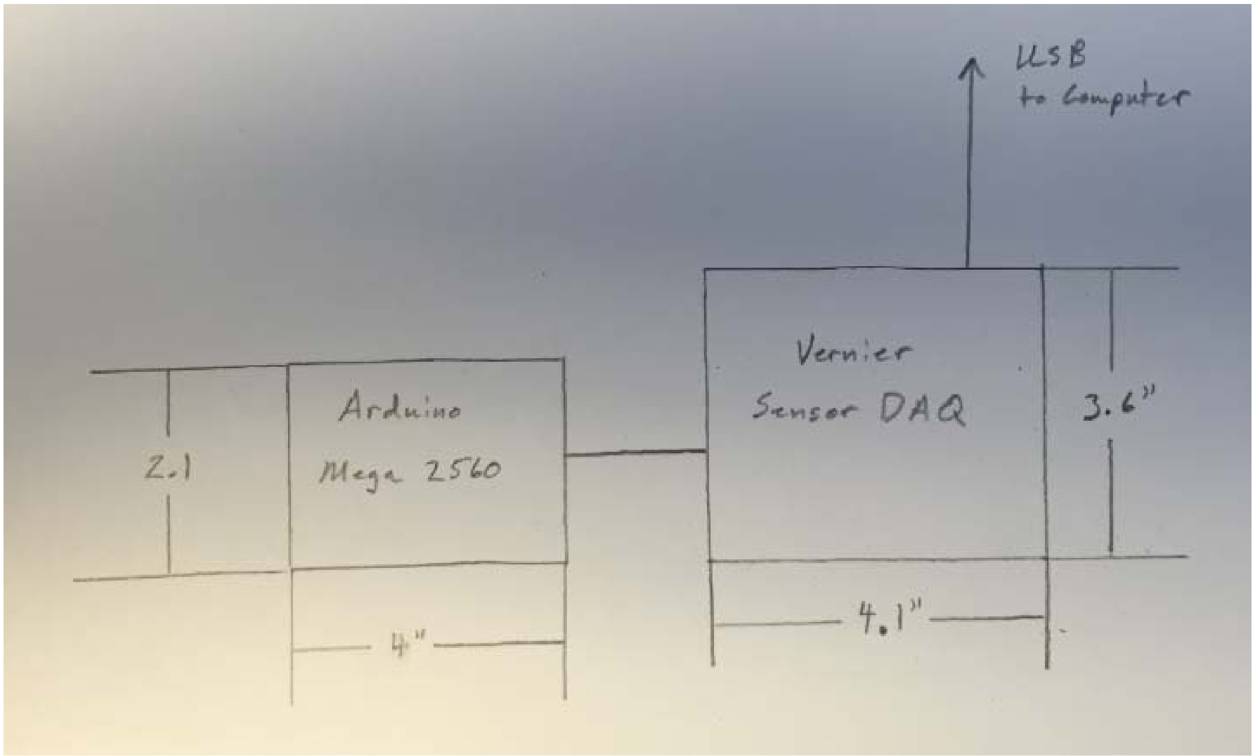


Figure 35: Computer Generated System Configuration

9.3.6 Electro-Mechanical System

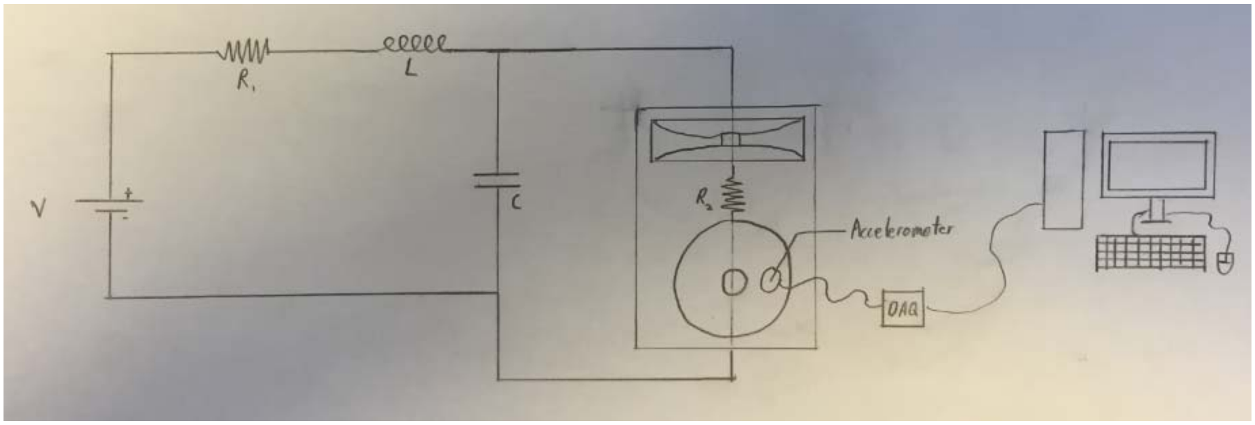
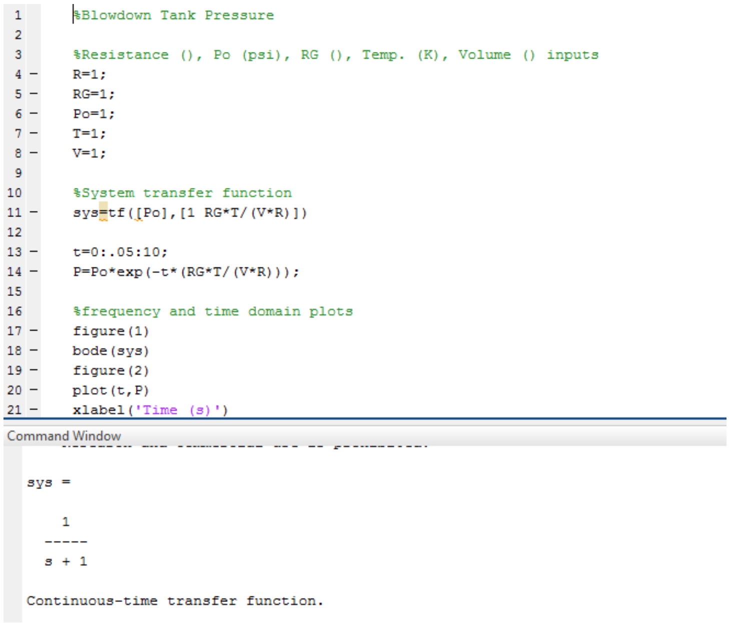


Figure 36: Electro-mechanical System Configuration

9.4 Calculations and Modeling Appendix

9.4.1 Fluid System Matlab Model



```
%Blowdown Tank Pressure

%Resistance (), Po (psi), RG (), Temp. (K), Volume () inputs
R=1;
RG=1;
Po=1;
T=1;
V=1;

%System transfer function
sys=tf([Po],[1 RG*T/(V*R)])

t=0:.05:10;
P=Po*exp(-t*(RG*T/(V*R)));

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
plot(t,P)
xlabel('Time (s)')
```

```
sys =

    1
  -----
  s + 1

Continuous-time transfer function.
```

Figure 37: Fluid System MATLAB Command window

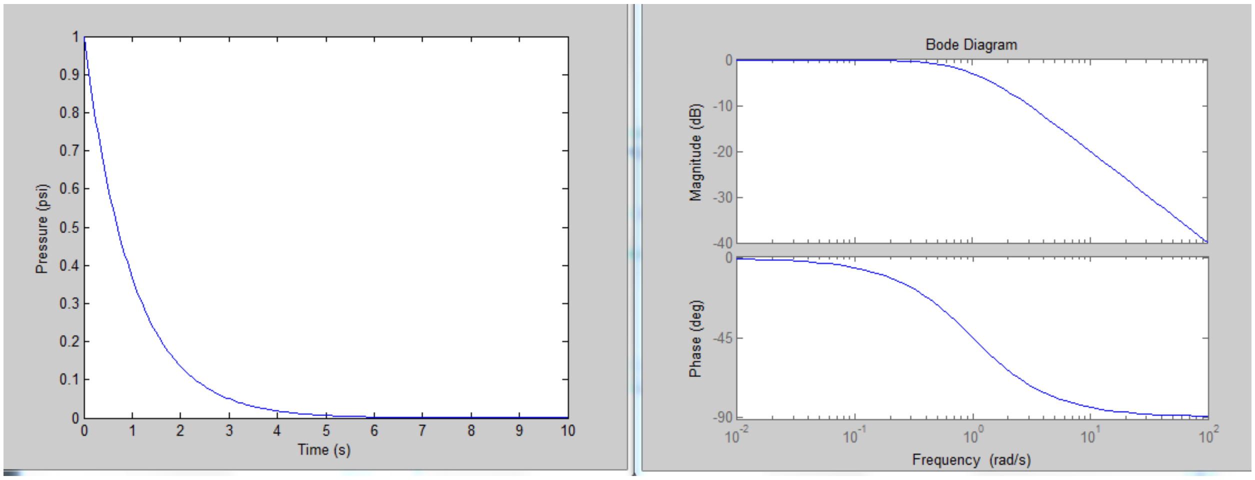
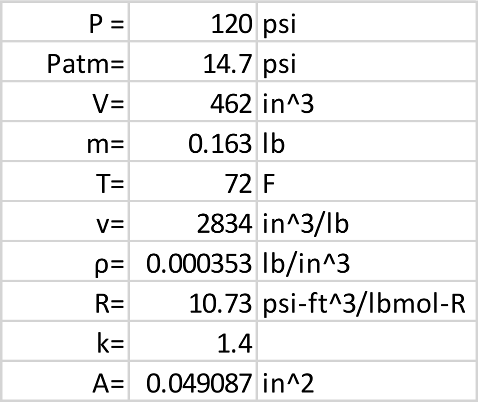


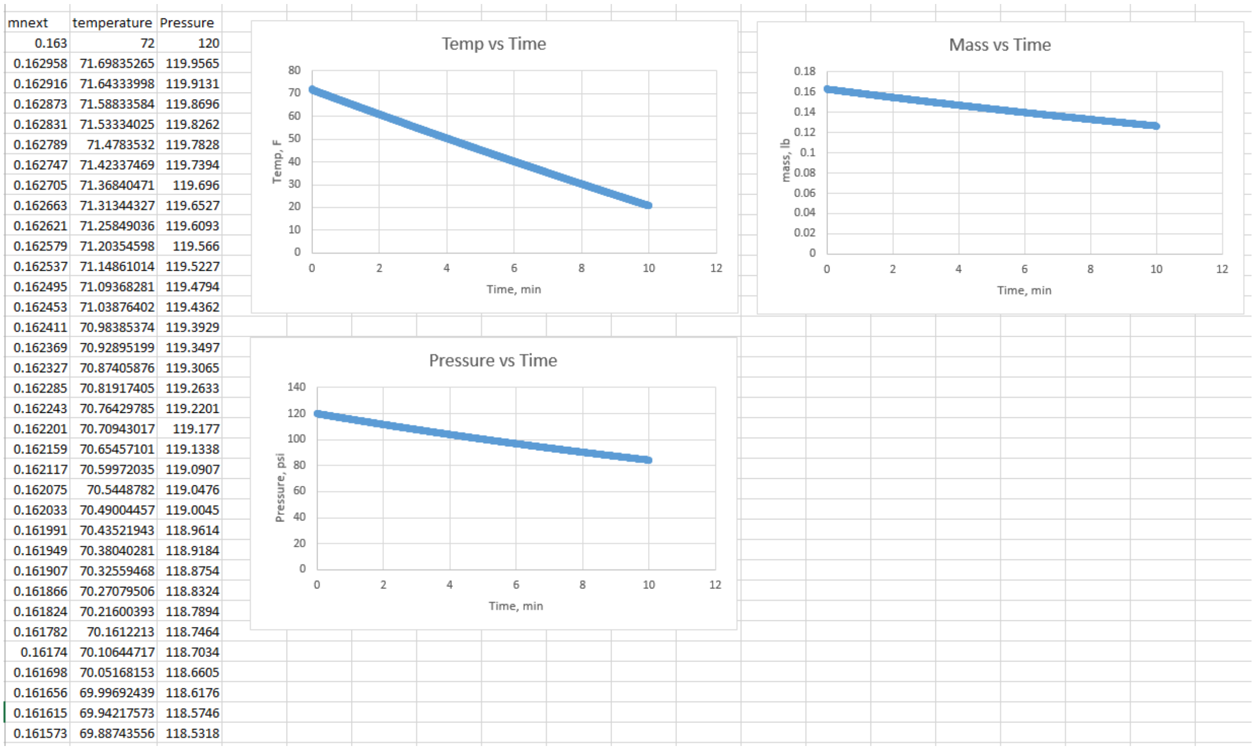
Figure 38: Fluid System MATLAB Time and Frequency Domain

9.4.2 Thermal System MATLAB Model and VBA Model



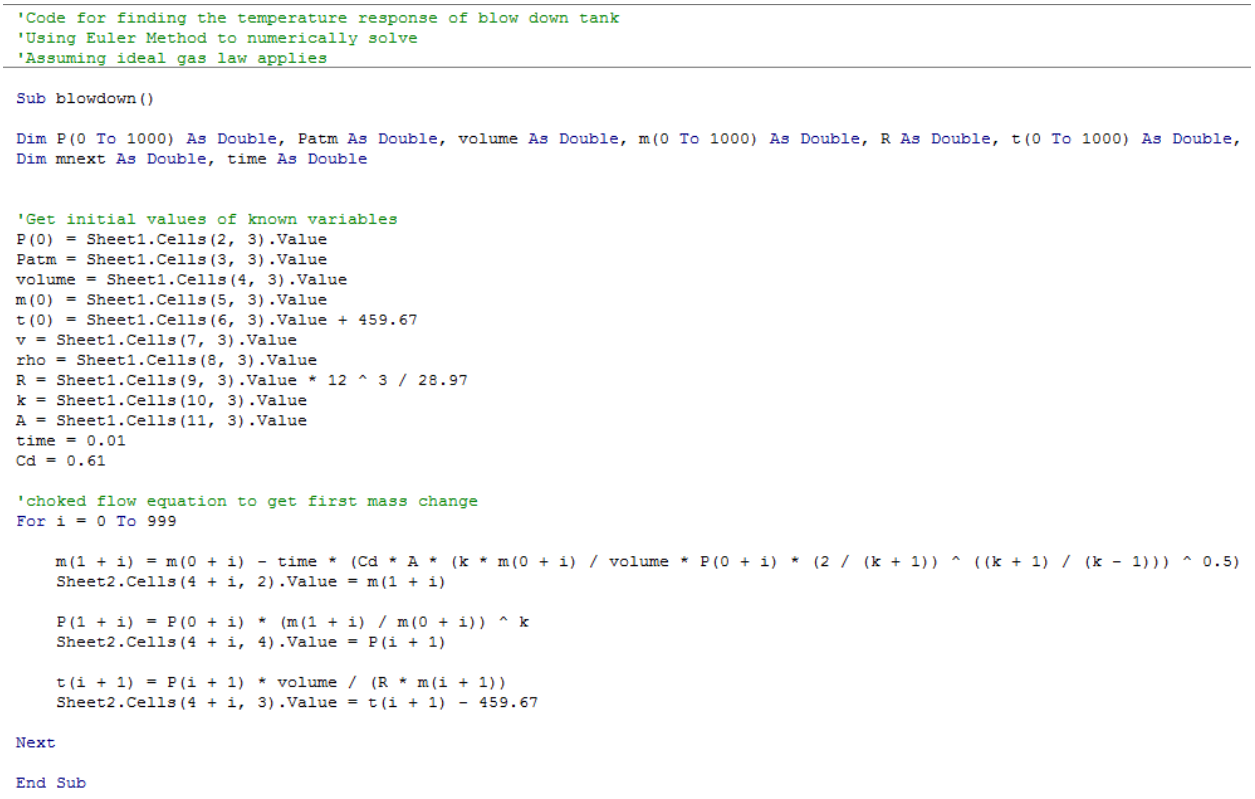
P =	120	psi
Patm=	14.7	psi
V=	462	in^3
m=	0.163	lb
T=	72	F
v=	2834	in^3/lb
ρ=	0.000353	lb/in^3
R=	10.73	psi-ft^3/lbmol-R
k=	1.4	
A=	0.049087	in^2

Figure 39: Choked Flow Excel Variable Inputs



mnext	temperature	Pressure
0.163	72	120
0.162958	71.69835265	119.9565
0.162916	71.64333998	119.9131
0.162873	71.58833584	119.8696
0.162831	71.53334025	119.8262
0.162789	71.4783532	119.7828
0.162747	71.42337469	119.7394
0.162705	71.36840471	119.696
0.162663	71.31344327	119.6527
0.162621	71.25849036	119.6093
0.162579	71.20354598	119.566
0.162537	71.14861014	119.5227
0.162495	71.09368281	119.4794
0.162453	71.03876402	119.4362
0.162411	70.98385374	119.3929
0.162369	70.92895199	119.3497
0.162327	70.87405876	119.3065
0.162285	70.81917405	119.2633
0.162243	70.76429785	119.2201
0.162201	70.70943017	119.177
0.162159	70.65457101	119.1338
0.162117	70.59972035	119.0907
0.162075	70.5448782	119.0476
0.162033	70.49004457	119.0045
0.161991	70.43521943	118.9614
0.161949	70.38040281	118.9184
0.161907	70.32559468	118.8754
0.161866	70.27079506	118.8324
0.161824	70.21600393	118.7894
0.161782	70.1612213	118.7464
0.16174	70.10644717	118.7034
0.161698	70.05168153	118.6605
0.161656	69.99692439	118.6176
0.161615	69.94217573	118.5746
0.161573	69.88743556	118.5318

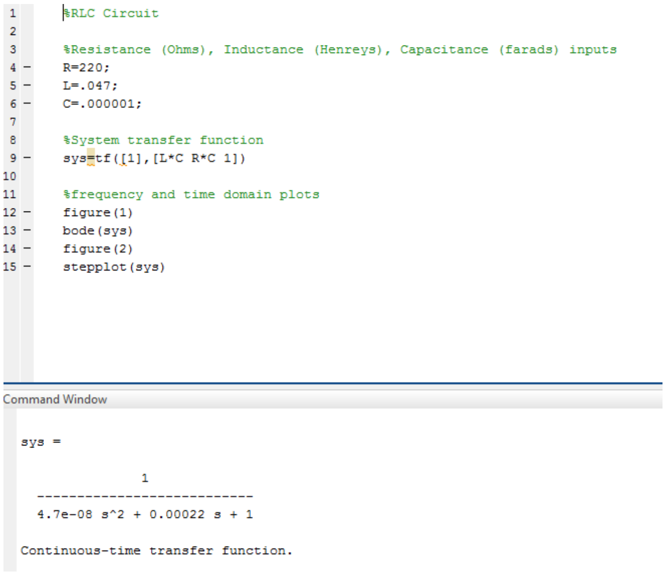
Figure 40: Choked Flow Analysis Excel Sheet



```
'Code for finding the temperature response of blow down tank
'Using Euler Method to numerically solve
'Assuming ideal gas law applies

Sub blowdown()

Dim P(0 To 1000) As Double, Patm As Double, volume As Double, m(0 To 1000) As Double, R As Double, t(0 To 1000) As Double,
Dim mnext As Double, time As Double


'Get initial values of known variables
P(0) = Sheet1.Cells(2, 3).Value
Patm = Sheet1.Cells(3, 3).Value
volume = Sheet1.Cells(4, 3).Value
m(0) = Sheet1.Cells(5, 3).Value
t(0) = Sheet1.Cells(6, 3).Value + 459.67
v = Sheet1.Cells(7, 3).Value
rho = Sheet1.Cells(8, 3).Value
R = Sheet1.Cells(9, 3).Value * 12 ^ 3 / 28.97
k = Sheet1.Cells(10, 3).Value
A = Sheet1.Cells(11, 3).Value
time = 0.01
Cd = 0.61

'choked flow equation to get first mass change
For i = 0 To 999

    m(1 + i) = m(0 + i) - time * (Cd * A * (k * m(0 + i) / volume * P(0 + i) * (2 / (k + 1)) ^ ((k + 1) / (k - 1))) ^ 0.5)
    Sheet2.Cells(4 + i, 2).Value = m(1 + i)

    P(1 + i) = P(0 + i) * (m(1 + i) / m(0 + i)) ^ k
    Sheet2.Cells(4 + i, 4).Value = P(i + 1)

    t(i + 1) = P(i + 1) * volume / (R * m(i + 1))
    Sheet2.Cells(4 + i, 3).Value = t(i + 1) - 459.67

Next

End Sub
```

Figure 41: Choked Flow Analysis VBA Code

9.4.3 Electrical System MATLAB Model



```
%RLC Circuit

%Resistance (Ohms), Inductance (Henreys), Capacitance (farads) inputs
R=220;
L=.047;
C=.000001;

%System transfer function
sys=tf([1],[L*C R*C 1])

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
stepplot(sys)
```

Command Window

```
sys =

               1
  --------------------------
  4.7e-08 s^2 + 0.00022 s + 1

Continuous-time transfer function.
```

Figure 42: Electrical System (RLC)-MATLAB Command Window

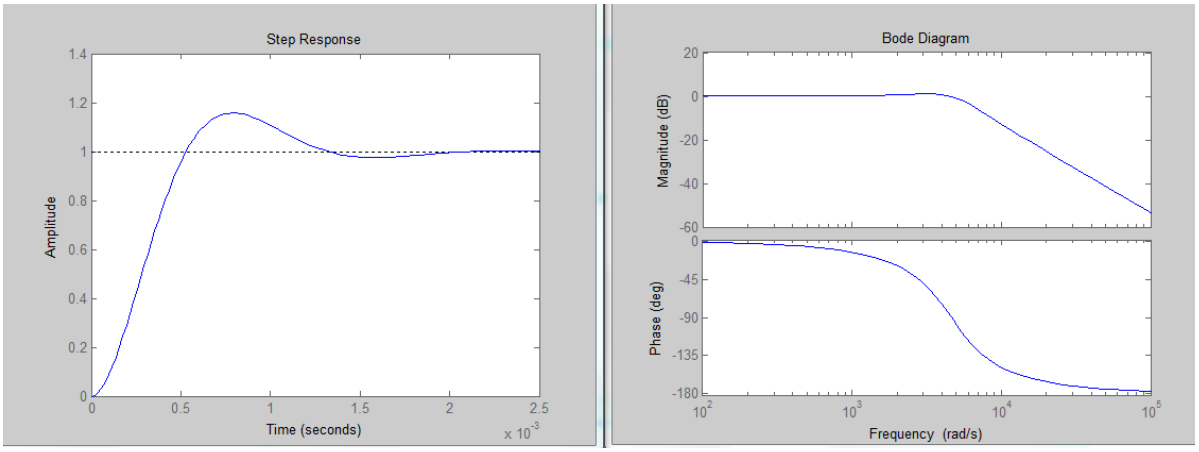
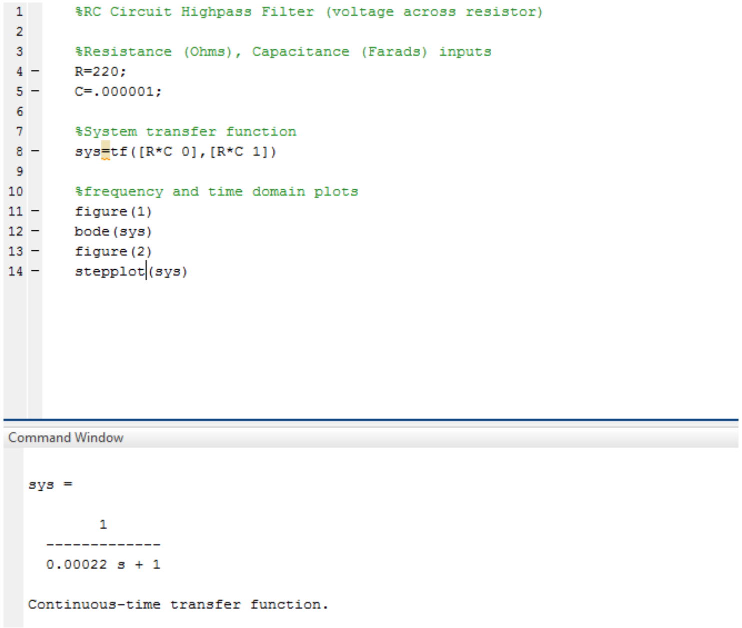


Figure 43: Electrical System (RLC)-MATLAB Time and Frequency Domain



```
%RC Circuit Highpass Filter (voltage across resistor)

%Resistance (Ohms), Capacitance (Farads) inputs
R=220;
C=.000001;

%System transfer function
sys=tf([R*C 0],[R*C 1])

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
stepplot(sys)
```

```
sys =

         1
  -------------
  0.00022 s + 1

Continuous-time transfer function.
```

Figure 44: Electrical System (High Pass)-MATLAB Command Window

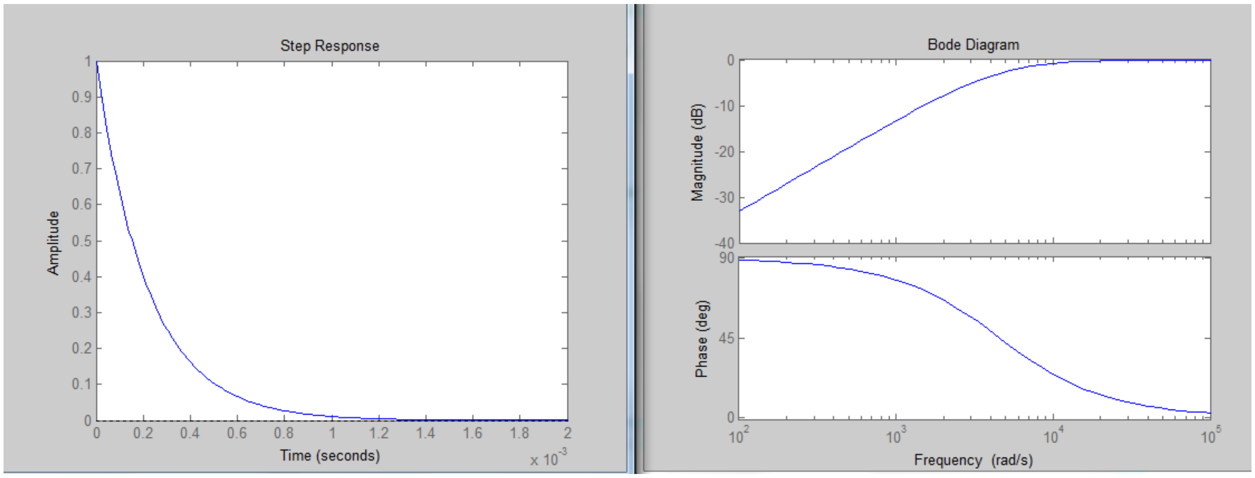
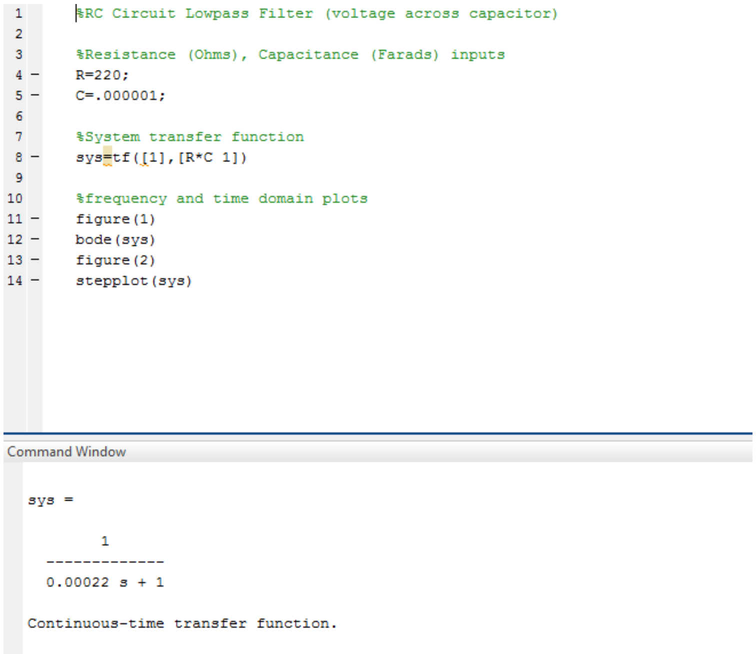


Figure 45: Electrical System (High Pass)-MATLAB Time and Frequency Domain



```
%RC Circuit Lowpass Filter (voltage across capacitor)

%Resistance (Ohms), Capacitance (Farads) inputs
R=220;
C=.000001;

%System transfer function
sys=tf([1],[R*C 1])

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
stepplot(sys)
```

```
sys =

        1
  -------------
  0.00022 s + 1

Continuous-time transfer function.
```

Figure 46: Electrical System (Low Pass)-MATLAB Command Window

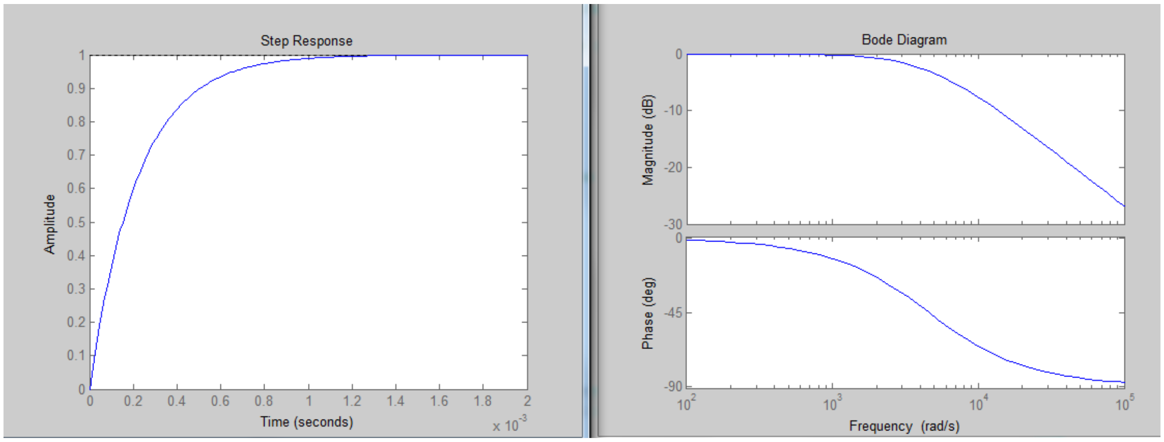
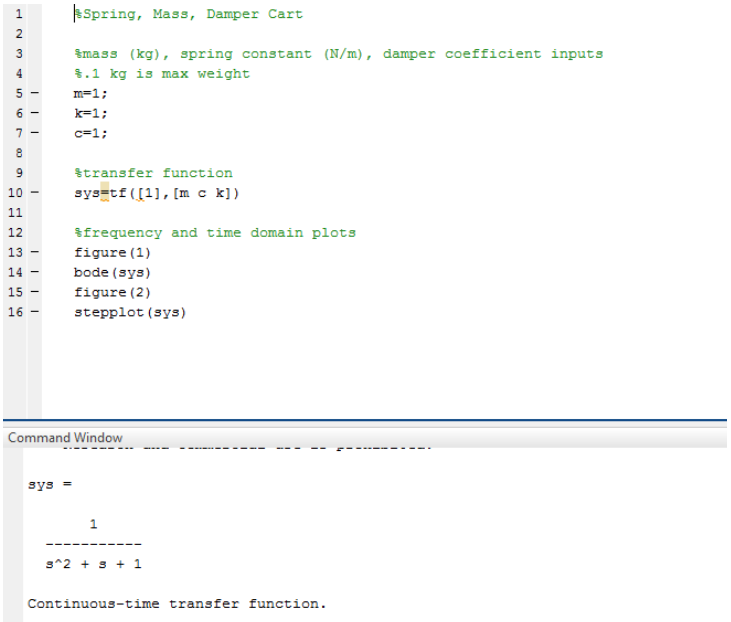


Figure 47: Electrical System (Low Pass)-MATLAB Time and Frequency Domain

9.4.4 Mechanical System MATLAB Model



```
%Spring, Mass, Damper Cart

%mass (kg), spring constant (N/m), damper coefficient inputs
%.1 kg is max weight
m=1;
k=1;
c=1;

%transfer function
sys=tf([1],[m c k])

%frequency and time domain plots
figure(1)
bode(sys)
figure(2)
stepplot(sys)
```

```
sys =

       1
  -----------
  s^2 + s + 1

Continuous-time transfer function.
```

Figure 48: Mechanical System-MATLAB Command Window

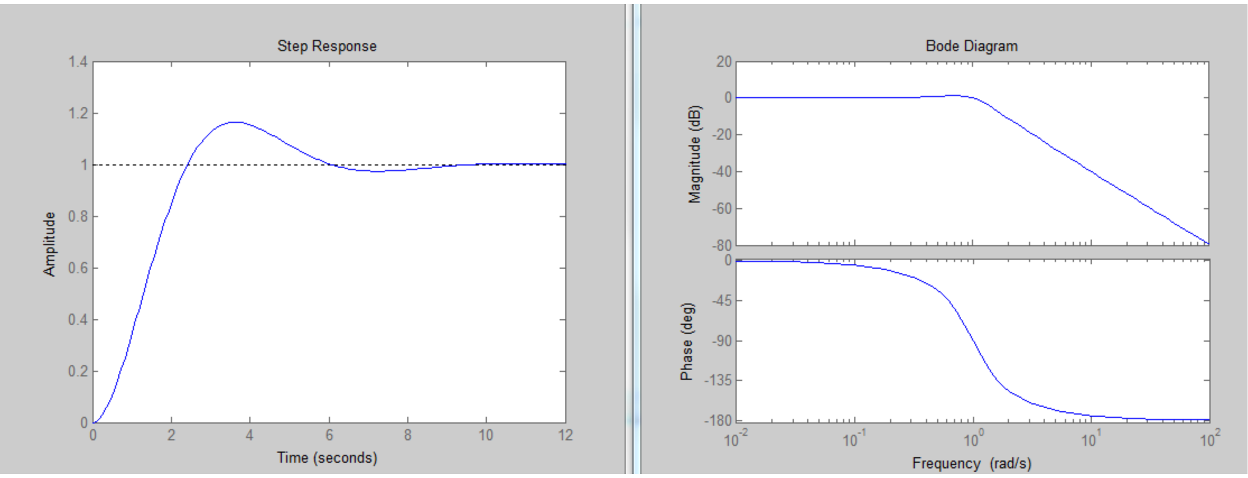


Figure 49: Mechanical System MATLAB Time and Frequency Response

Operation and Safety Document

By: Andy Freberg, Collin Jefferson, Mac McClure, Jordan McKee, Jason Proffitt

Contents

Document Introduction

This document details how to collect data from MATLAB and the physical systems, how to setup the physical systems, and how to operate the physical systems. This document does NOT detail how to build the physical systems or list the individual parts, for that refer to the “Construction Document”.

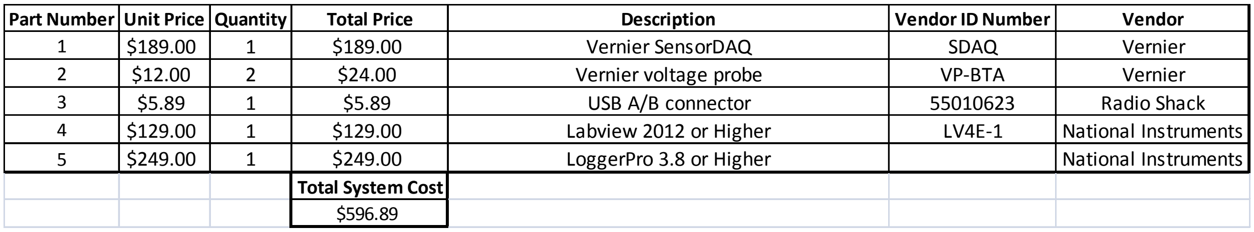
1.0 Data Acquisition

1.1 Introduction of Data Acquisition

For all the MATLAB models and physical systems, you will need to perform some sort of data acquisition in order to interpret and compare your data in Excel. The MATLAB models of each system have a simple procedure for data acquisition and moving it to Excel. We have 2 options for physical system data acquisition: LoggerPro or Labview. We prefer and advise using LoggerPro for all systems, but you may be limited to which program you can use depending on what program that is available to you. For example, you are limited to Labview if you are using the laptops in EN 215 Measurements Lab (the laptops mainly need a driver installed which is listed below).

1.2 Materials for Data Acquisition

The materials required to collect data for LoggerPro and Labview are listed below.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$189.00	1	$189.00	Vernier SensorDAQ	SDAQ	Vernier
2	$12.00	2	$24.00	Vernier voltage probe	VP-BTA	Vernier
3	$5.89	1	$5.89	USB A/B connector	55010623	Radio Shack
4	$129.00	1	$129.00	Labview 2012 or Higher	LV4E-1	National Instruments
5	$249.00	1	$249.00	LoggerPro 3.8 or Higher		National Instruments
			Total System Cost			
			$596.89			

Figure 50: Data Acquisition Materials

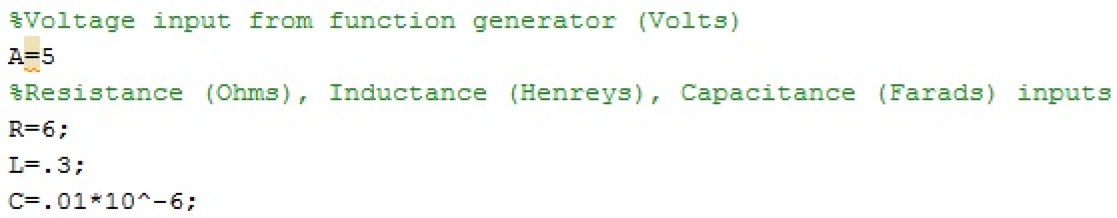
1.3 MATLAB Model Data Acquisition

The MATLAB models of each system can be used to show the ideal response of a system. It is usually easier for us to move MATLAB data over to Excel and use Excel to graph and compare ideal data to the physical system data. Below is the procedure for gathering MATLAB simulated data for a system and moving it into Excel.

MATLAB is used to simulate a system before you construct it as well as collect ideal response data for a system and the particular transfer function. Below is the procedure for gathering MATLAB simulated data for a system you wish to make into a physical system.

1. First you need to open the MATLAB file for your desired system and input type. The choices are on the Dropbox and are avaliable for each system.

2. The MATLAB files have coefficients corresponding to the characteristic equations of each system as well as some other constants in some systems. You have the ability to change these values in order to give a desired response. Below is an example of the RLC electrical systems coefficients.



```
%Voltage input from function generator (Volts)
A=5
%Resistance (Ohms), Inductance (Henreys), Capacitance (Farads) inputs
R=6;
L=.3;
C=.01*10^-6;
```

Figure 51: Coefficients in Command Window

3. Once you have set the coefficients and constants to your liking click “Run Section” to simulate your system. This may take a minute so be patient. Two figures will show up. One is the Bode and Frequency Plot and the other is your Time Plot. In the command prompt the transfer function will be generated.

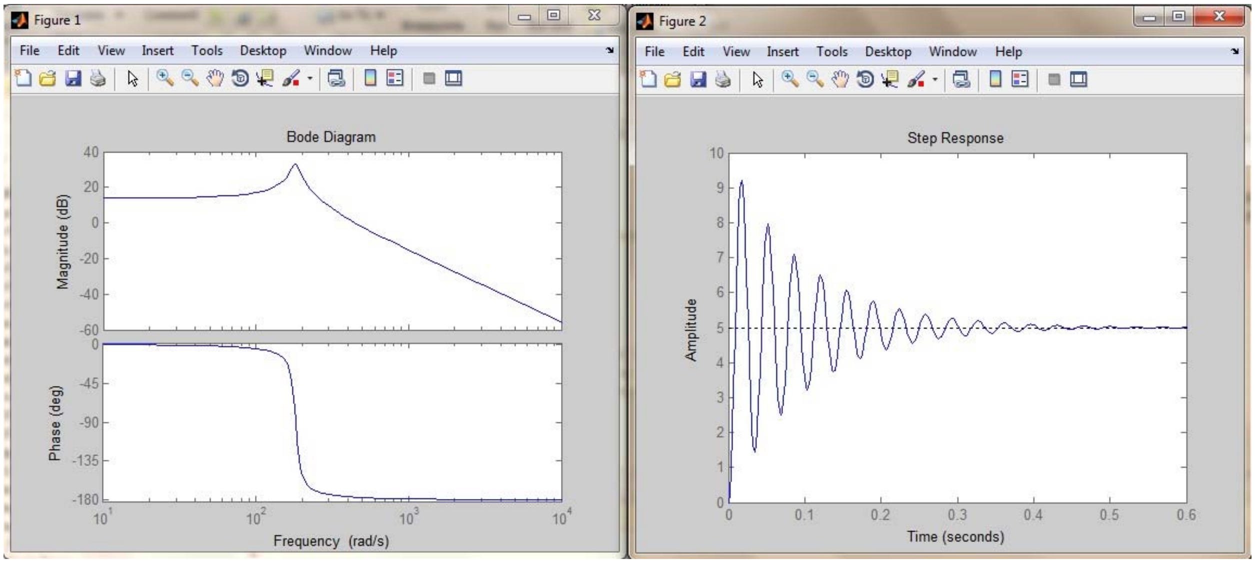
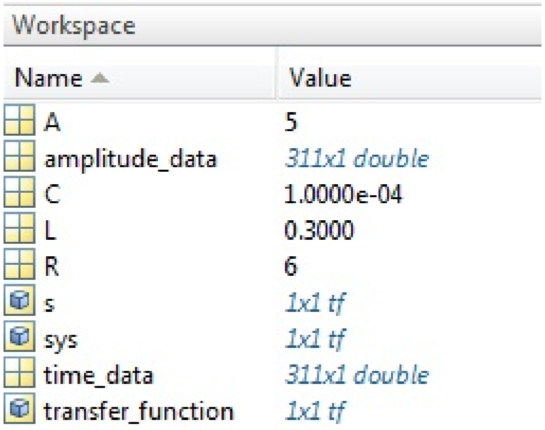


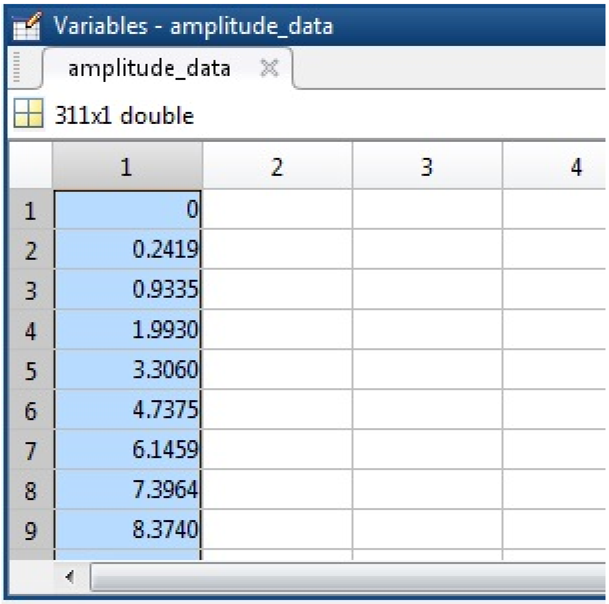
Figure 52: Bode, Frequency, and Time Domain Plots

4. To export your MATLAB data to Excel simply double click on the matrices that are in the format “### x 1” or “1 x ###” these are the row or column forms of the amplitude (pressure, voltage, etc) and the time data. An example is shown below “amplitude_data” and “time_data” are the desired matrixes, double click on them, then select all cells using CTRL+Shift+Down.



Name	Value
A	5
amplitude_data	*311x1 double*
C	1.0000e-04
L	0.3000
R	6
s	*1x1 tf*
sys	*1x1 tf*
time_data	*311x1 double*
transfer_function	*1x1 tf*

Figure 53: List of Arrays



	1	2	3	4
1	0			
2	0.2419			
3	0.9335			
4	1.9930			
5	3.3060			
6	4.7375			
7	6.1459			
8	7.3964			
9	8.3740			

Figure 54: Window after Double Clicking Array

1.4 Physical System Data Acquisition

1.4.1 Computer Software Setup and Drivers

The software that needs to be installed to record data is Labview 2012 or higher and a special driver for the Vernier SensorDAQ available at http://www.vernier.com/engineering/ni-labview/downloads/sdaq/. Below is what should be visible in the “Functions Palette” in the Labview VI.

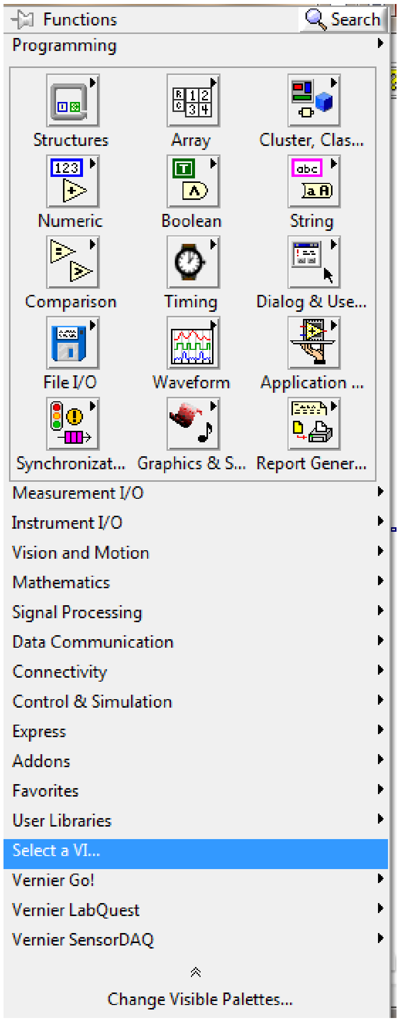


Figure 55: The Options that Need to be Avaliable are the Last 3

If you want to use LoggerPro for data acquisition you will need to install a driver that makes the Vernier SensorDAQ usable by LoggerPro. This driver is at http://www.vernier.com/support/drivers/

You now have the ability to operate your physical system. Below is the procedure for adjusting input and reading outputs to Excel using either Labview or LoggerPro.

1.4.2 LoggerPro Procedure

1. First attach all sensors to the Vernier SensorDAQ and plug it into the computer. Open LoggerPro.

2. Click on the drop down menu "Experiment", then "Set Up Sensors", then click "Auto Detect Sensors". If you do not have the proper drivers for Vernier SensorDAQ the asdf will be greyed out. To correct this make sure to download the driver listed above. Then close LoggerPro all the way and make sure the SensorDAQ is plugged in and re-open LoggerPro.

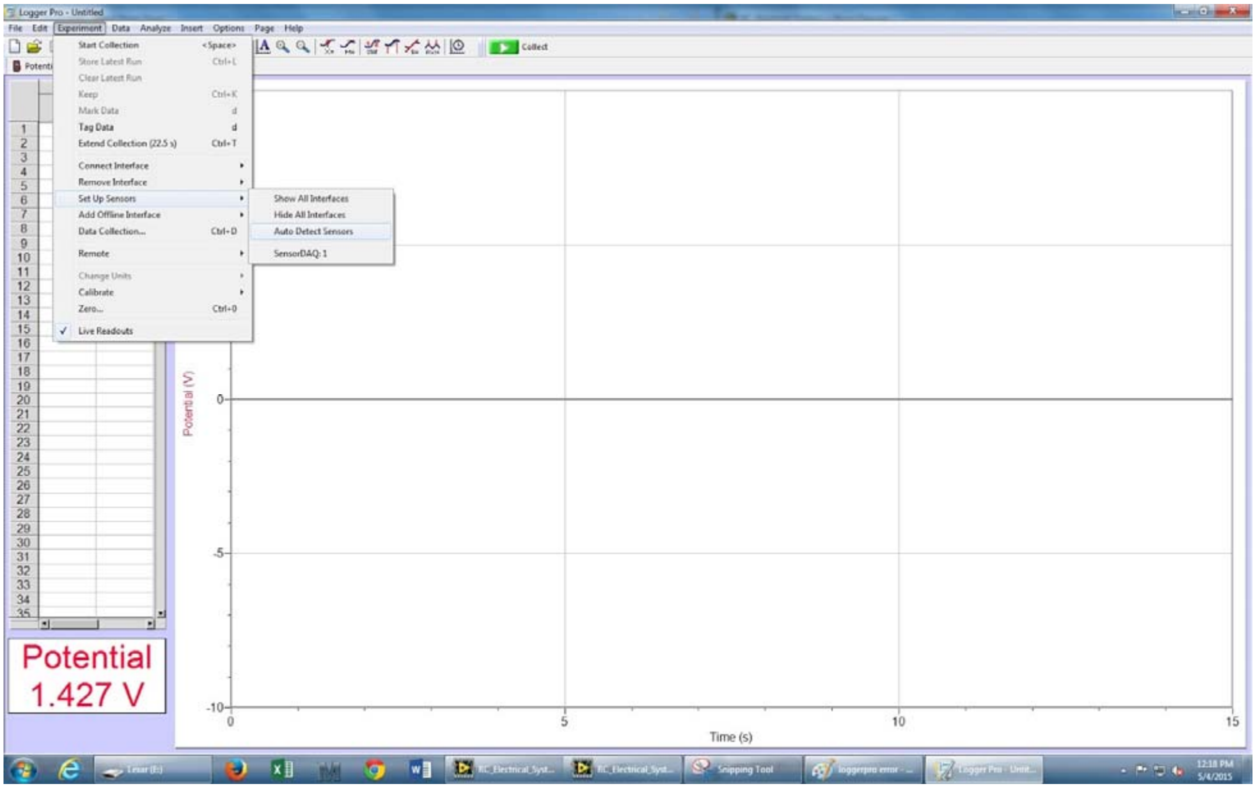


Figure 56: Highlighted Auto Detect Option

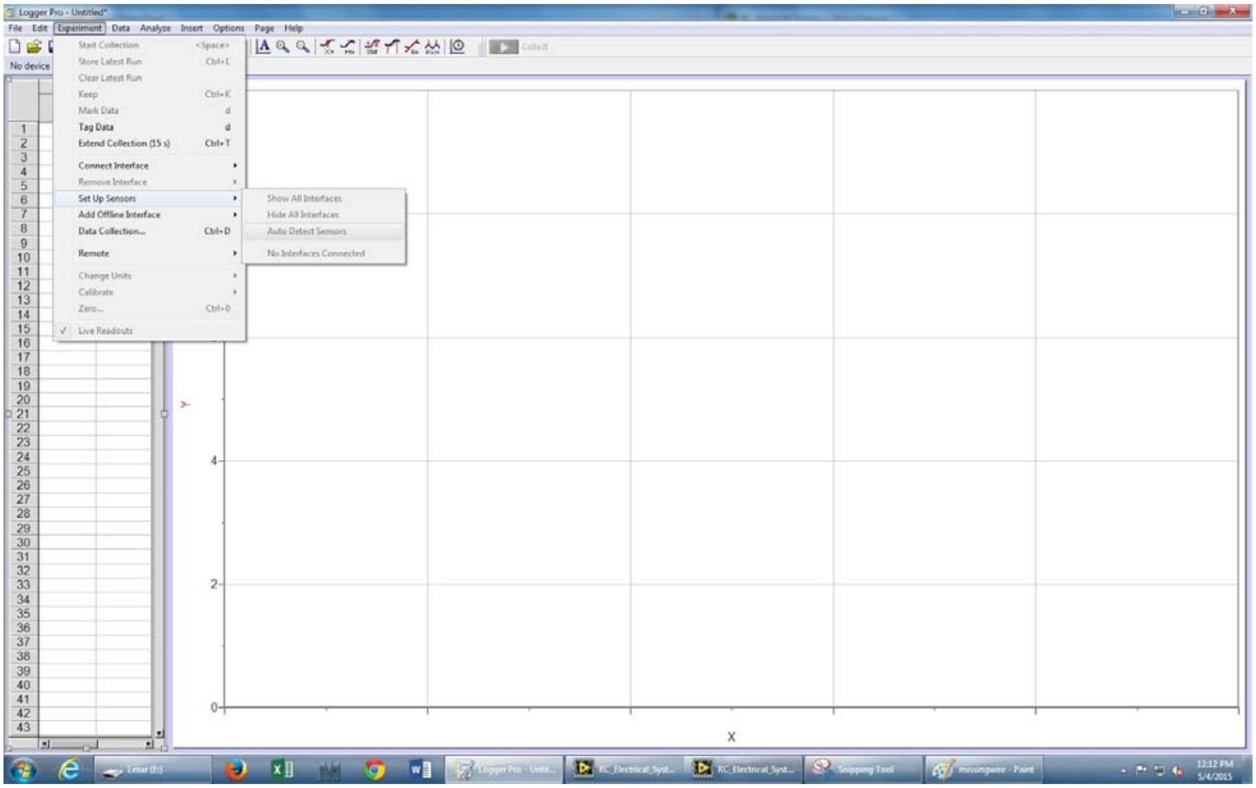


Figure 57: Non-highlighted Auto Detect Option

3. Once LoggerPro has detected the SensorDAQ and sensors it is time to calibrate them so that the data is in the proper magnitude range to be comparable to MATLAB data. Below is a list of the physical systems that require calibration and how to do it.

To calibrate your system in logger pro, click on the “experiment” tab at the top and open up the “calibrate” menu.

a. Pressure calibration

You must enter in two points to calibrate your system. Typically it is easy to use 0 psi as your first point and use any other pressure as your second point.

b. Thermal Calibration

The thermal calibration has already been done. In the calibration menu open the “equation” tab. Enter in 404 for the slope and -304 for the intercept.

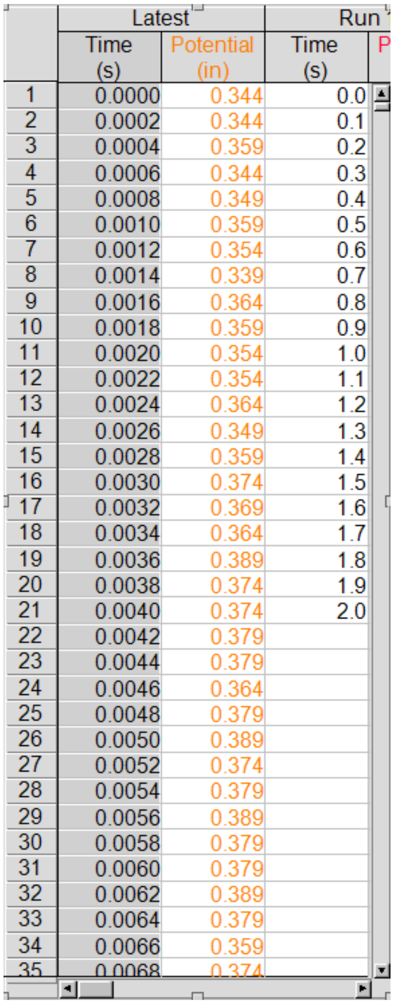
c. Electro mechanical calibration

Refer to the electro mechanical system info below.

4. Now you need to set up a time step and sample rate to ensure you are looking at a wide enough time range and collecting an appropriate amount of data points. To adjust this, click on the "experiment" tab at the top of logger pro. Open the data collection menu. From this menu you will be able to adjust the sample rate and overall run time.

5. Now you are ready to collect data. Sense LoggerPro collects live data you cannot just let it run continuously because it will stop at your time step. You will have to press "Collect" a small time before you perform the physical system experiment. Once you have collected the desired amount of data click "End" or just simply let your time step run out.

6. Now you can select your data by clicking on the title of the column and it selects all data points, copy, then paste to Excel.

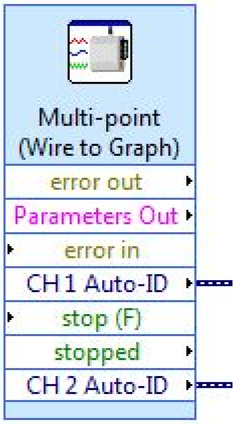


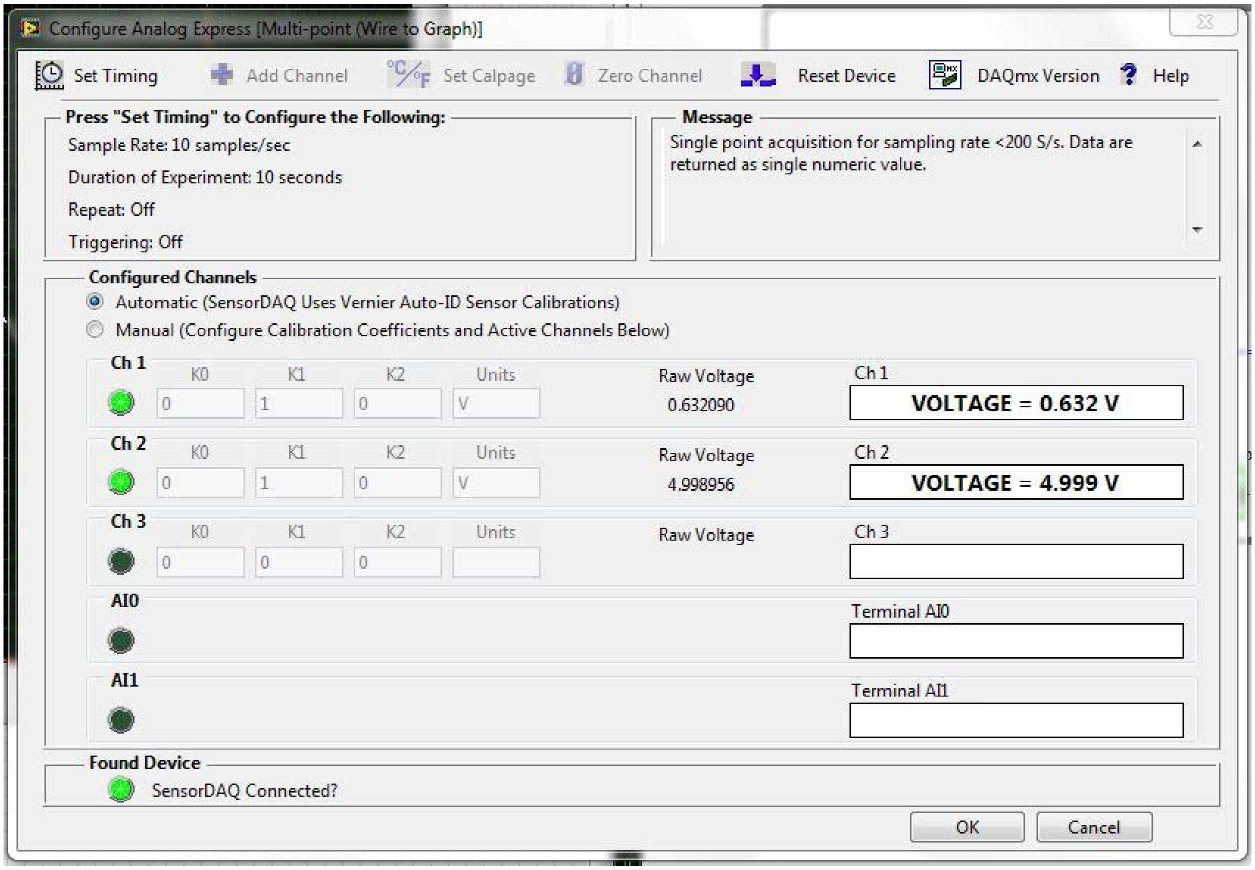
	Latest		Run	
	Time (s)	Potential (in)	Time (s)	P
1	0.0000	0.344	0.0	
2	0.0002	0.344	0.1	
3	0.0004	0.359	0.2	
4	0.0006	0.344	0.3	
5	0.0008	0.349	0.4	
6	0.0010	0.359	0.5	
7	0.0012	0.354	0.6	
8	0.0014	0.339	0.7	
9	0.0016	0.364	0.8	
10	0.0018	0.359	0.9	
11	0.0020	0.354	1.0	
12	0.0022	0.354	1.1	
13	0.0024	0.364	1.2	
14	0.0026	0.349	1.3	
15	0.0028	0.359	1.4	
16	0.0030	0.374	1.5	
17	0.0032	0.369	1.6	
18	0.0034	0.364	1.7	
19	0.0036	0.389	1.8	
20	0.0038	0.374	1.9	
21	0.0040	0.374	2.0	
22	0.0042	0.379		
23	0.0044	0.379		
24	0.0046	0.364		
25	0.0048	0.379		
26	0.0050	0.389		
27	0.0052	0.374		
28	0.0054	0.379		
29	0.0056	0.389		
30	0.0058	0.379		
31	0.0060	0.379		
32	0.0062	0.389		
33	0.0064	0.379		
34	0.0066	0.359		
35	0.0068	0.374		

1.4.3 Labview Procedure

1. The Labview program to be used is asdf. Open this program and the VI Front Panel will appear, press CTRL+E to get the VI Block Diagram.

2. The sampling settings need to be changed depending on the physical system and the components you decide to use. A good estimation of these settings can be inferred from the MATLAB figures and time constant of your system. To adjust the sample rate and number of samples you desire double click on the “Multi-point (Wire to Graph)” and go to “Set Timing”. Make sure the samples/second is greater than 200 or else there will be an error.





Press "Set Timing" to Configure the Following:

Sample Rate: 10 samples/sec

Duration of Experiment: 10 seconds

Repeat: Off

Triggering: Off

Message

Single point acquisition for sampling rate <200 S/s. Data are returned as single numeric value.

Configured Channels

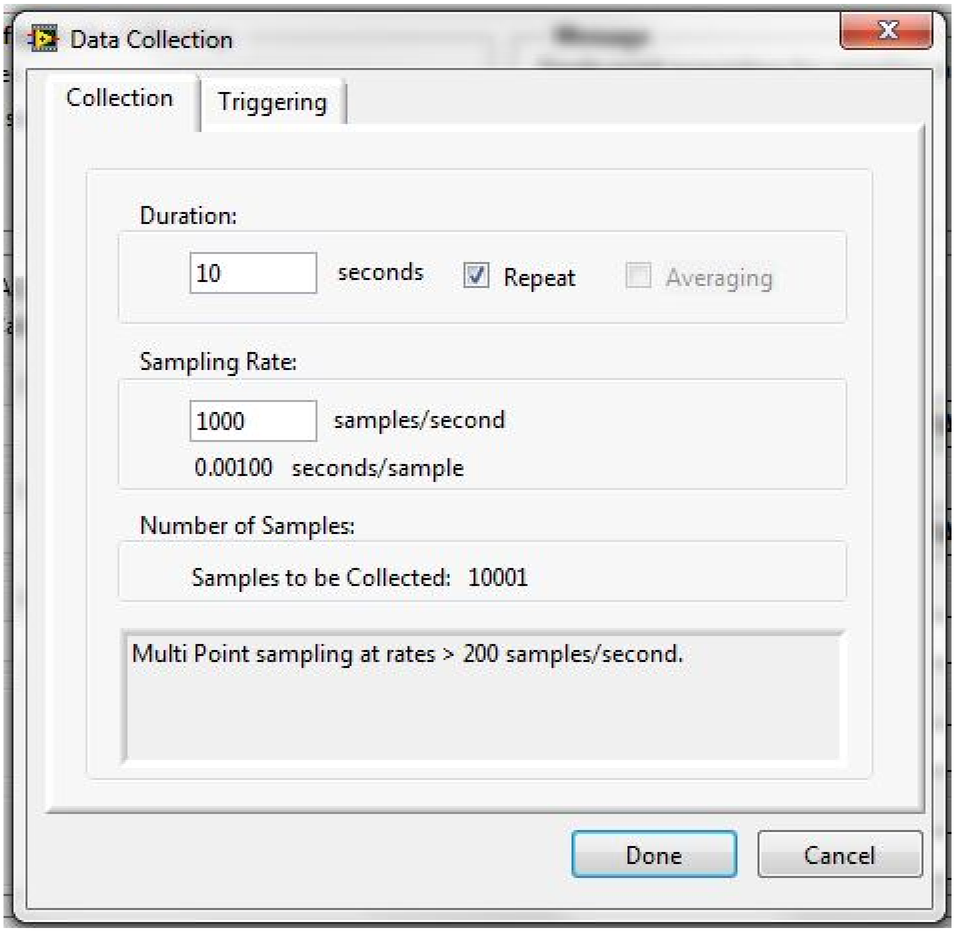
● Automatic (SensorDAQ Uses Vernier Auto-ID Sensor Calibrations)

○ Manual (Configure Calibration Coefficients and Active Channels Below)

	K0	K1	K2	Units	Raw Voltage	
Ch 1 ●	0	1	0	V	0.632090	Ch 1: VOLTAGE = 0.632 V
Ch 2 ●	0	1	0	V	4.998956	Ch 2: VOLTAGE = 4.999 V
Ch 3 ●	0	0	0			Ch 3:
AI0 ●						Terminal AI0:
AI1 ●						Terminal AI1:

Found Device

● SensorDAQ Connected?



Duration:

10 seconds ☑ Repeat ☐ Averaging

Sampling Rate:

1000 samples/second

0.00100 seconds/sample

Number of Samples:

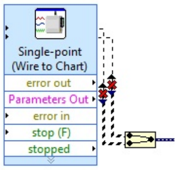
Samples to be Collected: 10001

Multi Point sampling at rates > 200 samples/second.

3. Run the Labview program. The graph will autoscale and will update once your desired time interval has elapsed and continue until the program is stopped. This means that Labview is NOT a live feedback program, if you want live graphing use LoggerPro. If the program is unable to run below are some common debugging items.

a. Make sure the DAQ icon is “Multi-point (Wire to Graph)” not “Single-point”. This is when samples/second is below 200.

b. If a DAQ channel is physically removed when editing the DAQ, the wiring on Labview may change and not be connected properly anymore. To fix this CTRL+B then rewire the desired channels.



4. You can stop at any time to look at a sample of data and scale the graph to your liking by right clicking on the graph and selecting "Properties".

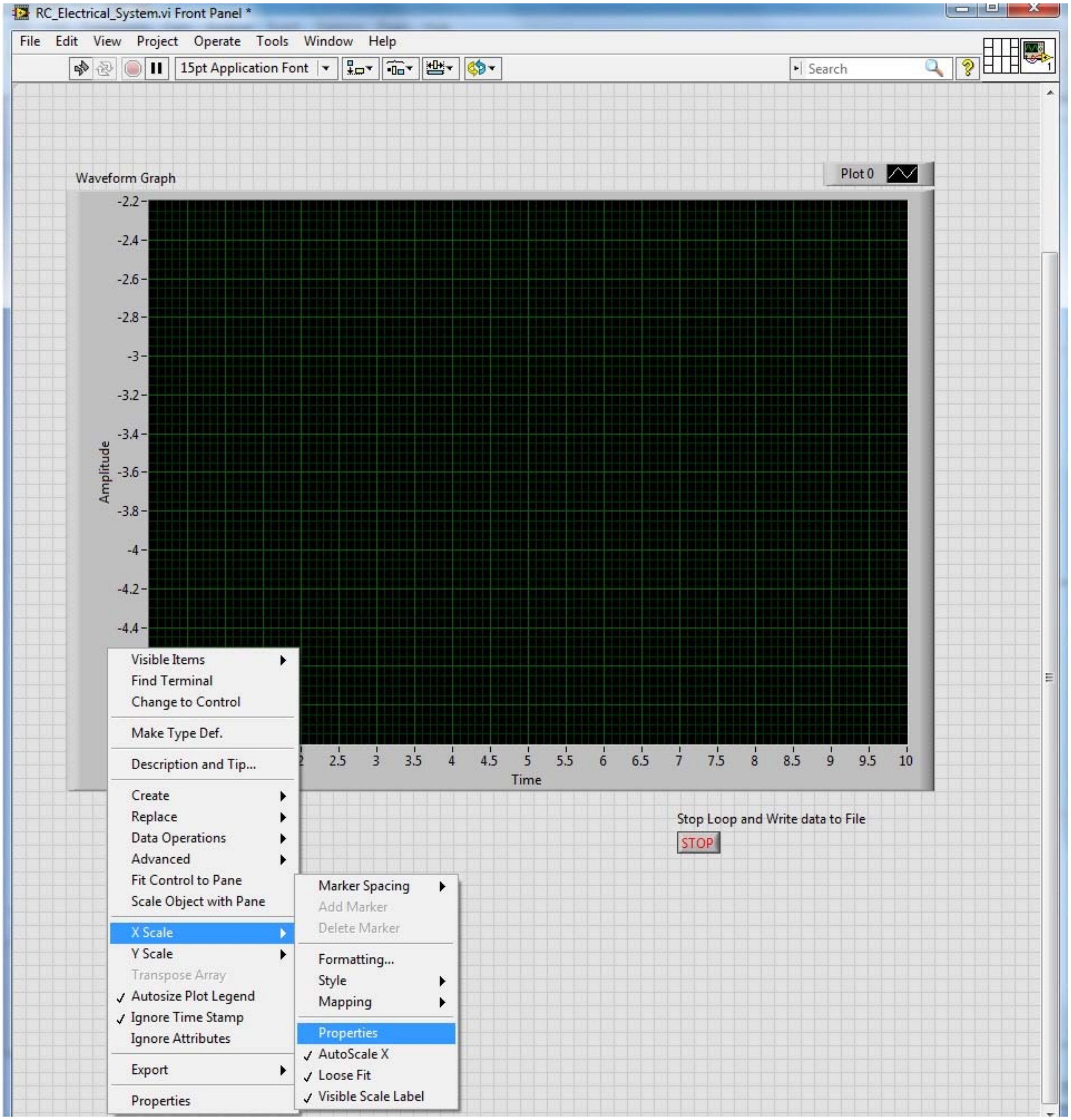
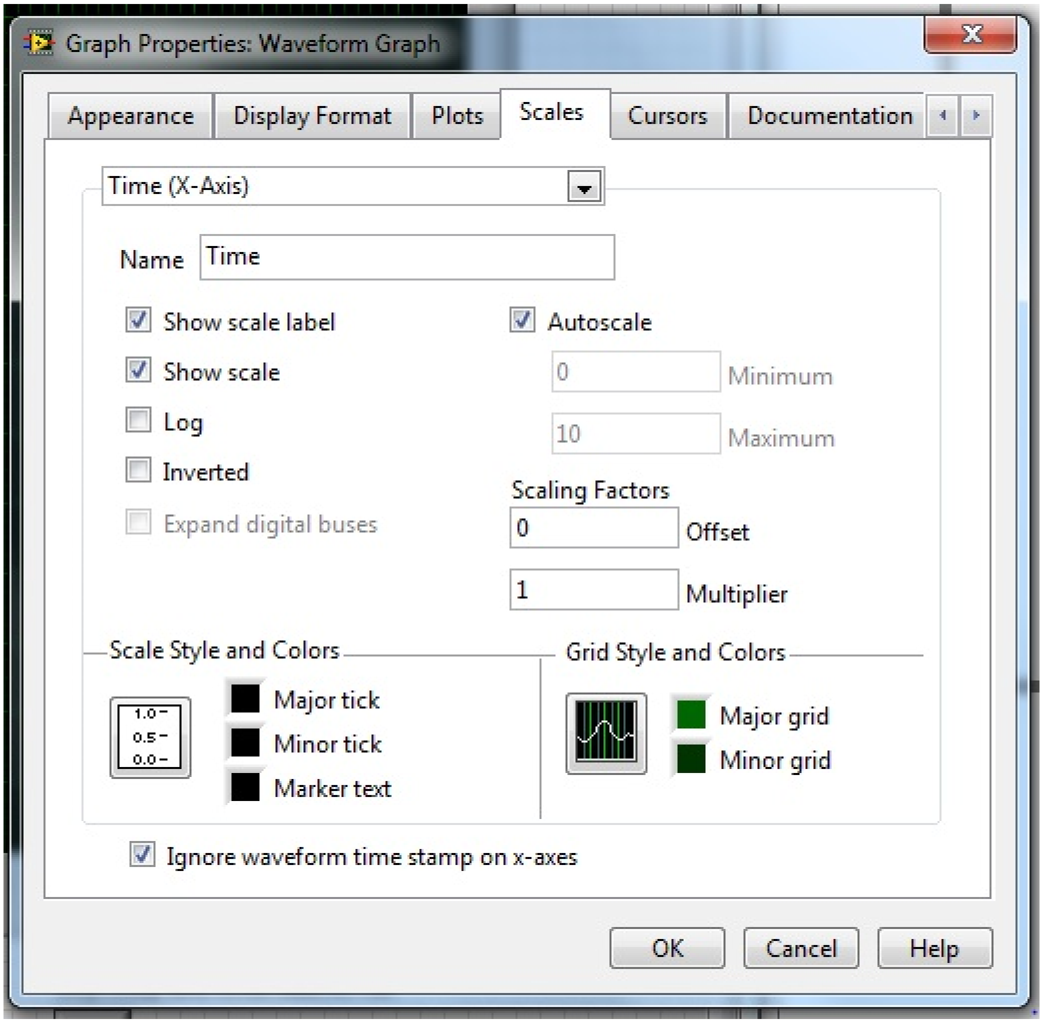


Figure 58: Drop down Menu



Time (X-Axis)

Name: Time

☑ Show scale label
☑ Show scale
☐ Log
☐ Inverted
☐ Expand digital buses

☑ Autoscale
0 Minimum
10 Maximum

Scaling Factors
0 Offset
1 Multiplier

Scale Style and Colors
■ Major tick
■ Minor tick
■ Marker text

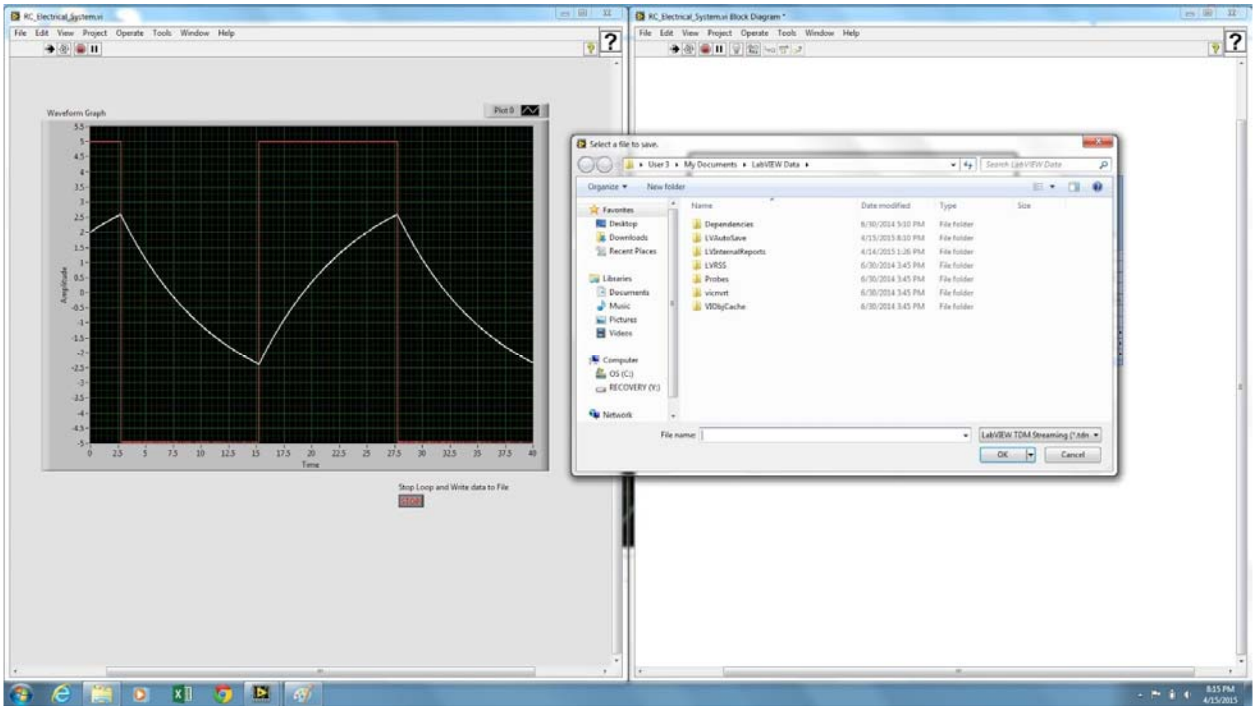
Grid Style and Colors
🟩 Major grid
🟩 Minor grid

☑ Ignore waveform time stamp on x-axes

Figure 59: Settings for the Graph

5. Once your program is running and you have a desired window of data you can write the data to Excel. First hit the “Stop Loop and Write to File” which tells the program to end cycling and write data. Sometimes the program will not stop, and the stop button will become unclicked after an iteration, simply re-press the stop button. There is no explanation for this at the moment.

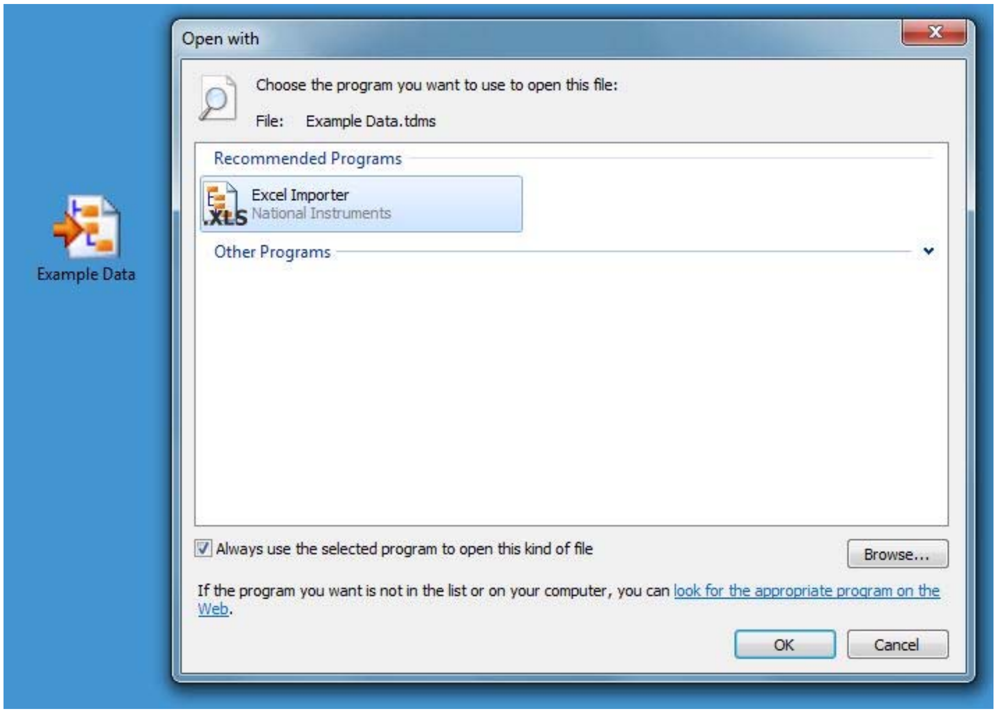
Once the iteration has stopped you will be prompted to save data. You can save the file anywhere, but remember where you have saved it.



Name	Date modified	Type	Size
Dependencies	6/30/2014 5:10 PM	File folder	
LVAutoSave	4/15/2015 8:10 PM	File folder	
LVInternalReports	4/14/2015 1:26 PM	File folder	
LVRSS	6/30/2014 3:45 PM	File folder	
Probes	6/30/2014 3:45 PM	File folder	
vicmvrt	6/30/2014 3:45 PM	File folder	
VIObjCache	6/30/2014 3:45 PM	File folder	

Figure 60: Save Block

Go to the saved data file, right click, “Open With”, and “Excel Importer”. Be careful to right click on the correct file, the correct fill will be a .tdms file with a graphic like the one below and there will be another file of the same name with no graphic which is the incorrect file.



Choose the program you want to use to open this file:

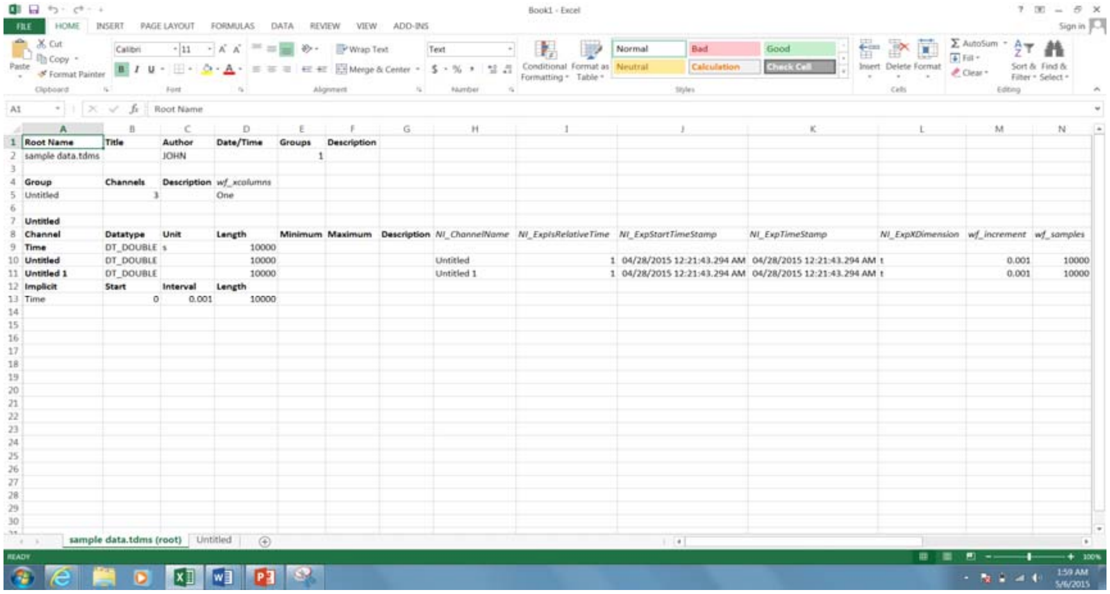
File: Example Data.tdms

☑ Always use the selected program to open this kind of file

If the program you want is not in the list or on your computer, you can look for the appropriate program on the Web.

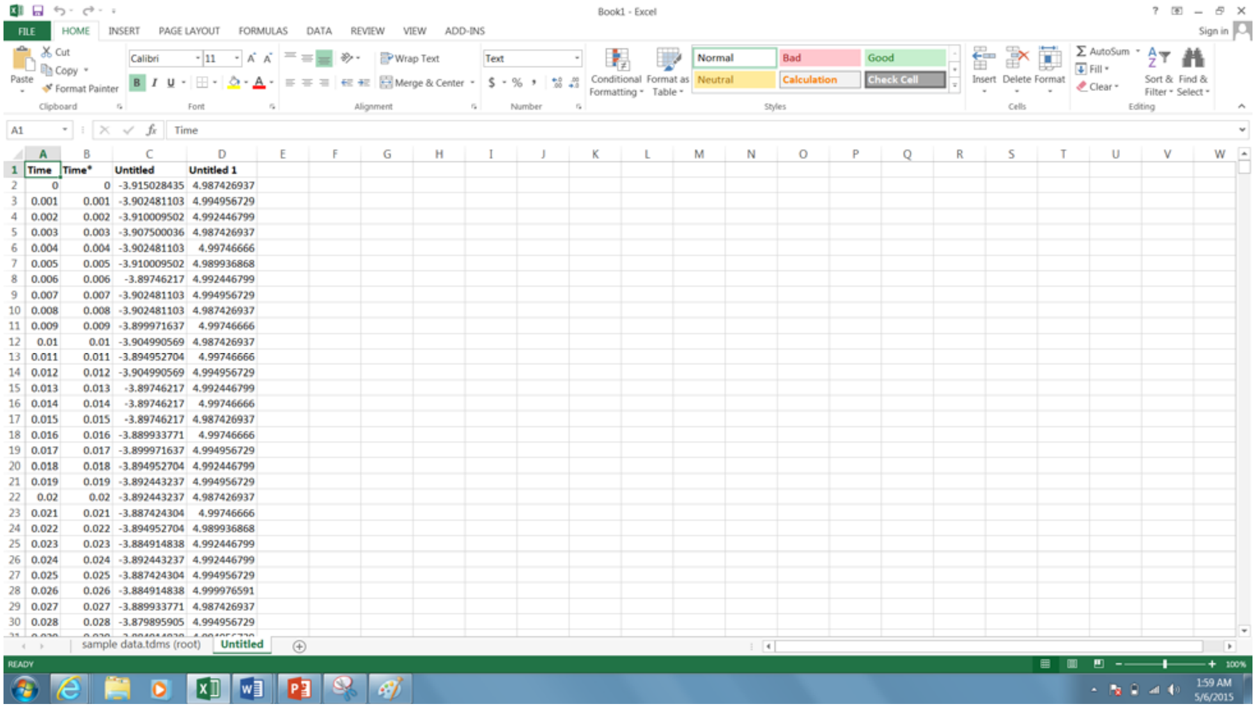
Figure 61: Opening Data into Excel

6. Your data will now be in Excel. The first sheet is information that is not useful to you, but the second sheet contains the data from the graph in Labview.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Root Name**	**Title**	**Author**	**Date/Time**	**Groups**	**Description**								
2	sample data.tdms		JOHN		1									
3														
4	**Group**	**Channels**	**Description**	*wf_xcolumns*										
5	Untitled	3		One										
6														
7	**Untitled**													
8	**Channel**	**Datatype**	**Unit**	**Length**	**Minimum**	**Maximum**	**Description**	*NI_ChannelName*	*NI_ExpIsRelativeTime*	*NI_ExpStartTimeStamp*	*NI_ExpTimeStamp*	*NI_ExpXDimension*	*wf_increment*	*wf_samples*
9	**Time**	DT_DOUBLE	s	10000										
10	**Untitled**	DT_DOUBLE		10000				Untitled	1	04/28/2015 12:21:43.294 AM	04/28/2015 12:21:43.294 AM	t	0.001	10000
11	**Untitled 1**	DT_DOUBLE		10000				Untitled 1	1	04/28/2015 12:21:43.294 AM	04/28/2015 12:21:43.294 AM	t	0.001	10000
12	**Implicit**	**Start**	**Interval**	**Length**										
13	Time	0	0.001	10000										

Figure 62: Sheet 1 the Useless Data



	A	B	C	D
1	**Time**	**Time***	**Untitled**	**Untitled 1**
2	0	0	-3.915028435	4.987426937
3	0.001	0.001	-3.902481103	4.994956729
4	0.002	0.002	-3.910009502	4.992446799
5	0.003	0.003	-3.907500036	4.987426937
6	0.004	0.004	-3.902481103	4.99746666
7	0.005	0.005	-3.910009502	4.989936868
8	0.006	0.006	-3.89746217	4.992446799
9	0.007	0.007	-3.902481103	4.994956729
10	0.008	0.008	-3.902481103	4.987426937
11	0.009	0.009	-3.899971637	4.99746666
12	0.01	0.01	-3.904990569	4.987426937
13	0.011	0.011	-3.894952704	4.99746666
14	0.012	0.012	-3.904990569	4.994956729
15	0.013	0.013	-3.89746217	4.992446799
16	0.014	0.014	-3.89746217	4.99746666
17	0.015	0.015	-3.89746217	4.987426937
18	0.016	0.016	-3.889933771	4.99746666
19	0.017	0.017	-3.899971637	4.994956729
20	0.018	0.018	-3.894952704	4.992446799
21	0.019	0.019	-3.892443237	4.994956729
22	0.02	0.02	-3.892443237	4.987426937
23	0.021	0.021	-3.887424304	4.99746666
24	0.022	0.022	-3.894952704	4.989936868
25	0.023	0.023	-3.884914838	4.992446799
26	0.024	0.024	-3.892443237	4.992446799
27	0.025	0.025	-3.887424304	4.994956729
28	0.026	0.026	-3.884914838	4.999976591
29	0.027	0.027	-3.889933771	4.987426937
30	0.028	0.028	-3.879895905	4.994956729

Figure 63: Sheet 2 the Useful Data

2.0 Electrical System

2.1 Introduction and Description

The physical electrical systems consist of RC and RLC circuits that are constructed on a breadboard which is attached to a baseplate that has a top box that can hide the breadboard. You have the ability to adjust what kind of response you want by changing components. A MATLAB program gives ideal response values and can be used to test component values. Labview or LoggerPro can be used to acquire data from the physical system. A video of us showing the system setup is available in the Dropbox.

2.2 Materials to Operate System

The material list required to run the electrical system is shown below.

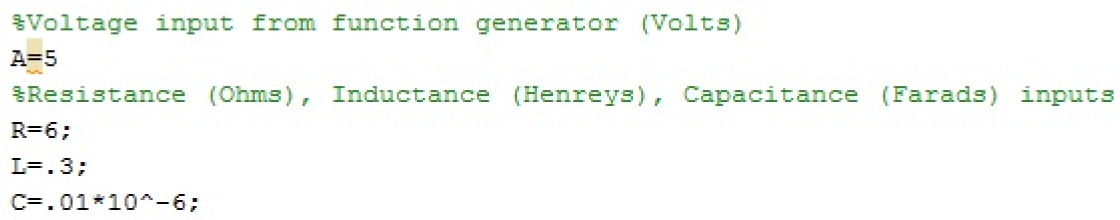
Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
2	$1.49	1	$1.49	100uF 50V 20% Radial-Lead Capacitor	2721044	Radio Shack
3	$7.99	1	$7.99	100-Piece 1/2-watt Carbon-filmed Resistors Assortment	2710306	Radio Shack
4	$39.06	1	$39.06	Hammond 159ZA Choke, 0.3H, 1A Inductor	159ZA	Hammond through Amazon.com
5	$23.80	1	$23.80	Hammond Fixed Inductor D.C. Filter Choke 5H	158Q	Hammond through Amazon.com
6	$8.49	1	$8.49	3 color set 22-gauge single strand wire	2781224	Radio Shack
			Total System Cost			
			$104.80			

2.3 Computer Modeling

The MATLAB models can used to simulate a system before you construct it, collect data to export to Excel, and find the transfer function. Below is the specifics on the electrical system which will reference Section 1.3.

1. First you need to open the MATLAB file for your desired electrical system and input type. The choices are available in the Dropbox.

2. The MATLAB files have coefficients for resistor (R), capacitor (C), inductor (L), and Amplitude (A). You can change these values to match your components. An important note for RLC circuits is that inductors have a built in measurable resistance that usually does not require the addition of a physical resistor, just input the resistance value of the inductor into MATLAB.



```
%Voltage input from function generator (Volts)
A=5
%Resistance (Ohms), Inductance (Henreys), Capacitance (Farads) inputs
R=6;
L=.3;
C=.01*10^-6;
```

3. Now refer to Section 1.3 for the specifics on how to run and acquire data from MATLAB.

2.4 Physical System Setup

The physical setup consists of the box and baseplate with the breadboard fixed to it. You have the ability to change out the resistor, capacitor and inductor values on the breadboard. (the inductor has a set of 3 screw holes to use for changing it out). Below is a picture of each of the possible setups Low Pass, High Pass, and RLC.

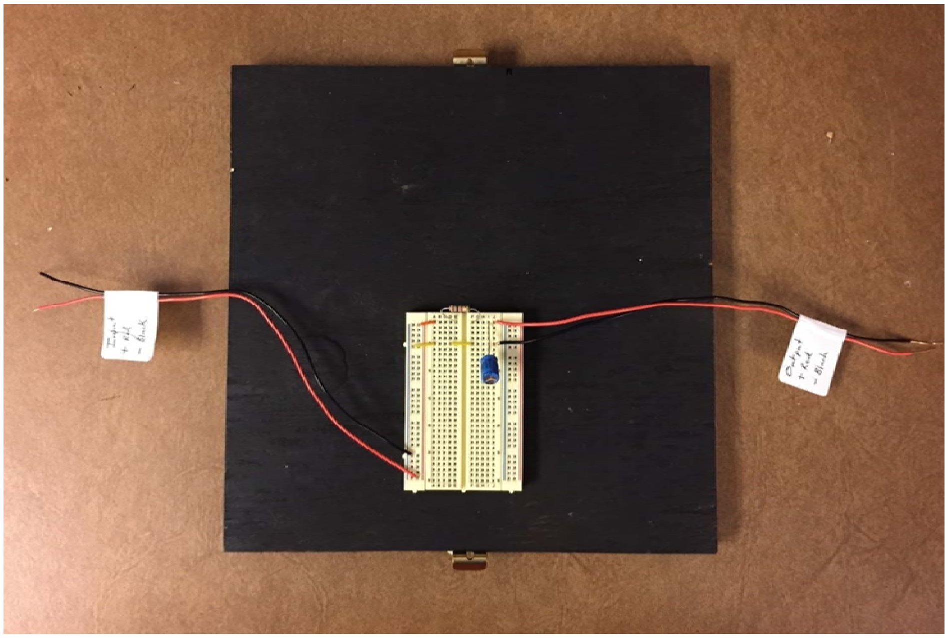


Figure 64: RC Circuit

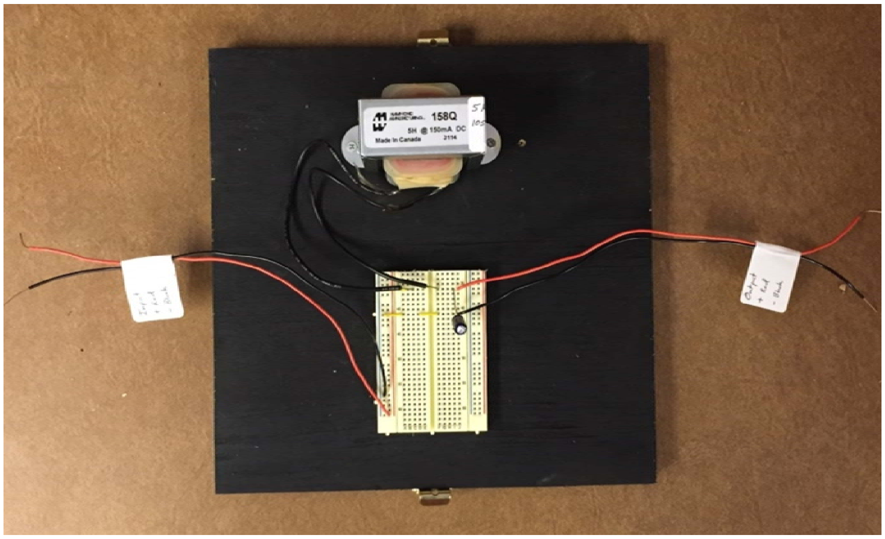


Figure 65: RLC Circuit

The RC and RLC circuits have the ability to be hidden from view in the black box.

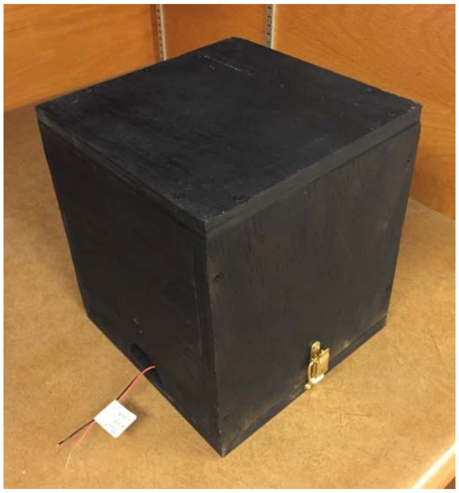


Figure 66: Black Box

Below are pictures of how to wire the electrical systems. You must plug the function generator into the “Input” labeled wires. The oscilloscope is plugged into the “Output” labeled wires, you can also attach the oscilloscope to the input with a second channel if desired.

The electrical system is now ready to be run for data acquisition. Below is the procedure for running the system, this will reference Section 1.4 for how to collect data.

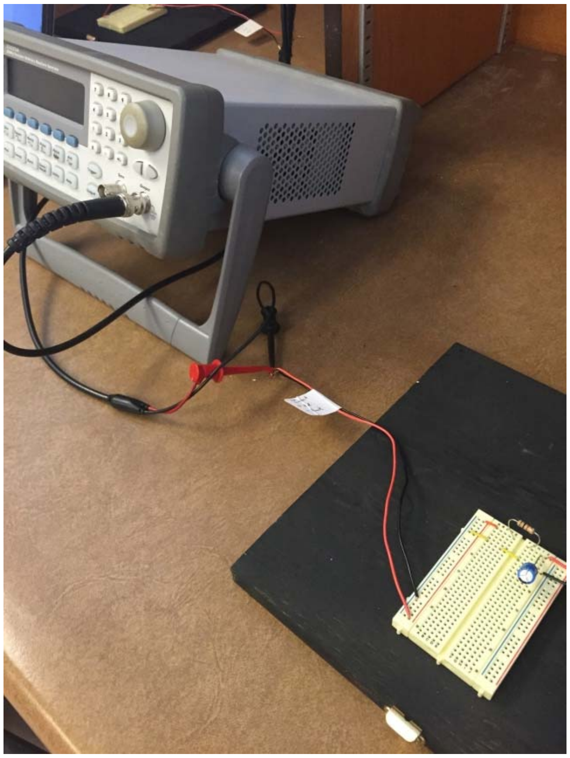


Figure 67: Input Wiring

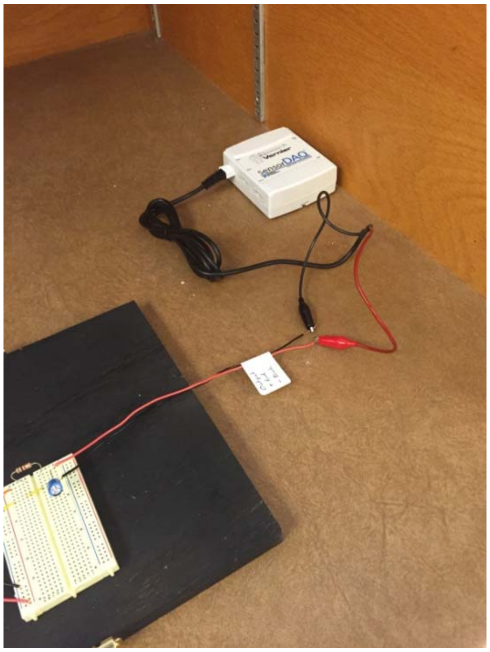


Figure 68: Output Wiring

2.5 Physical System Operation

The electrical system is now ready to be run for data acquisition. Below is the procedure for running the system, this will reference Section 1.4 for how to collect data.

1. Turn the function generator and oscilloscope on. Set the function generator to have a Vpp of 10V and a period of 10 time constants.
2. Click "output" on the function generator.
3. Adjust the time scale and voltage scale (x and y) on the oscilloscope to get a good view of the entire response.
4. Follow the steps in Section 1.4 to collect data.

2.6 Safety Considerations

The only safety concern with the electrical systems is the damaging of electrical components or electrocution from them. If you use large value capacitors (over uF) the risk of shorting one and shocking yourself increases. Just be sure not to touch capacitor leads together with your fingers and use a resistor to short them as shown below.

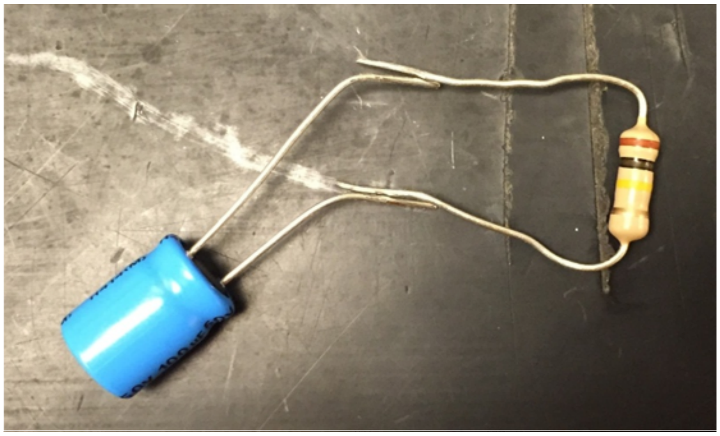


Figure 69: Decharging Capacitors

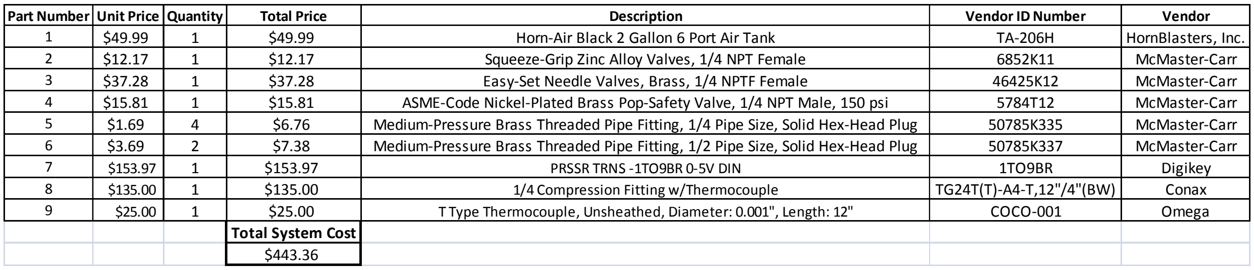
3.0 Choked Flow Blowdown System

3.1 Introduction of the Choked Flow Blowdown

The baseplate that has the pressure tank on it has the ability to perform 3 different experiments. The one covered in this section is the Choked Flow Blowdown which consists of allowing air out of a tank through a variable needle valve. You have the ability to change the opening size on the needle valve to achieve different flow rates. A MATLAB program gives ideal response values and can be used to compare real and ideal blowdown processes. The change in pressure vs. time is best tracked in LoggerPro so that a live graph can be generated and the data can be transferred to Excel. A video of us showing the system setup and operation is available in the Dropbox folders.

3.2 Materials for Choked Flow Blowdown

The Choked Flow Blowdown System materials list is shown below.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$49.99	1	$49.99	Horn-Air Black 2 Gallon 6 Port Air Tank	TA-206H	HornBlasters, Inc.
2	$12.17	1	$12.17	Squeeze-Grip Zinc Alloy Valves, 1/4 NPT Female	6852K11	McMaster-Carr
3	$37.28	1	$37.28	Easy-Set Needle Valves, Brass, 1/4 NPTF Female	46425K12	McMaster-Carr
4	$15.81	1	$15.81	ASME-Code Nickel-Plated Brass Pop-Safety Valve, 1/4 NPT Male, 150 psi	5784T12	McMaster-Carr
5	$1.69	4	$6.76	Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Solid Hex-Head Plug	50785K335	McMaster-Carr
6	$3.69	2	$7.38	Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Pipe Size, Solid Hex-Head Plug	50785K337	McMaster-Carr
7	$153.97	1	$153.97	PRSSR TRNS -1TO9BR 0-5V DIN	1TO9BR	Digikey
8	$135.00	1	$135.00	1/4 Compression Fitting w/Thermocouple	TG24T(T)-A4-T,12"/4"(BW)	Conax
9	$25.00	1	$25.00	T Type Thermocouple, Unsheathed, Diameter: 0.001", Length: 12"	COCO-001	Omega
			Total System Cost			
			$443.36			

3.3 Computer Modeling

The MATLAB program for choked flow has many constants and coefficients listed in it that we calculated. As follows is the equations used and reference to "asdfasf on how to use and collect data from this program.

We utilized the choked flow equation assuming the process was adiabatic until the pressure reached 30 psi:

$$\dot{m} = C_d A \sqrt{k \rho P (\frac{2}{k+1})^{\frac{k+1}{k-1}}}$$

where,

$\dot{m} = mass\ flow\ rate, \frac{slugs}{s}$

$C_d = discharge\ coefficient\ of\ valve$

$A = area\ of\ outlet, in^2$

$k = \frac{c_p}{c_v} specific\ heat\ ratio$

$\rho = density\ of\ air\ in\ tank, \frac{slugs}{in^3}$

$P = pressure\ of\ air\ in\ tank, \frac{slugs}{in - s^2}$

We also assumed that the air acted as an ideal gas so that we could use the ideal gas law:

$$PV = mRT$$

where,

$P = pressure\ of\ air\ in\ tank, \frac{slugs}{in - s^2}$

$V = volume\ of\ tank, in^3$

$m = mass\ of\ air\ in\ tank, slugs$

$R = ideal\ gas\ constant\ for\ air, \frac{psi - in^3}{slug - {}^\circ R}$

$T = temperature\ of\ air\ inside\ tank, {}^\circ R$

The final equation we used was developed from assuming a polytropic adiabatic process:

$$Pv^n = const.$$

where,

$P = pressure\ of\ air\ in\ tank, \frac{slugs}{in - s^2}$

$v = \frac{1}{\rho}\ specific\ volume\ of\ air\ in\ tank, \frac{in^3}{slugs}$

$n = k = \frac{c_p}{c_v} specific\ heat\ ratio$

To solve the differential equation we decided to use Euler's Method:

$$m'(t) = f\big(t, m(t)\big), \quad m(t_0) = m_0$$

$$t_{n+1} = t_n + h$$

$$m_{n+1} = m_n + hf(t_n, m_n)$$

where h is the time step size. We decided to use 0.01 seconds as our step size and run our simulation for 10 seconds total. To find the initial mass we used the ideal gas law. After determining what our initial mass was, we plugged it into our differential equation to solve for the next mass (using Euler's Method). Once we knew our next mass, we plugged that in to our polytropic process equation to solve for the new pressure. Once the new pressure was found, we were able to use that in our differential equation to solve for the next mass, thus creating our loop. Note that the conversion of the pressure from psi to slug/in-s is done in the Matlab code, and the user inputs the pressure in psi. The known variables for our experiment are shown below as well as how we found them:

$C_d = 0.51\ provided\ by\ vendor$

$A = 0.031416\ in^2\ determined\ from\ diameter\ of\ valve\ exit$

$k = 1.4\ known\ from\ adiabatic\ assumption$

$\rho_0 = 7.3 \times 10^{-6}\ \frac{slugs}{in^3}\ determined\ from\ initial\ mass\ of\ air\ and\ volume\ of\ tank$

$P_0 = 80\ psig\ we\ chose\ to\ pressurize\ the\ tank\ to\ this\ value$

$V = 462\ in^3\ known\ volume\ of\ the\ tank\ (2\ gallon\ tank)$

$m_0 = 0.003373\ slugs\ calculated\ using\ ideal\ gas\ law$

$R = 20608\ \frac{psi - in^3}{slug - °R}\ determined\ using\ \frac{\bar{R}}{M}\ where\ M\ is\ the\ molar\ mass\ of\ air$

$T_0 = 531.67\ °R\ assumed\ to\ be\ room\ temperature\ (72\ °F)$

To use the Matlab code, simply open the Matlab file “Blowdown_Tank_Choked_Fast_Good.m" and select “Run Section” at the top. This will run the code and output pressure vs. time and temperature vs. time plots. On the right side, the user can double click the “P” matrix and the “t” matrix to see each pressure and temperature value. The user can then highlight these values, copy them, and paste them in an excel file to create a plot in Excel.

3.4 Physical System Setup

The physical setup consists of the blowdown tank with the pressure transducer wired to the Vernier SensorDAQ. The Vernier SensorDAQ is reading the voltage change from the pressure transducer. Below is a picture of the wiring.

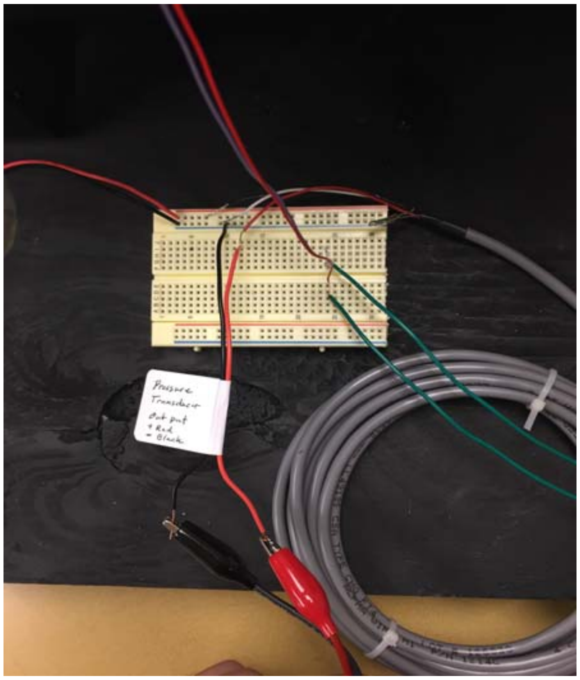


Figure 70: Pressure Tranducer Output Wiring

The pressure transducer requires a 8-28 volt power source. This can be achieved using a number of methods (powered breadboard, DC power supply), in our example we use a powered breadboard wired to our pressure transducer as shown below.

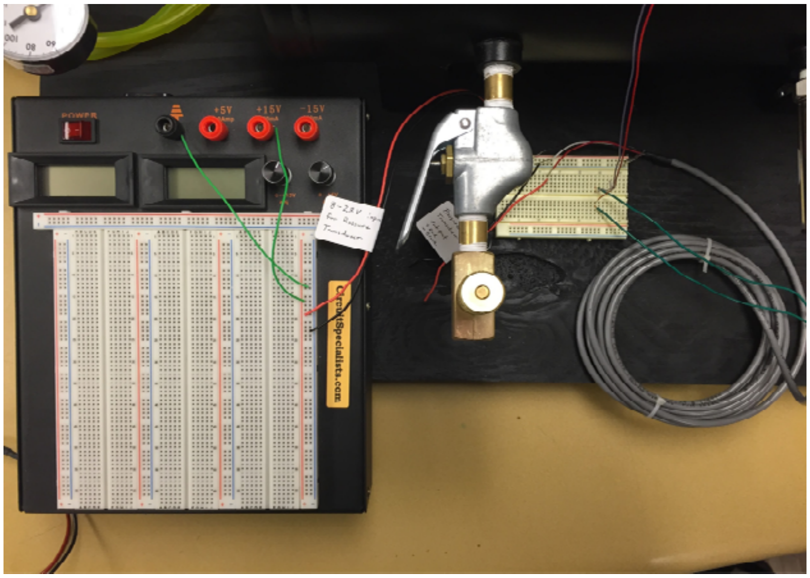


Figure 71: Pressure Transducer Power Wiring

3.5 Physical System Operation

You now have the ability to operate your choked flow system. Below is the procedure for operating the system which will reference Section 1.4 on how to collect data.

1. First make sure that the fill valve is closed (vertical) before the pressurization hose is connected. You have many options on how to fill the tank, but your option must uses an industrial female end NPT connector as shown below.

Figure 72: Charging the Tank with Air

2. Connect the female end and open the fill valve, this will fill the vessel with air. As you fill be sure NOT to go over 150 psi which is the max pressure for operating the tank. Going to 150 psi will pop the safety valve which can startle you when it happens. To stop the filling process close the fill valve (vertical).

Figure 73: Safety Valve and Gage

3. Set the needle valve to a desired opening size by turning it and observing the color on the inside of the collar. Once this is done you are now ready to perform the experiment.

Figure 74: (Left to Right) Quick Release and Needle Valve

4. Refer to [Section 1.4](#) for data acquisition. This will walk you through calibration, sampling settings, and data collection. To perform the release of the air completely open the quick release valve for the entire time of data collection.

3.6 Safety Considerations

The tank is rated for an operating pressure of 150 psi. We have installed a 150 psi pop safety valve which will not let the tank go over 150 psi. The air being released from the fill valve or the needle valve can come out at a fast rate so make sure not to stand too close or have objects near these openings.

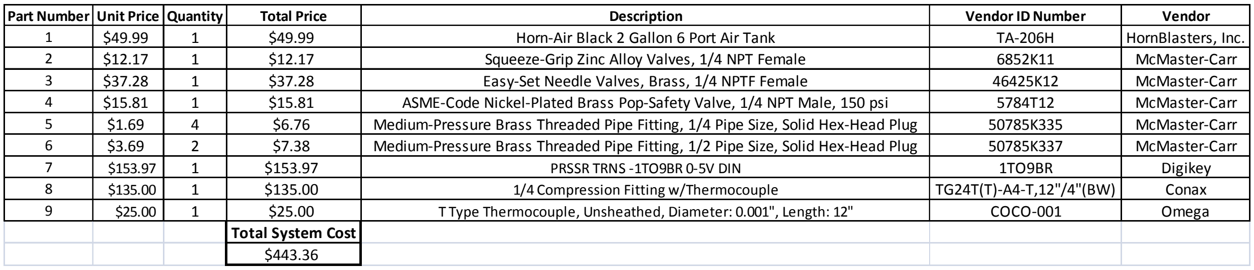
4.0 Laminar Blowdown System

4.1 Introduction of Laminar Blowdown System

The baseplate that has the pressure tank on it has the ability to perform 3 different experiments. The one covered in this section is the Laminar Blowdown which consists of allowing air out of a tank through a length of tubing. A MATLAB program gives ideal response values and can be used to compare real and ideal blowdown processes. The change in pressure vs. time is best tracked in LoggerPro so that a live graph can be generated and the data can be transferred to Excel. A video of us showing the system setup and operation is available in the Dropbox file.

4.2 Materials for Laminar Blowdown

The Laminar Blowdown System materials list is shown below, but they are the same as the Choked Flow one from above.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$49.99	1	$49.99	Horn-Air Black 2 Gallon 6 Port Air Tank	TA-206H	HornBlasters, Inc.
2	$12.17	1	$12.17	Squeeze-Grip Zinc Alloy Valves, 1/4 NPT Female	6852K11	McMaster-Carr
3	$37.28	1	$37.28	Easy-Set Needle Valves, Brass, 1/4 NPTF Female	46425K12	McMaster-Carr
4	$15.81	1	$15.81	ASME-Code Nickel-Plated Brass Pop-Safety Valve, 1/4 NPT Male, 150 psi	5784T12	McMaster-Carr
5	$1.69	4	$6.76	Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Solid Hex-Head Plug	50785K335	McMaster-Carr
6	$3.69	2	$7.38	Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Pipe Size, Solid Hex-Head Plug	50785K337	McMaster-Carr
7	$153.97	1	$153.97	PRSSR TRNS -1TO9BR 0-5V DIN	1TO9BR	Digikey
8	$135.00	1	$135.00	1/4 Compression Fitting w/Thermocouple	TG24T(T)-A4-T,12"/4"(BW)	Conax
9	$25.00	1	$25.00	T Type Thermocouple, Unsheathed, Diameter: 0.001", Length: 12"	COCO-001	Omega
			Total System Cost			
			$443.36			

4.3 Computer Modeling

Open the MATLAB file “Blowdown_Tank.m”. This is the MATLAB file for the laminar flow of the blowdown tank. The equations used are found using conservation of mass and the state equation for the gas.

Conservation of mass for the tank:

$$q_m = -\frac{dm}{dt} = -\frac{d(\rho V)}{dt} = -V\frac{d\rho}{dt} - \rho\frac{dV}{dt}$$

For a rigid tank:

$$\frac{dV}{dt} = 0$$

Which yields:

$$q_m = -V\frac{d\rho}{dp}\frac{dp}{dt}$$

The equation of state for the gas:

$$p = \rho R_G T \rightarrow \rho = \frac{1}{R_G T}P$$

For this case, we are making the assumption that the process is isothermal, therefore:

$$\frac{d\rho}{dp} = \frac{1}{R_G T}$$

Resistance in this case can be modeled as a linear and constant resistance:

$$q_m = \frac{1}{R}(P - P_a)$$

Combining 1, 2, and 3 and declaring P and P_a are gauge pressures which makes $P_a = 0$, we achieve:

$$\frac{VR}{R_G T}\frac{dp}{dt} + P = 0$$

This is the equation that we use in the MATLAB model and is used in the lab worksheet “Blowdown Tank Experiment”. The MATLAB model is setup to plot the response after the student has determined the transfer function and found P(t), which is:

$$P(t) = P_o e^{-t\left(\frac{R_G T}{RV}\right)}$$

Where,

R = 313715 1/m-s

R_G = 286.9 J/kg-K

P_o = 10 psi or 68947 Pa

T = 20°C or 293.15 K

V = 0.007571 m^2 or 2 gallons (volume of tank)

The MATLAB file will have commented code that will ask the students to determine P(t) and insert it into the code and have it plot over a time range of 5 seconds. Again, this MATLAB file is heavily associated with the word document “Blowdown Tank Experiment”.

4.4 Physical System Setup

The physical setup consists of the blowdown tank with the pressure transducer wired to the Vernier SensorDAQ. The Vernier SensorDAQ is reading the voltage change from the pressure transducer. Below is a picture of the wiring.

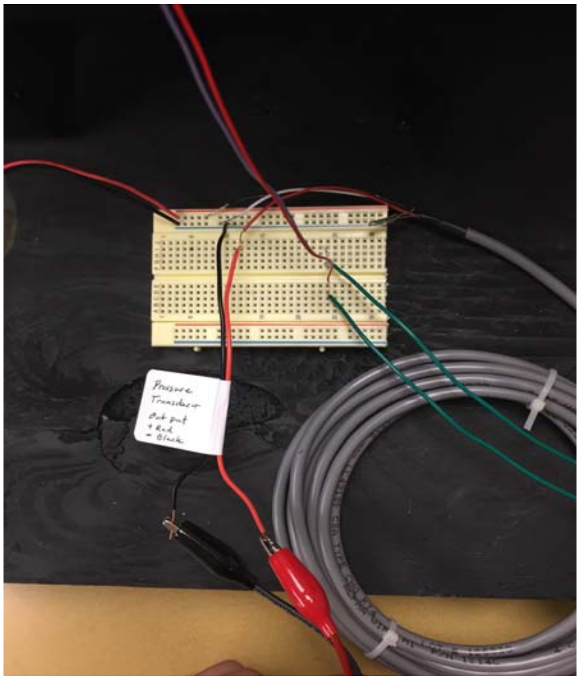


Figure 75: Pressure Transducer Wiring

The pressure transducer requires a 8-28 volt power source. This can be achieved using a number of methods (powered breadboard, DC power supply), in our example we use a powered breadboard wired to our pressure transducer as shown below.

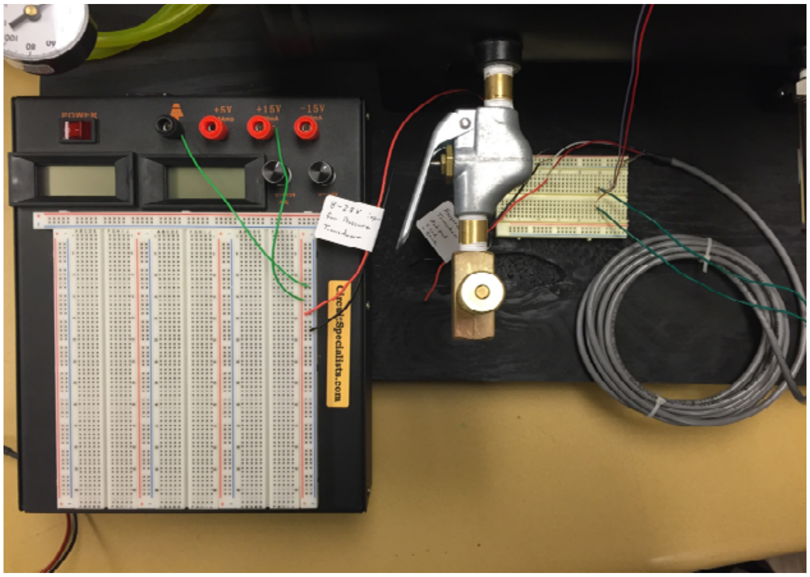


Figure 76: Pressure Transducer Power Wiring

4.5 Physical System Operation

The physical operation of the system is heavily associated with the word document “Blowdown Tank Experiment”.

Setting up in Logger Pro, You will first Calibrate the sensor. NOTE: Make sure LoggerPro has been zeroed before starting this experiment. To do this, make sure the voltage reading in the bottom left corner is 0. If not, press Ctrl+0 to zero the program. Ensure that the breadboard is also powered on before starting.

1. Select “Experiment” and click on “Calibrate”. From there you will select the SensorDAQ.
2. Fill the tank to a pressure. Make sure the valve is open when filling and closed before removing the hose. A pressure of about 30 psi is sufficient but the exact number can vary, so long as the the pressure the tank is at is the pressure recorded in the next step.
3. In “Reading 1” enter in the value read from the pressure gage on the tank and select “Keep”.
4. Release the air from the tank.
5. Once the tank is empty, under “Reading 2” you will enter in 0 psi and select “Keep” and then “Done”.
6. Now that the sensor is calibrated, you can begin the experiment. Since we are wanting laminar flow, we want to keep the pressure rather low.
7. Fill the tank to 10 psi and ensure that the valve is closed once filled. If you do fill the tank too much, slowly release the valve to let out excess air. You can note current pressure from the value in LoggerPro.
8. You will want to fasten the clear tube to the end of the needle nose valve.
9. Once fastened, in Logger Pro you will press the green “Collect” button at the top of the program.
10. Then release the valve and let the air out. Once the tank is empty, press the collect button to end collection.

4.6 Safety Considerations

The tank is rated for an operating pressure of 150 psi. We have installed a 150 psi pop safety valve which will not let the tank go over 150 psi. The air being released from the fill valve or the needle valve can come out at a fast rate so make sure not to stand too close or have objects near these openings. The length of tubing may whip around if let to set so be sure to hold it in place.

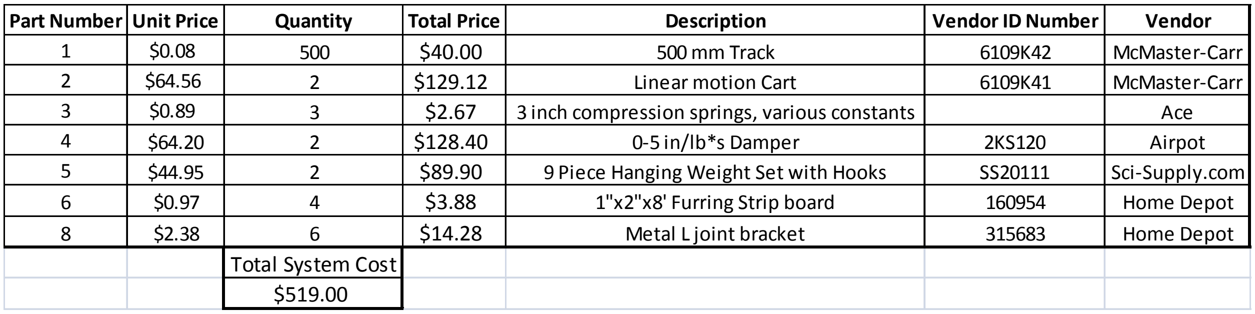
5.0 Mechanical System

5.1 Introduction and Description

The purpose of this system is to show an underdamped response for a physical spring-mass-damper system. This is a typical problem that students see a lot in class so it is a relevant example to see in real life.

5.2 Bill of Materials

The Mechanical System materials list is shown below.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	\$0.08	500	\$40.00	500 mm Track	6109K42	McMaster-Carr
2	\$64.56	2	\$129.12	Linear motion Cart	6109K41	McMaster-Carr
3	\$0.89	3	\$2.67	3 inch compression springs, various constants		Ace
4	\$64.20	2	\$128.40	0-5 in/lb*s Damper	2KS120	Airpot
5	\$44.95	2	\$89.90	9 Piece Hanging Weight Set with Hooks	SS20111	Sci-Supply.com
6	\$0.97	4	\$3.88	1"x2"x8' Furring Strip board	160954	Home Depot
8	\$2.38	6	\$14.28	Metal L joint bracket	315683	Home Depot
		Total System Cost				
		\$519.00				

5.3 Computer Modeling

To find the differential equations that model the system, we made free body diagrams for each mass in our system and analyzed the forces on these masses. This resulted in two second order differential equations:

$$\ddot{x}_1 = -\frac{1}{m_1}(c_1\dot{x}_1 + k_1x_1 - k_2(x_2 - x_1))$$

$$\ddot{x}_2 = -\frac{1}{m_2}(c_2\dot{x}_2 + k_2(x_2 - x_1))$$

To use this in MATLAB, these differential equations must be converted into four first order systems using the state variables shown below:

$$z_1 = x_1$$

$$z_2 = \dot{z}_1 = \dot{x}_1$$

$$z_3 = x_2$$

$$z_4 = \dot{z}_3 = \dot{x}_2$$

Once this relationship had been set up, we were able to convert the original differential equations into the four first order equations shown below:

$$\dot{z}_1 = z_2$$

$$\dot{z}_2 = -\frac{1}{m_1}(c_1 z_2 + k_1 z_1 - k_2(z_3 - z_1))$$

$$\dot{z}_3 = z_4$$

$$\dot{z}_4 = -\frac{1}{m_2}(c_2 z_4 + k_2(z_3 - z_1))$$

Now we are able to plug in these equations into our ode45 function in MATLAB. We also input the system parameters (k1, k2, m1, m2, c1, c2) into the MATLAB code. Make sure you have the "myode" script open and the "Mechanical_System_ODE" script open. Click run on the "Mechanica_System_ODE" script to run the file.

5.4 Physical System Setup

Make sure the accelerometers are aligned correctly so that the x direction is in the direction of motion. The x direction wire is the only one that needs to be plugged into the sensor DAQ. The springs can be easily replaced and the dampers can be adjusted to allow for more or less damping.

5.5 Physical System Operation

1. Pull back mass one (the mass with the spring and damper connected to it) 1-1.5 inches.
2. Hit collect in logger pro.
3. Release the mass and collect the data.

5.6 Safety Considerations

There aren't any real safety considerations for this system. Make sure you don't pull back the spring more than the said amount and you should be good.

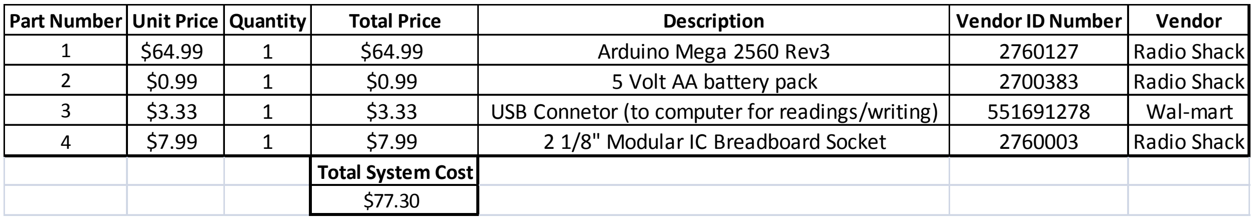
6.0 Computer Generated System

6.1 Introduction and Description

The purpose of the Arduino computer system is to simulate one of the other physical systems in the project. Since these systems will be concealed with black boxes, the Arduino can appear to be another system while being nothing more than a Runge-Kutta program running through with set variables. It is a neat system to incorporate and since its code can be changed, it is a very versatile system to be included.

6.2 Bill of Materials

The Computer Generated System materials list is shown below.

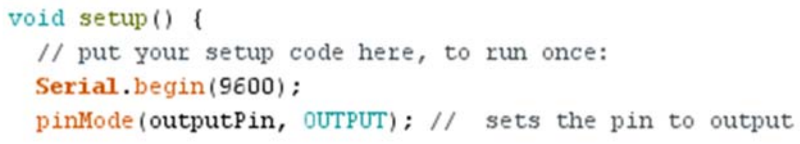


Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$64.99	1	$64.99	Arduino Mega 2560 Rev3	2760127	Radio Shack
2	$0.99	1	$0.99	5 Volt AA battery pack	2700383	Radio Shack
3	$3.33	1	$3.33	USB Connetor (to computer for readings/writing)	551691278	Wal-mart
4	$7.99	1	$7.99	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$77.30			

6.3 Computer Modeling

The Arduino uses the Arduino IDE to write in the code that will be uploaded to the board. The code uses C language. When the Arduino is plugged in, it will run the code in a loop infinitely.

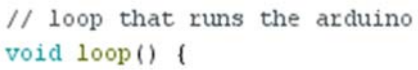
The first part of the code is the void setup() {}. Within this section {} you will declare your baud rate as 9600 and select which pin will be your output pin.



```
void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  pinMode(outputPin, OUTPUT); //  sets the pin to output
```

The variable ouputPin is an integer that can be set to several pins on the board. In our example, we use pin 9 as the output pin.

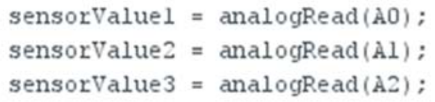
Now the code will go into the main loop.



```
// loop that runs the arduino
void loop() {
```

The void loop() is the section where the meat of the code resides. The Arduino will run this loop infinitely when plugged in after the code has been uploaded to the board. Within this loop you will declare your variables to be used in the code.

In the void loop you will also declare and set your input pins. In the code built, we used pins A0, A1, and A2.



```
sensorValue1 = analogRead(A0);
sensorValue2 = analogRead(A1);
sensorValue3 = analogRead(A2);
```

The sensorValue variables used will store the analog values read in through the corresponding pins of the board. These values are determined by having potentiometers connected through the pins. If potentiometers are not available, you can simply code in the value. For examplle:

sensorValue1 = 10;. You can repeat this for as many times as needed depending on how many variables you have in your system.

With all of the variables declared, the Runge-Kutta method can now be used. The method involves calculating four values to help in the approximation of the system curve.

To use this method, you will need to begin with an initial value problem.

$$\dot{y} = f(t, y), \quad y(t_0) = y_0$$

Pick a step size, h, larger than 0.

Having your function and step size, you will then calculate your four K values.

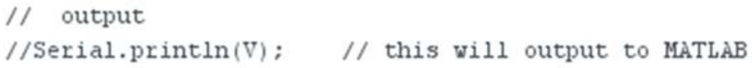
$$\begin{aligned}
k_1 &= f(t_n, y_n), \\
k_2 &= f(t_n + \tfrac{h}{2}, y_n + \tfrac{h}{2}k_1) \\
k_3 &= f(t_n + \tfrac{h}{2}, y_n + \tfrac{h}{2}k_2) \\
k_4 &= f(t_n + h, y_n + hk_3)
\end{aligned}$$

With your K values, you can then calculate the y value for t = t+h.

$$y_{n+1} = y_n + \tfrac{h}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right)$$
$$t_{n+1} = t_n + h$$

The code used in our model will run this through a while loop, where the number of loops ran through is equal to the total length of time divided by the time step.

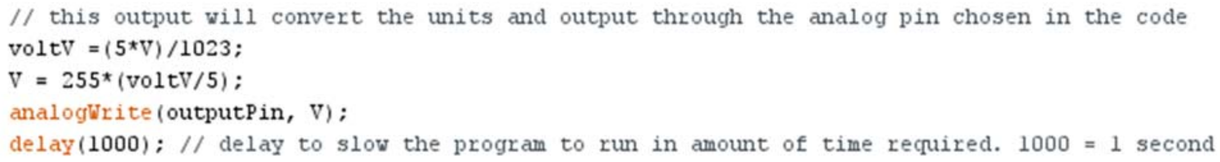
The output of the system can be through two methods: digital and analog. For the digital, it is simply using this code:



```
//  output
//Serial.println(V);    // this will output to MATLAB
```

This output can be used in MATLAB when testing your code. To do this, you will run the "serialcoms.m" MATLAB file and run the section. If the MATLAB at any point fails to plot the output for the board, be sure to type the command "fclose(Arduino)" to ensure that MATLAB is no longer using the port, as MATLAB and the Arduino IDE cannot both access the board at the same time.

For the analog output, the Arduino cannot output in true analog, it uses pulse width modulation. First we will convert the units of the output to ones that are useful to the analog output and then output them through the pin set as the output pin.

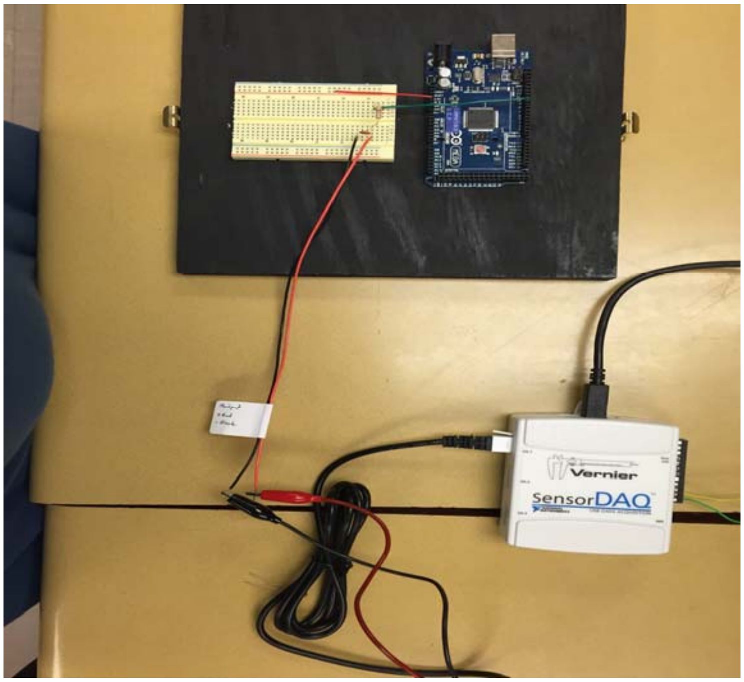


```
// this output will convert the units and output through the analog pin chosen in the code
voltV =(5*V)/1023;
V = 255*(voltV/5);
analogWrite(outputPin, V);
delay(1000); // delay to slow the program to run in amount of time required. 1000 = 1 second
```

This will output through the output pin and can be read by LoggerPro.

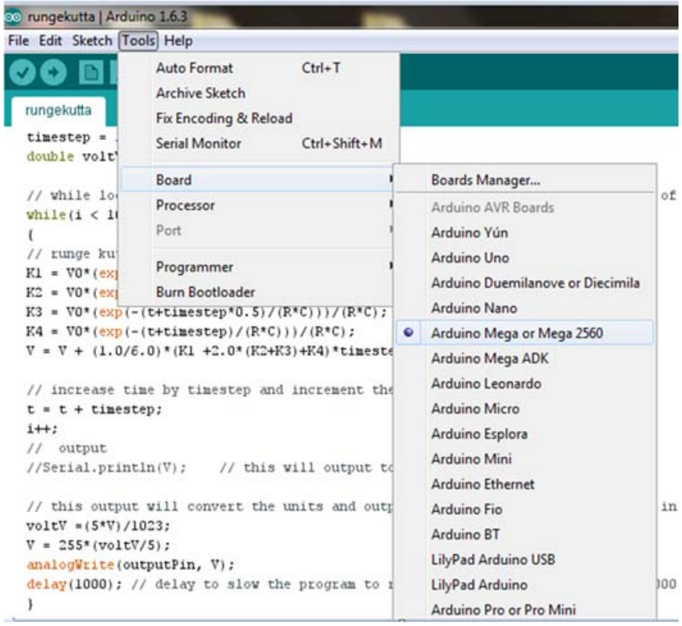
6.4 Physical System Setup

The physical setup consists of the Arduino Mega 2560 board, the USB cable to connect to the computer, a 5-12 volt power cable, and the low pass filter connected to the output to convert the output into analog. If you are using potentiometers, then those will be needed as well. The lowpass filter will output to the Vernier SensorDAQ. The Vernier SensorDAQ is reading the voltage change from the output pin of the Arduino after going through the low pass filter. Below is a picture of the wiring.



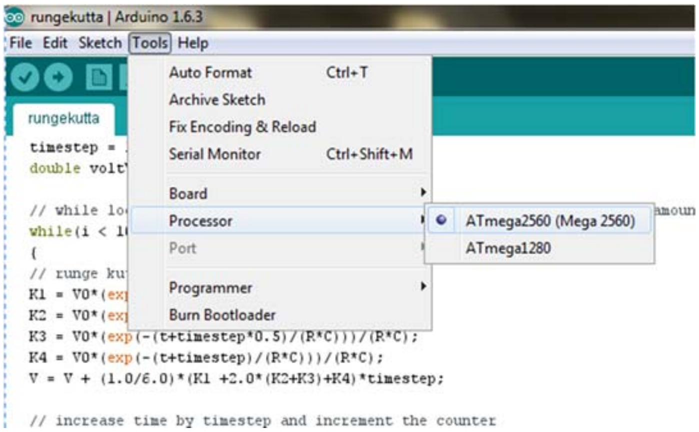
6.5 Physical System Operation

Setting up the Arduino to upload code to it, you will plug it in through the USB cable to the computer. Open the Arduino IDE and ensure you are using the correct settngs.



Board: ● Arduino Mega or Mega 2560

```
timestep = 
double volt

// while lo
while(i < 1
{
// runge ku
K1 = V0*(ex
K2 = V0*(ex
K3 = V0*(exp(-(t+timestep*0.5)/(R*C)))/(R*C);
K4 = V0*(exp(-(t+timestep)/(R*C)))/(R*C);
V = V + (1.0/6.0)*(K1 +2.0*(K2+K3)+K4)*timeste

// increase time by timestep and increment the
t = t + timestep;
i++;
//  output
//Serial.println(V);    // this will output to

// this output will convert the units and outp
voltV =(5*V)/1023;
V = 255*(voltV/5);
analogWrite(outputPin, V);
delay(1000); // delay to slow the program to 
}
```



```
timestep = .
double volt

// while lo
while(i < 1
{
// runge ku
K1 = V0*(ex
K2 = V0*(ex
K3 = V0*(exp(-(t+timestep*0.5)/(R*C)))/(R*C);
K4 = V0*(exp(-(t+timestep)/(R*C)))/(R*C);
V = V + (1.0/6.0)*(K1 +2.0*(K2+K3)+K4)*timestep;

// increase time by timestep and increment the counter
```

In the port section, ensure you have selected COM3. If port is not able to be selected, disconnect the Arduino and connect it again. Sometimes it does not like to connect to the computer.

The green checkmark will compile the code and the right arrow next to it will upload the code. Any errors will be displayed at the bottom of the screen.

To output into MATLAB, run the “serialcoms.m” file and run the section with the Arduino plugged into the computer and with the code uploaded to it. When using MATLAB, make sure that the output method your code is using is the serial output and the analog write output is commented out.

To output into LoggerPro with the analog output, ensure the serial output is commented out. Connect the Arduino to the power source which will plug into the wall and supply 5 volts to the pin. Connect a wire through the output pin through the given low pass filter of 4600 Ohms and 0.1 microfarads. The lowpass filter will then output to the sensorDAQ similar to the other systems.

6.6 Safety Considerations

The Arduino is a fairly safe experiment. One thing to note is the power source. The system will run 5 volts through it when plugged in. Because of this, the power source connected to the Arduino should be between 5-12 volts, with 12 being the absolute largest power source used. Even if you connect it to 9 volts, the board will ensure that only 5 volts runs through it. Be cautious of using 5 volts to power the board. Since power sources will not always operate at the value displayed, so if the source only had, say 4.8 volts, then the board would not be receiving the full 5 volts it is expecting to get and errors can occur.

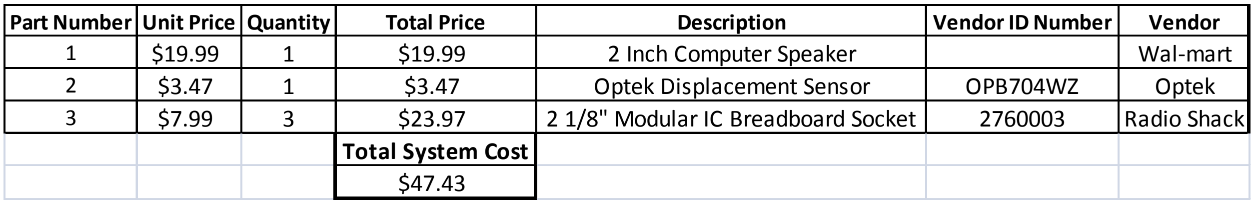
7.0 Electro-Mechanical System

7.1 Introduction and Description

The electro-mechanical system is designed to show students the displacement and frequency responses of a speaker system. This lab could be tweaked in the future to show the students how effective speaker frequency ranges are determined. For the time being, the students will be using an optical sensor to output displacement of a speaker cone and compare to a MATLAB model.

7.2 Bill of Materials

The Electro-Mechanical System materials list is shown below.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$19.99	1	$19.99	2 Inch Computer Speaker		Wal-mart
2	$3.47	1	$3.47	Optek Displacement Sensor	OPB704WZ	Optek
3	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$47.43			

7.3 Computer Modeling

The system was modeled using the sum of the forces:

$$m\frac{d^2x}{dt^2} = c\frac{dx}{dt} - kx + K_f i$$

$$m = mass$$

$$x = displacement$$

$$t = time$$

$$c = damping\ coefficient\ of\ speaker\ cone$$

$$k = spring\ coefficient\ of\ speaker\ cone$$

$$K_f = nBL = magnetic\ force\ constant\ dependent\ on\ current$$

$$n = number\ of\ coils\ of\ wire$$

$$B = magnetic\ field$$

$$L = inductance\ of\ coil$$

$$i = current$$

The sum of the voltages in an improvised KVL circuit:

$$v = L\frac{di}{dt} + Ri + K_b\frac{dx}{dt}$$

$v = voltage$

$L = inductance\ of\ coil$

$i = current$

$R = resistance\ in\ speaker$

$K_b = nBLr = back\ emf\ constant$

$n = number\ of\ coils$

$B = magnetic\ field$

$L = inductance\ of\ coil$

$r = radius\ of\ wire$

$x = displacement$

$t = time$

These two equations were combined into the transfer function:

$$\frac{X(s)}{V(s)} = \frac{K_f}{mLs^3 + (cL + mR)s^2 + \left(kL + cR + K_f K_b\right)s + kR}$$

Some of the coefficients are hard to obtain, so some of these (probably all except possibly the mass, number of coils, and radius of the wire) should be given to the students at the beginning of the lab. This means that the TAs responsible for this system should have at least one extra speaker to perform destructive testing on, particularly for spring and damping coefficients, number of coils, radius of wire, mass of cone, inductance of coil, and magnetic field of the magnet within the speaker.

7.4 Physical System Setup

The physical setup consists of the speaker used to perform the experiment, an optical sensor mounted firmly to a rigid frame, a power source for the optical sensor supplying 1.5 V, a signal generator (preferably with a power amplifier), and a SensorDAQ outputting into Logger Pro.. Below is a picture of the wiring. Below are some examples of the setup. The speaker and optical sensor setup may vary.

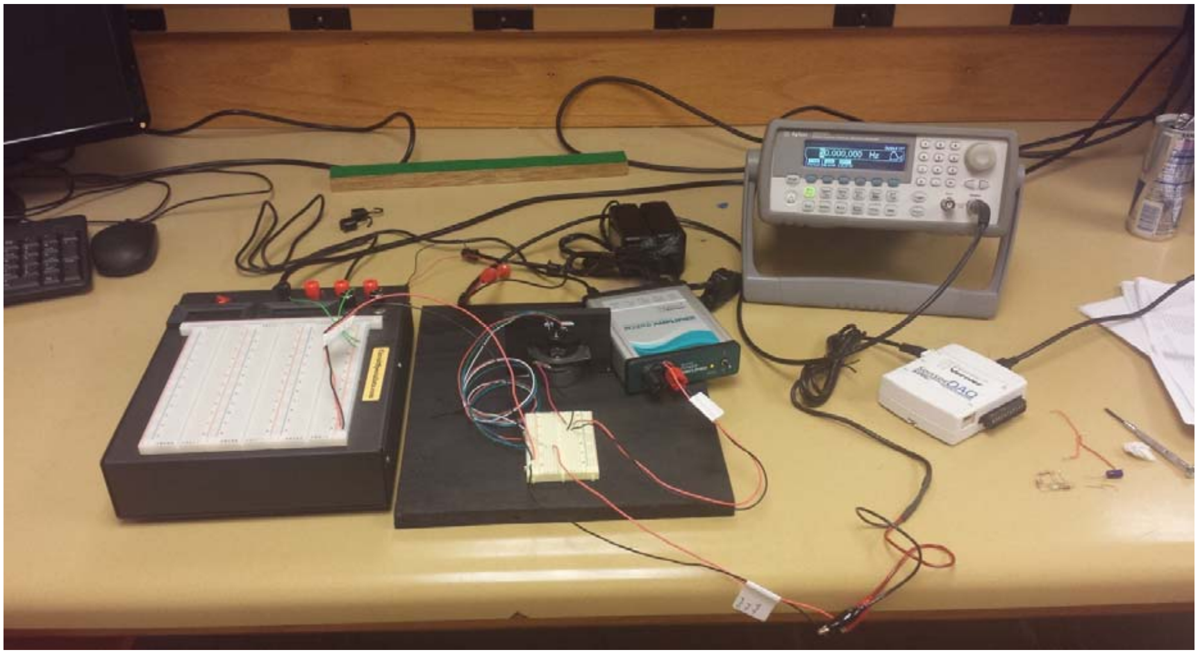


Figure 77: Setup of the Electro-Mechanical System

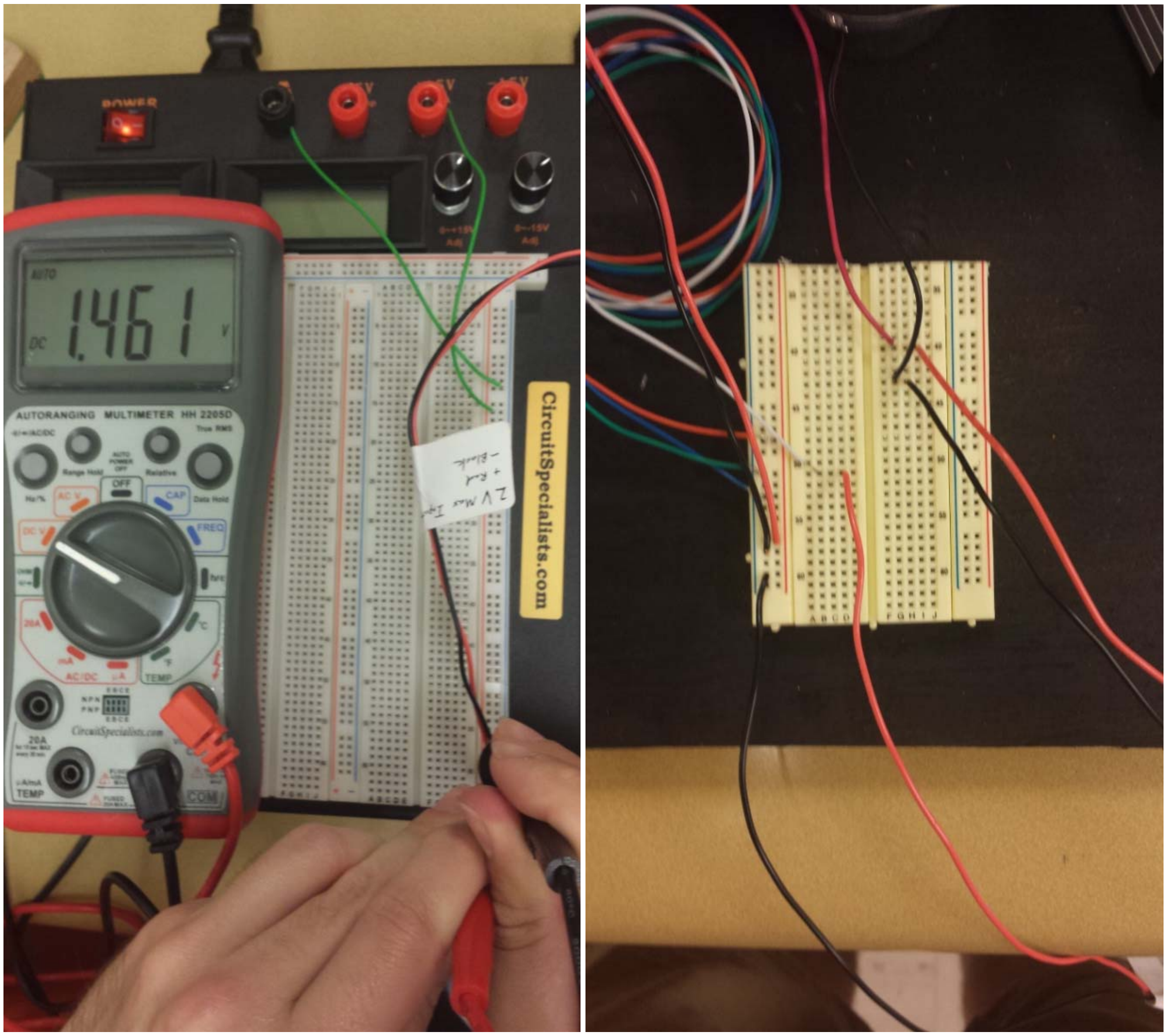


Figure 78: Power to Displacement Sensor

7.5 Physical System Operation

Note: Before recording data in Logger Pro, make sure that no one is standing near the speaker. The sensor is reading reflected light, and any change in lighting around it can skew results. Also, make sure to consult the datasheet for the optical sensor used in the lab to determine its linear region. Avoid taking any measurements outside this region.

Here are the steps to conducting the electro-mechanical lab:

1. Calibrate the system
   a. Insert a square wave to the speaker with a period between 30-60 seconds.

- b. Measure the distance between the optical sensor and the speaker using a caliper
- c. Calibrate the voltage read in Logger Pro to the distance obtained in part b
- d. Wait for the speaker to reach its next position
- e. Repeat steps b and c

2. Perform the experiment
   - a. Insert a sine function and change the frequency to any frequency up to 1000 Hz. Recommended frequency range is between 10-100 Hz.
   - b. Adjust the sampling rate to be at least 10x the frequency
   - c. Adjust the domain to be about 4-5x the period
   - d. Collect data

7.6 Safety Considerations

For the safety of the hardware, avoid using any voltages higher than those described earlier in the document. Do not handle wiring while system is turned on. Avoid high voltages and high frequencies to the speaker as damage could be done to the speaker system or user's ears. Do not have liquids around the lab.

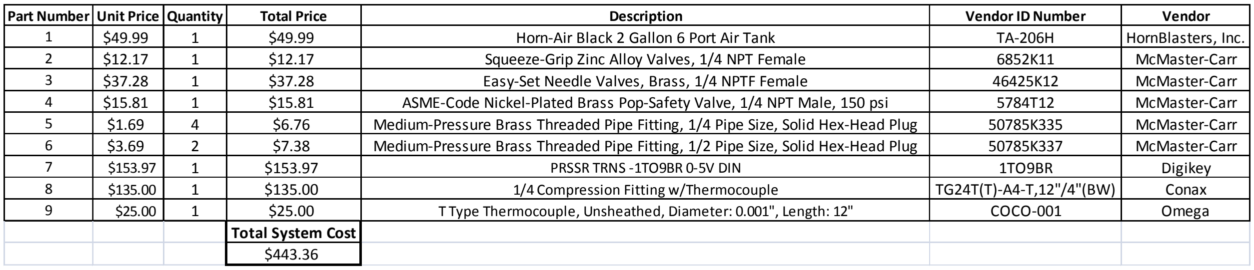
8.0 Thermal Blowdown System

8.1 Introduction and Description

The baseplate that has the pressure tank on it has the ability to perform 3 different experiments. The one covered in this section is the thermal response. For both the Choked Flow and Laminar blowdown process the temperature change can be measured. You can choose which flow you want to do with the Thermal Blowdown system and do it at the same time as one of the other processes if desired. This section will detail how to do the thermal part only though. A MATLAB program gives ideal response values and can be used to compare real and ideal blowdown processes. The change in temperature vs. time is best tracked in LoggerPro so that a live graph can be generated and the data can be transferred to Excel. A video of us showing the system setup and operation is available named "asdfasdfasdkj

8.2 Bill of Materials

The Thermal System materials list is shown below, but they are the same as the Choked Flow and Laminar Flow ones from above.



Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$49.99	1	$49.99	Horn-Air Black 2 Gallon 6 Port Air Tank	TA-206H	HornBlasters, Inc.
2	$12.17	1	$12.17	Squeeze-Grip Zinc Alloy Valves, 1/4 NPT Female	6852K11	McMaster-Carr
3	$37.28	1	$37.28	Easy-Set Needle Valves, Brass, 1/4 NPTF Female	46425K12	McMaster-Carr
4	$15.81	1	$15.81	ASME-Code Nickel-Plated Brass Pop-Safety Valve, 1/4 NPT Male, 150 psi	5784T12	McMaster-Carr
5	$1.69	4	$6.76	Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Solid Hex-Head Plug	50785K335	McMaster-Carr
6	$3.69	2	$7.38	Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Pipe Size, Solid Hex-Head Plug	50785K337	McMaster-Carr
7	$153.97	1	$153.97	PRSSR TRNS -1TO9BR 0-5V DIN	1TO9BR	Digikey
8	$135.00	1	$135.00	1/4 Compression Fitting w/Thermocouple	TG24T(T)-A4-T,12"/4"(BW)	Conax
9	$25.00	1	$25.00	T Type Thermocouple, Unsheathed, Diameter: 0.001", Length: 12"	COCO-001	Omega
			Total System Cost			
			$443.36			

Figure 79: Thermal System Materials

8.3 Computer Modeling

The modeling for this system is done in the Euler Method code that is used in the choked flow blowdown process. In this code, once the new pressure is found using the Euler Method, this pressure is plugged into the Ideal Gas Law to solve for the new temperature. Several problems exist in the current model. First, the model shows that the temperature will reach around -250 F. From conducting the experiment, the temperature only reaches 32 F. This is because of the latent heat of fusion. The second problem is that the model shows that the temperature reaches the 32 F much faster than it does when running the experiment. This is because there is water in the air that has a thermal mass which slows down the heat transfer process and our model does not account for this.

8.4 Physical System Setup

The physical setup consists of the blowdown tank with the thermocouple wired to the wheatstone bridge then to the Vernier SensorDAQ. The wheatstone bridge is powering the thermocouple and measuring the change in resistance depending on the temperature, then the Vernier SensorDAQ is reading the voltage change from the wheatstone bridge. Below is a picture of the wiring. The settings for the wheatstone bridge are shown below.

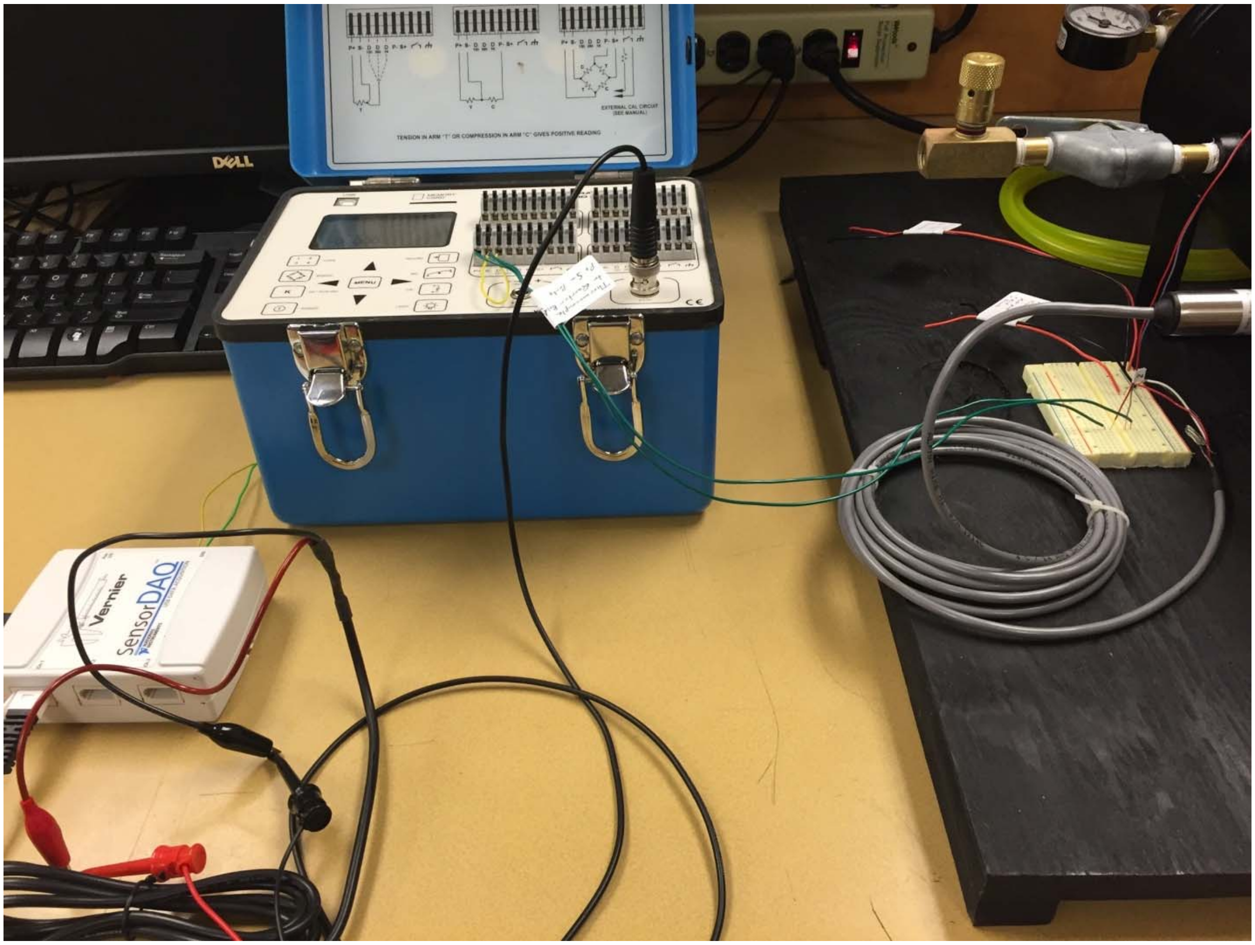


Figure 80: Overall Thermocouple Output Wiring

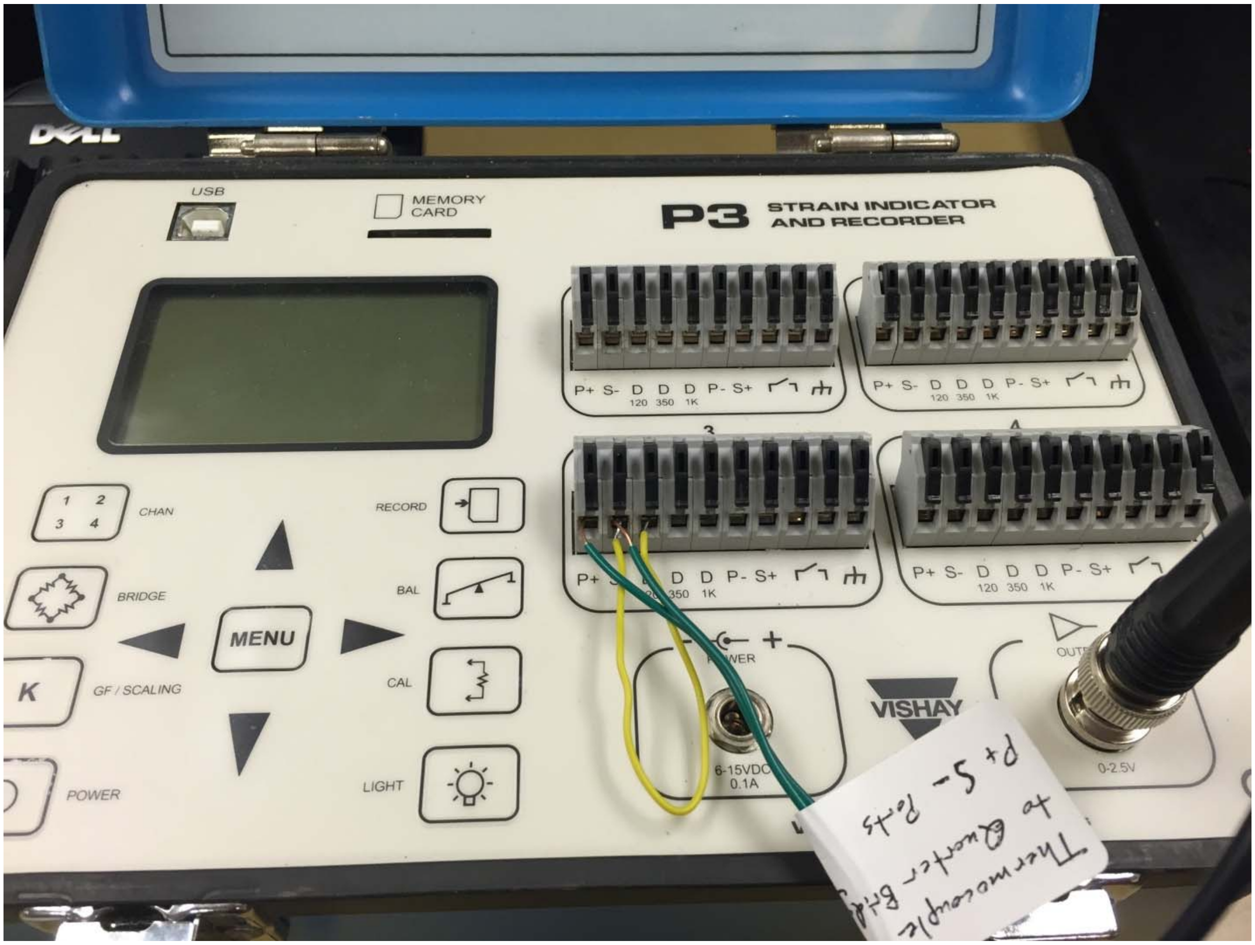


Figure 81: Close Up of Wheatstone Quarter Bridge Wiring

8.5 Physical System Operation

1. Perform the process shown in the choked flow section.
2. Refer to data acquisition section.

8.6 Safety Considerations

There aren't any real safety concerns for the thermal response. The tank doesn't get cold or hot enough to hurt humans.

9.0 Speaker-Spring System

9.1 Introduction and Description

The Speaker-Spring system suspends a spring and mass from a speaker, and students are tasked with using a function generator to find the resonate frequency of the system.

9.2 Bill of Materials

The Speaker-Spring System materials list is shown below.

- Vertical Rod & Base
- Speaker w/ mounting plate
- Power Amplifier
- Function Generator
- 3 different springs
- Masses appropriate for each spring

9.3 Computer Modeling

No computer modeling was needed for this system.

9.4 Physical System Setup

The Speaker-Spring system consists of a speaker suspended upside down from a vertical rod. Attached to the speaker cone is a plate with a threaded hole for a hook, from which the spring is suspended, with a mass hanging from the end. The speaker is connected to a function generator, which, when adjusted, will be used to find the resonant frequency.

9.5 Physical System Operation

After the system is set up, the following procedure should be used to find the resonate frequency of the system using the different springs and masses.

1. First measure each spring's unstretched length. Then, hang the spring and mass and measure the stretched length. Calculate the spring constant for each spring using:

$$k = \frac{mg}{x}$$

2. Calculate the theoretical resonant frequency of each spring using:

$$f = \frac{\sqrt{\frac{k}{m}}}{2\pi}$$

3. Experimentally determine the resonant frequency of the system for each spring.
    a. Hang a spring and its accompanying mass from the speaker.
    b. Set the function generator to the theoretical resonant frequency

4. Observe the vibration of the spring and mass. When the mass vibrates the most, the resonate frequency has been reached. In order to be sure, adjust the frequency above and below the frequency in question. The frequency in question can also be multiplied or divided by two to see the next level, which may be more apparent.

6. Calculate the percent difference between the calculated and experimental values.

9.6 Safety Considerations

Be careful when adjusting the frequency of the system. At or near the resonant frequency, there is a risk of the mass falling off of the spring.

10.0 Cantilever Beam System

10.1 Introduction and Description

The Cantilever Beam system demonstrates the natural frequency of a system, as well as the accuracy of estimations.

10.2 Bill of Materials

The Cantilever Beam System materials list is shown below.

- Cantilever Beam w/ Wheatstone bridge
- Blue Box
- Oscilloscope
- Mass set

10.3 Computer Modeling

No computer modeling was needed for this system.

10.4 Physical System Setup

The Cantilever Beam system should be properly connected to the blue box and the oscilloscope. Ensure that the input on the oscilloscope is “zeroed”. Below is an example of how to set up the strain gage in a half bridge to the blue box.

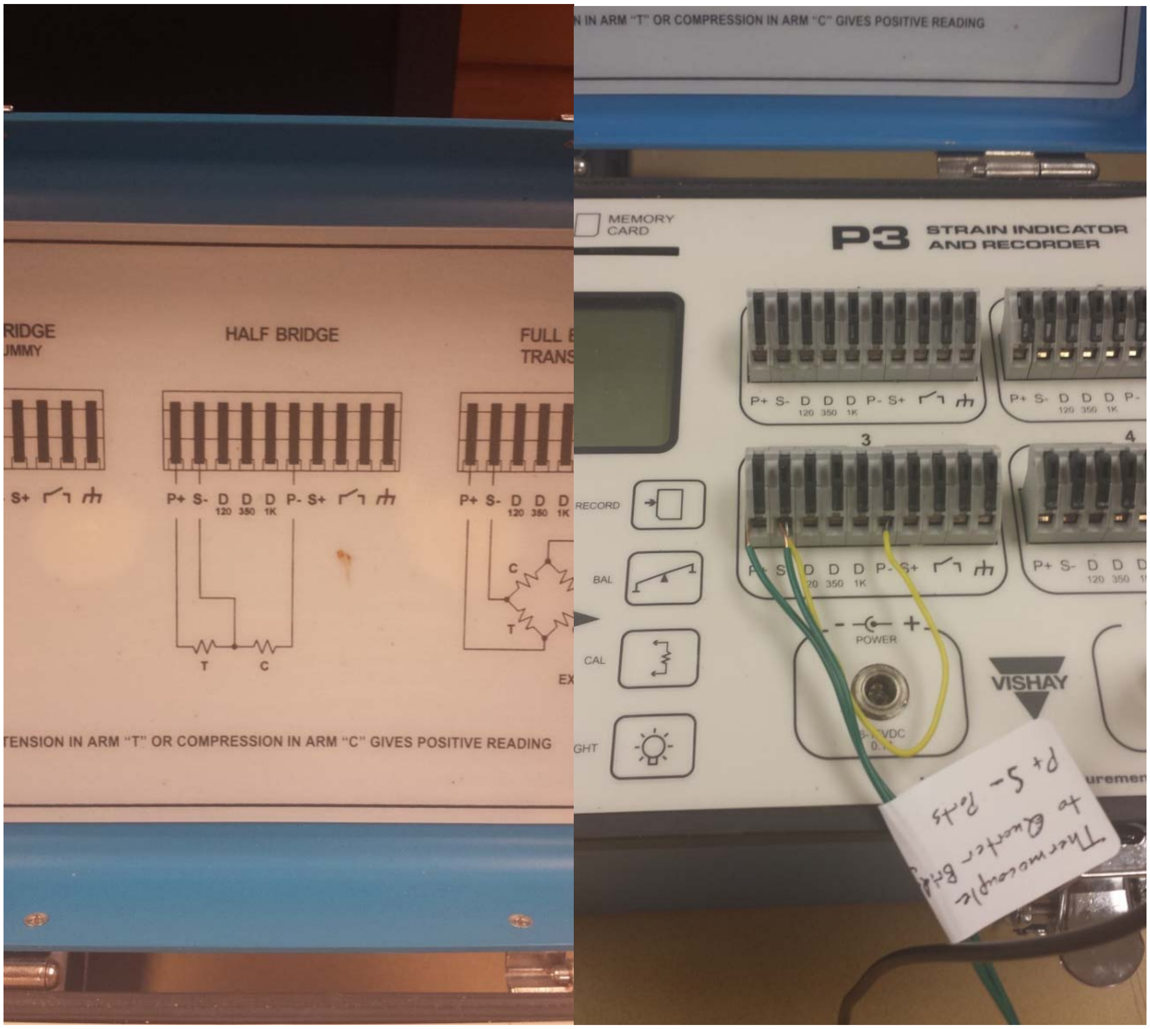


Figure 82: Wheatstone Half Bridge Wing

10.5 Physical System Operation

After the system is set up, the following procedure should be used to find the natural frequency of the system first with no mass and then mass added to the end of the beam.

1. Take note of the following properties of the beam:
    a. Length: 29 3/16 in.
    b. Modulus: 1.015 x 10^7 psi
    c. Width: 2 in.
    d. Thickness: 3/16 in.
    e. Weight: 1.075 lbs
2. Calculate the following:
    a. Displacement:

    $$y_m = \frac{WL^3}{3EI}$$

    b. Inertia:

    $$I = \frac{wt^3}{12}$$

    c. Hint:

    $$k = \frac{W}{y}$$

3. Calculate the natural frequency of the system.Note: For the mass of the system, assume the mass of the beam can be modeled as a lump mass at the end of the beam equal to ⅓ the mass of the beam.

$$\omega = \sqrt{\frac{k}{m}} \qquad f = \frac{\omega}{2\pi}$$

4. Now assume that we add a point mass of 1 kg (2.2046 lbs) on the end of the beam. Recalculate the natural frequency using the equations above.

5. Press on the end of the beam and let go. Record the frequency that the oscilloscope displays.

6. Now set the 1 kg weight on the end of the beam and repeat step 5.

7. Calculate the percent difference between the calculated and experimental frequencies for both cases.

8. Compare the two percent differences. Tell which frequency calculation was more accurate and why.

10.6 Safety Considerations

Be careful when vibrating the beam, so that the mass does not fall off.

MAE 3723 Lab Project - Construction Document

By: Andy Freberg, Collin Jefferson, Mac McClure, Jordan McKee, Jason Proffitt

Contents

1.0 Black Boxes and Baseplates

1.1 Introduction

The black boxes give the option for the physical system to be hidden. A visible system shows the components making it up and the values of those components. By hiding the system you can give the students data/graph and tell them to guess the coefficients of the system, or even to identify which type of system it is. The boxes are only for the Electrical, Computer Generated, and mechanical system. The Blowdown Process and Electro-Mechanical are mounted on baseplates only because operating them inside a box is not very feasible from a teaching point of view due to the difficulty presented to students.

1.2 Bill of Materials

The materials required, vendor info, and cost for building the black boxes is listed below.

Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$20.27	4'x8' 19/32 unsanded plywood	326135	Home Depot
1	$4.37	1-5/8" Fine tread drywall screws	158CDWS1	Home Depot
3	$11.61	Flat Black Spray Paint	J2853812	Home Depot
	Total System Cost			
	$36.25			

1.3 Construction

The boxes and base plates vary in size depending on the system. Below is a table of the box component dimensions based on the system. These measurements are for 19/32 inch thickness plywood.

	Components					
System	Base, in x in	Top, in x in	Front, in x in	Back, in x in	Left, in x in	Right, in x in
Electrical	9x9	9x9	9x9	9x9	9x8	9x8
Computer Generated	9x9	9x9	9x9	9x9	9x8	9x8
Mechanical	35x10	35x10	35x10	35x10	35x9	35x9
Blowdown	24x15					
Electro-Mechanical	12x10					

Cutting of the pieces is listed below.

The dimensions from above can be drawn out on the piece of plywood and should be cut with a table saw to ensure straight cuts. It will take a single piece of plywood to create all the boxes and baseplates and there will be some extra left over. After all the pieces are cut it would be advised to paint them the desired color, we painted ours black.

Assembly of the boxes is listed below.

1. Clamp the Front piece so that the over-hang is equal to the thickness of the Left piece (19/32 inch).

2. Use a 1/8 inch size drill bit to make two guide holes about 2 inches away from the corners and about 1/4 inch into the Front piece. This gives you a good guide for the screws so that you do not split the wood.

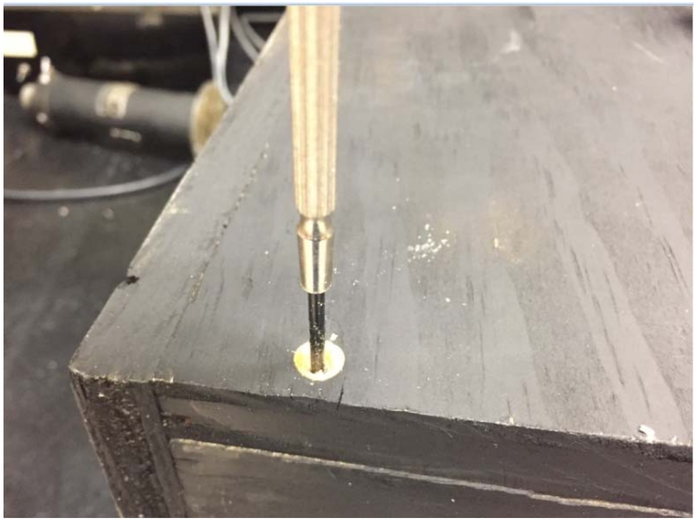


Figure 83: Creation of Guide holes

3. Use a Phillips head bit to screw in the 1-⅝ inch screws into the guide holes. Make sure that you go in straight and do not strip out a hole. If you strip out a hole place a toothpick into the hole and re-install in the screw.

4. Repeat steps 1-3 for the Left piece to the Back piece, then Back piece to the Right piece, finally the Right piece to the Front piece. This will give you a 4 sided box with no top or bottom as shown below.

5. Place the Top piece onto the four sided box. You will now drill two guide holes for each corner just like had been done earlier. Use a 1/8 inch size drill bit about 2 inches out from each corner and 1/4 inch into the top.

6. Install the 1-⅝ inch screws into the guide holes and fasten the top.

7. On the two sides cut out small semi-circles or squares whichever you desire so that the wires can come through on the systems.

8. Now you must install the latches that fasten the baseplate to the box. First place the top of the box onto the baseplate. Screw in the latch hooks midway on the baseplate as shown.

Figure 84: Placement of the Latch Hook

Then hold the loop part of the latch tight on the hook and mark the hole positions.

Figure 85: Marking, Guide holes, and Installation of the Latch

Make small guide holes with a small drill bit so that you can screw in the hooks easily.

Figure 86: Fully installed Latch

2.0 Electrical Systems

Figure 87: Completed Electrical RLC and RC

2.1 Introduction and Description

The electrical systems consist of 2 boxes, one for the RC circuit, the other for the RLC circuit. The construction of these systems is very simple compared to the others.

2.2 Bill of Materials

The materials required, vendor info, and cost for the electrical systems is listed below.

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
2	$1.49	1	$1.49	100uF 50V 20% Radial-Lead Capacitor	2721044	Radio Shack
3	$7.99	1	$7.99	100-Piece 1/2-watt Carbon-filmed Resistors Assortment	2710306	Radio Shack
4	$39.06	1	$39.06	Hammond 159ZA Choke, 0.3H, 1A Inductor	159ZA	Hammond through Amazon.com
5	$23.80	1	$23.80	Hammond Fixed Inductor D.C. Filter Choke 5H	158Q	Hammond through Amazon.com
6	$8.49	1	$8.49	3 color set 22-gauge single strand wire	2781224	Radio Shack
			Total System Cost			
			$104.80			

2.3 Construction

The construction of the electrical systems consists of fixing the materials onto the baseplate and making sure they do not conflict with the sides of the box. The steps are listed below.

1. First fasten the breadboard to the top of the baseplate, the top of the baseplate is where the hooks for the latches are up. The breadboards come with two sided foam tape attached to them, but if for some reason the tape is compromised or needs replacing extra has been

purchased and is available. Simply remove the tape cover and place the breadboard at least 1 inch from the edge of the baseplate.

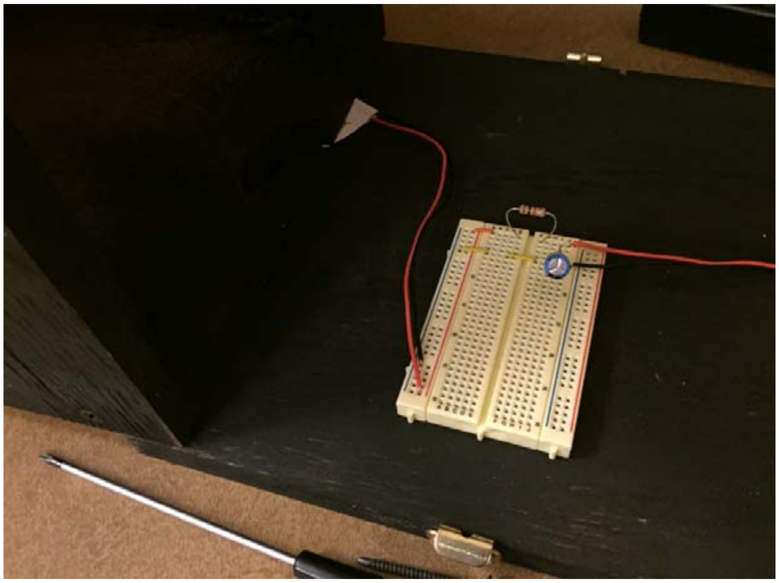


Figure 88: Breadboard Placement

2. Cut 2 lengths of red wire and 2 lengths of black wire at least 10 inches long. These will be used as input and output for the system.

3. Wire one set of red and black to the power rail on the left and label it "Input 5 Volt Max + Red - Black"

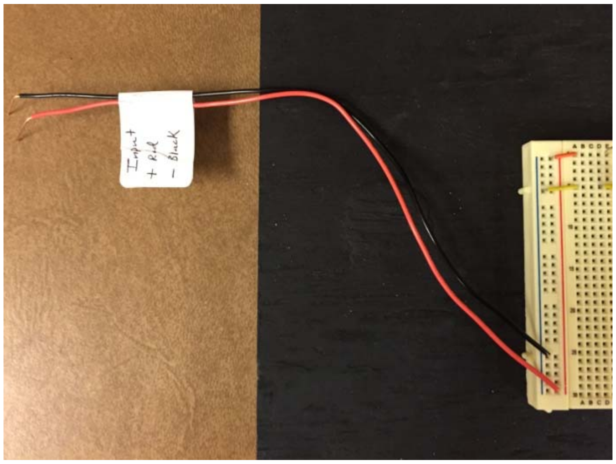


Figure 89: Input wires

4. Wire one set of red and black to the right side of the breadboard. The placement does not matter in this phase of construction, but it will matter when wiring your output during operation.

Label these wires “Output 5 Volt Max + Red - Black”. Now you have completed the RC circuit system.

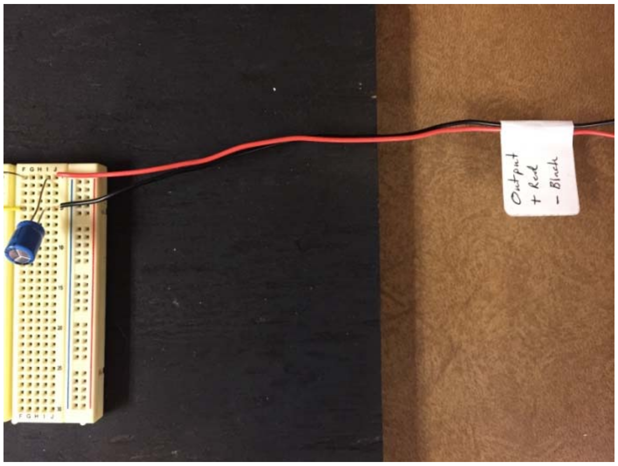


Figure 90: Output Wires

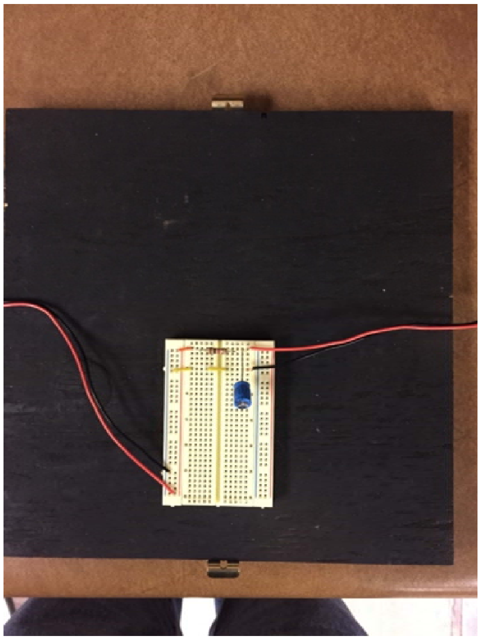


Figure 91: Finished RC System

5. Repeat steps 1-4 again on another baseplate. This will be RLC circuit where the inductor will be added.

6. Place the inductor at least 1 inch away from the edge of the baseplate. Drill guide holes using a 1/8 inch size drill bit only about ⅛ inch into the baseplate. Do this with the different size inductors giving holes for you to use if you decide to change out the inductor.

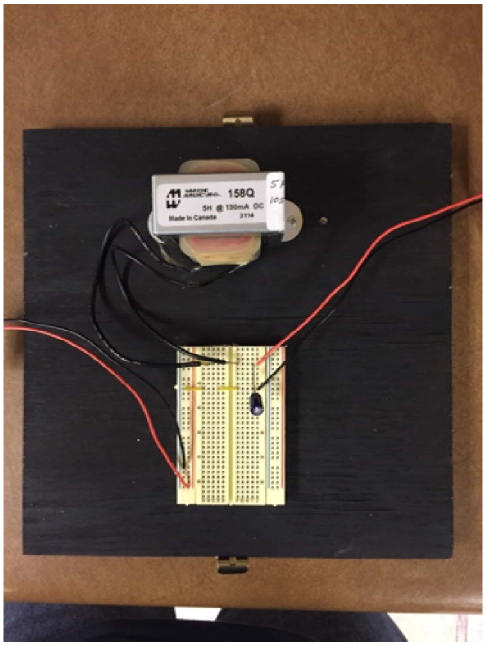


Figure 92: Finished RLC System

3.0 Blowdown Tank

3.1 Introduction and Description

The Blowdown Tank is what the Choked Flow, Laminar, and Thermal systems all use.

3.2 Bill of Materials

The materials required, vendor info, and cost for the Blowdown Tank is listed below.

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$49.99	1	$49.99	Horn-Air Black 2 Gallon 6 Port Air Tank	TA-206H	HornBlasters, Inc.
2	$12.17	1	$12.17	Squeeze-Grip Zinc Alloy Valves, 1/4 NPT Female	6852K11	McMaster-Carr
3	$37.28	1	$37.28	Easy-Set Needle Valves, Brass, 1/4 NPTF Female	46425K12	McMaster-Carr
4	$15.81	1	$15.81	ASME-Code Nickel-Plated Brass Pop-Safety Valve, 1/4 NPT Male, 150 psi	5784T12	McMaster-Carr
5	$1.69	4	$6.76	Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Solid Hex-Head Plug	50785K335	McMaster-Carr
6	$3.69	2	$7.38	Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Pipe Size, Solid Hex-Head Plug	50785K337	McMaster-Carr
7	$153.97	1	$153.97	PRSSR TRNS -1TO9BR 0-5V DIN	1TO9BR	Digikey
8	$135.00	1	$135.00	1/4 Compression Fitting w/Thermocouple	TG24T(T)-A4-T,12"/4"(BW)	Conax
9	$25.00	1	$25.00	T Type Thermocouple, Unsheathed, Diameter: 0.001", Length: 12"	COCO-001	Omega
			Total System Cost			
			$443.36			

3.3 Construction

The construction of the Blowdown Tank consists of fixing the pressure tank and breadboard onto the baseplate then making sure all the fittings and pipe are securely connected to the pressure tank. The steps are listed below.

1. The baseplate needs to be on 1in x 6 inch legs to make sure it sets flat once everything is attached. Cut the legs from the extra wood from the box construction then just simply screw them on the bottom of the baseplate using the ¾ inch screws.

Figure 93: Feet of the Blowdown Baseplate

2. Fasten the pressure tank 4 inches in from the short side and 2.5 inches in from the long side. This is done by making where the tank holes line up to then drilling them out with a 1/8 inch size bit. Finally, attach them with a 1/8 inch size bolt and nut. Shown below is the pressure tank fasten to the baseplate.

Figure 94: Tank fastened to Baseplate

3. Fasten the breadboard to the baseplate. The breadboards come with two sided foam tape attached to them, but if for some reason the tape is compromised or needs replacing extra has been purchased and is available. Simply remove the tape cover and place the breadboard on the larger open side of the baseplate next to the pressure tank as shown in the image.

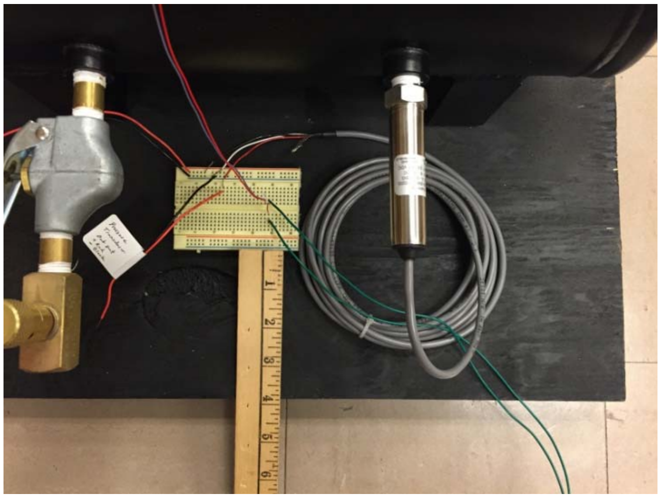


Figure 95: Breadboard Placement

2. Cut 2 lengths of red wire and 2 lengths of black wire at least 10 inches long and 2 lengths of green wire at least 16 inches long. These will be used as power supply and outputs for the system.

3. Wire one set of red and black to the power rail on the left and label it “8-28 Volt Input + Red - Black” This is to power the pressure transducer.

4. Wire one set of red and black to the right side of the breadboard. The placement does not matter in this phase of construction but it will matter when wiring your output during operation. Label these wires “Output Max + Red - Black”.

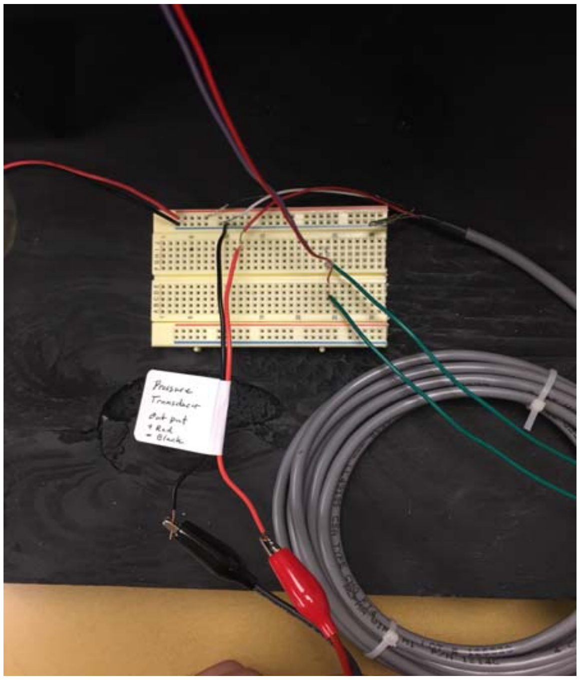


Figure 96: Input and Power wiring shown

5. Wire the green set of wires to the right side of the breadboard. The placement does not matter in this phase of construction but it will matter when wiring your output during operation. Label these wires “Output Thermocouple”.

6. Now you can start attaching fittings to the pressure tank. Fittings should be placed one at a time with at least 2 turns of pipe tape to ensure tight fit. Work from the tank out to the most extreme fittings. Assemble the fittings as shown in the photos.

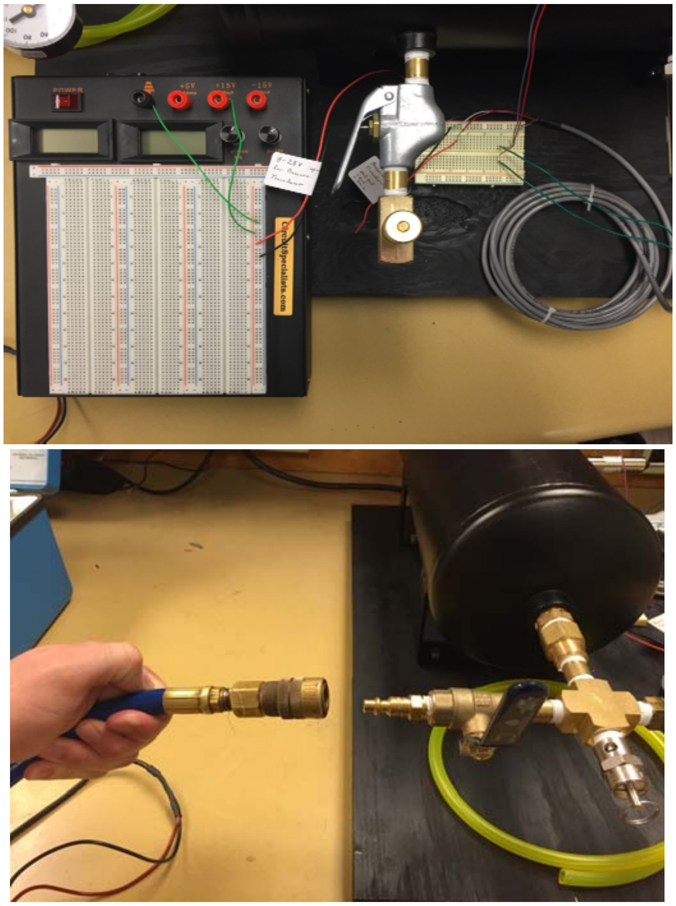


Figure 97: Fittings of the Blowdown Tank

4.0 Mechanical System

4.1 Introduction and Description

The Blowdown Tank is what the Choked Flow, Laminar, and Thermal systems all use.

4.2 Bill of Materials

The materials required, vendor info, and cost for the Blowdown Tank is listed below.

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$0.08	500	$40.00	500 mm Track	6109K42	McMaster-Carr
2	$64.56	2	$129.12	Linear motion Cart	6109K41	McMaster-Carr
3	$0.89	3	$2.67	3 inch compression springs, various constants		Ace
4	$64.20	2	$128.40	0-5 in/lb*s Damper	2KS120	Airpot
5	$44.95	2	$89.90	9 Piece Hanging Weight Set with Hooks	SS20111	Sci-Supply.com
6	$0.97	4	$3.88	1"x2"x8' Furring Strip board	160954	Home Depot
8	$2.38	6	$14.28	Metal L joint bracket	315683	Home Depot
		Total System Cost				
		$519.00				

4.3 Construction

There has not been any meaningful construction done on this system since the dampers have not come in. Had we had the materials, this is how the construction would have been handled:

1. Construct rigid frame to firmly attach track, dampers, and springs.

2. Place carts on track and attach them to springs and dampers appropriately.
   (For the model in question, attach spring and damper 1 between cart 1 and front wall, attach spring 2 between carts 1 and 2, and attach damper 2 between cart 2 and back wall)

3. Place Velcro in the bottom of carts and on the bottom of masses.

4. If appropriate, lubricate track (this will be essential for a sleeve bearing rail).

5.0 Electro-Mechanical System

5.1 Introduction and Description

The Blowdown Tank is what the Choked Flow, Laminar, and Thermal systems all use.

5.2 Bill of Materials

The materials required, vendor info, and cost for the Blowdown Tank is listed below.

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$19.99	1	$19.99	2 Inch Computer Speaker		Wal-mart
2	$3.47	1	$3.47	Optek Displacement Sensor	OPB704WZ	Optek
3	$7.99	3	$23.97	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$47.43			

5.3 Construction

The construction of the electro-mechanical system consists of fixing the materials onto the baseplate and making sure they do not conflict with the sides of the box. The steps are listed below.

1. First fasten the breadboard to the baseplate. The breadboards come with two sided foam tape attached to them, but if for some reason the tape is compromised or needs replacing extra has been purchased and is available. Simply remove the tape cover and place the breadboard at least 1 inch from the edge of the baseplate.

2. Cut 4 lengths of red wire and 4 lengths of black wire at least 10 inches long.

3. Wire one set of red and black wires from the +15V and Gnd to the power rails on the powered breadboard. You should be supplying 1.5V with the powered breadboard. Note: you don't have to use a powered breadboard. Any power source that can supply the 1.5V to your main breadboard will work.

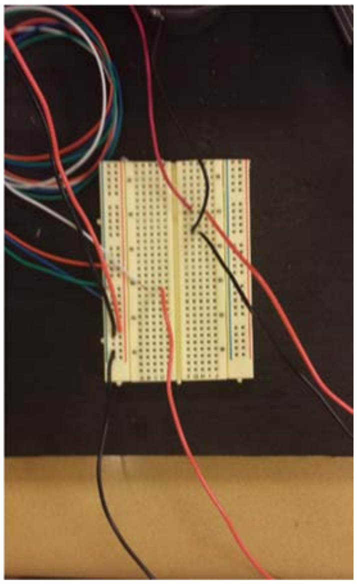
4. Wire one set of red and black wires from the power rail on the powered breadboard to the left power rail on the main breadboard and label it "Input 1.5 Volt Max + Red - Black"

5. Wire the blue and green wires from the optical sensor into the ground of the left power rail. Wire the orange wire into the power of the left power rail. Place the white wire anywhere on the main the breadboard.

6. Wire one of your black wires into the ground of the left power rail. Wire one of your red wires into the same row as the white wire from the optical sensor. Connect these wires into the sensor DAQ.

7. Wire the function generator to go into the power amplifier. The power amplifier used in this experiment is the Vernier power amplifier. If this power amplifier is not available, look up the specifications needed for your power amplifier. Use the last set of red and black wires to wire the amplifier output to two separate rows on the main breadboard.

8. Plug in the speaker into the same two rows you plugged in the amplifier into (make sure the red and black wires are matched up).



6.0 Computer Generated System

6.1 Introduction and Description

The computer generated system consists of the Arduino Mega 2560 board, a power cable (5-12 volts), a low pass filter (R = 4600 Ohms, C = 0.1 microfarads), the USB cable, various wires to connect the system together, and the box to conceal it.

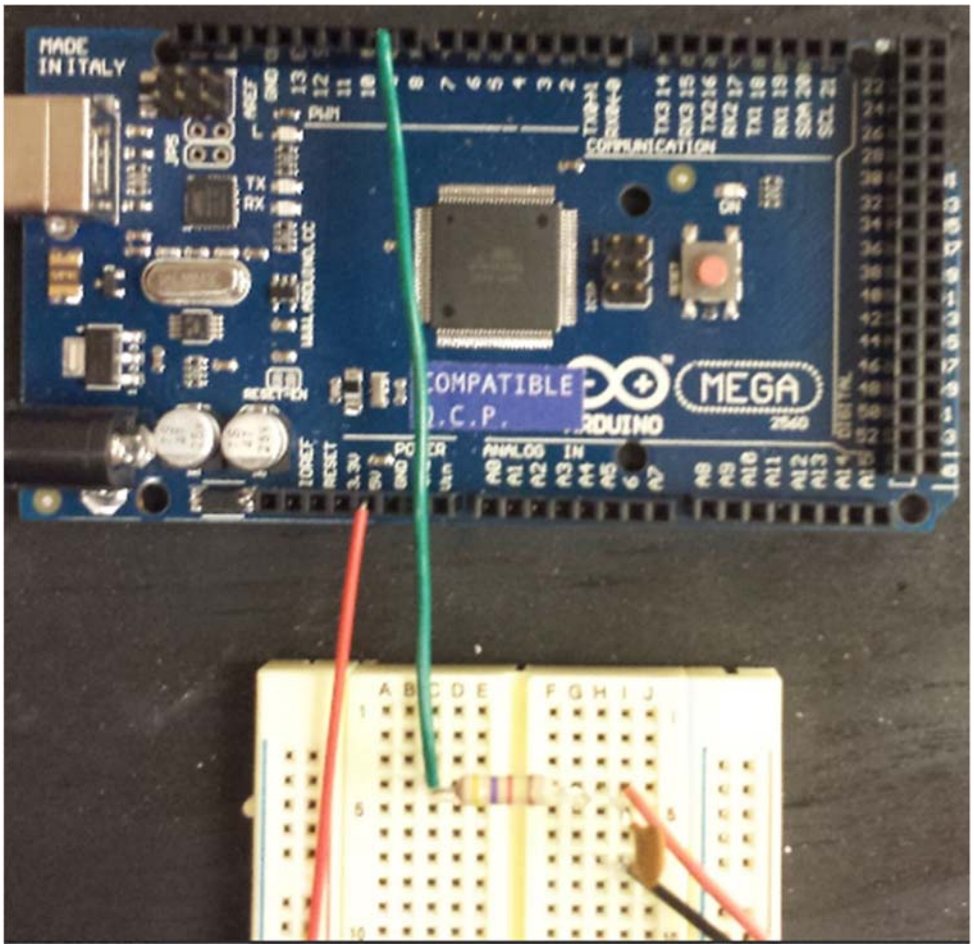
6.2 Bill of Materials

The materials required, vendor info, and cost for the Blowdown Tank is listed below.

Part Number	Unit Price	Quantity	Total Price	Description	Vendor ID Number	Vendor
1	$64.99	1	$64.99	Arduino Mega 2560 Rev3	2760127	Radio Shack
2	$0.99	1	$0.99	5 Volt AA battery pack	2700383	Radio Shack
3	$3.33	1	$3.33	USB Connetor (to computer for readings/writing)	551691278	Wal-mart
4	$7.99	1	$7.99	2 1/8" Modular IC Breadboard Socket	2760003	Radio Shack
			Total System Cost			
			$77.30			

6.3 Construction

The arduino is a very simple system to construct. A picture has been provided to show the connections with the wires.



The red wire is connected to the 5V pin for power, the green wire is the output pin wire and goes into the low pass filter, from the resistor to the capacitor. The lowpass output will have the red wire output to the DAQ and the black wire to ground. The breadboard is connected to the base of the box.