System Development for Health Monitoring of Structures

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ABSTRACT

The purpose of this project is to create a program that enables dynamic control of MRDs for experimentation. A setup utilizing a single simply supported concrete bar and a drop tower was used to collect data and experiment with the effects of different control models for MRDs. LabVIEW was used to create a program to display the input from the sensors as well as the signal that the current model will send to the MRD. The program was designed to be adapted and modified by future users for civil engineering applications. The program was tested by student users and lab employees.

Key words: Magnetorheological Damper, Concrete structures, LabVIEW

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1. INTRODUCTION

Buildings and structures are subject to a wide variety of forces from the everyday loads of wind and rain to the violent forces of storms and earthquakes. These forces are all capable of compromising them in some way whether by causing fatigue over time, making them difficult to use or, damaging them instantly. For example, the case of the infamous Tacoma Narrows Bridge when a combination of resonance due to wind and self-excitation caused the bridge to oscillate vertically (Billah K., et. al.). One possible way to equip buildings to mitigate the effects of these forces is by using Magnetorheological Dampers (MRDs). Magnetorhelogical dampers are shock absorbers filled with a fluid that alters the dampers resistance to movement when an electric current is applied. Magnetorheological dampers are already used in the automotive industry to create dynamic suspension (Guglielmino, E., et al.). MRDs would enable a building to dynamically react to the forces it experiences and could conceivably improve durability and building life. MRDs have been used in buildings to reduce the negative effects of applied forces since 2001 when the first full-scale implementation of MRDs in structures in the cable-stayed Dongting Bridge in China and the Nihon-Kagaku-Miraikan building in Japan (Cho, S. et. al.). However, using MRDs like this requires a control system in order to effectively dampen the response of the structures. For example, the Dongting bridge uses the dampers to reduce the damaging vibrations caused by wind and rain by applying a constant voltage (determined experimentally) when wind and rain conditions are expected (Chen et. al.).

The control models developed so far focus on low speed and low frequency applications (Ahmadian et. al.), like the wind loads mentioned earlier. Significantly less development has focused on impact loads like those caused by boats crashing into bridge supports or even the

September 11th attack on the World Trade Center. The long-term goal of research on MRDs is to develop active control models for dealing with these sorts of impact scenarios.

The main purpose of this project is to build a program to test and implement control models for experimenting with using MRDs in structures to modulate the effect of impact loads. The requirements for this program were based around the needs of researchers with little or no programming ability. The program needs to be able to read in data, display it, and then calculate what signal should be sent to the MRD. Ideally researchers should be able to use the program to experiment and collect data under radically different conditions and to change the control models, the number of MRDs, and the structure, with little or no additional programming. As part of this development process it was necessary to create a simple experimental set up (see Figure 1) for programmatically controlling the MRD that could later be generalized for future research. The necessary performance and other parameters were determined by using the experimental setup and program to try to implement control models.

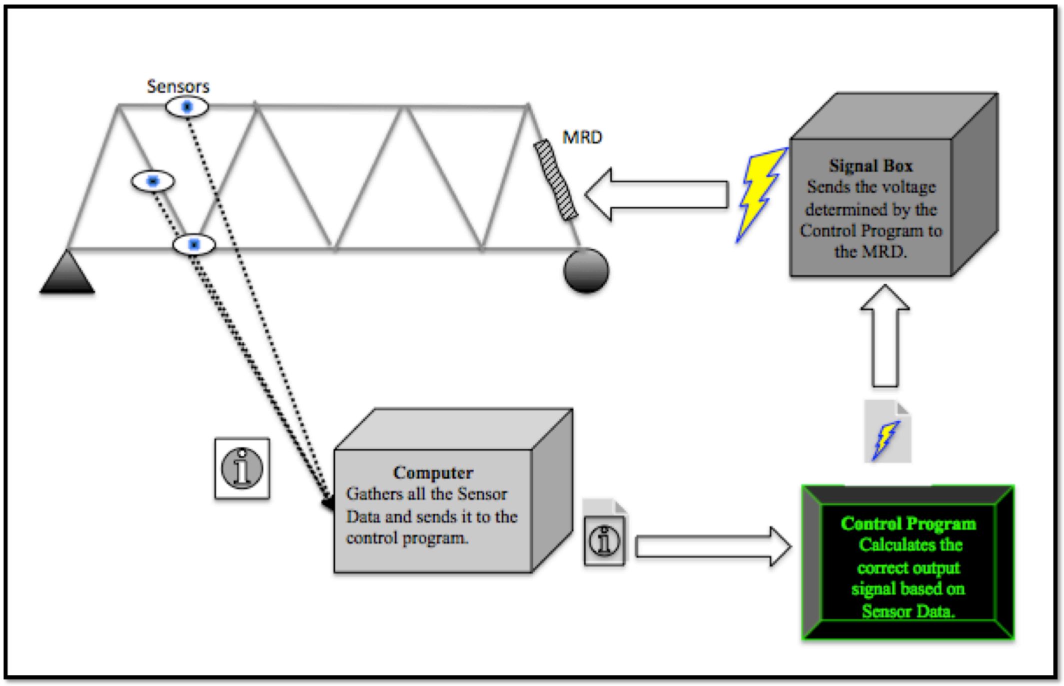

Figure 1 Diagram of Experimental Setup and Data flow through the system.

Implementing control models is difficult, because the model has to be able to take a variety of variables into account like strain, acceleration, and displacement. This is made more complicated because in attempting to idealize one behavior, other behaviors are compromised. For example reducing strain will cause greater changes in something that would compromise user comfort. Or if the MRD attempts to prevent large displacements it may contribute to wear on the beam by preventing some of the dissipation of energy due to flexure. The program created couldn't be tied to any one control model, but several basic control models were examined as part of the experimental process. The simplest control model is to apply a constant voltage when impact is detected. Another simple control model that is useful in experimenting is to send a randomly changing voltage. By constantly and randomly varying the voltage each test contains information about how the structures behavior changes for a wide variety of control behaviors.

For instance if the changes in voltage follow the sequence [0,2,3,1,4,3,2], the data can reveal what the behavior is if the voltage is held at those levels throughout the test as well as what the behavior is for an increasing voltage signal and a decreasing voltage signal.

Magnetorheological dampers are essentially pistons filled with magnetorheological (MR) fluid. Magnetorheological fluid is a fluid in which micron size ferromagnetic particles are suspended. When the fluid is exposed to a magnetic field the particles reorient themselves in chains that are more resistant to movement than the free floating suspended particles. (Guglielmino, E., et al.). Figure 2 shows a diagram of a simple MRD. The piston head contains the electromagnetic circuit and divides the interior of the damper into two chambers filled with MR fluid. As the piston moves MR fluid is forced through the gap between the piston head and the casing with resistance to movement proportional to the viscosity of the fluid (Nam,Y. et. al.). The MRD used in this project is a mono-tube shock absorber (Lord Corporation), in which all of the MR fluid is in a single tube (KYB Americas). It uses an accumulator of compressed Nitrogen to account for changes in volume as the piston moves (Nam,Y. et. al.). Some MR Fluid is able to react to changes in magnetic field within milliseconds (Bossis, G., et al.), however the factors limiting response time are usually the time to induce the correct current in the electromagnet and the delay caused by the controlling computer (Lord Corporation). MR Fluid acts essentially like a Newtonian liquid when not exposed to a magnetic field, and when in a magnetic field the MR fluid behaves more or less like a Bingham plastic (Lord Corporation).

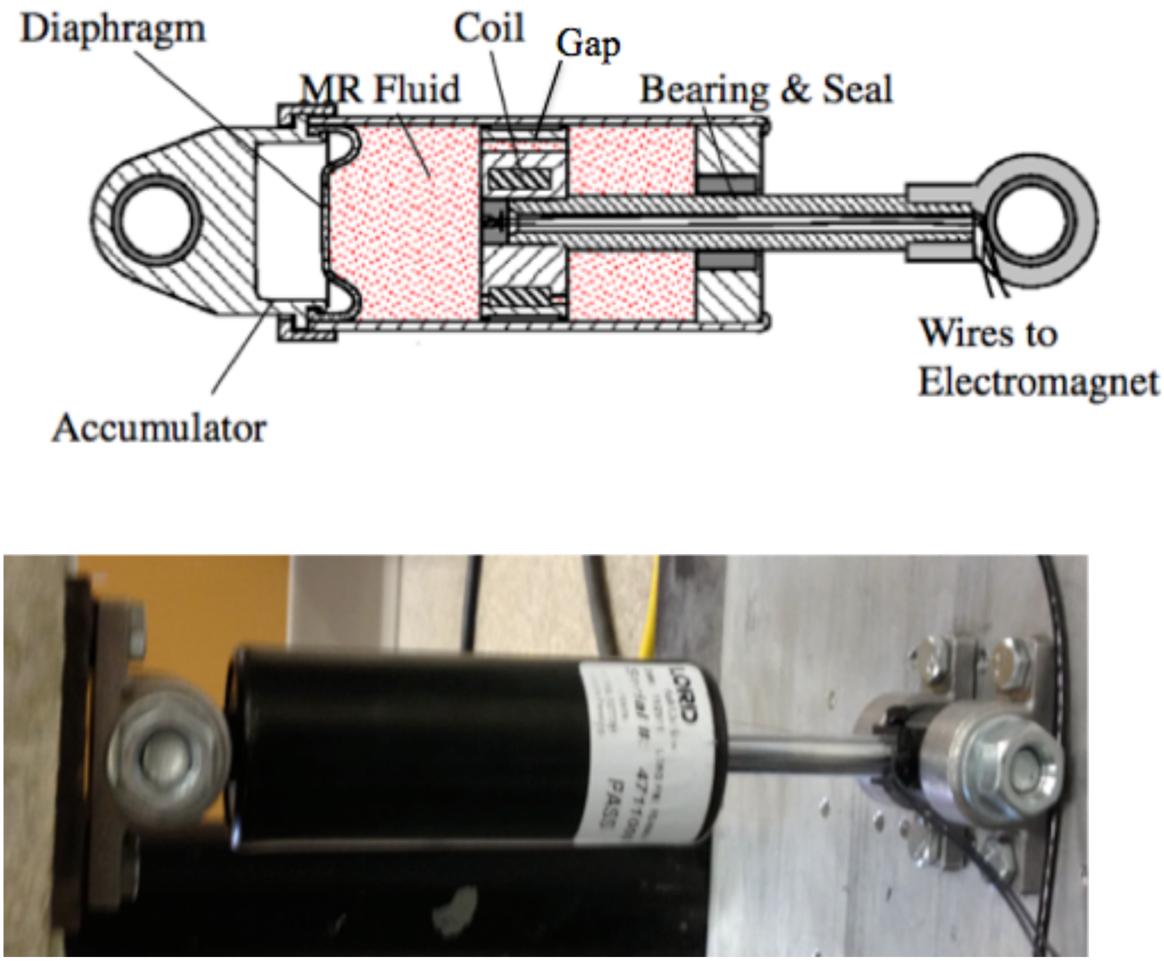

Figure 2 Diagram of an MRD (Cho, S. et. al.), next to the MRD used in this project. (Picture rotated to match the diagram).

A secondary concern of this project is the use of MRD damping systems in Structural Health Monitoring (SHM). SHM is the process of detecting damage in structural systems, which adversely affect the system performance (Ursu, I. et. al.). The same sensors in place to control the MRD can be used to gather data about the health of the structure they are in. There exist a wide variety of methods for performing SHM with no general algorithm for determining the degree and location of damage in all structures (Maia, N.M.M et. al.). Because of this, incorporating health-monitoring techniques is outside of the scope of this project. However, future research on the use of MRDs will need to take into account any change in the damage caused by impacts when an MRD damping system is implemented. Part of the need for flexibility in the range of sensors that can be used in the program is because the sensors in use will be a factor in determining what SHM techniques can be used and how sensitive to damage the detection system will be (Maia, N.M.M et. al.).

2. EXPERIMENTAL SETUP

Testing various control programs needs a system to apply forces to a bar, measure the resultant behavior, and control the MRD's response. The initial setup consists of two concrete bars of equal length joined by a metal plate act as a single, simply supported concrete bar 10x10x100cm. Two bars are used to enable more bending along the centerline. This bar is equipped with two accelerometers, a strain gauge, and a linear variable differential transformer (LVDT) as shown in the picture below. These measure the bending, deformation, and distance the beam moves. The beam has a MRD attached beneath it (at a point 1/3 of the way along the length of the beam). A weight is drop from a constant height by the drop tower, which causes the beam to vibrate.

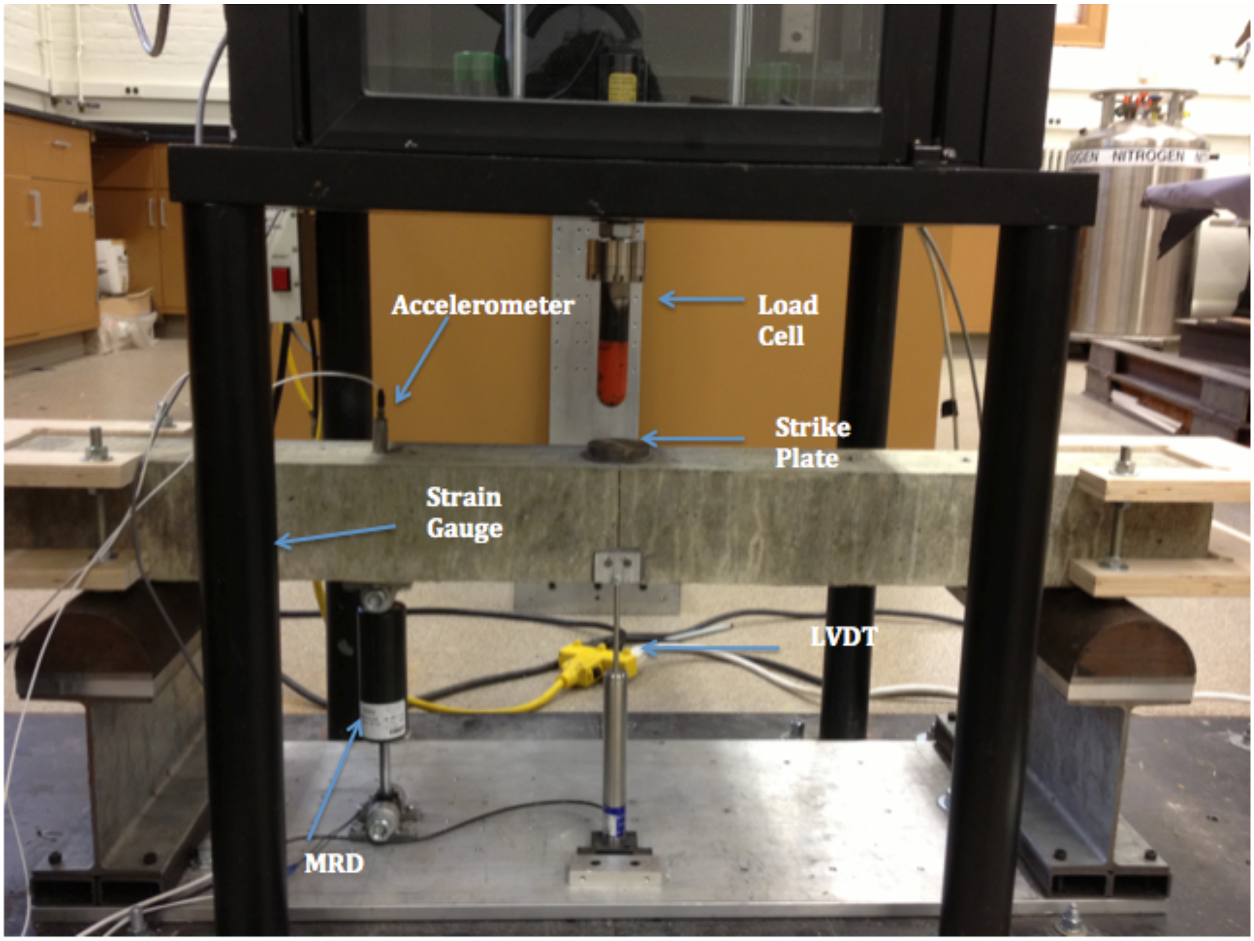

Figure 3 Picture of concrete bar setup beneath the drop tower in the lab.

Input and output was handled by data acquisition hardware from National Instruments, discussed further in section 2.2. The information from the sensors is sent to the control program via a National Instruments SCXI-1000 data acquisition module. The input/output connection was completed with a NI-9174 and a NI-9269 digital to analog converter added at the beginning of B-term. The National Instruments (NI) cDAQ-9174 USB Chassis and a NI-9269 Analog Output module work in conjunction to receive a signal from the computer and send out an analog voltage signal. The chassis connected to the computer sends the signal to a NI-9269 which sends the requested voltage to the Lords Voltage-Current Converter which sends a corresponding current to the MRD. The analog output is connected to the Voltage-Current converter by a axial cable that is stripped on one end to connect to the NI-9269.

The drop tower is a useful tool for testing the dynamic response of the concrete bar. It can be adjusted to a wide variety of weights and heights fairly quickly which would allow one to test whether the control model creates significantly different reactions at greater or lesser impact energies. It also possesses a mechanism for automatically returning to a preset height after each drop. This is useful for running multiple tests with the same variables in order to increase sample size as it ensures to within a small margin of error that the height is the same every time. The height is set by fastening a magnet along a post marked with distances within the cage. The arm can sense the magnet and will pick up the load cell and return to that height after every drop while in automatic mode.

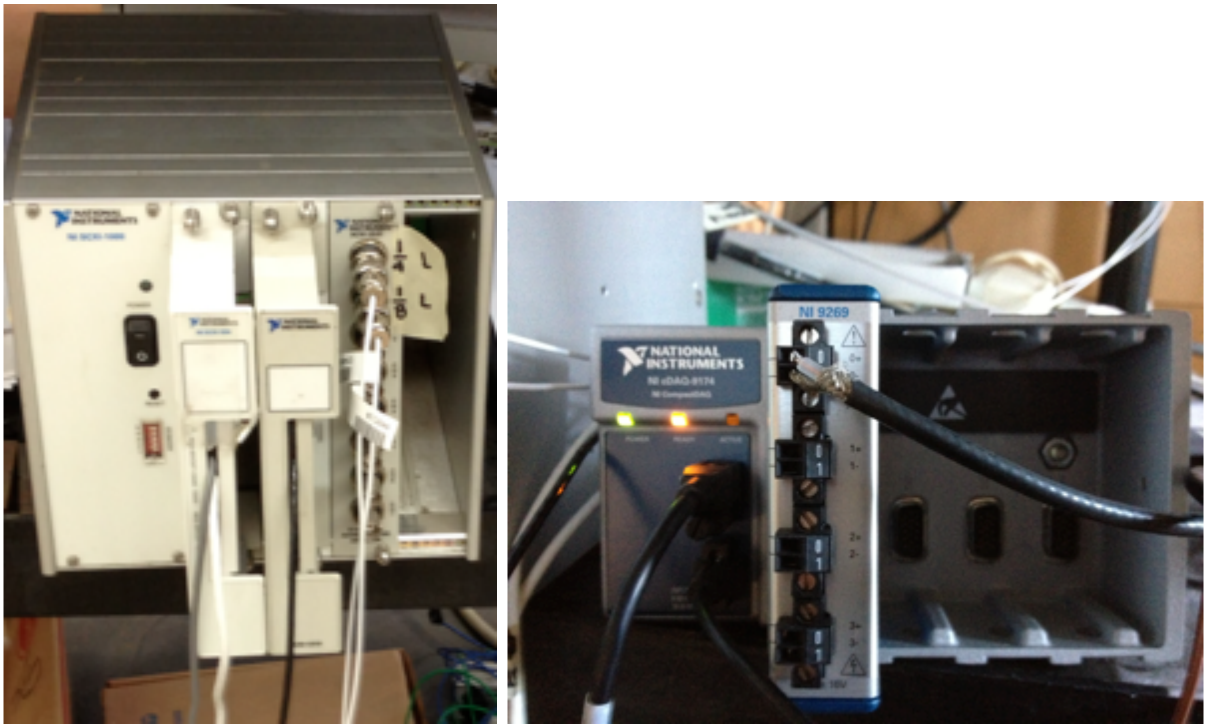

Figure 4 NI SCXI-1000 wired into the sensors used for this setup and the lab computer (Left) and NI-9269 for outputting voltage plugged into the NI cDaq-9174 Chassis (Right).

2.1 Notes on Hardware

The NI cDAQ-9174 Chassis and NI-9269 10V Digital to Analog Output Module were purchased as part of this project. The NI-9269 was chosen because it had the highest update rate of the modules examined (100kS/s) and allowed multiple channels to be stacked for a total voltage of 40V. The cDAQ-9174 was chosen as a cheap Chassis that works with the NI-9269 and because it has 4 outputs it can be used for future projects that may incorporate more MRDs or additional modules (National Instrument Corporation). The other output modules evaluated were the NI-9263, SCXI-1124, and NI 9264. These other modules were slower than the one chosen. The NI-9269 also has four output channels. Only one was needed for this experiment, but one of the first things future research is likely to look at is the use of multiple MRDs in a single system. Four was seen as a good compromise between the lack of flexibility of the next lowest down (two channels) and cost significantly less than the modules with more channels.

2.2 Preliminary Experiments

The fundamental experimental method was collecting impact data by dropping the load from a specified height with a simple model chosen to control the current being sent to the MRD. A height of 1.5 inches was chosen as an arbitrary height at which there was an observable level of reaction in the beam. The first experiment was an attempt to determine the effect of applying current to the MRD and how long it takes from the impact to there being a measurable change in the beam's behavior due to the change in current. This was accomplished by first collecting data with no current being sent to the MRD at all. This data was used to determine the boundary conditions that the program could use to detect the impact. This was determined by the data being read by accelerometer 1 (which is the accelerometer on the top of the beam directly over the MRD and the closest accelerometer to the centerline) and was decided to be either below -0.9 g or above -0.4 g.

The next set of data collected was to send 1 amp to the MRD when the acceleration data met those conditions. Later samples were collected with the current to the MRD being set and remaining at 1 amp before the impact in order to eliminate the timing variable and verify that the MRD was having an appreciable effect on the beams behavior. Further tests were done with one of these three behaviors specified for the current output. It was later discovered that the change in behavior was most noticeable at .3 amps and so testing with current going to the MRD began to use .3 amps.

3. CONTROL PROGRAM

LabVIEW was selected as the programming language for the control program. It was chosen because:

- it is a language developed for use in lab applications such as this one,
- it has a rich set of user interface options for controlling experiments an processes,
- there was already a body of work done which read and displayed sensor data,
- it is a graphical programming language that is easier for non-computer scientists to modify while performing further experiments,
- it was already integrated with the National Instruments input and output devices.

However, during testing, it became apparent that early versions of the program were not fast enough for the rapid responses required by this approach.

The nature of the timing constraints on the LabVIEW program first became apparent when it was shown that the time between each read started at 0.3 of a second and rapidly increased, such that in 10 samples it was taking over a second between reading each sample. Further refining the design brought the frequency to 1 sample every 2 ms. But in doing so a large portion of the original user interface functionality was lost. Previously the program displayed the data read from the sensors and the response sent to the MRD in real-time in waveform graphs that could be paused and scrolled through. These elements took up a significant amount of time while the program was acquiring data. The program consisted of a single button, which, when pressed ends the data collection and the data collected to a file.

In order to acquire data at a high enough rate to be useful a change in the program's data flow was necessary. Two approaches to this redesign were examined. Both approaches focused on separating the rate at which data was sampled (the number of samples read from the sensors per second) from the rate at which the program processed the data (the number of times the program calculated and sent the output signal per second). The first approach was to have two loops running concurrently. One loop would read the data for one instant of time and determine what the output should be based on that, while the other loop acquired samples over a longer period of time to be logged so that the beams response could be accurately examined. This approach would require finely tuned multithreading in order to make sure that both loops operated at the required speed and that neither loop tied up the system resources and prevented the other loop from running.

This proved difficult and it was rejected in favor of the second approach. In this approach a single loop was used which read all available samples from the input device, calculates the control signal, outputs the control signal, and logs all input and output data. Using this approach it was possible to take advantage of the input devices internal buffers to separate the sampling rate from the speed of the loop. While this approach allows for better data recording it came at the cost of responsiveness. In practice, output to the MRD was only being sent every 20 milliseconds. This was determined to be a necessary sacrifice as accurate data logging was a more important concern. Changing the program design in this manner meant that the UI elements previously removed could be partially restored.

3.1. The User Interface

The user interface for the finalized program flow was created to enable future users to perform advanced testing without any programming. It takes advantage of the NI-MAX program included with most National Instruments input/output devices to configure the connection to the devices and the device's sampling rate. The UI during testing allows users to define triggers, to see that data is being collected, and to review a graph of the data when acquisition is stopped.

After the initial design of the UI it underwent a period of testing. Potential users such as lab managers and graduate students were given a walk through of the program and asked to use it to collect data on their own. Their feedback was used to create some additional functionality like triggers that begin data collection when certain values are read from the input and a streamlined process for running the same test multiple times without rerunning the program. This process helped to identify potential problems and to highlight areas where the user interface needed to be improved. One of the major problems found was that the program allowed users to select invalid i/o tasks and would only notify the user of an error after the first test had been run. Other changes made based on user feedback included, changing names and labels to make their purpose more obvious, and changing the button layout to improve workflow. The fact that the graph did not update as data was being collected was a source of confusion. However, it was difficult to prevent this confusion because the update behavior of the graph couldn’t be changed without making the program too slow. In order to alleviate the problem the fact that the graph didn’t update during collection was stated explicitly in the application and the manual.

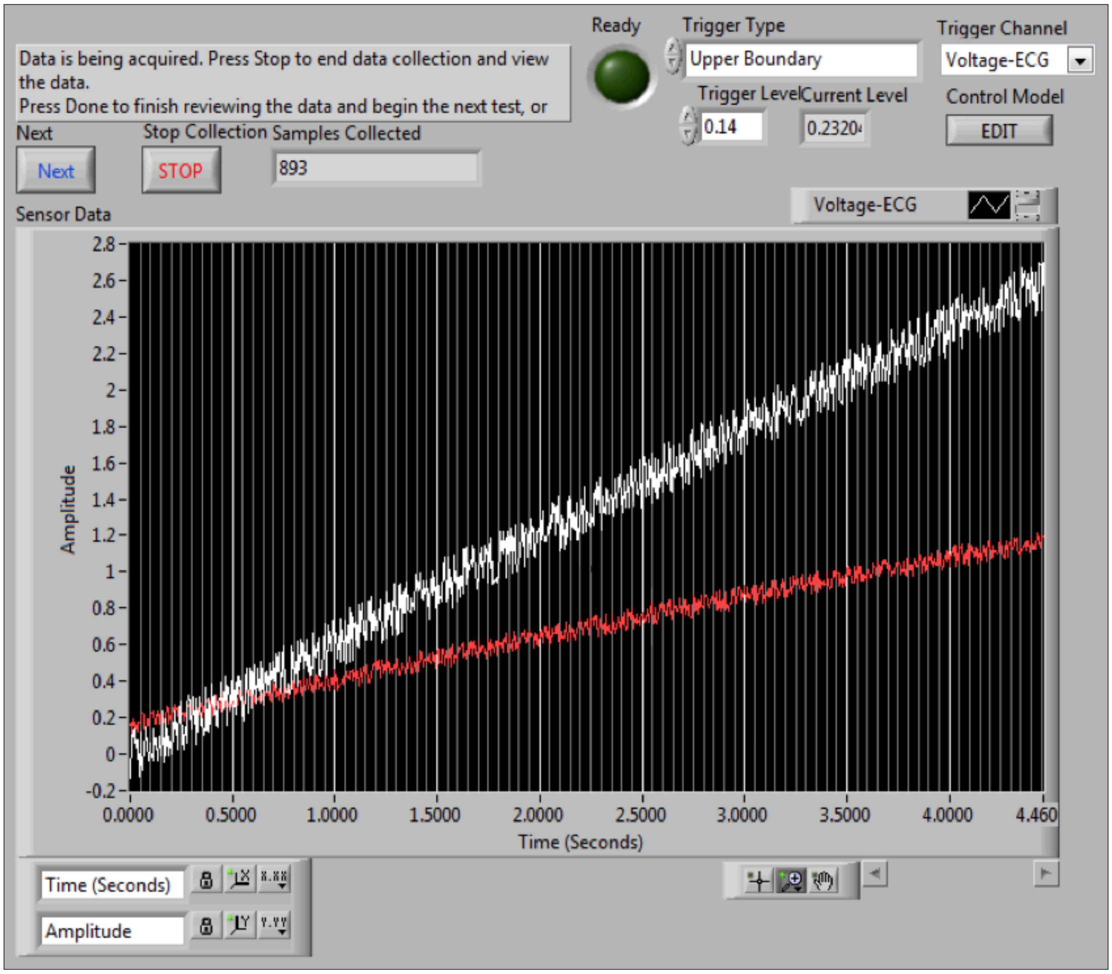

Figure 5 The finalized user interface for the data acquisition screen. The graph is showing two noisy sin functions.

4. ISSUES

There were a number of issues that were encountered throughout the project. The biggest issue was that the sampling frequency wasn't high enough to capture the data accurately, causing aliasing. Aliasing distorts the data by introducing frequencies into the data that didn't exist in the actual signal and removing frequencies that did (Travis, J. et. al.). In addition to this the data wasn't flowing through the program correctly, too many samples were being read per iteration to react to the beam. Restructuring the program to read a single sample per iteration of a fast loop mitigated the amount of time the beam took to react but wasn't fast enough to prevent aliasing. Other issues delayed progress with the experimental setup and program. The multi-meter being used wasn't reading correctly and couldn't be verified independently. The program also had an error in it that appeared sporadically when it attempted to write data to the output file that had been removed from the input buffer.

5. RESULTS

The first experiments performed were multiple impact tests using two MRD states. The first state had no current to the MRD and the second set the current to 1 amp when the impact was detected. These tests showed no change between the two MRD states being used. Later, this was discovered to be because the loop being used was not capable of reacting to the impact in real time. This data was collected at 5 kilohertz. Figure 5 shows graphs for the acceleration data over time for four tests, two for each MRD state. The large differences in the graphs between all of the tests show a lack of consistency that was present in all tests. This was later discovered to be because the sampling rate was too low to accurately show the data. The lack of consistency of the data seen in Figure 5 was confusing and at the time it hadn't yet been determined that the Nyquist frequency was above the sampling rate.

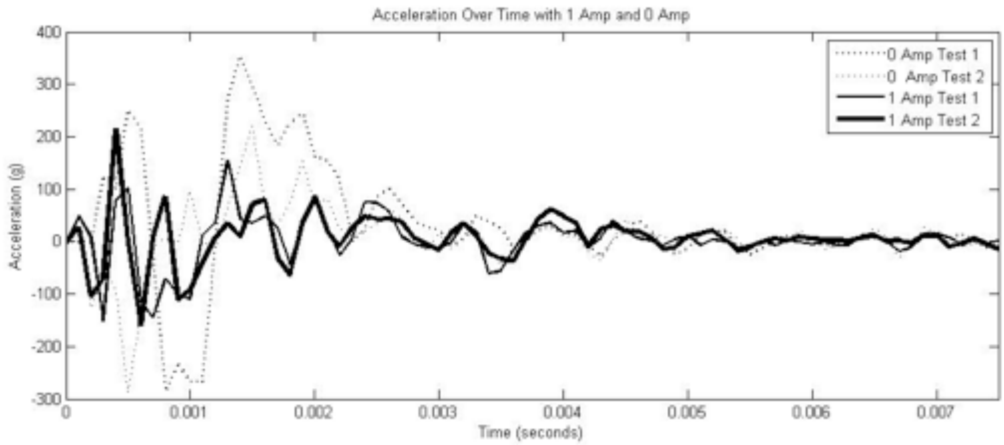

Figure 6 First set of data with 0 amps and 1 amp, activated when impact is detected.

Later tests were done at 10 kHz and analyzed by using Fourier transforms. These also lacked uniformity. The results of one such set of Fourier transforms can be seen in Figure 6 below. The Fast Fourier transform method was used on the acceleration data from one of the accelerometers. This data shows a large amount of inconsistency, implying that there are numerous frequencies present in the acceleration data. In addition to that, the amplitudes of the frequencies don't show a strong trend towards zero as the frequency increases. The fact that there is no clear end to the frequencies in the data before the 5000 Hz level suggests that the Nyquist frequency is above 5,000 Hz. Since the sampling rate needs to be at least twice the Nyquist frequency, the sampling rate of 10 kHz is insufficient.

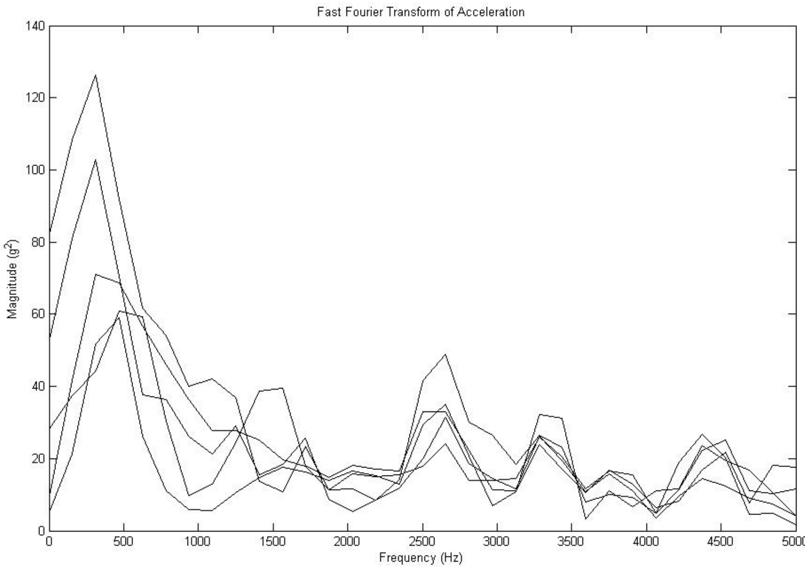

Figure 7 Fast Fourier Transform of Acceleration with a constant 1 Amp applied to the MRD (Multiple Tests).

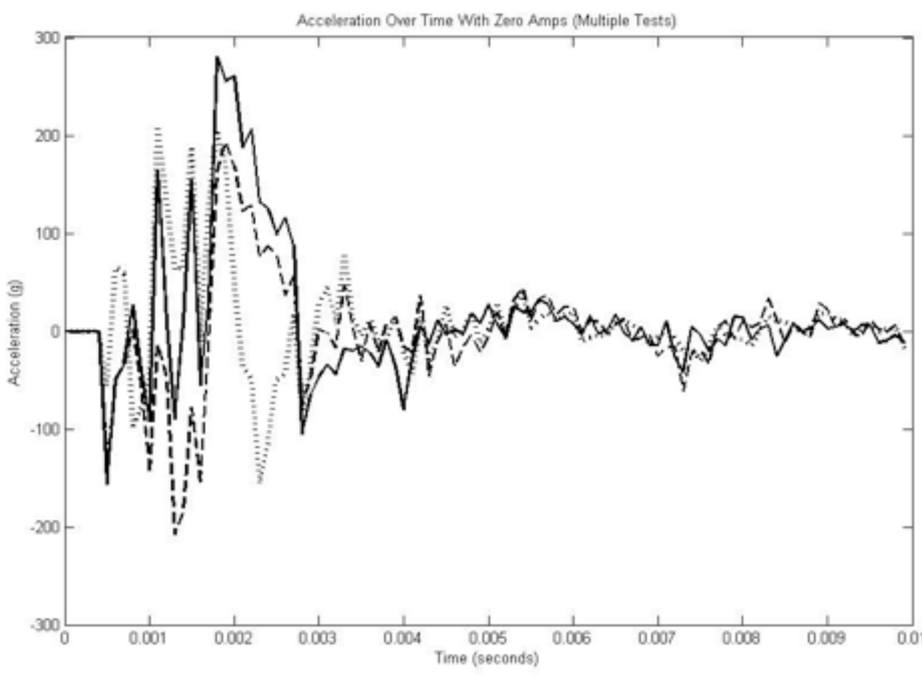

Figure 8 Acceleration Over Time of multiple tests with no current, sampled at 10 kHz.

The Fourier transform in Figure 6 shows that there is no frequency that appears consistently in multiple tests. Therefore, they do not conclusively show a difference between the beams behavior with and without current going to the MRD. This is because the sampling rate that was being used (10 kHz) seems to be too small to produce consistent results. Figure 7 above shows 3 tests performed from the same height and with the same weight but there is still a large amount of variability in the data. By performing tests with no current, any possible oddities caused by the MRDs behavior are removed confirming that the problem was with data collection.

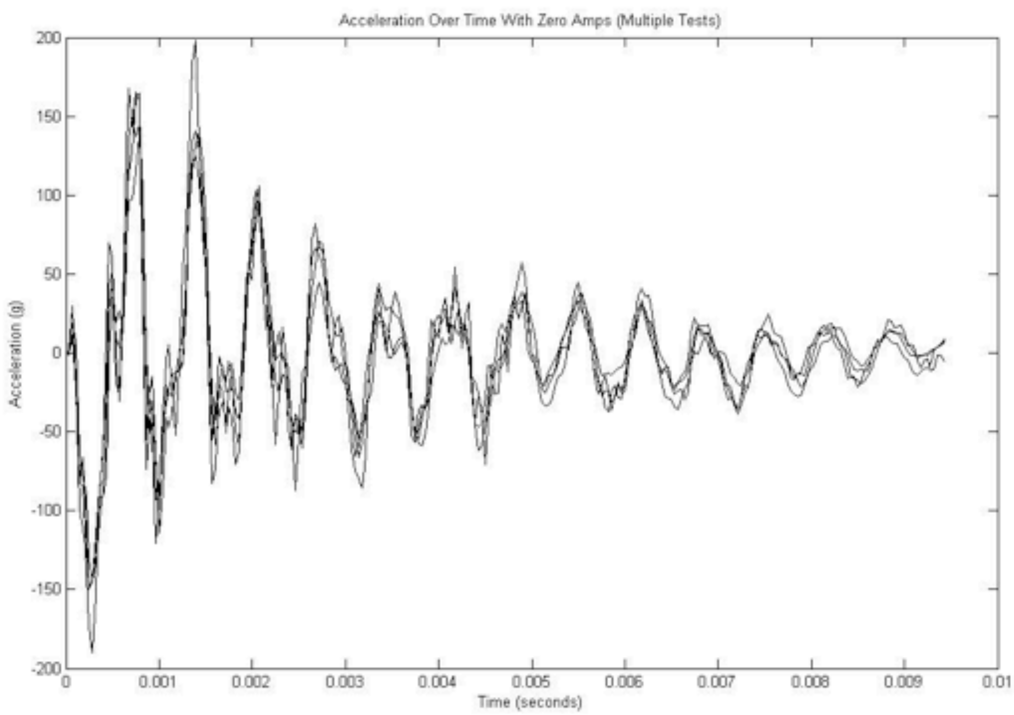

Figure 9 Acceleration Over Time of multiple tests (no current) sampled at rates of 28 kHz.

In order to determine what the minimum necessary sampling rate is another set of tests were done at the maximum sampling rate allowed by the hardware, 28 kHz, and used in a Fast Fourier Transform. As can be seen in Figure 8 the 28 kHz graph has significantly less difference between the tests. By normalizing and graphing the Fourier transform it is possible to determine the Nyquist Frequency, which is twice the largest frequency at which there is a large amplitude component. This frequency is used by the Nyquist-Shannon sampling theorem which states that the minimum sampling rate is the Nyquist frequency. Figure 9 shows the graph of all of the Fourier Transforms for the high sample rate data.

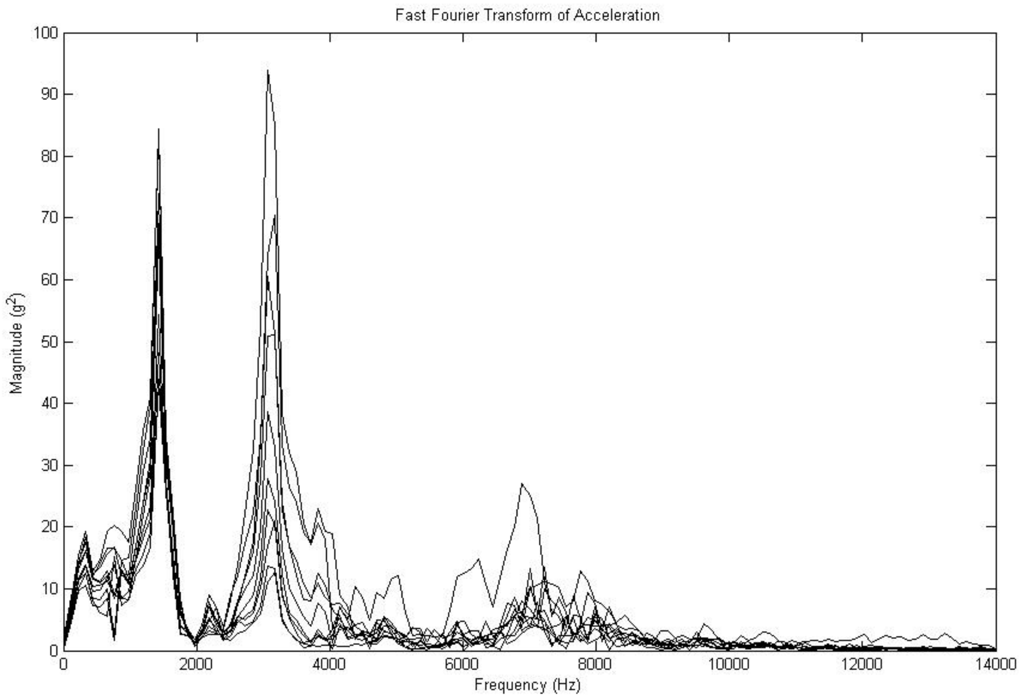

Figure 10 Fourier Transform of Acceleration Collected at 28 kHz. The largest magnitude component takes place at 1,500 Hz and ends at 5600 Hz

By using 5600 Hz as the point at which the component of the largest magnitude ends; the Nyquist Frequency is determined by multiplying by 2. The end result is that the minimum sampling rate necessary is approximately 11.2 kHz which fits with the large variability in the data recorded at 5kHz and 10kHz. This means that in order to get repeatable and consistent data the program needs to be capable of reading one sample every 0.09 ms.

6. FUTURE RESEARCH

One focus of this project is enabling future research into the use of MRDs to damp impact response in buildings. Future research could take the program created to begin developing a more advanced control model for damping impacts. This could be extended further by examining more complicated systems using different sensors or more MRDs. Other possible systems on the horizon are those which activate the damping system before the impact by sensing approaching objects, for instance a bridge which can sense a boat heading towards one of its supports and determines the weight and speed of the boat to predict and negate the force of its impact.

Future improvements to the program could focus on expanding it to better suit a variety of experiments based around controlled i/o to physical structures. It would also be beneficial to work on increasing the reaction speed of the program. This could be accomplished either through a program redesign, porting the program onto an embedded system so that the other processes of the computer would not get in the way, or even simply moving it to a different PC that with greater processing power.

7. CAPSTONE DESIGN

The capstone design criteria require that this project show design experience incorporating engineering standards and realistic constraints. Engineering judgment incorporating practicality, expense, and service life was used in deciding which hardware to buy to enable programmatic control of the MRD, as discussed in section 2.1. In addition to documentation provided by a National Instruments employee consulted prior to the beginning of this project, research was performed on the capability of the different hardware, as well as the performance likely to be required by the MRD and the computer. Further design work was performed in the process of creating and testing the experimental platform. The experimental setup was built and then tested to ensure that the computer could collect accurate data from the sensors and dynamically and reliably send an analog signal to the MRD. This was an iterative process in which errors were identified. Then possible causes for those errors were determined and tests were designed and performed to determine the actual cause and then fix the error. For example, during testing an error was found that the setup did not seem to send analog voltages correctly. The possible causes were identified to be faulty programming, faulty wiring, faulty hardware, or faulty equipment. Testing these possible causes eventually revealed that the true cause was a faulty multi-meter and switching to a different multi-meter showed that the voltages were being output correctly

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