RESEARCH PROJECT REPORT

Buildings That Resist Earthquakes Better

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ABSTRACT

The seismic disturbances caused by earthquakes can seriously damage a building or cause it to completely collapse, resulting in injury, death, and interruption to daily lives. Structural engineers attempt to overcome the issues caused by earthquakes by designing buildings that are better suited to resist them while maintaining cost effectiveness. In this program, we are studying damping devices (active and passive) used to affect the natural frequency and/or the damping coefficient of the building. The first experimental design we used involved determining the stiffness and natural frequency of a single storey steel building model. We then altered this original undamped design by adding base isolators and later a viscous damper to test the response with a similar initial disturbance. The second experimental design uses a computer controlled shake table and active damping device to simulate earthquakes of varying intensity. Overall, the results show that base isolators are effective passive damping mechanisms, but active damping mechanisms are by far the most effective way to prevent structural damage.

Key Words: damping, frequency, damping coefficient, stiffness, active damping, passive damping, base isolators, viscous damper

INTRODUCTION:

Our project was designed for us to explore the effects of different damping methods on structures when different disturbances are introduced. First we studied the effects of different disturbances (such as chirps, sine waves, and impulses) on a system where no damping devices were used. We analyzed the damping coefficient and circular frequency for that scenario. Then we systematically performed the same experiment for a structure with base isolators, passive viscous dampers, and active dampers.

LITERATURE REVIEW:

JOURNAL ARTICLE NOT FROM MENTOR'S LAB

Lucchini, A., Monti, G., and Kunnath, S. (2008). "Seismic behavior of single-story asymmetric-plan buildings under uniaxial excitation." *Earthquake Engineering and Structural Dynamics,* 38, 1053-1070.

Engineers look at different asymmetry effects as well as the factor of ground motion. Engineers also look at different strength and stiffness analyses. In all cases, asymmetric designs always elicit an irregular response.

MAGAZINE SCIENTIFIC REVIEW ARTICLE (<5 yrs old)

Yi, J., Kim, D., and Feng, M. (2009). "Periodic seismic performance evaluation of highway bridges using structural health monitoring system." *Structural Engineering and Mechanics,* 31(5), 527-544.

The engineers constructed an experiment where they measured the ambient vibration of a bridge under normal conditions. Then they conducted output-only acceleration tests and recorded the results. Then they built a model to test various responses under earthquake conditions. They found that it is possible to monitor and update the bridge.

SCIENTIFIC RESEARCH PUBLICATION FROM MENTOR'S LAB

Unknown author. (2009). "One professor's winning formula." *Quanser News*, 11.

Dr. Cohen wanted to bring new hands-on equipment to the University of Cincinnati engineering department in order to attract more students and achieve better results. Just as Dr. Cohen predicted better equipment and labs stretched the students to see how many engineering disciplines are inter-related, and grew the students into better and deeper engineers. Now other engineering departments are taking note of Dr. Cohen’s methods.

HISTORICAL ARTICLE

Kerr, R. (1980). "Quake prediction by animals gaining respect." *Science*, 208(4445), 695-696.

This article by Richard Kerr from 1980 served as a historical reference for the field of using animal behavior as a predictor for earthquakes. This article discussed several different manifestations of unusual animal behavior as it relates to an impending earthquake. Kerr mentioned the ideas of low-frequency sound waves and electromagnetic phenomena, which has been reiterated in more recent research projects.

JOURNAL ARTICLE

Kirschvink, J. (2000). "Earthquake prediction by animals: evolution and sensory perception." *Bulletin of the Seismological Society of America, 90*(2), 312-323 .

This article by Joseph Kirschvink is one of the most referenced sources on the topic of animal behavior as it relates to earthquake prediction. The author discussed the evolutionary mechanisms involved, and gave special attention to the detection of P and S waves by animals as a precursor to earthquakes. Kirschvink proposed several testable hypotheses related to “animal behavior, sensory physiology, and genetics.”

POPULAR SCIENCE PUBLICATION

Mott, M. (2003). “Can animals sense earthquakes?” National Geographic News, <http://news.nationalgeographic.com/news/2003/11/1111_031111_earthquakeanimals.html> (June 30, 2009).

Maryann Mott’s article from National Geographic presents the three major positions about the validity of using animal behavior as an indicator of impending earthquakes (For, Against, Needs More Research). Although the USGS does not support the idea, scientists around the globe, particularly in China and Japan, have continued research into this topic.

BOOK

Ikeya, M. (2004). *Earthquakes and Animals: From Folk Legends to Science*. World Scientific, Singapore.

In his book *Earthquakes and Animals*, Motoji Ikeya discussed the scientific evidence that corresponds to legendary reports of mysterious phenomena occurring before an earthquake hits.

Through several different methods, including Electromagnetic Seismology, Ikeya posited that earthquake forecasting may indeed be possible in the future.

GOALS:

Rachel:

1. To find connections between biology and other areas of science such as engineering and earthquakes.
2. To gain experience from more seasoned teachers.

Grant:

1. To work cooperatively with other teachers and mentors to find effective and practical teaching strategies.
2. To bring my curriculum to life through real world applications and community connections.

OBJECTIVES:

1. Study the natural system response when different disturbances (sine waves, chirps, impulses) are introduced.

2. Study the system's response when base isolators are introduced.

3. Study the system's response when passive viscous damping is introduced.

4. Study the system's response when active damping is introduced.

5. Compare the damping coefficient, circular frequency, and settling time for the above objectives when the same disturbances are introduced in order to determine if using actuators, sensors, and computers produce significantly better results.

RESEARCH STUDY DETAILS:

1. **EQUIPMENT CALIBRATION**

We used the Linear Variable Displacement Transducer (LVDT) to measure the system's natural response, response with base isolators, and passive damping response. See Figure 1.

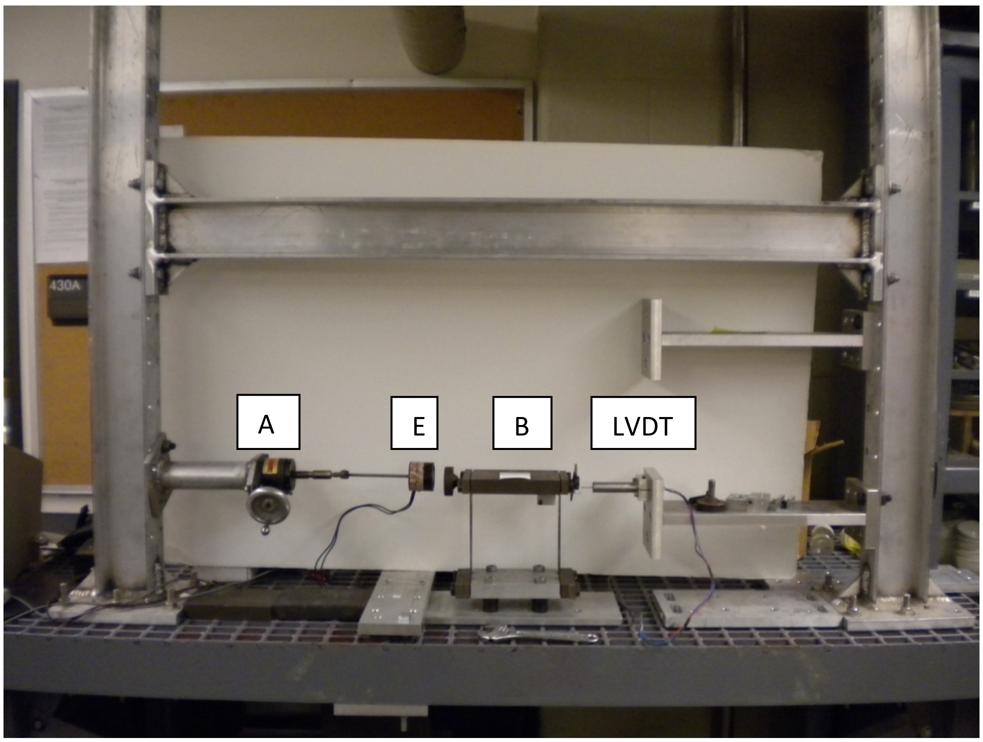


Figure 1. Experimental Setup with actuator (A), electromagnet (E), one story building on base isolators (B), and linear variable displacement transducer (LVDT).

First, we needed to calibrate the LVDT. We calibrated the LVDT by using the set up below to incrementally increase the displacement and measure the corresponding change in voltage. See Figure 2.

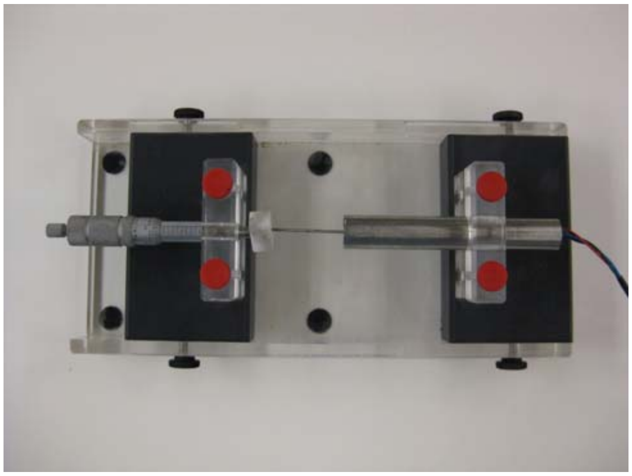


Figure 2. Linear Variable Displacement Transducer Calibration System.

The graph showing the calibration of the LVDT can be found in Figure 3. The x-axis is time in seconds. The y-axis is the change in volts. Each step represents one turn of the LVDT calibration device, which measures 1/40 of an inch displacement. So we turned the dial 10 separate times and measured the change in voltage.

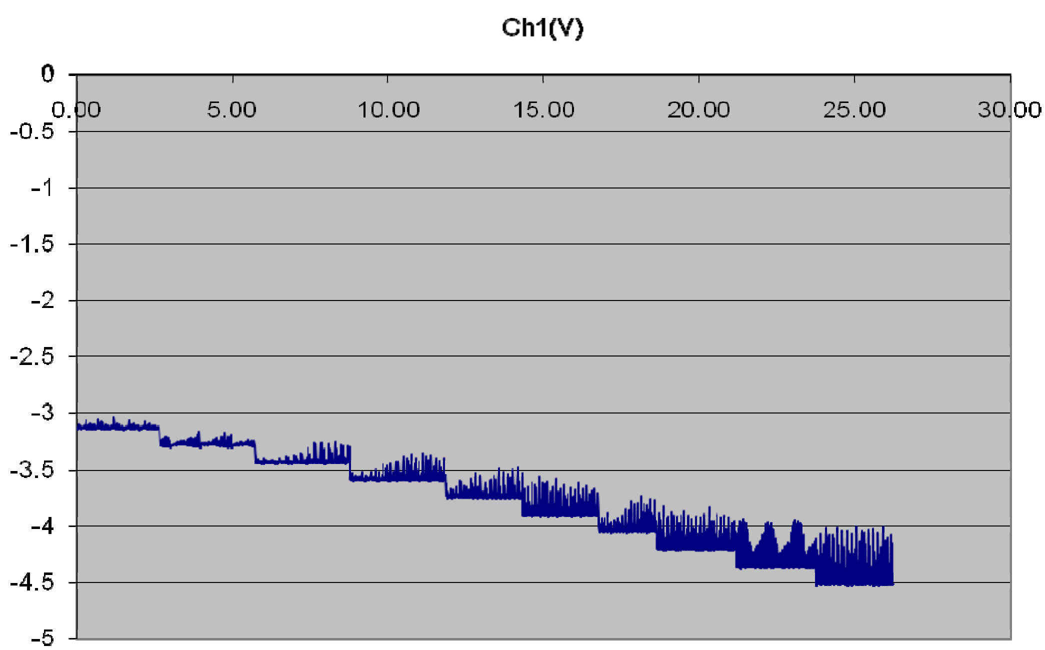
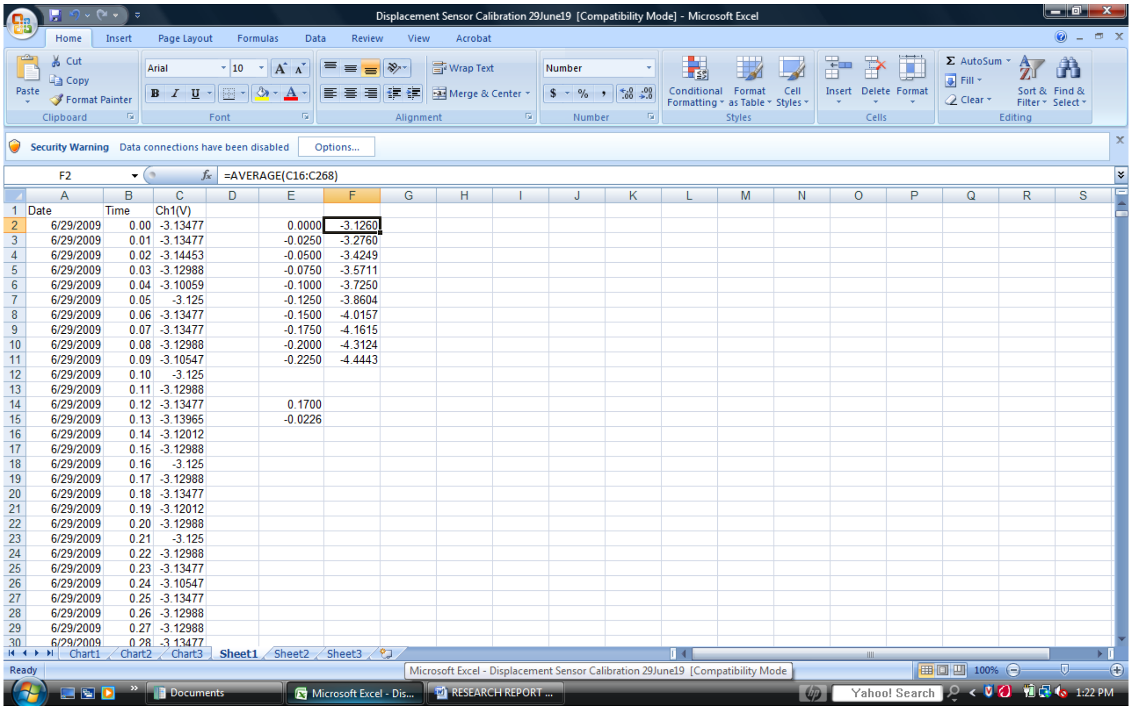


Figure 3. LVDT calibration raw data.

Then we used Excel to average the values in each range, as there were multiple data points for each time point. See Figure 4.



	A	B	C	D	E	F
1	Date	Time	Ch1(V)			
2	6/29/2009	0.00	-3.13477		0.0000	-3.1260
3	6/29/2009	0.01	-3.13477		-0.0250	-3.2760
4	6/29/2009	0.02	-3.14453		-0.0500	-3.4249
5	6/29/2009	0.03	-3.12988		-0.0750	-3.5711
6	6/29/2009	0.04	-3.10059		-0.1000	-3.7250
7	6/29/2009	0.05	-3.125		-0.1250	-3.8604
8	6/29/2009	0.06	-3.13477		-0.1500	-4.0157
9	6/29/2009	0.07	-3.13477		-0.1750	-4.1615
10	6/29/2009	0.08	-3.12988		-0.2000	-4.3124
11	6/29/2009	0.09	-3.10547		-0.2250	-4.4443
12	6/29/2009	0.10	-3.125			
13	6/29/2009	0.11	-3.12988			
14	6/29/2009	0.12	-3.13477		0.1700	
15	6/29/2009	0.13	-3.13965		-0.0226	
16	6/29/2009	0.14	-3.12012			
17	6/29/2009	0.15	-3.12988			
18	6/29/2009	0.16	-3.125			
19	6/29/2009	0.17	-3.12988			
20	6/29/2009	0.18	-3.13477			
21	6/29/2009	0.19	-3.12012			
22	6/29/2009	0.20	-3.12988			
23	6/29/2009	0.21	-3.125			
24	6/29/2009	0.22	-3.12988			
25	6/29/2009	0.23	-3.13477			
26	6/29/2009	0.24	-3.10547			
27	6/29/2009	0.25	-3.13477			
28	6/29/2009	0.26	-3.12988			
29	6/29/2009	0.27	-3.12988			
30	6/29/2009	0.28	-3.13477			

Figure 4. Excel sheet.

Using Excel to plot the displacement and averages we were able to create the following graph (Figure 5) showing volts vs. inches.

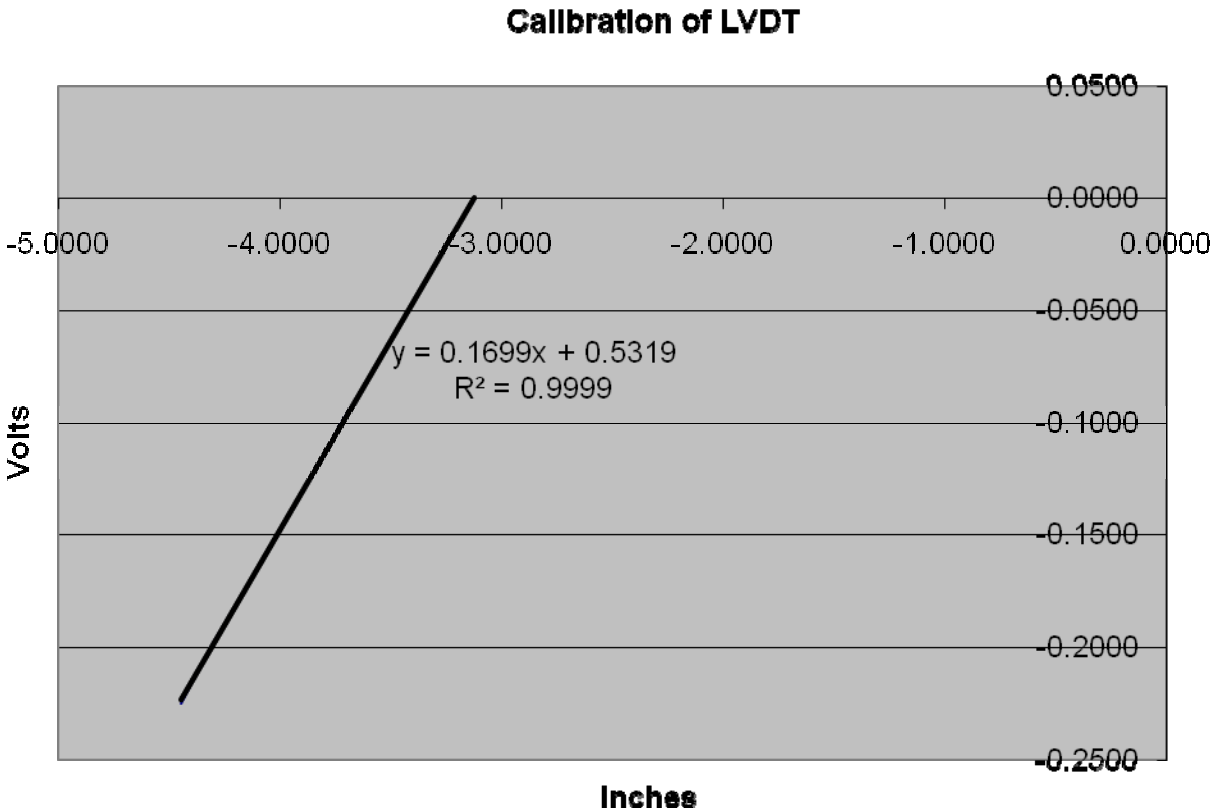


Figure 5. Calibration of LVDT, volts with respect to inches.

2. RESPONSE WITH NO DAMPING DEVICE

Next we wanted to analyze the natural response of a single storey steel structure when no damping devices were introduced. An electromagnet is used to displace the structure approximately one inch, and then when the electromagnet is turned off, sensors record the displacement with respect to time as the system damps itself out. We used the Virtual Bench Logger software from National Instruments to record the displacement every one thousandth of a second. Since the LVDT measures the displacement in volts, the following graph was generated (Figure 6).

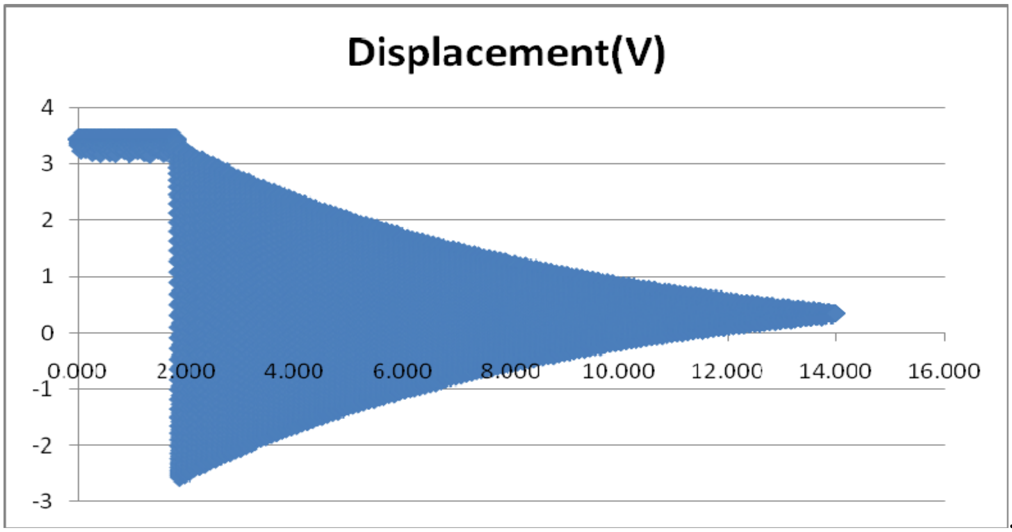
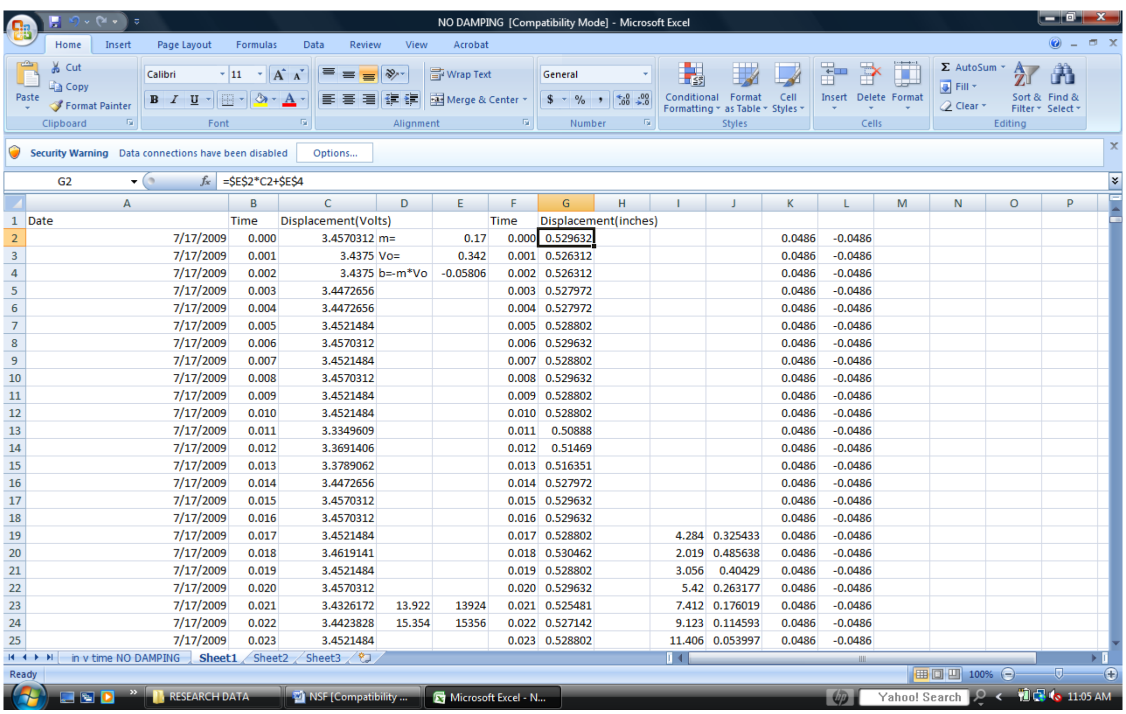


Figure 6. Displacement in volts vs. time.

We then had to convert the data in volts to inches by using the equation $v_{in} = m(v_{volts}) + B$, where v_{in} is the value in inches, m is the calibration constant, v_{volts} is the value in volts, and b is the offset value. We returned to Microsoft Excel to make these calculations. See Figure 7.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Date	Time	Displacement(Volts)			Time	Displacement(inches)					
2	7/17/2009	0.000	3.4570312	m=	0.17	0.000	0.529632				0.0486	-0.0486
3	7/17/2009	0.001	3.4375	Vo=	0.342	0.001	0.526312				0.0486	-0.0486
4	7/17/2009	0.002	3.4375	b=-m*Vo	-0.05806	0.002	0.526312				0.0486	-0.0486
5	7/17/2009	0.003	3.4472656			0.003	0.527972				0.0486	-0.0486
6	7/17/2009	0.004	3.4472656			0.004	0.527972				0.0486	-0.0486
7	7/17/2009	0.005	3.4521484			0.005	0.528802				0.0486	-0.0486
8	7/17/2009	0.006	3.4570312			0.006	0.529632				0.0486	-0.0486
9	7/17/2009	0.007	3.4521484			0.007	0.528802				0.0486	-0.0486
10	7/17/2009	0.008	3.4570312			0.008	0.529632				0.0486	-0.0486
11	7/17/2009	0.009	3.4521484			0.009	0.528802				0.0486	-0.0486
12	7/17/2009	0.010	3.4521484			0.010	0.528802				0.0486	-0.0486
13	7/17/2009	0.011	3.3349609			0.011	0.50888				0.0486	-0.0486
14	7/17/2009	0.012	3.3691406			0.012	0.51469				0.0486	-0.0486
15	7/17/2009	0.013	3.3789062			0.013	0.516351				0.0486	-0.0486
16	7/17/2009	0.014	3.4472656			0.014	0.527972				0.0486	-0.0486
17	7/17/2009	0.015	3.4570312			0.015	0.529632				0.0486	-0.0486
18	7/17/2009	0.016	3.4570312			0.016	0.529632				0.0486	-0.0486
19	7/17/2009	0.017	3.4521484			0.017	0.528802		4.284	0.325433	0.0486	-0.0486
20	7/17/2009	0.018	3.4619141			0.018	0.530462		2.019	0.485638	0.0486	-0.0486
21	7/17/2009	0.019	3.4521484			0.019	0.528802		3.056	0.40429	0.0486	-0.0486
22	7/17/2009	0.020	3.4570312			0.020	0.529632		5.42	0.263177	0.0486	-0.0486
23	7/17/2009	0.021	3.4326172	13.922	13924	0.021	0.525481		7.412	0.176019	0.0486	-0.0486
24	7/17/2009	0.022	3.4423828	15.354	15356	0.022	0.527142		9.123	0.114593	0.0486	-0.0486
25	7/17/2009	0.023	3.4521484			0.023	0.528802		11.406	0.053997	0.0486	-0.0486

Figure 7. Excel Sheet.

After these calculations were completed, we used Excel to graph time on the horizontal axis and displacement in inches on the vertical axis to create a graph of the natural system response, Figure 8.

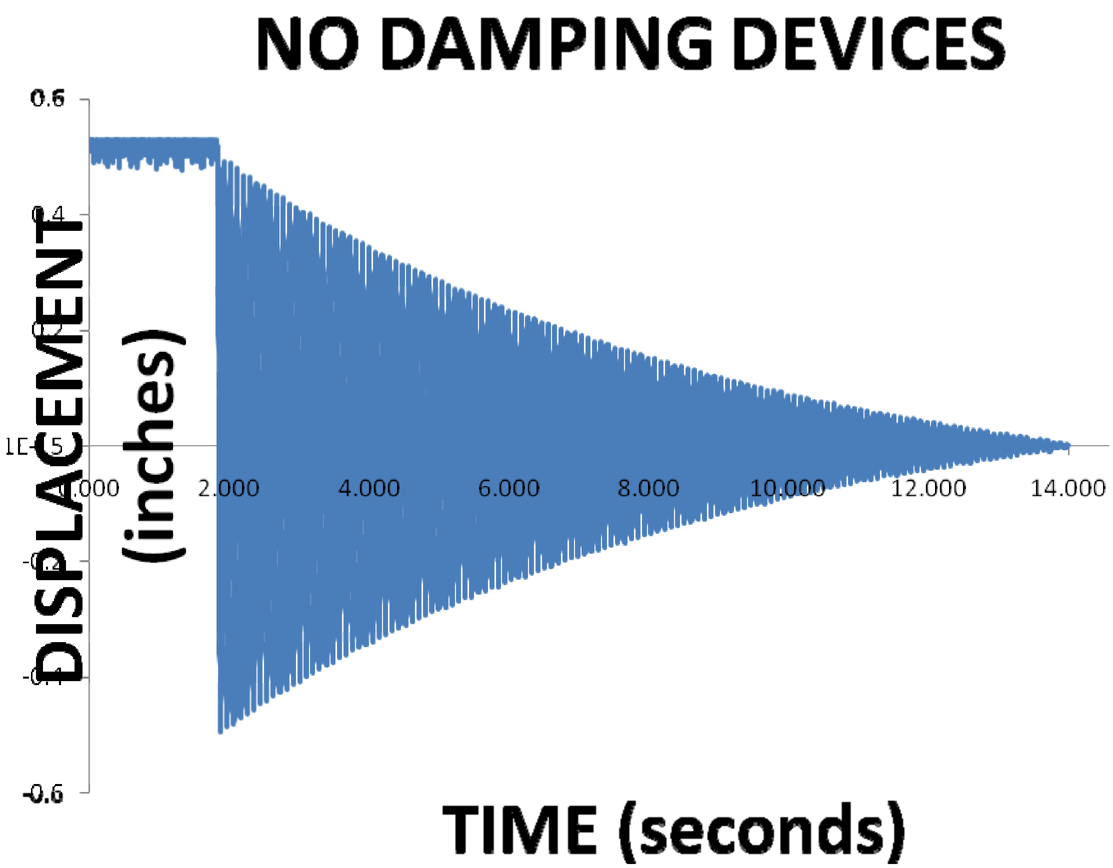


Figure 8. Basic experimental setup, displacement with respect to time.

We wanted to figure the equation for the exponential regression so we took a number of peaks and plotted them on the same grid and used the exponential regression function to create a trendline and corresponding equation. See Figure 9.

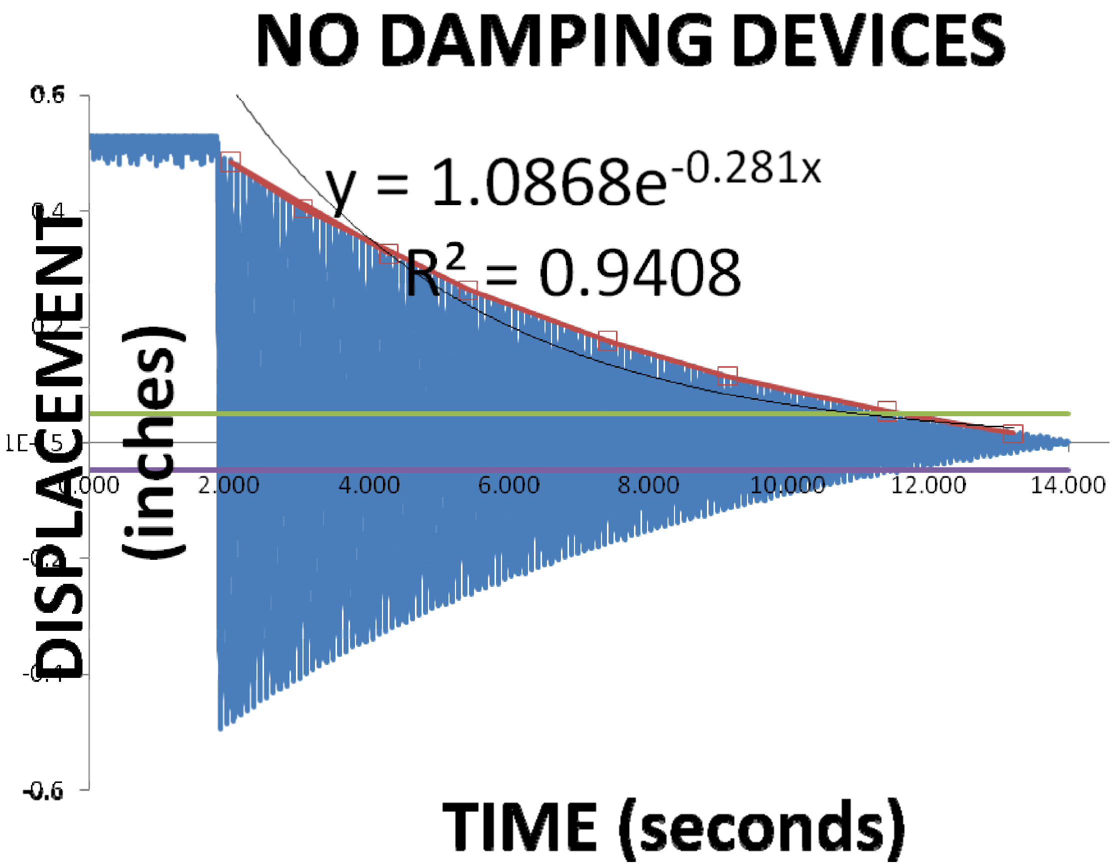


Figure 9. Single storey, undamped building model.

We did all of this to get the coefficient on e which turned out to be -0.281.

We also needed to calculate the number of peaks per second in order to multiply by 2 pi to get the average radians per second. We did this by estimating the peak on the graph and then going into the table and finding the actual time a maximum occurs. We did this for our first peak and last peak and counted the number of peaks in between to get 66.84 radians per second. With these two values we had a system of two variables and two equations that we solved in order to find the damping coefficient ζ and circular frequency ω_n.

$\lambda = -\omega_n * \zeta$

$-0.281 = -\omega_n * \zeta$

$\omega_d = \omega_n * \sqrt{(1-\zeta^2)}$

$66.84 = \omega_n * \sqrt{(1-\zeta^2)}$

$\omega_n = 0.004$

$\zeta = 66.84$

3. **RESPONSE WITH BASE ISOLATORS**

We performed the same experiment on the system with the addition of base isolators, which is illustrated in Figure 10.

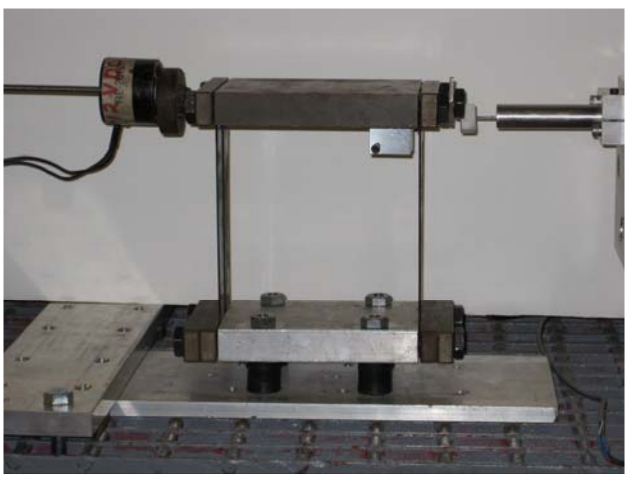


Figure 10. Base isolation experimental setup.

The same procedure for data capture and analysis was utilized as was previously described for the undamped system. Refer to Figure 11.

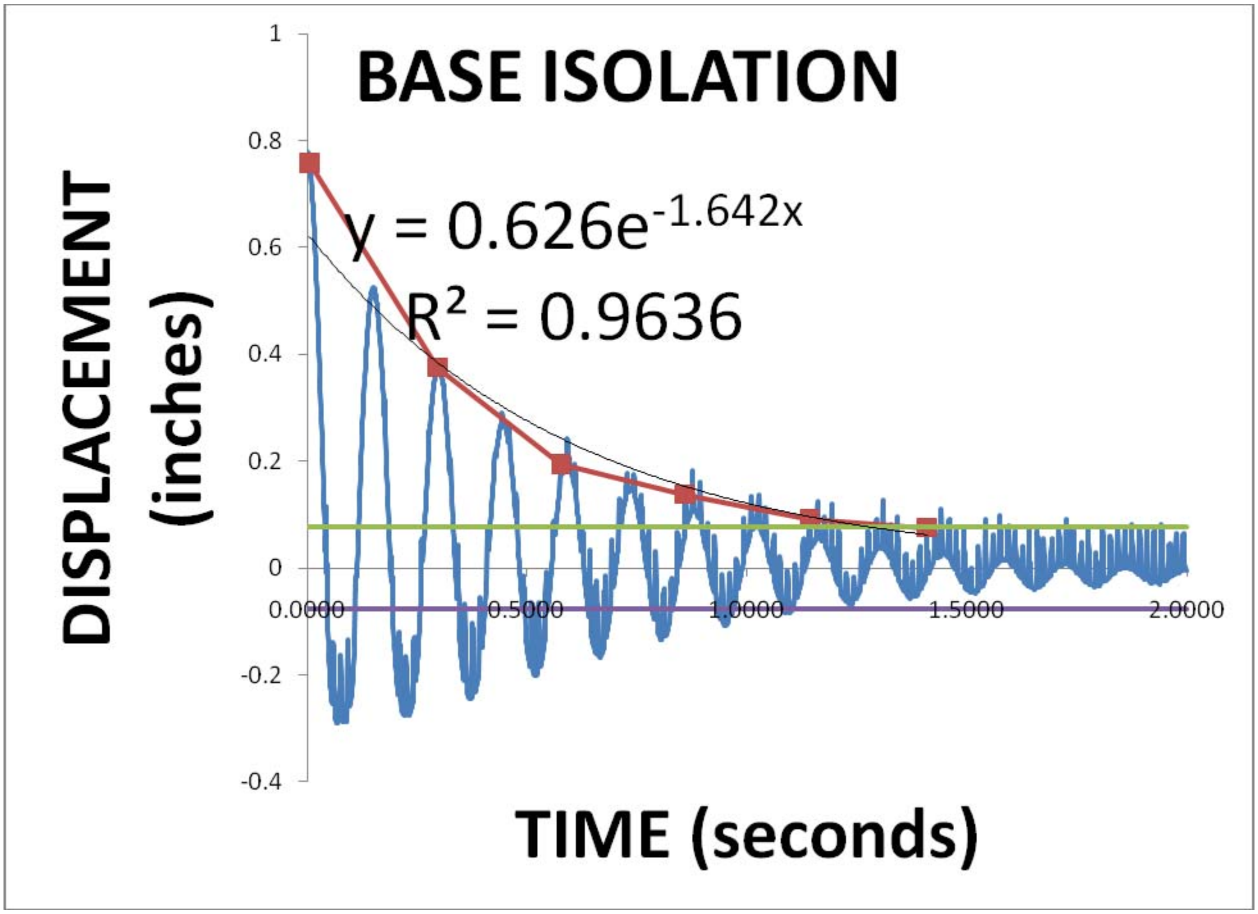


Figure 11. Base isolation, displacement with respect to time.

The damping coefficient and the circular frequency were calculated using the same method as for the experiment with no damping, but I will list our results in a table at the end of the experiments.

4. **RESPONSE WITH PASSIVE VISCOUS DAMPING**

Next we performed the same experiment on a system with the passive viscous damper. One experiment we filled the viscous damper with canola oil and the other with soap. The experimental setup is illustrated in Figure 12. The graphs of the experiments are shown below in Figures 13 and 14.


Figure 12. Viscous Damper Setup

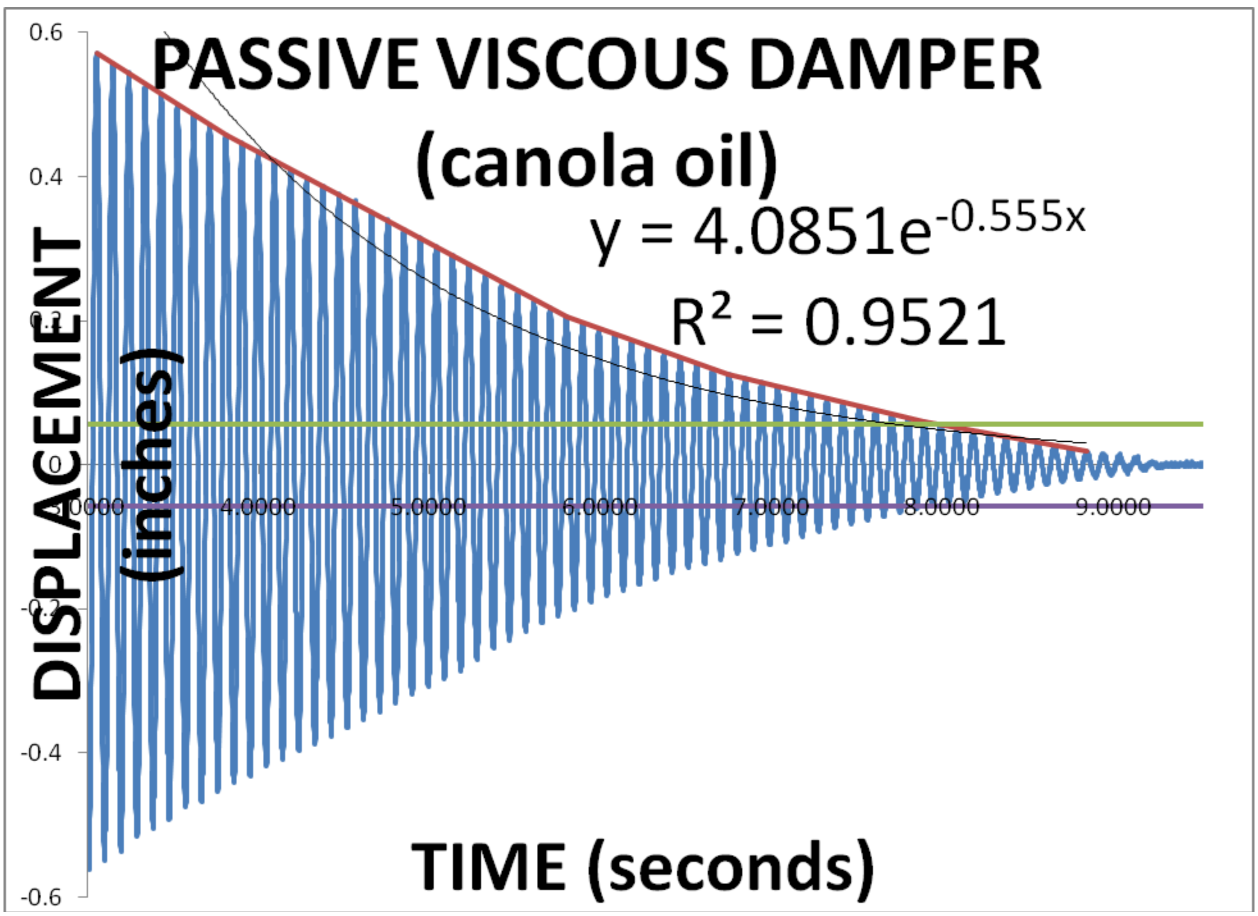


Figure 13. Passive viscous damping using oil, displacement with respect to time.

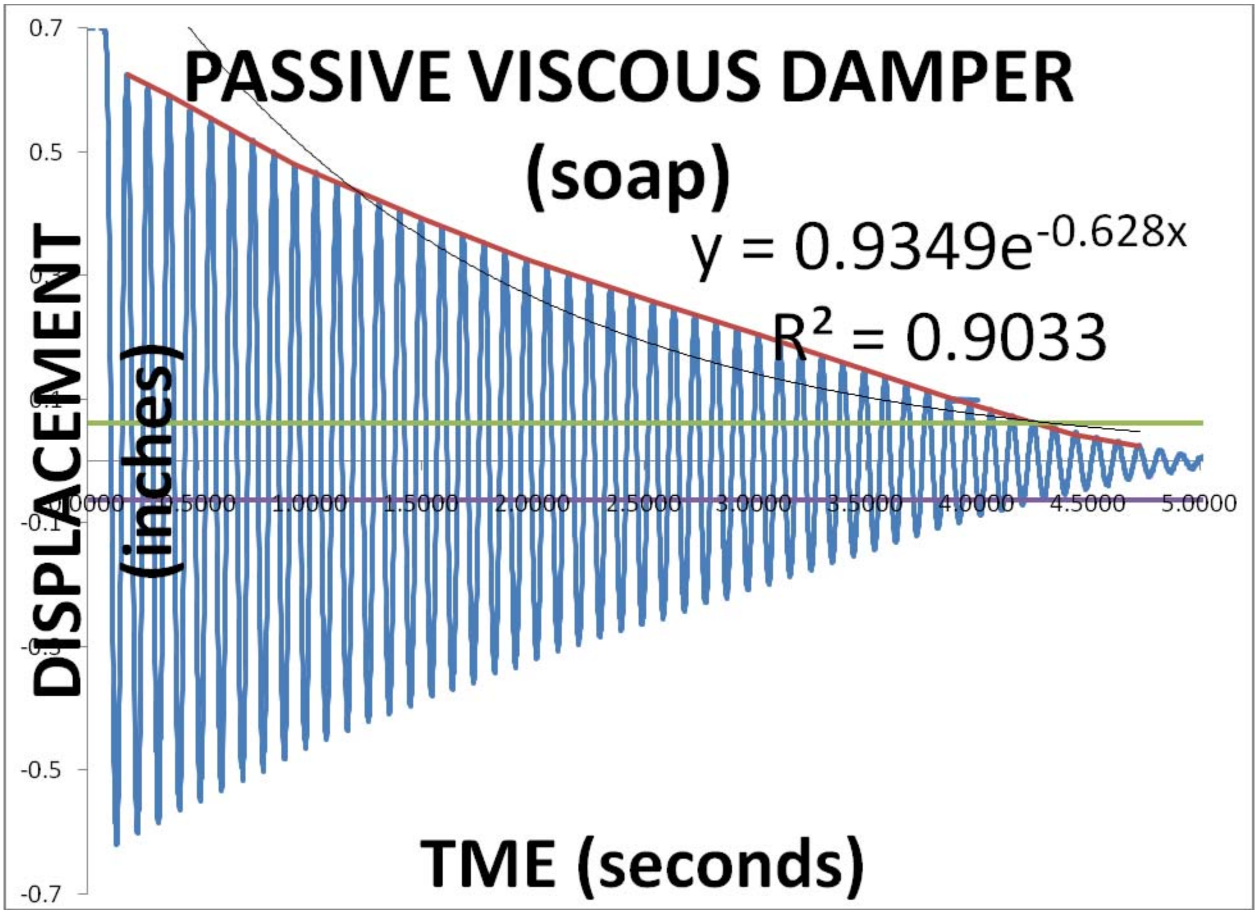


Figure 14. Passive Viscous Damping using soap, displacement with respect to time.

5. **RESPONSE WITH ACTIVE DAMPING**

In order to perform the active damping experiments, we had to go to a different lab with alternative experimental setups. These experiments were performed in the University of Cincinnati's Engineering Department's controls lab. Because the building model was different than the one we had used in the passive damping experiments, we measured displacement in this new setup with the damping turned off and then with the damping turned on in order to have a fair comparison. The building model is shown in Figure 15. The resulting graphs are shown in Figures 16 and 17.

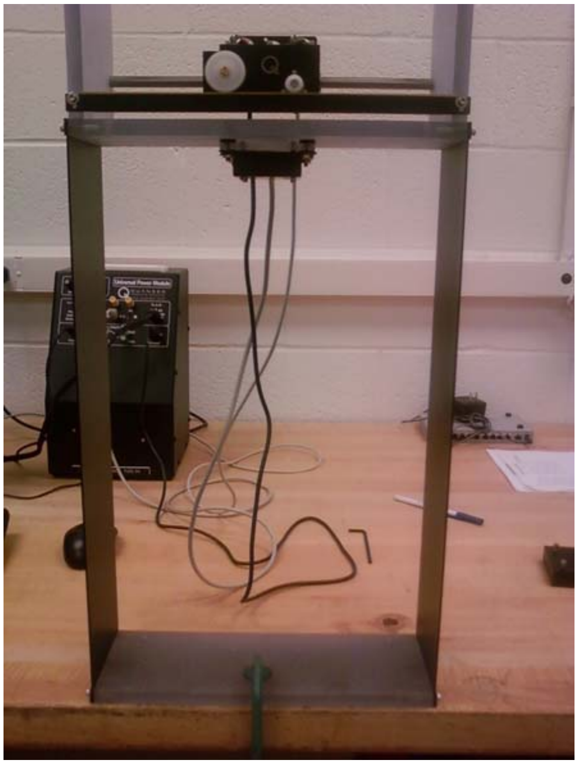


Figure 15. Single storey, with active mass damper.

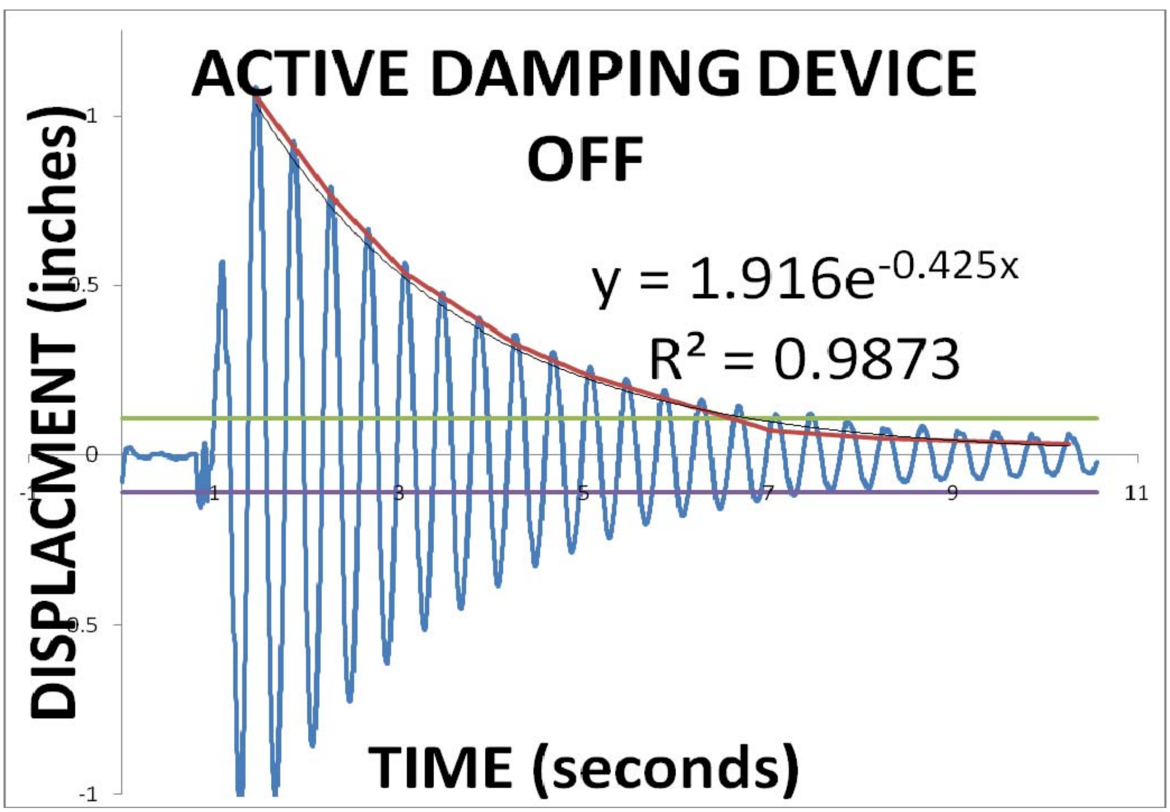


Figure 16. Active mass damping device turned off.

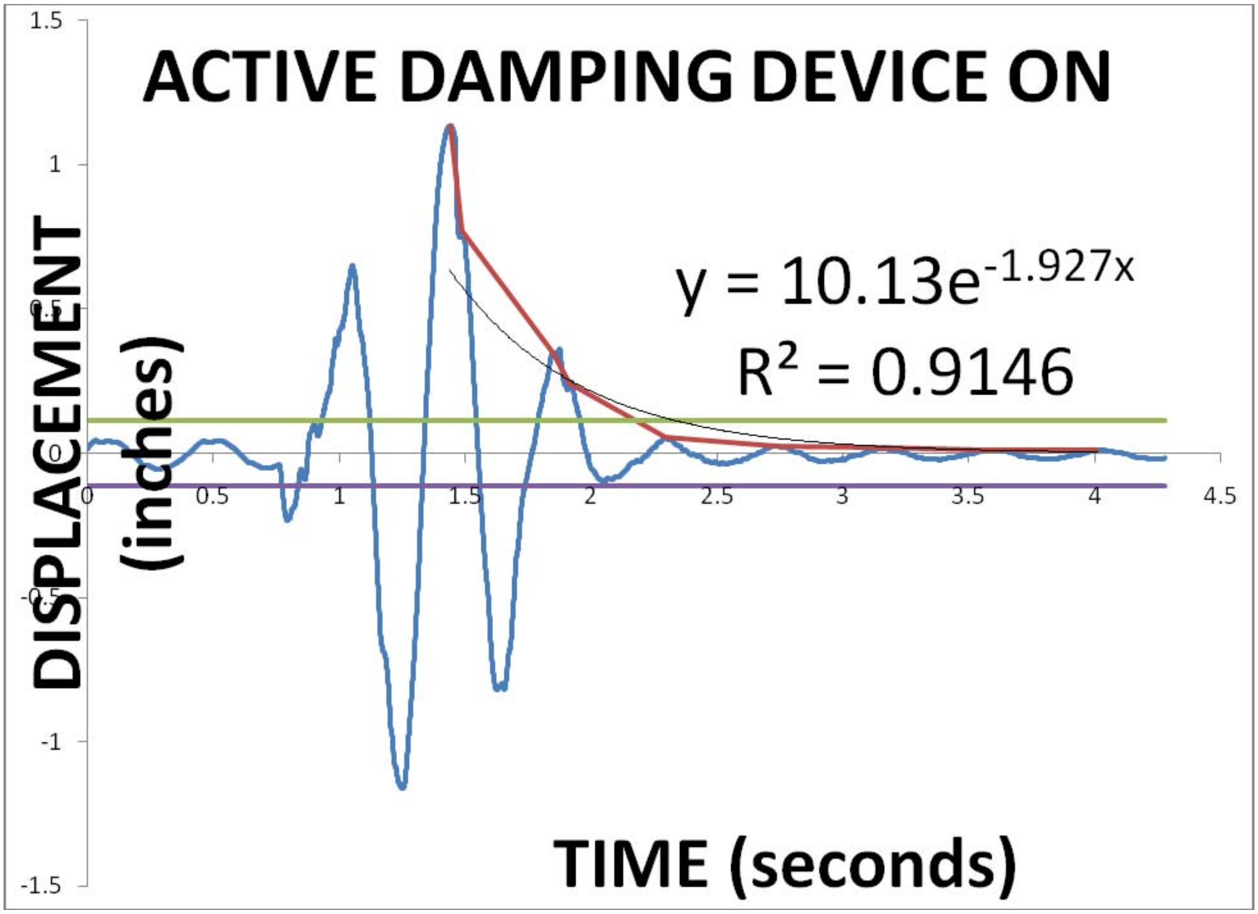


Figure 17. Active Mass Damping Device turned on.

6. SETTLING TIME

Before we summarize our findings, we did analyze another aspect of the data. On the finished graphs that have the equations we also plotted a green and purple vertical line that represent a +/- 10% range from the initial peak. We measured the time from the first peak to the time the graph stayed in between the green and purple line for each of our experiments. The resulting calculation is called settling time and shows how many seconds it takes the system to achieve a 90% recovery from the initial shock. These findings and our previous findings are summarized in the next section.

RESEARCH RESULTS:

In general, as the damping coefficient increases the circular frequency and the settling time decrease. We summarized our findings in the following table.

	DAMPING COEFFICIENT	CIRCULAR FREQUENCY	SETTLING TIME (secs)
NO DAMPING	.4%	66.84	9.58
PASSIVE DAMPING (OIL)	.8%	67.35	4.84
PASSIVE DAMPING (SOAP)	.9%	66.65	4.08
PASSIVE BASE ISOLATION	3.7%	44.01	1.94
ACTIVE (NO)	2.8%	15	6.03
ACTIVE (YES)	13%	14.78	.52

CONCLUSIONS:

Of the passive damping mechanisms (base isolators and viscous dampers) base isolators damp out the disturbance most efficiently. Active damping mechanisms damp out disturbances even more efficiently than any passive damping mechanism. Active damping mechanisms have shown to be worth the expense of actuators and computers based on the results of our experiments.

RECOMMENDATIONS:

Based on the results of our experiments engineers participating in new constructions in highly active seismic zones should consider the use of active damping methods to prevent the loss of life and expenses incurred by damaged or collapsed structures.

ACKNOWLEDGEMENTS:

Dr. Anant Kukreti, Dr. Kelly Cohen, Ravi Chalasani, Sanooj Edalalth, Chelsea Sabo, Nick Hanlon, Andrea Burrows, Eugene Rutz, Dr. Millard, Jim Clasper, Ted Baldwin, Dr. Dan Oerther

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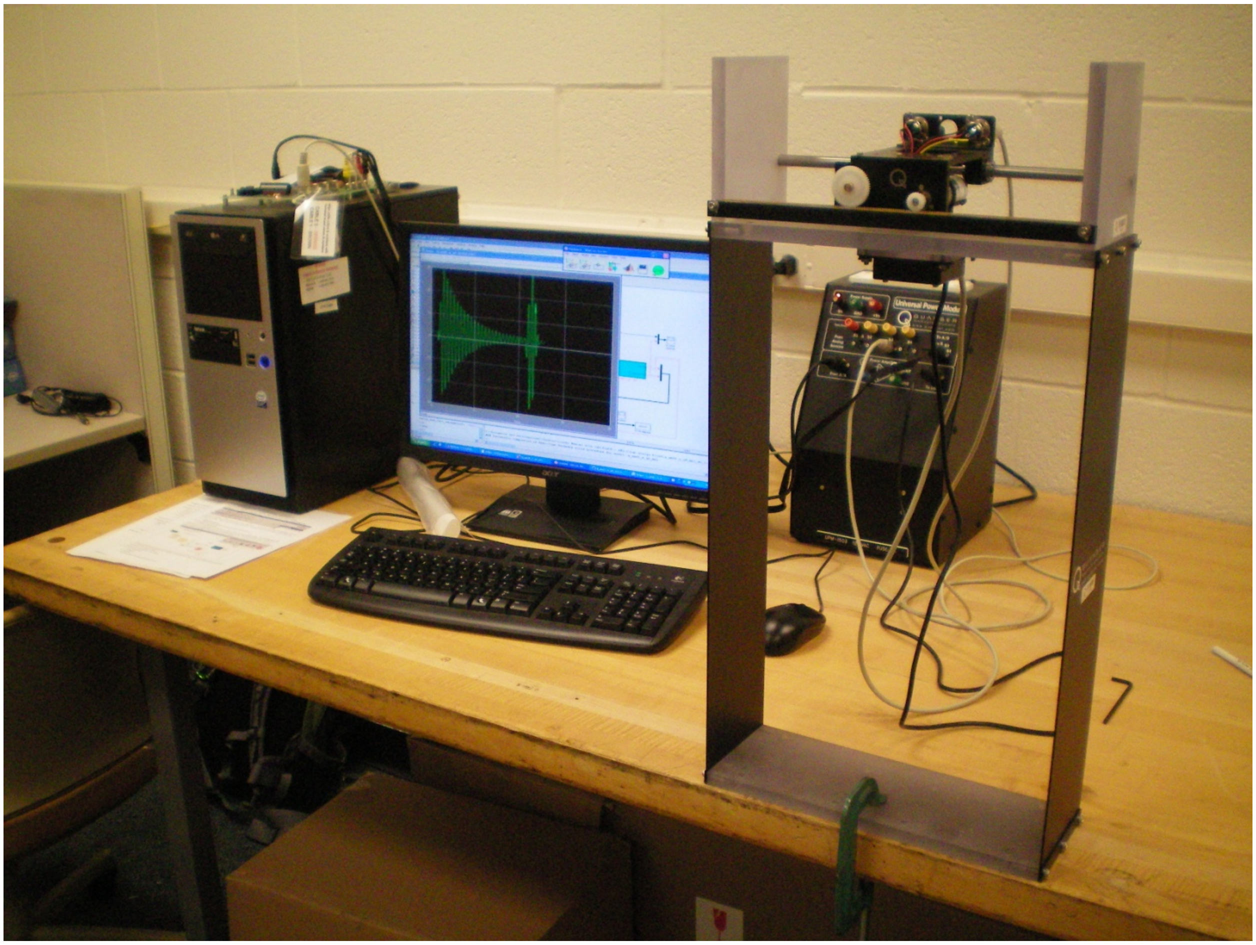
Unknown author. (2009). "One professor's winning formula." *Quanser News*, 11.

Yi, J., Kim, D., and Feng, M. (2009). "Periodic seismic performance evaluation of highway bridges using structural health monitoring system." *Structural Engineering and Mechanics*, 31(5), 527-544.

Grant installing the viscous damping device.

Rachel learning the Active Damping System software.



Active Damping System Setup in Controls Lab.

EQUIPMENT TRAINING:

1. Linear Variable Displacement Transducer (LVDT): used to measure the displacement in volts of a structure when a disturbance is introduced

2. Virtual Bench Logger software: used to record the displacement every thousandth of a second

3. Microsoft Excel: used to graph data, find maximum values, and exponential regression

4. Quanser Active Mass Damper on a one floor system resting on flexible steel: system utilized for all active mass damping experiments and earthquake simulations.

5. Remote access through web cam to controls lab: ability to access equipment via the internet for demonstrations in the classroom.