Hydraulic Regenerative Vehicle Suspension

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Jason David Hedlund

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Advisor: Dr. Xun Yu

December 2010

Acknowledgements

I would like to thank my advisor, Dr. Xun Yu for his support with my research over the past two years. His experience and history with research excellence motivated me to do the best work I could.

In addition to my advisor, I would also like to express my gratitude to my committee members, Dr. Ryan Rosandich and Tom Ferguson for their assistance and guidance.

Others who deserve recognition for their generous support include Dr. Daniel Pope, Darrell Anderson, and Sampson Moore.

Finally, I would like to thank the Office of the Vice Chancellor for Academic Administration for the funding support.

Abstract

This paper looks into the feasibility of a hydraulic regenerative suspension system for vehicles. The linear motion from vehicle vibration is converted into rotational motion by using a double-acting hydraulic cylinder, a hydraulic motor and associated hydraulic system. The rotational motion drives an electrical generator, converting mechanical energy into electrical energy. The energy recovery system was designed, constructed, and tested in lab and on an all-terrain-vehicle (ATV). While the average power output and efficiency were not as high as expected, several paths for future improvement were discovered. It appears that the sizing of components in this small scale system is critical to achieve more desirable power outputs and efficiencies.

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

The suspension systems in modern cars, trucks, ATVs and other vehicles do a great job of dissipating energy. In fact, that is exactly what they are designed to do. Any bump in the road or terrain causes the forward energy in a vehicle to be converted into vertical energy. Without suspension systems the vehicle would be forced into the air, resulting in reduced friction between the tire and the road, and ultimately reduced control and comfort of the car. A vehicle that dissipates more of this vertical energy will have a safer and smoother ride for its occupants.

It is believed that the energy being wasted in modern vehicle suspensions systems can be harvested and converted, prior to dissipation, into a form that can be utilized elsewhere in the vehicle. More specifically, this energy can be converted into electrical energy that could be used to charge the car battery. This could possibly offset some or all of the work done by the alternator, resulting in increased fuel efficiency. If implemented in electric vehicles, this regenerated energy could recharge the battery, extending the range of these vehicles.

The goal of this study was to develop a hydraulic regenerative vehicle suspension system, to test its feasibility to harvest vehicle vertical vibration energy, and to study its impact on the suspension damping. Several iterative prototypes were developed and tested experimentally in both a lab and on the road, on an all-terrain-vehicle (ATV). ATVs are often driven on extreme terrain, putting their suspension to work, which makes them a great candidate for this study.

2. LITERATURE REVIEW

While mechanically regenerative systems have been investigated to harvest energy from a variety of objects such as backpacks, shoes, and other vibration structures [1-3], few have studied the impact of mechanical regenerative suspension systems on vehicles.

2.1 Energy Conversion Techniques

Theoretically, there are many ways to convert the kinetic energy in vibrating/oscillating structures into a more usable form. The goal is to determine which method is most efficient while maintaining cost effectiveness.

2.1.1 Piezoelectric

M. F. Daqaq and J. Wagner also proposed an energy harvesting system for vehicles based on the piezoelectric materials (PZT) [4]. However, the energy conversion efficiency of piezoelectric materials is strongly influenced by the operating frequency. Harvesting energy from piezoelectric materials is most efficient around their resonant frequency (normally > 100Hz), which is much higher than the vehicle vibration frequency range (normally < 10Hz). In addition, most piezoelectric materials are ceramic materials that cannot sustain the long-term vibration of vehicles.

2.1.2 Electromagnetic

Other research related to generating electricity from suspension vibration is focused on electromagnetic energy harvesting [5-8]. However, the linear electromagnetic energy harvesting system is associated with high material costs.

2.1.3 Electro-chemical

Electro-chemical regenerative suspension was also researched by Zheng *et al.* [9]. This type of system could offer advanced control of system damping in exchange for a more complex design.

2.1.4 Hydraulics

Recently, a group of MIT students was reported to have developed a regenerative suspension system using hydraulics, but no technical paper of this work was reported. Hydraulics could offer a relatively simple, capable, and cost effective system.

3. METHODS

A schematic of the regenerative suspension system is shown in Figure 1, and the completed test system on an ATV is shown in Figure 2. The system consisted of a double-acting hydraulic cylinder, mounted in parallel with the original front-right spring and damper on a small ATV. Only one shock absorber was modified in order to compare any changes between the new system and original (front-left). Any motion in the original system would result in equal motion in the attached regenerative system. The original damper was drained of its hydraulic fluid, as the new hydraulic cylinder would act as a rough replacement for the damping. Each of the two ports of the double-acting hydraulic cylinder was linked to either the input or output of a hydraulic motor. Also, because of the volume change caused by the cylinder rod moving in and out of the system, a hydraulic diaphragm accumulator was placed between the rod-end port of the cylinder and the hydraulic motor. The shaft of the hydraulic motor was coupled directly to the shaft of a DC motor (acting as a generator).

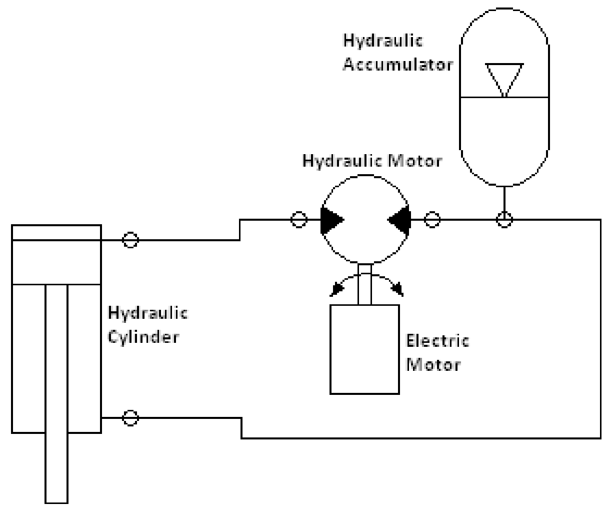

Figure 1: Regenerative Suspension System Schematic

A compression/tension load cell was threaded to the end of the hydraulic cylinder in order to measure the force being applied. The position of the cylinder rod was measured using a linear potentiometer, mounted in parallel with the original suspension and the hydraulic cylinder. The instantaneous voltage drop over a constant 48 Ohm resistor, which was connected across the terminals on the DC motor, was measured during testing. The load cell, linear potentiometer, and voltage were measured and recorded by a laptop during testing, at a sampling frequency of 100Hz.

The equipment used for this study is listed in Tables 1 and 2. The equipment making up the regenerative suspension system is displayed in Table 1; Table 2 displays the data acquisition equipment.

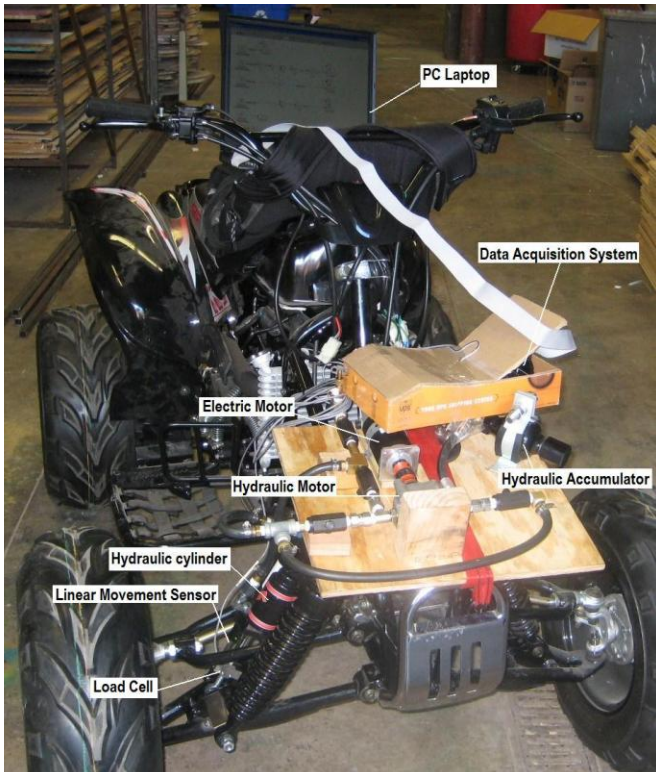

Figure 2. Installed Regenerative Suspension System

Table 1. Regenerative Suspension Equipment

Equipment	**Model**
ATV	SSR Q250 W2
Double Acting Cylinder	Norgren RLD02A-DAP
Hydraulic Accumulator	Parker AD007B25T9A1
Hydraulic Motor	Unknown (3.28 cm^3/rev)
DC Servo Motor	MCG ID23004

Table 2. Data Acquisition System Equipment

Equipment	**Model**
Linear Potentiometer	Celesco CLP-150
Load Cell	Omega LC703-1K
Data Acquisition Card	MC DAS16/12AO
Universal Screw Terminal Board	MC CIO-MINI50
50 Pin Cable	MC CPCC-50F-39
Laptop Computer	Compaq Presario V5000
DAQ Sofware	Matlab
Servohydraulic Test System	MTS Landmark

The variables being collected consisted of time (s), position (mm), Force (N), and generated voltage (V), from which more useful variables were derived. This information was collected through the data acquisition equipment with Matlab. The sensors and data acquisition equipment listed in Table 2 were connected to the laptop, for use with Matlab, through the custom circuit network seen in Figure 3. The use of inverting opamps was necessary to amplify the load-cell output voltage to a usable range. Capacitors were added to the circuit to act as low-pass filters. The necessary magnitude of capacitance was calculated using Eq. 1, with a cutoff frequency (f_c) of 200Hz.

$$C = \frac{1}{2\Omega R f_c} \tag{1}$$

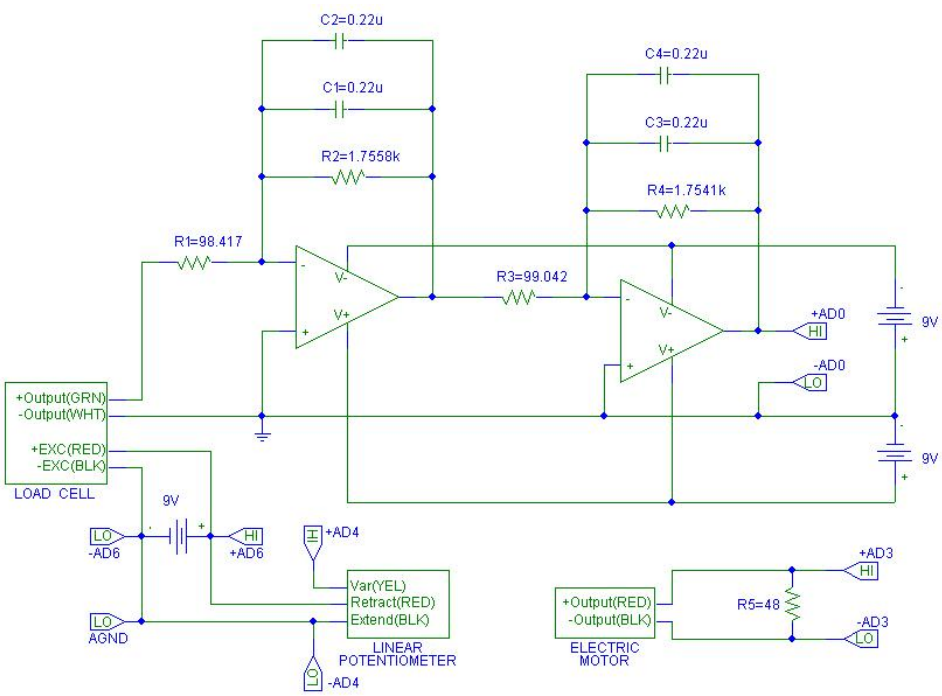

Figure 3. Data Acquisition Circuit

The Matlab Simulink model seen in Figure 4 was developed to obtain the input signals and convert them into useful information.

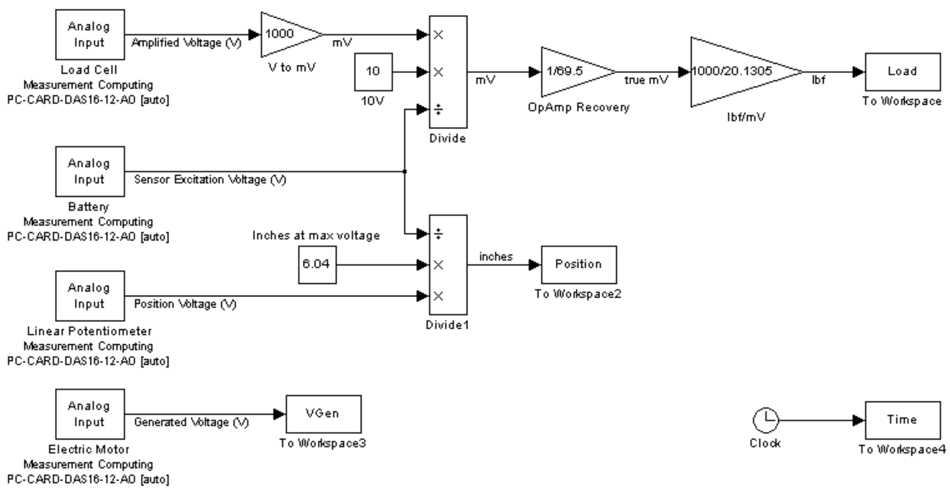

Figure 4. Matlab Simulink Model for Data Acquisition

Variables that were calculated based on the collected values were velocity (mm/s), power input (W), power output (W), efficiency, and damping (Ns/mm). Equation 2 calculates the velocity at n (v_n), based on the difference in positions before and after time n. In Eq. 3, the instantaneous power input is a function of the force and velocity at time n. The average mechanical input power (Eq. 4) is a function of the instantaneous input power and the number of samples (N). Equation 5 displays the root mean square voltage, a function of instantaneous voltages and the number of samples. The average electrical power output (Eq.6) is a function of RMS Voltage and the resistance of the resistor. Equation 7, the efficiency, is equal to the ratio of power output to power input.

$$v_n = \frac{x_{n+1} - x_{n-1}}{2 * \Delta t} \tag{2}$$

$$Input\ Power_n = F_n * v_n \tag{3}$$

$$Input\ Power_{AVG} = \frac{\sum Input\ Power_n}{N} \tag{4}$$

$$V_{RMS} = \sqrt{\frac{\sum V_n^2}{N}} \tag{5}$$

$$Output\ Power_{AVG} = \frac{V_{RMS}{}^2}{\Omega} \tag{6}$$

$$Efficiency_{AVG} = \frac{Output\ Power_{AVG}}{Input\ Power_{AVG}} \tag{7}$$

3.1 In-Lab Experimentation

Before testing the system on the road, experiments were run in a lab environment. Initially, tests were performed following an uncontrolled and ad hoc procedure in which the suspension system was oscillated manually. Later, the system was tested on a servohydraulic testing system to ensure controlled and repeatable results.

3.1.1 Manual Oscillations

To manually oscillate the suspension system, a test subject repeatedly applied and released their weight on the suspension while standing in the driver’s position on the ATV. It is understood that this procedure is inadequate for repeatability for future comparisons. However, this method did provide a way to quickly achieve results for early analysis.

3.1.2 Servohydraulic Test System

In order to obtain consistent and reliable results which are not feasible through manual oscillations, a servohydraulic test system was used. This system, seen in Figure 5, allowed the system to be tested at varying frequencies and amplitudes.

Figure 5. MTS Servohydraulic Test System

Table 3 shows the experimental parameters for the test performed with the servohydraulic test system. More experiments were planned, with increasing frequency and reduced amplitude. However, during the second test, excessive pressure built up and burst a hydraulic hose. Due to time constraints, the system was not repaired and retested at this time.

Table 3. Servohydraulic Test System Experimental Parameters

Duration (s)	**Frequency (Hz)**	**Amplitude (mm)**
60	0.10	45

3.2 On-Road Experimentation

The ATV was tested on-road prior to the in-lab servohydraulic system tests discussed earlier. However, for comparison, the sets of in-lab experiments were grouped together for better comparison. In order to test the system on the road, it was installed on the ATV. The ATV was driven in a straight line along a paved road, experiencing input only from the small imperfections in the pavement.

4. RESULTS

4.1 In-Lab Experimentation

As mentioned earlier, in-lab testing consisted of both manually oscillating the suspension and using a servohydraulic test system. The results of these experiments are provided in the following sections.

4.1.1 Results from Manual Oscillations

The following results were collected using the methods discussed in section 3.1.1. Figure 6 displays the position of the hydraulic cylinder rod over the course of a five second sample. For comparison, this same sample was used for all of the plots in this section. Note that an increasing position corresponds to compression of the cylinder. It can be seen that maximum displacement of the cylinder rod, over a single period, was approximately 13 millimeters. Based on the position variable, the velocity plot shown in Figure 7 was derived. A positive velocity corresponds to compression of the cylinder; a negative velocity relates to extension.

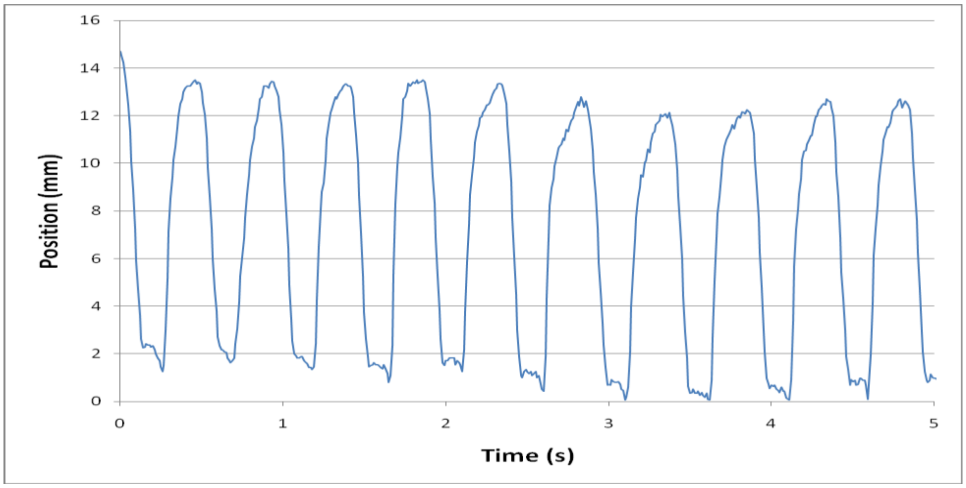

Figure 6. Hydraulic Cylinder Rod Position

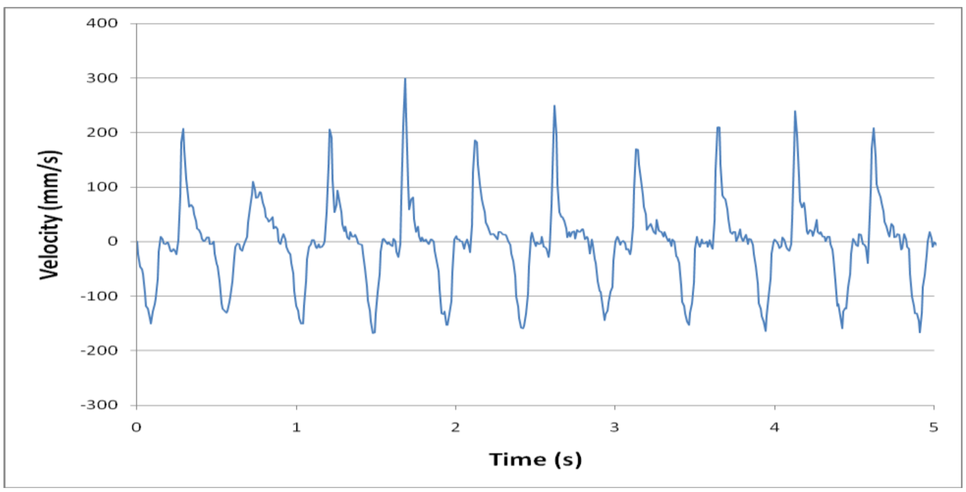

Figure 7. Hydraulic Cylinder Rod Velocity

The linear force being applied to the hydraulic cylinder rod over the duration of the test can be seen in Figure 8. A negative load corresponds to extension of the hydraulic cylinder, while positive loads correspond to compression.

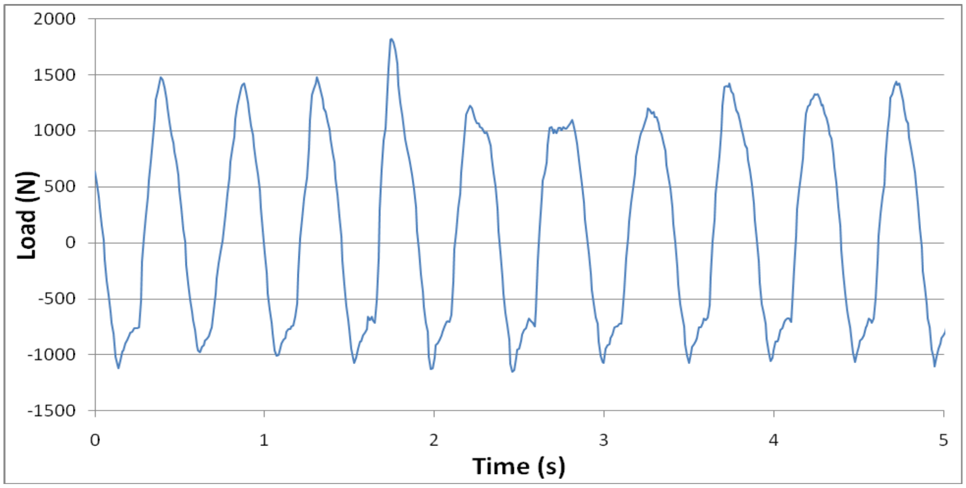

Figure 8. Load Applied to Hydraulic Cylinder Rod

Figure 9 displays the voltage generated as a result of the oscillations. It can be seen, just before 2 seconds, that the voltage was clipped at -10 volts. This is a result of the allowable range of the data acquisition equipment. Fortunately, it appears that the clipping didn't chop a significant amount of data.

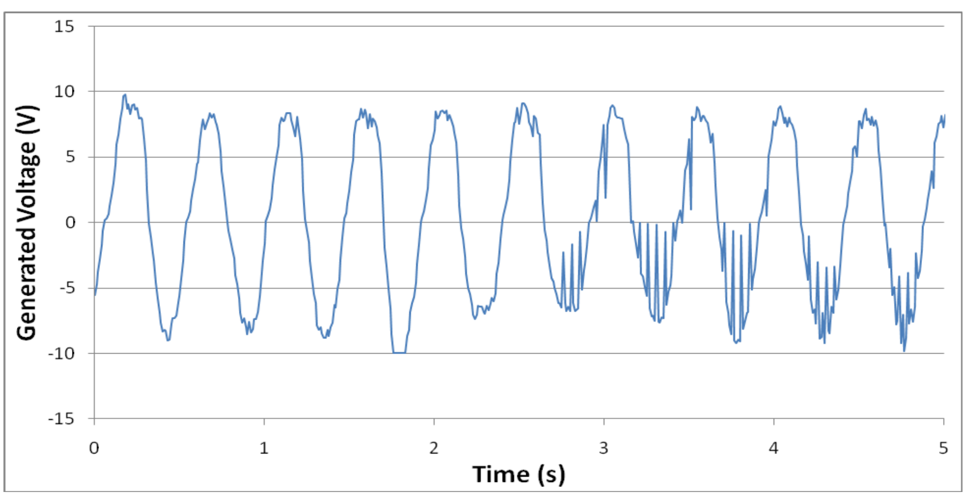

Figure 9. Voltage Generated at Electric Motor

Based on the instantaneous force and rate of change of position data, the instantaneous mechanical power input to the hydraulic cylinder was calculated and can be seen in Figure 10. Figure 11 shows the electrical power output from the electric motor. Because the voltage measurement was clipped at -10 volts, prior to 2 seconds, and the power output was calculated based on the measured voltage, Figure 11 also reveals this clipping. Again, it seems to not be a significant amount of lost data.

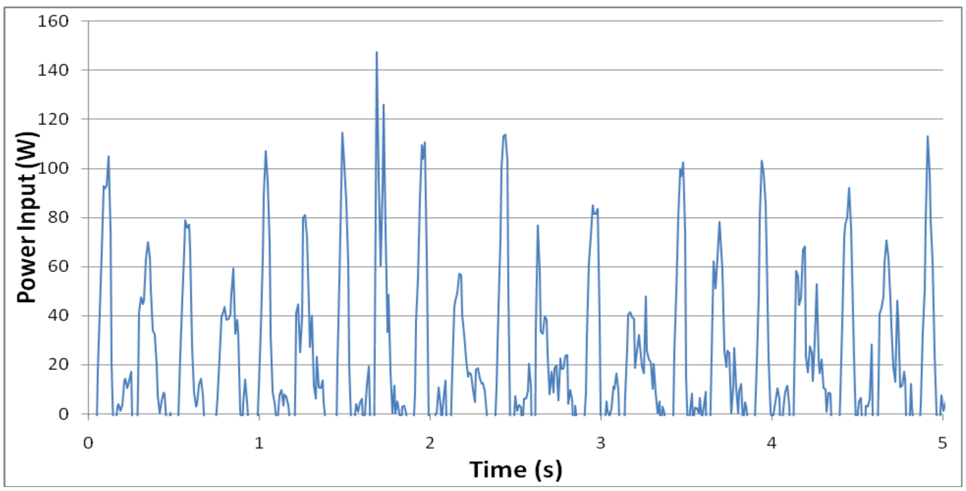

Figure 10. Mechanical Power Input to Hydraulic Cylinder

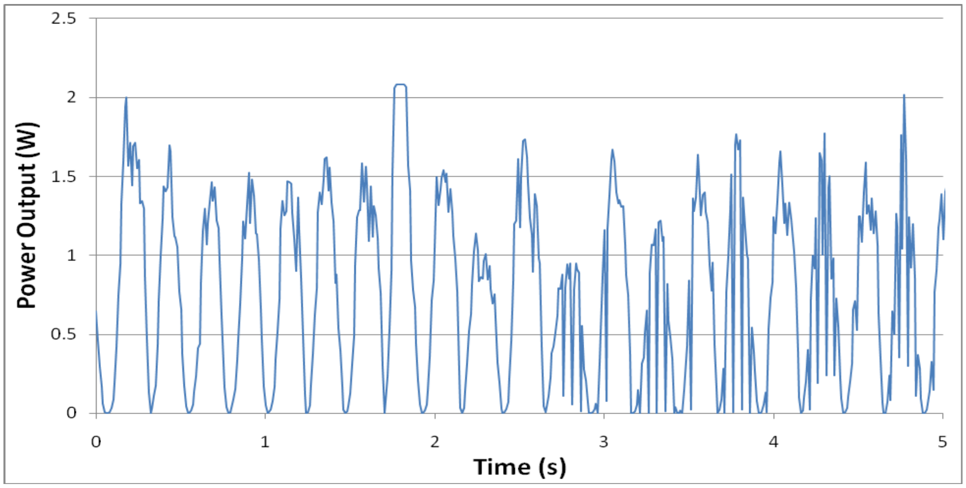

Figure 11. Electrical Power Output at Electric Motor

The force-velocity (damping) plot for the regenerative suspension system is shown in Figure 12. Ideally, this plot should show a linear trend, centered at zero, with a positive slope. The upper right quadrant would represent the damping associated with compression of the suspension while the lower left quadrant would represent the damping associated with extension of the suspension system. While the data shown in Figure 12 does follow a consistent pattern, it does not show the expected results. This is likely a result of the hydraulic accumulator introducing a time-lag into the system. The damping will be important in future tests to determine the impact of the regenerative suspension system on the performance of the vehicle handling.

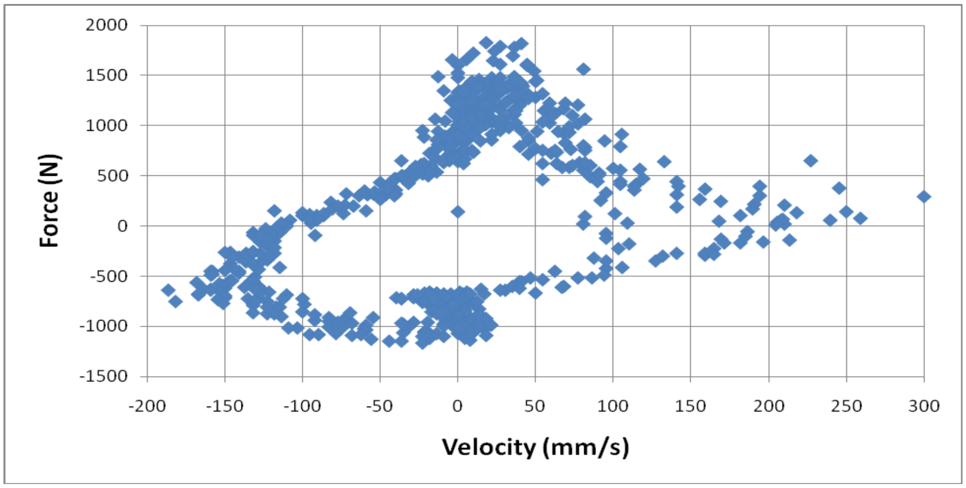

Figure 12. Overall Damping of Regenerative Suspension System

4.1.2 Results from the Servohydraulic Test System

The following results were acquired through the servohydraulic test system experiment. The experiment parameters, as mentioned in Section 3.1.2, were set to run for 60 seconds at 0.10 Hertz and a 45mm amplitude. Figure 13 displays the position of the hydraulic cylinder rod over the 60 second duration. Note, again, that an increasing position corresponds to compression of the cylinder. It can be seen that maximum displacement of the cylinder rod was 45 millimeters, as expected from the preset parameters. Based on the position variable, the velocity plot shown in Figure 14 was derived. Again, a positive velocity corresponds to compression of the cylinder; a negative velocity relates to extension. It can be seen that the peak velocities occur at the inflection points on the position plot, as expected.

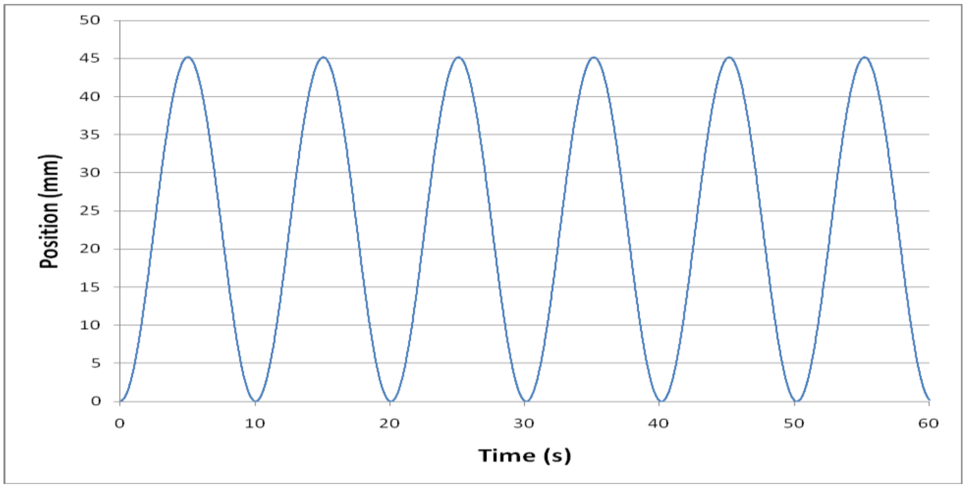

Figure 13. Hydraulic Cylinder Rod Position

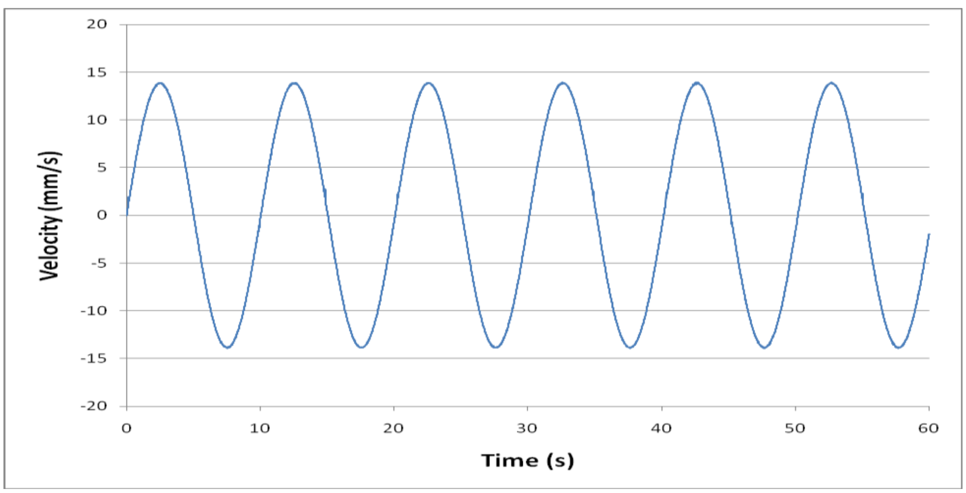

Figure 14. Hydraulic Cylinder Rod Velocity

The linear force being applied to the hydraulic cylinder rod over the duration of the test can be seen in Figure 15. Again, a positive load corresponds to compression of the hydraulic cylinder, while negative loads correspond to extension. Comparing Figure 14 and Figure 15, it can be seen that peak velocities and loads roughly align, as expected.

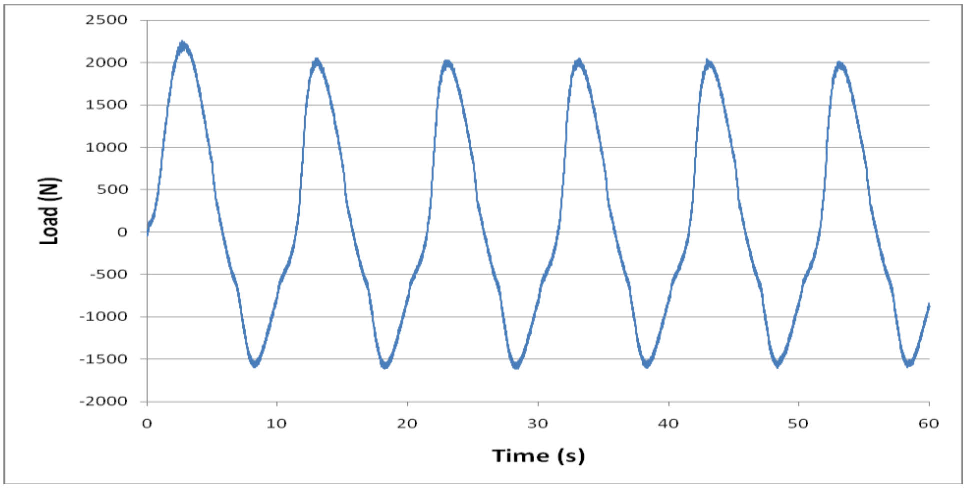

Figure 15. Load Applied to Hydraulic Cylinder Rod

Figure 16 displays the voltage generated as a result of the oscillations. This voltage is significantly less than that seen in Figure 9, during the manual oscillations. As, the electric motor was observed to be rotating, it was expected that the voltage would be much higher than what was collected. The signal also appears to be very noisy; it is believed that the data acquisition system may have malfunctioned or the electric motor was damaged during this test.

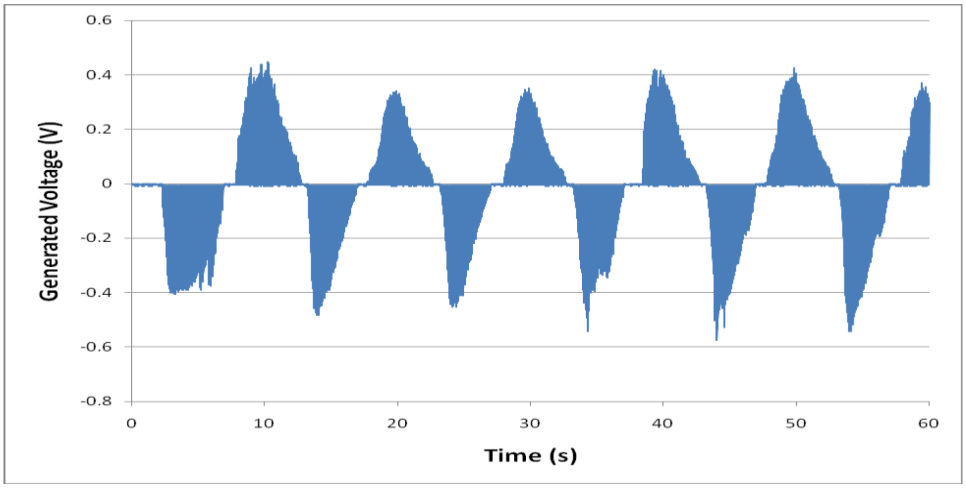

Figure 16. Voltage Generated at Electric Motor

Based on the instantaneous force and rate of change of position data, the instantaneous mechanical power input to the hydraulic cylinder was calculated and can be seen in Figure 17. Figure 18 shows the electrical power output from the electric motor. Because the voltage measurement is believed to be unreliable, the electrical power output is also unreliable. Unfortunately, this is one of the primary desired variables for this test.

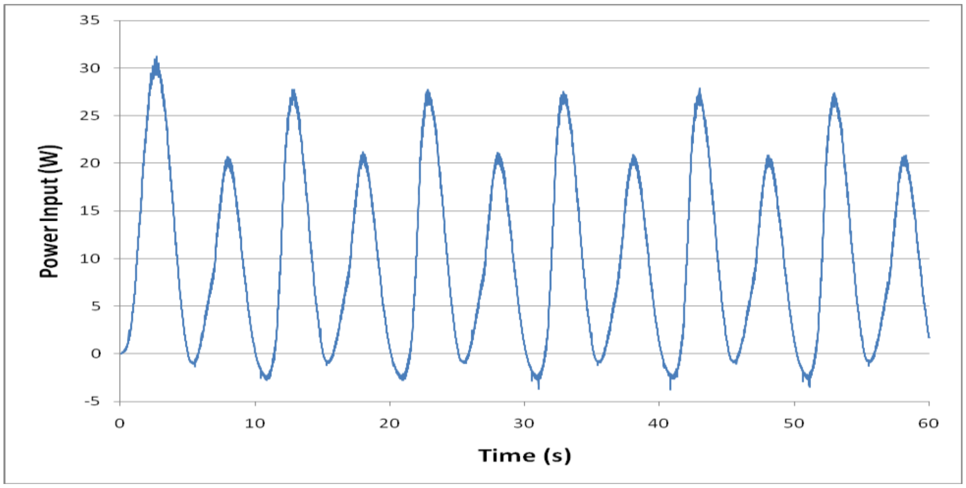

Figure 17. Mechanical Power Input to Hydraulic Cylinder

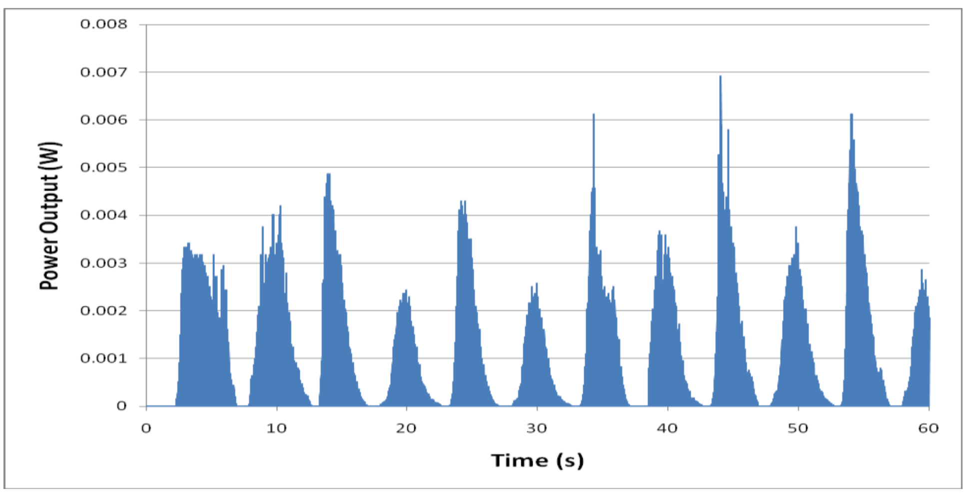

Figure 18. Electrical Power Output at Electric Motor

The force-velocity (damping) plot for the regenerative suspension system is shown in Figure 19. Similar to the results in Figure 12, Figure 19 does not show the ideal linear fit. However, the slope of the data does follow a positive linear trend, which was expected. Again, the reason for the non-linear data is likely due to a delay in the force caused by a lag from the hydraulic accumulator. A best fit line was fitted to the plot for an estimate of the damping coefficient. The approximate damping coefficient for this system is about 110 Ns/mm.

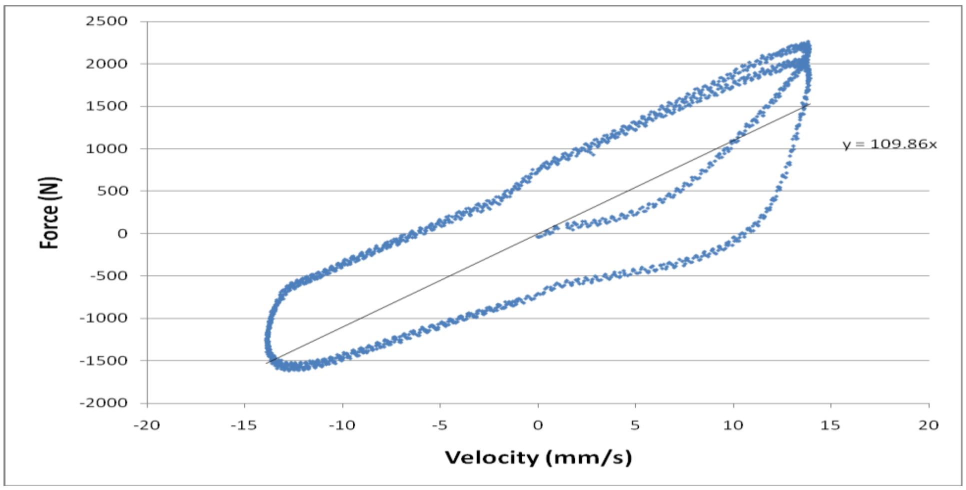

Figure 19. Overall Damping of Regenerative Suspension System

4.2 On-Road Experimentation

The following results were acquired through on-road tests. Figure 13 displays the position of the hydraulic cylinder rod over a 120 second sample. The same sample was used for all of the plots in this section for comparison. Again, increasing position values correspond to compression of the cylinder. It can be seen that maximum occurrence of displacement of the cylinder rod was approximately 15 millimeters. The positive and negative cylinder rod velocities, seen in Figure 21, correspond to compression and extension, respectively, of the cylinder.

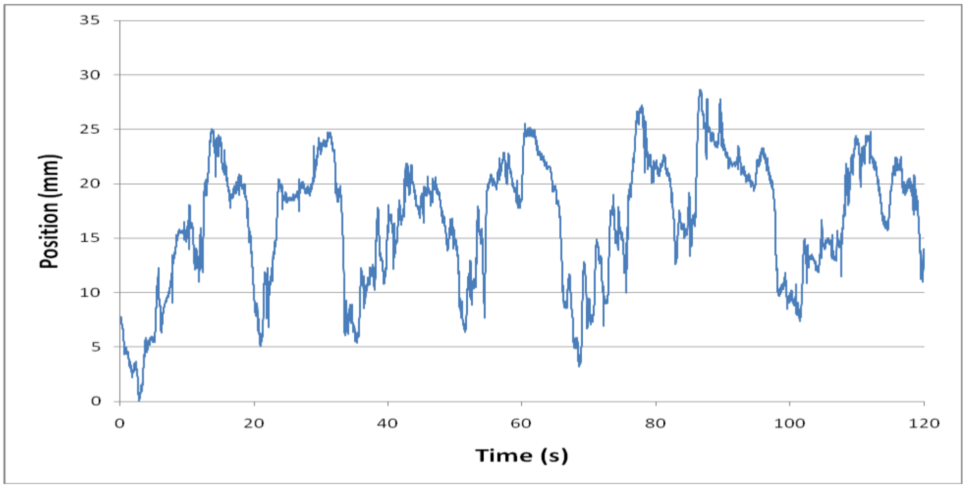

Figure 20. Hydraulic Cylinder Rod Position

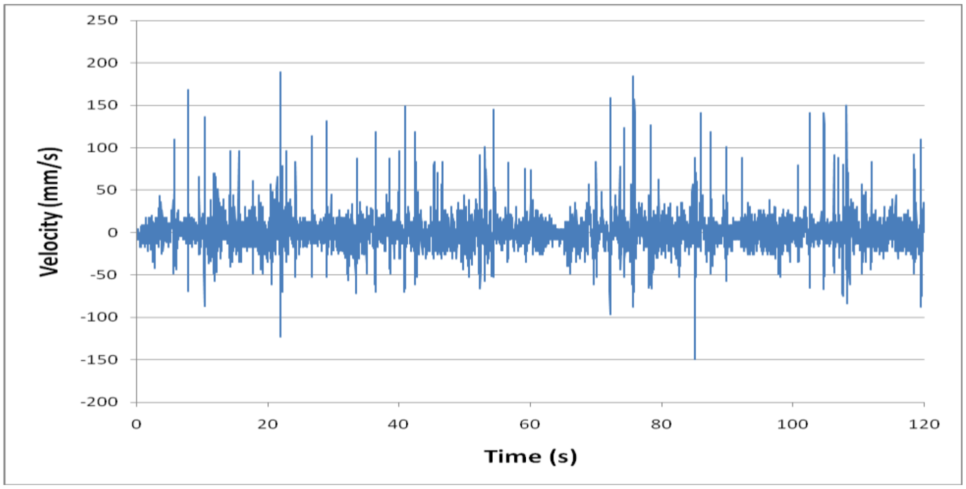

Figure 21. Hydraulic Cylinder Rod Velocity

The linear force being applied to the hydraulic cylinder rod over the duration of the test can be seen in Figure 22. Again, a positive load corresponds to compression of the hydraulic cylinder, while negative loads correspond to extension.

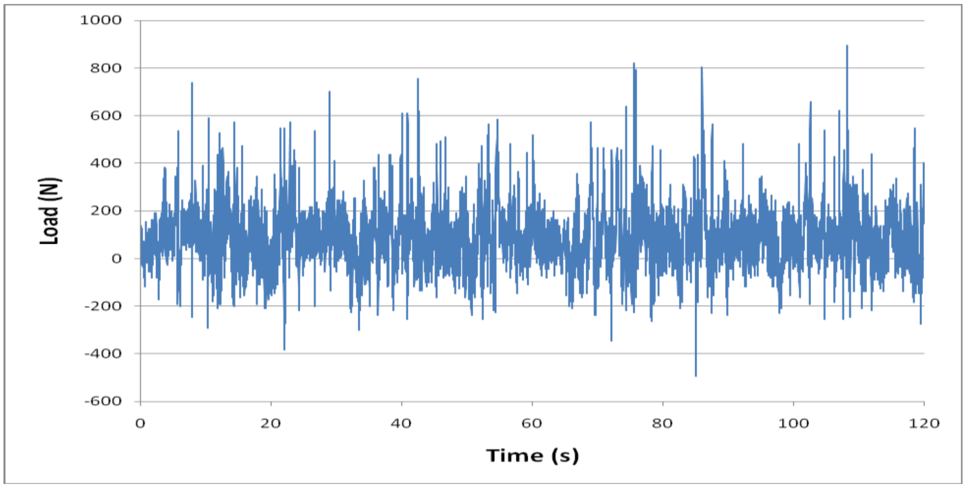

Figure 22. Load Applied to Hydraulic Cylinder Rod

Figure 23 displays the voltage generated as a result of the oscillations. The voltage has many high-magnitude spikes, but is quite low on average. This is to be expected due to the infrequent bumps on the road.

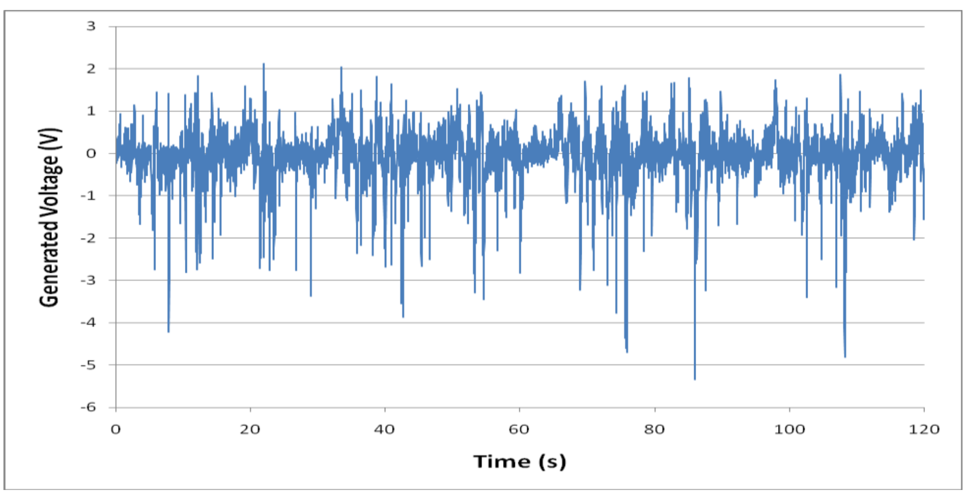

Figure 23. Voltage Generated at Electric Motor

The instantaneous mechanical power input to the hydraulic cylinder was calculated, based on the force and velocity of the cylinder rod, and is shown in Figure 24. Figure 25 shows the electrical power output from the electric motor. Because the voltage output was quite low, so was the electrical power output.

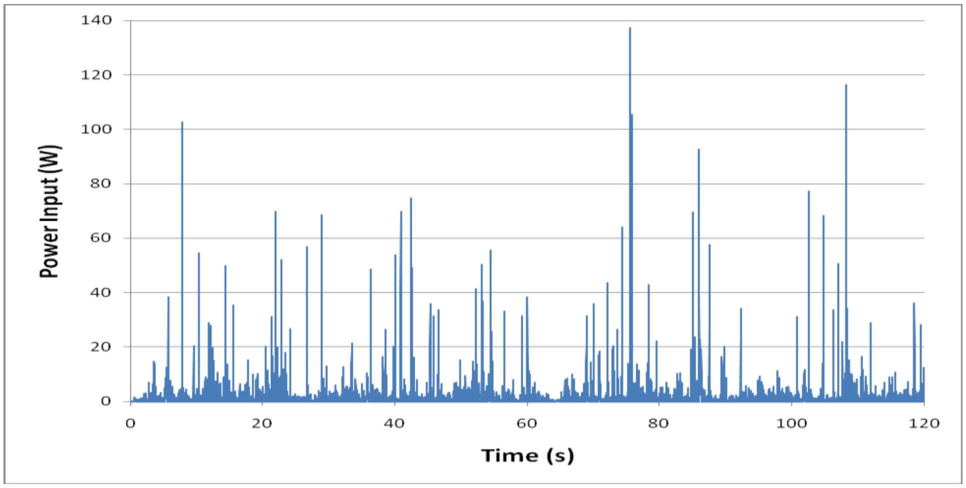

Figure 24. Mechanical Power Input to Hydraulic Cylinder

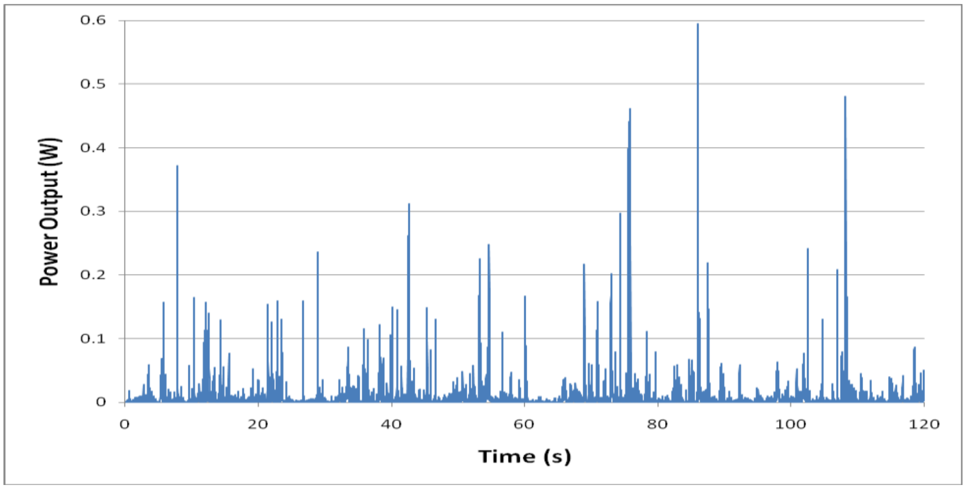

Figure 25. Electrical Power Output at Electric Motor

The force-velocity (damping) plot for the regenerative suspension system is shown in Figure 26. Because the velocities generated in this experiment were are result of low-amplitude, high frequency vibrations, this plot does not show an accurate representation of the true damping.

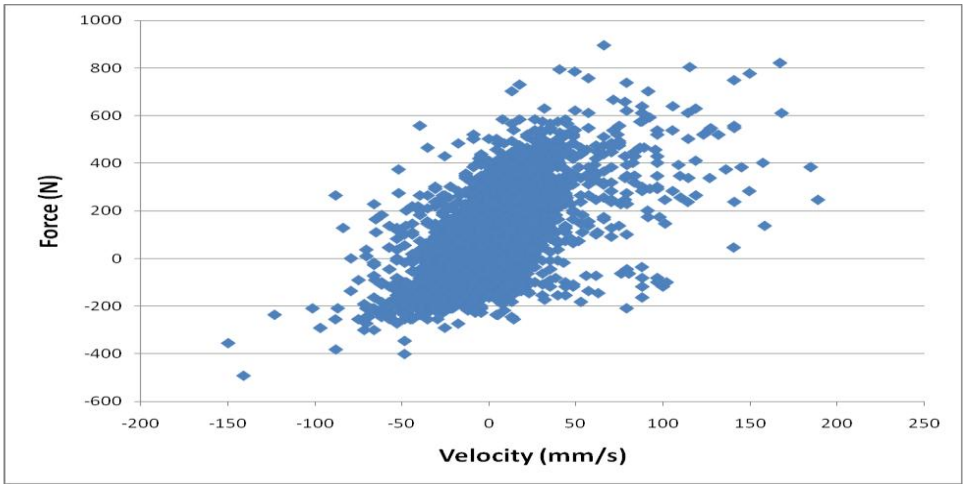

Figure 26. Overall Damping of Regenerative Suspension System

4.3 Summary of Results

The average results for generated voltage, input and output power, and efficiency for the two in-lab experiments and the on-road experiment are shown in Table 4.

Table 4. Regenerative Suspension System Results

	In-lab (manually)	In-lab (controlled)	On-road
RMS Voltage (V)	6.13	0.20	0.62
Input Power (W)	21.41	9.62	1.46
Output Power (W)	0.78	0.00	0.01
Efficiency (%)	3.66	0.00	0.55
Damping (Ns/mm)	-	110	-

5. ECONOMIC ANALYSIS

In order for an energy-regenerative suspension system to be considered for implementation, it should be economically justified. It is assumed that some amount of energy can be recovered and converted into a form that will be beneficial for the vehicle's electrical system. Besides generating some benefit to this system, there are likely some drawbacks to this type of system as well. For instance, there will be added weight, altered suspension damping, and the financial cost of the system which need to be evaluated against the benefits of the power generation.

While it is difficult to estimate real values for the monetary costs associated with this type of system, there are many factors to be considered. Several significant costs include, but are not limited to, the cost of research and development, materials cost, manufacturing cost and maintenance cost.

6. CONCLUSION

A working hydraulic regenerative system was installed on the suspension of an ATV and tested in lab by manual oscillation, controlled oscillations, and on the road during a driving test. The results of these test proved that there is hope for a hydraulic energy recovery system; however the system's efficiency and power output must be improved. The speeds and forces from an off-road drive should exceed the forces exerted in lab and increase both power output and efficiency. Future work on this study should be in determining the most efficient sizing of each component in the system, specifically focusing on the DC motor, as well as standardizing a testing procedure to ensure repeatability. The final goal is the development of a product that could be scaled for varying sizes of vehicles.

7. BIBLIOGRAPHY

[1] Rome, L., Flynn, L., Goldman, E., and Yoo, T., 2005. "Generating Electricity While Walking with Loads". *Science*, Vol. 309, pp. 1725-1728.

[2] J. Granstrom, Feenstra, H. A. Sodano, and K. Farinholt, 2007, "Energy harvesting from a backpack instrumented with piezoelectric shoulder straps", Smart Materials and Structures, Vol. 16, pp.1810-1820.

[3] H. A. Sodano, D. J. Inman and G. Park, 2005, "Comparison of piezoelectric energy harvesting devices for recharging batteries", Journal of Intelligent Material Systems and Structures, Vol. 16, pp.799-807.

[4] S. Roundy, 2005, "On the effectiveness of vibration-based energy harvesting", Journal of Intelligent Material Systems and Structures, Vol. 16, pp.809-823.

[5] Zhang, Y., Huang, K., Yu, F., Gu, Y., and Li, D., 2007. "Experimental Verification of Energy-regenerative Feasibility for an Automotive Electrical Suspension System". *Vehicular Electronics and Safety*, pp. 1-5, 13-15.

[6] Ebrahim, E., Hammad, N., and Abu-el-nour, A., 2004. "Electric-power recovery for the mechanical damper in a vehicle-suspension system using artificial intelligent control". *Vehicle System Dynamics*, 41, pp. 647-656.

[7] Goldner, R., Zerigian, P., and Hull, J., 2001. "A Preliminary Study of Energy Recovery in Vehicles by Using Regenerative Magnetic Shock Absorbers". *SAE International*, pp. 1-9.

[8] Zheng, X., Yu, F., and Zhang, Y., 2008. "A Novel Energy-regenerative Active Suspension for Vehicles". Journal of Shanghai Jiaotong University, Vol. 13, pp. 184-188.

[9] M. F. Daqaq and J. Wagner, "Supplemental vehicle power thought innovative energy harvesting", Thrust Area 1 project, Automotive Research Center. (http://arc.engin.umich.edu/arc/research/ta1/T1_13.htm)

[10] MIT News, 2009, "More power from bumps in the road", http://web.mit.edu/newsoffice/2009/shock-absorbers-0209.html.