2014

Low Frequency Improvements to Commercial Geophones

Brian Michael Holden
Louisiana State University and Agricultural and Mechanical College

LOW FREQUENCY IMPROVEMENTS TO COMMERCIAL GEOPHONES

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Electrical Engineering

in

The Division of Electrical and Computer Engineering

by
Brian Holden
B.S.E.E., Louisiana State University, 2009
December 2014

ACKNOWLEDGEMENTS

I would like to thank my graduate advisor, Dr. Martin Feldman, as well as my examination committee members, Dr. Juan Lorenzo and Dr. Kidong Park. This would not be possible without their help and guidance.

TABLE OF CONTENTS

ABSTRACT

Commercial geophones have been used in the field of geology for many years. They are commonly used to detect oil and gas deposits and create three dimensional simulations of the earth. Geophones are commonly made up of a spring mounted magnetic mass moving back and forth in a wire coil to create a voltage. The response of the coil is proportional to the velocity of the ground. At various frequencies, seismic events can be measured using a geophone. However, most commercial geophones only allow accurate measurements of frequencies down to approximately five hertz. By using a feedback circuit, an attempt will be made to accurately measure seismic motions at lower sensor frequencies. This will be evaluated with a shaking table that is displaced at known frequencies, taking measurements of the output of the feedback circuit. The results of the feedback circuit will be compared to the results taken of the geophone on the same shaking table to show how much better this device will detect seismic activities at lower frequencies.

INTRODUCTION

A geophone is a device which measures ground movement by converting detected motions into voltage. This paper studies a circuit which enhances the detection of small motions of the earth at low frequencies. The circuit will compare the measurements to those taken by a modified geophone.

Typically, most commercial geophones measure motions at frequencies down to 5 hertz (Hz). Frequencies below this range are not detected very accurately by commercial geophones. This limitation is the main motivation for this research.

Chapter 1 will explain in more detail how the commercial geophone works. This chapter will include various uses of commercial geophones and their importance in geology and oil discovery.

Chapter 2 will describe the apparatus used to test both the designed circuit and the commercial geophone. This chapter will also include how the measurements were taken and which factors were taken into consideration when colleting the data. Also, this chapter will go into detail of how the system was set up to allow for accurate testing.

Chapter 3 will show the work of the circuit. It will include a diagram of the circuit along with explanations of how it works.

Chapter 4 will compare the data of the commercial geophone and of the feedback circuit. Also to be shown is the data collected from the circuit detecting motions down to below 3 Hz.

Chapter 5 will show conclusions about how the designed circuit fares against the commercial geophone. In addition, the future work and future goals of this research will be discussed.

CHAPTER 1: GENERAL GEOPHONE INFORMATION

1.1 Background on Geophones

This chapter will go into further detail of how a commercial geophone works and also practical uses for commercial geophones. As mentioned in the introduction, a geophone is a device which detects motions in the earth and converts detected motions into voltage. As shown in Figure 1.1.1, geophones are commonly made up of a spring mounted magnetic mass moving back and forth in between a wire coil to create a voltage. The response of the coil is proportional to the velocity of the ground [Barzilai, 2000].

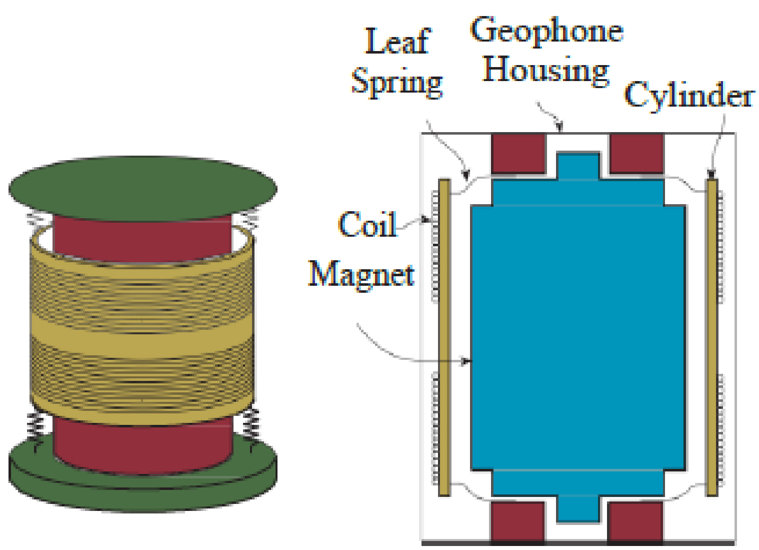

Figure 1.1.1 [Barzilai, 2000]

Commercial geophones are used to detect seismic activity. The measured voltage in commercial geophones is what is used to determine the seismic activity of the earth. Geophones are mainly used to find new sources of oil within the earth. This is done by sending shock waves into the ground and measuring how long it takes for the rocks below the surface to reflect these waves back to the surface. Pounding the earth with

vibrator trucks is one way shock waves are generated. The time it takes for the waves to get back to the surface is measured by commercial geophones. This data is used to create seismic lines which are three-dimensional displays below the earth's surface.

Geophones may also be used to detect seismic faults well below the earth's surface. This can be observed in the same ways geophones are used to detect new oil and gas reserves. From the models created from the detected echoes from the seismic vibrations, seismic faults can be located and accurately modeled. This is important to help detect where earthquakes are more likely to strike. Also, it can measure any shifts or changes below the surface to detect where earthquakes may occur in the future.

Some of the main advantages of using geophones are that they are relatively cheap and require no power source. Many geophones are used in a configuration shown in Figure 1.1.2, where they are lined up to detect various echoes at various points below the surface. Because no power is needed, as many geophones as necessary can be used to achieve this configuration.

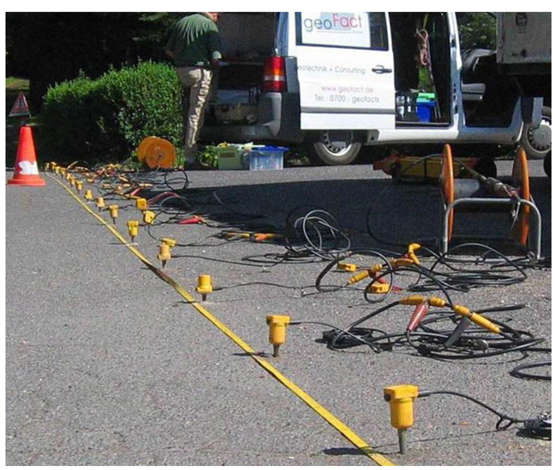

Figure 1.1.2

However, some drawbacks to using commercial geophones are that they display poor sensing down to lower frequencies (less than 5 Hz). This limits geophones to what

they can be used for. Since they detect poorly at lower frequencies, earthquakes cannot be detected by geophones. The frequencies detected by geophones from earthquakes are in the cHz range which geophones do not accurately display. For the test run for this research, the geophone used had a 10 Hz sensor. The state of the art geophones have frequency sensors down to 4.5 Hz. Also, at lower frequencies, the ratio of the noise to the signal increases which effects the users' ability to accurately measure the recorded data. For these reasons, commercial geophones may not be the best device to use at lower frequencies. There are devices which use can detect seismic activity down to lower frequency, however, these are very expensive (~$10,000).

Much of the research done in these fields of study would not be possible without the use of commercial geophones. However, commercial geophones can be improved. By creating a device to help detect seismic activity down to frequency below 5 Hz, geophones could go even further in helping to predict earthquakes and finding new sources of oil.

CHAPTER 2: STAGE APPARATUS

2.1 Feedback System

The goal of this research is to create a device which measures seismic activity at frequencies below 5 Hz. To achieve this goal, a feedback system might serve as a good alternative to commercial geophones. Feedback systems allow for increased stability and can be easily changed to achieve the goals of this research. To test both the feedback system and commercial geophone, a designed apparatus was used to ensure quality testing.

2.2 Main Stage Block Diagram

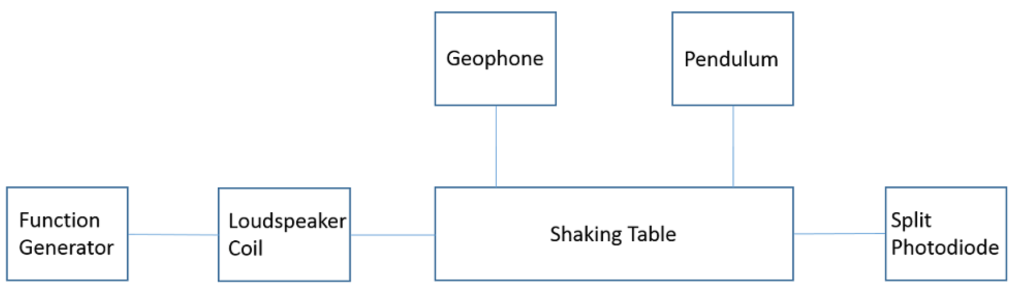

Figure 2.2.1

This block diagram above shows the various systems at work while testing the commercial geophone versus the feedback circuit. A loudspeaker coil, driven by a function generator, drives the shaking table. The shaking table supports the sub-stage which has the commercial geophone and feedback system on top of it. The loudspeaker coil drives the table at a known frequency while measurements are taken of the geophone

and feedback system. A laser on the shaking table aimed at the split photodiode is used to make sure there is a uniform movement of the table.

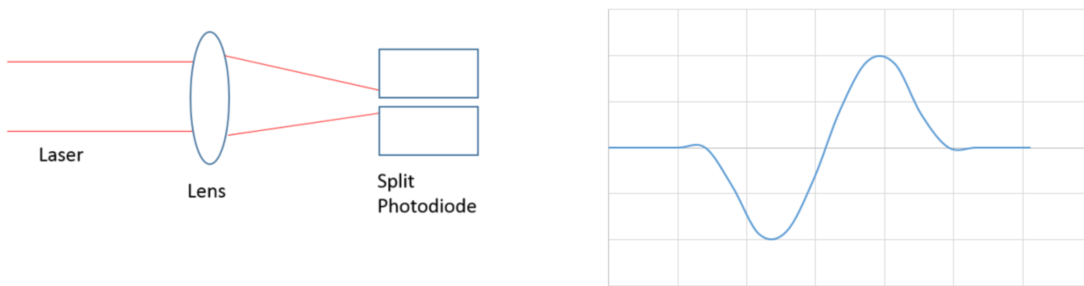

Figure 2.2.2

As the laser moves from left to right a signal, a response similar to what is shown in Figure 2.2.2 is observed across the split photodiode.

2.3 Sub-Stage Block Diagram

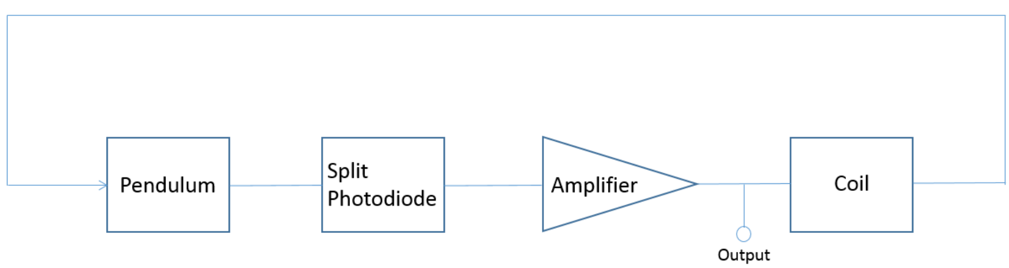

Figure 2.3.1

As shown in the diagram above, is the block diagram of the various systems of the sub-stage. The pendulum with a lens attached to the bottom has a laser aimed at it. As the pendulum moves from left to right, the laser beam is focused through the lens and moves across the split photodiode. The split photodiode is used as the input to the amplifier

which sends a signal to the coil which controls the pendulum. Below is a side view of how the sub-stage looks.

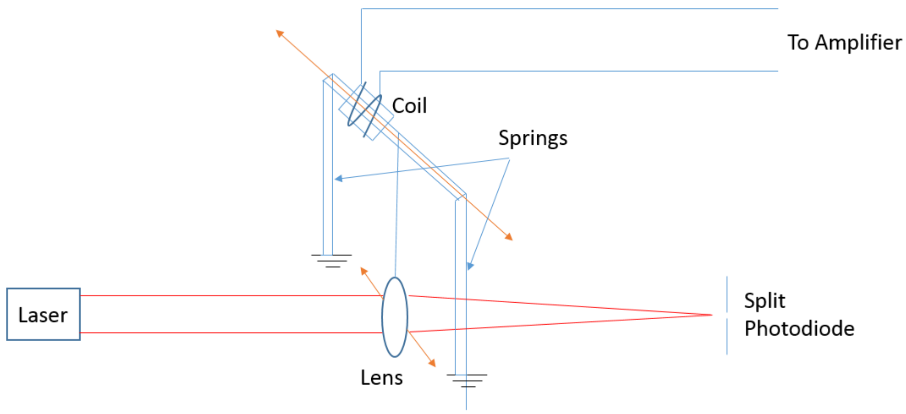

Figure 2.2.2

2.4 Main Stage

The apparatus is made up of two stages. The main stage is a flat wood block. Also apart of this stage are two hacksaw blades. These hacksaw blades are used to move the sub-stage back and forth to mimic vibration in the earth. The hacksaw blades are fairly rigid which do not allow for too much movement.

Also included on this stage is another split photodiode. As mentioned earlier, this split photodiode is used to measure the uniformity of motion of our sub-stage. Uniformity of motion can be determined from the signal measured from the split photodiode. A laser, off to the side of the sub-stage, was pointed at an adjustable mirror on the sub-stage. This laser was glued to the table countertop to prevent any movement in between measurements. As the sub-stage moves back and forth, the laser moves across the split photodiode. If the signal from the split photodiode is a symmetrical sine wave, uniformity has been achieved. This was done to make sure the sub-stage moves smoothly without any unwanted motions that cannot be seen by the naked eye.

2.5 Sub-Stage

Connected to the main stage by the hacksaw blades is the sub-stage. The sub-stage supports several components. First, there a laser on the sub-stage pointed at another small adjustable mirror. From the mirror, the laser beam is aimed at a lens at the bottom of a pendulum. This was done to focus the beam onto the split photodiode on the sub-stage. The signal from this split photodiode attached to the sub-stage is the input to the amplifier circuit. As the pendulum moves the lens back and forth, the laser beam moves back and forth across the split photodiode.

Next, the lens at the bottom of the pendulum is connected to the rod which is controlled by the movement of the magnet in between the coil. The magnetic coil is attached in between a rod held up by two metal springs which allow the rod to move back and forth. The input to the coil is from the output of the amplifier circuit. The signal from the laser on the sub-stage moving back and forth across the split photodiode is the input the circuit as mentioned above. The output of the circuit is the input to the coils. As the lens moves back and forth to move the laser beam across the split photodiode, the coils are working to counteract that movement. For example, as the lens moves to the left, the coils will move to the right to counteract the movement until the lens is stationary and the signal of the split photodiode is zero.

Finally, the sub-stage is clamped to a rod which is attached to the loudspeaker. The purpose of this is to move the sub-stage back and forth to mimic vibrations in the earth. The loudspeaker is off to the side of the sub-stage and is glued to the table to allow for accurate measurements. This also prevents the wire that is attached to it from moving at any unwanted angles while the measurements are being taken.

A function generator is used to drive the loudspeaker. The wire connected to the loudspeaker is clamped to the sub-stage. As the loudspeaker moves back and forth, the sub-stage moves with it. This allows the frequency of the sub-stage to be varied while taking the required measurements.

The commercial geophone is also attached to the top of the sub-stage so the same motions observed by the geophone circuit can be observed by the geophone. This allows for testing between the commercial geophone and the feedback system. The output of the geophone and feedback system is attached to an oscilloscope to determine all signals as observed when the sub-stage is in motion.

CHAPTER 3: CIRCUIT DESIGN

3.1 Layout of the Amplifier Circuit

This circuit has two main stages which are the amplifier and follower stage. The signal from the laser aimed at the split photodiode is the input to the circuit. As the signal moves from across the photodiode, an ac signal is produce as the v_{in} input.

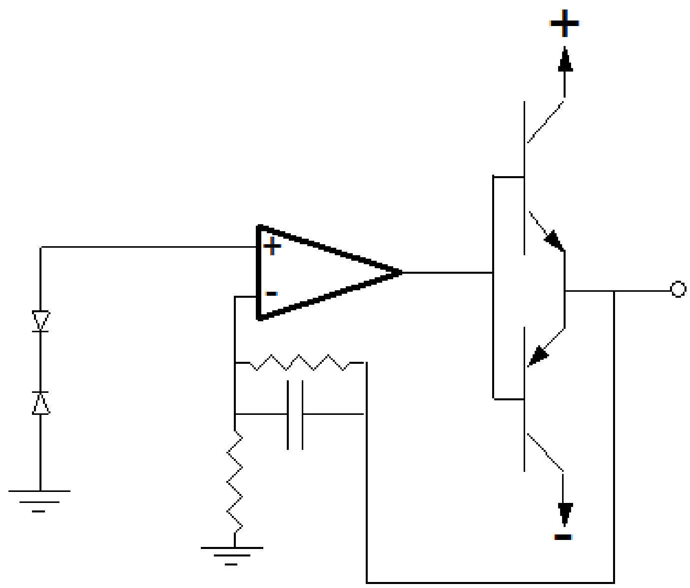

Figure 3.1.1

The amplifier stage is made up of an operational amplifier (op-amp). The configuration of this op-amp will be a non-inverting op-amp. From the diagram shown, the output of the op-amp is the input to the follower stage. The follower stage is made up of two bipolar junction transistors (BJTs). The BJT on top is an npn transistor while the transistor below is a pnp transistor. The input to both of the bases of the transistors comes from the output of the op-amp. When the output of the op-amp is positive, the npn transistor conducts and the pnp transistor is reverse biased. The emitter voltage from the

npn transistor is the voltage sent to the output of the coils. When the output of the op-amp is negative, the pnp transistor conducts and the npn transistor is reverse biased. The emitter voltage from the pnp transistor is the voltage sent to the output of the coils.

The output to the coil of the feedback system is also what is fed back to the op-amp at the negative terminal. The input to the negative terminal of the op-amp is fed back into the circuit through R1 and R2 with a capacitor in parallel with R2. The value of the input can be calculated with a simple voltage division shown in Eq. 1 [Horenstein, 1995].

$$v_{-} = \frac{R_2}{R_2 + R_1} \times v_{out} \qquad \text{Eq. 1}$$

$$A = \frac{v_{out}}{v_{-}} = \frac{R_2 + R_1}{R_1} \qquad \text{Eq. 2}$$

If Eq. 1 is rearranged to solve for $\frac{V_{out}}{V_{-}}$, Eq. 2 is the result where A is the gain of the circuit. The values for R_1 and R_2 are 10KΩ and 100KΩ, respectively. This creates a gain of approximately 10. In addition, parallel with the R_2 resistor is a 100 pF capacitor.

CHAPTER 4: FEEDBACK CIRCUIT RESULTS

4.1 Pendulum Resonant Frequency

This chapter will display the results obtained by the feedback system compared with the testing of the commercial geophone. As mentioned in previous chapters, both the pendulum and the commercial geophone were tested under the same conditions so the results will be fair compared to each other. The first step in testing the feedback circuit was obtaining the resonant frequency of the pendulum without feedback. This was done by driving the loudspeaker, which is driving the shaking table, at known frequencies until a resonance was observed. Below is a graph displaying the resonant frequency of the pendulum.

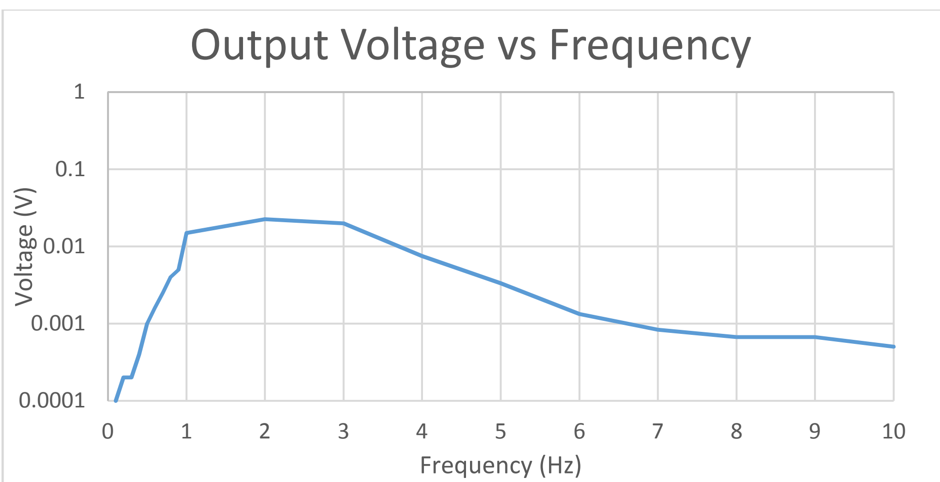

Figure 4.1.1

As shown by the graph above, the resonant frequency is around 2-3 Hz. At frequencies above 2-3 Hz, the output voltage starts to decline. The measurements that were taken in this graph were taken up to 10 Hz. However, since the resonant frequency was observed to be 2-3 Hz, all subsequent data only goes up to 3 Hz. Also, the goal is to improve data

taken at lower frequencies because the geophone is already adequate at taking data above approximately 5 Hz.

4.2 Geophone and Feedback Circuit Results

Next, the data was taken from the geophone and the pendulum with feedback connected. Both the geophone and pendulum were driven by the shaking table which was driven by the loudspeaker at known frequencies. The frequencies ranged from .1 – 3 Hz at .1 Hz intervals. Below is a semi-logarithmic graph of the frequency response of the geophone.

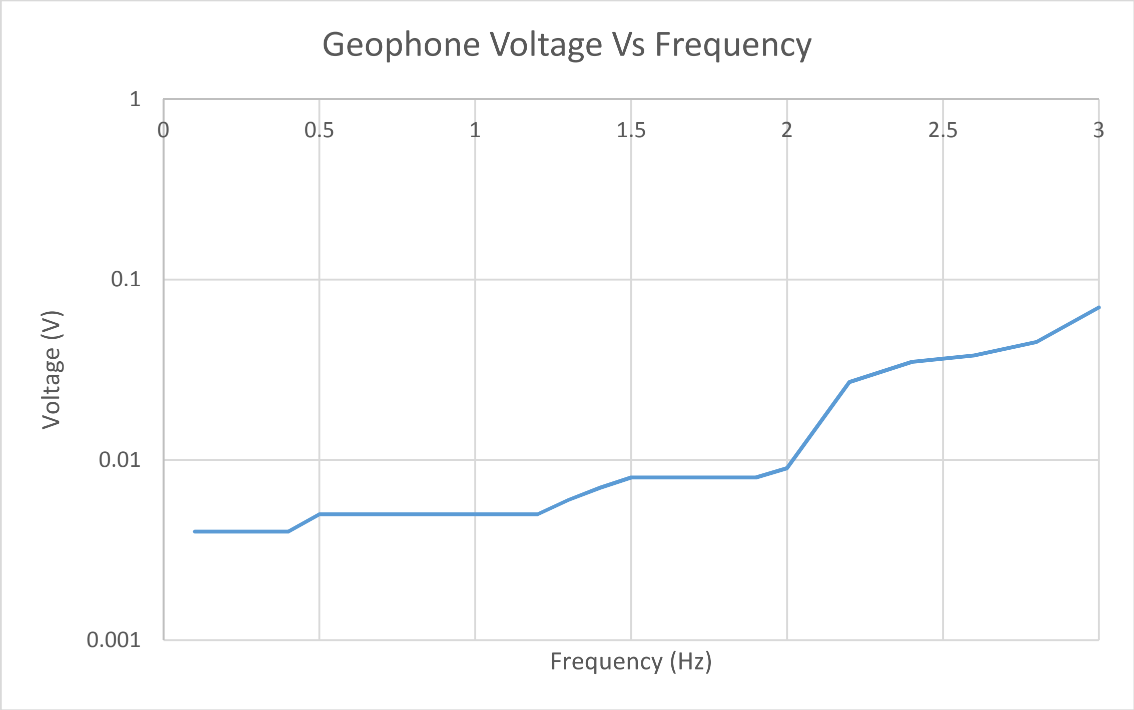

Figure 4.2.1

As shown by the graph above, the voltage stays mostly flat throughout and gradually begins to climb toward frequencies above 3 Hz. The voltage is flat from .5 to 1.2 Hz because at frequencies that low, the noise to signal ratio is much higher at lower frequencies. This is a display of one of the main disadvantages of commercial geophones,

as mentioned earlier. The geophone we tested has a sensor frequency of 10 Hz so at around 10 Hz and above, the voltage can be accurately measured.

Figure 4.2.2 is a semi-logarithmic graph of the results from the feedback circuit.

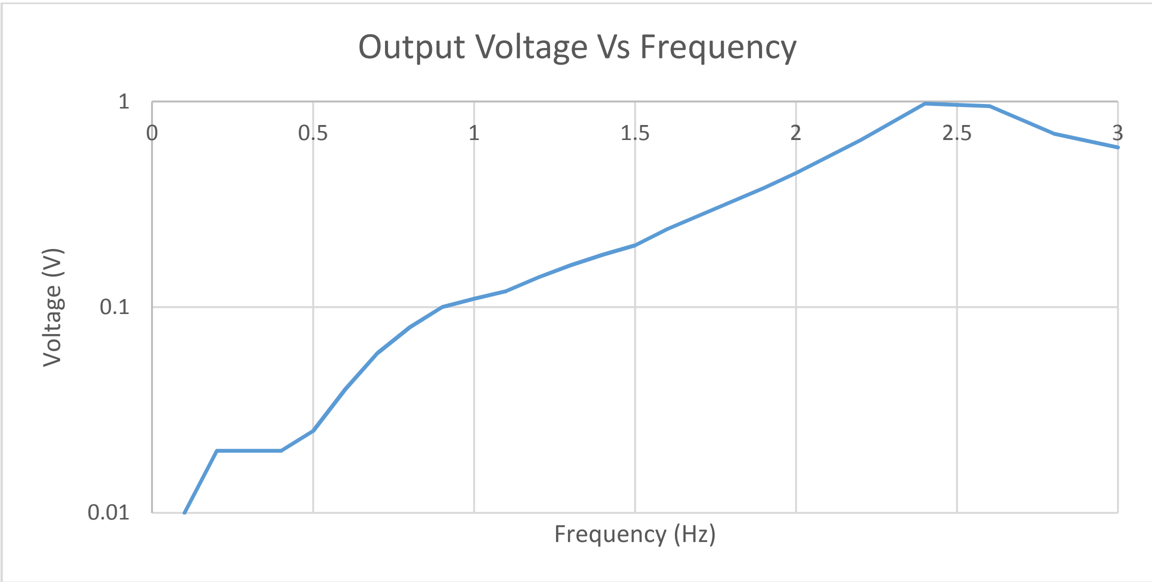

Figure 4.2.2

From this graph, there is a better response at lower frequencies. From frequencies of .1 to 2.5 Hz, the voltage steadily increases. At 2.5 Hz, which is about where the resonant frequency is for the pendulum, the results start to fall off. For the commercial geophones, the graph stays flat from .1 to 1.2 Hz. This is because of how large the noise to signal ratio becomes at lower frequencies for commercial geophones.

With both the geophone and feedback circuit being tested under the same conditions, this shows that the feedback circuit can measure voltages down to frequencies below the sensor frequencies of most commercial geophones. From .1 – 3 Hz, the geophone does not accurately display the data and most of the signal is lost to noise down to lower frequencies. This is where the feedback circuit will come into great use since it has been shown to accurately measure signals at frequencies below 3 Hz.

4.3 Preliminary Results of Amplifier Attached to Geophone

In addition to the work done with the pendulum system, work has been started on a different way to improve geophone measurements at lower frequencies. This can be done by attaching a capacitive amplifier onto the end of a geophone. This will connect the geophone to a virtual ground and help to avoid the signal to noise ratio problem encountered with commercial geophones. The graph below is a semi-logarithmic plot of the frequency response with the capacitive amplifier attached to the geophone.

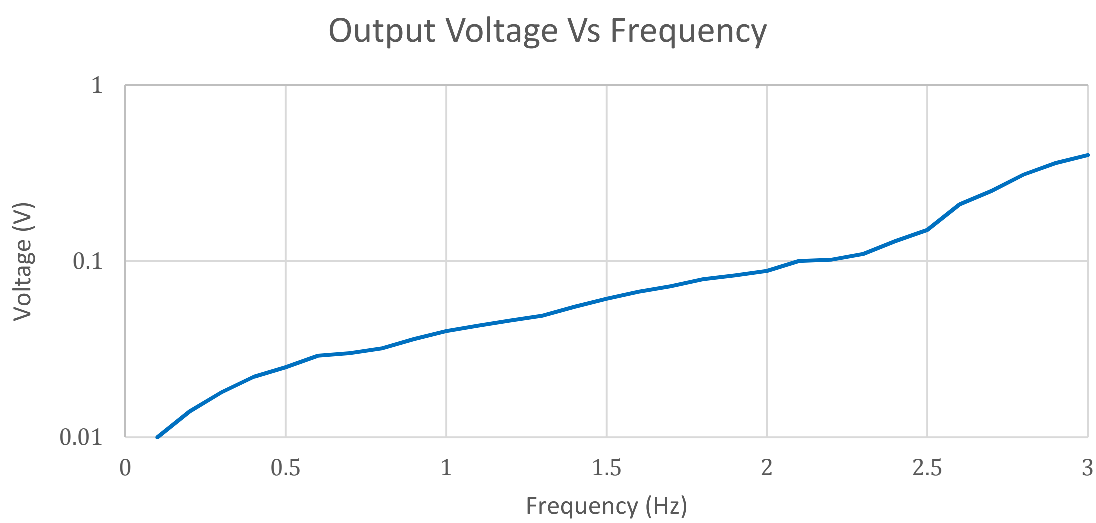

Figure 4.3.1

These results were taken using a capacitive amplifier with a gain of 100. From .1 – 3 Hz, the graph moves in a linear fashion. There is no noise problem down at lower frequencies using this method but more testing needs to be done in order to fully understand how this work and how it may impact the measurements geophone make down to lower frequencies.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Summary of Thesis

Commercial geophones have been very important in the field of geology for the use of environmentalists, as well as, helping to find oil and gas deposits. With the help of this research, a feedback circuit can be used to one day replace geophones for measurements of data at low frequencies.

General background information was given in Chapter 1. This included the mechanics behind how commercial geophones work using a magnetic mass moving back and forth in a wire coil to create a voltage. The response of the coil is proportional to the velocity of the ground. This chapter also introduced how they are used in the field to detect oil and gas deposits and to create three-dimensional simulations of the earth. Finally, their limitations were introduced stating how down to lower frequencies, most commercial geophones measure data inaccurately.

Chapter 2 introduced a solution to solve the limitation using a feedback circuit. Feedback circuits allow for more stability and can be easily modified to achieve the goals of this problem. Also, this chapter introduced how the feedback circuit will be tested against the commercial geophones using the stage and sub-stage. The stage consisted of a sub-stage being swung back and forth at a known frequency by connecting it to a loudspeaker driven by a function generator. The sub-stage had a laser on it which was directed at a split photodiode. The laser was focused on the split photodiode through a lens hung on a pendulum. This signal from the split photodiode was fed into the feedback circuit which controlled the coil. This pendulum is controlled by the coil as it moves back and forth from the output of the feedback circuit.

Chapter 3 describes the feedback circuit. It shows the design of the circuit and how it is used to stabilize the pendulum upon any detected movements. It also shows the various resistor and capacitor sizes used for the design of this circuit.

Chapter 4 displays the results of this research. Shown first is the how the resonant frequency of the pendulum was found. From this, we noticed the frequency at which the pendulum we would start to see a drop off in its measurements. Then we tested the commercial geophone side-by-side with the feedback circuit. The results clearly show that the feedback circuit takes accurate data at lower frequencies than the commercial geophone. In addition to this, preliminary work was done on testing the geophone with a capacitive amplifier attached to it.

5.2 Future Work

Looking ahead to the future, the work done on this device can be significantly improved. This device was tested in a lab which simulated the movements of the earth. Although the testing was very thorough in the lab, testing in the real world will be better for obvious reasons. This device will hopefully be used in the field one day to help detect earthquakes and find oil and gas deposits more efficiently.

To do this, this system needs to be tested on different systems under a myriad of real world simulated conditions. For example, actual side-by-side testing in the field next to a geophone detecting vibrations from a vibrator truck to determine how low the sensor frequency can go. Also, making changes to the circuit maybe beneficial to lower the sensor frequency of the device. This can be done by adding time constants or filter stages to improve the feedback. The combination of these two ideas could vastly lower the sensor frequency to make for a better and more efficient device.

In addition to this, there has been preliminary testing on putting an amplifier on the geophone to help raise the signal at lower frequencies. Different configurations of the amplifier have already been tried with some success thus far. Through testing in future research, this may be another simple and effective way to gather data from a geophone at lower frequencies.

5.3 Future Goals

The future goals of this work could be very helpful in improving geophones if future research can be done. The future goals of this work include getting the sensor frequency in the cHz range, printing the circuit on a printed circuit board to allow for better portability, and creating new systems to test the effectiveness of this circuit. Getting the sensor frequency down to the cHz range will allow this device to detect earthquakes. This could be used in high risk areas where earthquakes strike. And by printing this circuit on a PCB, this will allow for this device to be made portable at a relatively low cost. With this future work in sight, this device could have a profound impact.

REFERENCES

[1] Barzilai, Aaron. (2000). *Improving the Performance of a Geophone through Capacitive Position Sensing and Feedback.* Ph.D. Dissertation, Mechanical Engineering, Stanford University, January 2000.

[2] Horenstein, Mark. (1995). Microelectronic Circuit and Devices (2nd Edition).

VITA

Brian Holden is a native of Baton Rouge, LA, and received his bachelor's degree at Louisiana State University in December 2009. He went on to become a graduate student at Louisiana State University in the Division of Electrical and Computer Engineering. He anticipates to receive his master's degree in December 2014 and to continue working to receive his Ph. D upon graduation.