BetterBots Educational Robot
Vibration Sensor Electronics

Final Report
REV 3

Team 2

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BetterBots 'Mr.Ohm' Educational Robot

Sponsor - Daniel Walker

Table of Contents

Table of Figures

1.0 Introduction/Executive Summary

The purpose of this project was to make improvements to the BetterBots 'Mr. Ohm' educational robot. This robot is sponsored by Daniel Walker's company Betterbots. The robot is designed to provide a platform for computer science students to learn the electronic design process. The 'Mr. Ohm' educational robot is designed to utilize discrete electronics to exemplify topics in electrical engineering.

Effort began on the project by deciding which of the robot's sub-systems we wanted to work to improve. Of the twelve sub-systems, the Vibration Sensor electronics were chosen for this project. The initial goal was to reduce the signal to noise ratio of the Vibration Sensor electronics. This would allow the robot to be able to sense smaller vibration signals. Since seismic data is of such low frequency, a reduction in flicker noise would be the best improvement. Research pertaining to flicker noise was then done by the team. Upon simulation of the Vibration Sensor electronics, an error was found within the circuitry. The second stage of the Vibration Sensor, the Low Frequency Amplifier, was found to have too much gain for the circuit to operate. This dilemma led to a refocusing of the project's goals. The updated goals of the project revolved around four main endeavors. First, data was to be gathered on the first stage, or the Low Leakage Amplifier, of the Vibration Sensor electronics. Parts for this circuit were ordered, the circuit was built, and testing was done. Second, data was to be collected on the vibration sensor itself. This was done through physical with the vibration sensor. Third, the required gain of the common emitter amplifier and the Low Frequency Amplifier was to be determined. The team did not have the available parts to build this stage of the Vibration Sensor electronics, but insights could be made from testing the vibration sensor. Lastly, a Low Frequency Amplifier Common Emitter circuit was designed by the team to fix the issues that the original Low Frequency Amplifier had. The team didn't have the available parts to build this circuit either, but simulations were conducted to get an idea of the expected data. The gain issues pertaining to the Low Frequency Amplifier didn't allow for the initial goal to be met. However, the updated goals were able to be fulfilled.

2.0 System Description

The BetterBots 'Mr. Ohm' educational robot project is designed to provide a platform for computer science students to learn the electronic design process. The robot is also an ongoing experiment in community-based electrical engineering. The 'Mr. Ohm' educational robot is designed to utilize discrete electronics to exemplify topics in electrical engineering.

The 'Mr. Ohm' robot contains a variety of subsystems. The subsystem focused on is the vibration sensor electronics. The vibration sensor electronics allow the 'Mr. Ohm' robot to detect and interact with its environment's low frequency vibrations. These vibrations may communicate information about the robot's external environment. The vibration sensor electronics receive, detect, and amplify signals from the robot's piezoelectric vibration sensor. There are existing vibration sensor electronics on the BetterBots website, but improvements are needed. Noise sources in the existing electronics need to be understood, characterized, and where possible improved.

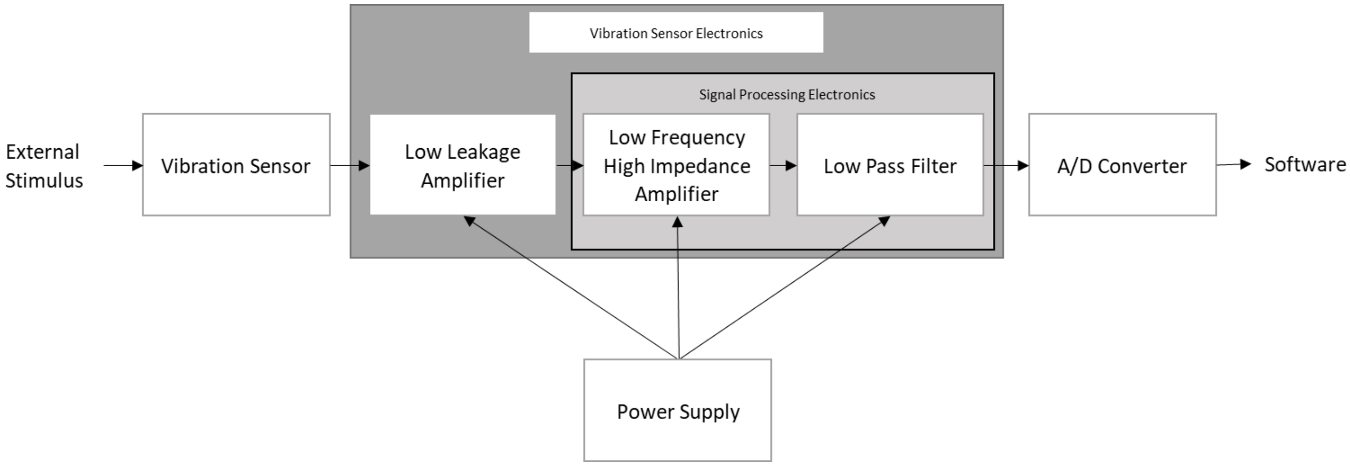

Figure 1: *System-Level Block Diagram for the Existing Solution*

2.1 Major Components

The vibration sensor electronics consists of six major parts: the vibration sensor, a low leakage amplifier, a low frequency high-impedance amplifier, an active low pass filter, and a microcontroller.

2.1.1 Vibration Sensor

The vibration sensor will be able to pick up and measure vibrations in the surrounding environment. The sensor functions as a cantilever-beam type accelerometer with a loaded mass at the end to accurately sense low frequency vibrations like pedestrian footfall. Acceleration deflects the beam due to the inertia of the loaded mass and a piezoelectric response creates an output voltage across the electrodes of the sensor. The threshold will be set by the user.

2.1.2 Low Leakage Amplifier

The low leakage amplifier receives the voltage signal from the vibration sensor and modifies the response for later stages. This involves a low-leakage junction-gate field-effect transistor (JFET) as a voltage to current converter, followed by a bipolar junction transistor (BJT) acting as a current sink to convert the measurement back to an amplified voltage signal. This circuit also includes a low pass filter to decrease high frequency noise from the output signal.

2.1.3 Low Frequency High-Impedance Amplifier

The Low Frequency High-Impedance Amplifier amplifies the comparatively small input signal into a much higher amplitude signal. The Low Frequency High-Impedance Amplifier provides most all the gain within the vibration sensor electronics.

2.1.4 Active Low Pass Filter

The low pass filter removes high frequency noise that may have been inadvertently captured or amplified by previous stages. This is important to avoid passing high frequency signals that may not be sampled correctly by the Analog to Digital Converter (ADC). This allows the ADC to sample more slowly.

2.1.5 Microcontroller

The student programmers using the BetterBots Mr. Ohm Educational Robot will interact with the vibration electronics by receiving data from it. The signals captured and processed by the vibration sensor electronics will be delivered to the microcontrollers ADC to be utilized by the student users.

2.2 System Interfaces

The system interfaces are detailed below.

2.2.1 External Interfaces

The system's external interfaces are detailed below.

2.2.1.1 Vibration Sensor to Vibration Sensor Electronics

The vibration sensor must be easy to connect and disconnect from its accompanying electronics. It should be attached with a terminal block or connector with similar ease of use.

2.2.1.2 Electrical Power to Vibration Sensor Electronics

Electrical power must be delivered to the vibration sensor electronics. The power provided to the vibration sensor in the existing design is delivered via a 3.3V and 6V connection to the Mr. Ohm Educational Ro bot's internal power supply. As not to overburden the internal power supply the vibration sensor electronics must present a sufficiently high impedance.

2.2.1.3 Microcontroller to Vibration Sensor Electronics

The BetterBots Mr. Ohm educational robot is intended to be used by computer science students for programming. The software created by these users will run locally on the microcontroller. The computer science student's access to the vibration sensor is through the delivery of vibration sensor data to the microcontroller Analog to Digital Converter interface.

2.2.1.4 Environmental Interface

The BetterBots Mr. Ohm educational robot is intended for use in a learning environment. This learning environment will be typical of an indoor classroom environment with moderate non-condensing humidity and temperatures below 90 F and above 32 F.

2.2.2 Internal Interfaces

Internal interfaces between subsystems of the Vibration Sensor Electronics are described in subsections below.

2.2.2.1 Vibration Sensor to Low Leakage Amplifier Interface

The Vibration Sensor has poor current supply capabilities, so the following amplifier must have high input impedance. To accomplish this, a JFET with an extremely high gate impedance is selected.

2.2.2.2 Low Leakage Amplifier to Low Frequency High Impedance Amplifier Interface

The Low Leakage Amplifier uses an emitter follower buffer that isolates the high impedance node and produces a low impedance output. This output then feeds into the Low Frequency Amplifier.

2.2.2.3 Low Frequency High Impedance Amplifier to Low Pass Filter Interface

The output of the low frequency amplifier connects to the low pass filter through an AC coupling capacitor, presenting a high impedance to the output of the Low Frequency High Impedance Amplifier.

2.2.2.4 Low Pass Filter to Microcontroller Interface

After the vibration sensor signal has been amplified and filtered the signal is sent to an analog to digital converter present on the microcontroller.

2.2.2.5 Power Supply to Vibration Sensor Electronics Interfaces

Various stages of the vibration sensors signal processing circuitry require 6V and 3.3V DC power sources which are supplied by multiple power supply busses present in the system.

3.0 Detailed Design

Of the subsystems listed and described in part 2 of this document, the scope of the detailed electronics design is primarily in the Low Leakage Amplifier, Low Frequency High Impedance Amplifier, and the Active Low Pass Filter. These parts of the design are described in greater detail below in their respective subsections.

3.1 Low Leakage Amplifier

In the scope of our work, the Low Leakage amplifier was analyzed, constructed, and tested. The Low Leakage amplifier design was not modified. The Low Leakage Amplifier design is shown below in Figure 2.

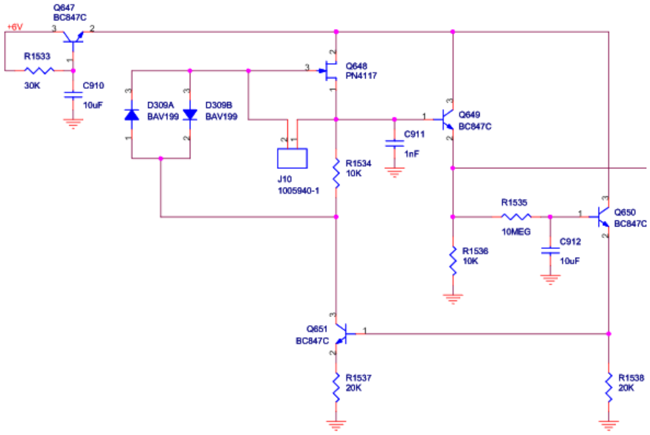

Figure 2: *Low Leakage Amplifier Existing Design*

The low leakage amplifier was implemented on a breadboard and tested for functionality in terms of gain, bandwidth, and noise. The implemented and tested breadboard version is shown below in Figure 3.

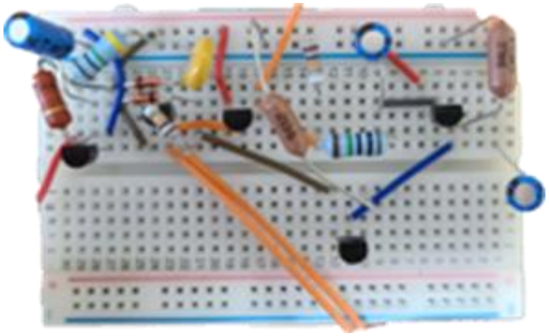

Figure 3: *Low Leakage Amplifier Breadboard*

We physically tested this vibration sensor both by connecting it directly to an oscilloscope and by connecting it to a breadboarded version of the low leakage amplifier. Our breadboarded low leakage amplifier is shown below in figure 4.

From these physical measurements we were able to observe seismic noise in the environment. Below in figure 9 we can see the result of light stomping near the sensor.

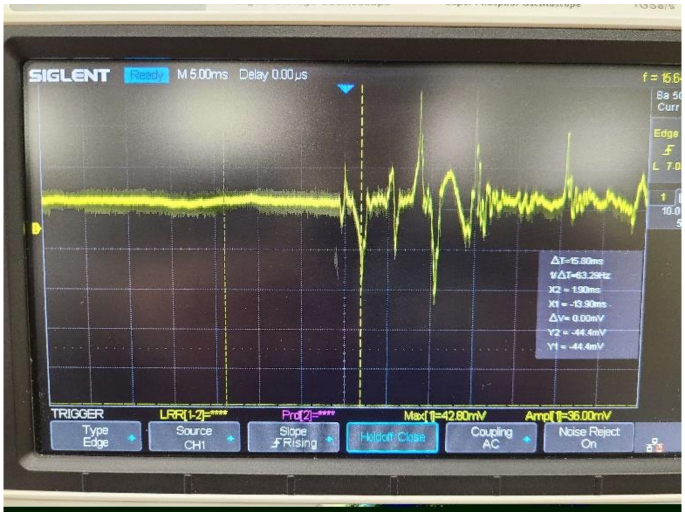

Figure 4: Resulting signal from light stomping near sensor.

In figure 9 the plot is as 10 mV/division, and the signal is ~ 50 mV peak to peak.

3.2 Low Frequency High-Impedance Log Amplifier

The Low Frequency High Impedance Amplifier was created using the existing design as a starting point. The existing amplifier design had troubles with saturation due to the high system gain required. Modifications were first made to reduce the gain of this amplifier. This revision also switched amplifier architectures to a simplified common emitter amplifier. Later upon further testing of the vibration sensor we discovered that a higher gain and higher dynamic range was required than either of these amplifiers could deliver. To overcome this hurdle, we created a new log amplifier through modification of the sponsor’s unrelated existing circuit.

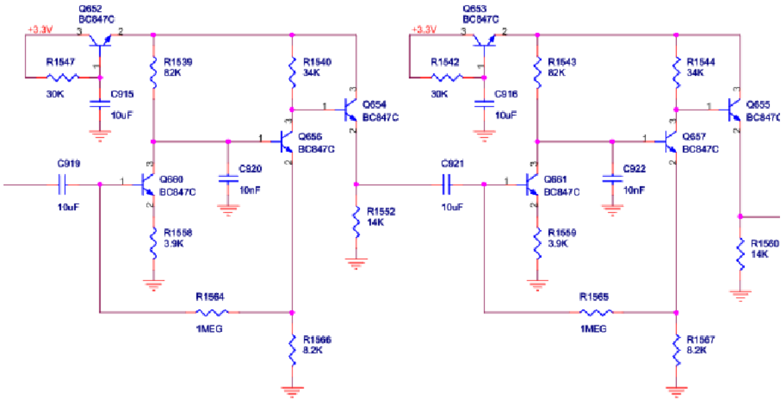

Figure 5: *Existing Low Frequency High-Impedance Amplifier*

Since the Existing Low Frequency High-Impedance Amplifier is two repeated amplifiers in series, we will first examine only one section.

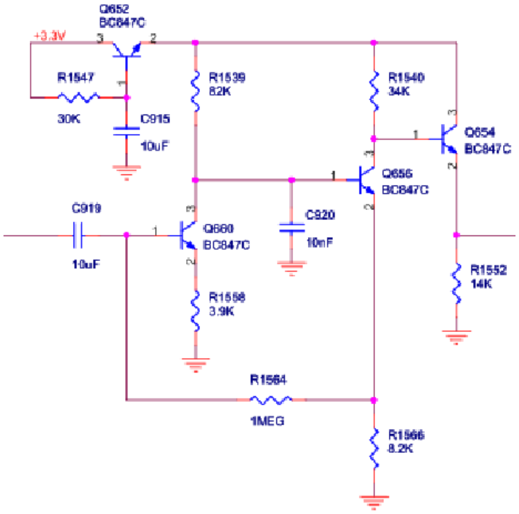

Figure 6: *One half of original design of Low Frequency High Impedance Amplifier*

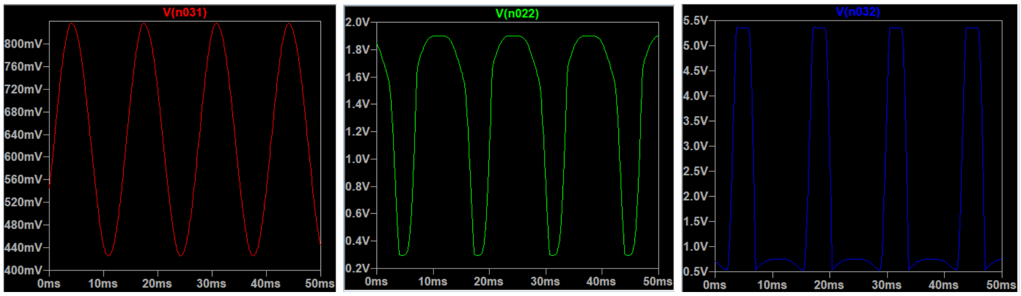

Figure 7: *Waveform shape as measured at the input of low freq amp, in the middle at the capacitor, and at the output. Simulated with 4.4 mVrms at input to low leakaage amplifier.*

As we can see, with a sine wave input to the origional amplifier, a highly distorted signal that nearly fills the entire power supply voltage results. These simulations are performed with a 4.4 mVrms signal input to the low leakage amplifier. The gain from the low leakage amplifier is already impactful, the very high gain in the low frequency high impedance amplifier is too much. Because the input signals may be far greater than 4.4mV as shown in figure 9, amplifiers with greater dynamic range are required.

In physical testing with the low leakage amplifier shown in figure 8 we were not able to capture any signals of seismic noise from walking, so to determine the gain required in the low frequency high impedance amplifier, we performed a measurement on an existing amplifier. As shown below in figure 10, Using a Stanford research systems low noise current preamplifier we found that someone jumping across the room created ~50 pA (peak) of current into a 1M input impedance. 50e-11 amps*1e6 ohms=0.5 mV. If we want this signal to fill half of a 3.3V ADC, the required voltage gain would be (3.3/2)/.0005 = 3300 V/V = 70.37 dBV. The gain of our low frequency high impedance amplifier may be slightly lower than this, as the analog to digital converter can resolve signals smaller than half its power supply voltage used in calculation above. In our design we aimed for 60dB of gain.

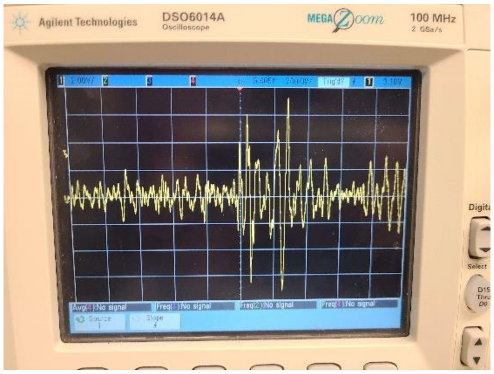

Figure 8: *Walking across the room, observed using amplifier test equipment.*

Before performing the measurement shown in figure 7, we first attempted to replace the existing low frequency high impedance amplifier with a simple common emitter design. The thought process was that this lower gain would avoid saturation. Unfortunately, this would not accommodate large signals and modifications were required.

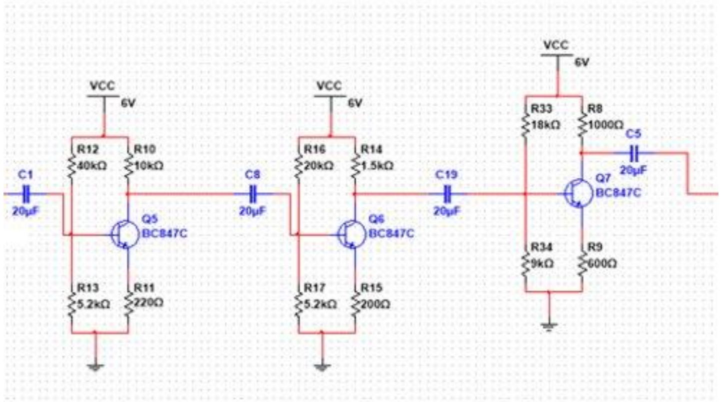

Figure 9: *Simplified Common Emitter Amplifier with Reduced Gain*

To accommodate large input signals a log amplifier was designed from an existing circuit provided by the sponsor. The log amplifier is intended to increase dynamic range and perform more desirably in saturation. The log amplifier design is shown below.

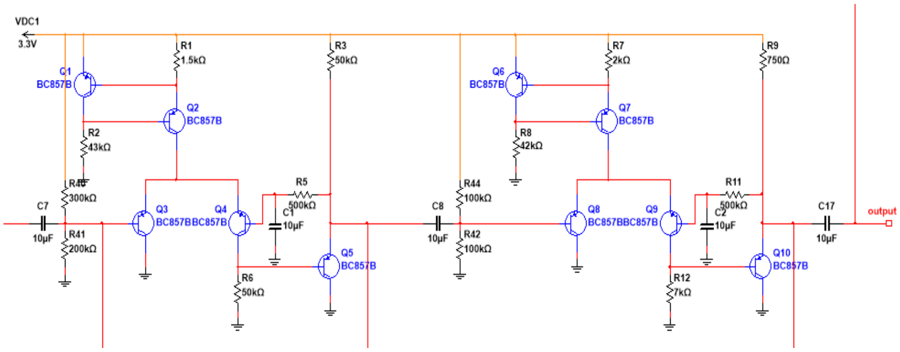

Figure 10: *Log Amplifier with Increased Dynamic Range*

The log amplifier performs as expected: the amplifier clips nicely with signals that are too large. Shown below is the output of the log amp when its output is clipping. This is a notable improvement from the behavior seen in figure 6.

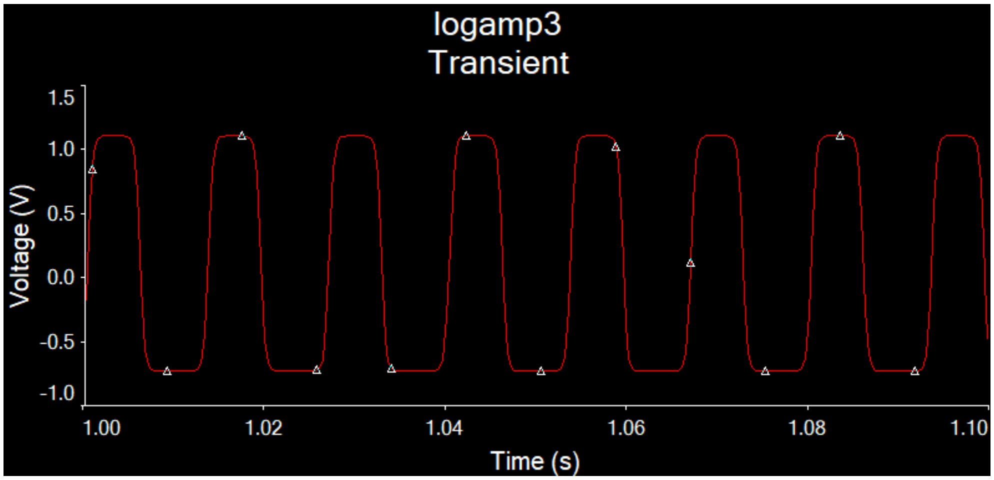

Figure 11: *Clipping without serious distortion using log amplifier*

Now that the amplifier can clip cleanly on large signals, it may have a large gain without fear of substantial distortions.

3.3 Active Low Pass Filter

The active low pass filter is designed to have a sharp cutoff to reduce noise. The Active Low Pass Filter existing design had a passband that was too narrow, having a corner frequency around 50 Hz. Modifications were made to adjust the cutoff frequency to make the corner higher, around 200 Hz. These modifications were made to allow for higher frequency signals to be received. We expect that noise due to walking will be around ~75 Hz. [4]

Our determination of the walking noise frequency is based on existing literature. Below is an excerpt from reference 4, a seismic noise study.

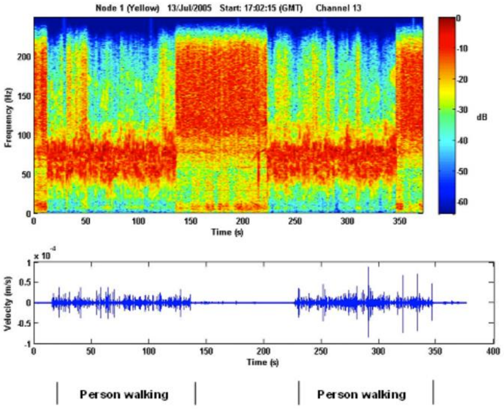

Figure 2. Spectrogram (top) and time series display (bottom) of a 375-s record of vertical ground motion in which segments of seismic noise alternate with segments of footstep-induced ground motion. The spectrogram is normalized at each second to the maximum amplitude over all the frequencies at that time. This causes the apparent maximum energy level to be the same at each time regardless of the walker's activity (moving or stationary).

Informaion from graphs at left:

1. Maximum velocity $V_{max} \approx 1 \cdot 10^{-4}$ m/s
2. Average frequency observed when walking = 75 Hz

So:

$$V = 1 \cdot 10^{-4} \cdot \sin(75 \cdot 2\pi \cdot t)$$

$$A_{max} = \max\left(\frac{d}{dt}\left(1 \cdot 10^{-4} \cdot \sin(75 \cdot 2\pi \cdot t)\right)\right)$$

$$\Rightarrow 1 \cdot 10^{-4} \cdot 75 \cdot 2\pi \cdot 1 \approx 0.04 \text{ m/s}^2$$

$$\Rightarrow 0.004 \text{ gs}$$

Since the sensor has a 1.1 V/g sensitivity, the signal is ~0.0044 Volts

Figure 12: *Excerpt from Peck, L. [4] (left) and associated calculations (right)*

As we can see from the calculations on the right of figure 12, the expected signal size is roughly 4.4 mV peak.

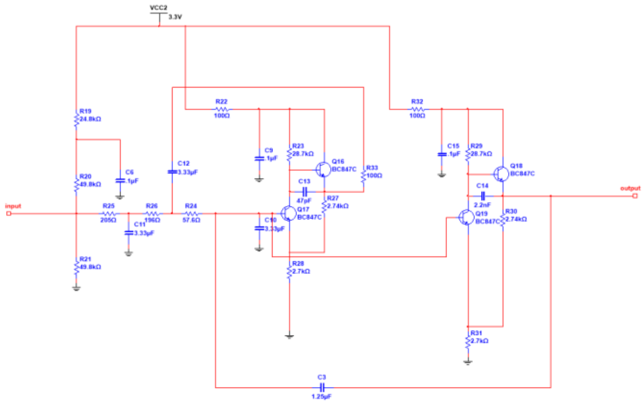

***Figure 13**: Modified Active Low Pass Filter Schematic*

The above schematic shows the modified low pass filter design. This design has been corrected for wider bandwidth and less ringing, as shown below in figure 14.

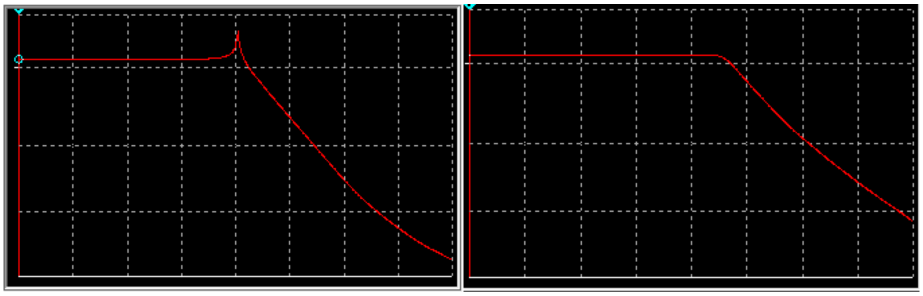

Figure 14: *Original design (left) and modified design (right) bandwidth.*
Both plots are from 50 dB to -200 dB and 10 mHz to 1MHz.

As we can see, the corner is now at a higher frequency to capture more of the input signal and the ringing from the previous design has been reduced.

4.0 Test Procedure and Results

Test procedures for the vibration sensor electronics are outlined below. This excludes the Low Leakage Amplifier physical testing and verification as this was not in the scope of this work; Where applicable, Results shown below are from simulations.

4.1 System Bandwidth and Amplitude Response Test

System bandwidth may be measured two ways depending on equipment availability. One method is with a dynamic signal analyzer or spectrum analyzer and the other is the function/sweep generator method.

4.1.1 Dynamic Signal Analyzer or Spectrum Analyzer Method

Using a Dynamic Signal Analyzer (DSA) or Spectrum Analyzer equipped with a swept sine or tracking generator respectively the bandwidth and amplitude response of the vibration sensor electronics may be measured. In either case the instrument must be able to support 10 mHz to 100 Hz.

Measurement Process:

Step 1: Connect the Swept Sine or Tracking Generator to the vibration sensor terminal block.

Step 2: Connect the Vibration Sensor Electronics' output that would normally go to the Analog to Digital Converter to the input of the DSA/Spectrum Analyzer.

Step 3: Sweep the generated signal over the range from 1 MHz to 100kHz, recording the amplitude response.

Proceed to 4.1.3

4.1.2 Function/Sweep Generator Method

If a DSA or Spectrum analyzer is not available, the amplitude response may be obtained with a function generator and a digitizing oscilloscope. The function generator can be swept over the range of frequencies between 10 mHz and 100 Hz and the amplitude response recorded using FFT on the oscilloscope. If the function generator cannot create swept sines, then it may be swept manually and plotted.

Proceed to 4.1.3

4.1.3 Expected Results

From either of the previous methods an amplitude vs frequency graph should be achieved. The highest gain part of the amplitude should have a flat frequency response between ~10s of mHz to ~100 Hz. The observed gain should match the simulated result shown in the figure below:

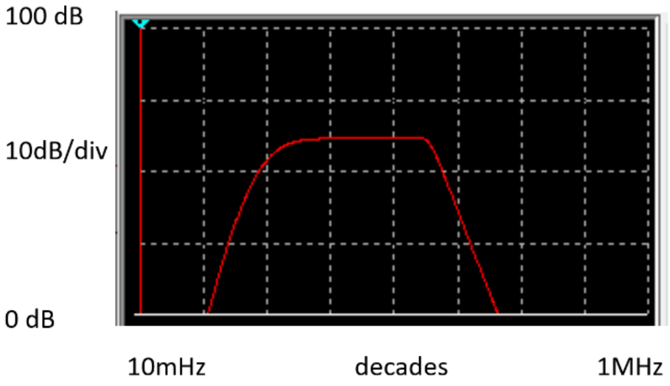

Figure 15: *Frequency Response of Total System*

4.2 System Noise Test

The vibration sensor electronics' noise vs frequency may be measured with a Dynamic Signal Analyzer (DSA) or Spectrum Analyzer (SA) with frequency capabilities between 10 mhz and 100 Hz. With the vibration sensor input terminal block shorted with a small (~1cm) piece of wire, connect the output terminals to the input of the analyzer (DSA or SA) and observe the noise floor. Details of this measurement should be documented in your DSA/SA manual.

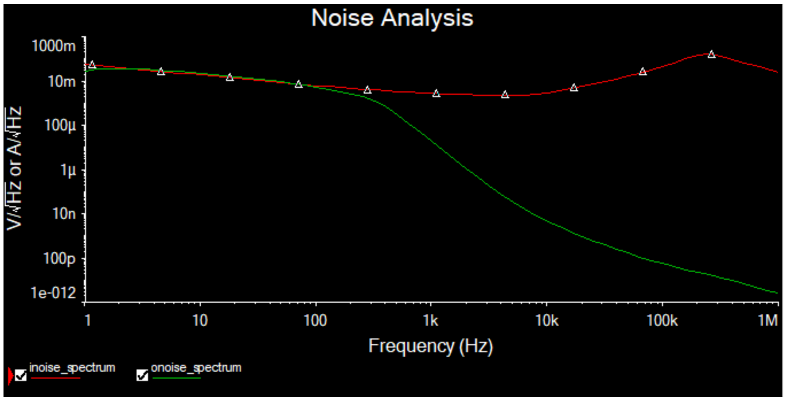

Figure 16: *Total System Noise from 1 to 1 MHz*

4.3 Input Leakage Test

Input leakage current can be tested by a resistance measurement or a current measurement, both are described in the following subsections.

4.3.1 Resistance Measurement Method

The input resistance may be measured directly using an ohm-meter connected directly to the vibration sensor input terminal blocks. A resistance greater than 1 MOhm should be observed.

4.3.2 Current Measurement Method

Using a power supply and a current meter or multimeter the leakage current may be measured directly. The power supply and current meter should be connected in series and their respective ends connected to the vibration sensor input terminal block. The power supply should be set to 1 V. A current of less than 1 uA should be observed on the current meter.

5.0 Conclusions

Although the initial goal set by the team of reducing the signal noise of the Vibration Sensor electronics couldn't be met, the overall goal of making improvements to the BetterBots 'Mr. Ohm' educational robot was accomplished. The updated goals of gathering data relating to the Low Leakage Amplifier, gathering data related to the vibration sensor, determining the required gain of the common emitter amplifier and the Low Frequency

Amplifier, as well as assessing the effectiveness of a Low Frequency Amplifier the team designed were met. With the vast majority of our goals being accomplished, our sponsor seemed to be pleased with the work done.

This project did pose a serious challenge for the team. The students had never been involved in a project that dealt with such advanced circuitry and testing. A great quantity of research was required in order to better understand circuitry and to meet the set goals. The ability of the team to work together and adapt was reflected in the quality of work. Overall, the project was seemingly a success.

6.0 Recommendations for Future Work

Although the scope of the team's project was only limited to a single semester, there were several potential ideas discussed that could further improve upon the operation of the Vibration Sensor electronics. One of the primary concerns for the successful operation of the vibration sensor was the interference of low frequency noise, such as flicker noise, due to its relative proximity to the seismic signals that were focused on. Implementation of a Correlated Double Sampling technique, and the addition of the required electronics and software to realize it, were discussed as a method to isolate the desired signal from the unwanted low frequency noise.

Throughout the team's time on this project, regular meetings were held with the sponsor as well as teams from Minnesota State University where the students worked collaboratively, sharing findings and discussing ways to improve sensor circuity. Another Minnesota team had also selected the Vibration Sensor electronics and thus the team was able to share the collected data on the vibration sensor, as well as the new circuit designs. It is the team's hope that they can take some of these findings and build upon them, possibly implementing a Correlated Double Sampling technique to further improve the operation of the Vibration Sensor system.

7.0 References

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