ECE 445: Modular Add-On for Noise Cancelling Headphones

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Team 18

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Abstract

Noise Cancelling Headphones are a major component of the consumer audio industry. These devices provide the regular function of playing back audio with the addition of reducing, or in some cases completely cancelling, ambient noise. Although providing, high performance, the cost of these devices is prohibitive for most regular consumers to purchase. In this report, we detail a novel strategy for adding noise cancelling capabilities to any existing pair of over ear headphones through an add-on accessory. By doing this, we provide a cost effective, robust, and durable solution that fulfills a gap in the audio market.

Contents

1 Introduction

1.1 Motivation

Noise cancelling headphones provide high quality ambient noise reduction/cancellation, however, their price remains a prohibitive entry point for most consumers. When comparing products on the current market, products such as the the Bose Soundlink II can be found. These headphones feature high quality speakers and Bluetooth wireless connectivity, and are sold for $200. On the other hand, the Bose Quiet Comfort 35 headphones offer the same features, however adds ambient noise cancelling, and is offered for the price of $350. This means that just noise cancelling is being offered at the price of $150, a cost that is most often untenable for the average consumer[6].

1.2 Solution

To fill this void in the market, we propose a small, modular device that can be added on to an existing set of over ear headphones in order to implement noise canceling on them. This is done by the user placing microphones on either ear cup, which then connects to our device, implementing the noise cancelling. In order to implement this solution, a few goals had to set. Firstly, the created device must be cheap enough so that even if bought with an average set of consumer headphones, the total price would still be less than half of our benchmark headphones, the Bose QC 35. Secondly, the quality of ambient noise reduction must be within 25% of the Bose QC 35. Finally, the product must be durable, and have a battery life that is comparable to the Bose QC 35.

2 Design

2.1 Methodology

To design this product, core component, the Noise Cancelling circuit was developed first. This portion of the design involved 4 major components: microphone filtering, signal inverting, phase delaying, and mixing. Secondly, the power circuit was designed such that adequate power rails and current could be provided at times of peak usage. Finally, the micro-controller portion of the product was designed so that the device could be controlled over Bluetooth and be adjusted to user parameters.

2.2 Goals

To ensure the final product reached expected levels of performance, a set of goals were established not only to make sure that the best possible product was made, but also to ensure that the project was feasible and could be done in the given amount of time. Our goals were as follows:

- The Bose QC 35 headphones are shown to have a significant level of noise cancelling, especially at lower frequencies[9]. In order to build a competitive product, we wished to achieve 25% of the noise cancelling performance of the Bose QC 35. This will be measured by amplitudes of external noise heard within the headphones at various frequencies.
- The cost of the product must be low. Arbitrarily, the value of $50 was chosen. With such a value, a user can purchase a high quality set of over ear headphones for $100 and with our add-on, still pay less than half the price of Bose QC 35 headphones.
- The product must be easy to install onto nearly any existing set of over-ear headphones. This then meant we could not expect the user to have any electronics skills, and so we aimed for installation to only involve mounting microphones onto the headphones.
- Battery life of the device must be on par with the Bose QC 35. This also meant that the design must be portable and low power while still delivering performance.
- The tuning of the circuit by the user must be seamless and should be performed easily without electronics skills.

2.3 Design Concept

The following diagram (Figure 1) details the layout of the product:

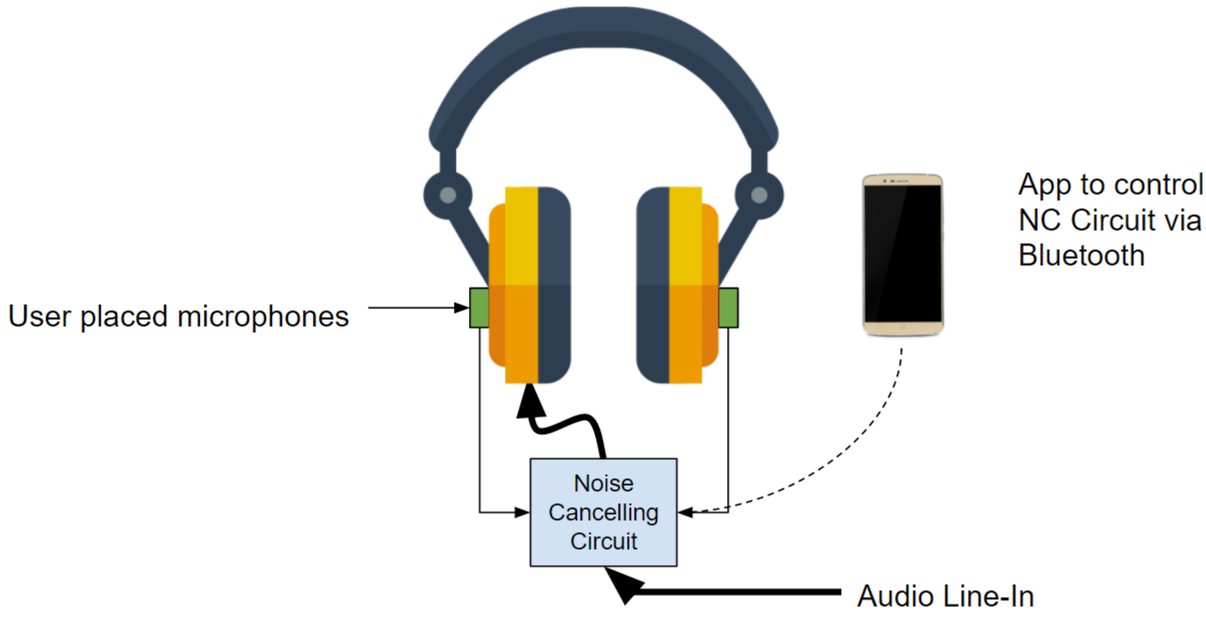

Figure 1: Functional Design Concept for the noise cancelling add-on.

As can be seen from the diagram, the core noise canceling circuit will be contained in an add-on box into which an existing pair of headphones plug in. The user will place microphones onto their headphones for the noise cancelling circuit. Finally, a mobile application will be used to control parameters of the noise cancelling circuit via Bluetooth.

2.4 Component Blocks

Our product has a high level functionality that revolves around three core components: the noise cancelling circuit, the microcontroller, and the power circuit. This can be seen in the following block diagram:

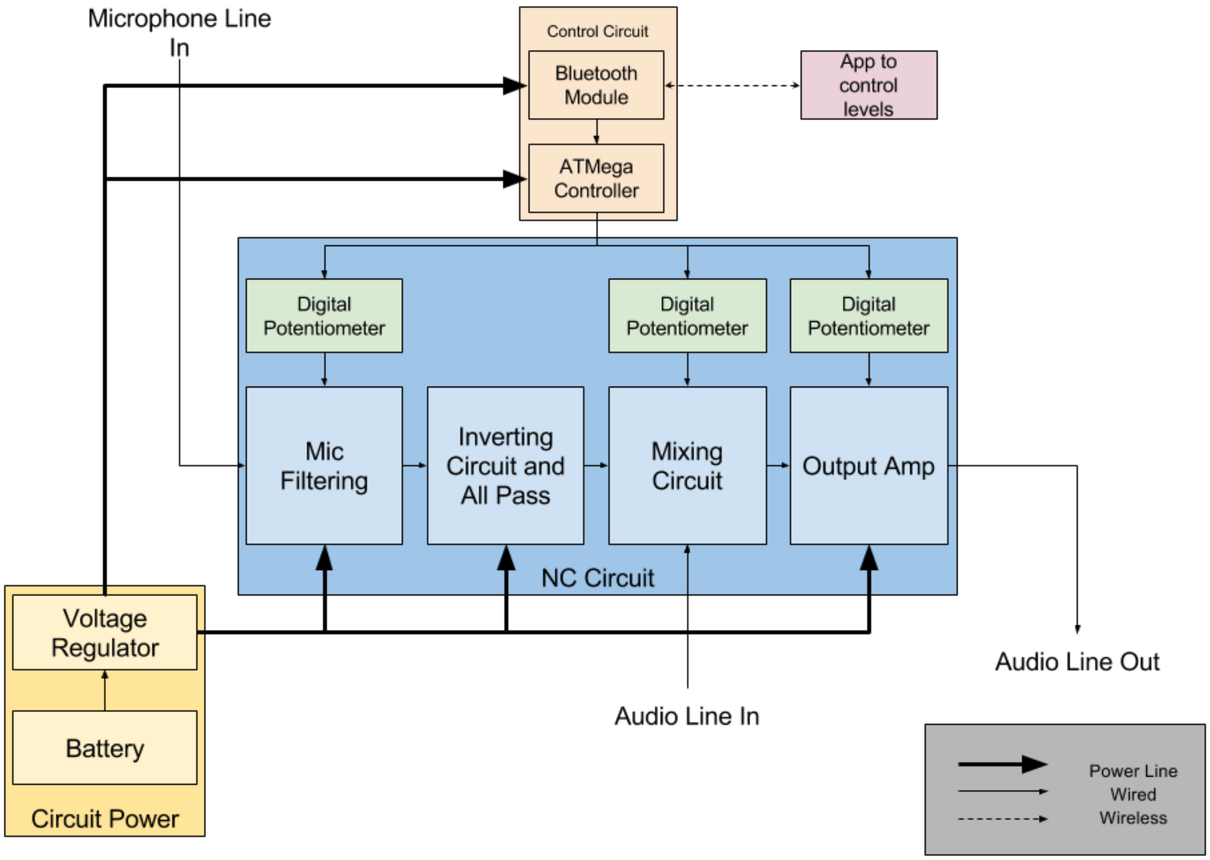

Figure 2: Block diagram detailing the high level architecture of the full product

The noise cancelling component consists of 4 major components. The mic filtering is stage is used to clean microphone noise and prepare the signal for inversion and amplification. The inverting circuit and all pass filter stage does two tasks. First, it takes the microphone signal and inverts and amplifies it to appreciable audio levels. Next a phase delay is applied with an all pass filter to prepare the signal for mixing. The mixing circuit takes in both the inverted, shifted microphone signal and the desired audio input and sums the two, creating a noise cancelled audio output. finally, this output signal is amplified to the user's desire and sent to the headphones. The digital potentiometers that are present on the noise cancelling circuit exist so that the parameters of the circuit can be adjusted via the Bluetooth controller, such as gain in the various stages of amplification.

The power circuit is quite simple, but has a crucial task. Comprising of the batteries and the voltage regulator, the power circuit will filter output power and also control charging of the batteries. The batteries are charged through a micro-USB port, which is part of the voltage regulator. In addition, the power circuit will provide power rails for both the microcontroller and the operational amplifier in the noise cancelling circuit.

Finally, the control circuit will be used to tune the parameters of the noise cancelling circuit. For this purpose, the control circuit consists of an ATMega controller[14] that will be used to control the digital potentiometers in the noise cancelling circuit. This communication will be done either via a protocol such as I2C or simple voltage levels. To give the user an interface to the microcontroller, a Bluetooth module is going to be added so that a mobile application can interface with the microcontroller.

3 Implementation

3.1 Noise Cancelling Circuit

3.1.1 Microphone filtering

The ANC circuit can be divided into 4 separate modules, the first of which is the filter for the microphones, which provide the signal for the unwanted ambient noise. This filter does two things, firstly it increases the amplitude of the signal from the microphone, and secondly, it prevents high frequency noise from appearing at the output of the microphone by creating a low pass filter on the power supply. The diagram for the circuit is displayed below.

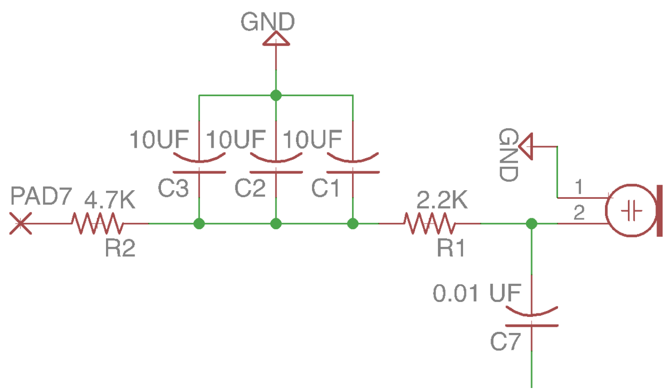

Figure 3: Microphone amplification circuit. The output signal can be seen coming form capacitor C7.

Based on the design of a low pass filter with a resistance of 4.7k Ω and a capacitance of 30uF, we are cutting off frequencies above 1.2 Hz, preventing any high frequency noise from entering the microphone output signal. This is, of course, found using the simply low pass filter cutoff frequency equation:

$$f_c = \frac{1}{2\pi RC} \tag{1}$$

This is also characterized in a magnitude vs frequency graph:

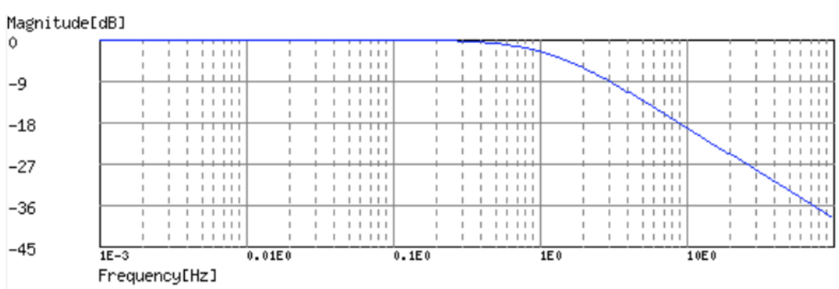

Figure 4: Magnitude of the input signal VS the frequency

3.1.2 Inverting Microphone Pre-Amp

This then feeds into the second part of the circuit, the inverting op-amp[1] for the noise signal. This amplifier is designed to have a utility gain of 22, as the input microphone signal will still be relatively weak compared to the input audio signal, and to invert the signal provided by the microphones. In addition, the

DC component of the microphone will be reduced here, allowing for better noise cancellation output. The LM4562[2] is being used here due to its high performance, low noise, and dual op-amps per chip, allowing for stereo noise cancellation. The LM4562 is powered by a ±6V supply. The schematic of this portion can be found below:

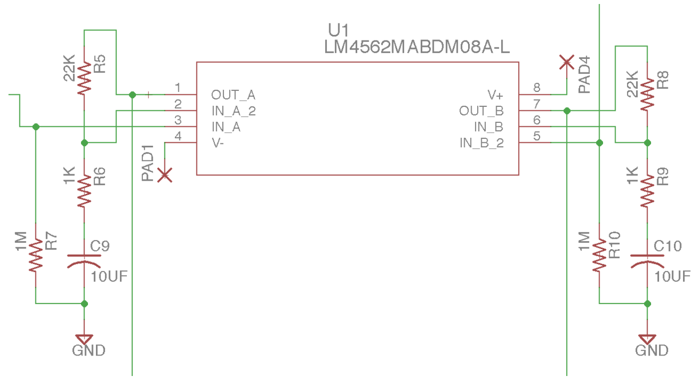

Figure 5: The inverting microphone pre-amp. Inputs can be seen coming into pins 3 and 5, while outputs are seen leaving pins 1 and 7.

3.1.3 All Pass Filter

The all pass filter takes in the inverted noise signal and outputs a phase shifted signal that accounts for the delay between the microphone receiving the signal, the signal being processed, and finally being sent to the speakers. Of course, since light travels faster than sound, this delay must be added, otherwise constructive interference may occur and will diminish sound quality. To design this module, the frequency we are centering our phase shift, and hence our noise cancelling around, must be found. We selected 700Hz as our centering frequency based on multiple reports[4][5] that found that most ambient/traffic noise centers around this frequency. The circuit for the all pass filter is detailed below:

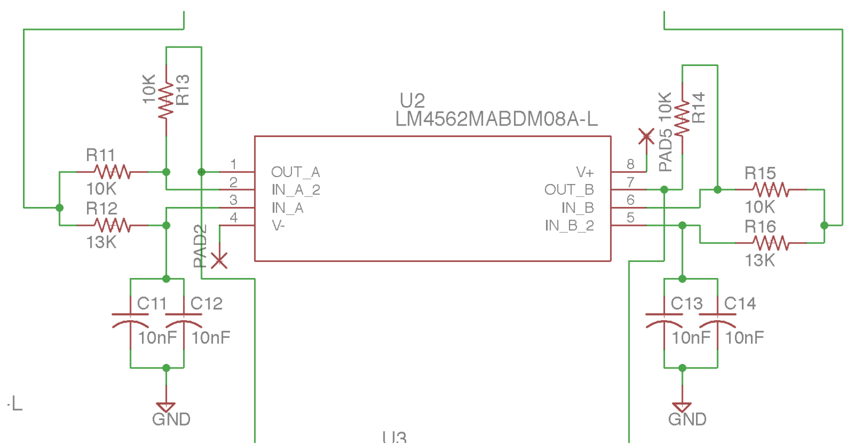

Figure 6: All pass filter design

This design is based off of standard all pass filter designs[7] that have been presented. To calculate our values for capacitors and resistors the distance between our microphone and speaker needed to be known. Upon measurement this was found to be 2 centimeters. With this being known, we could calculate the time it takes for the noise to propagate from microphone to speaker, and thus calculate the phase delay needed for the all pass filter:

$$\begin{aligned} V &= \frac{d}{t} \\ t &= \frac{d}{V} \end{aligned} \tag{2}$$

$$\begin{aligned} P_D &= t * f * 360 \\ &= \frac{d}{V} * f * 360 \\ &= 11.1\texttt{degrees} \end{aligned} \tag{3}$$

With the phase delay calculated, the guide[7] was simply followed to get capacitor and resistor values. The same op-amp was used here to reduce cost and because of the high performance of the op-amp.

3.1.4 Summing/Mixing Amplifier

The mixing amplifier is designed to be the same as the inverting amplifier, however, it does not have the inverting component of the inverting amplifier. In addition, the secondary change is that the gain of this amplifier is variable. AD5246[3] digital rheostats are being used to variably adjust the gain of the amplifier. These digital rheostats are being controlled by an ATMega micro-controller[14], which is in turn being managed by a smartphone. The schematic for the mixing amplifier is as follows:

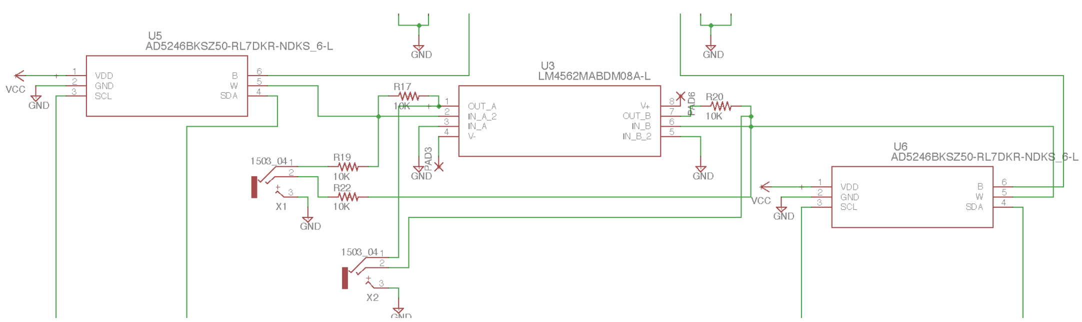

Figure 7:

The input of the op amps comes from both the microphone all-passed signal, and the input audio source. In addition, this op-amp serves as the final output to the 3.5mm output jack. The design for this op-amp was taken from the standard TI guide[1].

3.2 Recharging Circuit

We're using two 3.7V rechargeable Li-Ion batteries running at 3000mAh each, responsible for two power rails, at 5V and -5V. This circuit is responsible for powering the rest of the circuit: control circuit, Bluetooth module, and ANC circuit. The design of the batteries, charging circuit, and casing can be seen in Figure 14.

Because of the size of the batteries and overall heat concerns, it's ultimately decided that power will not be on the PCB, as the PCB is devoted mainly to control and active noise cancellation. For the final product, attaching converters, which are more stable than building our own op-amp voltage amplifiers, outside of the PCB should be sufficient. We built a casing for the battery, and attached the charging chip onto the side.

For the recharging portion, a TP4056 linear chip with a mini-USB attachment for input supply. Here is the circuit provided in the proposal. In retrospect, this schematic is not complete. We have added three power rails, so we will need three step-up converters, as well as an inverter.

We can estimate efficiency based on the graph provided by the TP4056 documentation.

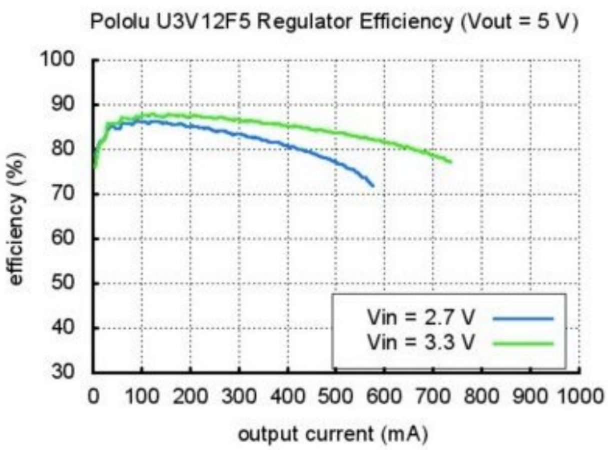

Figure 8: Graph of charging efficiency of battery.

The TP4056 takes pin 1 and 5 of the mini USB at 1A (5V) for input and and outputs a standard 4.2V to charge the 3.7V Li-Ion battery. According to the documentation, the charging current should be 37% the battery capacity. To charge the battery, it should be $3000\texttt{mAh} * .37$, which corresponds to 1.2K Ohm surface mount resistor.

3.3 Control

3.3.1 Physical Control Circuit

The control circuit contains two main components: the ATMega328P Chip[14] and the HC-05[15] Bluetooth Module. These allow for wireless control of the entire noise-cancelling circuit through a smartphone application. This application controls parameters such as microphone sensitivity, microphone mix level, and output level in order for the user to have fine control over all aspects of the module. Because the ATMega microcontroller[14] can easily communicate with the chosen Bluetooth module and can directly translate packets sent to it into commands to control the noise-cancelling portion of the circuit, it is chosen as the core component of the control circuit , since the bluetooth module would be unable to function properly without the microcontroller's help.

As shown in the above figure, the ATMega chip[14] is hooked up to the HC-05 module[15] in a way such that the serial inputs of the ATMega are connected to the outputs of the HC-05 Bluetooth Module[15] in order to receive packets directly from the module. Three output pins are selected to control the different potentiometers within the noise-cancelling circuit. The ATMega328P operates between 1.8V and 5.5V, so our VCC is hooked up to a steady 5V coming from the power circuit. This means that the output of the ATMega will also be up to 5V, leading to the digital potentiometers to control the noise cancelling circuit.

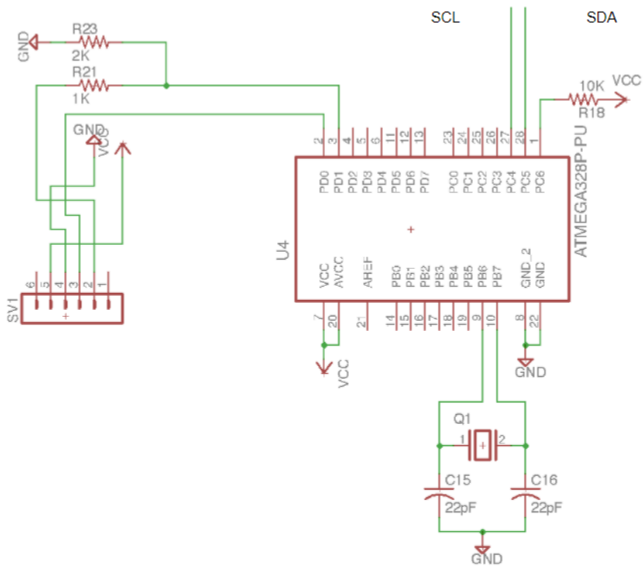

Figure 9: Control Circuit Design

3.3.2 Arduino Code

The Arduino code is what handles the packets received from the bluetooth modules, and informs the ATMega[14] chip what to do with the information. In the below figure, the simple logical flow chart is shown: The code works by simply constantly polling the serial ports of the ATMega328P for non-zero pack-

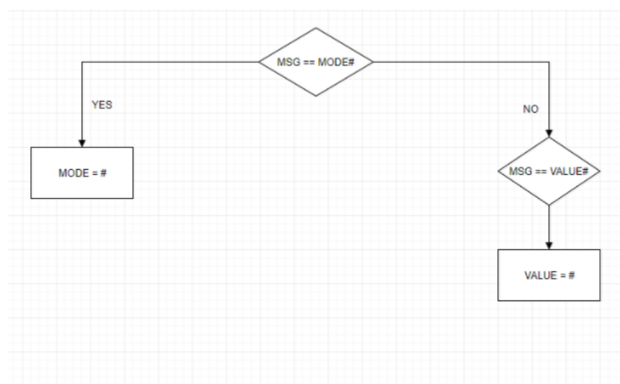

Figure 10: Arduino Code Flow Chart

ets. If any are found, the ATMega chip will step through the logic shown above. The code first checks the mode signal sent from teh mobile application to inform the ATMega about which pin the user wants to adjust the output voltage of. The ATMega remembers the mode, and any subsequent numerical values sent to the module will be set to become the output level of that pin until the ATMega is set to another mode or pin number.

3.3.3 Android Application

The android application controls the different aspects of the noise-cancelling circuit, namely the microphone levels, mixed audio levels, and final output levels. When launched, the home screen is shown to the user as shown in Figure 15.

Once the application is launched, the user must connect the device by pressing the button in the bottom right hand corner with the universal Bluetooth icon. Once pressed, a list of possible devices is displayed, shown in Figure 16. In this case, the device to connect to in question is the HC-05 Bluetooth module.

Finally, after the device is successfully connected, the user is now able to change the output levels of the device. This can easily be done by using the slider that will pop up, and simply dragging it left and right depending on the user's preferences, which can be seen in Figure 17.

3.4 PCB Design

In addition to designing the schematic for the ANC, a PCB must also be designed to house all of the components such that functionality is maintained and the product size is minimized, as it is meant to be a portable device. The PCB that was finally designed is as such:

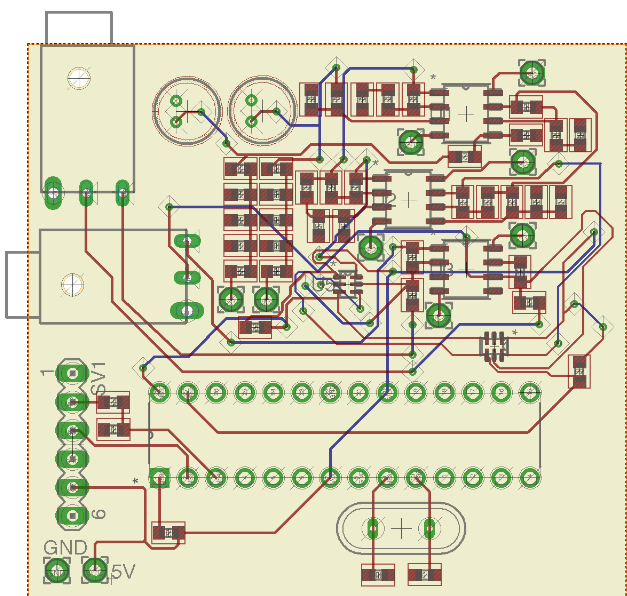

Figure 11: ANC PCB, with both front and back layers

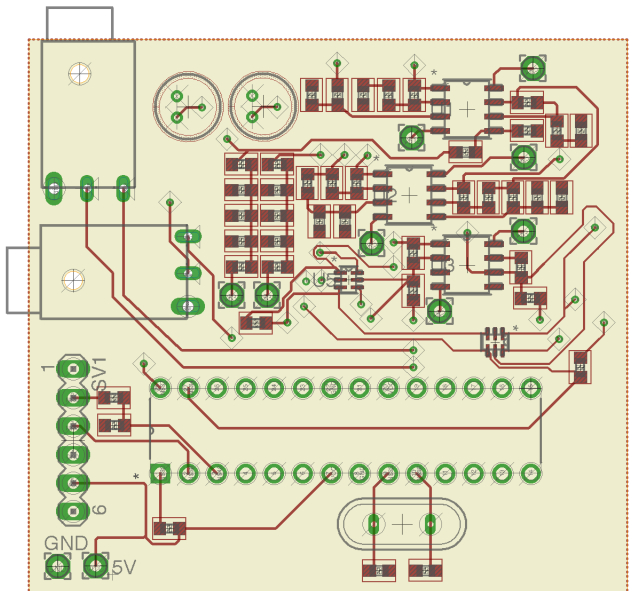

Figure 12: ANC PCB, with the front (top) layer traces.

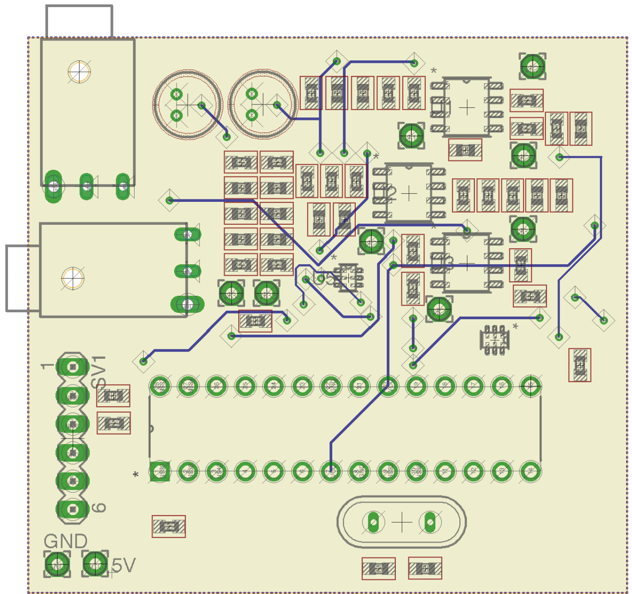

Figure 13: ANC PCB, with back (bottom) layer traces.

This PCB contains the integration of the ANC with the ATMega micro-controller and Bluetooth module. All components are designed so that they occupy a minimum amount of space, but do not contribute to interference. In addition, for ease of assembling the circuit, the components are mounted such that they somewhat resemble the design in the schematic. This can be seen with the microphone voltage noise filters and also the 3 op-amps. Both the top and bottom layer have ground fills to reduce the number of traces. In addition, the bottom plane was used whenever possible so that the top layer could remain simple for soldering purposes.

The keen observer will notice that even though the Bluetooth module is mentioned to be integrated in the PCB, it is not present on the design. This is because, for ease of design and to keep the PCB as compact as possible, the Bluetooth board has been broken out and will be attached at the headers near the ATMega. In addition, the power supply circuit has been broken out completely. Since the power supply remains as a difficult component to model, we have decided to make all signals pads that can be separately wired on the PCB. This allows for flexibility when working with the power supply and at worst, will allow us to use a bench power supply to power the device.

The size of this PCB leaves something to be desired, as it could be smaller considering the size of the components. However, due to the prototype nature of this PCB, that can be improved on in the second iteration.

4 Verification

Testing for all the components was done in a similar fashion. All tests were conducted using ±6V supply power and measured on an oscilloscope. Each module was measured independently from each other and is assumed to work as a whole component. Test results are as follows.

4.1 Inverting Amplifier

The inverting portion of the noise cancelling circuit was tested by inputting a 700Hz, 15 Volt amplitude signal and shifting it 180 degrees in phase. As can be seen by the oscilloscope output in Figure 20, a 180 degree phase shifted signal was generated. One thing to note, however, is that some frequency ”jostling” was noticed on the scale of 2-5 Hertz. Nevertheless, over thousands of samples, the mean remained around 700Hz, thus proving the functionality of the circuit.

4.2 All-Pass Filter

The all pass filter was tested by inputting a arbitrary noise signal centered at 700kHz at 8V into the circuit. The output was directly measured for phase shift. On the oscilloscope, a final phase shift of 11.154 degrees was measured relative to the input signal. It is regrettable that more granularity could not be provided in terms of the phase shift, however an error of 1.4% is acceptable in our design and should not be noticed by the user. This error originates from the fact that the noise signal is across a spectrum of frequencies and is not a pure signal, such as a sine wave. However, using such a signal for testing was critical, as it is what our circuit would be measured against. The output of this circuit module can be seen in Figure 21.

4.3 Mixing Amplifier

The mixing amplifier was tested by inputting a 700Hz sine signal at 8V into the op-amp and a inverted 700Hz sine signal at 8V, relative to the first signal. Measured on an oscilloscope, our final output, expected to be zero, was 8mV. The higher performance is to be expected as we are no longer using passive components to sum our signals. The rheostats could not be tested as they had not arrived, thus the adjustable gain was not tested. Full results are shown in Figure 22

4.4 Analysis of Noise Cancelling Performance

In order to quantitatively test the performance of the noise cancelling circuit, a simple test was conducted. A video consisting of airplane cabin noise[12] was played through the noise cancelling circuit as an input for the microphone. This same signal was then mixed into the noise cancelling output and the overall cancelling results were measured. First an analysis on the input signal was done, whose FFT is in Figure 23.

As can be seen from the FFT, the input signal has quite a bit of bass rumble coming from the jet engines, and lots of high end hiss, coming from the air conditioning systems. After passing through our noise cancelling circuit, the output was as shown in Figure 24.
By analyzing the noise cancelling output, we can see that a significant reduction has been done on the bass end of the signal. in fact, we have significantly reduced the noise around the centering frequency of our circuit. Nevertheless, our top end cancelling does leave something to be desired, in fact, the very top end (over 15kHz) performance is actually worse than not wearing the headphones. The following table details the full frequency results:
As can be seen, around 700Hz, around 38% noise cancelling was achieved, so our goals were achieved for noise cancelling. The Bose QC 35 headset achieves consistent noise cancelling across the spectrum, however, also buckles under high frequencies.

Table 1: Amplitude of various frequencies on different noise cancelling headsets

	50Hz	100Hz	500Hz	700Hz	1KHz	2KHz	5KHz	10KHz	15KHz
Our Solution	1.88	1.75	1.63	1.38	1.48	1.74	1.94	2.38	2.6
QC 35	0.86	0.91	0.78	0.94	1.13	1.28	1.3	1.52	1.8
None	3.06	2.96	2.81	2.76	2.84	2.91	2.95	2.85	2.54

4.5 Control Circuit

The control circuit was tested by supplying it with 5V and ground from the power rails of the power circuit. Once it was confirmed that the ATMega328P[14] and the HC-05 Bluetooth Module[15] were both receiving power, the pins of the ATMega were then measured with a multimeter. The module was connected to the the Bluetooth application, and the output voltage of pins wired up were monitored to be between 0V and 5V, depending on where the slider was dragged. As such, we were able to verify that the control circuit was in fact functioning correctly as a stand-alone module ready to be integrated with the rest of the project.

4.6 Charging Circuit

The recharging circuit was tested by using a USB2.0 Male to Mini-B, inputting a 1A signal at 5V. Upon charging, the CHRG red LED signal lights, and upon terminal, the green STDBY signal lights, which implies that the charger for the Li-ion battery works. A 3.7 voltage line is outputted by the signal that powers the battery. As expected, we can see that the when connected, a green light shows that there is input power, and an orange light shows that it is charging. This is seen in Figure 18 and in Figure 19.

We also looked at the power drawn in each circuit component to calculate how many hours the batteries can last on one charge.

Table 2: Power consumption analysis for circuit parts

	Power Consumption
Noise-Cancelling Circuit	1.270W
Control Circuit	33.75 mW
Total	1.304 W

Looking at our circuit. Our batteries provide 6000 milli-amp hours of charge. We tested how much current each part of our circuit parts through probing and using the power formula, resulted in 23 hours of active noise cancelling use. This, slightly above the battery life of QC35s, satisfies our benchmarks.

4.7 Cost Analysis

We see that we can make each unit for less than $30 when we take into consideration the bulk cost. Full cost breakdowns are detailed in Table 3. What is critical to note from this number is that even if the user were to purchase $100 headphones, they would still be paying nearly one-third the cost of a full set of Bose QC 35 headphones. This is a massive improvement considering that you can get slightly more than one-third of the performance with potentially less than one-third of the cost, accomplishing exactly the goal we set out to fulfill.

Table 3: Power consumption analysis for circuit parts

Part	Prototype Cost	Bulk Cost
LM324 Quad Opamp (2)	\$0.52 per	\$0.16 per
CMA-4544PF-W Microphone (2)	33.75mW \$0.82 per	\$0.3795 per
MCP4151-103E/P Digital Potentiometers (6)	\$0.95 per	\$0.71 per
SJ1-3525N Headphone Jack (2)	\$0.76 per	\$0.3799 per
ATMega328P	\$2.18 per	\$1.816 per
HC-05 Bluetooth Module	\$11.00 per	\$11.00 per
3.7V Rechargeable Li-ion Battery 18650 (2)	\$3.26 per	\$3.26 per
TP4056 Board (1)	\$0.67 per	\$0.67 per
.9V-5V Booster Module (1)	\$0.41 per	\$0.41 per
USB micro 2.0 typeB receptacle (1)	\$0.84 per	\$0.469 per
Total:	\$34.52 per (PCB cost added)	\$28.98 per (PCB cost added)

5 Conclusion

5.1 IEEE Code of Ethics

With regards to the IEEE code of ethics, we will strive to "to improve the understanding of technology; its appropriate application, and potential consequences," and also "disclose promptly factors that might endanger the public or the environment." One thing to note is that even though the circuit has a normal protection function that we have recently learned is that there is no reverse polarity, and connecting the battery the wrong way will fry the chip. The user should be informed of Li-ion battery safety concerns. There could also be bluetooth vulnerability issues we may need to warn the user about.

5.2 Lessons Learned

In terms of functionality, we have gotten most of our parts to work individually. Most of the core functionality can be shown to work individually. However, the modular unit breaks down upon integration, as there was a short on the PCB. Throughout the semester, we were consistently reminded as to how difficult audio can be; to successfully do this project, one must have a firm grasp of specific domain knowledge. For example, on the onset of this project, we didn't know that op-amps could be a source of noise for the circuit, or that we needed to add a phase shift to account for the speed of sound traveling into the mic and into your ear.

Lastly, we learned that for a large project like this one, where multiple parts are needed, an ample amount of time must be allotted for integration. We didn't have time in the end to debug all of our integration problems. As such, complete integration onto our pcb was unsuccessful.

When we look at what we have done relative to other noise cancelling headphones on the market, we have created a usable, inexpensive, module with a long-lasting battery. Our control circuit enables bluetooth control, and our noise-cancellation circuit is shown to reduce noise by a considerable amount.

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[15] HC-05 BLuetooth Module Datasheet http://www.electronicaestudio.com/docs/istd016A.pdf

Appendix A Images

The following gallery contains images that were too large to include inline in the document:

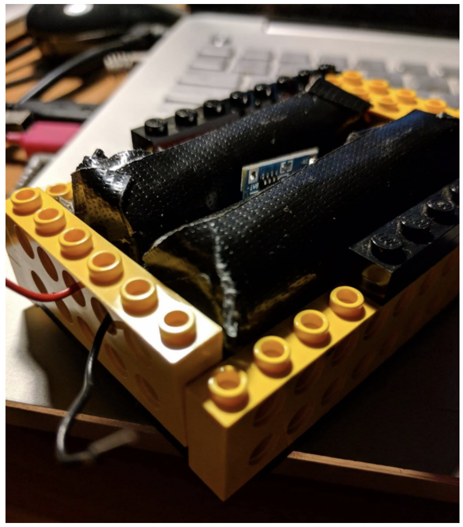

Figure 14: Lithium-Ion batteries in casing.

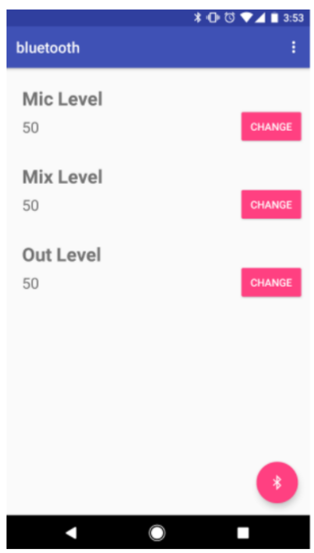

Figure 15: App Home Screen

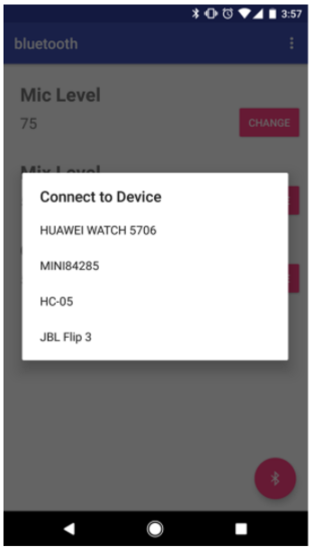

Figure 16: App Bluetooh List

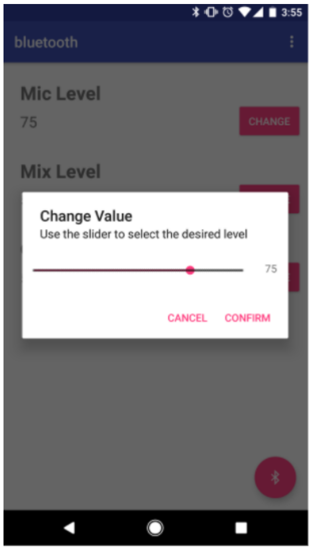

Figure 17: App Value Slider

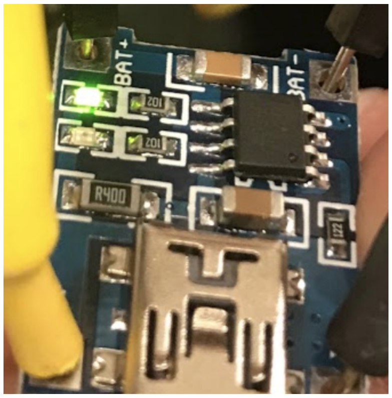

Figure 18: Battery is on standby

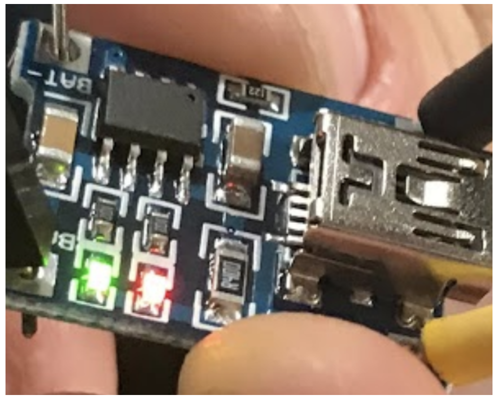

Figure 19: Battery is charging

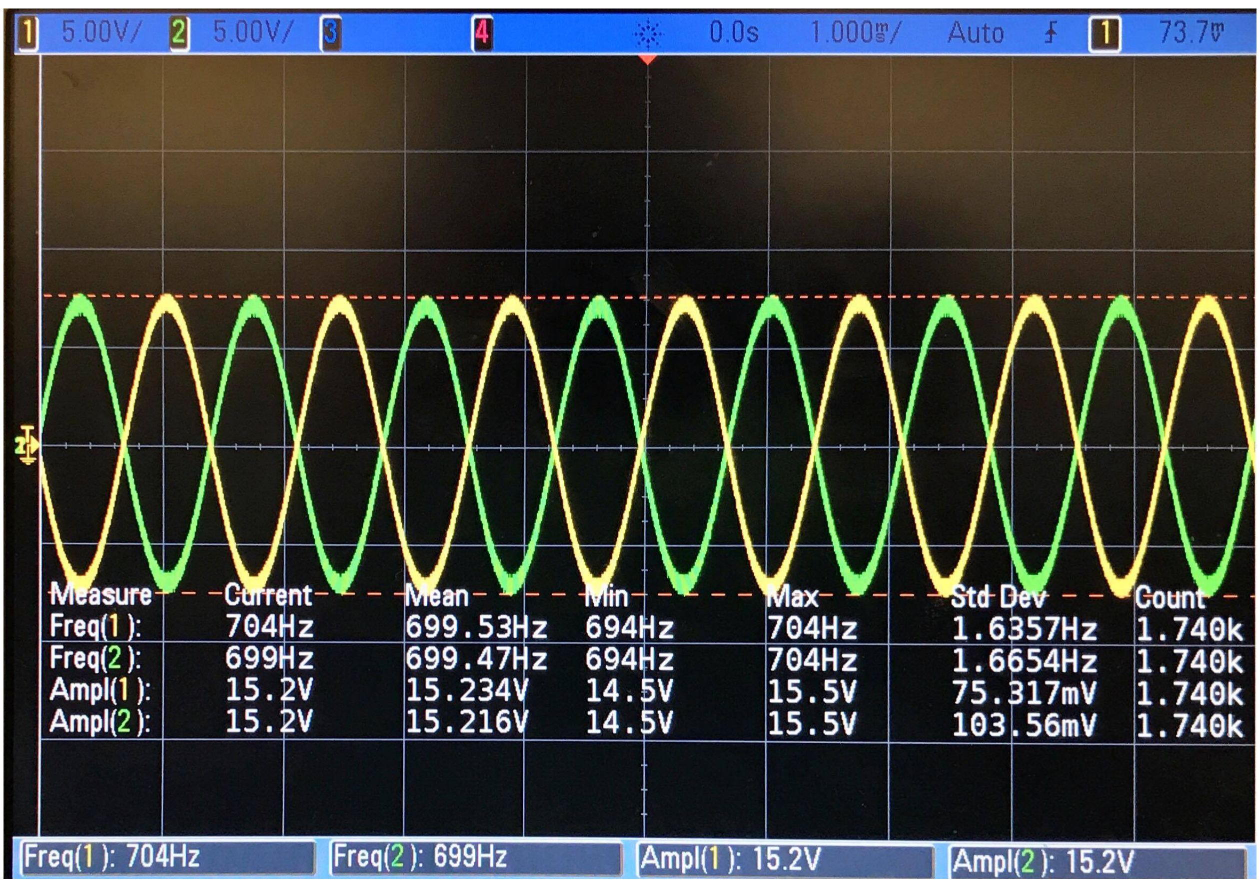

Figure 20: Measurements of the inverting circuit. The input signal can be seen in green while the output is in yellow. The phase shift measured is 180 degrees, as expected.

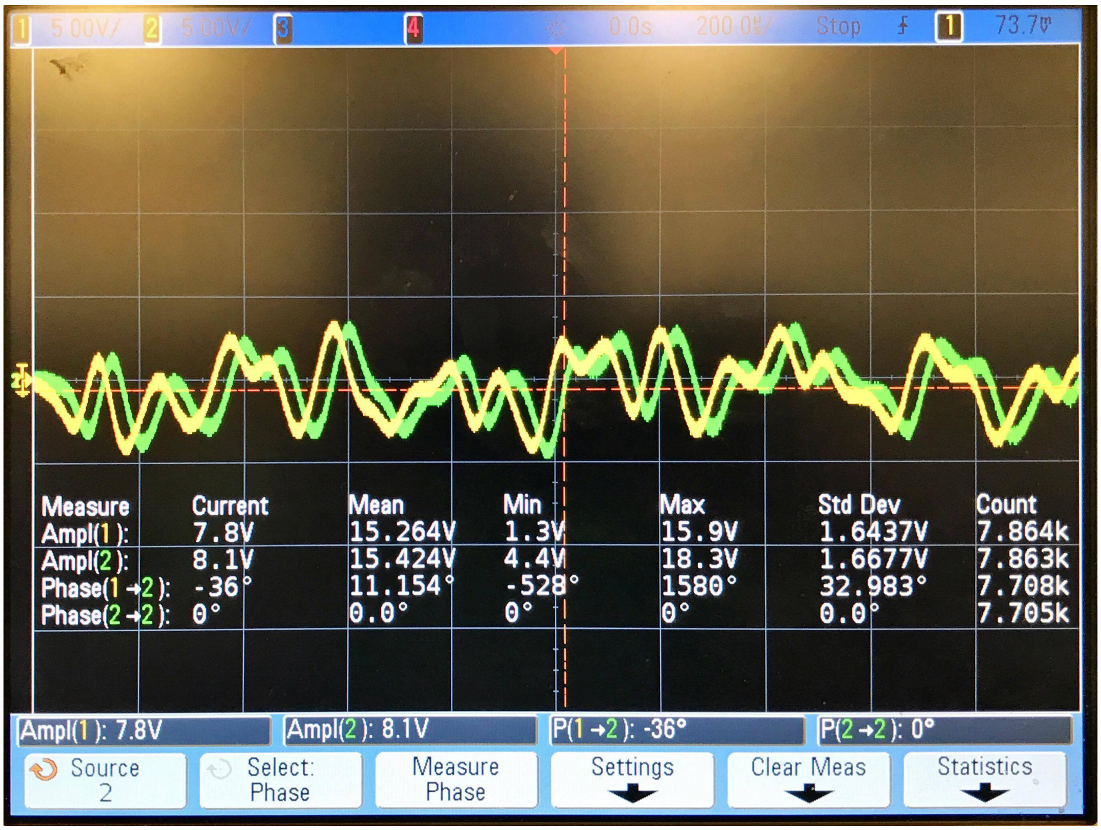

Figure 21: Measurements of the all pass circuit. The input signal can be seen in yellow while the output is in green. The phase shift measured is 11.154 degrees on average, as expected.

Figure 22: Measurements of the mixing circuit. The input signal can be seen in yellow while the output is in blue. The shifted signal is seen in pink. The output was measured as 0mV, which is to be expected.

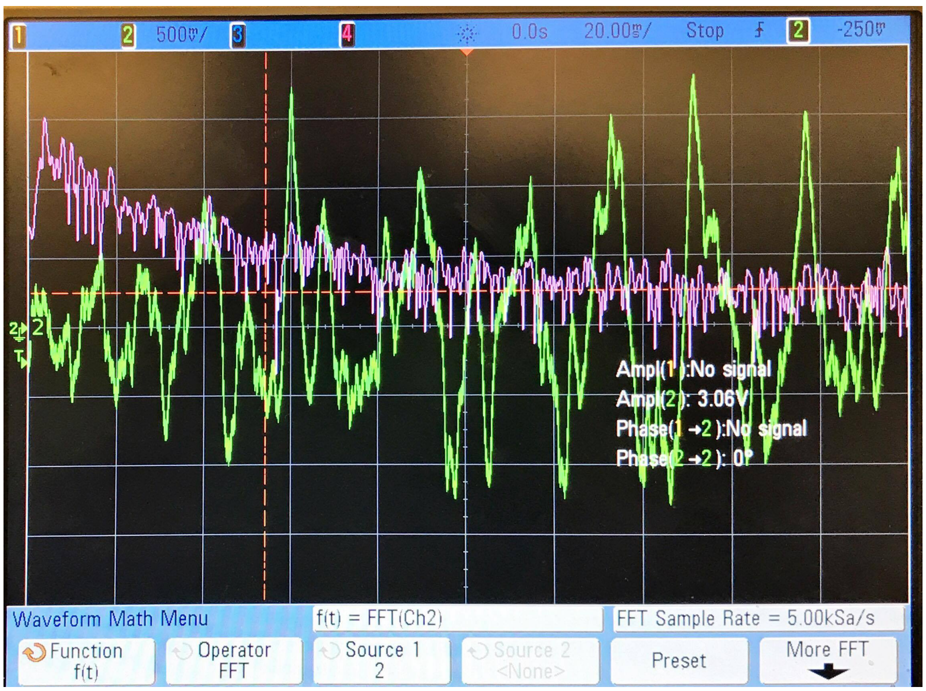

Figure 23: FFT Analysis on the unmodified input signal

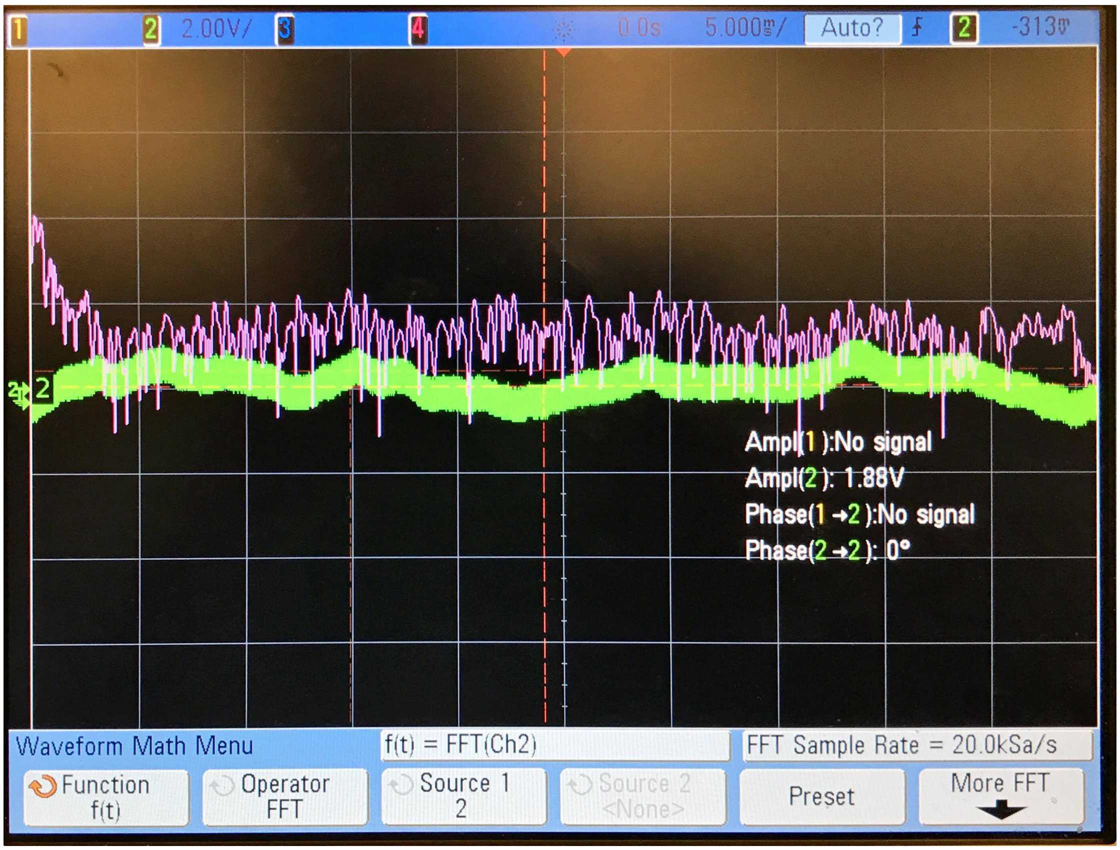

Figure 24: FFT Analysis on the noise cancelled signal. As can be seen in comparison with Figure 23, the lower end noise has been reduced, leading to some noise cancelling effect, however, the upper band of frequencies remains largely unaffected.