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Abstract

This document provides a guide for students who would like to implement our low-cost volume control project. This experiment can be implemented with the discussed control system, however students are welcome to build off of it and explore other control systems. In this document, we discuss the theory and implementation of this project as well as results and observations made in the process of working on it.

To make this a low-cost project, the speakers are built using primarily some wire, paper, magnets, and an audio cable. The control circuit is built using 4 audio amplifiers and various resistors and capacitors, as well as a potentiometer to control the volume level. The circuit includes an input amplifier, the controller, and finally an output amplifier. The output amplifier is required to easily hear the speaker output, however the input amplifier can be not included for the purpose of reducing the project cost slightly. The total implementation cost of 1 volume control project is around 10 dollars.
1 Introduction

In this section the project is introduced as well as the explanation of the theory governing the volume control feedback.

1.1 Purpose

Controls courses often focus on the use of digital control. In the learning process, digital control is extremely helpful to aid students in grasping how different control laws and theories can be applied. This is especially noticeable with computing softwares such as MATLAB, where one can create a plant model in MATLAB or even use the transfer function to analyze a plant and create a system. These softwares contain a plethora of functions and tuning capabilities that help simplify and quicken the process of controller design. Sometimes in this process the physical implementation of the controller can become lost. After all, many simple control systems can be simply constructed using resistors and capacitors. Therefore, this project can hopefully be used as an introduction to implementing controls in hardware.

1.2 Background

Sound is extremely complex. Each person sounds different, there are different tones, volumes, pitches, etc. In this project the focus is on volume. Volume control is practically everywhere in modern life. Your phone, computer, TV, stereo, and speakers all have volume controllers. Today, most of these are digital controllers however much can be learned by creating a simple analog volume control. In the 1980s Peter Baxandall, a pioneer of analog electronics for audio usage, published his paper in *Wireless World*, discussing what is now known as the Baxandall Active Volume Control circuit. His controller uses feedback gain control.

This project is centered on Baxandall's Volume Controller and exploring its use and behavior. The theory behind this controller is discussed in the Theory section of this report.

In addition to the Baxandall gain controller, there is an input amplifier before the Baxandall Controller. Following the controller is an output amplifier directly before the speaker output. The amplifier stages help amplify the audio signal to be audible from the low cost speaker. Figure 1 shows the input amplifier and Baxandall gain control circuit.
The input amplifier consists of an inverting amplifier with gain equal to $\frac{R_1}{R_7}$. This gain can be changed to see its effect on the output signal.

1.3 Theory of Baxandall Active Volume Control

The Baxandall Volume Controller uses basic shunt feedback. Audio signal represent sound as an electrical voltage. The output of the controller continues to be an audio signal. This voltage in and voltage output behavior characterizes a series-shunt feedback system. The negative feedback is driven by the inverting amplifier in Figure 2 below. This schematic depicts the Baxandall Volume controller.

The gain characteristics of the controller are a function of the percentage of the potentiometer rotation, where the maximum gain is set by this ratio of two resistors. For analysis purposes this potentiometer can be modeled as two resistors: $R_{(1-x)}$ and $R_x$. $R_{(1-x)}$ helps model the percentage of resistance before the wiper, while $R_x$ models this percentage after the wiper. The first amplifier of this circuit is constructed as
a non-inverting amplifier such that the Vin of the amplifier comes from the output of the potentiometer. This amplifier is also a voltage follower and thus the output of the amplifier is that of the input Vx. This Vx is then sent through to the inverting amplifier with a gain of G.

\[
G = \frac{-R_5}{R_4}
\]

Using Kirchhoff’s current law and nodal analysis, the transfer function of this controller can be written as follows.

\[
\frac{V_{out}}{V_{in}} = -\frac{R_x}{R_1-x + \frac{R_4}{R_5}}
\]

The final result is that the volume of the audio signal is controlled via the potentiometer.
2 Implementation

This section discusses in details the required materials for this project, as well as instructions for building the circuit.

2.1 Required Parts and Equipment

To build the speaker, the following parts are required. Assuming one already has the wire and other material which can be found in most households, such as the paper and straws, this speaker can be built for a total of $0.71. For the purpose of this project, Professor Betty Lise Anderson was nice to provide the materials for two speakers. Speaker instructions to build the speaker can be found at Professor Anderson’s Outreach website [1].

Table 1: Speaker Parts List

<table>
<thead>
<tr>
<th>#</th>
<th>Unit</th>
<th>Description</th>
<th>Vendor</th>
<th>PN</th>
<th>Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sheet</td>
<td>Paper (or print out template)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piece</td>
<td>Cardboard, 6’ square</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Each</td>
<td>1/4 in x 1/10 in Thick Disc, Grade N42, Rare Earth Neodymium Magnets</td>
<td>Applied Magnets</td>
<td>ND011-1</td>
<td>$0.10</td>
</tr>
<tr>
<td>3</td>
<td>Meters</td>
<td>30 AWG Magnet wire, enameled</td>
<td>Small parts</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3/4&quot; length</td>
<td>&quot;Jumbo&quot; drinking straw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2&quot; length</td>
<td>1/4&quot; diameter dowel or something of similar diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5**</td>
<td>Each</td>
<td>Audio Cable</td>
<td>Mycablemart.com</td>
<td>FS-3MM-03MM</td>
<td>$1.23 (divided by 2)</td>
</tr>
</tbody>
</table>

* example: MW-30-01, 1lb spool (~1000 Meters), $20

** Each cable as purchased can be cut in half, creating two usable cables
The following table lists the parts required to build the Control and Amplifier circuits. This system can be built without the amplifiers, however because the low-cost speakers are not of high quality material, it will be extremely difficult to hear the output of the speaker without them.

Table 2: Controller and Amplifier Parts List

<table>
<thead>
<tr>
<th>#</th>
<th>Unit</th>
<th>Description</th>
<th>Vendor</th>
<th>PN</th>
<th>Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>each</td>
<td>LM386 Audio Amplifier</td>
<td>Digikey</td>
<td>LM386N-1/NOPB</td>
<td>$0.98</td>
</tr>
<tr>
<td>3</td>
<td>each</td>
<td>1K Ohm Resistor</td>
<td>Digikey</td>
<td>CF12JT1K00CT-ND</td>
<td>$0.14</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>22k Ohm Resistor</td>
<td>Digikey</td>
<td>CF12JT22K0CT-ND</td>
<td>$0.14</td>
</tr>
<tr>
<td>2</td>
<td>each</td>
<td>100k Ohm Resistor</td>
<td>Digikey</td>
<td>CF12JT100KCT-ND</td>
<td>$0.14</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>0.1 uF Capacitor</td>
<td>Digikey</td>
<td>399-4331-ND</td>
<td>$0.31</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>10000 pF Capacitor</td>
<td>Digikey</td>
<td>BC1078CT-ND</td>
<td>$0.31</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>220 uF Capacitor</td>
<td>Mouser</td>
<td>667-EEU-FM1E221</td>
<td>$0.46</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>0.022 uF Capacitor</td>
<td>Digikey</td>
<td>399-4169-ND</td>
<td>$0.35</td>
</tr>
<tr>
<td>2</td>
<td>each</td>
<td>100 pF Capacitor</td>
<td>Digikey</td>
<td>BC2657CT-ND</td>
<td>$0.30</td>
</tr>
<tr>
<td>1</td>
<td>each</td>
<td>22 uF Capacitor</td>
<td>Digikey</td>
<td>1189-1892-ND</td>
<td>$0.63</td>
</tr>
<tr>
<td>4</td>
<td>1/10 pkg</td>
<td>Alligator-Alligator Clip Leads</td>
<td>Digikey</td>
<td>501789 (package of 10)</td>
<td>$4.00</td>
</tr>
<tr>
<td>1</td>
<td>Each</td>
<td>25K Ohm Audio Potentiometer</td>
<td>Digikey</td>
<td>313-1500F-25K</td>
<td>$1.50</td>
</tr>
<tr>
<td></td>
<td>Breadboard, Wire</td>
<td>** many of these can be found in any campus lab room</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The total cost associated with the controller and amplifier circuit $10.52, making the total cost for this project to be $11.23. This cost however can be greatly lowered for the components being purchased in bulk as opposed to being in single quantities.

Not included in this list is the power source. The circuit runs well at 9V. One can either choose to use a DC power supply or 9V battery. This ability for the circuit to be battery operated help make it a very versatile project.
In addition to the above supplies, the following lab equipment was used for testing.
- DC Power Supply
- Multimeter
- Oscilloscope
- Signal Generator
- dSPACE Software
- DS1104 Interface card
- Analog Input cables
- Wire stripper, wire cutters, soldering tools

2.2 Procedure

Begin by following the steps to assemble the circuit shown in Figure 3. A larger image can also be found in Appendix A1.

![Circuit Schematic Image]

Figure 3: Implementation Circuit Schematic

Circuit:
1. Add LM386 to breadboard. A vertical arrangement is nice.
2. Connect all of the pin 4 connections of the LM386s to the bottom voltage rail (ground) bus on the breadboard. Also connect pin 3 (amplifiers 1 and 3) and pin
2 (amplifier 4) to the ground bus. Appendix A2 contains the pinout diagram for the LM386

3. Connect all of the pin 6 connections to the top voltage rail on the breadboard

4. Add C9 and R14 in parallel between pin 3 and pin 5 on amplifier 1. Also connect R15 in series to pin 2 on amplifier 1.

5. Connect a wire from pin 2 to pin 5 on amplifier 2. In series from pin 5, add R4, which is then connected to pin 2 on amplifier 3.

6. Connect C6 and R5 from pin 2 on amplifier 3 to pin 5 on the same amplifier.

7. Solder wires to the three potentiometer terminals. Connect the ground terminal of the potentiometer to pin 5 on amplifier 1. Connect the output to C7 and R12 in series, connecting pin 3 on amplifier 2 between C7 and R12. Connect the other end of R12 to ground. The positive terminal on the potentiometer is connected to pin 5 on amplifier 3.

8. From pin 5, connect R11 and R9 in parallel, with the other side of the resistors connected to ground. C1 is added in series with R9 to pin 3 on amplifier 4.

9. Connect pin 1 on amplifier 4 to pin 8 using C2. Add C3 from Vcc on amplifier 4 to ground.

10. Add C4 in series from amplifier 4 pin 5.

**Speaker:**
The speaker can be assembled by following the instructions provided by Professor Anderson’s Outreach Website [1]. There is no need to complete the last step of tightly twisting the metal ends of the cable wires to the burned ends of the speaker wires. This can still be done to gain insight into how the speaker sounds without any control and amplification. The instructions also contain troubleshooting tips if the speaker isn’t working. To hear the speaker before connecting to the control circuit, one’s ear will need to be close to the speaker diaphragm in order to hear the audio signal.

**Audio Input to Circuit:**
Use alligator clips to connect input wires of circuit to audio cable. Connect either the red or white wire on the audio cable to pin 2 of amplifier 1. Connect the remaining wire to ground.

**Circuit to Speaker:**
Use alligator clips to connect the output of amplifier 4 to the speaker. Connect 1 speaker to the unconnected side of C4. Connect the 2nd speaker wire to ground.

**Testing:**
Power bottom and top rail buses of breadboard to a 9V battery or 9V DC Power Supply. Connect audio cable to audio output (MP3, Computer, etc) and play. Adjust potentiometer to hear volume change.
One can connect the input and outputs of the circuit to an oscilloscope to see the
circuit’s effect. The effect of the Baxandall Active Volume Control Circuit can also be
observed. This circuit can also be connected to a DSPACE board for additional
graphing analysis.

Different signals other than audio can be observed using an oscilloscope and signal
generator. One can observe how the oscilloscope output changes for signals of different
shapes, frequencies, and peak-peak voltages on the signal generator.
3 Discussion and Results

Included in this section are results obtained through various tests and simulations.

3.1 The Circuit’s Inputs and Outputs

In the process of understanding the relationship between frequency and amplitude of the provided audio input for the circuit, an audio signal and its characteristics were first analyzed on a digital oscilloscope by providing an input from a signal generator and observing the output on oscilloscope. This was accomplished by supplying the circuit with many frequencies at values of frequency ranges of 100 Hz, 10 kHz, 50 kHz, and 100 kHz.

Figure 4: System Output to 100 Hz Frequency

Figure 5: System Output to 10 kHz Frequency
The system input is an audio file that is represented as a sine wave mathematically. The oscilloscope graphs above show the shape of the signal at a 100 Hz that can be approximated to be a sine wave. The signal looks a bit distorted due to noise generated from op amps and other components in the circuit. As the frequency increases, the signal becomes saturated and reaches its limit for it to be audible. Saturation and clipped signals at the edges were noticed for frequencies of 10, 50, and 100 KHz. Knowing that the audible range of frequencies for human to be between about 20 Hz-20 kHz, the saturated frequencies higher than this range are not heard, and the circuit provided shows that in the graphs above. Although 10 kHz is a frequency that fits in the audible frequency ranges, the graph above show it being saturated on the edges and that can be explained by the noise introduced to the system via the length of the wires used to wire the circuit on the breadboard and other noise produced from the circuit.

Testing was performed on the circuit output to note observations when the amplitude or frequency of an input voltage is changed. Results showed that adjusting frequencies does not impact the output signal, while adjusting the amplitude produces amplified and scaled output signal. It was then concluded that the circuit behaves as a proportional controller to achieve the purpose of volume control and signal amplification.
3.2 Experimenting with dSPACE

After constructing and wiring the circuit on the breadboard as explain previously, data analysis were performed and collected using dSPACE. The input voltages from the circuit were sent from our music onto the board then taken to dSPACE to collect and plot as the voltage input. The output voltage of the controller, which is also the output of the system, was sent to dSPACE to plot and compare against the input voltage of the circuit. Figures below show the input and output signal plotted on the same graphs while changing the resistance of the potentiometer to control the volume of the signal.

- Observations:

Signal is sent from the computer is converted to various voltage readings and values that are then inputted to the circuit. The output of the system is also read on dSPACE and the Figure 8 below show how the two signals compare. The circuit’s purpose is to control the volume of an analog input when the resistance of the potentiometer changes in the means of strengthening the signal. Strengthening an audio signal translates into increasing its amplitude which is done by scaling it by a gain factor. This agrees with the results seen previously when connecting the circuit to the oscilloscope to observe how the amplitude and frequency change at all. Thus, it is similar to having a proportional controller designed to scale the amplitude and control the volume that way.

It was attempted to design a PID controller in Simulink where it sends its output voltage to the speaker and it receives its input from the audio jack. Knowing that the circuit behaves as a proportional controller from previous experimentations in Section 3.1, expectations were to hear the sound at a high volume when increasing the K proportional parameter. However, noise was mostly delivered from the speaker and this can be due to a wire connection being loose, or the use of long wires impacting audio data and causing it to become lost.
Figure 8: Input and Output Audio Signal while being adjusted

Figure 8 above shows variations of the amplitude while controlling the sound of the signal via change of resistance of the potentiometer. As the knob on the pot was turned full turn clockwise, the volume of the sound sounds the highest while the opposite is true.

Figure 9: Half Clockwise Rotation of Potentiometer
Figure 10: Full Clockwise Rotation of Potentiometer

Looking at Figures 9 and 10, one can easily see how moving the potentiometer clockwise causes the output of the signal to have a greater amplitude. Likewise, the half clockwise turn has a lower magnitude. This is an example of how changing the potentiometer affect the output of the circuit.

3.3 Designing a PID Controller in Simulink MATLAB

The system was initially simulated using Simulink Library in MATLAB before obtaining all the parts for constructing the circuit as our system. The Simulink model feeds the system with a sinusoid as an analog signal generated from a signal generator or inputted from a song that is read into a list of data in MATLAB. These data can then be analyzed and plotted for analysis. The actual system that was initially designed takes an input signal that is represented as voltage readings. Its absolute value is multiplied by the output of the designed controller, passes through a buffer, then a maximum function to obtain the highest value of the signal to subtract it from a reference input and then fed back again to the system input. The feedback loop occurs when the maximum amplitude is being controlled by the design PID controller in Simulink and subtracted from a reference input that is a constant value. The buffer block is used to slow down the frame rate of the input signal in order for the Maximum function block in Simulink to perform computation on it to produce the highest amplitude value. Unbuffer block is also used for similar reasoning. Below is a Figure of the overall system modeled in Simulink.
The input to the model consists of 2 sinusoidal signals modulated together through multiplication. The two sine signals have frequencies of 600 and 1000 Hz and are shown below:

The choice of the controller was chosen to be a PID controller since it has been used in previous labs and there was a strong interest in seeing how the system would work and behave when implemented. A Discrete PID Controller block was used from Simulink library and was used in discrete time since the data needs to be sampled at a slow rate to be able to detect the highest amplitude of the incoming signal and be able to control it using PID controller. The controller takes the amplitude value calculated by the
maximum function and compared it to the desired reference constant value of choice 10. The figure below shows the output of the controller when running the system.

![Controller output w/ a sinusoidal input signal and ref. input of 10](image)

**Figure 14: Controller output w/ a sinusoidal input signal and ref. input of 10**

From the circuit schematic, the output of the Controller is the same as the output of the entire system both shown in above figure.

It was expected that the output of the controller would eventually by time level off and reach the desired reference constant value as seen previously in the Temperature Control Lab performed. This indicate that the system can be modelled and represented as a first order linear system with transfer function of the format: \( \frac{K}{Ts + 1} \)

The PID parameters were tuned within the block used and the parameters were set to be: Proportional P=1, Integral I = 2, and Derivative D = 0. The use of Integral controller in this designed PID controller is to minimize the error being accumulated between the constant reference input and the inputted sine signal. The error starts out being large initially, but it is lowered after some discretization as shown in Figure above.
3.4 System Disturbances

Throughout testing and building of the volume control circuit the largest issue experienced was due to noise being interjected into the system.

The frequency range of audible sound is from 0 Hz up to 20 kHz. Furthermore most audio files are sampled at 44.1 kHz. In testing, output from a laptop served as the audio input for the controller.

Adding to the noise levels are the components. For the purpose of creating a low-cost project, the components we used are not of high audio quality. The amplifier is a low voltage audio amplifier, however the passive components are not specifically chosen for use with audio signals. The resistors and capacitors are standard and not meant for ultra-low audio distortion. The potentiometer is an additional possibility for the influx of noise to the system. By using a breadboard, noise within the various connections allows noise to appear. All of these combine to cause a noisy situation and at times the circuit was difficult to tune in order to get it working. One way to improve this would be to solder all of the components to a perfboard.
4 Conclusion

In conclusion, this lab combines the use of small and fairly cheap components such as amplifiers, resistors, and capacitors to construct a simple circuit that controls the volume of an audio signal via variations of resistance on the potentiometer. Throughout construction a number of issues were experienced, but mainly all pertained to the hardware used and the noise experienced within the circuit.

All in all, much can was learned during this project and much can be learned from this project. We hope that this can be a starting point for a future student projects and that it will be a useful learning tool for them. This project can and should be continued. There are a ton of resources and different circuits that can be implemented for the use with audio signals. Echo, noise cancellation filters, other types of input sources can be used; the opportunities are endless!
References


Appendix

A1 Circuit

Here is a larger image of the circuit diagram shown in Figure 3.
A2  LM386 Amplifier
Figure A1 shows the pinout diagram for the LM386 chip used in this project, for added reference.

Figure A2: LM386 Pin Diagram
A3  Physical Implementation
The following images depict a physical implementation of the volume control project.

Figure A3.1: Circuit (view 1)
Figure A3.2: Circuit (view 2)

Figure A3.3: Overall Implementation (circuit and speakers)