

Headphone Amplifier & Equalizer

Design Report

SDMay05-01

Team Members

Jennifer Bruner, EE
Mike Dierickx, EE
Rachel Hager, EE
Kurtis Kenne, EE

Client

Senior Design

Faculty Advisors

John Lamont
Ralph Patterson III

DISCLAIMER: This document was developed as a part of the requirements of an electrical and computer engineering course at Iowa State University, Ames, Iowa. This document does not constitute a professional engineering design or a professional land surveying document. Although the information is intended to be accurate, the associated students, faculty, and Iowa State University make no claims, promises, or guarantees about the accuracy, completeness, quality, or adequacy of the information. The user of this document shall ensure that any such use does not violate any laws with regard to professional licensing and certification requirements. This use includes any work resulting from this student-prepared document that is required to be under the responsible charge of a licensed engineer or surveyor. This document is copyrighted by the students who produced this document and the associated faculty advisors. No part may be reproduced without the written permission of the senior design course coordinator.

Date Submitted

December 6, 2004

Table of Contents

List of Figures	ii
List of Tables	iii
List of Definitions	iv
Executive Summary	1
Acknowledgements.....	3
Problem Statement	3
Operating Environment	3
Intended User(s) and Use(s)	4
Assumptions and Limitations	4
Expected End Product and Other Deliverables	5
Approach Used	6
Detailed Design.....	11
Resource Requirements	22
Project Schedule.....	26
Project Team Information	28
Conclusion	29
Appendices.....	30
Appendix A – Project Poster.....	30
Appendix B – Axial-Lead Parts List.....	31
Appendix C – Surface Mount Parts List.....	32
References	33

List of Figures

Figure 1: A Device Similar to that Envisioned for the Project ¹	5
Figure 2: Metal Casing ²	10
Figure 3: Plastic Casing ³	10
Figure 4: Front and Back Device Ends	10
Figure 5: Chu Moy Acoustic Simulator Design ⁴	12
Figure 6: PSpice Layout of Moy's Acoustic Simulator	12
Figure 7: Amplifier Design ⁵	14
Figure 8: Natural Cross-Fed Delay Filter Headphone Amplifier (One Channel) ⁶ ...	15
Figure 9: Headphone Amplifier Circuit ⁷	15
Figure 10: Eaton's Headphone Amplifier ⁸	16
Figure 11: Three-Band Baxandall Equalizer ⁹	17
Figure 12: PSpice Design of Equalizer	18
Figure 13: Three-Band Resonant Equalizer ¹⁰	19
Figure 14: Resonant Filter EQ Stage ¹¹	19
Figure 15: General Design Flowchart	20
Figure 16: Final Device PSpice Schematic	21
Figure 17: Original Gantt Chart of Project Tasks	26
Figure 18: Updated Gantt Chart of Project Tasks	27

List of Tables

Table 1: Original Personnel Effort Estimate in Hours per Task.....	22
Table 2: Updated Personnel Effort Estimate in Hours per Task.....	22
Table 3: Original Estimate of Other Resource Requirements	23
Table 4: Updated Estimate of Other Resource Requirements	23
Table 5: Original Estimated Parts and Material Costs.....	24
Table 6: Updated Estimated Parts and Material Costs.....	25
Table 7: Dates Associated with the Original Gantt Chart.....	26
Table 8: Dates Associated with the Updated Gantt Chart	27

List of Definitions

Class A Audio Amplifier: An amplifier built with only one transistor allowing maximum linearity, or consistency of amplification. Maximum theoretical efficiency is 25%, practical efficiency is 10%, and the amplification is virtually perfect.

Class B Audio Amplifier: An amplifier built with two bias transistors allowing much higher efficiency, about 75%, than Class A. Most circuits built with operational amplifiers fall into this category, since they possess two transistors to bias the output. The distortion is arguably inaudible, but noticeable on an oscilloscope,

Class D Audio Amplifier: This is a completely switched-mode amplifier operating in the digital domain using four output transistors. Practical efficiencies can exceed 95%, but the distortion can be problematic at very high amplification levels. This type of amplifier is used in most small electronics, such as cellular phones and laptop computers.

Spectre, PSpice: These are two computer circuit simulation programs that can be used to test designs without building them.

Operational Amplifier: This is a somewhat basic circuit element built from semiconductors. It has many analog applications and is the cornerstone component of many circuits. There are many types with different characteristics such as response time, maximum power output, slew rate, and many others.

Cross-fed Delay Filter: The purpose of this device, which is to be included in this project, is to simulate a better surround sound experience than is achieved with standard stereo headphones. The basic idea is that, with headphones, right channel sounds are heard only in the right ear, and left channel only in the left. Contrary to perhaps one's first intuition, this does not create a realistic stereo experience, because normal sounds, or sounds from proper speakers, are not heard in such a way. Sounds are positioned by the human brain based on which ear hears them first and which ear hears them the loudest, so this type of filter will simulate both the time delay and attenuation to audio by the width of the human head, making headphones have the genuine surround effect of stereo speakers.

Executive Summary

This project entails designing and manufacturing a device to be connected to a personal audio device (such as a portable CD or MP3 player) that will perform three major functions. These functions are as follows:

- **Amplification:** The device will increase the volume of the audio beyond what is possible with just the standard audio device, and will also provide a “cleaner” amplification with less distortion than would be achieved by listening at the same volume with solely the audio device.
- **Equalization:** The device will allow the control of the relative of high-pitched, mid-pitched, and low-pitched sounds so that the audio may be fine-tuned to the listeners’ preference.
- **Soundstage Simulation:** This is the process of eliminating the lack of stereo soundstage that occurs when listening to headphones. The human ear positions audio (left, right, far, near) based on not simply hearing it in one ear or the other, but through considering which ear it hits first and how much quieter and later the audio is perceived in the other ear. By considering these differences, audio is positioned to be coming from a certain source by the brain. Speakers offer the recreation of this soundstage from a recording, but headphones eliminate it by limiting the audio to one ear or the other. This device will simulate the effect of listening on proper speakers.

The product will possibly run on a battery source of six - 1.2 volt (AA) NiMH rechargeable batteries, and these batteries will charge internally through the use of a 12 volt DC power input, delivered by a wall wart or other 12 volt DC source. At this point in the project there are some questions about whether or not the power supply, which is being supplied by another design team, will be of an acceptable size for the project. The design also may not require all the power available in these batteries, but will run instead from a single 9 volt rechargeable battery.

In particular, the design took place keeping in mind a few cornerstone requirements of the project. First, the item must be portable, meaning it should be small and “pocket-sized,” with a small enough weight to be carried conveniently. Also, the cost per unit should not exceed about \$50.00, and this was considered as designs were chosen.

The power supply represents the last remaining design decision for the project. Currently, computer simulation testing is coming to a close and a breadboard implementation will be tested in a lab setting. Upon completion of the lab testing, power requirements will be known and the power supply decision can be made. The goal is for the unit to run on one charge for about a day’s usage, which should not be less than four hours, or greater than about ten hours.

The design process has been more technically a selection process up to this point. Each of the three functions, defined above, has been designed separately based very closely on designs that have been provided by various authors through the internet. Upon the selection of each individual element, it was tested in a computer simulation to see if it operated within specifications. At this point, computer simulation is complete and breadboard testing has begun.

Upon successful results from the breadboard design and a decision on power supply technology, a method of breadboard implementation and a manufacturer will be considered and chosen. After the boards have been manufactured, the units will be soldered and placed into the later-selected casing type, and ready for usage.

At this point in the project, tasks seem on-schedule and no problem has been so large as to drastically to change the project's direction or schedule.

Acknowledgements

For help with the completion of this report, the team would like to acknowledge the help of Professors Lamont and Patterson. Along with performing their tasks as advisors and helping to bring enough understanding to the team to make this report possible, they also provided extensive feedback regarding the product design.

Problem Statement

It has been found that some portable audio systems have insufficient power output to drive a set of high-fidelity headphones. To correct this, an amplifier circuit needs to be designed and developed. In addition to improving the audibility of this device using an amplifier, an equalizer needs to be developed in order for the user to have the ability to adjust the different frequencies of the music output. Finally, to eliminate the excessive stereo localization that occurs with headphones, a cross-fed delay filter will be added to the device. This combined implementation will also need to be as small as possible and come designed in an attractive case so that the users have the ability to carry it with them.

With the power supply being developed by another team, this project lies with designing and developing the combined amplifier, equalizer, and cross-fed delay circuit. The amplifier circuit will be developed so that the user has the ability to use either a 3.5 mm or a 6.5 mm headphone jack without the need for an adapter. In order for the user to have the ability to adjust the different frequencies of the music, a three-band equalizer will be developed. This equalizer will allow the user to adjust the low, middle, and high frequencies of the transmitted signal. This will give the user a great advantage of fine-tuning the output to suit their musical taste. Lastly, the cross-fed delay filter will provide a more realistic surround experience than is possible from normal devices. In addition to this filter, a control for balance will also be added to the portable system. The combined circuit will have the ability to operate on a 12 volt DC or a 120 volt AC power supply, as well as have an internal power supply of six - 1.2 volt (AA) NiMH rechargeable batteries.

Operating Environment

The operating environment for the headphone amplifier and equalizer device will encompass all portable uses. This device will be used in an outdoor environment, therefore it has the possibility of being exposed to extreme temperatures. As with any portable device, the headphone amplifier and equalizer will also need to be durable so that it can withstand the possibility of getting dropped. This device is intended for music listeners who wish to enhance their listening pleasures. It is assumed that the user(s) will not submerge the device in water.

Intended User(s) and Use(s)

The intended user(s) of the headphone amplifier and equalizer device is the general public, more specifically, people who are enthusiasts of music. This device is being created so that the user has more control over the sound quality of the output signal.

The expected end use(s) of the headphone amplifier, equalizer, and cross-fed delay device are in conjunction with a portable audio system, such as a CD or MP3 player. This device is not expected to be used in conjunction with a high-power audio system for use at a concert hall, but rather for individual use for enhanced listening pleasure.

Assumptions and Limitations

Assumptions

Prior to initiating the project, the group had to state several assumptions in order to accomplish the required objectives. These assumptions were stated as follows:

- Only one user will be using the unit at any one time, and processing only one stereo audio signal.
- The end-product will be used to drive a pair of headphones in the range of 32 ohms to the high-end of 600 ohms of impedance.
- The system will, at an absolute maximum, drive approximately 1.5 W through the 32 ohms per channel headphones to create 120 dB of sound pressure as a maximum possible (but perhaps not comfortable) level.
- The end-user of this product will be someone who is familiar with audio systems.
- The system will be controlled by the power switch, which will be turned on/off by the user.
- Three-band equalization with 15 dB attenuation maximum will be all the needed equalization.
- Equalization will be in stereo, but each channel will not need to be separately controllable.
- The end-product will use balance and gauged volume controls as opposed to independent volume controls.
- The price of the final product should not exceed \$75.00, with a goal of \$50.00.
- The product will need to run on the provided power supply for about 8 hours between recharging under normal amplification conditions.

Limitations

In addition to the aforementioned assumptions, a number of limitations have also been imposed. These limitations include the following:

- The team will operate within a finite budget.
- The system must possess the ability to operate at 120 volt AC (with DC “wall wart”), 12 volt DC, and on an internal power supply of six - 1.2 volt (AA) NiMH rechargeable batteries.
- The system must be able to connect to a portable audio system and headphones.
- The system will at a minimum include a 3.5 mm input jack, two headphone jacks (one 3.5 mm and one 6.5 mm), a volume control, a balance control, a power switch, three-band equalizer controls, and a pilot light, all of which will be labeled.
- Since the system will be portable, its dimensions should be no larger than 5” x 5” x 2.5” and weigh no more than two pounds.
- The system should be able to withstand extreme temperatures, and be durable enough to withstand being dropped.

Expected End Product and Other Deliverables

The main objective of this project is to design and develop a quality combined headphone amplifier, equalizer, and cross-fed delay filter circuit that is compatible with most portable audio systems (as shown in Figure 1 below).



Figure 1. A Device Similar to that Envisioned for the Project¹

The second objective of this project is to take the optimized breadboard circuit and convert it into an actual printed circuit board, cased implementation. The expected end product is a complete, finalized system including internal power supply and case. The system will include an internal power supply of six - 1.2 volt (AA) NiMH rechargeable batteries, the jacks for external power supplies (120 volt AC / 12 volt DC) and a user's manual.

The desired outcome of the project will be the ability to amplify and equalize the transmitted output signal from an audio device. Such endeavors will allow future users of the system to enhance their listening pleasures. The end product will be completed in its entirety by the close of May 2005.

One of the requirements set forth by senior design was to create a poster describing in detail the problem statement and the proposed solution to the chosen project. This project poster was created using Microsoft PowerPoint with slide dimensions of 32" by 40". After the slide was designed and edited, it was printed on campus and mounted on to a foam board so that it could be displayed in Coover Hall. A copy of the project poster can be found in Appendix A on page 25.

Approach Used

This section describes in detail, the design objectives, functional requirements, and design constraints involved with the headphone amplifier and equalizer device. Included in this section are also the different considerations taken with regards to technical approach and testing, as well as recommendations regarding the project path.

Design Objectives

At the most basic level, the objective of the design was to make sure all three major functions would work properly. In particular, however, the goal was to make a device that can be manufactured cheaply, below the desired the \$50.00 price point, but with as little sacrifice in quality as possible while remaining in the price range.

In particular, the equalizer needed to be at least three bands. The power output needed to be commensurate with driving at least 600 ohm impedance headphones, and the soundstage simulator needed to be completely functional.

Lastly, the circuit needed to be reasonably-sized so that it could be implemented in a pocket-sized breadboard implementation. This requirement limited the part count to about 200 surface mount pieces.

Functionality Requirements

This project will have certain necessary functions that must be met in order for the project to be considered a success. These requirements are outlined below.

1. Power Amplification

The unit must amplify the power being output by a personal audio device to allow larger impedance headphones to be driven with more power and with more clarity. The unit must provide a “cleaner” amplification than most standard personal audio devices so that higher volumes may be enjoyed without distortion. The unit must also be able to drive stereo headphones with impedances of 32 ohms up to 600 or more ohms. In particular, the unit should drive headphone loads as low as 32 ohms per channel with a maximum of 1.5 W of total power, which will provide about 120 dB of sound pressure as an absolute, upper-bound maximum. Also, a balance control between the two channels will be implemented.

2. Equalization

The unit must allow for at least three-band equalization of the audio signal, with logarithmically spaced and slightly overlapping bands of equalization. Equalization will occur without digital conversion of the audio and allow at least a ± 15 dB change in amplitude. The equalization will be in stereo, but it will not be variable between the left and right channels.

3. Input and Output

The input to the device should be ultra-high impedance and should accept a stereo audio signal with up to an approximately 8 volt signal swing. This is the limit of the power supply and should accept the signal from any portable device without clipping. This input will be fed in from a standard 3.5 mm inch headphone jack. The output will support headphones with both 6.5 mm and 3.5 mm plugs without the need for an adapter.

4. Cross-fed Delay

The unit should simulate a surround environment with a cross-fed delay filter that prevents the sound from being completely localized in each ear. In reality, the human ear positions sound not by just hearing it one ear, as standard headphones allow, but by hearing it in both ears, with some delay and attenuation in the signal that reaches the opposite ear. The purpose of this part of the circuit will simulate the acoustics of actual positional hearing.

5. Casing

The unit should be approximately “pocket-sized”. Its dimensions shall not exceed 5” x 5” x 2.5”. The unit should be relatively lightweight (weigh under two pounds) and have easy access to controls. On the unit, there will be volume adjustment and balance control, the three-band equalizer control, a power switch and a power LED.

Design Constraints

There are also certain things which this product must not do in order to meet the requirements. These constraint considerations are outlined below.

1. Battery Lifetime

The unit will be powered by a DC source of six - 1.2 volt (AA) NiMH rechargeable batteries that will be supplied to the project. This source will also accept line power. Although the exact specifications of this power supply are yet unknown, the unit must be able to run, at mid-level amplification driving 32 ohm headphones, at least eight hours without requiring a battery recharge. It is believed that this represents an amount of time between recharges that should fit most users' needs. It may be possible to extend the listening time far beyond this, depending on the condition of the power supply. Assuming the supply uses six standard AA NiMH cells, the device will be able to draw up to about 1100 mA of current to run for this amount of time.

2. Cost

The cost of the unit, if sold commercially, will not exceed \$75.00. Effort will be made to keep the cost below \$50.00 if this can be done with compromising other design requirements. Much care will be used in selecting parts that work well enough at a relatively small cost.

Technical Approach Considerations and Results

There will be two distinct phases of this project. The first phase will involve designing the circuit. Any design, of course, must be tested and then re-tested. There are many ways to test the validity of a circuit design, the most obvious of which is a computer circuit simulator program such as Spectre or PSpice. Initially, the design will likely be done on paper using theory to develop transfer equations for both parts of the circuit. The circuit design can also be tested on the lab in a solderless breadboard implementation. In most cases, a computer simulation is used instead of this method, but both methods are likely to be used. This is because the operation with physical components will need to be seen, especially the operational amplifiers, whose exact characteristics may not be modeled by a computer program. Because of this circuit's heavy dependence on operational amplifiers and the wide variety of op amp specs available, the lab test seems extremely necessary. Extensive research will be conducted on operational amplifier characteristics to choose the best product for this application. It should also be noted that there are programs available that will design a frequency filter circuit with resistors and capacitors and inductors if the user specifies a desired transfer function. This could greatly help with the equalizer design. There are also a number of ways to implement the delay filter, some of which only involve passive components and

others involving operational amplifiers. More in-depth research will be done before a decision is made on the design for the delay filter.

The second phase of this project will consist of the final implementation of the design into a complete, finished unit. There are a wide variety of PCB techniques and technologies that can be selected from, including complicated multi-layered boards as well as simple boards that can be made locally in a few hours. The benefits of each possible PCB choice will be weighed before making the final decision. Also, of course, there are many types of casings, varying in terms of their material, their size, and durability. Research will be conducted to determine which casing best suits the particular needs.

The operational amplifier chosen was the OPA134 by Burr-Brown, in the singly packaged model to eliminate crosstalk. The individual circuits were chosen which is discussed thoroughly in the following section.

During the course of this semester the design for the headphone amplifier and equalizer device has been simulated using PSpice. Once breadboard testing is successfully completed this semester, the next step in the process is to fabricate the design onto a printed circuit board (PCB). Using Cadence's Layout Plus, the PCB will be designed.

During the design process it was decided that seven devices should be created in entirety. This however raises the question of cost with regards to parts and PCBs. Past senior design teams have used Advanced Circuits (www.4pcb.com) which has a \$33.00 special for each board. With the necessity to fabricate seven devices in total, this sky rockets the cost for boards alone to \$231.00.

With further research, two companies have been found that manufacture PCBs at a low cost. The first company, PCBFabExpress, charges \$13.00 per PCB with a minimum purchase of five boards. This company also has a five day turn-around. The company's website can be found at www.pcbfabexpress.com. The second company, PCB Express Inc., has a cost of \$15.00 per PCB with no minimum purchase required. The company's website can be found at www.pcbontime.com.

Once breadboard testing is completed, a clearer understanding of the PCB specifics will be known. This will help with the selection of the better company for board fabrication.

After the PCB is completed and all components are soldered, it will be necessary to mount the board into an enclosure or a casing. There are several manufacturers that make casings similar to what is needed. Most of the manufacturers market their casings through retailers such as DigiKey (www.DigiKey.com) and Mouser (www.Mouser.com). Casings are available made of both plastic and metal, can be watertight, and are available in a number of styles. The metal casings are more expensive. However, metal casings would offer shielding from electromagnetic waves which may affect the performance of the circuits. While on the other hand, plastic casings are cheaper and would help to protect the device in the event it was dropped.

Prices range from \$2.00 - \$15.00 depending on the type of material and the size of the casing. Some plastic casings are also available with compartments for batteries. Most casings feature removable front and sometimes rear panels to mount controls. After the size of the PCB and power supply is known, an appropriate sized casing will be selected and ordered. The figures below offer an example of the casing dimensions.

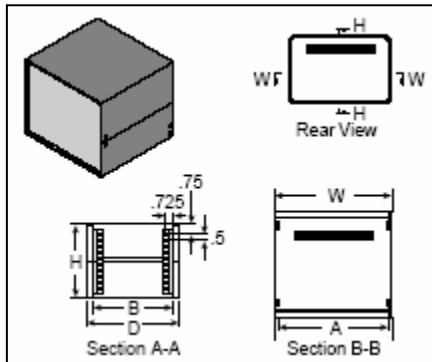


Figure 2. Metal Casing²

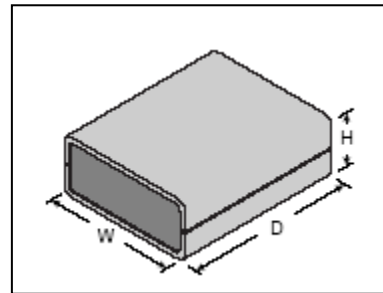


Figure 3. Plastic Casing³

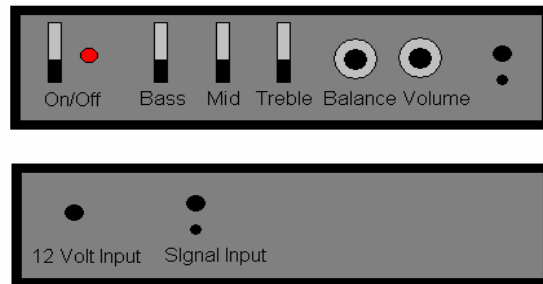


Figure 4. Front and Back Device Ends

Other considerations with regards to casing include the front and back case ends functionality. Figure 4 above shows an estimate of what the front and back ends of the device should look like.

Testing Approach Considerations

The type of testing that will take place on the final packaged product should be similar to the breadboard testing. The unit will be tested formally in the lab with a signal generator to check numerically the power amplification and equalization cut-offs. Also, the unit should be tested using a CD player or other portable audio devices to see its “real-world” performance. On this final device, the battery life under different conditions will be tested thoroughly. Ways to effectively test shock resistance will be considered

(specifically, “drop” resistance in this case). Finally, the overall usability will be tested by people from outside of the project that have been identified as potential users, and their feedback will be considered part of the testing.

Specifically, lab testing will use sinusoidal inputs of varied frequencies to make sure that amplification works the same across all frequencies and that there is no frequency attenuation in the audio spectrum. The operational amplifiers have been chosen specifically to avoid this. Furthermore, the equalizer will be tested again at very specific frequencies to make sure it attenuates and amplifies in exactly the intended way. Lastly, similar signals will be used to make sure that the soundstage simulate passes audio as it is supposed to, which is to say that low frequencies should be passed almost completely between the stereo channels and high frequencies should be attenuated between the channels.

Furthermore, the breadboard will be fed real audio so that the “real world” performance can be seen. Upon completing the units, some will be loaned out to people both involved and not involved with the project and their feedback will be considered. They will be asked, of course, to comment on its performance in terms of audio quality and battery life. Also, the testers will be asked to make comments about the devices controls and interface, as well as its size and casing. If there enough similar comments, it may be possible to make certain types of changes at the end of the project, but it seems likely that suggestions made at this stage may simply need to be documented as issues to be addressed later, after the end of this project.

Recommendations Regarding Project Path

In general, it seems the project should continue on its current path. So far, any trouble has been very minor and it seems as if the project will finish within time and within specifications.

Detailed Design

This section describes in detail, the designs that have been chosen for the acoustic simulator, the amplifier, and the three-band equalizer. Included in each section is a description of why the specific design was chosen, as well as the reasons for rejections of alternatives.

Acoustic Simulator Design

The following circuit (Figure 5) is the one which will be used for the acoustic simulator. This design, created by Chu Moy from HeadWize, was chosen for the following reasons:

- It is a simple RC-type filter that creates a more realistic sound image in headphones by electronically mimicking the "shaded" inter-channel, cross-fed delay of normal hearing.
- It does not use inductors and is less sensitive to load impedance.
- The filter can drive either a headphone amplifier or headphones directly with the headphone amplifier as the source.
- Putting the filter before the amplifier eliminates any impedance interaction between the filter and the headphones.
- Since the simulator will be used ONLY as an input stage to a headphone amplifier, the "High Z" version will be used. This version scales the resistor and capacitor values by a factor of 10 (x10 resistors and ÷10 capacitors) to get a higher input impedance (about 2000 ohms), which is a better match for the line outputs of preamps and other audio sources.
- The headphone amplifier itself should have an input impedance of 5K ohms or higher.

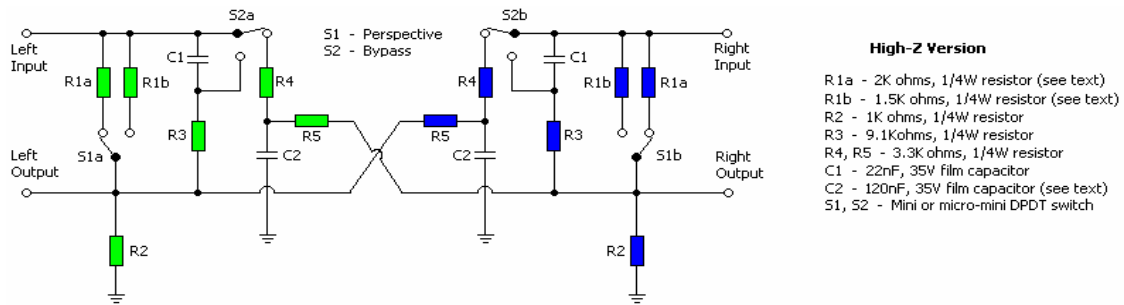


Figure 5. Chu Moy Acoustic Simulator Design⁴

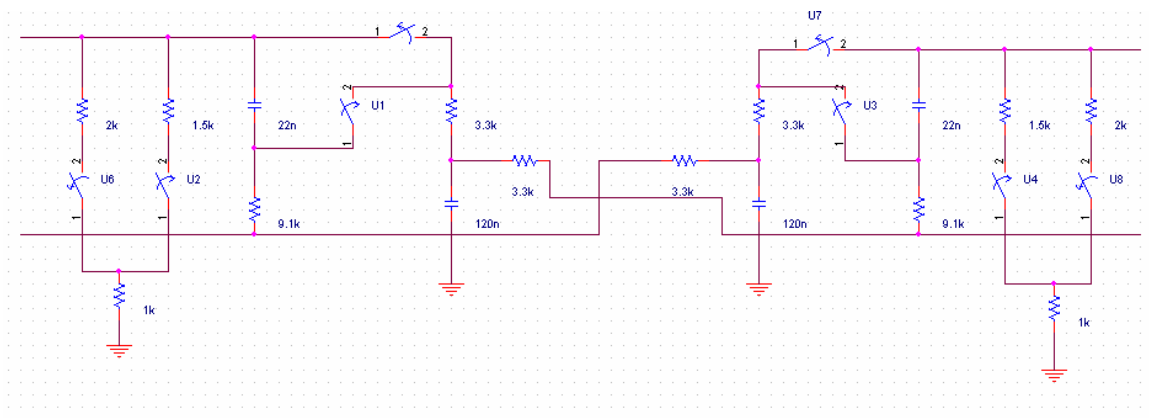


Figure 6. PSpice Layout of Moy's Acoustic Simulator

Amplifier Design

The following circuit is the one which will be used for the amplifier. This design, created by Chu Moy, was chosen for the following reasons:

- Each channel uses a single Burr-Brown OPA134 op amp in a non-inverting configuration.
- It has adequate current capability to drive most headphones without an output stage.
- The amplifier is ideal as a booster for power-conserving stereo sources such as portable CD players and for interfacing with passive EQ networks such as tone controls or a headphone acoustic simulator.
- The total cost for this design should be no more than \$20.00 - \$25.00.
- The OPA134 was selected for its excellent specs: FET inputs for high input impedance and low offset current, 8 MHz bandwidth, 20uV/S slew rate, ultra low noise, ultra low distortion, etc.
- It can run on as little as ± 2.5 volts and includes built-in current limiting.
- The OPA134 costs less than \$3.00 per unit from DigiKey Electronics.
- It comes in a dual version: the OPA2134, but the single version is easier to wire and avoids thermal crosstalk distortion between the channels.
- The OPA134 has a dormant current of about 4mA and will not drain the battery excessively. It can output almost 40mA into a short circuit at room temperature. Modern dynamic headphones need about 10mW to reach full volume.
- The OPA134 is wired as a non-inverting amp with a gain of 11. At this gain, the output impedance of the amplifier is less than 0.2 ohms throughout the audio range.
- The high-pass filter C1-R2 at the input blocks DC current and has a corner frequency of about 15Hz.
- R5 is an optional load resistor, which reduces residual hiss when the amp is driving low impedance headphones (32 ohms). Because the voltage drop across R5 reduces the maximum output of the amplifier, it is recommended that a 50 ohm resistor is used (or as low as 30 ohms). If there is still residual hiss with low impedance phones, then the resistor value can be increased to 100 ohms.
- A 9 volt alkaline battery can power the amp for several days of continuous play (high-capacity NiCad and NiMH rechargeable batteries will also work).
- The amp is lightweight, and is well-suited for people on the go who like to take with them a complete listening system.
- Low overall cost and high quality parts are used.

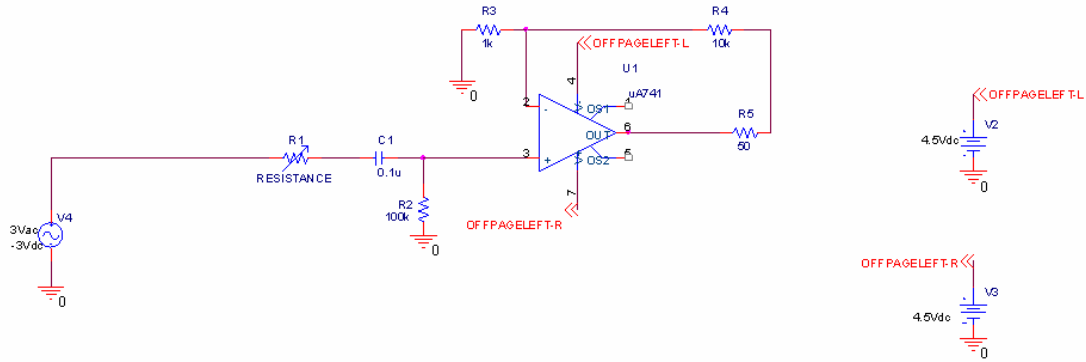


Figure 7. Amplifier Design⁵

Pocket Headphone Amplifier (one channel)

The design does have a volume control. Resistor R1 is a dual, audio-tapered mini potentiometer. The potentiometer that is being considered for use is a dual 10K Panasonic P2G1103. The P2G1103 potentiometers have a maximum value of 10K ohms and can be ordered from DigiKey. The Panasonic potentiometers come in 10K and 50K values, and are available from DigiKey. A physically larger, more common 100K potentiometers can be used if the value of resistor R2 is increased to between 200K and 1M, and can be obtained from Radio Shack. (Capacitor C1 can remain at 0.1uF, and the threshold frequency of the high pass filter will decrease with larger values of R2.)

Other Considerations

The following circuit (Figure 8), by Jan Meier, is a design for a headphone amplifier with a natural cross-fed delay filter that was considered for use in the project. This circuit was not chosen due to the increased number of components used. The use of two operational amplifiers increases the cost of the overall product. The switch S1a,b provides only provides two distinct levels of cross-fed separation, effectively changing the “wideness” of the soundstage, or the listener’s perceived position relative to the sound. This circuit requires complicated parallel wiring of S1a and S1b together. This design was meant for a desktop implementation, not to be used in a portable setting.

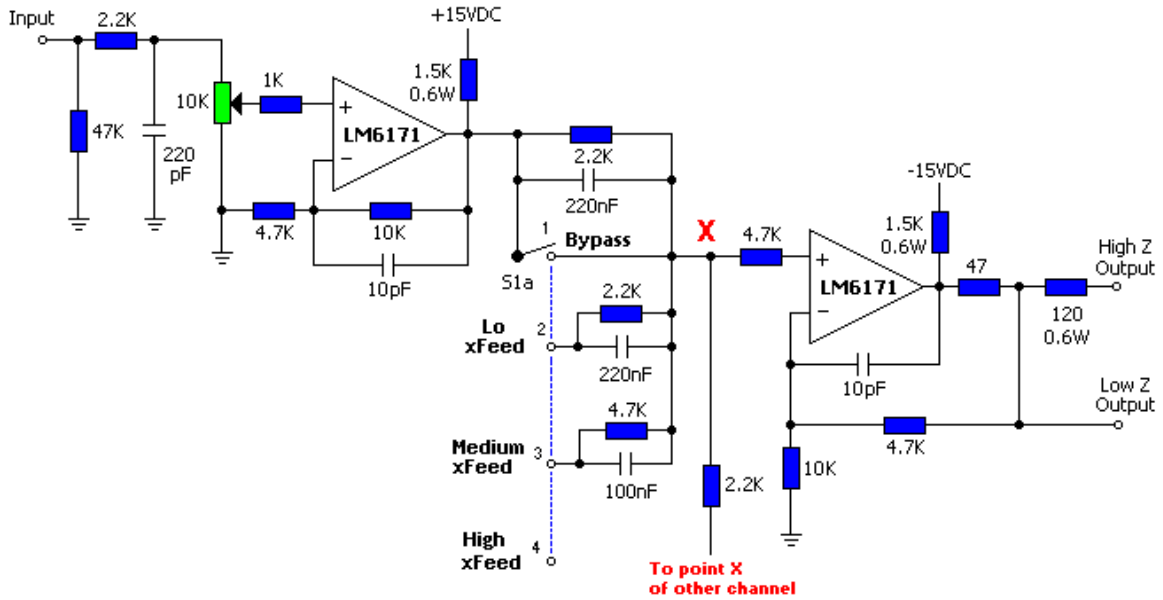


Figure 8. Natural Cross-Fed Delay Filter Headphone Amplifier (One Channel)⁶

The next circuit (Figure 9), by Toni Kemhagen, is another design for a headphone amplifier with a natural cross-fed delay filter that was considered for use in the project. Again, this circuit was not chosen due to the increased number of components used. The use of three operational amplifiers increases the cost of the overall product. Just one channel uses two completely separate ± 9 volt battery supplies, one for the input buffers and voltage amplifiers and the other for the output stage only. The amp is a little larger and heavier than would be optimal for a portable device due to the fact that it uses four 9 volt batteries.

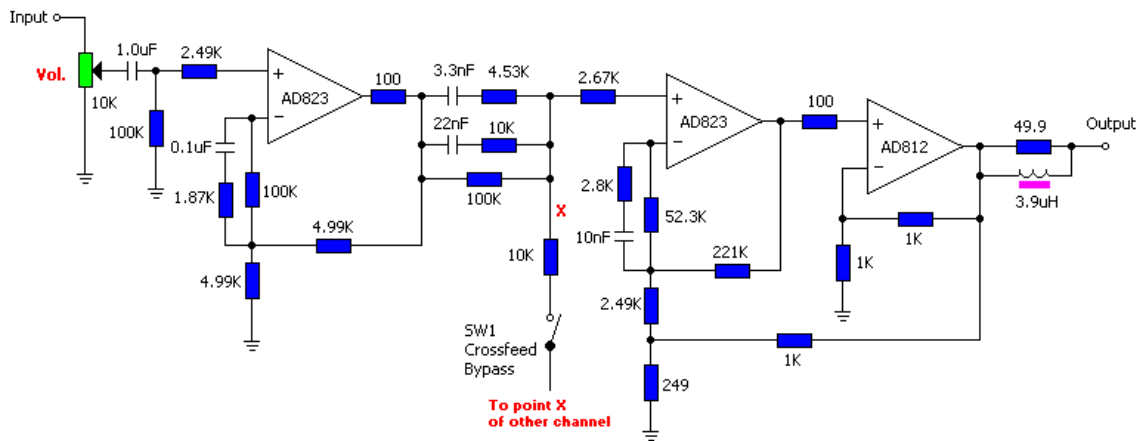


Figure 9. Headphone Amplifier Circuit⁷

The next circuit (Figure 10), by Earle Eaton, is also a design for a headphone amplifier that was considered for use in the project. This circuit was not chosen due to the design specifications that were required for this project. This circuit uses a remote power supply. Although this reduces the possibility of induction noise, it does not make for a very portable device.

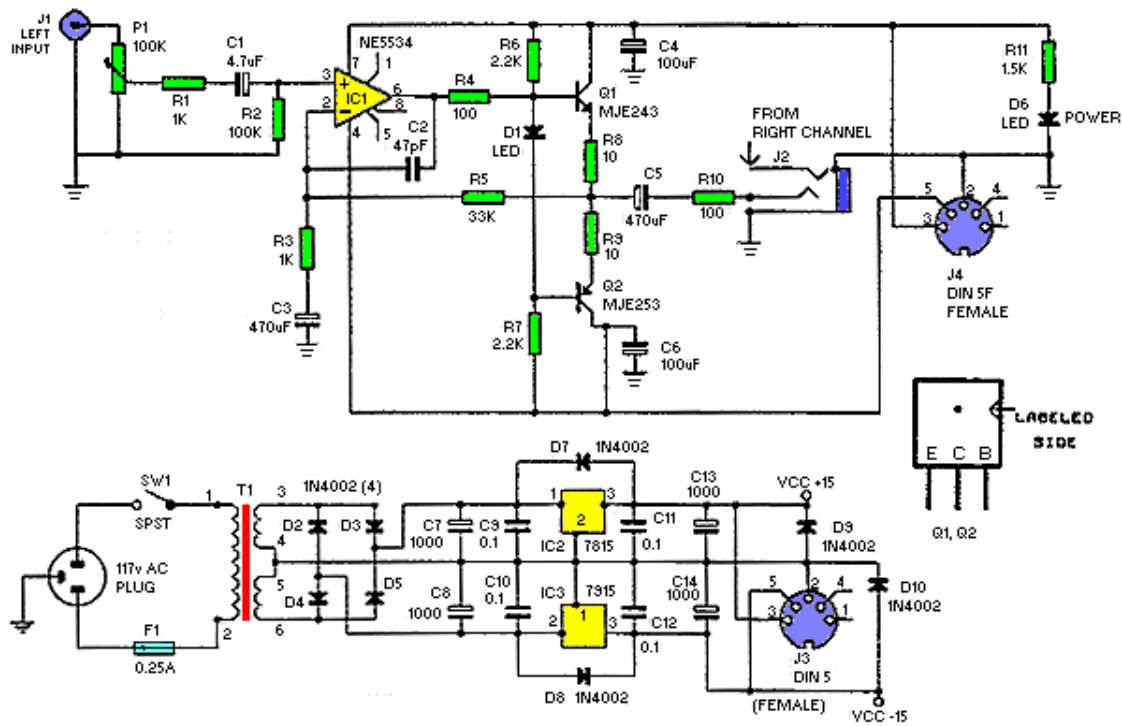


Figure 10. Eaton's Headphone Amplifier⁸

Equalizer Design

After deliberation, a three-band, fully analog Baxandall-type equalizer was chosen. Its schematic is featured below, in Figure 11. This design, although common, was found on the HeadWize website and edited slightly.

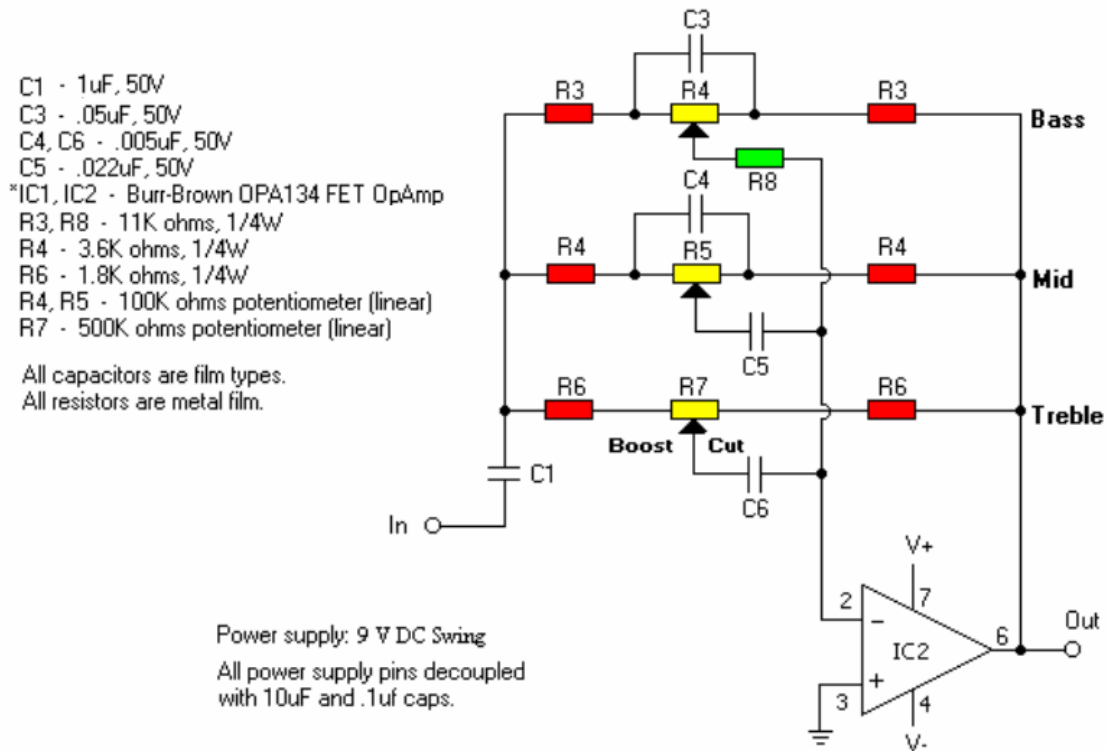


Figure 11. Three-Band Baxandall Equalizer⁹

This design has a number of advantages. There was a project constraint to use at least three bands of equalization, but the equalization did not need to be fully analog. However, looking at the relative cost of linear potentiometers, the part which appears three times in each channel, compared to the switches and extra parts needed for discrete-type switching, it was decided that the added features of a fully analog adjustability were not at all offset by the cost savings of the discrete system, which were on the order of pennies per channel.

This design, compared to others to be discussed later, uses a very small number of parts and yet seems to perform in a very robust manner. It features three bandpass filters each at a well-spaced frequency for audio. These center frequencies for each of the three bands are as follows:

$$f_{bass} = \frac{1}{2\pi(R3)(C3)} = 290Hz$$

$$f_{mid} = \frac{1}{2\pi(R4)(C4 + C5)} = 1050Hz$$

$$f_{treble} = \frac{1}{2\pi(R6)(C6)} = 17000Hz$$

These frequencies give very respectable logarithmic spacing, with the treble perhaps shifted slightly higher than would be ideal. According to the designers, this may make the control of the high-end treble more subtle, with a smaller noticeable cut or gain than in the other channels. However, it is believed this will not bother most listeners as the bass and midrange adjustment are the most important in almost all cases. According to HeadWize, the total gain/cut in each band in this circuit is a possible 20 dB. However, since the treble band is a little off-center, its effectible audible gain/cut around 10000 Hz is closer to 15 dB. This meets the design goal of having a 15 dB swing in the equalizer.

In Figure 12 below is the PSpice design used to simulate the circuit's response. The voltage rails are set to a 9 volt swing anticipating the use of a similar power supply.

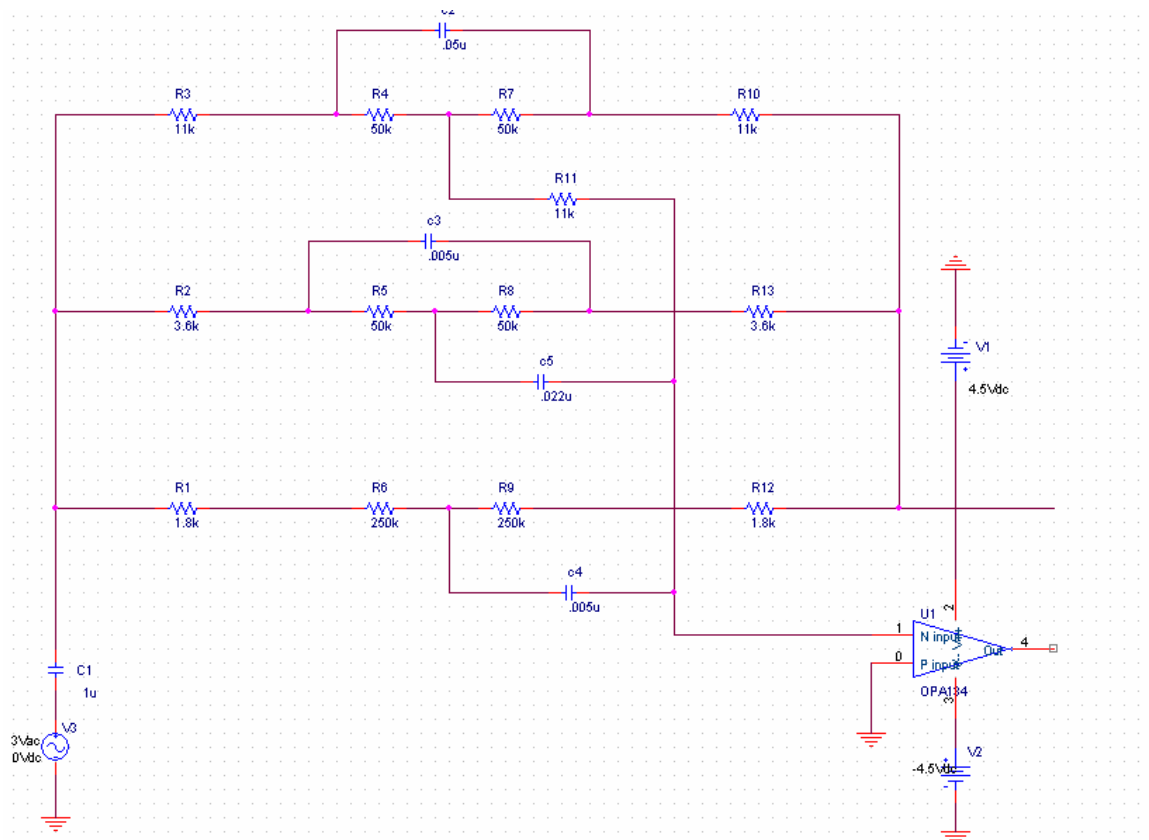


Figure 12. PSpice Design of Equalizer

Figure 13 below shows the most carefully considered, but ultimately rejected equalizer design, again from HeadWize. Many available designs did not feature all three bands that were required for the project.

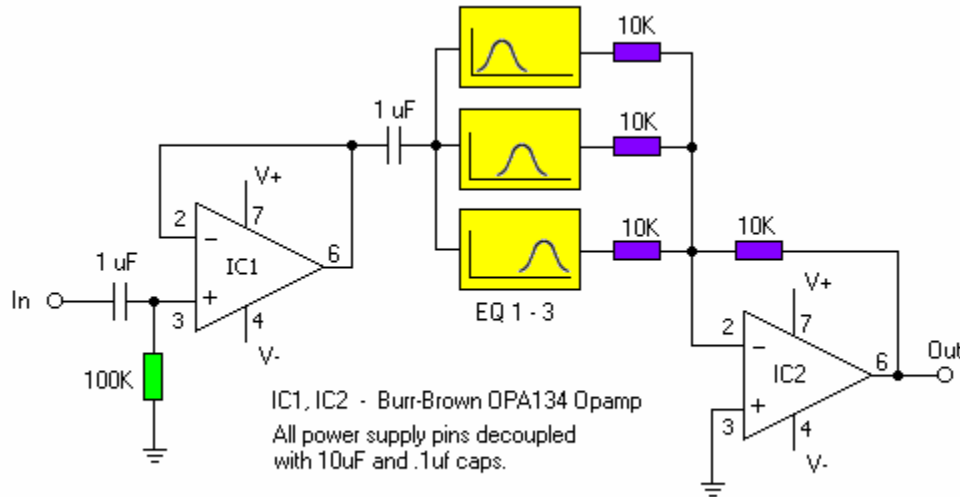


Figure 13. Three-Band Resonant Equalizer¹⁰

In this figure, each band (bass, mid, and treble) has its own individual adjustable active Baxandall type filter. This filter is shown below in Figure 14.

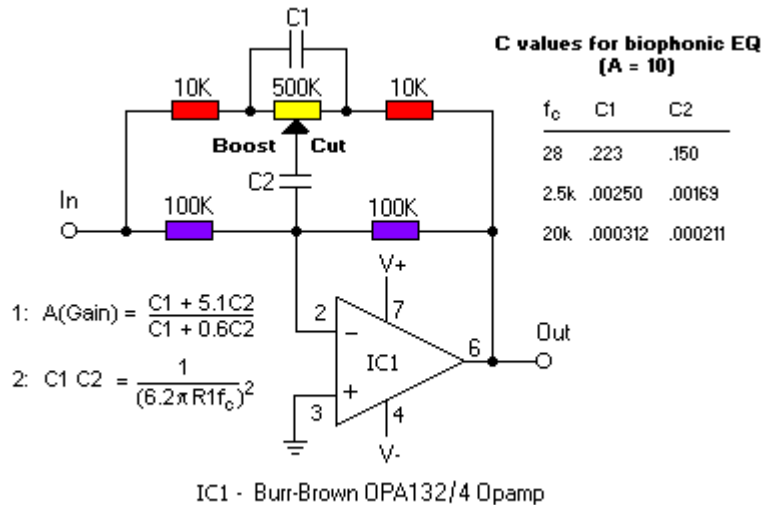


Figure 14. Resonant Filter EQ Stage¹¹

This design, even without the somewhat optional input voltage follower, requires four operational amplifiers per channel, making the cost of simply the equalizer soar well beyond \$25.00. According to HeadWize, however, the response in each channel is very controllable and this equalizer would offer what can be considered perhaps the best possible equalization with the parts available. This endorsement, however, didn't seem enough to justify the increased cost, especially considering that perhaps the main thrust of this project will be the acoustic simulation part of the circuit, rather than the equalization.

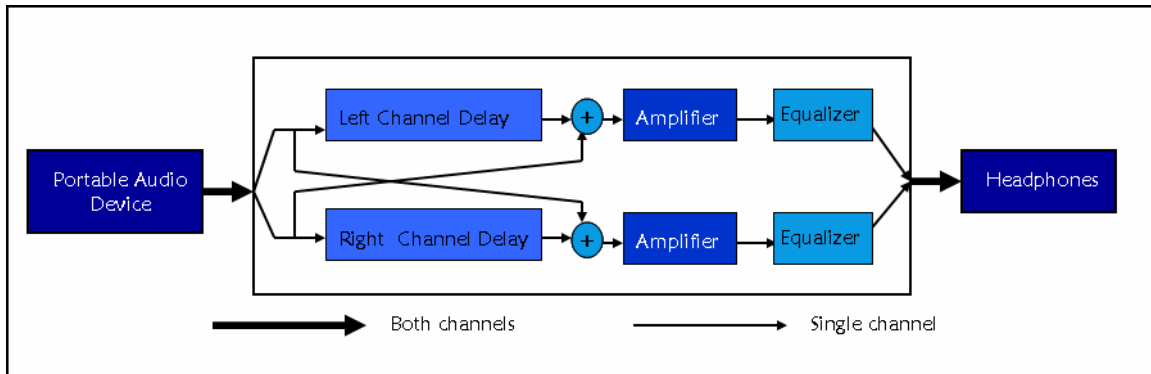


Figure 15. General Design Flowchart

To implement the complete circuit together, the acoustic simulator will be attached at first to the output from the audio source. The input impedance of the acoustic simulator will be just over 1500 ohms, well above the 5 to 20 ohms of output that will come from the source, meaning the input coupling will be nearly lossless.

This stage, with its high impedance, will be fed into the amplifier next, taking advantage of its virtually infinite input impedance. Finally the signal will be equalized, with the operational amplifier in the equalizer driving the final output headphones. It should be noted that is perhaps counter-intuitive, since the equalizer is usually in the pre-amp stage. However, in this design, the equalizer is active and actually has amplification properties within itself. This, coupled with the fact that the equalizer stage has very low input impedance as well as low output impedance makes it a poor candidate to follow the cross-feeding stage, with its high output impedance. Therefore, the cross-fed signal is immediately amplified equally at all frequencies (volume control) before being equalized. The equalizer, with its operational amplifier output, is as good a headphone driver as the amplifier stage. The general design flowchart is shown above in Figure 15. The final design in PSpice is shown on the following page in Figure 16.

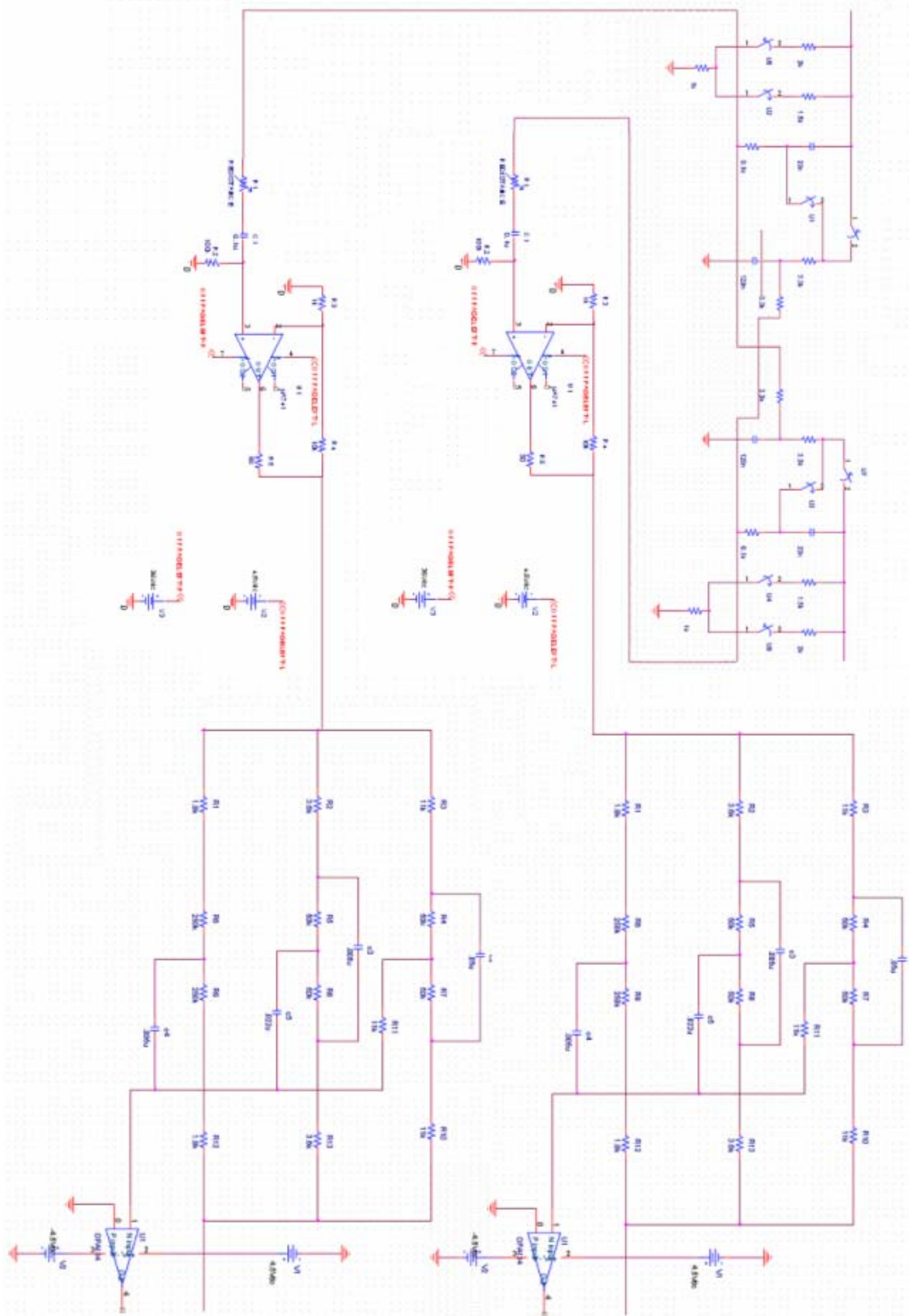


Figure 16. Final Device PSpice Schematic

Resource Requirements

The resource requirements for the headphone amplifier and equalizer device can be divided into labor and finances. The team will provide the majority of the labor with some work also being completed by Jason Boyd, a technician that will assist in the assembly of the PCBs. See Table 1 for the original personnel hour estimates required for each task. As tasks 1 through 5 have now been completed, see Table 2 for the updated personnel hour estimates. The following is a list defining what each project task entails:

- Task No. 1 – Problem Definition
- Task No. 2 – Pre-Design Research
- Task No. 3 – Technology and Part Considerations
- Task No. 4 – Initial Design
- Task No. 5 – Simulation Test
- Task No. 6 – Breadboard Implementation and Testing
- Task No. 7 – Fabrication on PCB
- Task No. 8 – Final Product Completion
- Task No. 9 – Final Product Testing
- Task No. 10 – Product Documentation
- Task No. 11 – Product Demonstration
- Task No. 12 – Reporting and Evaluation

Table 1. Original Personnel Effort Estimate in Hours per Task

Personnel Effort Requirements (hours)													
	Tasks												
Team Personnel	1	2	3	4	5	6	7	8	9	10	11	12	Total
Kurtis Kenne	12	10	15	6	10	20	10	18	16	31	12	7	167
Mike Dierickx	12	10	18	5	10	22	13	18	16	29	12	7	172
Rachel Hager	12	10	15	6	10	22	13	18	16	31	12	7	172
Jennifer Bruner	12	10	18	5	10	20	10	18	16	29	12	7	167
Totals:	48	40	66	22	40	84	46	72	64	120	48	28	678

Table 2. Updated Personnel Effort Estimate in Hours per Task

Updated Personnel Effort Requirements (hours)													
	Tasks												
Team Personnel	1	2	3	4	5	6	7	8	9	10	11	12	Total
Kurtis Kenne	10	8	13	6	8	20	10	18	16	31	12	7	159
Mike Dierickx	10	8	12	5	10	22	13	18	16	29	12	7	162
Rachel Hager	10	8	13	6	8	22	13	18	16	31	12	7	164
Jennifer Bruner	10	8	12	5	10	20	10	18	16	29	12	7	157
Totals:	40	32	50	22	36	84	46	72	64	120	48	28	642

As tasks 1 through 5 have been completed, it has taken less time than expected. As work on the project continues, the estimated hours for the remaining tasks have not been altered. As the project is now in the hardware implementation stage, the time estimated is reasonable, as it accounts for possible debugging issues and other testing considerations.

Table 3 below, displays the original estimate of other resource requirements. Other resource requirements are estimates of the time that will be spent and the costs involved, selecting the appropriate parts, ordering, and finally assembling the headphone amplifier and equalizer devices. Table 4 displays an updated version of the estimated resource requirements as more work has been done researching different companies for part selection.

Table 3. Original Estimate of Other Resource Requirements

Other Resource Requirements (hours)			
Item	Team Hours	Other Hours	Cost
Project Poster	12	0	\$50.00
Parts (per device):			
PCBs	15	1	\$50.00
Op-amps, resistors, capacitors	19		\$50.00
Case	12	0	\$25.00
Assembly Services:			
Soldering	0	4	0
Mounting in case	12	0	0
Total:	70	5	\$175.00

Table 4. Updated Estimate of Other Resource Requirements

Updated Estimate of Other Resource Requirements (hours)			
Item	Team Hours	Other Hours	Cost
Project Poster	12	0	\$50.00
Parts (per device):			
PCBs	15	1	\$15.00
Op-amps, resistors, capacitors	19		\$25.00
Case	12	0	\$15.00
Assembly Services:			
Soldering	0	4	0
Mounting in case	12	0	0
Total:	70	5	\$105.00

The senior design program will provide the necessary funds for parts. Equipment and parts costs will include the items to run the amplifier and the equalizer and the miscellaneous parts necessary to implement the various circuit integration tasks. Printing costs resulting from the poster design and production were estimated not to exceed \$50.00. See Table 5 below for the original estimated financial budget for this project.

Table 5. Original Estimated Parts and Material Costs

Other Resources		
Item	W/O Labor	With Labor
Project Poster	\$50.00	\$50.00
Parts (per device):		
PCBs	\$50.00	\$50.00
Op-amps, resistors, capacitors	\$50.00	\$50.00
Case	\$25.00	\$25.00
Subtotal:	\$175.00	\$175.00
Assembly Services:		
Soldering	Donated	Donated
Subtotal:	\$0.00	\$0.00
Labor at \$10 per hour		
Kurtis Kenne		\$1,670.00
Mike Dierickx		\$1,720.00
Rachel Hager		\$1,720.00
Jennifer Bruner		\$1,670.00
Subtotal:	\$0.00	\$6,780.00
Total:	\$175.00	\$6,955.00

As the current step in the project is breadboard implementation, this table only offers an estimate for the parts and PCB costs. Table 6 on the following page displays an updated estimate for parts and material costs. These values however, are still subject to change as testing goes underway, as the designs might require alteration to fit the desired outcome. Another possible cause for a change in cost estimate is the number of devices that are designed and built.

Table 6. Updated Estimated Parts and Material Costs

Other Resources		
Item	W/O Labor	With Labor
Project Poster	\$50.00	\$50.00
Parts (per device):		
PCBs	\$15.00	\$15.00
Op-amps, resistors, capacitors	\$25.00	\$25.00
Case	\$15.00	\$15.00
Subtotal:	\$105.00	\$105.00
Assembly Services:		
Soldering	Donated	Donated
Subtotal:	\$0.00	\$0.00
Labor at \$10 per hour		
Kurtis Kenne		\$1,590.00
Mike Dierickx		\$1,620.00
Rachel Hager		\$1,640.00
Jennifer Bruner		\$1,570.00
Subtotal:	\$0.00	\$6,420.00
Total:	\$105.00	\$6,525.00

Project Schedule

This project will cover both the fall 2004 and spring 2005 semesters. Figure 17 below shows the original estimate of the time periods the team will be working on each of the required tasks in order to finish the final product on time. Each of the tasks will be completed by the last day of the task duration. Although team members will not actively meet as a group over holidays and the semester break, the project will continue and individuals may still put forth effort. Over semester break, the team will be waiting for the fabrication of the PCBs and will have started on the final documentation of the project.

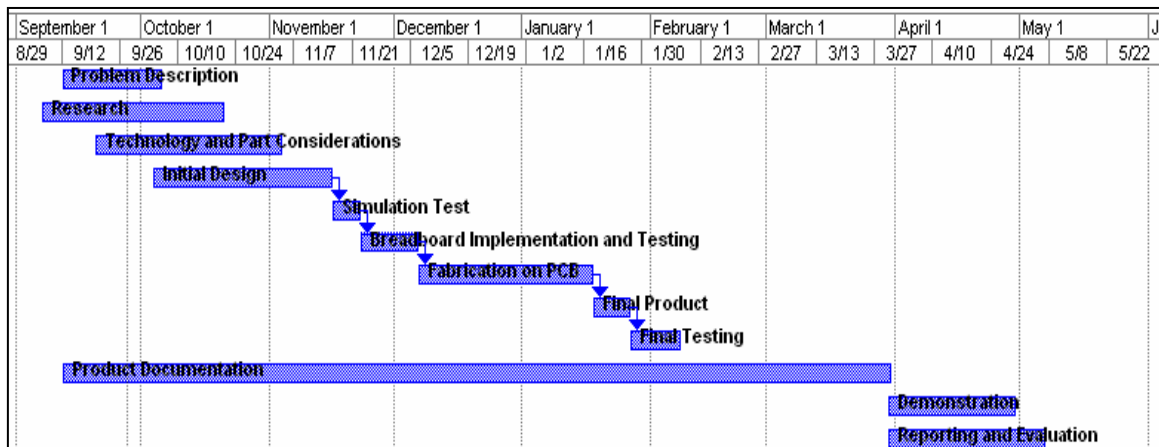


Figure 17. Original Gantt Chart of Project Tasks

Table 7. Dates Associated with the Original Gantt Chart

Task Name	Duration	Start	Finish
Problem Description	18 days?	Sun 9/12/04	Tue 10/5/04
Research	33 days?	Tue 9/7/04	Wed 10/20/04
Technology and Part Consider	33 days?	Mon 9/20/04	Wed 11/3/04
Initial Design	31 days?	Mon 10/4/04	Mon 11/15/04
Simulation Test	5 days?	Tue 11/16/04	Mon 11/22/04
Breadboard Implementation ar	10 days?	Tue 11/23/04	Mon 12/6/04
Fabrication on PCB	30 days?	Tue 12/7/04	Mon 1/17/05
Final Product	7 days?	Tue 1/18/05	Wed 1/26/05
Final Testing	8 days?	Thu 1/27/05	Mon 2/7/05
Product Documentation	82 days?	Tue 12/7/04	Wed 3/30/05
Demonstration	23 days?	Wed 3/30/05	Fri 4/29/05
Reporting and Evaluation	28 days?	Wed 3/30/05	Fri 5/6/05

As work on the project continues, the research and technology and parts considerations tasks have taken longer than expected. This is shown in the updated Gantt chart in Figure 18 below.

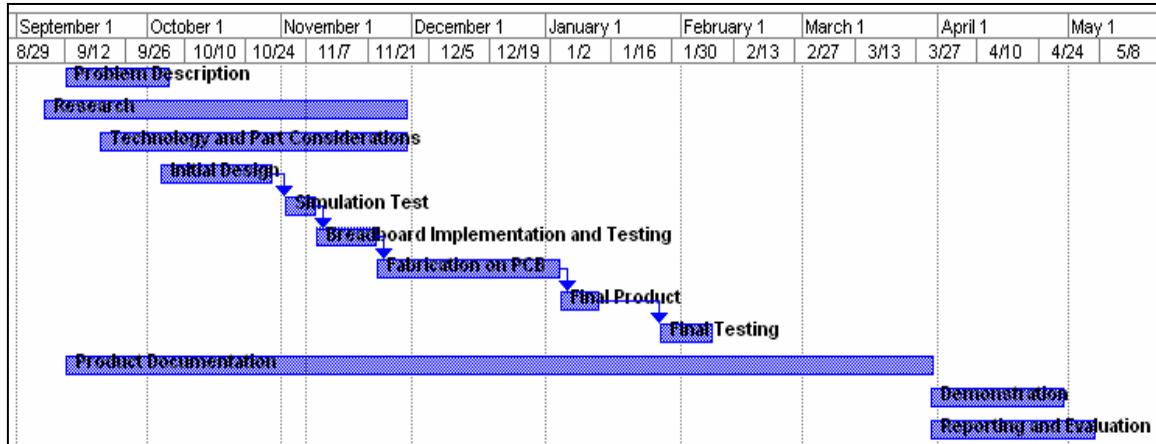


Figure 18. Updated Gantt Chart of Project Tasks

Table 8. Dates Associated with the Updated Gantt Chart

Task Name	Duration	Start	Finish
Problem Description	18 days?	Sun 9/12/04	Tue 10/5/04
Research	61 days?	Tue 9/7/04	Mon 11/29/04
Technology and Part Considerations	51 days?	Mon 9/20/04	Mon 11/29/04
Initial Design	20 days?	Mon 10/4/04	Fri 10/29/04
Simulation Test	5 days?	Tue 11/2/04	Mon 11/8/04
Breadboard Implementation and Testing	10 days?	Tue 11/9/04	Mon 11/22/04
Fabrication on PCB	30 days?	Tue 11/23/04	Mon 1/3/05
Final Product	7 days?	Tue 1/4/05	Wed 1/12/05
Final Testing	8 days?	Thu 1/27/05	Mon 2/7/05
Product Documentation	144 days?	Sun 9/12/04	Wed 3/30/05
Demonstration	23 days?	Wed 3/30/05	Fri 4/29/05
Reporting and Evaluation	28 days?	Wed 3/30/05	Fri 5/6/05

Project Team Information

The project team consists of four electrical engineering students and is advised by two faculty advisors, Professor Lamont and Professor Patterson. The client for this project is the Senior Design Program. Contact information for all significant members of the team is provided below.

Faculty Advisors

Ralph Patterson III
326 Town Engineering
Ames, Iowa 50011-3230
Office Phone: 515-294-2428
Home Phone: 515-232-9933
Fax: 515-294-6760
repiii@iastate.edu

John W. Lamont
324 Town Engineering
Ames, Iowa 50011-3230
Office Phone: 515-294-3600
Home Phone: 515-292-5541
Fax: 515-294-6760
jwlamont@iastate.edu

Team Members

Jennifer Bruner
Electrical Engineering
204 Jewel Dr. Apt. 5
Ames, Iowa 50010
Cell: 515-450-9269
bruner80@iastate.edu

Mike Dierickx
Electrical Engineering/Physics
2351 Wallace Rambo
Ames, Iowa 50013
Phone: 515-572-2088
Cell: 515-708-1270
mikedx42@iastate.edu

Rachel Hager
Electrical Engineering
8115 Buchanan Hall
Ames, Iowa 50013
Phone: 515-572-6134
Cell: 515-451-9453
rachelh@iastate.edu

Kurtis Kenne
Electrical Engineering
125 Campus Ave. #17
Ames, Iowa 50014
Cell: 641-430-0545
kkenne@iastate.edu

Conclusion

In summary, there is a perceived need for a device that will amplify, equalize, and flesh out the stereo effects in the audio signal output by a portable audio device, such as a CD or MP3 player. The purpose of this project is to design such a device and build one or more prototypes in complete self-contained casing. This product will be designed in a number of different phases, with the final goal being fully-functional and cased prototypes ready for use. The product will hopefully benefit the discerning headphone listener, and allow him or her to have greater control over the listening experience than is allowed by his or her portable audio device alone. This project will represent a union of three distinct personal audio products currently available commercially all placed into economical package that will maximize the amount of circuitry and utility that can be placed into one small unit.

At this point in the project, the detailed circuit design has been completed. The current phase of this project now lies with PSpice simulations. Breadboard implementation and testing will begin shortly. Once testing has been successfully completed, fabrication onto PCB will take place as the semester comes to a close. So far all tasks have remained on schedule and no problems have been encountered that could drastically change the specifications of the project. The project will continue on the estimated schedule.

Appendix A – Project Poster

Headphone Amplifier and Equalizer

Abstract

With most portable audio systems, the listener has no ability to equalize the audio signal to suit their music preference. It is also found that most portable audio systems have insufficient power output to drive a set of high fidelity headphones with an impedance range varying from 32 ohms to 600+ ohms. Lastly, headphones do not present an acceptable soundstage for "surround" audio, as the left and right channels are localized to each ear. To eliminate these problems a combined amplifier, equalizer, and cross-faded delay filter circuit (or soundstage simulator) will be designed and developed. The end product will be a portable, user-friendly device that is completely encased and ready for manufacturing.

Problem Statement

- Portable audio systems:
- Provide insufficient power to drive high-fidelity headphones
 - Offer no equalization adjustments
 - Offer no stereo soundstage imaging

Operating Environment

The operating environment for the headphone amplifier and equalizer will encompass all portable uses. This device will be used in both indoor and outdoor environments. It is assumed that the user will not submerge the device in water.

Intended User(s) and Use(s)

The intended users of the headphone amplifier and equalizer device are the general public, or more specifically people who are enthusiasts of music. This device is being created so that the user has more control over the sound quality of the output signal.

The intended end uses of this device are in conjunction with a portable audio system, such as a CD or MP3 player. This device will not be used in conjunction with a high-power audio system with external speakers because one of its primary features is the soundstage simulation for headphone use only.

Assumptions

- The device will be used to drive a pair of high-fidelity headphones with an impedance range varying from 32 ohms to 600+ ohms.
- The device will drive about 400 mW through the 32 ohms per channel headphones to create a maximum of 120 dB of sound pressure level.
- Three-band equalization with a maximum 15 dB attenuation will be used.
- Equalization will be in stereo, but each channel will not need to be equalized separately.

Limitations

- The device must have the capability to operate at 120 volts AC, 12 volts DC, and primarily on an internal power supply of six - 1.2 volt (AA) NiMH rechargeable batteries.
- The device will include at minimum a 3.5 mm input jack, two headphone jacks (one 3.5 mm and one 6.5 mm), a volume control, a balance control, a power switch, 3-band equalizer controls, and a pilot light.
- Since the device will be portable, it must be able to withstand extreme temperatures and be durable enough to withstand being dropped.

Expected End Product

The expected end product of this project is an encased, combined headphone amplifier, equalizer, and cross-faded delay filter circuit that is compatible with most portable audio systems. The finalized device will include an internal power supply of six - 1.2 volt rechargeable batteries, the jacks for external power supplies (120 volts AC / 12 volts DC) and a user's manual. This device will allow users to enhance their listening pleasure by giving them the ability to amplify and equalize the transmitted output signal from an audio device.



Project Requirements

Design Objectives

- Design a portable device that will enhance music listening
- Encase device with a user-friendly interface

Functional Requirements

- Volume must be adjustable
- Signal must be controllable with a 3-band equalizer
- Left and right volume must be balanceable
- Device must have a power switch with an ON indicator LED

Design Constraints

- Device must be compact and portable
- Device must have the capability to operate at 120 volts AC, 12 volts DC, and contain an internal power supply of six - 1.2 volt (AA) NiMH rechargeable batteries

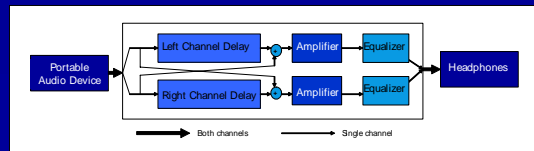
Measurable Milestones

- Problem definition
- Product design
- Breadboard implementation and testing
- Fabrication on PCB
- Final product testing
- End product demonstration

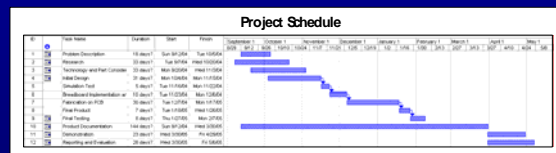
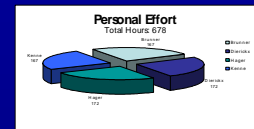
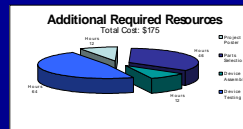
Technical Approach

Testing Considerations

- PSpice will be used to simulate and test initial design
- Breadboard implementations will be tested with various portable audio devices
- Cadence will be used to design and test PCB layouts
- Final product will be thoroughly tested with various portable audio devices



Estimated Resources



Closing Summary

In summary, there is a perceived need for a device that will amplify, equalize, and create a stereo soundstage in the audio signal output by a portable audio device, such as a CD or MP3 player. The purpose of this project is to design such a device and build one or more prototypes in complete self-contained casing. This product will be designed in a number of different phases, with the final goal being fully-functional and case prototypes ready for use. The product will hopefully benefit the discerning headphone listener, and allow him or her to have greater control over the listening experience than is allowed by his or her portable audio device alone. This project will represent a union of three distinct personal audio products currently available commercially all placed into economical package that will maximize the amount of circuitry and utility that can be placed into one small unit.

May0501 Project Team Information

EE Team Members: Jennifer Bruner
bruner80@iastate.edu
Mike Dierdix
mikedx42@iastate.edu
Rachel Hager
rachelh@iastate.edu
Kurtis Kenne
kkenne@iastate.edu

Client: Iowa State University
ECpE Department
Senior Design Program

Faculty Advisors: John Lamont
Ralph Patterson III



Project Website: <http://seniord.ee.iastate.edu/may0501>

Appendix B - Axial-Lead Parts List

The following axial-lead parts list was created with parts from both DigiKey and Mouser Electronics catalogs.

Amplifier			
2	50k audio taper pot	P2G1503-ND	DigiKey
2	10k audio taper pot	P2G1103-ND	DigiKey
2	100K	100KXBK-ND	DigiKey
2	10K	10.0KXBK-ND	DigiKey
2	50K	49.9KXBK-ND	DigiKey
2	1K	1.00KXBK-ND	DigiKey
2	0.1uF cap	478-2298-ND	DigiKey
2	OPA134PA op amp	OPA134PA-ND	DigiKey
Acoustic Simulator			
1	2K	2.00KXBK-ND	DigiKey
1	1.5K	1.50KXBK-ND	DigiKey
1	1K	1.00KXBK-ND	DigiKey
1	9.1K	9.09KXBK-ND	DigiKey
2	3.3K	3.32KXBK-ND	DigiKey
1	0.022uF cap	478-2309-ND	DigiKey
1	0.120uF cap	478-2300-ND	DigiKey
EQ			
2	1uF cap	478-2047-ND	DigiKey
2	0.047uF cap	478-2320-ND	DigiKey
4	0.0047uF cap	478-2318-ND	DigiKey
2	0.022uF cap	478-2309-ND	DigiKey
6	11K	11.0KXBK-ND	DigiKey
4	3.6K	3.57KXBK-ND	DigiKey
4	1.8K	1.82KXBK-ND	DigiKey
2	100k dual ganged pot LINEAR	31VW501	Mouser
1	500k dual ganged pot LINEAR	31VW505	Mouser
2	OPA134PA op amp	OPA134PA-ND	DigiKey

DigiKey: www.DigiKey.com

Mouser: www.Mouser.com

Appendix C - Surface Mount Parts List

The following surface mount parts list was created with parts from both DigiKey and Mouser Electronics catalogs.

2	3.5mm audio jack	CP-3524SJ-ND	DigiKey
Amplifier			
2	50k audio taper pot	P2G1503-ND	DigiKey
2	10k audio taper pot	P2G1103-ND	DigiKey
2	100K	P100KFCT-ND	DigiKey
2	10K	P10.0KFCT-ND	DigiKey
2	50K	P49.9KFCT-ND	DigiKey
2	1K	P1.00KFCT-ND	DigiKey
2	0.1uF cap	PCF1506CT-ND	DigiKey
2	OPA134PA op amp	OPA134UA-ND	DigiKey
Acoustic Simulator			
1	2K	P2.00KFCT-ND	DigiKey
1	1.5K	P1.50KFCT-ND	DigiKey
1	1K	P1.00KFCT-ND	DigiKey
1	9.1K	P9.09KFCT-ND	DigiKey
2	3.3K	P3.32KFCT-ND	DigiKey
1	0.022uF cap	PCF1498CT-ND	DigiKey
1	0.120uF cap	PCF1507CT-ND	DigiKey
EQ			
2	1uF cap	PCF1547CT-ND	DigiKey
2	0.047uF cap	PCF1502CT-ND	DigiKey
4	0.0047uF cap	PCF1173CT-ND	DigiKey
2	0.022uF cap	PCF1498CT-ND	DigiKey
6	11K	P11.0KFCT-ND	DigiKey
4	3.6K	P3.57KFCT-ND	DigiKey
4	1.8K	P1.82KFCT-ND	DigiKey
2	100k dual ganged pot LINEAR	31VW501	Mouser
1	500k dual ganged pot LINEAR	31VW505	Mouser
2	OPA134PA op amp	OPA134UA-ND	DigiKey

DigiKey: www.DigiKey.com

Mouser: www.Mouser.com

References

1. Portable Headphone Amplifier and Equalizer. 2001. 12 Sept. 2004
<http://HeadWize.com/projects/showfile.php?file=cmoy2_prj.htm>
2. Metal Casing. 2001. 08 Nov. 2004
<<http://www.mouser.com/catalog/620/1194.pdf>>
3. Plastic Casing. 2001. 08 Nov. 2004
<<http://www.mouser.com/catalog/620/1194.pdf>>
4. Chu Moy Acoustic Simulator Design. 1993. 28 Oct. 2004
< http://headwize.com/projects/showfile.php?file=cmoy1_prj.htm>
5. Amplifier Design. 1998. 28 Oct. 2004
< http://headwize.com/projects/showfile.php?file=cmoy2_prj.htm>
6. Natural Cross-Fed Delay Filter Headphone Amplifier. 1999. 28 Oct. 2004
< http://headwize.com/projects/showfile.php?file=meier_prj.htm>
7. Headphone Amplifier Circuit. 2001. 28 Oct. 2004
< http://headwize.com/projects/showfile.php?file=kemhagen_prj.htm>
8. Eaton's Headphone Amplifier. 1993. 28 Oct. 2004
< http://headwize.com/projects/showfile.php?file=eaton_prj.htm>
9. Three-Band Baxandall Equalizer. 2002. 24 Oct. 2004
<http://headwize.com/projects/showfile.php?file=equal_prj.htm>
10. Three-Band Resonant Equalizer. 2002. 24 Oct. 2004
<http://headwize.com/projects/showfile.php?file=equal_prj.htm>
11. Resonant Filter EQ Stage. 2002. 24 Oct. 2004
<http://headwize.com/projects/showfile.php?file=equal_prj.htm>