AFFORDABLE FREQUENCY SELECTIVE HEARING AMPLIFIER

An Undergraduate Research Scholars Thesis

by

ALMAHA A. BAHZAD AND HIND S. AL-MULLA

Submitted to the LAUNCH: Undergraduate Research office at
Texas A&M University
in partial fulfillment of requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Faculty Research Advisors: Dr. Muhammad Zilany
Dr. Joseph Boutros

May 2023

Major: Electrical Engineering

RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

We, AlMaha A. Bahzad and Hind S. Al-Mulla, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with our Faculty Research Advisors prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

TABLE OF CONTENTS

Page

ABSTRACT

Affordable Frequency Selective Hearing Amplifier

AlMaha A. Bahzad and Hind S. Al-Mulla
Department of Electrical and Computer Engineering
Texas A&M University

Faculty Research Advisor: Dr. Muhammad Zilany
Department of Electrical and Computer Engineering
Texas A&M University

Faculty Research Advisor: Dr. Joseph Boutros
Department of Electrical and Computer Engineering
Texas A&M University

One of the most prevalent diseases affecting human communication is hearing loss. About one in every six people has a hearing deficit globally. Many people suffer from hearing loss but cannot afford a hearing aid because of the high cost set by manufacturers. In this study, we aim to design a frequency-selective hearing amplifier that could be used as an alternative to hearing aids by having an external controller and separate earpieces. The controller allows the user to select the correct frequency bands to be amplified according to the listeners' degree of hearing loss. As a starting point, we have divided the frequency range of hearing into three bands: 125 Hz to 1 kHz, 1 Hz to 4 kHz, and 4 Hz to 8 kHz. The microphone picks up the signal, and the Analog-to-Digital Converter (ADC) converts the signal to digital form which then goes through a microcontroller where filtering and amplification take place. The amplified frequency band of the signal is then added to the rest of the signal and rescaled before a Digital-to-Analog

Converter (DAC) converts the signal to an analog form. Analog signals would go through a second amplifier to adjust the overall speech level that can be heard via the earpiece. The circuit components in the amplifier could be adjusted to produce the desired amount of amplification. The proposed design is tested thoroughly to ensure that a wide range of amplification is achieved for a wide range of listeners with various degrees of hearing loss.

ACKNOWLEDGEMENTS

Contributors

We would like to thank our faculty advisors, Dr. Muhammad Zilany and Dr. Joseph Boutros, and our colleagues AlDana Al-Dosari and Muhammad Mohid, for their guidance and support throughout the course of this research.

Thanks also go to our friends, colleagues and the department faculty and staff for making my time at Texas A&M University at Qatar a great experience.

Finally, special thanks to our families for their encouragement for their patience and love.

The components used for the affordable frequency selective hearing amplifier were provided by Dr. Joseph Boutros, Sawsan Shukri, and Wesam Mansour. The analyses depicted in the affordable frequency selective hearing amplifier were conducted in part by the department of Electrical and Computer Engineering at Texas A&M University at Qatar.

Funding Sources

The department of Electrical and Computer Engineering at Texas A&M University at Qatar provided funding for the Affordable Frequency Selective Hearing Amplifier project.

NOMENCLATURE

NITS	Noise – Induced Hearing Threshold Shifts
NIHL	Noise – Induced Hearing Loss
NHANES	National Health and Nutrition Examination Surveys
FDA	Food and Drug Administration
OTC	Over-the-Counter
ADC	Analog-to-Digital Converter
DAC	Digital-to-Analog Converter
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
LED	Light Emitting Diode

1. INTRODUCTION

1.1 Motivation

The sense of hearing is one of the most powerful senses that people have. Hearing is a mechanical sense that converts physical vibrations into electrical signals, that enables people to hear sounds [1]. Hearing abilities vary among individuals, with some having a greater frequency range than others. Older individuals, in particular, often experience hearing loss and are unable to hear high frequencies [2]. The National Institute on Deafness and Other Communication Disorders (NIDCD) has reported that only 16 percent of people between the age range of 20 – 69 have obtained hearing aids, but 30 percent of people above the age of 70 have used or are using hearing aid devices [3].

In the United States, 35 million of the population suffer from some degree of hearing loss [4]. In both 2008 and 2018, as shown in Figure 1, the U.S. was estimated to be the fourth-highest country with the greatest number of people suffering from hearing loss [5]. However, more than 25 million of people with hearing loss in the U.S. do not have hearing aids [6]. Several individuals in the U.S. fall below in the low-income bracket. This factor leads to a high percentage of the population being unable to afford a hearing aid, the costs of hearing aids could reach up to more than $2,000 [7]. Meanwhile, insurance companies do not cover the total cost of a hearing aid. Therefore, several low-earning individuals are unable to afford the high-priced hearing aids.

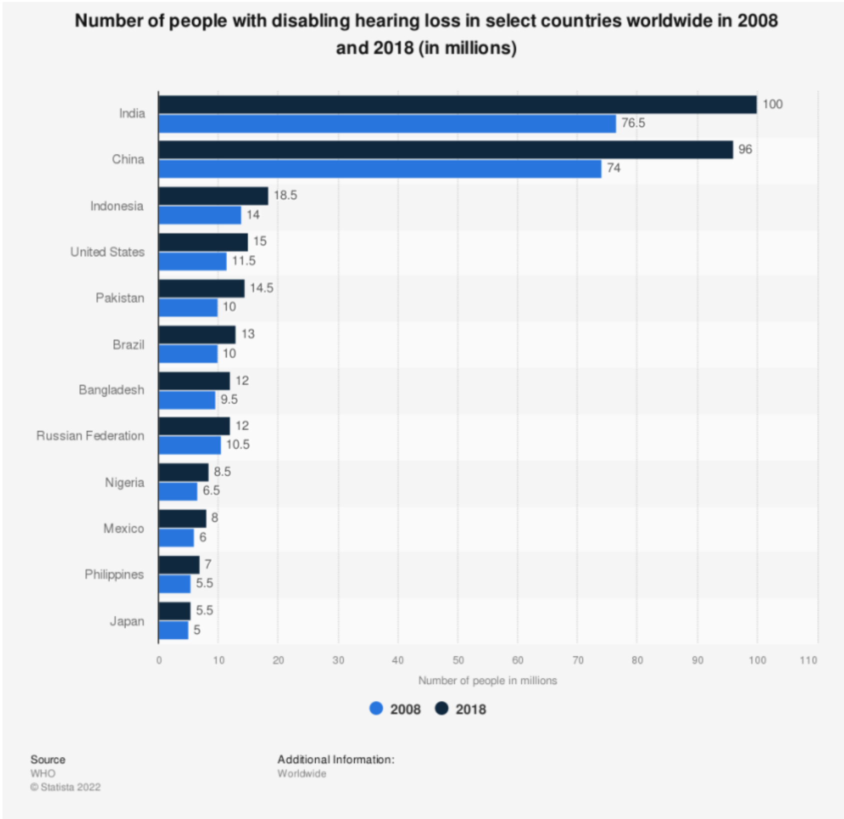

Figure 1: Number of people in millions with hearing loss worldwide in 2008 and 2018 [5].

1.1.1 Causes of Hearing Loss

Hearing loss is a reduction in the ability to hear sounds, which can occur in one or both ears. There are several types of hearing loss, including conductive, sensorineural, and mixed hearing loss [8].

1.1.1.1 Conductive Hearing Loss

Conductive hearing loss happens when sound is prevented from traveling effectively to the inner ear a problem in the outer or middle ear prevents sound from traveling effectively to the inner ear. This type of hearing loss can be caused by various factors, including blockages in the ear canal, fluid in the middle ear [8], or otosclerosis, which is an abnormal bone growth in the middle ear [9].

1.1.1.2 Sensorineural Hearing Loss

Sensorineural hearing loss is caused by damage to the inner ear or the auditory nerve, which carries sound from the inner ear to the brain. The causes of this hearing loss can be aging, which is also known as presbycusis, exposure to loud noise, certain medication like ototoxic medications, head injuries and trauma, diabetes, or infections like measles and meningitis [8]. Ménière's disease, a disorder in the inner ear that affects an individual's hearing and balance [8], can also cause temporary or permanent hearing loss, which occurs when there is a build of fluids in the inner ear [9].

1.1.1.3 Mixed Hearing Loss

Mixed hearing loss is a combination of conductive and sensorineural hearing loss. The main causes of mixed hearing loss are genetic disorders, infections, and head trauma [10]. Mixed hearing loss can also arise progressively over a period of time if one hearing loss is worsened by another. A person with long-standing conductive hearing loss, for example, may have age-related hearing loss (sensorineural) as they age [10].

1.1.2 Effect of Hearing Loss on Adults

A study conducted by Dr. Hossein Mahboubi at the University of California Irvine showed that approximately 23 million adults aged 20 – 69 years old in the United States, suffer from noise – induced hearing threshold shifts (NITS), which is the first symptom of noise – induced hearing loss (NIHL) [11]. The study initially included 2,543 males and 2,863 females, which totaled to 5,406 individuals who underwent audiometric screenings; all the data was included in the National Health and Nutrition Examination Surveys (NHANES) database [12]. Evaluations were focused on estimating the prevalence of unilateral, bilateral, and complete NITS, as well as the correlations between hearing threshold, gender, and age groups. Individuals who have bilateral NITS suffer from hearing loss in both ears, whereas individuals with unilateral NITS have hearing loss in one ear only. Subjects who were diagnosed with total NITS are considered to have severe hearing loss.

Based on the study, the unilateral and bilateral NITS prevalence was 9.4% and 3.4% respectively [12]. The prevalence of total NITS is the highest, as the results show that 12.8% of the population have total hearing loss [12]. The study's results show that the prevalence of hearing loss is more prominent in white and Hispanic men aged 40 years old and older [12]. The results show that 15.1% of the males tested have unilateral NITS, and 6.4% have bilateral NITS [12]. In contrast, the prevalence of unilateral and bilateral NITS in females tested were only 4.3% and 0.7%. The prevalence of overall NITS was found to be 21.5% in males, and 5% in females [12].

Older people with audiometrically measured hearing loss are less likely to report hearing problems, despite the fact that they are more likely to have high-frequency losses and their speech frequency losses are more severe than the losses younger people experience, as explained by Dr. Kathleen Bainbridge and Dr. Margaret Wallhagen [12]. In Figure 2, it is illustrated that individuals under the age of sixty years old are more likely to diagnose themselves with hearing loss, as opposed to the older individuals whose hearing losses were audiometrically assessed [13]. Furthermore, the findings of the study show gender variations in the prevalence of NITS. Males had a higher prevalence of unilateral and bilateral NITS than females, as shown in Figure 2a versus Figure 2b.

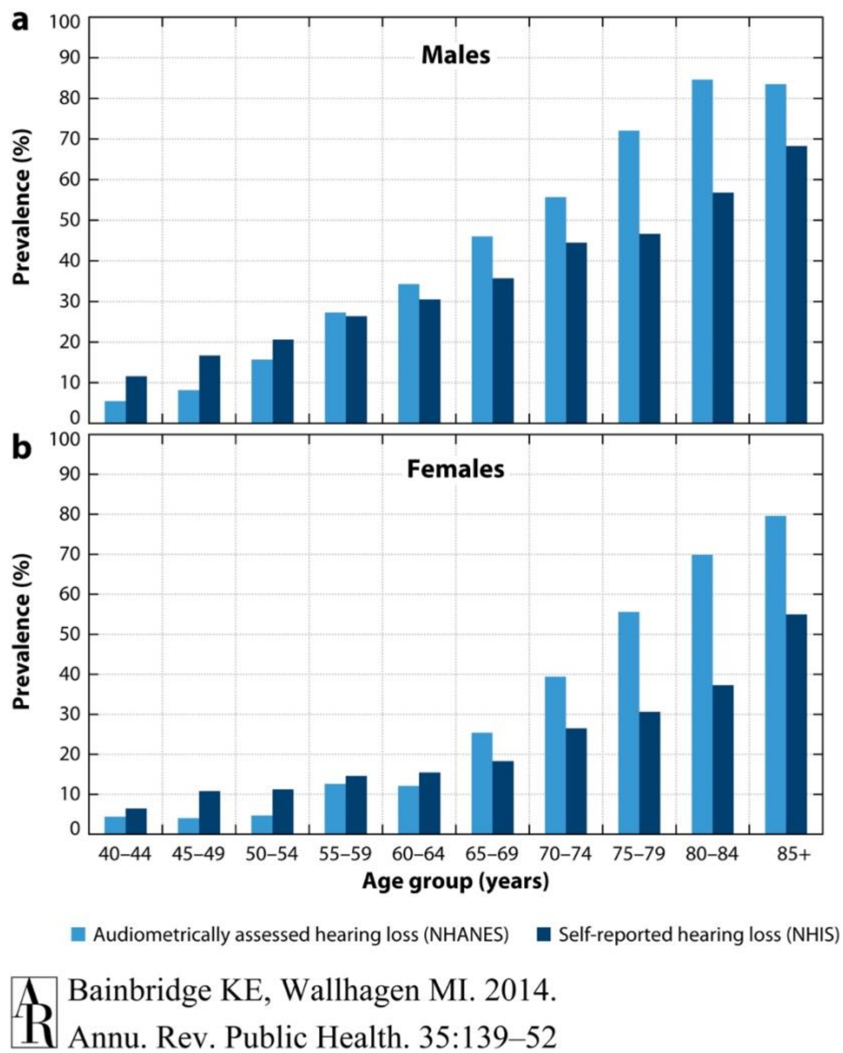

Figure 2: a) Prevalence of audiometrically assessed and self-reported hearing loss by age group in males. b) Prevalence of audiometrically assessed and self-reported hearing loss by age group in females [13].

The prevalence of hearing loss in the United States has changed over time. The prevalence of mild and severe bilateral hearing loss among males and females in the United States is depicted in Figure 3. It can be observed that the male population aged 20 – 69 years is more likely to have bilateral hearing loss than females in the same age group. Additionally, the figure indicates that the prevalence of hearing loss has declined during the 1990s and stabilized since the 2000s. The plot in Figure 3a shows that the prevalence of bilateral hearing loss is always high until around 1995, where the percentage and the range have decreased. In contrast, the prevalence of the female population aged 20 – 69 years old with bilateral hearing loss is almost half, as seen in Figure 3b.

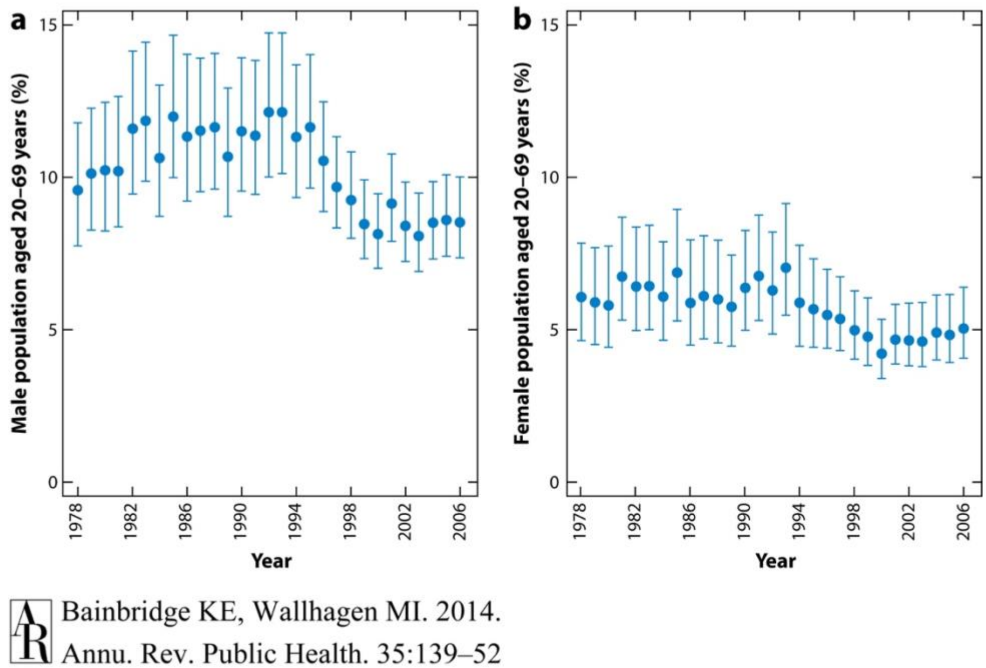

Figure 3: a) Age-standardized prevalence of bilateral hearing loss by age group in males. b) Age-standardized prevalence of bilateral hearing loss by age group [13].

It is estimated that by the year 2030, the number of people aged 65 and older in the United States will have increased from fewer than 48 million to approximately 73 million [13]. It is anticipated that more than 41 million persons aged 65 and older will suffer from hearing loss, either unilaterally or bilaterally [13].

1.1.3 Effect on Work Environment

As the prices of hearing aids available nowadays are unaffordable, individuals with low incomes cannot afford to purchase one. The cost issue significantly affects employees' lives as they experience a more challenging work environment than those with normal hearing. A decrease in an individual's yearly income due to hearing loss could be decreased by $30,000, thus collecting a wage of $23,481 on average, while individuals with typical hearing receive $31,272 on average [14]. This is a significant amount, especially for those with low incomes, and can have long-lasting effects on an individual's financial stability. Individuals who suffer from mild hearing loss tend to avoid income losses as the risk reduces by 90% – 100%, while for those with moderate to severe hearing loss, the risk is reduced by 65% – 77% [14].

In noisy workplaces such as construction sites, hearing loss may cause numerous issues. An individual with hearing loss may have difficulty understanding or communicating with colleagues, leading to misunderstandings and miscommunications, or even causing a safety hazard [15]. Additionally, this can also result in decreased productivity, as individuals may take longer to complete tasks or may make more errors due to communication difficulties.

Those who have hearing loss may also experience feelings of isolation and exclusion in the workplace, both of which can have a negative impact on the individual’s general well-being as well as their level of job satisfaction [16]. Furthermore, accident risks increase when the workers cannot hear warning signals or alarms, which can not only put themselves in danger but also their colleagues.

It is essential for employers to provide support and accommodations for individuals with hearing loss to ensure that they can perform their job duties to the best of their ability. Some accommodations include implementing emergency notification systems, like strobe lights on fire alarms, and providing assistive listening devices for the individuals [14].

1.2 Background

Hearing aids are electronic devices that capture surrounding sounds via a microphone. The signals are converted and amplified from analog signals to digital signals to send to the speaker [17]. Hearing loss is classified into distinct degrees of severity, as represented in Table 1 in an article by an audiology researcher, Dr. John Clark [18].

Table 1: Hearing loss severity levels.

Severity level of hearing loss	Sound level
Normal hearing	-10 dB – 15 dB
Slight hearing loss	16 dB – 25 dB
Mild hearing loss	26 dB – 40 dB
Moderate hearing loss	41 dB – 55 dB
Moderately severe hearing loss	56 dB – 70 dB
Severe hearing loss	70 dB – 90 dB
Profound hearing loss	91+ dB

Hearing aids play a crucial role in assisting people with hearing problems, especially the elderly. The elderly aged 70 and above have gradually lost higher frequencies of sound signals, and around one-third of this age category requires a hearing aid [19]. However, the high cost of hearing aids continues to be an impediment for many people; the price is affected by several factors such as equipment used, the technology used, and the services provided by the audiologist for self-adjustment and the customization of the hearing aid [3]. The Food and Drug Administration (FDA) has recently raised the Over-the-Counter Hearing Aid Act, which allowed hearing aid to be accessible and affordable for adults in the U.S. [20]. This act allows hearing aids to be sold directly to customers without requiring a doctor's medical examination or prescription. This can assist to lower the cost of hearing aids and make them more affordable for people in need.

Hearing aids have been developed for mild-moderate hearing loss, where the signals ranging from 250 Hz – 8 kHz were amplified to three settings (45, 55, and 65 dBA) with two adjustments, for increasing the volume and fine-tuning the signal [21]. One of the main reasons for the high cost of hearing aids is the equipment used to manufacture them, such as microphones that convert sound into a digital signal. To address this issue, researchers created Micro-Electro-Mechanical Systems (MEMS) microphones that are not only more cost-efficient but also more power efficient. These microphones are intended for use in hearing aid applications and have a frequency range of 100 Hz to 10 kHz. Another factor contributing to the high cost of hearing aids is the employment of specific batteries that are only available in clinics. Researchers have found that rechargeable hearing aids would be more cost-effective in the long run since they would eliminate the need for regular battery changes [22].

1.2.1 Benchmarking

Previous research of similar projects has been gathered and analyzed which is essential before designing any project to know how previous solutions were specifically designed, tested, and used. Table 2 shows the difference between our proposed solution and two other existing solutions in the market. On one hand, Lively 2 Lite is a hearing aid with a frequency range of up to 9.5 kHz and will be pre-programmed based on each individual's hearing loss. Thus, the hearing aid will provide the user with an output closer to the natural sound heard by those with typical hearing with an amplification of 50 dB for mild to moderately severe cases. However, the price of this hearing aid is $1,195 [23].

On the other hand, Audien EV1 Hearing Aid is a low-priced hearing amplifier with a cost of $89.00, this is approximately close to our proposed solution. The Audien EV1 Hearing Aid has an amplification range of 300 Hz – 4500 Hz and is recommended for individuals with mild to moderately severe hearing loss [24]. The amplification of sounds is only for low and mid ranged frequencies, as the Audien EV1 hearing aid does not amplify sounds with high frequencies [24]. Our design aims to provide easiness to the users where the filtering and amplification happen due to the selection and choice of the user.

Table 2: Comparison between existing products and our proposed solution.

	Lively 2 Lite [25]	**Audien Hearing Aids EV1 [24]**	**Proposed Solution**
Technical Approach	Uses Digital Signal Processing	Amplifies low – medium frequencies	Design filter to amplify frequency bands, using microcontroller depending on the user switch selection
Price	$1,195.00	$89.00	$38.96
Technical compliance with Standards	FDA, IP68	FDA certified	FDA-2020-D-1380
Amplified Range	Pre-Programmed for each person	300 Hz – 4500 Hz	125 Hz – 8000 Hz
Type of hearing loss	Mild to moderately severe 50 dB	Mild – Moderately Severe 20 dB – 50 dB	Mild to moderately severe 40 dB
Mode of Operation	Need smartphone device to control and modify the settings	Only volume knob to adjust volume	Doesn't need any external device. Controlled through three mode switch and volume knob

1.3 Benefits

Patients suffering from hearing loss having the opportunity to be able to finally listen to their surroundings would result in a boost in excitement and joy. Untreated hearing loss could increase the risk of suffering from various health issues.

1.3.1 Improved Social and Health Life

The audiology expert Harvey Abrams mentioned "People begin to withdraw from activities that would put them in touch with others and that can lead to loneliness and depression [26]." An increase in the number of individuals having access to an affordable hearing aid to use for prolonged periods of time would make them feel less isolated from social interactions and thus reducing the risk of dementia and depression. In an article published by the Boys Town Hospital, a man named Curt Crouch has struggled with hearing loss for several years, which made it difficult to participate in gatherings, as he was not able to clearly hear the conversations, which made the individual feel disconnected [27]. However, when he had acquired hearing aids, he was able to rediscover the joy of being a part of conversations and interactions; said by Crouch "It's nice to be part of the whole activity during the holidays when there are lots of people around [27]."

Using a hearing aid will also reduce the chances of the person losing their ability to balance as the brain no longer has to work harder to process sound, allowing it to focus on other tasks.

1.3.2 Employment Opportunities

People with hearing loss would struggle to have normal conversations with people. This could be detrimental to their pursuit of employment, therefore leading to a great loss in income as mentioned in Section 1.1.3. With an affordable hearing aid, individuals are now able to apply for jobs that rely on human interaction, and this, in turn, will contribute to economy of the country.

1.3.3 Developing Creativity

Hearing loss would mean that people are unable to develop different hobbies such as learning musical instruments. Treated hearing loss enables individuals to explore different hobbies and improve upon existing ones. Developing hobbies allows individuals to be creative, which enables them to express themselves in different ways thus increasing internal satisfaction. This could reduce the risk of suffering from health problems such as depression.

1.3.4 Educational Improvements

Hearing aids could be used as assistive technology to help children born with hearing disabilities develop their language and provide them with learning experiences similar to those with typical hearing, by being able to hear the teacher's explanation and interacting in the classroom. Also, it will develop their social skills in the school environment and will prevent them feelings of isolation or difference.

1.4 Objective

This project aims to tackle the issue of expensive hearing aids that result in many people being unable to afford them. The controller will allow the user to select from a frequency band that will be amplified. The user selection will depend on which frequencies they are able to hear the least. Creating a more standardized product will allow us to keep the costs low and be accessible to more people who suffer from hearing loss and are unable to afford the high prices set by manufacturers.

1.5 Standards Followed

The FDA has established regulatory requirements for Over-the-Counter (OTC) hearing aids and amplifiers in docket FDA-2020-D-1380, which grants adults with hearing impairment immediate access to the devices without needing a medical prescription or audiometry tests. The

OTC hearing aids must satisfy the rules, which include labeling, performance characteristics, and design requirements [28].

The 21 CFR 800.30 standard published by the Federal Register in the Code of Federal Regulations (CFR) requires that any warnings and necessary information regarding the hearing aid must be clearly labeled on both the inside and outside of the package. Additionally, a diagram must be included in the package that illustrates the operating controls, user adjustments, and the battery compartment, as well as information and instructions on how the controls can be adjusted for the user. The OTC hearing aids shall function within numerous electroacoustic limits, including but not limited to the frequency bandwidth response, where the frequency can reach below 250 Hz and above 5 kHz [29].

2. METHODS

2.1 System Overview

The project's main goal is to address the issue of prohibitively expensive hearing aids that prevent people with hearing loss from purchasing them. As a result, the costs will be kept low along with making the product accessible to people in the market and help countries escape the monopoly that large hearing aid manufacturers create by setting extremely high prices. Therefore, to achieve these goals, a frequency-selective hearing amplifier device that detects the sound signal and amplifies a frequency band based on the user's selection is designed.

The entire module consists of a printed circuit board (PCB) that hosts the filters and amplifiers. To begin with, the audio signal from the microphone on the designed device is picked up and an Analog-to-Digital Converter (ADC) converts these analog signals to digital signals. Based on the position of the switch which corresponds to the user's selection on the device, one of three frequency bands 125 Hz to 1 kHz or 1 to 4 kHz or 4 to 8 kHz is amplified depending on which one is selected on the device. The entire signal will pass through a filter, and the required frequency band based on the selection will be amplified and added back to the original signal allowing the user to clearly hear all bands at a normal rate rather than amplifying all bands. This will eliminate the discomfort that most lower-end hearing aids cause as they amplify all frequencies and are not sustainable for long-term use. This whole process will occur in the microcontroller and a Digital-to-Analog Converter (DAC) converts the signal to an analog signal. Therefore, this signal will be output using the separate earpiece used by the user as illustrated in Figure 4.

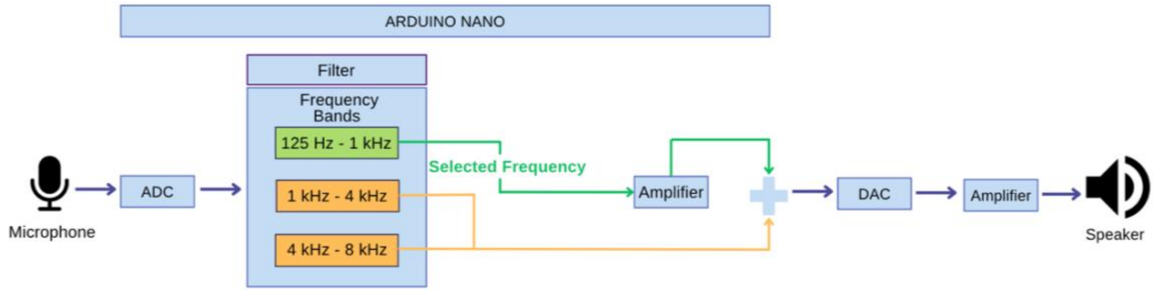

Figure 4: Example of a 125-1 kHz frequency band being amplified. The other two frequency bands bypass the amplification stage and are added to the amplified version of the 125 - 1 kHz band.

The reason behind choosing these specific ranges of frequency bands is because most of the speech information is within the band 125 Hz to 8 kHz and the conventional audiogram is also done over the same frequency range. We aim to make a hearing aid compatible with mild to severe hearing loss cases by only amplifying the non-heard frequency band depending on the hearing loss profiles of the listeners. We took this range of 125 Hz – 8000 Hz and divided it into three frequency bands, which will serve as the basis for the frequency selection option on our device. One of the unique features of the device apart from it being affordable to a wide range of patients, is that this frequency selection method on the device is easier to make and accessible to all. The users will be provided with step-by-step instructions on a user guide document to ensure that they know exactly how the hearing aid works and can refer to it in case of any issues that may occur. The user guide will have specific details such as how to pick the preferred frequency band, whether it is 125 Hz to 1 kHz or 1 kHz to 4 kHz or 4 kHz to 8 kHz, and how or where to place the separate earpiece. Another unique feature is the separate earpiece option is available, therefore unlike actual hearing aids where patients are required to customize the hearing aid based on the size of the ear, the user can use a comfortable separate earpiece that specifically fits their ear.

The difference between the female and male frequencies and harmonics are immense which is an important factor that has been considered throughout the design. The fundamental frequencies of a female voice, which are the lowest and most prominent frequencies of the voice, normally vary from 350 Hz to 3,000 Hz [30]. This range is substantially higher than the frequencies of a male voice, which normally has a peak frequency of 900 Hz and begin around 100 Hz [30]. Another prominent difference between male and female voices is the range of their harmonics. The harmonic range of female vocals is normally between 3,000 and 17,000 Hz, while harmonics in male voices normally span from 900 to 8,000 Hz [30].

2.2 Components Used

To ensure that the project is working in an efficient matter, we went through various testing stages and challenges that resulted in remove, adding, and changing different components. Many different types of components were tested to make sure that the right one was used within the final design.

Table 3 below shows all the components used throughout this project including all components used for the testing stage and the final project design. However, several components were only used for the purpose of testing and were removed from the final design of the device as they were no longer needed. One of the most important factors considered when choosing the components of the project was the price of each of these components to maintain low costs. Another factor was quality, even though low-cost products were used to ensure an affordable device for the users, it is essential to consider good quality components to achieve the main goals of the project.

Table 3: Components used throughout the project.

Components Used
LMP393 OMNI Directional Microphone
Arduino Uno/Nano
20KΩ Potentiometer
Amplifier
UDA1334 DAC
Amplifier with Volume Knob
6W Speaker
Light Emitting Diode (LED)
2-Switchers
Resistors and Capacitors
Battery
Oscilloscope and Function Generator

2.2.1 Microphone

To verify the use of a proper microphone that is appropriate for this particular application, many different types of microphone component types were individually evaluated. However, the omni-directional LMP393 microphone was found to be the most effective for the specific purpose of the project.

2.2.2 Analog to Digital Converter

An Analog-to-Digital Converter (ADC) was used to convert the analog signals picked up by the omni-directional microphone to digital signals to be understandable by the microcontroller. The ADC used is built-in within the Arduino Nano microcontroller. The built-in ADC is 10-bit therefore it has a feature of being able to scale an analog signal in a range of 0-1023 with a maximum input voltage of 5V [31]. One of the challenges faced throughout the project was that whether 10-bit ADC was to enough to amplify up to 60 dB.

2.2.3 Arduino Nano

Apart from having a built-in ADC, the original signal is filtered and amplified based on the hearing loss profiles of the listeners using the Arduino program (See Section 2.3 for more information).

2.2.4 Digital to Analog Converter

A Digital-to-Analog Converter (DAC) was used to convert the digital signals, after all the frequency ranges has been filtered and the desired frequency range were amplified and added together to analog signals. The 12-bit UDA1334 DAC was used which has a jack module that would be used for the purpose of connecting the separate earpiece by the user.

2.2.5 Amplifier

Apart from the amplification done by the Arduino program, (in Section 2.3.3: Amplifying the Signal), another amplifier component was used after the DAC, the PAM840 Amplifier, to amplify the analog signals from the DAC. Another Amplifier, with the same chip, is connected having volume knob to control the volume of the output signal. Both amplifiers, PAM8403, have a 3W power with a 4Ω Load and 5V Power Supply and with a high efficiency that could reach up to 90% [32].

2.3 Arduino Microcontroller

An Arduino Uno Microcontroller has been initially used which has a built-in ADC that converts the original signals of the surroundings. The built-in Pulse Width Modulation (PWM) within the Arduino Uno acts as a DAC converts the signals, after filtration and amplification, to digital signals along with all necessary connections as shown in Figure 5.

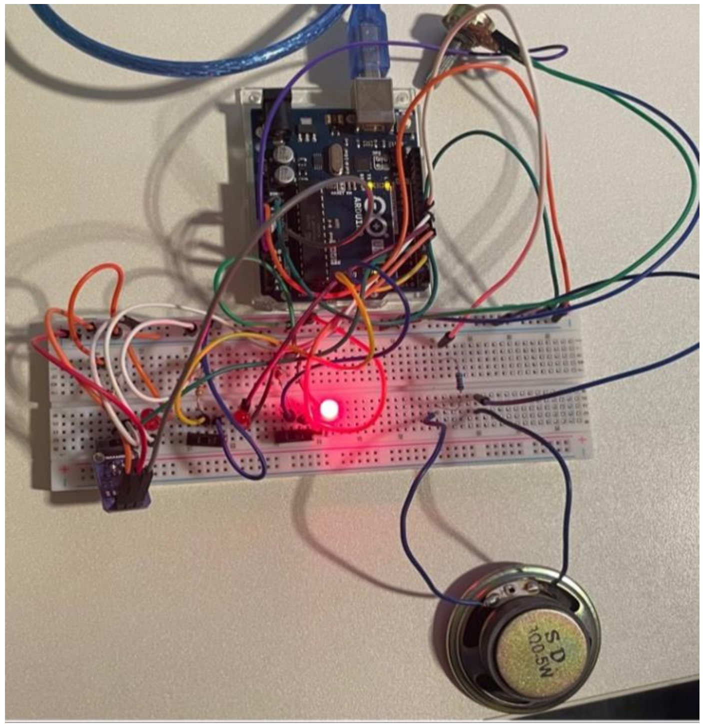

Figure 5: System overview of the circuit with Arduino Uno.

However, the Arduino Uno was then replaced with an Arduino Nano having similar connections, to allow the device to be more user friendly, portable, and smaller in size. The Arduino Nano has a built-in ADC similarly to the Arduino Uno, but a DAC was added to convert the digital signals to analog signals along with other components as shown in Figure 6.

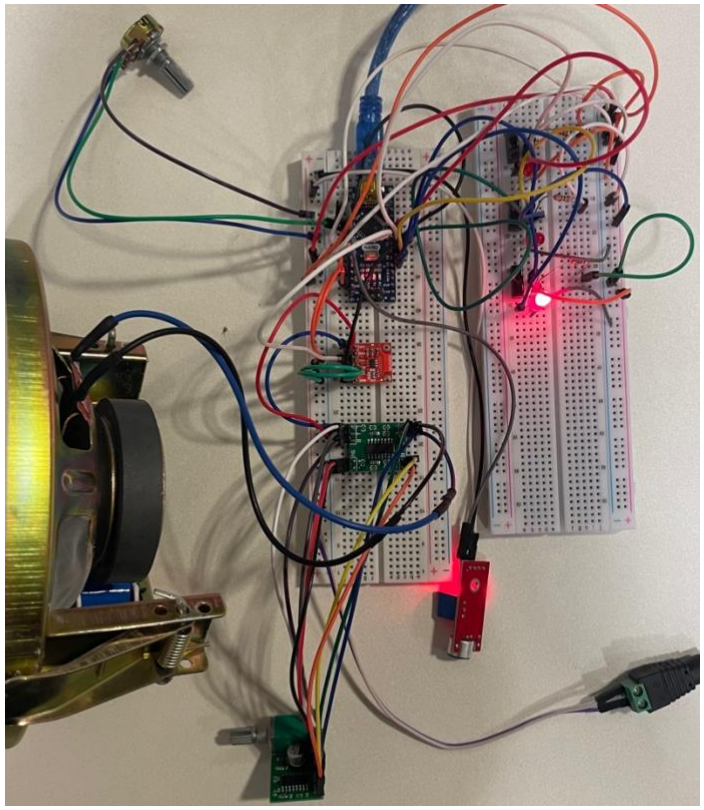

Figure 6: System overview of the circuit with Arduino Nano.

The software part of the project has been split into four different parts which will be in detail explained below.

2.3.1 Detecting the Sound Signals

The first step was to detect the sound signals by testing the microphone. Different microphone components were tested along with the required connections from the microphone component to pins A0 and GND on the Arduino Nano board. The omni-directional LMP393 microphone was found to be the most effective for the project during the testing procedure.

The section of the code for using the microphone to pick up sounds from the surroundings is represented by lines 78 and 79 (see Appendix A for the code), where the signal from the A0 pin was previously read. The value of 520 was deducted from the reading of the microphone since the adjustable gain's output level has a value of about 520 when there is no input.

2.3.2 Filtering the Signals

The second step was to carry out the filtering part of the different frequency bands after detecting the signal via the omni-directional MAX4466 microphone. This was done by applying Butterworth second order (See Appendix B: Butterworth Equation) which is a more accurate filtering method. The first crucial step done was to calculate the sampling frequency as shown below:

$$\frac{16\ MHz}{128} = 125\ kHz \tag{1}$$

$$\frac{125\ kHz}{13} = 9615\ Hz \cong 9600\ Hz \tag{2}$$

Initially, the crystal frequency of the Arduino Nano board is 16 MHz which was divided by the ADC clock speed with a value of 128 as shown in equation (1). Furthermore, the resulted value was divided by 13 because each conversion in the board takes 13 ADC clocks, shown in equation (2) above. Finally, the sampling frequency was calculated to be 9615 Hz however, this was rounded down to 9600 Hz to be understandable by the software.

This code is an Arduino program written in C++ that implements a real-time signal processing application. It uses a potentiometer and three switches to select different cut-off frequencies for two Butterworth filters. The section of the code for filtering the signals of the three different bandwidths are represented by lines 28 to 79 (see Appendix A for the code). The header files "Filters.h" and "AH/Timing/MillisMicrosTimer.hpp" are included, which provide functions for digital signal processing and timing control, respectively. The library was used as it has a built-in function to calculate the coefficients of the Butterworth second order equation. The pin assignments are defined using #define statements, and the pin modes are set in the setup function. Lines 28 to 34 were used to declare and initialize all the necessary variable needed throughout the code. The gain and sampling frequency are declared as float and double variables, respectively.

The sampling frequency was set to 9600 Hz in the code as shown from the calculation above. Then, the lower and higher cut-off frequencies for the two Butterworth filters were initialized to 1000 Hz and 4000 Hz respectively. The normalized cut-off frequencies were calculated from the actual cut-off frequencies and sampling frequency. The lower and higher normalized cut-off frequencies were first initialized to their main equation to further be calculated within the code. The equation for the normalized lower and higher cut-off frequencies are shown below in equation (3) and equation (4), respectively.

$$Lower\ Normalized\ Cut-Off\ Frequency = \frac{2 \times Lower\ Cut-Off\ Frequency}{Sampling\ Frequency} \quad (3)$$

$$Higher\ Normalized\ Cut-Off\ Frequency = \frac{2 \times Higher\ Cut-Off\ Frequency}{Sampling\ Frequency} \quad (4)$$

A Timer object was created using the "micros" template, which measures the time interval between successive samples at the sampling frequency. This was used to plot the graph in terms of microseconds per sample. Within the Arduino software, the second order Butterworth low and high pass filtering was created. Two Butterworth filters are created using the "butter" function template from the "Filters.h" library. The filter order is set to 2, and the normalized cut-off frequencies are passed as arguments.

Furthermore, the program was designed to turn ON the desired LED based on the frequency band of the switch. The three switches are checked using the digitalRead function to select different cut-off frequencies for the two Butterworth filters. For example, when the desired frequency band is 125 Hz – 1 kHz, the first LED will be turned ON and similarly for the other two frequency bands therefore the cut-off frequencies will be modified within the code based on the selected band. Otherwise, if none of the switches are pressed, all the LEDs will be OFF, and the default cut-off frequencies will be used based on the whole frequency band range so the lower cut-off frequency will be set to 125 kHz while the higher cut-off frequency will be set to 8 kHz. In addition, based on the if statements in the code, the normalized lower and higher cut-off frequencies will be updated. The filtered signal and the original signal are sent to the serial port for visualization using the Serial.print function.

2.3.3 Amplifying the Signal

The third step was to amplify the desired signal based on the position of the switch on the device. Currently, a 20 kΩ potentiometer was used as an input and defined at the header of the code while connected to an Analog Port to control the gain (see Appendix A for the code). The gain variable reads and converts the analog values from the potentiometer to gain values ranging from 1 to 25. The generated filtered signal was multiplied by the gain to get the amplified signal. However, the initial main goal of this project is to amplify the desired frequency band up to 50 dB – 60 dB.

2.3.4 Flow Chart of the Code

The flow chart shown in Figure 7 represents the steps used within the software part of the project (See Appendix A for the code).

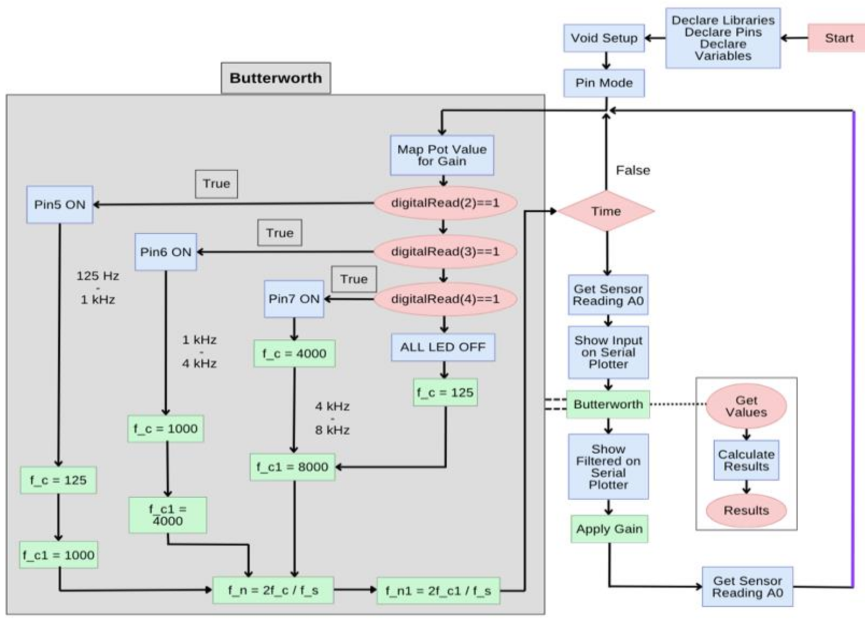

Figure 7: Flow Chart of the code in Arduino. This figure was generated using Canva.

2.3.5 Output Signal via the Speaker

To test the audio a 6W speaker, as shown in Figure 6 above, was used to test the audio signal. The 6W speaker has been further removed and replaced by the DAC which has a jack module to be used to insert the separate earpiece into the device by the user along with the connections shown in Figure 8.

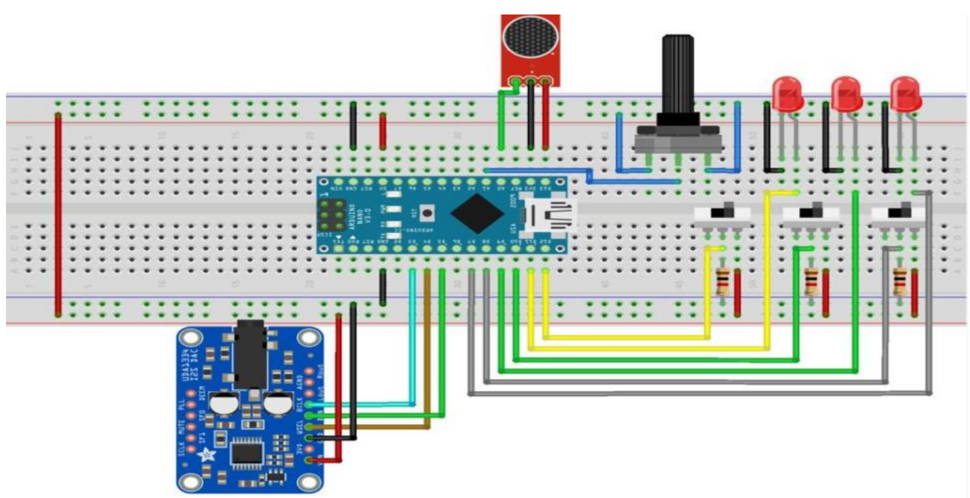

Figure 8: Connections of the breadboard. This figure was generated using Fritzing.

2.4 Hardware

After testing and ensuring that the circuit works properly, energy calculations were done based on the components used for the final device to calculate the battery needed for the hardware design. The final components of the circuit are:

- Microphone
- Arduino Nano
- Potentiometer
- Three switches
- Three 100Ω resistors
- Three LEDs
- UDA1334 DAC
- Separate earpiece

To calculate the battery needed, it is essential to consider the main power-consuming component. The Arduino Nano has a power consumption of typically around 0.1W while the UDA1334 DAC has a power consumption of approximately 0.05W. The small earpiece power consumption can vary, but to carry out the calculation an assumption of 0.1W is considered while the three LEDs have a power consumption of only 0.1W (since only one LED lights up at a time). Therefore, the total power consumption is calculated by summing up power consumption of each component as shown in equation (4) below.

$$Total\ Power\ Consumption = 0.1W\ +\ 0.05W\ +\ 0.1W\ +\ 0.1W\ =\ 0.35W \tag{4}$$

Then, we need to calculate the energy required in watt-hours (Wh) for the system to have a 1-hour backup time. The formula for calculating the energy required is shown below in equation (5).

$$Energy\ required\ =\ Total\ power\ consumption\ *\ Backup\ time \quad (5)$$

$$=\ 0.35W\ \times\ 1h\ =\ 0.35Wh$$

To convert this energy into milliampere-hours (mAh), we need to know the battery voltage. Assuming a 5V battery, the formula for calculating the battery capacity is shown below in equation (6).

$$Battery\ capacity\ (mAh)\ =\ (Energy\ required\ (Wh)\ /\ Battery\ voltage\ (V))\ *\ 1000 \quad (6)$$

$$=\ (0.35Wh\ /\ 5V)\ *\ 1000\ =\ 70mAh$$

Given that the Arduino Nano requires 5V to start working, it should be considered to use a battery with a slightly higher capacity than the calculated value above to consider any issues such as inefficiencies or variations in component consumption. A 100mAh or 150mAh 5V battery should be sufficient for this project design.

A Printed Circuit Board (PCB) is designed by constructing the circuit on EAGLE CAD, and 3D printing will be used to produce a case for the device with a suitable power supply.

3. RESULTS

3.1 Introduction

In this section, we will describe the results from the output of different parts of the project including the signals from the microphone, processed signals through filtering and amplification as well as the final amplified signal from the output of the DAC, in order to demonstrate and ensure that the device is working properly as specified.

3.2 Microphone Signals

To begin with, the first step done was to pick up the initial sound signal by the microphone (when "Hello ECEN" was said into the microphone) with all circuit components properly connected to the microcontroller and other components. Figure 9 shown below illustrates the original sound signal without any filtering or amplification done. This step was essential to test and ensure that the microphone is working properly before carrying out the filtering and amplification steps. The plot generated has the x-axis in microseconds and the amplitude of the acting frequency in milli-decibels on the y-axis.

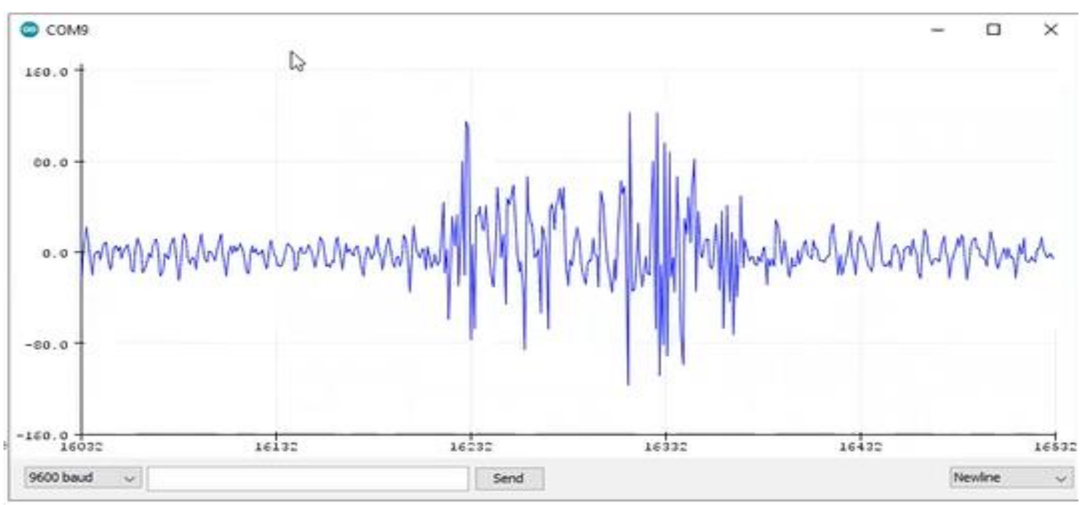

Figure 9: Output of the microphone.

3.3 Filtered Signals

After ensuring that the microphone signal is picked up, this initial sound signal when ("Hello ECEN") was compared with the filtered signals for all three frequency bands individually for 125 Hz to 1 kHz, 1 kHz to 4 kHz, and 4 kHz to 8 kHz as shown in Figures 10, 11, and 12 respectively. On the plots, the blue lines represent the original signal while the red one represents the filtered signal, the time is measured in microseconds on the x-axis and the amplitude of the acting frequency in milli decibels on the y-axis.

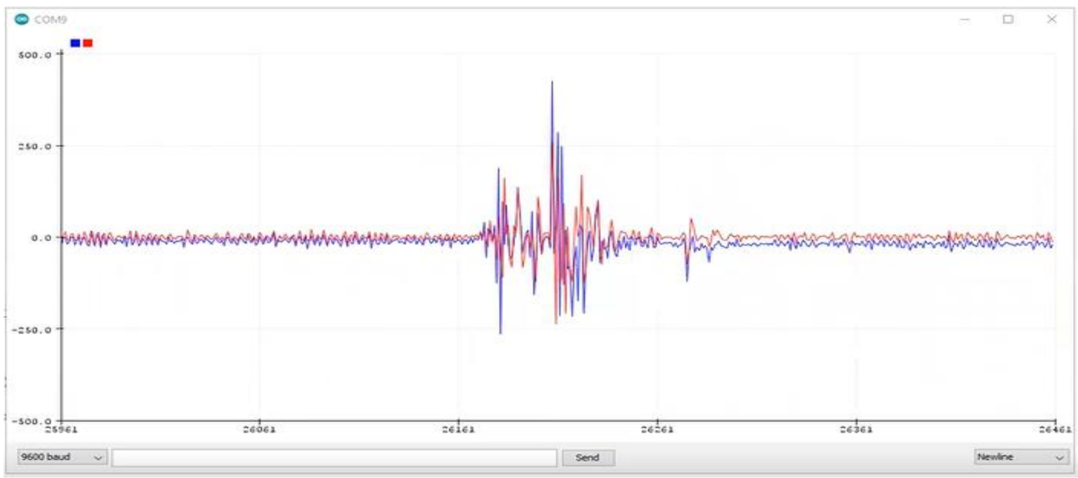

Figure 10: Original and filtered signals for the 125 kHz to 1 kHz frequency band.

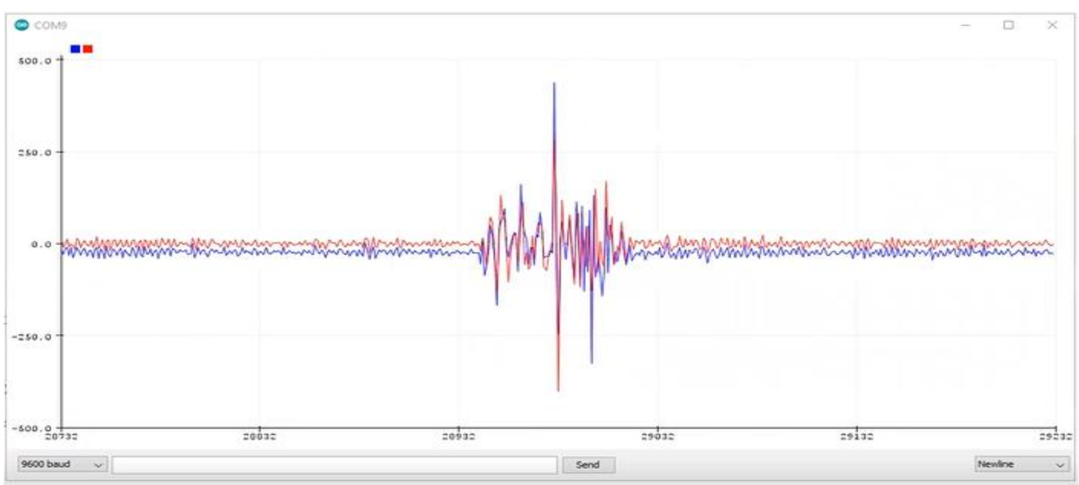

Figure 11: Original and filtered signals for the 1 kHz to 4 kHz frequency band.

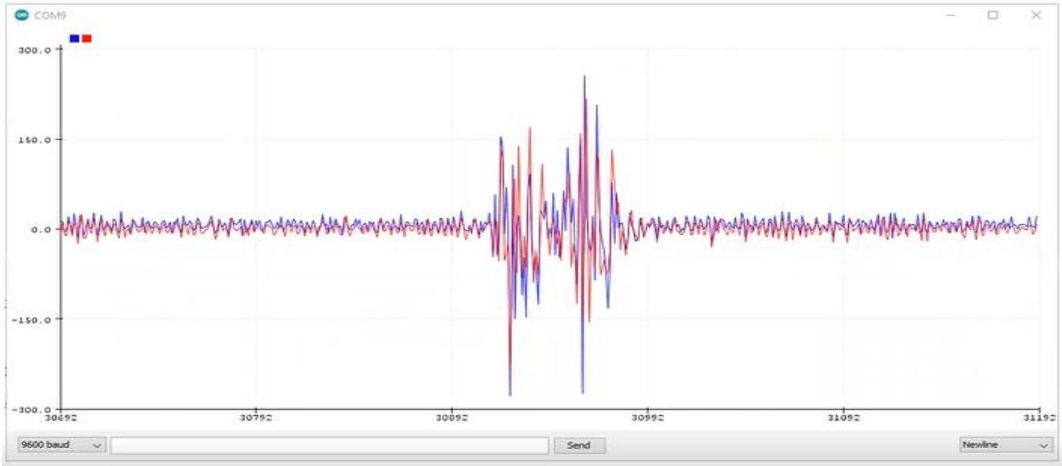

Figure 12: Original and filtered signals for the 4 kHz to 8 kHz frequency band.

3.4 Amplified Signals

After the original sound was filtered (See Section 3.2), the filtered signal was amplified by 24 dB and compared with the filtered signals for all three frequency bands individually for 125 Hz to 1 kHz, 1 kHz to 4 kHz, and 4 kHz to 8 kHz as shown in Figures 13, 14, and 15 respectively. On the plots, the blue lines represent the filtered signal while the red one represents the amplified signal, the time is measured in microseconds on the x-axis and the amplitude of the acting frequency in milli decibels on the y-axis.

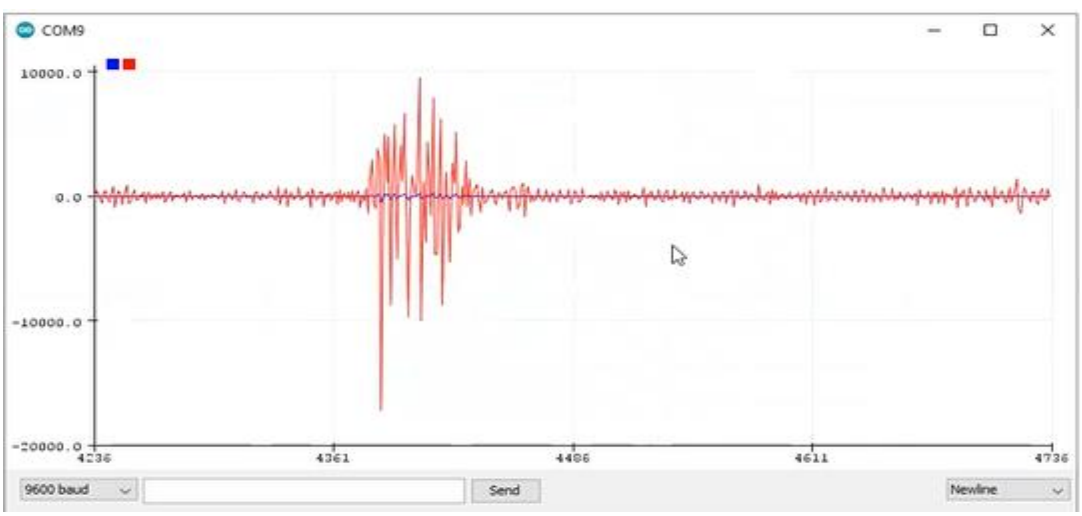

Figure 13: Filtered and amplified signals for the 125 kHz to 1 kHz frequency band.

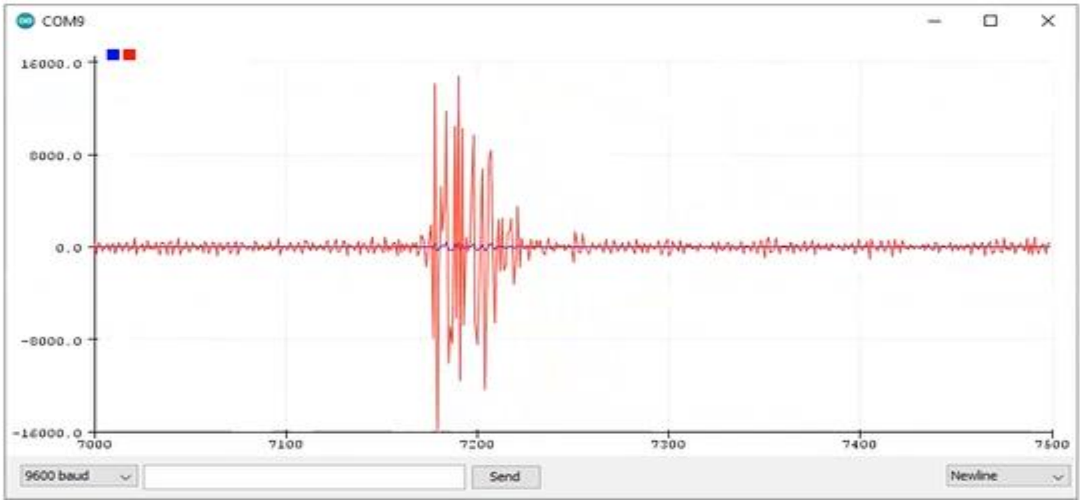

Figure 14: Filtered and amplified signals for the 1 kHz to 4 kHz frequency band.

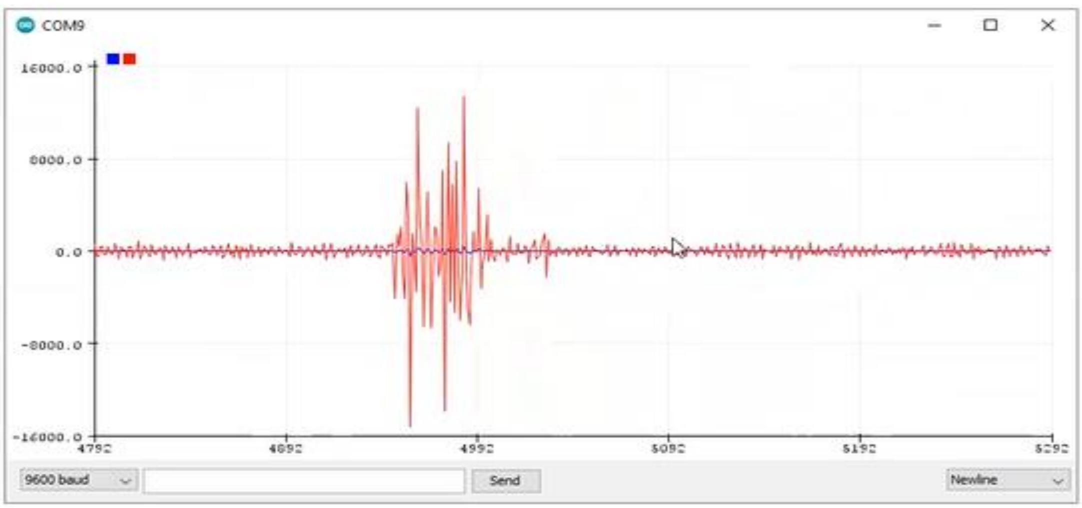

Figure 15: Filtered and amplified signals for the 4 kHz to 8 kHz frequency band.

As we can notice in the figures above, initially, the maximum amplified range within the Arduino is up to 24 dB as shown in the Figures above. However, after connecting all the components needed for the final design including a potentiometer, to control the gain, the maximum amplified range could be increased to up to 40 dB.

3.5 Cost Analysis

To maintain one of our unique features of being affordable, a huge amount of research has been done to ensure the using of effective components with low prices for the project. Table 4 below shows the components used in the final project with each corresponding price. Summing up all the components used for one device, the total cost is $30.5.

Table 4: Individual components used with their corresponding prices.

Component	**Price (per component)**
OMNI Directional Microphone	$3.57
Potentiometer	$0.27
Arduino Nano	$6.87
Digital to Analog Converter with Headphone Jack	$8.99
Resistors (x3)	$0.06
LED (x3)	$0.16
2-Switcher (x3)	$0.40
Battery	$8.94

4. CONCLUSION

Hearing loss can be caused by various factors such as genetics, aging, ear infections, and exposure to loud noises. It was found that NITS was more common among men, older adults, and those with lower income and education levels [11]. Untreated hearing loss may have severe consequences, with an increased risk of experiencing a variety of health problems, including mental health issues such as depression due to social isolation [26]. In order to reduce the negative effects of hearing loss, hearing aids have been designed to amplify sound and make it easier for people with hearing difficulties to hear.

Hearing aids can be expensive, and not everyone can afford them. In today's market, there is demand for low-cost, personalized hearing aids that fulfill standard technical compliance. As a result, the research was conducted to develop a hearing aid that is both affordable and satisfies the needs of persons with varied degrees of hearing loss. The aim has been on developing a device with adjustable gains in numerous frequency bands to assist individuals with varying degrees of hearing loss.

The frequency selection approach adopted in this design offers users a range of frequency bands to select from, including 125 Hz – 1 kHz, 1 kHz – 4 kHz and 4 kHz – 8 kHz. This approach ensures that the hearing aid is useful for everyone, regardless of gender, i.e., the female voice has higher fundamental frequency as compared to the male voice. The frequency selection switch also makes the product unique and cost-effective, as commercially available hearing aids digitally process the entire bandwidth of the audio signal, resulting in higher costs.

The design architecture of the low-cost adjustable hearing device includes multiple processes. A microphone detects the sound signal, which is then converted from analog to digital via ADC. The signal is then filtered using a Butterworth 2nd order filter based on the frequency selections made by the user. The filtered signal is amplified and then converted back to the analog domain by the DAC. The design processes are carried out using the Arduino Nano board, which is more user-friendly, portable, and smaller in size when compared to the Arduino Uno board.

To test the efficacy of the adjustable hearing device, it was tested with the input audio signal "Hello ECEN," and signal filtering was performed across all three frequency bands. When the filtered signal was amplified and compared to the unfiltered original signal, it was observed that the amplified signal had no distorted frequency components within the passband. As compared to the input audio signal, the filtered and amplified signal had 100 times the decibel power, indicating a considerable improvement in sound amplification within the desired band.

Finally, the affordable adjustable hearing equipment developed as a result of this research can offer a cost-effective solution to individuals suffering from hearing loss. The different frequency bands enable individualized hearing aids, and the design architecture, based on the Arduino Nano board, is user-friendly and efficient. The Affordable Frequency Selective Hearing Amplifier has the potential to make hearing aids more accessible for people who would not otherwise be capable of purchasing them, ensuring that everyone has access to quality hearing care.

REFERENCES

[1] C. Sherman. "The Senses: Hearing." https://dana.org/article/the-senses-hearing/ (accessed.

[2] "What sounds can people hear?," Aug 2, 2017 2017 [Online]. Available: https://dosits.org/science/measurement/what-sounds-can-we-hear/.

[3] S. Lindberg, "Hearing Aids in 2023: Why Do They Cost So Much?," ed, 2022.

[4] Worldometers.info, "United States Population," 12 January, 2023 2023. [Online]. Available: https://www.worldometers.info/world-population/us-population/#:~:text=The%20current%20population%20of%20the,year%20according%20to%20UN%20data.

[5] J. Elflein. "Number of people with disabling hearing loss in select countries worldwide in 2008 and 2018." (accessed.

[6] S. Kochkin, "35 million Americans suffering from hearing loss," 2009. [Online]. Available: https://www.hear-it.org/35-million-Americans-suffering-from-hearing-loss.

[7] M. Mroz, "Hearing aid prices," 2022. [Online]. Available: https://www.healthyhearing.com/help/hearing-aids/prices.

[8] D. Burke, "Hearing Loss," 2019. [Online]. Available: https://www.healthline.com/health/hearing-loss.

[9] ASHA, "Causes of Hearing Loss in Adults." [Online]. Available: https://www.asha.org/public/hearing/causes-of-hearing-loss-in-adults/.

[10] M. Mroz, "Types of hearing loss," 2022. [Online]. Available: https://www.healthyhearing.com/help/hearing-loss/types.

[11] M. D. Hossein Mahboubi, M.P.H.,1 Shawn Zardouz, B.A.,1 Sepehr Oliaei, M.D.,1 Deyu Pan, M.S.,2 Mohsen Bazargan, Ph.D.,2 and Hamid R Djalilian, M.D.1, "Noise-Induced Hearing Threshold Shift among U.S. Adults and Implications for Noise-Induced Hearing

Loss: National Health and Nutrition Examination Surveys," 03/03/2012 2012. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3743535/#R3.

[12] K. E. B. a. M. I. Wallhagen, "Hearing loss in an aging American population: extent, impact, and management," 2014. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/24641557/.

[13] J. H. L. In-Hwan Oh, Dong Choon Park, and MyungGu Kim, "Prevalence of hearing loss by age group," 2014. [Online]. Available: https://www.researchgate.net/figure/Prevalence-of-hearing-loss-by-age-group_fig5_270290890.

[14] hearinghealthfoundation.org, "Workplace Hearing Loss," 2020. [Online]. Available: https://hearinghealthfoundation.org/hearing-loss-in-the-workplace.

[15] hearlifewell.com, "How Hearing Loss May Affect Your Job," 2018. [Online]. Available: https://hearlifewell.com/how-hearing-loss-may-affect-your-job/.

[16] thcp.co.uk, "HOW CAN HEARING LOSS AFFECT YOUR EVERYDAY LIFE?," 2018. [Online]. Available: https://www.thcp.co.uk/blog/hearing-care/how-can-hearing-loss-affect-your-everyday-life.

[17] WebMD, "How Do Hearing Aids Work?," 2021. [Online]. Available: https://www.webmd.com/healthy-aging/video/video-hearing-aids-explained.

[18] J. G. Clark, "Uses and abuses of hearing loss classification," 08/1981 1981. [Online]. Available: https://www.researchgate.net/publication/16145943_Uses_and_abuses_of_hearing_loss_classification.

[19] G. Hickish, "Hearing problems of elderly people," (in eng), *BMJ,* vol. 299, no. 6713, pp. 1415-1416, 1989, doi: 10.1136/bmj.299.6713.1415.

[20] F. a. D. Adminstration, "FDA Issues Landmark Proposal to Improve Access to Hearing Aid Technology for Millions of Americans," ed, 2021.

[21] T. T. Perry and P. B. Nelson, "Self-Adjustment of Hearing Aid Amplification for Lower Speech Levels: Independent Ratings, Paired Comparisons, and Speech Recognition," *American journal of audiology,* vol. 31, no. 2, pp. 305-321, 2022, doi:

10.1044/2022_AJA-21-00164.

[22] S. Mallik, D. Chowdhury, and M. Chttopadhyay, "Development and performance analysis of a low-cost MEMS microphone-based hearing aid with three different audio amplifiers," *Innovations in Systems and Software Engineering*, vol. 15, no. 1, pp. 17-25, 2019/03/01 2019, doi: 10.1007/s11334-019-00325-7.

[23] A. Flores, "Lively 2 Hearing Aids," 2022. [Online]. Available: https://www.hearingtracker.com/hearing-aids/lively-2.

[24] A. Hearing, "EV1 Hearing Aid (Pair)," 2023. [Online]. Available: https://audienhearing.com/products/ev1.

[25] Lively. "Lively Lite 2." https://www.listenlively.com/product?model=lively2lite (accessed.

[26] T. Ehrenfeld, "Health benefits of hearing aids," 2022. [Online]. Available: https://www.healthyhearing.com/help/hearing-aids/health-benefits

[27] B. T. N. R. Hospital, "Hearing Aids Helped Curt Enjoy Family and Social Gatherings Again," January 4, 2019 2019. [Online]. Available: https://www.boystownhospital.org/knowledge-center/hearing-aids-improve-lifestyle.

[28] C. f. D. a. R. Health. "Regulatory Requirements for Hearing Aid Devices and Personal Sound Amplification Products." Food and Drug Adminstration (FDA). https://www.fda.gov/regulatory-information/search-fda-guidance-documents/regulatory-requirements-hearing-aid-devices-and-personal-sound-amplification-products (accessed.

[29] C. o. F. Regulations, "Over-the-counter hearing aid controls.," 2023. [Online]. Available: https://www.ecfr.gov/current/title-21/chapter-I/subchapter-H/part-800/subpart-B/section-800.30.

[30] A. George, "Male vs Female Voice Actors — The Differences and What to Choose," 2021. [Online]. Available: https://bunnystudio.com/blog/male-vs-female-voice-actors-the-differences-and-what-to-choose/#:~:text=The%20Frequency%20Distinctions&text=Female%20voice%20fundamentals%20may%20range,out%20at%20about%20900%20Hz.

[31] R. INDIA, "Arduino Nano – Analog Input." [Online]. Available:

https://roboindia.com/tutorials/arduino-nano-analog-input/#:~:text=Arduino%20Nano%20has%2010%20bit,dividing%20input%20values%20by%204.

[32] D. Incorporated, "FILTERLESS 3W CLASS-D STEREO AUDIO AMPLIFIER," 2012. [Online]. Available: https://www.mouser.com/datasheet/2/115/PAM8403-247318.pdf.

APPENDIX A: CODE

Arduino Code:

```
//The Filter Library: https://github.com/tttapa/Arduino-Filters
// The code was inspired given the example with the library
// Modified by AlDana Al-Dosari, AlMaha Bahzad and Muhammed Mohid.
// Last Modified: 31 January 2023

#include <Filters.h> // Import Filters Library

#include <AH/Timing/MillisMicrosTimer.hpp> // Import Time Library to use time in microseconds
#include <Filters/Butterworth.hpp> // import butterworth filter directory from Filters
#define pot A2;   // define potentiometer connect to analog pin for gain control

void setup(){
  Serial.begin(9600); //setup of Serial module, 9600 bits/second
  pinMode(A2,INPUT); //potentiometer
  pinMode(2,INPUT); //switch A (0.125 - 1 kHz)
  pinMode(3,INPUT); //switch B (1 - 4 kHz)
  pinMode(4,INPUT); //switch C (4 - 8 kHz)
  pinMode(5,OUTPUT);//LED A
  pinMode(6,OUTPUT);//LED B
  pinMode(7,OUTPUT);//LED C
  digitalWrite(5,LOW);//LED A OFF
  digitalWrite(6,LOW);//LED B OFF
  digitalWrite(7,LOW);//LED C OFF

}
float gain; // Declare gain variable
// Sampling frequency
const double f_s = 9600; // Hz, base on arduino frequency
```

```
// Cut-off frequency (-3 dB)
double f_c, fc1; // Declaring lower/higher  cut-off frequency
double f_n, f_n1; // lower/higher normalized cut-off frequency

// Sample timer
Timer<micros> timer = std::round(1e6 / f_s); // timer in microseconds
// Second-order Butterworth filter
auto filter = butter<2>(f_n);  // creating lowpass filtered signal
auto filter1 = butter<2>(f_n1); // creating highpass filtered signal

void loop(){
gain=map(analogRead(A2),37,980,1,25); //map(sensor value reading from A2, 10KOHMS MIN, 10KOHMS
MAX, lower gain, max gain)

 // if the first switch (0.125 - 1 kHz) activated
 if((digitalRead(2)==1)){ // switch A is activated
  digitalWrite(5,HIGH); // LED ON
  digitalWrite(6,LOW); // LED OFF
  digitalWrite(7,LOW);// LED OFF
  // modify cut-off frequency
     f_c = 125;       // 125  Hz
     f_c1 =1000;}    //  1000 Hz

 else if(digitalRead(3)==1){
  digitalWrite(6,HIGH); // LED ON
  digitalWrite(5,LOW);  // LED OFF
  digitalWrite(7,LOW);  // LED OFF
      f_c= 1000;     //  1000 Hz
      f_c1 =4000;}   //  4000 Hz

 else if(digitalRead(4)==1){
  digitalWrite(7,HIGH); // LED ON
  digitalWrite(6,LOW); // LED OFF
```

```
    digitalWrite(5,LOW); // LED OFF


        f_c= 4000;      //  1000 Hz
        f_c1 =8000;}   //   8000 Hz
  else {
    f_c = 125;     // 125  Hz
    f_c1 =8000;    // 8000 Hz
    digitalWrite(7,LOW); // LED OFF
    digitalWrite(6,LOW); // LED OFF
    digitalWrite(5,LOW);} // LED OFF

   f_n = 2 * f_c / f_s; // normalized lower cut-off frequency
   f_n1 = 2 * f_c1 / f_s; // normalized higher cut-off frequency

 if (timer){ int i=analogRead(A0); // to detect the sound signals
    Serial.print(i-520); // Original Audio, Blue
    Serial.print("Original Audio: ");
    Serial.print((filter1(i))-(filter(i))); // Filtered Audio, Blue
    Serial.print("Filtered Audio: ");
    Serial.println(((filter1(i))-(filter(i)))*gain); // First normalized filer low , red
    Serial.print("Amplified Audio: ");
 }
  delay(1);  //20ms delay
}
```

APPENDIX B: BUTTERWORTH EQUATION

Butterworth filter equation for 2nd order:

$$y[n] = b_0x[n] + b_1x[n-1] + b_2x[n-2] - a_1y[n-1] - a_2y[n-2]$$

x[n] is the current input sample

y[n] is the current output sample

x[n-1] and x[n-2] are the previous input samples

y[n-1] and y[n-2] are the previous output samples

b_0, b_1, and b_2 are the feedforward filter coefficients

a_1 and a_2 are the feedback filter coefficients

Butterworth filter design equation for 2nd order in the z-domain:

$$H(z) = \frac{b_0 \ + b_1z^{-1} \ + b_2z^{-2}}{1 + a_1z^{-1} + a_2z^{-2}}$$

The filter coefficients:

$$b_0 = \gamma^2 - \alpha * \gamma + 1$$

$$b_1 = 2 * (\gamma^2 - 1)$$

$$b_2 = \gamma^2 + \alpha * \gamma + 1$$

$$a_1 = 2 * (\gamma^2 - 1)$$

$$a_2 = \gamma^2 - \alpha * \gamma + 1$$

$$\gamma = \frac{1}{tan\,(\frac{\pi f_n}{2})}, f_n = \frac{2f_c}{f_s}\ ; \alpha = 2\,cos\left(\frac{2\pi\left(k+\frac{1}{2}\right)}{N}\right)$$

γ: pre-warping factor, α: damping factor

fn: normalized frequency, fc: cutoff frequency, fs: sampling frequency

k: index of the filter section (0,1,2,..), N is the filter order (N=2)

APPENDIX C: PERMISSION STATEMENT

Figure 1:

Statista

Authorised Users are granted a nonexclusive, non-transferable, limited right to access and use for research purposes the Online Services and Materials made available to you. The rights granted exclusively to Authorised Users are as follows: (a) The right to use Materials for research purposes, and the right to copy Materials into user‘s analyses, presentations, documents, and other similar forms of work or research material; that includes Printing, and archiving of statistics for internal purposes and a fair use of downloaded statistics; (b) The right to publish and distribute Materials, unless otherwise prohibited by existing applicable intellectual property laws and copyright laws; (c) For the avoidance of doubt, downloading and storing Materials in an archival database is prohibited. The Online Services and the Materials are protected by copyright, intellectual property laws, and other laws that prevent unauthorised access and use. If you are not an Authorised User, you are not permitted to access or use the Online Services requiring a paid subscription for any purpose whatsoever. If you nevertheless access and use the Online Services or Materials requiring a paid subscription without authorization, your access and use will be governed by these General Terms and Conditions and you will be liable to Statista for any breach of the General Terms and Conditions as well as for unauthorised access and payment for use at the rates in the applicable Price Schedule; (d) The right to Email, fax, download or make printouts using the commands of the Online Services and the right to create a single printout of Materials accessed or downloaded by any other lawful means (collectively, “Authorised Printouts”).

Figures 2 and 3:

National Library of Medicine