Tactile Auditory Sensory Substitution

BME 301
University of Wisconsin - Madison
May 9, 2007

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Abstract

High frequency hearing loss is a problem common among people of all age groups. People who suffer from this type of hearing loss often lose the ability to hear certain consonant sounds. The goal of this project is to use sensory substitution, a technique for presenting environmental information missing in one sensory modality to another, to help replace this missing high frequency information. Our designed sensory substitution device takes recorded sound, filters it into four different channels based on frequency, and then outputs all four channels to a sound card. The sound card outputs to a circuit that amplifies the sound, reduces the noise, and changes the voltage so it can drive the transducers. The circuit then outputs to the four vibrotactile transducers. The four transducers will then vibrate in response to specific bands of high frequency sound inputs. Different fricative sounds will stimulate different vibrotactile transducers based on the frequency of the sound, allowing the user to associate a particular spatio-temporal pattern of vibration with an unheard sound. Use of this device, to supplement for the loss of high frequency hearing, should aid the user in daily communications in regard to speech and hearing.

Product Design Specifications Summary

The final design should meet requirements in the areas of performance, safety, cost, and ergonomics. It should help to substitute for high frequency hearing loss to the extent of helping the user with everyday communication. The system should be able to detect speech spoken at the normal 60 dB level and separate it into four arbitrary, tunable frequency bands above 1500 Hz. It should also be able to transmit vibrations at a frequency of 250 Hz resulting in a skin displacement of 1 _m. Aesthetically and ergonomically, the device should be comfortable to the user and be hidden behind the ear. The device should be safe such that the transducer terminals are insulated from the skin and the electronics powering the system should be isolated from the user. The product design specifications can be viewed in its entirety in Appendix I.

Background

High Frequency Hearing Loss

The number of hearing impaired Americans has more than doubled in the past 30 years with nearly 50 percent of Americans over the age of 65 affected.[1] It not only affects the elderly however, 1.4 million children under the age of 18 also have a hearing condition.[2] The two most common types of hearing loss are conductive and sensorineural. Conductive hearing loss is defined as the condition when sound is not transmitted correctly through the middle ear and into the inner ear. It is often described as having the ears plugged all day. It can be caused by wax buildup or even infection. This type of hearing loss can often be medically cured.

The most common type of hearing loss is sensorineural. About 90 percent of individuals who are hearing impaired have sensorineural hearing loss.[1] This condition, also known as nerve deafness, consists of either damage to the inner ear or the nerves which transmit the messages from the ear to the brain. It is caused by disease, birth injury, or even aging. The most common form of sensorineural hearing loss is high frequency hearing loss. This is where an individual loses the ability to hear certain high frequency constants such as Sh, S, T, Th, P, or F sounds, as seen in Figure 1. Since these are some of the most common used consonants in the English language, high frequency hearing loss is truly detrimental to every day communication.

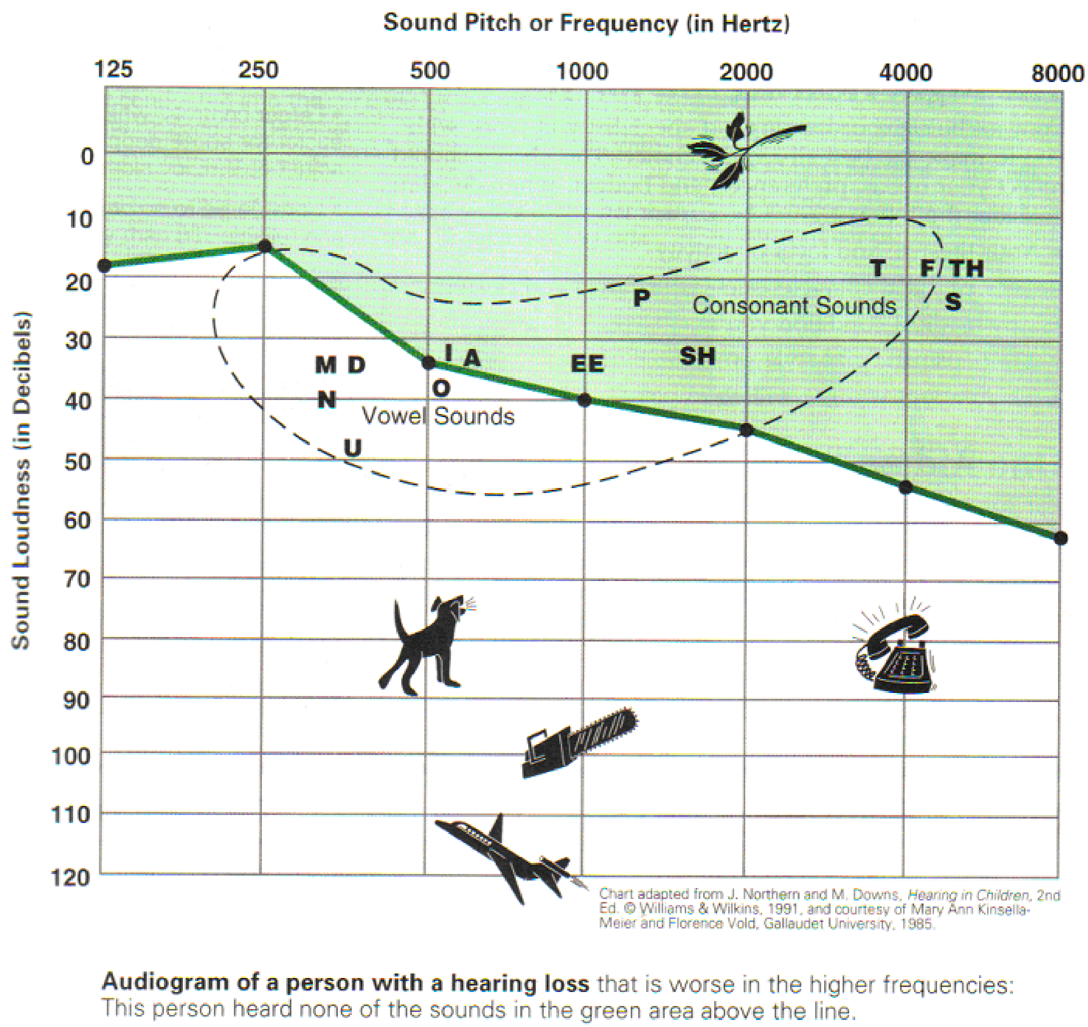


Figure 1: Audiogram of missing consonant frequencies[3]

Most elderly Americans suffer from some form of high frequency hearing loss, along with 14.9 percent of children.[1] High frequency hearing loss is not easily medically fixed. Hearing aids do not do an adequate job of resolving the problem of high frequency hearing loss because they only amplify the sound. This amplification is only useful when there is a deficit but not total loss, as in high frequency hearing loss, since the actual nerve that receives these high frequencies is dead. Consider a piano with no strings. No matter how hard the keys are hit, there is still not going to be any sound. Similarly, no matter how loud the hearing aid makes the sound, a person with high frequency hearing loss cannot hear sounds in those frequencies. Obviously, something more than hearing aids needs to be considered in order to help the rising number of people with high frequency hearing loss.

Sensory Substitution

Sensory substitution is presenting environmental information absent in one sensory modality to another. Sensory substitution can be seen in many actions people perform throughout their everyday lives. For example, a person substitutes the sense of touch for sight when reaching into their pocket to retrieve an object. Other common examples are the use of sign language to substitute vision for hearing or Braille which substitutes the sense of touch for sight (specifically for reading). In this project, the device will substitute high frequency sounds with vibrotactile stimulation, thus substitute part of the hearing spectrum for touch.

Existing Sensory Substitution Products

There are a few existing devices which aim to use sensory substitution by substituting for hearing using vibrotactile or electrotactile stimulation, but these products are made specifically for people with complete hearing loss. For example, the Tickle Talker™ uses vibrotactile stimulation on the fingers of the user. Each finger receives stimulation from a different range of frequency and based on the pattern, strength, and duration of the vibration, the user can pick out a certain frequency range. Since this form of sensory substitution covers the entire spectrum of hearing, it is not sensible for a person with only high frequency hearing loss to use the device. They would have to sift through way too much information to get the signals they needed. With such a large learning curve, the user must spend hours with the device to learn minimal amounts of words. For example, after more than 40 hours of training, a certain user could only identify 70 words.[4] The user with only high frequency hearing loss could adapt at a much faster rate to only a high frequency stimulator because they are only missing certain sounds, not the entire spectrum.

Other similar devices include the Tacticon 1600 and the Tactaid VII. The Tacticon 1600 uses electro stimulation by putting electrodes on a belt around the user's abdomen.[5] This device also covers the whole spectrum of hearing and has a steep learning curve. In similar ways, the Tactaid VII, seen in Figure 2, uses vibrations covering the entire range of human hearing.[5] The vibrators are attached to the user's sternum, each corresponding to a certain frequency range.

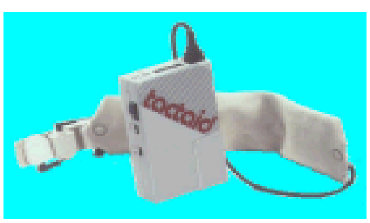


Figure 2: The Tactaid VII [6]

Final Design

Design Overview

The design consists of vibrotactile transducers placed behind the ear and frequency analysis for speech and consonant recognition. Speech is recorded onto a personal computer and filtered by a specific frequency range to isolate certain consonant sounds. Each specific frequency range will correspond to one channel which will be outputted from the Roadie soundcard to the multi-channel circuit. The circuit will amplify the outputted voltage from the soundcard, measure it against a baseline voltage to eliminate noise, and then convert the voltage into a form that will drive the transducers. If the voltage signal has a large enough amplitude it will be sent to the vibrotactile transducers and they will vibrate, communicating the missing high frequency information to the user.

Cool Edit Capture and Processing

Voice sounds are originally recorded using a computer and an attachable computer microphone. Once sounds are acquired, they are edited using Syntrillium Software's Cool Edit Pro version 2.1. The raw recorded file is first filtered to reduce the amount of background noise. This is performed by selecting a portion of the file that is pure noise, uploading it as the noise profile, and then eliminating this unwanted portion of sound from the file. After noise reduction, the sound file is edited into four different frequency bands: 1.6 – 2 kHz corresponds to p, i, and m sounds, 2.0-3.0 kHz corresponds to ch and sh sounds, 3.0-3.5 kHz corresponds to ch and f ssounds, and 4.5-8.0 kHz corresponds to s and th sounds. In order to do this the original noise reduced sound file is run through a simple FFT filter that reduces any sound outside of the selected frequency range to 0 dB and amplifies the sound in the specific frequency range five times. Each time the original file is run through the FFT filter, the outputted file is saved as a separate track, each containing a specific portion of the high frequency information present in the original recording. An example of this sound processing is shown in Figure 3. This shows the word sixty vs. the word fifty and the corresponding amplitude spikes which signify energy in that frequency region. For example, the s sound in sixty on shows up in channel 4. Thus, channel 4 will vibrate and alert the user, so he or she will be able to discriminate the two words.

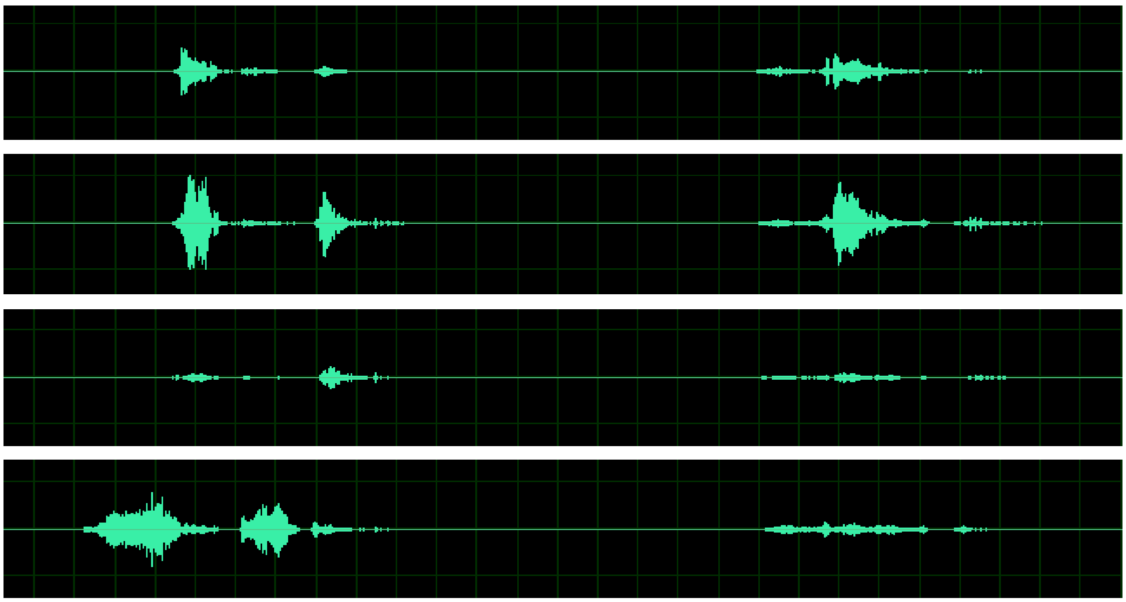


Figure 3: The amplitude spikes of the words sixty (on the left) and fifty (on the right) from channel 1 (on the top) through channel 4 (on the bottom).

In order to play the tracks properly, each track is selected to either be output to a left mono or right mono output. In order to have as little sound as possible come out of the left channel for a track that is to be outputted to a right channel, the tracks are panned to the appropriate side. The separate tracks can then be overlapped using Cool Edit's multi channel playing and recording feature, and encoded as a wma file. This final output file can then be played in media player and is encoded to output each frequency subdivision of sound to a specific channel of the audio output.

Soundcard

The audio output device in use is the Turtle Beach Audio Advantage Roadie external soundcard. The soundcard allows for 5.1 channel surround sound, thereby having a total of 6 channels for outputting sound. Four of these channels are used to output the separate tracks consisting of different frequency bands to the circuit of the device. The Roadie has a maximum output level of 1 – 2 V for each output channel. The voltage levels outputted from this device for the wma files from the computer are at a level between 0 mV and 50 mV, too small and of the wrong wave form to drive the vibro motors. Therefore, the circuit must amplify the signal and convert it to a form that is usable by the motors.

Signal Processing Circuit

The goal of the circuitry and the signal processing is to convert the audio signal from each channel of the sound card into appropriate vibrations of the motor. Since the prototype currently utilizes software to separate the original audio signal into four distinct bands, the signal processing stages are not used for filtering, but instead solely for waveform shaping. The output from each channel of the sound card is a time-domain signal that consists of only the frequencies that were within the passband of the software bandpass filters. Each channel is then processed by identical multistage circuits that result in waveforms that are able to drive the vibro-tactile motors. Each individual stage of the multistage circuit is further described for one of these channels.

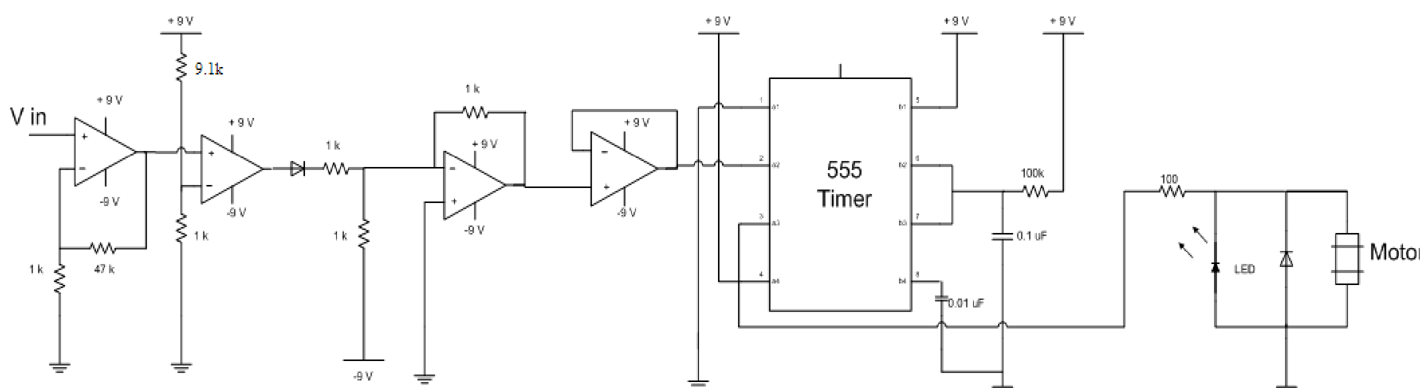
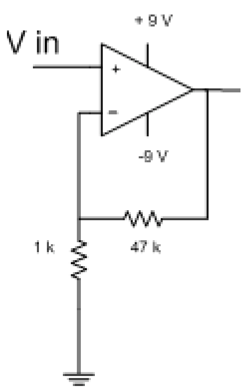


Figure 4: The signal processing stages for a single channel from the sound card

First Stage- Voltage Amplifier

The first stage of the circuit employs a uA741 operational amplifier in a non-inverting voltage amplifier configuration. This is needed to amplify the 50 – 70 mV signal that comes from each sound card channel. The voltage gain is set by the ratio of the two feedback resistors, 47 k_ and 1 k_, therefore, the voltage gain for the first stage is 47 V/V. The output signal of the first stage is the amplified signal with amplitude of between 2 and 3.5 V whenever there is energy in the specific frequency band.



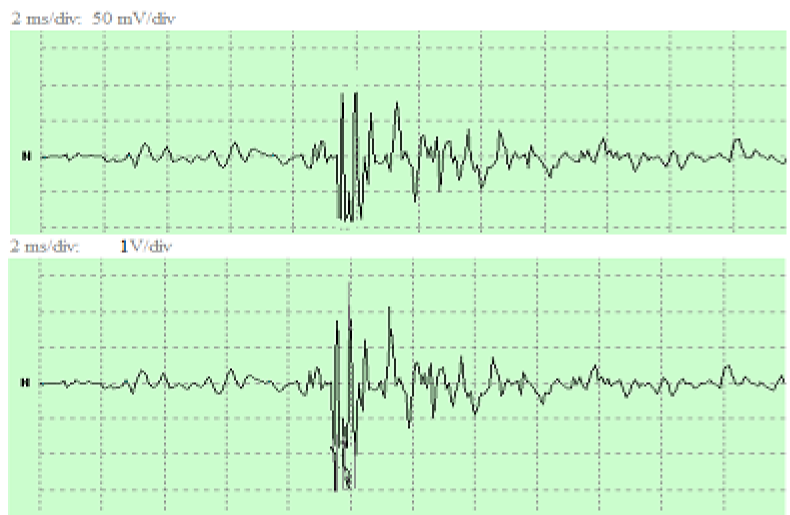
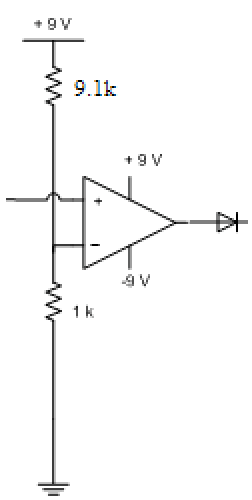


Figure 5: First stage voltage amplifier. Notice how the sample output waveform (bottom) is simply the amplified version of the sample input waveform (top).

Second Stage- Comparator with Diode

The second stage of the circuit is a comparator circuit that is used to generate a saturated waveform whenever there is significant acoustic energy in the frequency band. The comparator saturates with a high voltage when the signal is above the reference voltage, and the comparator saturates with a low voltage when the signal is below the reference voltage. The reference voltage used is 1 V, which based on observation, was determined to be able to eliminate any low amplitude noise present in the signal while retaining the important characteristics of the waveform. The reference voltage is set by a voltage division of a 9.1 k_ and a 1 k_ resistor. The saturation voltage is dependent on the positive power supply (+Vcc) and the negative power supply (-Vcc) of the operational amplifier, in this case +Vcc = 9V and –Vcc = -9V. A diode is used at the comparator output to eliminate all the instances of negative saturation in order to generate pulses that switch from a low voltage of 0V to a high voltage of around 7 V. Even though +Vcc = +9V, the high saturation voltage was only observed to be around 7 V because a 0.7 V voltage drop occurs across the diode. The 9 V batteries are not ideal power supplies, and the operational amplifiers cannot exactly reach +Vcc due to voltage drops across the P-N junctions of the bipolar junction transistors within the uA741 architecture.[7]



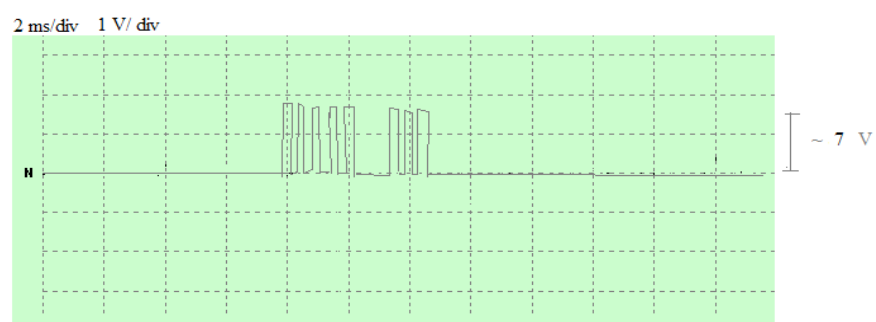
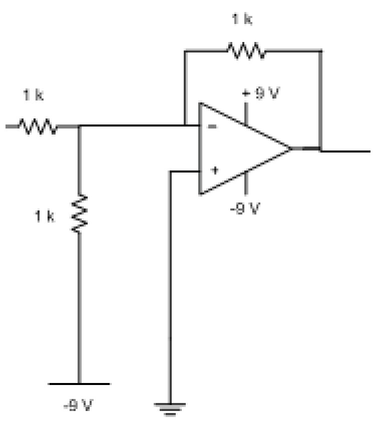


Figure 6: Second stage comparator with diode to set the low saturation voltage at 0 V. Also shown is an example output waveform of the second stage.

Third Stage - Inverting Summer

The third stage of the circuit is necessary to prepare the waveform for a later monostable stage. Since the retriggerable monostable circuit requires a high voltage to low voltage trigger, the signal needs to be inverted. Also, the specific implementation of the monostable used in the circuit operates in the range from 0 V to 9 V, so a DC offset voltage is required. To meet these two requirements in a single stage, an inverting summer amplifier with unity voltage gain is used to sum a -9 V DC offset into the signal. The signal output after this summer stage is a series of high frequency pulses that switch from a high voltage of 9 V to a low voltage of around 2 V whenever there is sufficient energy in the frequency band.



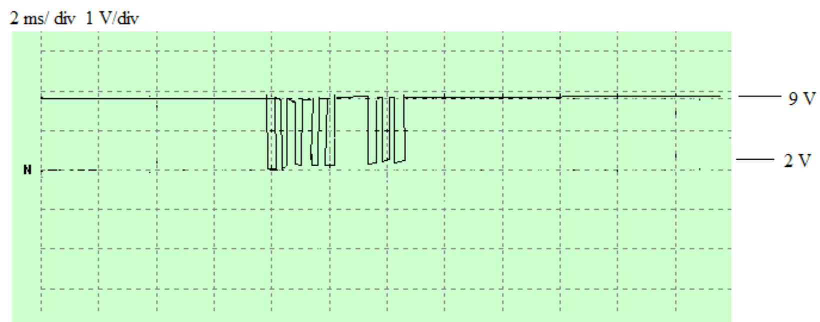


Figure 7: Third stage inverting summer circuit needed to invert the signal and add a -9 V DC offset to the signal.

Fourth Stage - Voltage Follower (Buffer)

A buffer follows the inverting summer circuit in order to provide a high input impedance load to the third stage. This ensures that the there is no loading in the transfer from the third stage to the monostable stage that drives the motor. The output of the amplifier is directly connected in negative feedback to the inverting input terminal to provide low output impedance and to prevent any signal loss. The signal at the output of this stage is identical to the input of this stage as a result of this configuration.

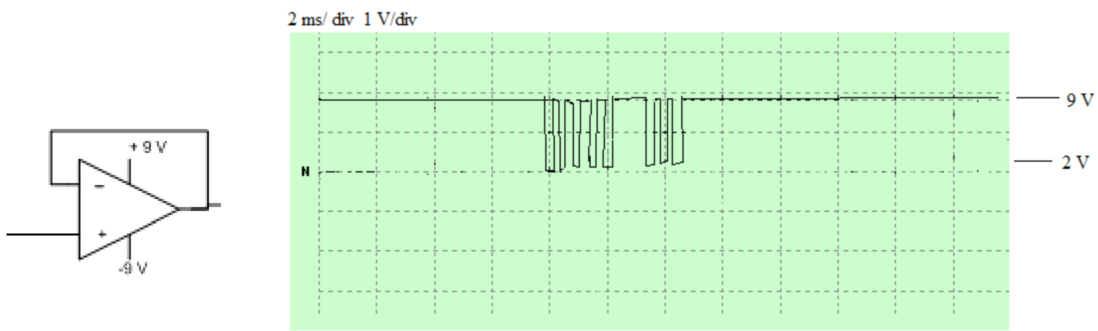


Figure 8: Fourth stage buffer prevents any loading or signal loss in transferring the signal from the summer to the monostable. The output signal is identical to the input signal of this stage.

Fifth Stage- Retriggerable Monostable

The final stage of each channel is a retriggerable monostable stage that is used to provide the necessary current and voltage to the motor. There are multiple ways to implement a monostable circuit, but for this application, using a 555 timer proves the most cost effective and efficient. The 555 timer functions as two comparators in conjunction with a digital flip-flop component to provide a voltage square wave whenever the trigger signal drops below a certain voltage threshold.[7] The duration of each square pulse is determined by a resistor and a capacitor that are set external to the timer in order to give a single time constant response.

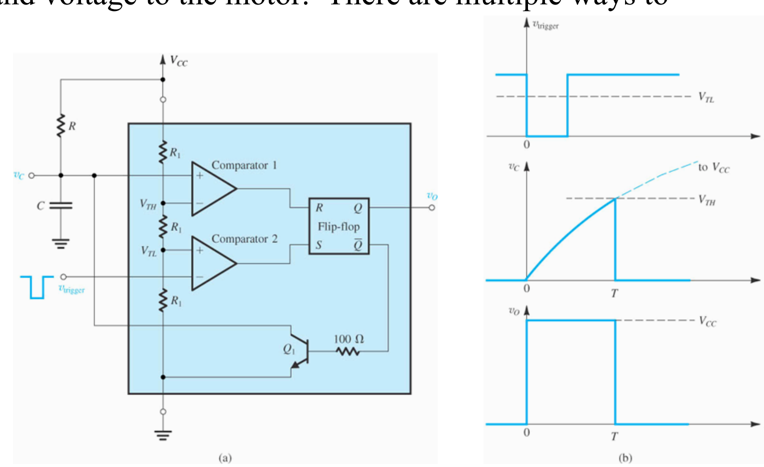
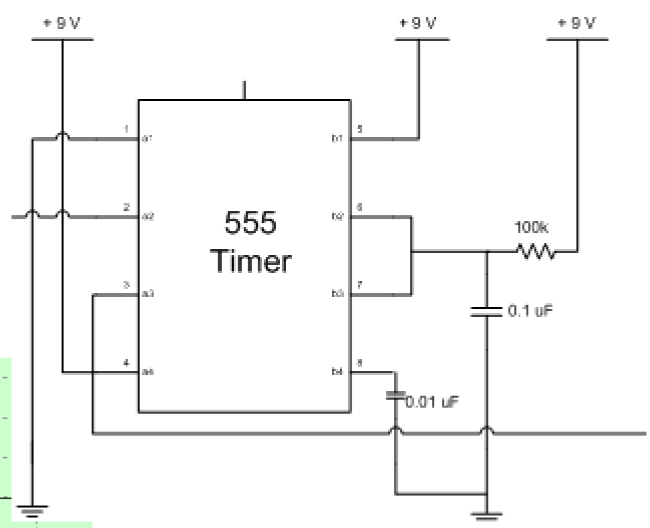
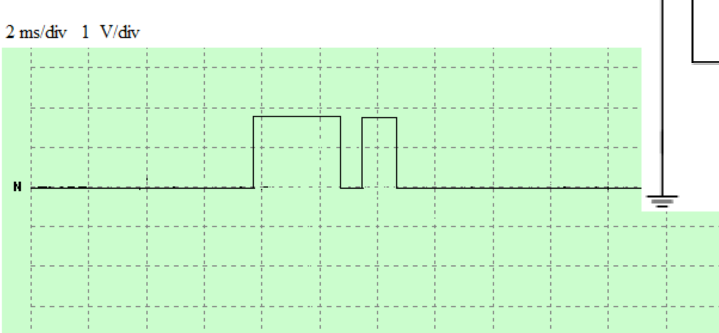


Figure 9: Implementation of a retriggerable monostable circuit (a). The conversion of high voltage to a low voltage trigger into a low voltage to high voltage output (b). [7]

The trigger, in this case, is the signal containing high frequency pulses that are output from the buffer. The pulses from the buffer cannot be directly used to drive the circuit because the short duration of high voltage signal is unable to supply the motor with enough current. Using bipolar junction transistors in a current amplification role was proven only to function with constant frequencies, but ineffective with audio waveforms. The monostable converts each high frequency pulse into a 10 to 20 ms square pulse to overcome this problem. The duration of the square pulses that is set by the RC time constant allows some of the higher frequency pulses to form overlapping square waves. The overlap keeps the signal at a high voltage for a longer period of time depending on the amount of energy in the frequency band. These energy dependent square waves are able to modulate the motor's strength of vibration.

The amplitude of the generated square wave is determined by the positive power supply voltage, Vcc = 9 V. The monostable threshold voltage for the trigger signal is set at one-third of Vcc by the internal architecture of the 555 timer.[7] The trigger signal shaped up to this point accommodates this 3 V threshold by having the pulses switch from 9 V to 2 V whenever a square wave needs to be produced. The output waveform that appears at the timer output is a 9 V non periodic square wave.





The Load – Vibro-tactile Motor and LED

Figure 10: First stage monostable circuit with a time constant of 10 ms (top). The output signal is a non-periodic square wave that is used to drive the motors (left)

The square wave output from the monostable is used to drive the vibro-tactile motor and LED. Voltage dividers are included to ensure that the motor and LED are at a safe voltage. A reverse-biased diode is in parallel with the motor and acts as a means to protect the motor when the signal switches the motor off quickly. When the motor is switched off quickly, its inductance can draw an unsafe amount of current through it without the presence of the diode. The position of the diode is such that its P-N junction will become forward-biased when the motor is switched off, allowing current to be drawn safely to electrical ground. The LED in the circuit is supplied the appropriate 2.5 V by the 100 _ voltage division. This allows the light to turn on whenever the motor is vibrating.

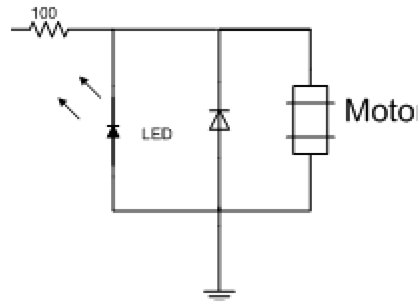


Figure 11: Motor and LED circuit with protection diode.

Vibrotactile Transducers

Two different areas were researched for the tactile stimulation part of the prototype, vibrotactile and electrotactile. Vibrotactile stimulation involves generating vibrations that activate mechanoreceptors in the skin while electrotactile stimulation passes current through the skin which directly stimulates afferent nerves. For our final prototype, four Solarbotics VPM2 flat disk motors were chosen to alert the user of missing high frequency information. Vibrotactile transducers were chosen because of their ease of acquirement and implementation with the tradeoff of having higher power consumption.

The amount of vibration that is appropriate for the user is determined by the characteristics of mechanoreceptors known as Pacinian Corpuscles. These mechanoreceptors are sensitive to gross pressure changes and higher frequency vibrations applied to the skin. They are also classified as fast afferent type II (FA II), referring to their ability to adapt after sending an action potential.[8] It has been shown that the minimum threshold amplitude needed to stimulate these receptors varies with the frequency of vibration. In one study, the minimum threshold for the average subject was measured to be 1 mm at 5 Hz and 1 _m at 200 Hz. These values are indicative of a trend that at higher frequencies, less amplitude of skin displacement is needed to activate Pacinian Corpuscles. The optimal range of sensitivity, however, was discovered to be in the range of 60 Hz to 250 Hz.[8]

The Solarbotics VPM2 flat disk motors exhibit several key features which made them advantageous for implementation in the final design. The sensation that the user perceives is more consistent with a mechanical stimulus because the transducer is only displacing the skin as opposed to sending currents through the skin in the case of electrotactile stimulation. The small size of the motors, 12 mm in diameter and 3.4 mm thick, lends to increased discrimination between separate motors. Also, the motors vibrate at a frequency of approximately 200 Hz which is in the ideal perceptive frequency range presented earlier.

Figure 12 – Solarbotics VPM2 Motor[9]

Another positive aspect of these motors is their relatively low cost, $4.00 each, coupled with there ease of implementation. One minor disadvantage was the relatively large power consumption, drawing 40 mA at 2.5 V for a power rating of approximately 100 mW.[9]

Placement of Transducers

Since, the Pacinian corpuscle senses slight pressure and vibrations, the transducers must be able to stimulate the Pacinian corpuscles, which are of different prevalence in different parts of the body. Three areas of placement, inside the ear (ITE), behind the ear (BTE), and the back of the neck, were considered. Each considered area was on the head for the easiest and least conspicuous placement.

In the final design, it was determined the tactors will be placed behind the ear for a number of reasons. This position would allow for the device to be nearly completely concealed from outsiders looking from the front or the opposite side. Also, the device will not get in the way of a hearing aid, and if needed, can be directly connected to the hearing aid fairly easily. Another advantage of this placement is due to the decreased mobility of the region, the user's everyday movements will not be affected by the device placed behind the ear. Vice versa, the user's movements will not interfere with the sensing of vibrations. A minor complication is bone conduction by the mastoid process which could help with propagation of the vibrotactile signal, or could make spatial discrimination more difficult depending on the amount. One of the few disadvantages of this placement is that its attachment may be impeded by the hair of the user.

After choosing the area behind the ear to house the transducers, the sensitivity of the region was tested to find the optimal distance between the tactors, as well as the exact locations in that region that each transducer would be placed. Through a two point discrimination test, it was found that there should be two tactors on the mastoid process and two on the skin below it. The most advantageous distance between each tactor, if they are stimulated at similar frequencies, was also determined. The results of the two point discrimination of the skin behind the ear are shown in Appendix II. It was determined that stimulations similar in frequency need to be 25 mm apart on the mastoid process and tactors on the skin below the mastoid process must also be 25 mm apart. The last tactor on the mastoid process and the first one on the skin below it must only be 20 mm apart. This is due to increased sensitivity of detecting different stimulations if stimulating different structures since one is directly on the bone and one is on the skin below it. This can also be seen in the results in Appendix II.

The study also showed a learning curve involved with the sensitivity of the skin. Each subject became more sensitive in that region as the testing progressed. This could mean that after having the tactors on the skin for a long period of time, the user would become more accurate in discerning the stimulations, and thus make a better substitution for the hearing loss. This could also mean that the tactors would not need to be as far apart as originally thought.

Housing Unit for Transducers

The vibrotactile transducers need to be in a vibration dampening environment in order to decrease the chances of interference from one transducer on another. For example, if Tactor 1 were to fire, the user should not be able to feel the entire device vibrate and think it might be Tactor 4 firing. The material that the transducers are held together with must also be flexible so it can curve to different shapes of ears. Also, it must be tough and long lasting. To satisfy these requirements, sponge rubber was chosen to house the vibrators. It is flexible so it can curve around the ear to become more discrete and comfortable, yet it is firm and tough so it will be long lasting. It is also shock absorbing to dampen vibrations.

The sponge rubber used is 5 mm thick and 20 mm wide. The length of the housing unit depends on the two point discrimination thresholds that were found so that the user can independently identify each tactor as its own. There is 30 mm between the center of each tactor on similar structures (i.e. Tactors 3 and 4 on the mastoid process and Tactors 1 and 2 on the skin below). Tactors 2 and 3, however, need less distance between them so there is 25 mm between the centers of those tactors. Since the vibrotactile transducers being used are 12 mm in diameter, this makes a distance of 18 mm between the outer edges of Tactors 3 and 4 and Tactors 1 and 2 and a distance of 13 mm between the outer edges of Tactors 2 and 3. This is less than the recommended distance found by the two point discrimination test but with practice the user should be able to discern the tactors. This is supported by the two point discrimination test, which found that patients did get better at discerning as the test went on.

In order to maximize direct skin contact the tactors stick out from the sponge rubber housing. Of the 3 mm thickness of the tactors, 2 mm is in the sponge rubber, and 1 mm is outside of the rubber. This makes direct skin contact much easier, especially with the addition of an adhesive or other attachment mechanism. There is also a groove cut in the sponge rubber for the wires coming out of the tactors. This better stabilizes the tactors and causes less interference of direct skin contact for the user since the wires do not get in between the tactors and the skin. The housing unit is covered in a cloth in order to seal in the wires and transducers, as well as make the device more discrete and more comfortable for the user. The housing unit without the outer covering is shown in Figure 13.

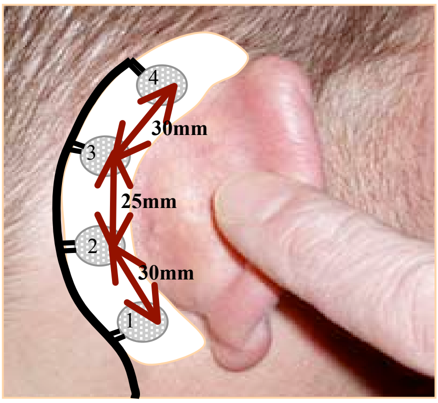


Figure 13: The housing unit for the transducers and the distances between them.

Attachment

Different methods of attachment are still being considered, including adhesive or a hook apparatus. Since the attachment of this device involves direct skin contact, any adhesive used must be suitable to use on the skin. The adhesive should be rated for medical device attachment to the skin, so the device is not accidentally released by the adhesive. It must be able to be removed and applied easily and without any skin trauma, as well as be resistant to dirt and moisture. Most importantly, it needs to be comfortable for the user. An example of an adhesive which satisfies these needs is medical grade polyethylene. With all of these requirements in mind, an adhesive would be the most discrete out of any of the options. A disadvantage is it could get messy for the user to apply an adhesive everyday.

To solve this problem, another small device could be added in order to reduce the amount of adhesive that needs to be used, along with reducing the amount of times the user would need to apply the adhesive. This could be a hubbing station for the housing unit. It could be something the housing unit slides, snaps, or screws into that stays connected to the skin for longer periods so the user would not have to apply adhesive everyday. Velcro could also be used in this fashion, with half of the Velcro attached to the skin for longer periods of time. A disadvantage to this method is it could get in the way of the direct skin contact of the tactors. With this in mind however, the housing unit could be redesigned to accommodate.

The last method of attachment being considered is a hook apparatus around the ear. This method is the most noticeable to outsiders, but it is also the easiest for the user to use. This method can also be used in conjunction with the adhesive as well. This means that the hook would be a life support for the system in case the adhesive does not hold properly.

Device Testing

The objectives of testing our device are to show that subjects can feel and discriminate between the transducers, are able to learn and distinguish between the vibrational patterns, and can determine what is being said based on the audio and device information provided.

Testing Setup:

Subject: Human subject who does not suffer from any type of hearing loss will be used for the initial round of device testing.

Device Understanding Test: The subjects will be told how the device works and what high frequency consonant sounds each transducer will vibrate in response to. The transducers will then be placed on the subject behind one ear. The subjects will also be notified that an LED will light up whenever its corresponding transducer is vibrating.

Then a series of words that contain a high frequency consonant sound will be played for the subject. There will be a break between each word in which the subject will say what transducers vibrated and what sound the vibration represented.

Efficacy Test: Once the subject has passed this initial check phase, the efficacy of the devices will be tested. The subject will be played a sentence in which the high frequency consonant sounds will be inaudible and the device will be used to interpret the missing sound. Once the subject has heard the sentence they will be asked to write down the sentence played to them using both the audible and vibratory stimulation provided.

Test on Patients with High Frequency Hearing Loss: Once the learning curve test and efficacy tests are completed on subjects with normal hearing, both tests will be repeated on subjects that suffer from high frequency hearing loss. This will allow for more accurate efficacy conclusions to be made about the device.

Future Work

Adjustments need to be made to our device design in order to allow for the device to be used in the everyday communications of its user. This will entail implementing a real-time processing system, so that there is not a significant time delay between the input of sound and the vibrational signal. Also, methods and techniques will be developed to miniaturize the device to make it more aesthetically pleasing and portable.

In order to move forward with device development human testing also needs to begin. The human testing as outlined in the testing section of this report will first test the difficulty of learning how to use the device as well as the difficulty in recognizing the different vibrational patterns. Once it is shown that a subject can be taught how to interpret the information provided by the device, the efficacy of the device will be tested. Through this, it will be shown that the device is useful in the everyday communication of subjects with high frequency hearing loss.

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Appendix I: Product Design Specifications

Tactile Auditory Sensory Substitution
Jimmy Fong, Jack Page, Ryan Thome, Becky Jones, Matthew Valaskey

Function:

High frequency hearing loss is the most common form of hearing loss experienced. It is caused by damaged nerve ends on the hairs in the cochlea. People with high frequency hearing loss cannot hear high frequency sounds such as 's', 'f', 'sh', 'ch', 't', and 'p' sounds. Since these sounds are some of the most used in the English language, high frequency hearing loss immensely inhibits communication.

Individuals with high frequency hearing loss tend to rely on hearing aids, which amplify sounds. However, the hearing loss cannot be fixed with amplification of these high frequency consonants because the person simply cannot hear in that frequency range, the volume does not make a difference. Instead of amplification, these missing consonants can be communicated by sensory substitution. In other words, a sense other than hearing can be used to send the auditory information to the brain. The goal is to design and develop an auditory substitution device that through the use of vibro-tactile stimulation can substitute for regional frequency hearing loss. Individual vibrators will represent certain frequency ranges, and when the user feels the specific vibration attributed to certain frequency range, the user will be able to identify the sound.

After using the device for an extended period of time, the user will no longer have to concentrate on the vibrations but will be able to "hear" the high frequency sounds. Due to the plasticity of the brain, the brain will interpret the vibrations as sounds and fill in the gaps for the user, and communication will be restored.

Client Requirements:

- The device will substitute for high frequency hearing loss to the extent of helping the user in everyday communication.
- The device will use vibro-tactile stimulation.
- The device should be self contained, portable, and discrete.
- Complete a testable prototype for analysis of frequency range and wear-ability.

Design Requirements:

1. Physical and operational characteristics

a. Performance requirements

- It will increase the user's quality of communication by allowing the user to recognize high frequency consonants and incorporate them into word recognition through vibro-tactile stimulation.
- This device should use the programmable functions of computer software to recognize and separate certain high frequency sounds and communicate them to the vibro-tactile stimulator.

b. Safety

- A current of more than 5 mA should not pass through the device and into the user.
- The device should not heat to over 43° C (110° F) while in use.

c. Accuracy and Reliability

- Be able to pick up and transmit sound that is detected at normal speaking level of 60 dB
- Be able to process and substitute for the consonants T, F, S, Th, Sh, and P when coming from a variety of different vocal tones enough to improve scores on standard speech recognition evaluation tests, Word Intelligibility by Picture Identification (WIPI), sentence level Bamford-Kewal-Bench test (BKB), and PLOTT test for vowel and consonant discrimination.
- Human Hearing Frequency Range: 20 – 20,000 Hz
- Speech Frequency Range: 125 – 8,000 Hz
- High Frequency Hearing Loss: above 1,000 Hz

Sound	Frequency (Hertz)
T	3500
F	4000
S	4000
Th	4000
Sh	2000
P	1500

d. Life in Service

- The transducers should last at least 3 years.
- The sound processing unit, along with its microphone, should last 10 years.
- Adhesive should last at least through an entire day.
- On a single battery charge the device should last approximately 5 days, similar to that of a common hearing aid so they can be charged at the same time.
- Common hearing aid batteries have an output voltage of 1.4 V and have power ratings between 140 and 640 mAh. With daily use of the device being about 14 hours the device should draw from 2 - 10 mA of current from the battery.

e. Operating Environment

- The device will be located near the ear.
- Elements such as wind, rain, sun and sweat should not cause the device to vibrate for non-spoken noises, output dangerous levels of current or distort outgoing signals.
- Eventually test the prototype on human subjects in a lab setting.

f. Ergonomics

- The device should not move during normal physical activity.
- Transducer unit should be hidden by the ear.
- Device should be comfortable to the user.

- The controls of the processing unit should be small enough to keep them discrete yet still be able to be manipulated.
- Attach vibro-tactile device with adhesive that will not cause irritation.
- The location of the transducer should be easily repeatable.

g. Size
- The transducer unit should be no more than 10 cm in length, 2 cm wide, and 1 cm thick.
- The processing unit should be no more than 15 cm in length, 5 cm wide, and 2 cm thick.

h. Weight
- The weight of the processing unit should be no more than 8 oz.

i. Materials
- Adhesive which holds the transducer unit in place should not irritate skin, leave large amounts of residue, or be painful to remove.
- Soft, durable, and vibration dampening housing unit

j. Aesthetics, Appearance, and Finish
- Unit should be flesh-colored and not overtly noticeable to others.
- Adhesive attachment used for transducer unit should not leave large amounts of residue and should not be painful to remove.

2. Production Characteristics

a. *Quantity*: The device should be able to be produced in mass quantities.

b. *Target Product Cost*: The device should cost between $300 and $500, which is approximately 5-10% of the total cost of a hearing aid.

3. Miscellaneous

a. Standards and Specifications: FDA approval of a class II device. Must follow regulation code 21 CFR 812 and 21 CFR 50 for testing.

b. Customer: Adjustable frequency ranges depending on what the user needs most

c. Patient-related concerns: Device should not cause discomfort and should not be overly noticeable.

d. Competition:
- Tickle Talker
- Tacticon 1600
- Tactaid 7 – http://www.tactaid.com/tactaid71.html

Appendix II: Results of the Two Point Discrimination Test on the Region Behind the Ear

Subject	Stimulation	Distance apart (mm)	Placement A = both stimulations on mastoid process B = both on skin below C = one on bone, one on skin	Number of times the subject recognized two distinct stimulations
1	1 - 3	15	A, B, and C	0/2 at each site
	4	25	A	0/3
	5		B	2/3
	6		C	2/3
	7	35	B	3/3
	8		C	3/3
	9	19	A	0/2
	10		B	2/3
	11		C	1/2
	12	20	A	0/2
	13		B	1/2
2	1	10	B	0/3
	2	16	B	0/3
	3	36	B	0/1
	4	50	B	2/2
	5	36	B	2/2
	6	35	B	2/2
	7	16	B	0/2
	8	25	A	0/2
	9		B	2/3
	10		C	3/3
3	1-3	15	A, B, and C	0/2 at each site
	4-6	20	A, B, and C	0/2 at each site
	7	25	A	0/3
	8		B	2/3
	9		C	0/3
	10	30	A	0/2
	11		B	2/3
	12		C	0/2
	13	39	B	2/2
	14		C	3/3
	15	35	B	2/2
	16		C	2/2
	17	30	A	1/3
	18		B	2/3
	19		C	3/3

	20	25	A	0/4
	21		B	3/4
	22		C	0/4
	23	20	A	2/3
	24		B	0/3
	25		C	0/3

Table 1: Under the placement heading A means both stimulations occurred on mastoid process, B means both were presented on the skin below the mastoid process, and C means that one was on bone, and one was on the skin. There was increased sensitivity at placement C.