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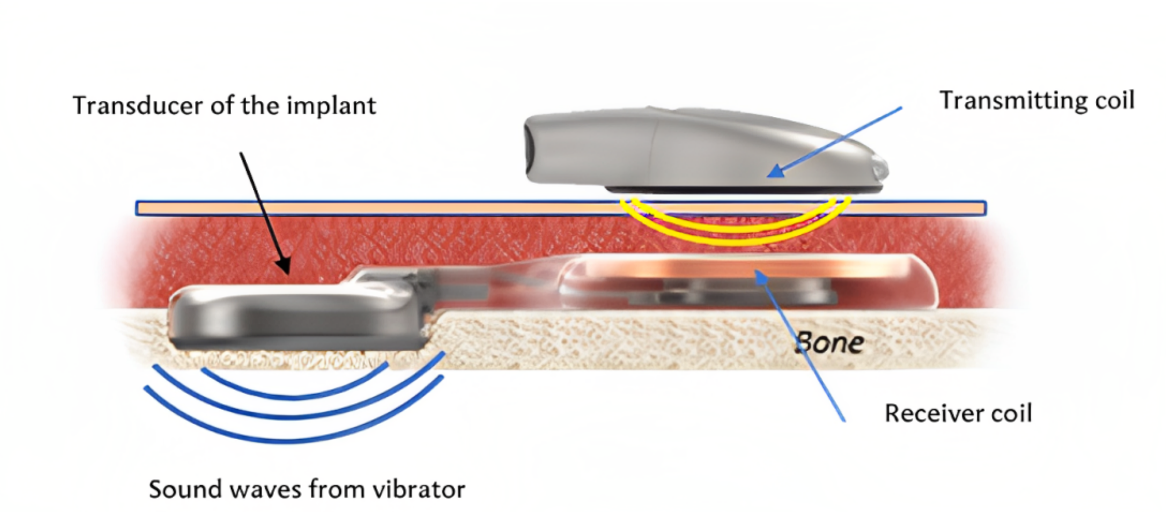

Implantable electronics for next-generation hearing implant

Bachelor's thesis in electrical engineering

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Department of Electrical engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

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Cover: Figure showing an illustration of the hearing aid in use. The figure was provided and is used with the permission of Oticon Medical.
Gothenburg, Sweden 2023

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Abstract

Conductive hearing loss occurs when the transmission of sound is impeded, meaning that the sound waves are not naturally conducted to the inner ear. This type of hearing loss fails to stimulate the cochlea and therefore, the perception of sound is lost. Bone conduction hearing devices are used as treatment for this condition. The devices aim to conduct the sound via the skull bone, which requires an implant to achieve optimal sound quality. The transducer is part of the implant and is responsible for the conduction of sound waves through the skull. In this project, the task was to identify and modify optimal electrical circuitry that could be used to drive the transducer in a bone-conduction hearing device. It was also investigated whether the use of a battery alternative such as a voltage multiplier would be suitable in the implant. The final product would also ideally be non magnetic in order to not disrupt images during MRI scans. The components which will be tested are provided by Oticon Medical AB.

In order to effectively run the transducer, it requires a driver to amplify the received signals. Several commercial driver's were provided for evaluation. A driver was found to provide adequate amplification, and further assessment regarding the driver's properties were made. Properties that were important to assess regarding the driver were its power consumption and MRI compatibility. The result of the project is a driver which can enable the transducer to provide high output force, ultimately making it a supplement to already existing constituents in Oticon Medicals's hearing devices. The driver was modified with the purpose of making it MRI compatible, however time constraints hindered the confirmation of the total MRI compatibility of the device. A battery alternative was found to the driver, however the voltage provided by the battery alternative was too low, warranting further investigation.

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Terminology

- AC - Alternating Current
- AM - Amplitude Modulation
- BCD - Bone Conduction Device
- DC - Direct Current
- DCR - Direct Current Resistance
- MRI - Magnetic Resonance Imaging
- PWM - Pulse Width Modulation
- RMS - Root Mean Square
- THD - Total Harmonics Disturbance
- SPL - Sound Pressure Level
- OFL - Output Force Level

1

Introduction

The work was carried out at the facilities of Oticon Medical AB and the Department of Electrical Engineering at Chalmers University of Technology. Oticon Medical specializes in designing and manufacturing hearing aids. This paper discusses how to effectively innovate new-generation hearing devices. A solution to the required specifications will serve as a stepping stone to further development and innovation.

1.1 Background

Conductive hearing loss is when the vibration of sound is impeded somewhere in the outer or middle ear, preventing it from reaching the inner ear and the cochlea. The cochlea converts sound vibrations into electrical signals that can be interpreted by the brain. This is why it is called conductive hearing loss, because the sound can not be conducted effectively through the pathway of the outer and middle ear due to, for example, damage or a hole in the eardrum [1]. To treat this condition, bone conduction hearing devices can be used. In contrast to conventional hearing aids that transmit sound through the middle ear, this type of amplification eliminates the need for any component of the device to be inserted into the ear canal. The bone conduction hearing devices utilize transducers to convert electrical signals into mechanical vibrations that can be conducted through the skull bone [2].

1.2 Purpose

After the sound has been picked up by the external microphone, converted into electrical signals and processed, the signals need to be amplified to a suitable level for the transducer. The main goal of this project is to evaluate commercial drivers that can amplify the processed signals, the process for how this works can be observed in figure 2. The desired driver has certain specifications regarding power consumption and MRI compatibility which need to be met.

1.3 Limitations

This project will be conducted by 2 people in an approximately 5-month time frame, starting in January and ending in June. Limitations that will have to be put into the project are that no changes to any components before and after the driver will be made. No modifications will be made to the transducer. Only components on the driver can be modified.

1.4 Clarification of the questions

During the procession of the project, the following investigations will be conducted:

- Evaluate commercially available drivers to determine the ability to drive the transducer.
- Identify and verify potential modifications of chosen candidate driver(s) to improve power efficiency.
- If the driver contains an iron core inductor the aim is to evaluate the possibility and consequences to use an air core inductor.
- Determine the driver’s MRI compatibility.

2

Theory and methods

2.1 Bone conduction hearing device

In this research paper, the hearing aid system that will be discussed is the BCD system. The BCD system operates by maintaining the integrity of the skin while transmitting the sound signal through the skin with the help of a magnetic inductive system from the external device to the implanted device. The external device captures sound waves and converts them into electrical signals. The transducer then induces the resulting vibrations to the skull bone, these vibrations are then received by the cochlea, and the corresponding sound waves are converted to electrical signals, which are then transmitted to the brain [3]. Figure 1 illustrates approximately how the system works.

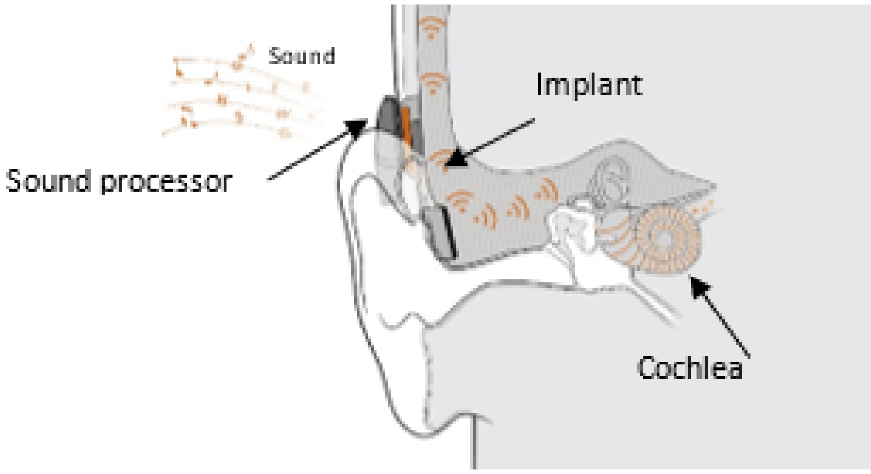

Figure 1. Shows an illustration of how the BCD system typically works. The figure was provided and is used with the permission of Oticon Medical.

2.2 Hearing aid components

In this part, the components associated with the driver will be discussed. The different components of the hearing aid can be observed in figure 2.

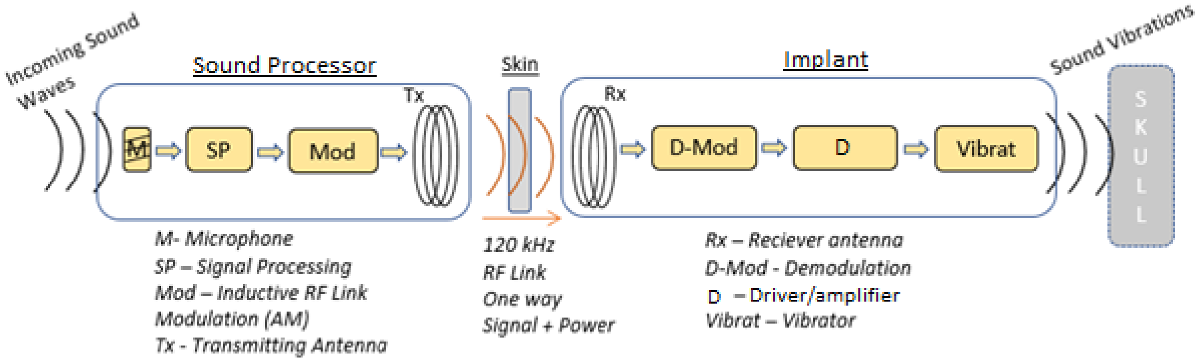

Figure 2. Illustrates the components of the hearing aid, including the external sound processor and the surgically implanted implant. The figure was provided and is used with the permission of Oticon Medical.

2.2.1 AM modulator/demodulator

The goal of AM modulation is to multiply the modulating signal with a carrier wave to transmit the sound wave through the skin to the transducer. The carrier wave typically has a high frequency to allow a wider availability of bandwidth, which makes the transmission of multiple signals more efficient. The AM demodulator effectively demodulates the AM signal in order to obtain the original sound wave. It achieves this by rectification, filtering, and smoothing the signal. Diodes are used as rectifiers, allowing only half cycles of the signal to pass through while blocking the other half cycles. Filtering, in particular, low pass filters are used to filter out the high frequency of the carrier wave [4]. Furthermore, capacitors can be used to “smooth” the signal. The capacitors charge during the peak of the rectified signals, and this charge gradually dissipates during the low points, resulting in a more continuous and “smooth” waveform. The demodulated signal may be weak after demodulation, which is why it often needs to be amplified after the demodulation is complete.

2.2.2 Driver/amplifier

In a hearing aid, a driver/amplifier can be used to increase the signal for the transducer. An amplifier is a device for increasing the amplitude of a signal, and it achieves this by taking power from a power supply and controlling the output to have a larger amplitude compared to the input signal [5]. In this specific hearing aid, the demodulated signals are quite small, which is why a driver that can provide good enough amplification is needed in order to drive the transducer.

2.2.3 Transducer

A transducer is the component in the bone conduction hearing device that converts electrical signals into mechanical vibrations in order to transmit sound. There are many different kinds of transducers but the most relevant one for this paper is the piezoelectric transducer. The way the piezoelectric transducer works is that when electrical signals are received by the transducer, it undergoes mechanical deformation. This motion drives vibration to the skull, allowing for skull bone conduction hearing [6].

2.3 MRI problem

Magnetic resonance imaging (MRI) is an imaging technique that utilizes magnetism and radio waves to generate images of the body's internal structures [7]. The strong magnetic fields generated by MRI scans cause disturbance in any device or object with magnetic properties. The objects with magnetic properties also distort the MRI image, causing an electromagnetic shadow. Because of this, it is important to limit the amount of magnetic material in bone-conduction hearing devices if a subject is going to undergo an MRI scan. When the external device and the implanted device are disconnected, there should be no magnetic field generated by the implant during MRI scans and therefore leading to no electromagnetic shadow distorting the image. Many components in modern-day electronics contain magnetic material, if any of the components in a hearing aid are magnetic, they should be considered to be removable or replaced with non-magnetic material.

2.4 Battery Alternative

One of the challenges of the project was to investigate if the driver could run without the use of a battery connected to the driver's power supply. The use of batteries has several disadvantages. One of them is that batteries are a source of environmental pollution. Both the production and disposal of batteries have harmful effects on the environment. By finding alternative solutions to power the driver, the amount of waste produced by the industry would decrease. Further advantages of replacing the additional battery in the hearing device are cost savings and convenience. To replace the additional battery in the hearing aid, the idea was to connect the driver's power supply to the input of the AM demodulator. Since the driver's power supply needs between 2.5 to 5 DC voltage to function and the input from the AM demodulator is AC, this AC voltage needs to be converted into DC and eventually multiplied in order to fit the driver's specifications.

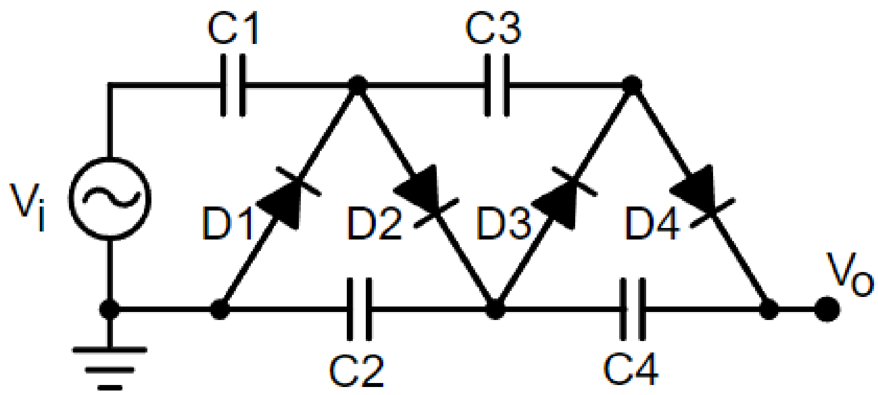

Figure 3. Shows the circuit design of a voltage multiplier.

The basic principle is to use a series of diodes and capacitors which convert the AC to DC and multiply the input voltage [8]. The input voltage is rectified by diodes, allowing only the positive half-cycles of the AC waveform to pass through. This allows the capacitors to store charge during the positive half cycles while preventing them from losing too much charge during the negative cycles. The charge would still dissipate gradually during the low points of the rectified signals, causing a voltage ripple. However it was determined that this voltage ripple would not have a significant impact. The addition of two diodes and two capacitors effectively doubles the input voltage; if additional stages are constructed in the same way, the input will increase further. The resulting output is a DC voltage which was needed for the driver.

2.5 Conducting the tests and Hardware

To conduct the tests needed for the project, a test and verification bench was needed, which was provided by Oticon Medical, where measurements were made using the hardware available at Oticon Medical and Chalmers.

2.6 Instruments and equipment for measurement.

During the tests, measuring instruments such as multimeters were used to verify how much resistance a resistor had and to verify and ensure that the power supply supplies the right amount of voltage. Oscilloscopes were a measurement tool used a lot throughout the project to measure the input and output signals and to observe the results, and most of the measurements were done using the oscilloscope. The oscilloscope that was provided at Oticon Medical also had the feature of being able to send out sinusoidal signals. Therefore it was also used as a function generator, Although later on in the project, AM signals were needed to give a more accurate reflection of real life. Therefore, the oscilloscope had to be connected to an AM waveform generator to produce AM signals. As the oscilloscope could not send a sweep signal, a function generator at Chalmers was used to observe the amplifier's results from a sweep instead of testing individual frequencies. A so-called skull simulator was used as well in order to measure the output force provided by the transducer. A skull simulator is a device which is used to mimic a human skull, which a transducer is mounted upon and to which the Skull simulator measures the force generated by the transducer. The table listing all the instruments and models can be seen in Table 1.

Table 1 shows the most important instruments utilized, including their respective models and the purpose of the instrument.

Instrument	Model	Purpose
Oscilloscope	ROHDE&SCHWARZ RTM3004	Measuring and transmitting signals.
Power supply	Aim-TTi EX752M	To supply DC voltage.
Multimeter	FLUKE-787B	Measuring DC voltage and component (resistors) values.
Sweep function generator	Keysight 35670a	For transmitting sweep signals
AM waveform generator	Keysight 33500b series	To transmit AM signals.
Skull simulator	TU-1000	Used to measure the force output.
Hearing instrument analyzer	Verifit 2	To measure OFL and THD at constant dB SPL values.

2.7 Simulations

Online Simulations were also conducted before starting construction of the electrical design to observe whether the idea worked in theory. The program which was used to conduct these simulations was Multisim which is an electronic simulation program, of which the license was provided by Chalmers. Some designs first constructed on Multisim before being constructed in real life are, for example, the AM demodulator which was first evaluated online before being constructed in real life. Matlab was used for the different tests to analyze results.

4

Results and discussion

4.1 The Drivers

Four commercial drivers provided by Oticon Medical were utilized throughout the project, with one particular driver identified as meeting the criteria for further testing. The crucial factors of the drivers are that they have low power consumption, high Amplification, and a low THD. The initial test conducted primarily focused on evaluating the amplification of the driver and the power consumption of the driver, the goal being to have as low of a power consumption as possible, and whether or not it contained an iron core inductor. The test involved transmitting a sinusoidal wave signal with around an amplitude of 200mV and frequencies ranging from 100Hz - 10kHz into the driver connected with the transducer.

4.1.1 Results of the initial tests

In this section, the results of the initial tests will be briefly gone through, and an evaluation will be carried out to determine the potential of the drivers, and to observe if any of them would be a match for the project.

The first driver: The first driver, according to the specifications, would provide a good amplification. The driver's controls were deemed too complicated as the driver required PWM and sinusoidal signals to drive. Therefore, this driver was ruled out rather quickly in favor of some of the other drivers.

The second driver: Although the second driver provided adequate amplification, the measurements from the power consumption revealed a very high power consumption exceeding the predefined limit, even at low frequencies. Consequently, it was determined that this driver was also unsuitable for this project.

The third driver: The third driver provided a considerable amplification, which would fit the project well. The Power consumption of the driver was measured, and the results were good as the power consumption was quite promising, landing below the power consumption limit. The only downside of the driver that could be noted was the fact that it contained an iron core inductor which would need to be replaced or removed further on.

The fourth driver: The test results from the fourth driver showed that it provided an acceptable amplification. From the power consumption measurements, it was deemed not to be too high. Nevertheless, the third driver outperformed this driver regarding amplification and power consumption. Therefore, it was disregarded in favor of the third driver.

Therefore, after testing the drivers, it was found that the third driver was the best as this driver showed very promising results. Therefore, it was decided that further and more thorough testing would be done using this driver to evaluate if it could meet the requirements of the project.

4.2 Further testing

Further testing was done on the third driver, still using a sinusoidal wave. However, instead of using a fixed value on the frequency and changing it manually, a full sweep wave was sent to see the results for many different frequencies. The sinusoidal wave had an RMS value of 50mV and used around a 5V DC supply voltage to power the driver. The driver was used at the highest amplification setting. In this experiment, the Skull simulator was also connected to measure the force output of the Transducer against the skull simulator. The picture shown below in figure 4 shows how the test was done.

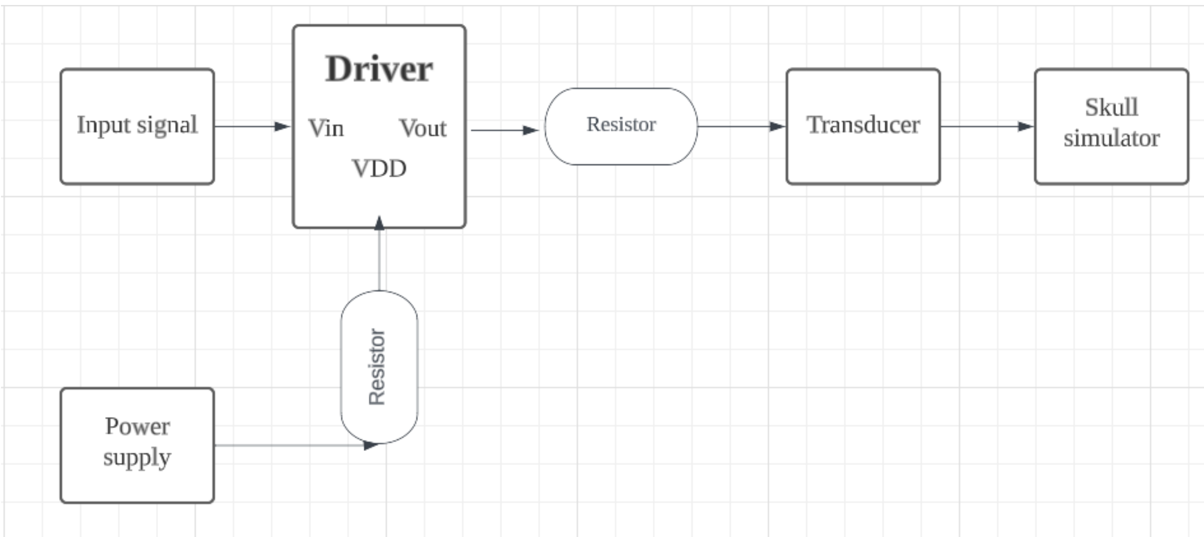

Figure 4. Shows how the setup is connected for the testing

The values that were important to note were the power consumption of the driver, the power of the transducer, and the Force output over the skull simulator. The Results of the tests are shown in the figures below.

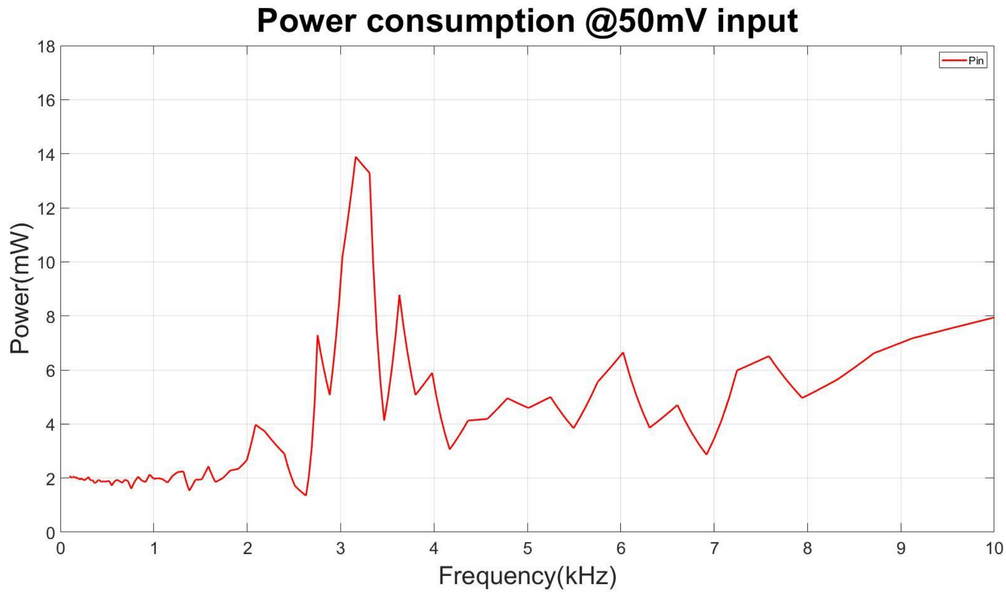

Figure 5. Shows the graph for the power consumption of the driver

The figure shown above in figure 5 is the power consumption of the driver between 100 Hz to 10kHz. The results given were below the maximum allowed power consumption for this investigation. Equation (1) shows how the power consumption was calculated.

$$\text{Pin} = \text{VDD} \cdot \frac{U_R}{R} \qquad (1)$$

The formula for calculating the Power consumption of the driver where 4.98V is VDD, U_R is the voltage over the resistor, and R is the resistor which is 1Ω.

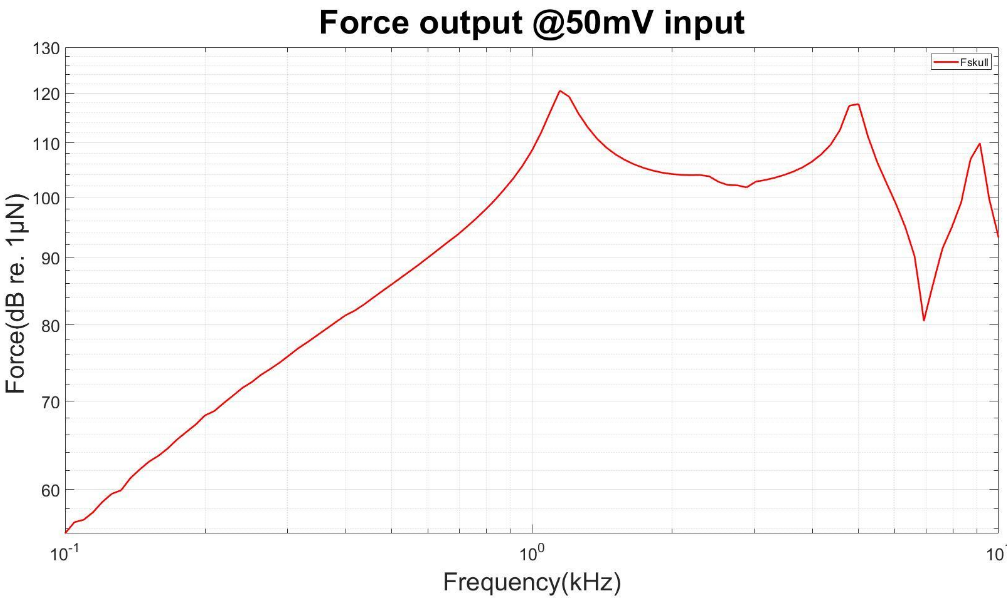

Figure 6. Shows graph for the output force over the skull simulator

Figure 6 shows the force of the transducer over the skull simulator. As can be observed in the figure is a peak at around 1kHz this is due to the Resonance top of the transducer and that's when the largest amount of force is outputted by the transducer. The equation used for the graph is shown in equation (2).

$$F_{Skull} = 20 \cdot \log_{10}(\frac{Vout}{0.2} * 10^{6}) \quad (2)$$

The formula for the output force from the skull simulator expressed in units of decibel relative to 1 micro newton (dB re. 1µN), Vout is the output voltage from the skull simulator with a sensitivity factor of 0.2V/N.

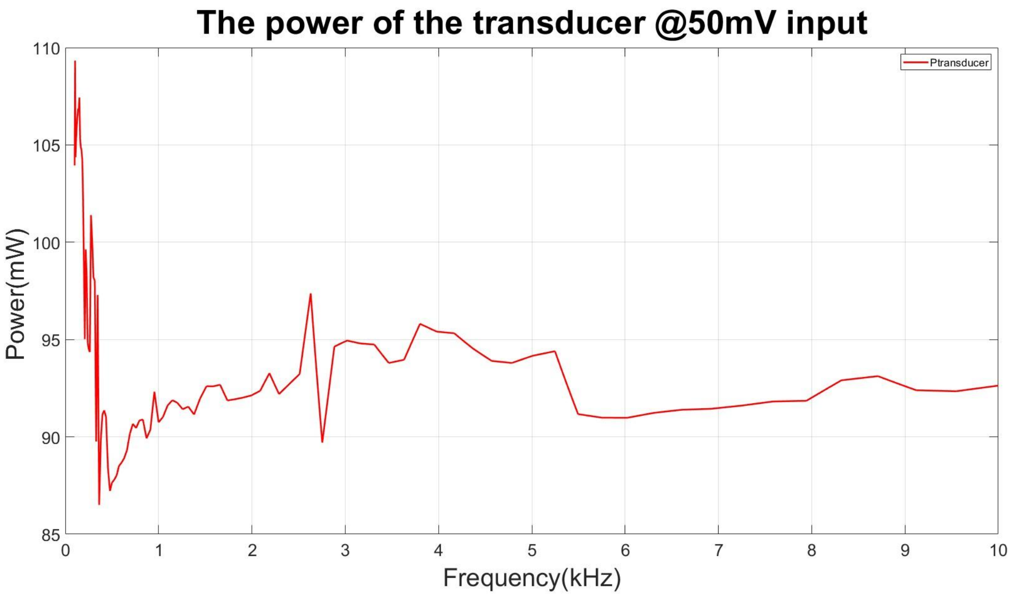

Figure 7. Shows the graph for the power over the transducer.

The power over the transducer can be observed in figure 7. The driver provides relatively high power to the transducer compared to the driver's power consumption. The formula to calculate the power is shown in equation (3). The input power of the driver was never measured in this test, although the input power should be approximately the same as the output power. Nonetheless, measuring the input power and comparing it with the output power is highly recommended to observe if any losses happen in the signal. These results were promising and it was decided that the main aim would be to use this driver moving forward with the project.

$$P_{Transducer} = V_{Transducer} \cdot I_{Transducer} \quad (3)$$

The formula for the Power of the Transducer where $P_{Transducer}$ is the power of the transducer, $V_{Transducer}$ *is the voltage of the transducer and* $I_{Transducer}$ *is the current of the transducer.*

4.3 AM Demodulation

The AM demodulator is a component that Oticon Medical has already designed and which is in use in their hearing aids. Therefore, the AM demodulator would also need to be constructed in real life to provide more accurate measurement results for this project.

4.3.1 AM Demodulation Simulations Online

The AM dmeodulator was designed first online before being constructed in real life the design of which is shown below in figure 8.

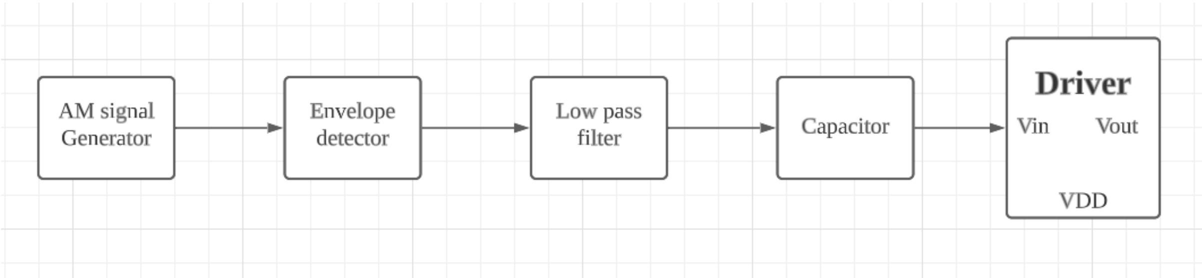

Figure 8. Shows the design of the AM demodulator connected with the Driver.

First, the AM signal goes through a diode. This is done to remove the positive or the negative side of the signal depending on which direction it is facing. In the simulation for this design, the direction of the diode is facing left, which means that the positive side of the AM signal is removed. The decision was made in order to have a positive input wave into the voltage multiplier, as having the negative side going into the AM demodulator will make no difference as the polarity of the input signal makes no difference on the final output signal. This diode makes up the first component in the envelope detector, which aims to demodulate the signal by removing all high-frequency components of the signal. This is constructed by putting a resistor and a capacitor in parallel, and the formula as to how these components were calculated is shown below in equation(4). The design of the envelope detector is illustrated in figure 9 and the output signal can be observed in figure 10.

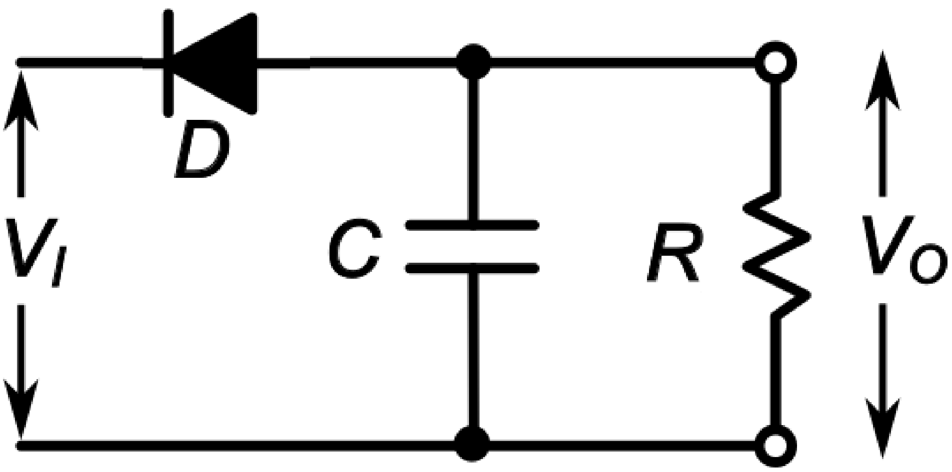

figure 9. Illustrates the design of the envelope detector where D is the diode, C is the capacitor and R is the resistance.

$$\frac{1}{F_H} < RC < \frac{1}{F_{audio}} \qquad (4)$$

The formula for calculating the components of the envelope detector where R is the resistor, C is the capacitor, F_H is the frequency of the carrier wave and F_{audio} is the highest audio frequency.

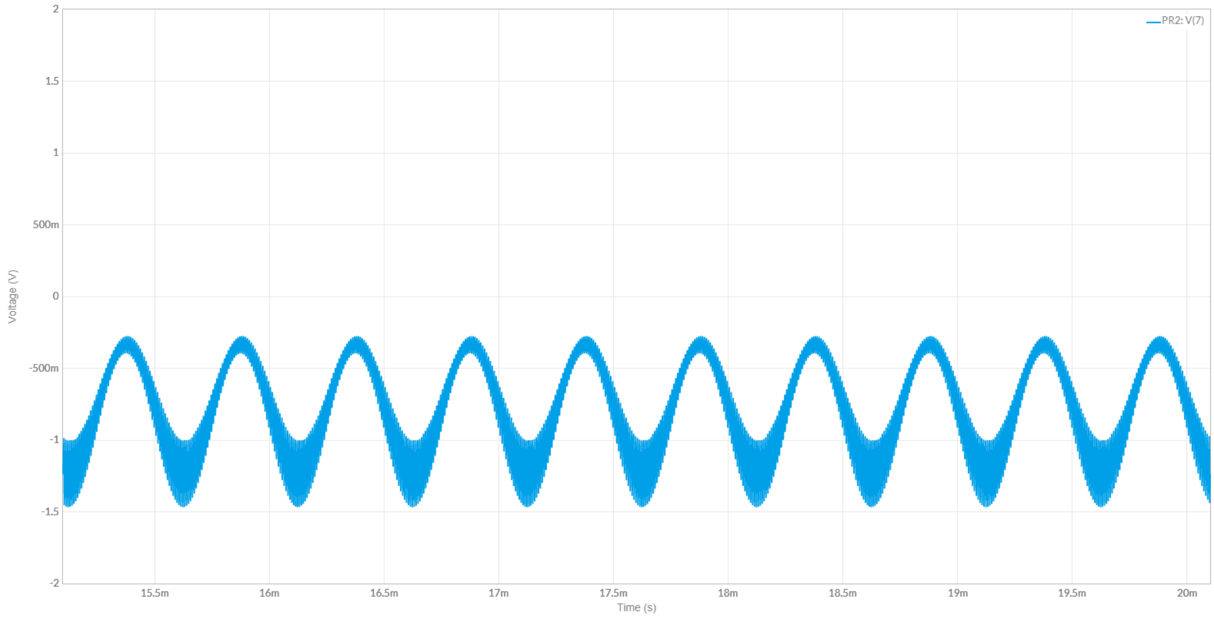

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Figure 10. The AM signal after the envelope detector.

After it has gone through the envelope detector, some unwanted disturbances can be observed in the signal. The signal is sent through a low pass filter to remove all the unwanted disturbances from the signal and in order to make the signal smoother. The low pass filter comprises a resistor and a capacitor, and the components of the low pass filter were calculated according to the formula in equation(5) and the result of which can be shown in figure 11.

$$F_H = \frac{1}{2\pi \cdot RC} \qquad (5)$$

The formula for calculating the components of the low pass filter, where R is the resistor, C is the capacitor and F_H *is the cut-off frequency.*

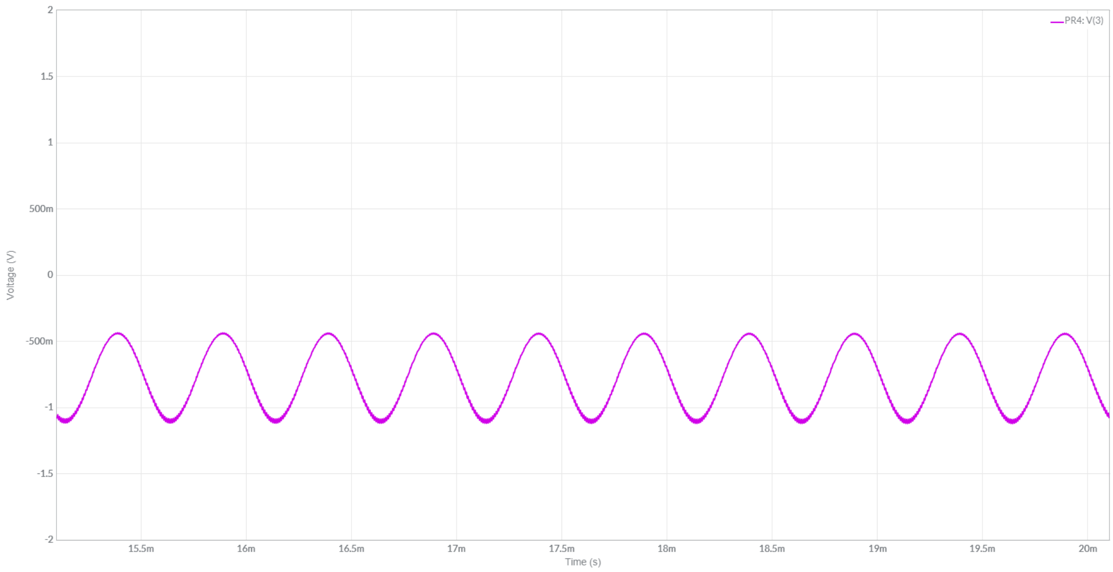


Figure 11. The Signal after the low pass filter

The last step is to remove the DC offset, which is currently present on the signal. The offset can be removed by implementing a capacitor, and a suitable capacitor was chosen for this purpose. This signal will be used instead of a direct sinusoidal signal in further testing to provide a more accurate representation of the signal in real life. But first, the design must be implemented in real life to see if it yields similar results to the simulations. The final result of the AM demodulation is shown below in figure 12.

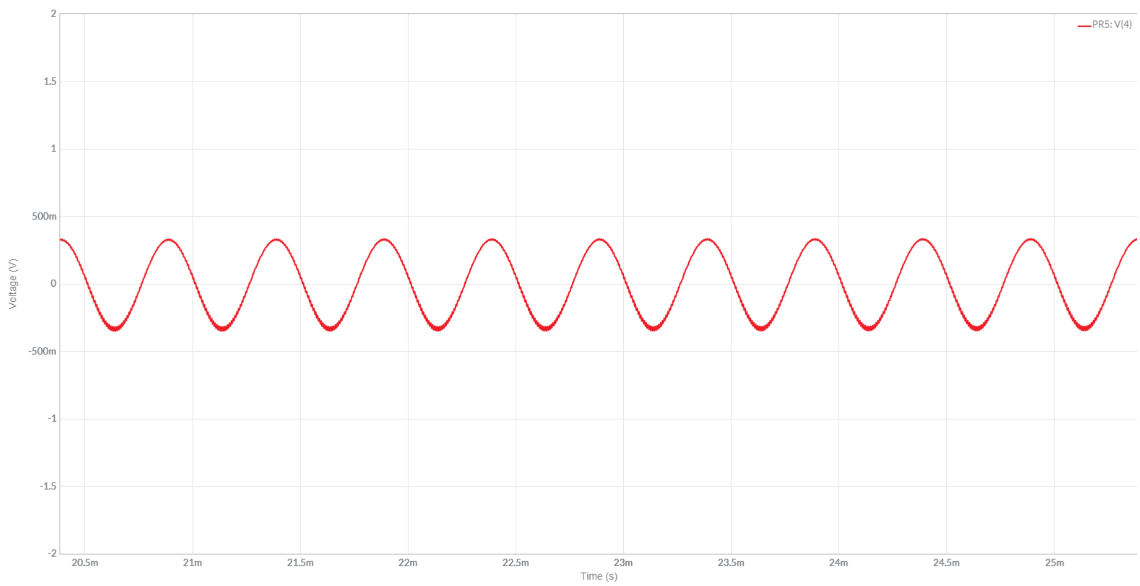


Figure 12. The signal after going through the last capacitor.

4.3.2 AM Demodulation measurement results

The AM demodulator from the simulation was constructed in real life. figure 13 - 16 show the AM Demodulator's results in real life.

Figure 13. The AM Signal input to the AM demodulator.

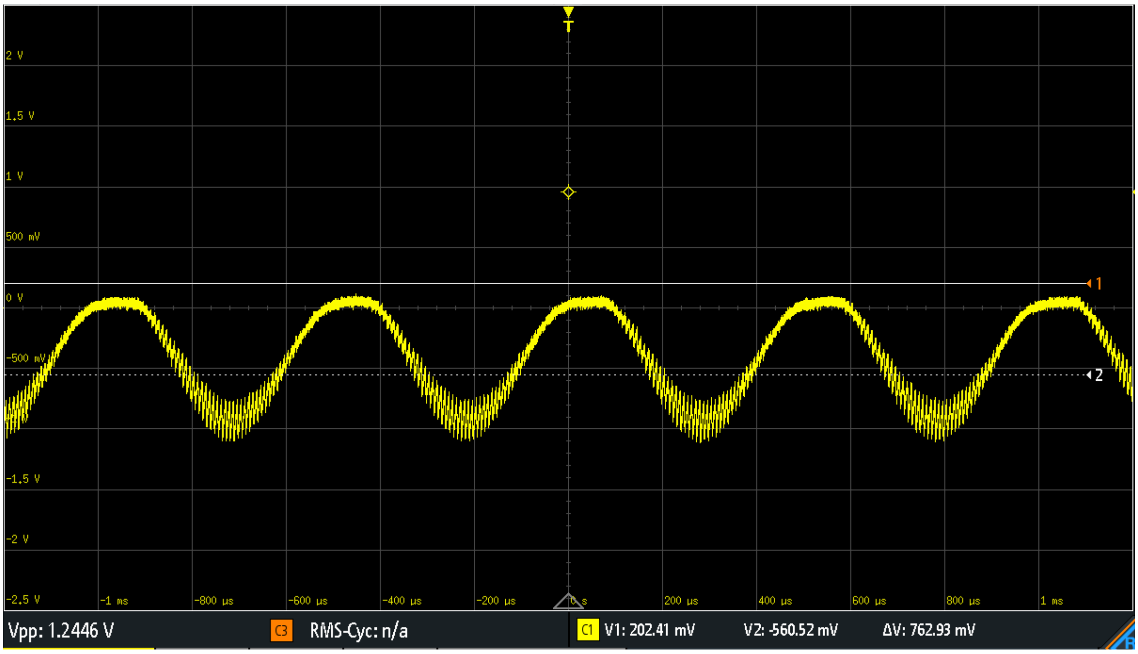


Figure 14. The signal after going through the envelope detector.

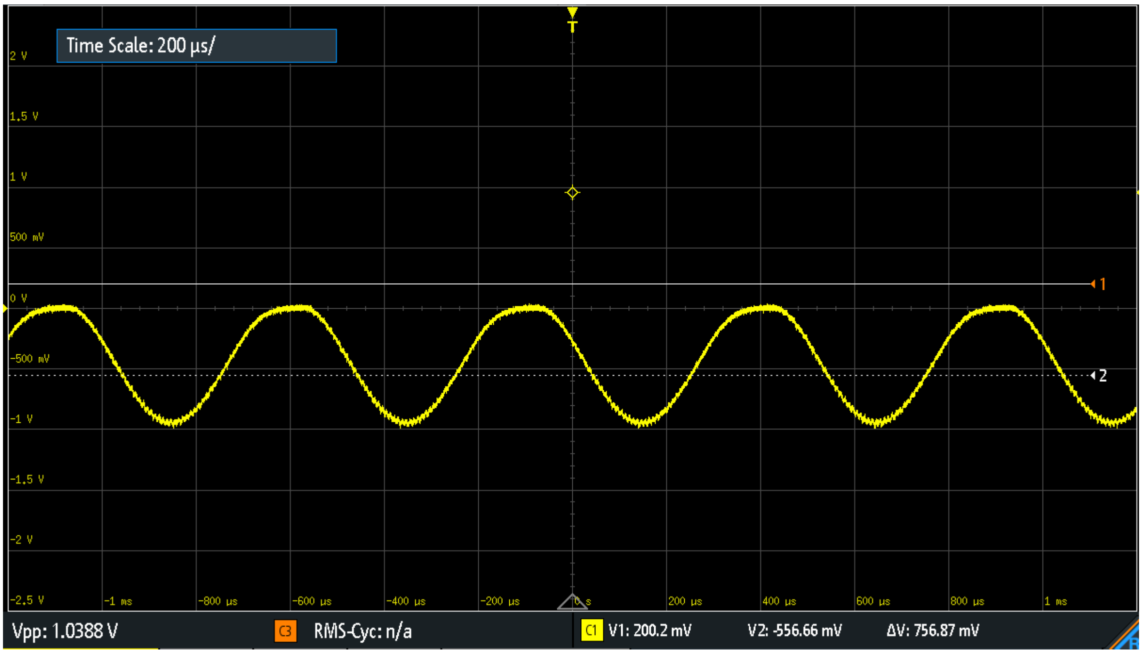


Figure 15. The signal after going through the Low pass filter.

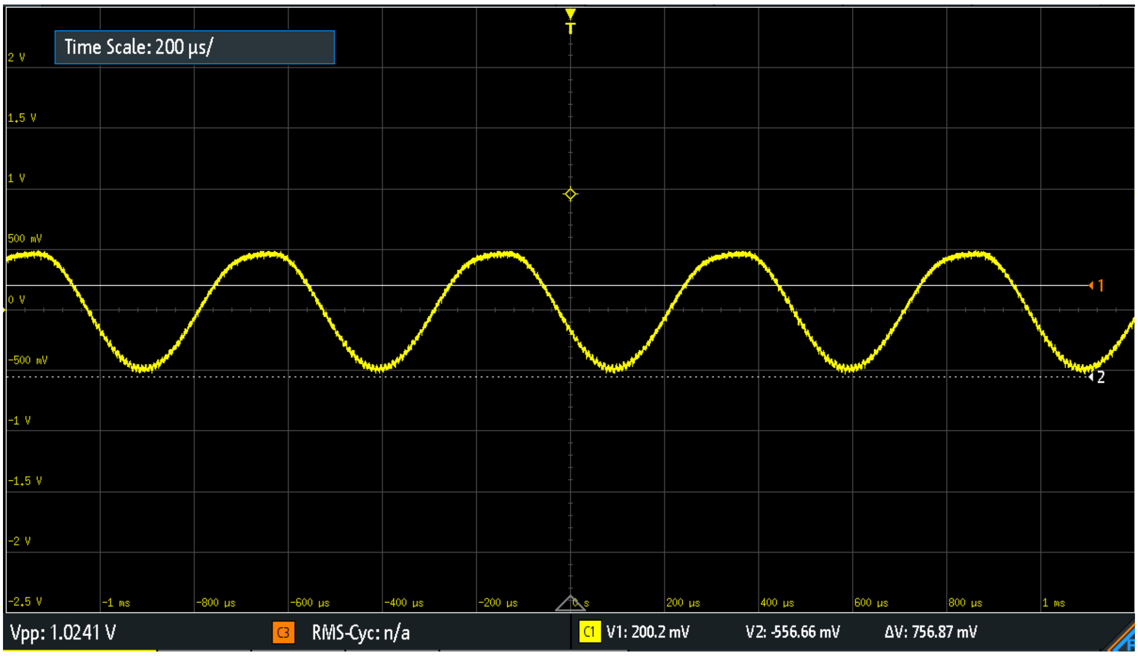


Figure 16. The output signal from the AM demodulator.

The results of the measurements in real life do agree with the simulations which had been made online. It was decided that this design would be the one used moving forward.

4.4 Voltage multiplier

In this section the voltage multiplier will be evaluated in simulation and in practical conditions in order to determine whether the voltage multiplier could work as a battery alternative.

4.4.1 Voltage multiplier simulation

The first step was to design it online and test if it worked in simulation before constructing it in real life. The idea is to have the positive cycle of the AM signals go into the voltage multiplier and the negative side of the signal go into the AM demodulator. It is still unknown whether the voltage multiplier will even work or if it might affect the output voltage of the AM demodulator too much, making it too much of a liability. Therefore, it needed to be tested in simulation. *Figure 1* shows approximately how the design was constructed. This design gave a good output voltage which would supply sufficient enough supply voltage in order to run the driver.

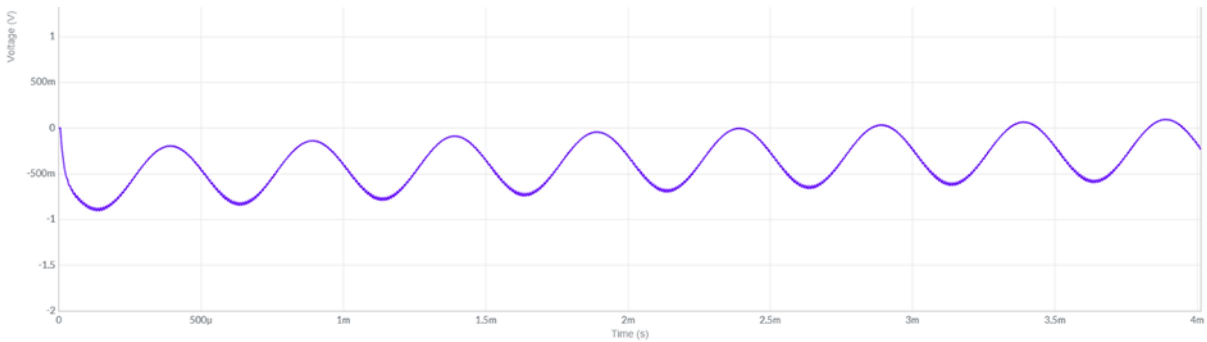


Figure 17. Shows the output of the AM demodulator in the simulation when the voltage multiplier is connected onto it.

When the voltage multiplier was connected to the AM demodulator, it could still provide an adequate DC voltage output. The voltage multiplier has a minimal impact on the output signal of the AM demodulator as shown in figure 17, therefore it was decided to test the design in practical conditions.

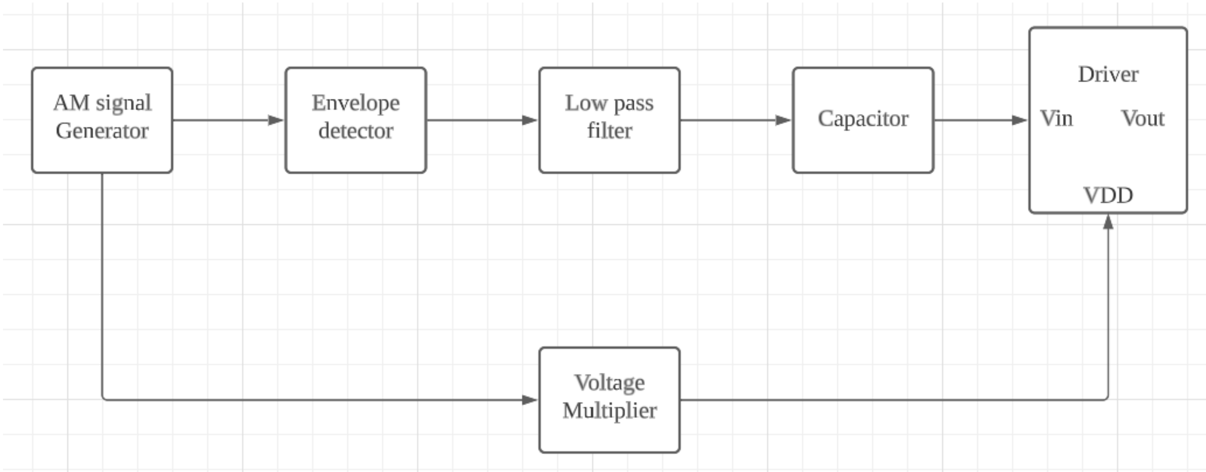


Figure 18. Shows how the voltage multiplier will be connected in the circuit

4.4.2 Voltage multiplier In real life,

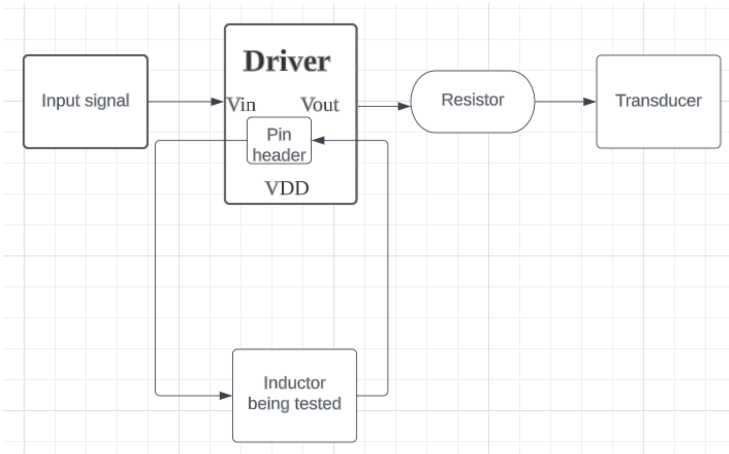
Unfortunately, Oticon Medical did not have the proper diodes therefore in order to build the voltage multiplier, proper diodes needed to be identified and purchased. Once the diodes arrived, the circuit was constructed, and the result measured was similar to the simulation results. Therefore, it was decided to test the voltage multiplier in the overall circuit by connecting it to the driver, as shown in figure 18. The voltage multiplier was connected between the input of the AM demodulator and the driver, the positive half cycles of the AC waveform from the AM signal was needed in order to provide a positive DC voltage to the driver, which is why the diode previously mentioned was facing left. However, once the voltage multiplier was connected to the driver, the output voltage of the voltage multiplier dropped. Therefore another stage was added to the circuit to address the issue, but it still could not supply enough voltage to the driver. It was realized that the driver's load impedance had not been accounted for in the simulations, the simulations were modified to account for this, and a circuit designed to supply enough voltage was designed. However, the voltage multiplier still could not supply enough voltage to the driver even though it worked in simulation. An impedance difference between the voltage multiplier and the driver probably causes this. It could be attributed to the fact that a voltage multiplier might send out a current that proves too high for the driver, therefore the driver limits the voltage intake. Thus it was decided to drop this experiment for this project and eventually further investigation by others would be needed. Theories as to what went wrong will be discussed later on in the report.

4.5 Driver inductor problem

There was additionally a problem with the driver as the driver contains an iron core inductor. This inductor would therefore need to be substituted with a non-magnetic inductor. Ten different versions of inductors were purchased, including air core inductors, silica inductors, and plasma inductors, which are all non-magnetic. Tests were conducted to determine if any of the purchased inductors could yield comparable results as to when the original inductor is used. The important specifications that were sought after were that the new inductor is non-magnetic, that the width and length of the inductor fit onto the board, that the inductance is similar to the original, and that the DCR is as low as the previous one.

4.5.1 Driver non-magnetic inductor test station and results

A test station was needed to be set up to conduct the tests with the different inductors to see which of the inductors could reflect the same results as when using the original inductor. The original inductor needed to be soldered off from the board. However, an idea for how the tests would be made was needed, because just simply soldering on one inductor every time and doing the tests one by one would be time-consuming and could eventually risk doing damage to the driver. Therefore a test station was needed, where the tests could be done efficiently and with minimal risk of damaging the driver. The original inductor was removed from the board, and a pin header was soldered on where the original inductor was located. Two wires were attached to the pin header to test the different inductors. The design of which can be seen in figure 19. Tests were done on all the inductors, and eventually, one inductor showed promising results. Therefore, it was decided that further testing needed to be performed with this inductor. The inductor that showed promising results was an air gap inductor.



a)

b)

Figure 19. Where a) shows how the test bench was designed and b) shows how a pin header looks like.

4.5.2 Comparing the original inductor with the air gap inductor.

The air gap inductor was soldered onto the driver, and tests were done to observe the power consumption at different frequencies.

Table 2 table a) shows the results from the tests done with the normal inductor and b) shows the results from the tests done with the air gap inductor.

Frequency	Power consumption
100Hz	7.25mW
1kHz	11.25mW
10kHz	55.5mW

a)

Frequency	Power consumption
100Hz	7.5mW
1kHz	12.25mW
10kHz	62 mW

b)

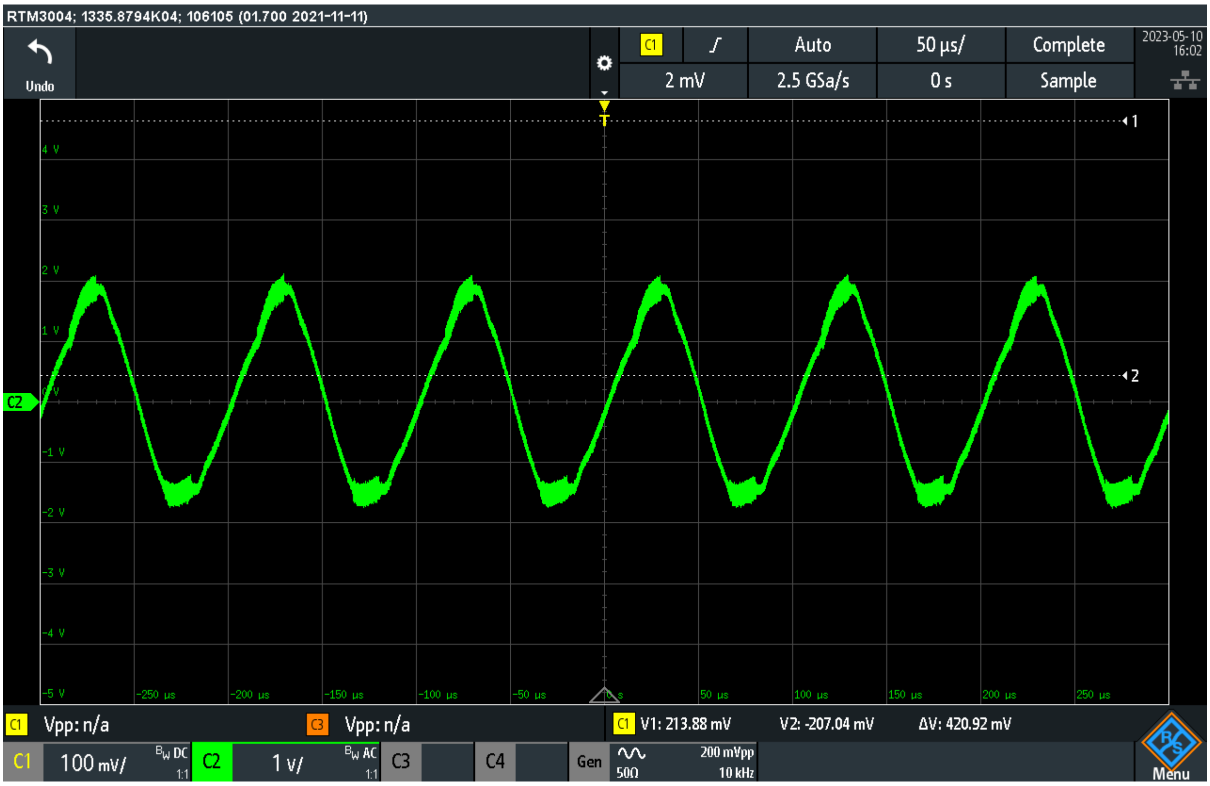


Figure 20. The output with the original inductor

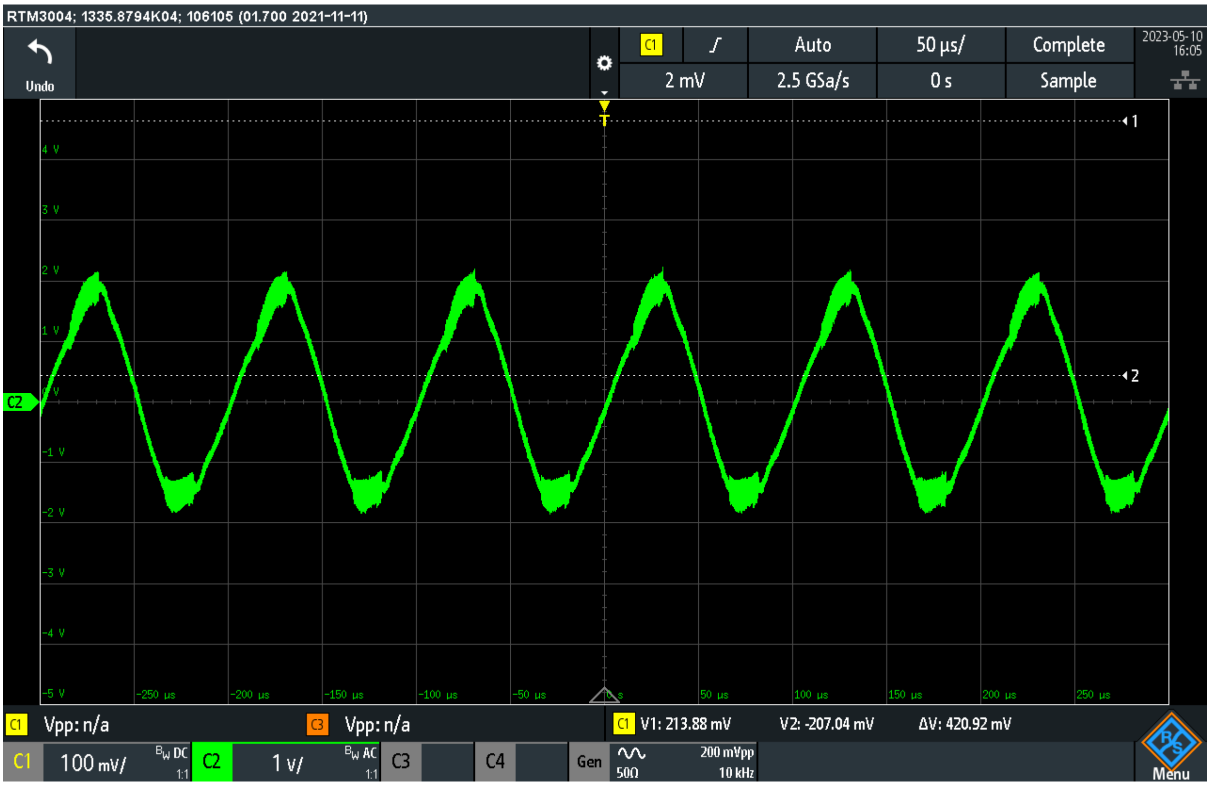


Figure 21. The output with the air gap inductor

While the output signal with the air gap inductor is almost identical which can be seen in figure 20 and figure 21, there is an unfortunate increase in power consumption, as shown in table 2. This is likely because the DCR of the air gap inductor is much higher than the original inductor. Additionally it is possible that the observed power consumption could be attributed to damages on the driver. Therefore running the driver with the air gap inductor would be too much of a liability. Nevertheless, it was realized that the driver could be operated without an inductor. This is likely due to the fact that the hearing aid deals with relatively low frequencies ranging from 100Hz to 10kHz, meaning the impedance of the inductor, even at the highest frequency, is negligible. The equation for the impedance can be shown with the formula below in equation(5). This could lead to eventual issues further along the line, which would need to be investigated.

$$X_L = 2\boldsymbol{\pi} \cdot f \cdot L \quad (4)$$

Formula for the reactance of the inductor where X_L is the reactance of the inductor, f is the frequency and L is the inductance.

$$Z_L = R + jX_L \quad (5)$$

Formula for the impedance of the inductor where Z_L is the impedance of the inductor, R is the the resistance of the inductor and X_L is the reactance of the inductor .

4.6 Complete system measurement results

The final tests were to check the difference in running the driver with and without an inductor. Tests were also done using the link and the AM demodulator to make the test reflect real life as much as possible. The link represents the AM signal being sent from the AM modulator through the skin into the implant. The figure below in figure 22 shows how the tests were conducted.

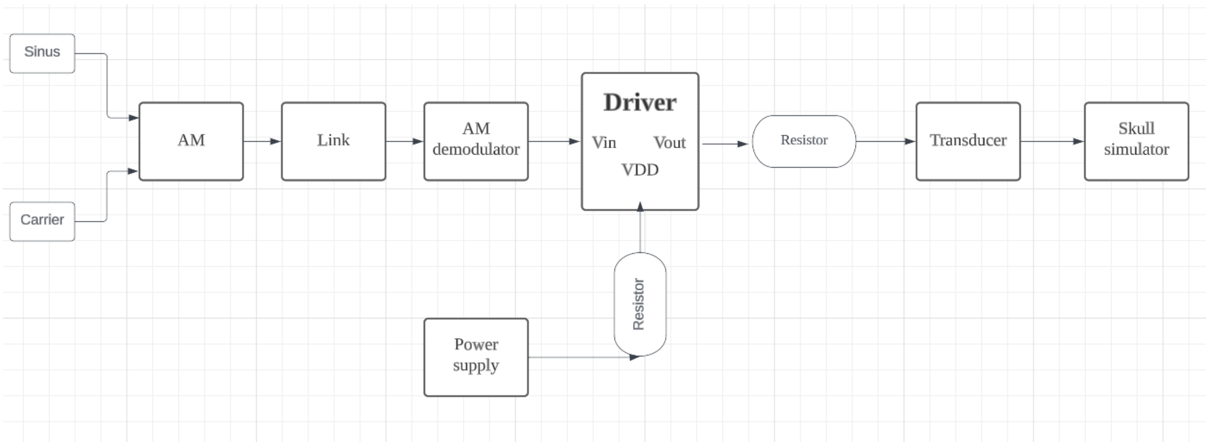


Figure 22. Shows the test setup of the final test with the link and AM demodulator connected.

The initial test aimed to measure the power consumption difference between the driver with an inductor and without an inductor additionally, the output force on the skull simulator was compared between the two.

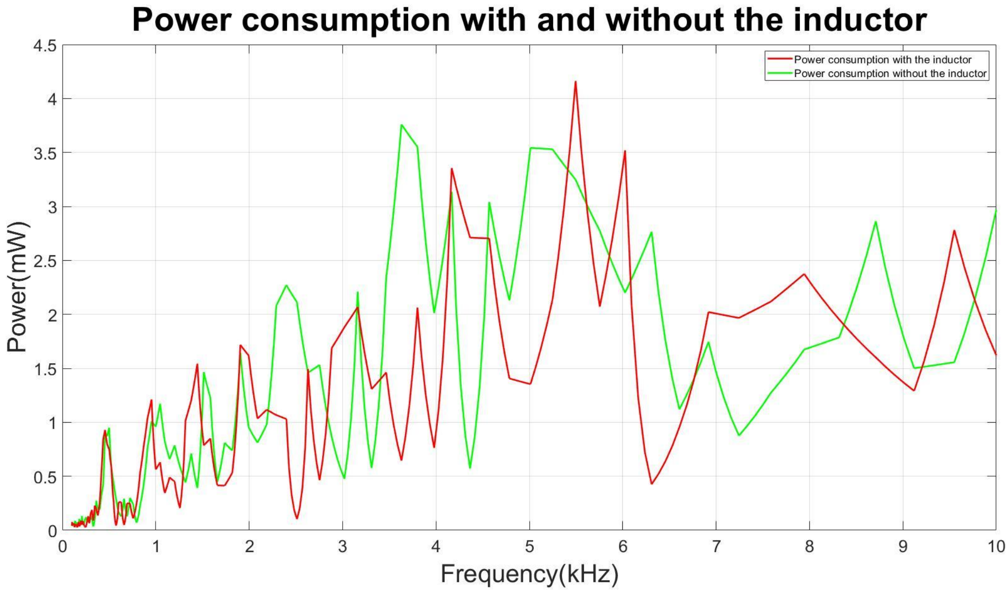


Figure 23. Shows the power consumption for the driver without the inductor shown in green and with an inductor shown in red.

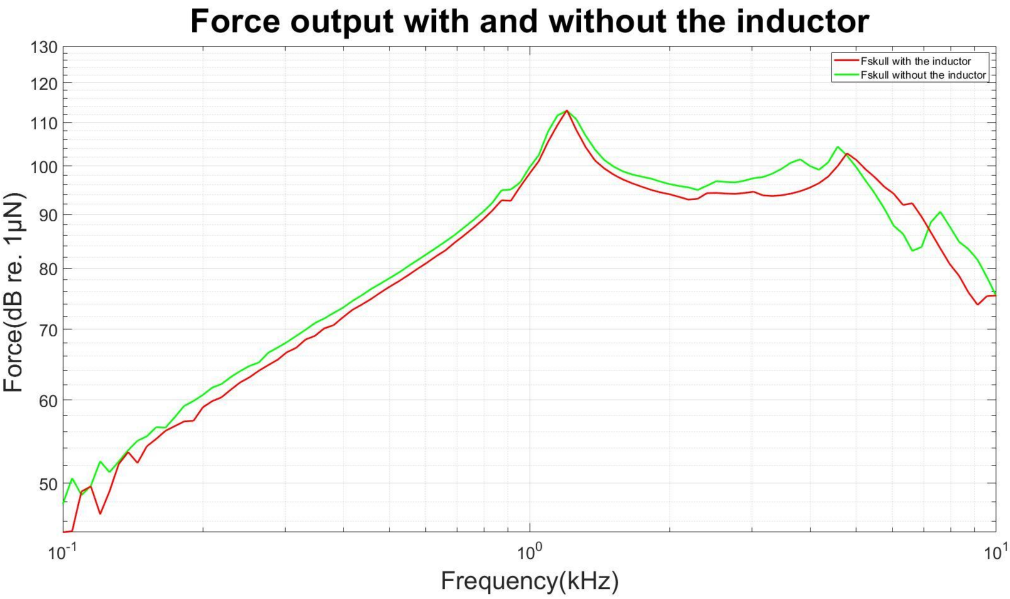


Figure 24. Shows the force output for when the Inductor is connected, shown in red and when the inductor is not connected, shown in green.

As can be observed in figure 23 and figure 24, the removal of the inductor has almost no impact on the output force and only minimal impact on the power consumption. The power consumption was calculated using equation(1) and the force output was done using the equation shown in equation(2). This observation indicates that the driver operates relatively the same whether it has an inductor or not.

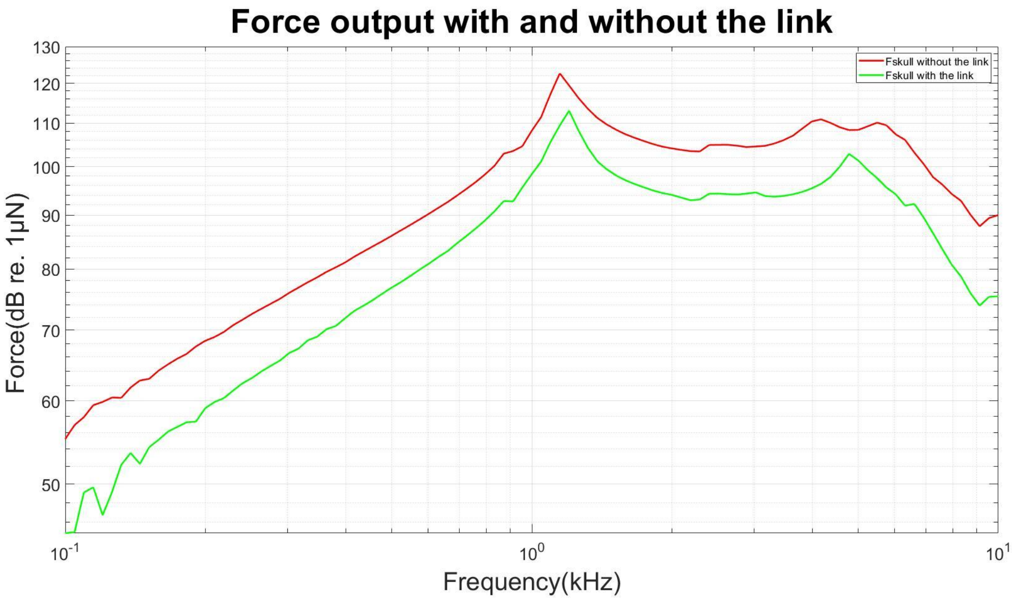


Figure 25. Shows the force output using a link shown in red and without the link shown in green.

When the link is in use, the output force of the transducer is reduced by around 9.5 dB which can be observed in figure 25. This force output was calculated using equation(2). This demonstrates approximately how much the output force would be in a real-life hearing aid. The output force is higher without the link due to the losses in the link between the AM signal and the driver.

The final tests were done the same way as the link test, with the objective of measuring the force level for different dBs, and to determine the THD.

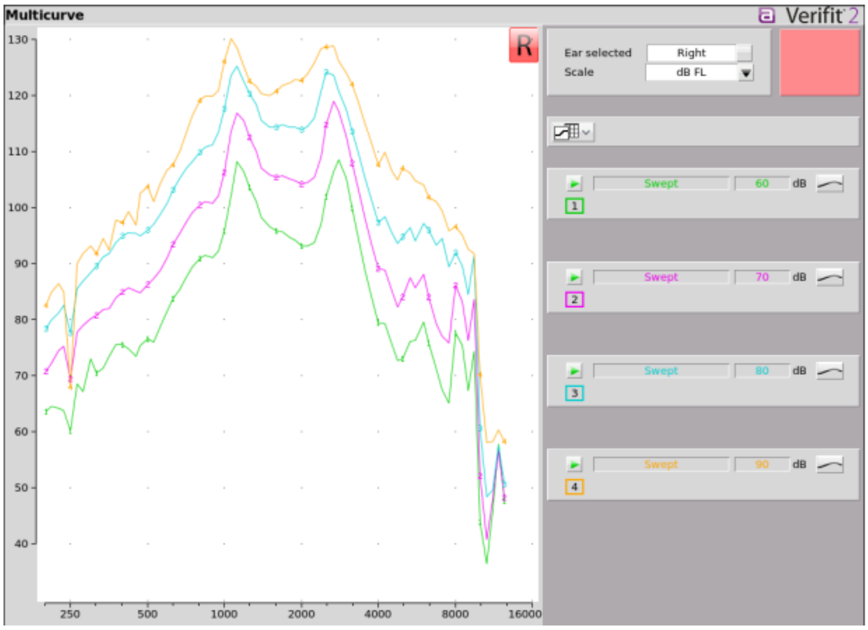


Figure 26. Shows the result from the force level test ranging from 60dB - 90dB

This test was done to investigate the maximum achievable force of the transducer across different force levels. As depicted in figure 26, the transducer reaches a maximum of around 130dB when 90dB SPL is applied, showing that 130dB is the highest force that can be output before it reaches its limit. It can also be noted that the output force level in figure 26 at 60-65dB SPL input sound more or less corresponds to the force level from a constant input voltage of 50mV on the skull simulator, as shown in figure 24. A test was also done to compare the output with and without an inductor, as shown in figure 27. The test results of that figure indicate that removing the inductor has negligible impact on the force level.

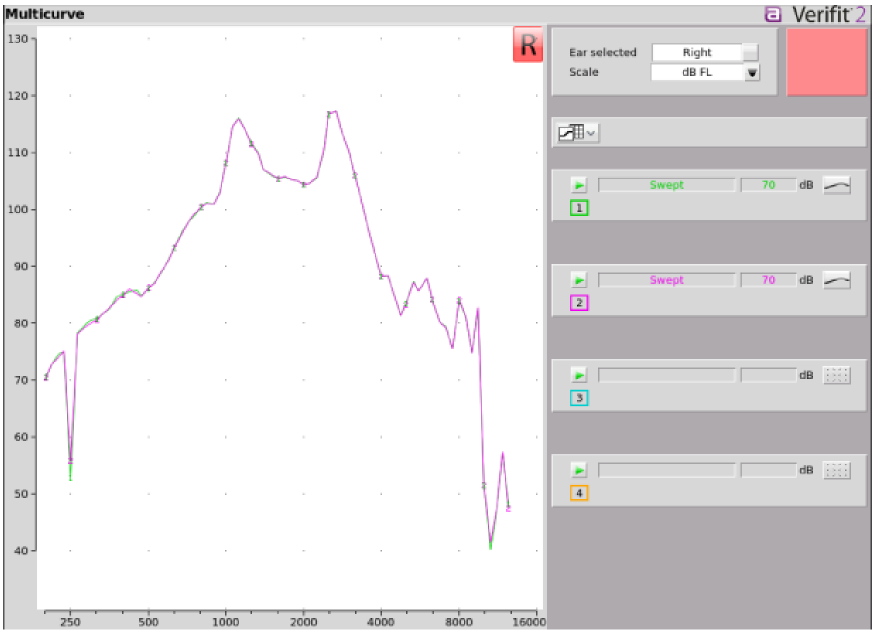


Figure 27. Shows the comparison of using the Inductor shown in purple and not using the inductor shown in green..

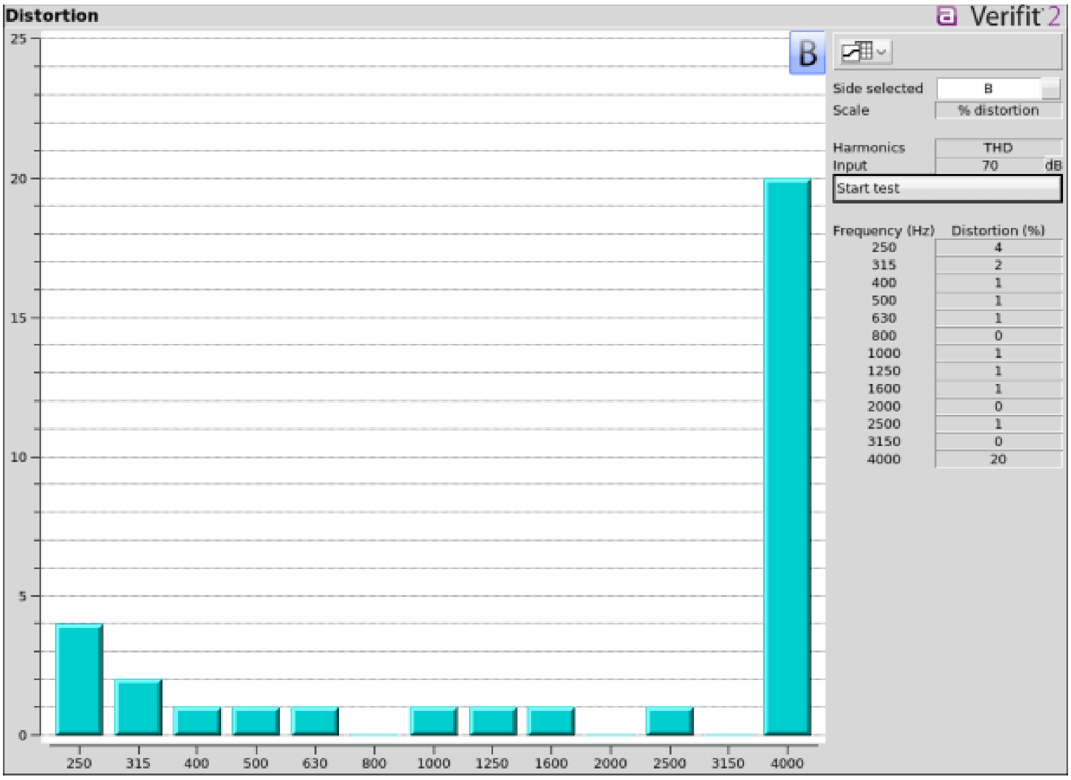


Figure 28. Shows the THD results from the test.

Figure 28 depicts the THD of the hearing aid circuit, which can be observed to be quite good as the distortion should be as low as possible and preferably a distortion under 6%. This is the case for all of the shown frequencies except at 4000 Hz which shows a significantly higher distortion level compared to the other frequencies. This specific frequency was cross-validated using another measuring tool, where it showed a much lower distortion level. Therefore the distortion is high at 4000 Hz due to a fault with the measuring equipment. If a more accurate result is needed, the test would have to be done using more accurate measuring equipment.

4.7 Challenges and possible explanations

Several challenges have arisen throughout the course of the project. For example a lot of time was devoted to implementing the voltage multiplier in the hearing aid. Once the multiplier was connected to the load, which in this case was the driver’s power supply pin, a voltage drop occurred. The voltage drop was substantial enough to prevent the driver from receiving its required voltage in order to function properly. Although this issue was never resolved, a number of theories were discussed as to why this method has limitations such as voltage drop under load conditions. The voltage drop likely occurs due to the current drawn by the driver from the multiplier when the two are connected. Some of the charge stored by the capacitors is discharged when the load is connected, in order to provide current to the load. This results in a lower voltage of the capacitors, leading to less output voltage from the multiplier. An idea to further investigate this could be impedance matching between source and load. When impedance matching between source and load is achieved, the maximum amount of power transfer occurs, and losses are minimized [9].

As for the MRI compatibility of the driver, the solution was to remove the inductor with the magnetic core since removing it had no significant impact on the performance of the driver. A possible explanation to this is that the testing frequencies (up to 10 kHz) were too low to affect the inductor's impedance. An inductor's impedances is proportional to frequency, the higher the frequency, the higher the impedance will be. In this case it seems that the highest testing frequency of 10 kHz causes the inductor to have an impedance which is negligible and therefore does not affect the results.

5

Conclusions

The purpose of this project was to evaluate and investigate if any commercial driver could amplify the processed signal enough in order to drive the transducer with as low power consumption as possible. In this project a couple of commercial drivers were tested and eventually one driver fulfilled the requirements since the driver provides a high output force and is able to drive the transducer sufficiently. As can be observed in the tests, the driver produces a low THD and quite a low power consumption, thus regarding the purpose of this project, the demands put on the commercial driver have been met. Regarding the questions which were asked in the beginning of the project;

- Evaluate commercially available drivers to determine the ability to drive the transducer.
- Identify and verify potential modifications of chosen candidate driver(s) to improve power efficiency.
- If the driver contains an iron core inductor the aim is to evaluate the possibility and consequences to use an air core inductor.
- Determine the driver's MRI compatibility.

The first question is very clearly answered as there is a driver which can drive the transducer well. The second question was not necessarily expanded on that much and in this project, the design of the amplifier itself was not modified to try and improve the power efficiency. The only modification that was done to the driver was to remove the inductor, with the idea to make it MRI compatible. The third question was investigated a fair bit, tests revealed that an air gap inductor would lead to a higher power consumption than that of the original inductor. Although as mentioned, the solution to this problem was to proceed without an inductor since it had no significant effects on the performance of the driver. In this project an MRI scan test was never done due to time constraints. It would likely pass the MRI test but this would require further testing to be guaranteed.

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