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Evaluation of a novel and efficient transcutaneous energy transfer link for bone conduction hearing devices

Master's Thesis in Biomedical Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Open Toroid Link Gothenburg, Sweden 2020

Abstract

Background: Implantable hearing devices of various designs, specifications and intended use are available today and are used to treat patients suffering from various types of hearing loss. Active transcutaneous bone conduction devices represent one such system, where sound is converted into vibrations that are transmitted to the skull and thus to the cochlea via bone conduction. In a transcutaneous system, the implant containing the transducer is placed under intact skin and the power is transferred through the skin via a transcutaneous energy transfer (TET) link. The efficiency of such a link is dependent on the skin thickness, which can vary from a few up to about 15 millimetres. An improved link design would enable a higher sound output, opening up new possibilities for treating patients with severe hearing loss with these systems, while also increasing battery lifetime and reducing the size of the system. A novel link, the Open Toroid (OT) link was evaluated and optimized for efficiency. The solution consists of an external transmitting coil with a toroid ferrite core with a gap of 5 mm and an implanted receiving coil with an air core, electrically and dimensionally matched. The OT-link has potentially a higher energy transfer efficiency compared with a TET-link since the gap between the transmitting and receiving coils is constant and since the toroid core and windings concentrates the flux. The main objective of this thesis was to investigate the performance and the efficiency of a link based on a toroid and to compare it with a conventional TET-link system in terms of efficiency of power transmission.

Materials & Methods: The influence of winding pattern, ferrite core material, wire diameter and misalignment between receiving and transmitting coils were systematically investigated. Evaluation was performed on a measurement system comprising a signal generator, a sound processor, a transducer, a skull simulator and a signal analyser. The energy transfer efficiency was evaluated for the OT-link and compared that with a TET-link using the same system level measurement setup.

Results: The OT-link outperformed the TET-link with regards to energy transfer efficiency. The power transfer efficiency was improved two to ten times for the OT link compared with the TET-link depending on the skin thickness and toroid parameters. More evenly distributed winding pattern, larger wire diameter up to 0.3 mm and more frequency specific ferrite core material improved the efficiency. The OT link showed robustness and stability as different alignments of the toroid in relation to the receiving coil resulted in only minor changes in efficiency.

Conclusion: In conclusion, the present study demonstrate that the OT-link provides an efficient alternative for transcutaneous energy transmission for bone conduction devices.

Keywords: Bone Conduction, Implant, Radio Frequency Link, Toroid, Transcutaneous Energy Transfer

Acknowledgements

In dedication to my family, friends and colleagues...

In the middle of my thesis project I was involved in an accident which not only affected the project, but my whole life. I would like to express my most sincere gratitude to my family, friends and colleagues for being there for me and supporting me through this time. I would not be here without you.

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Wilhelm Helgesson Råbergh, Gothenburg, April 2020

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Definitions and Abbreviations

AC - Air Conduction
AM - Amplitude Modulation
BAHS - Bone Anchored Hearing System
BC - Bone Conduction
BCI - Bone Anchored Implant
CI - Cochlear Implant
dB - Decibel
dBHL - Decibel Hearing Level
dBSPL - Decibel Sound Pressure Level
dBV - Decibel relative 1 Volt
DSP - Digital Signal Processing
HW - Hardware
$\boldsymbol{K - factor}$ - Energy transfer efficiency factor
MRI - Magnetic Resonance Imaging
N/A - Not Applicable
OT - Open Toroid
RF - Radio Frequency
SW - Software
TET - Transcutaneous Energy Transfer

1
Introduction

When it comes to quality of life and coping with everyday life such as work, family and friends, people subjected to a temporary impairment quickly relates to life before this impairment. With hearing, damages to the ear can sometimes become permanent and irreversible. However, there are several different solutions that could help with hearing. Depending on the type of damage, different solutions could be of benefit. One of these solutions are bone conduction devices, which can compensate the lost hearing to different extents, given that the cochlea in the inner ear is functional. The devices can achieve that, by sending vibrations through the skull bone which reaches the cochlea.

1.1 Background

There are several bone conduction hearing devices available today. One important such device is the Bone Anchored Hearing System (BAHS) or Bone Anchored Hearing Aid (BAHA), made available by Oticon Medical AB (Askim, Sweden) with the Ponto system and by Cochlear AB (Mölnlycke, Sweden) with the Baha®. The solutions consist of a titanium screw implanted in the temporal bone of the skull onto which a skin penetrating (percutaneous) abutment is attached. By connecting a sound processor to the abutment, a direct connection to the skull bone is obtained. This type of bone conducting hearing device allows for direct drive of vibrations in the skull, which is very effective. It also requires that the abutment permanently penetrates the skin. Different challenges arise from this method. There is always a risk of adverse skin reactions, such as inflammation and infection. Hence, the user is required to actively take care of the skin around the abutment, keeping it clean and making sure the skin is not irritated. Moreover, the cosmetic factor of which the user might be discouraged by own choice due to appearance, as well as the responsibility and

commitment in maintenance.
A possible improvement is the placement of the transducer, which is indirectly attached to the skull where the titanium screw is attached. A more optimal positioning would be closer to the ear canal in the temporal bone as this is closer to the cochlea [16]. The vibrations would then need to travel shorter distance in the bone before reaching the cochlea and less amplification of sounds would be required for the same perceived sound level.
In an attempt to address some of these concerns, such as cosmetics and maintenance and utilise the more efficient placement, transcutaneous devices have emerged as an alternative. Here, the skin is left intact with the transducer positioned under the skin and the energy is transferred through the skin via an inductive link.
Examples of this type of solutions are the Bone Conduction Implant BCI [1] and the Bone Bridge (MED-EL, Innsbruck, Austria). In brief, these devices consist of two parts, the transducer which is surgically implanted under the skin together with a Radio Frequency (RF) coil and a magnet, the skin is then allowed to heal, keeping it intact. The sound processing unit together with the battery and a RF coil is placed on the outside of the skin, attached with a magnet, where signals and energy are transmitted over the RF coils. However, the wireless connection made up by the RF coils in these devices have resulted in a less efficient energy transfer compared with the percutaneous BAHS solution. There is opportunity to place the transcutaneous transducer closer to the cochlea compared to the BAHS, thereby regaining some of those losses, especially in the high frequency area [16]. The sound processor can also be easily attached or detached.
A drawback with the transcutaneous bone conducting devices are the presence of the implanted magnet as well as the magnets in the transducer. In case of the patient needing magnetic resonance imaging (MRI), there will be restrictions in maximum MRI effect used. In addition, large artefacts will be inevitable, making analysis in the head area difficult. As new MRI machines tend to an increased number of Teslas and recent studies shows that the MRI's are used more within health care and is increasing yearly across the world [2].
This information suggests that a further development of transcutaneous bone conduction device could benefit from improvements. Where

an increased energy transfer efficiency, a more optimal position of the transducer and MRI transparency are the main improvements identified.

1.2 Project description

The goal of this project was to construct and evaluate prototypes of a novel energy link for bone conduction hearing applications. The project is based on previous research at Oticon Medical, scientific studies within the field and experiments and measurements. The novel link is an open toroid (gapped toroid core) coil with electrical characteristics similar to a toroidal transformer. The hypothesis is that the link can provide a more efficient energy transfer to a bone conduction device, be optimised for better performance and at the same time be suitable for a wider range of users.

1.3 Aims

The main objective of this thesis was to investigate the performance and efficiency of a novel link based on a toroid, for signal and energy transfer in a transcutaneous bone conduction implant. These main attributes have been divided and clarified into the following specific aims.

- Develop a bench model to evaluate the energy transfer efficiency of a link system based on an open toroid (OT) link
- Determine the influence of
    1. toroid core material,
    2. wire diameter and winding pattern of the transmitter and receiver coil, and
    3. misalignment between transmitter and receiver coils on the energy transfer efficiency.
- Compare the OT-link system with a conventional TET link system in terms of energy transfer efficiency.

2
Theory

2.1 Hearing and hearing physiology

Hearing is the phenomena of sound from vibrations resulting in sound waves that are transmitted through air and direct or indirect vibrations that can travel through bone. The types of sound vibrations can be perceived in different ways and in the end, result in nerve signals from the cochlea to the brain's auditory system. The ear can be generalized in the outer, middle and inner ear, figure 2.1. The outer and middle ear enables air conduction hearing, while the inner ear is necessary both for bone conduction (BC) and air conduction (AC) hearing.

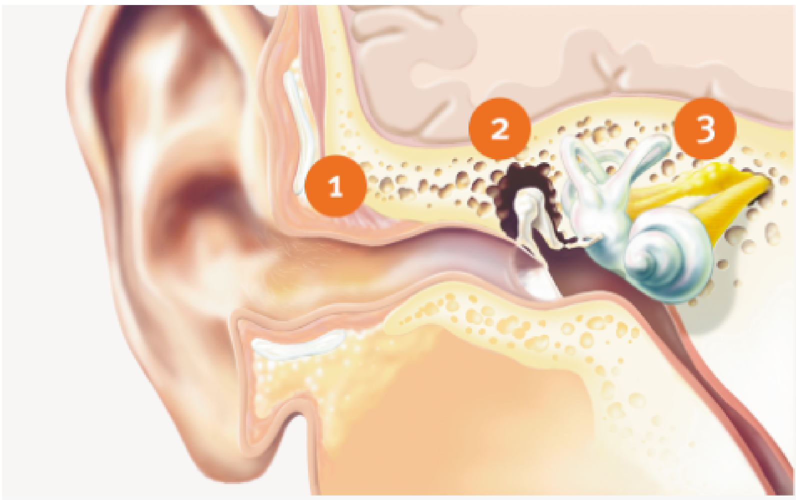


Figure 2.1: Illustration of the anatomy of the human ear where (1) is the outer ear, (2) is the middle ear and (3) is the inner ear. Courtesy of Oticon Medical AB.

2.1.1 Air conduction

Air conduction hearing could be considered the primary auditory path for normal hearing people as this is how most sounds from our environment are perceived. The external part of the hearing organ consists of the Pinna and the Concha of the outer ear. The Pinna is what is referred to as the ear in a non-scientific manner, the Concha is a resonant hollow and together they help direct sound waves into the ear canal. This anatomy amplifies the sound by increasing the pressure, humans are especially perceptive to sounds in the range of 2 kHz to 5 kHz [3]. In the end of the ear canal, the ear drum or tympanic membrane is located, which is the first part of the middle ear. This is where the sound waves are translated into mechanical vibrations as the tympanic membrane is connected to the Cochlea through the bones, Malleus, Incus and Stapes, in that order, constituting the auditory Ossicles The Ossicles are connected to the oval window of the Cochlea, the pressure variations of the outer ear is translated through the middle ear and gives rise to variations in the Cochlea. This results in the Cochlear nerve which ultimately sends neural information through to the brain. An illustration of the anatomy of the human ear can be seen in Figure 2.2.

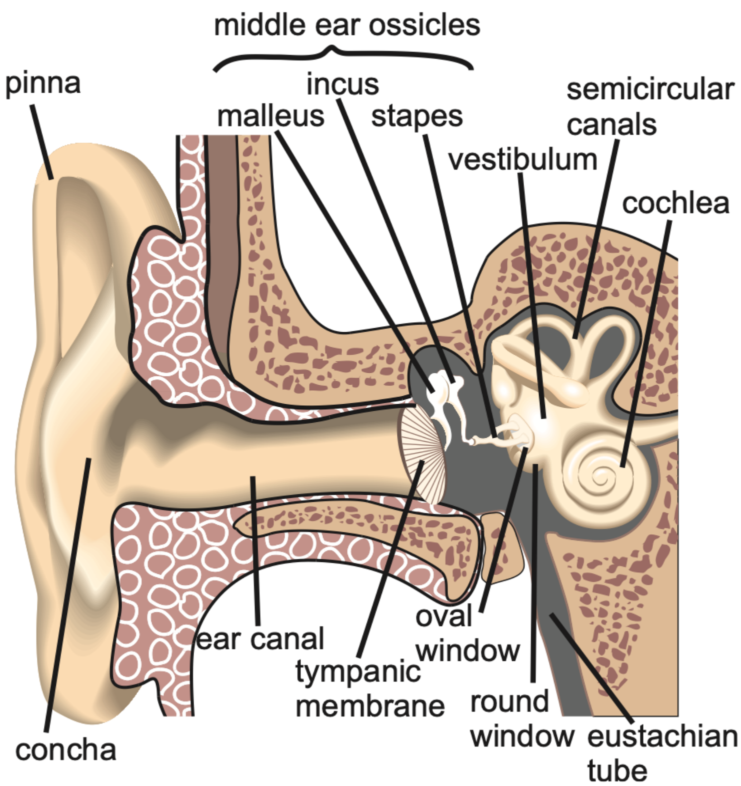


Figure 2.2: Detailed anatomy of the human ear [8]

2.1.2 Bone conduction

Bone conduction is the secondary auditory path leading the sound to the Cochlea as the result of vibrations in the skull bone. Looking at the full anatomy of the human ear one can see the Cochlea is nearly enclosed in the temporal bone through which vibrations can be transmitted. However, bone conduction hearing is much more complex where vibrations are transmitted through the ear canal, with inertial forces, as well as Cochlear fluids. The sources from where the bone conduction sounds originate can be many, and the most prominent ones are probably direct mechanical vibrations either through the skin or right in the skull for example a bone conduction hearing device, or the voice of one own. Bone conduction hearing from surrounding sounds is 40 dB to 60 dB less effective than air conduction during normal circumstances [7].

2.1.3 Hearing impairment

Hearing impairment (also known as hearing loss) can occur in many ways and affect people to different extent. However, the world health organization (WHO) estimates that around 466 million people suffers from disabling hearing loss [14]. The most common hearing loss, is called sensorineural hearing loss where the most common factors are due to ageing and being subjected to loud noises during a period of time [15]. What causes this loss of hearing is a consequence of damaging the cochlear hair cells that normally enables the translation of vibrations in the cochlea into signals in the sensory nerve and further to the brain. Depending on the severity of the hearing impairment, the usual solution is an air conduction hearing device which essentially amplifies sounds through a speaker placed in the ear canal where the sounds are further transmitted to the middle ear. Conductive hearing loss includes any cases where AC hearing is hindered, either temporarily or permanently such as irritation, inflammation, tumorous formation or genetic malformation leading to damage of the ossicles.

The extent of a hearing impairment is typically divided into five different levels, ranging from not hearing the softest sounds such as whispers, until total deafness, where a person does not hear a single thing [11][12], figure 2.3.

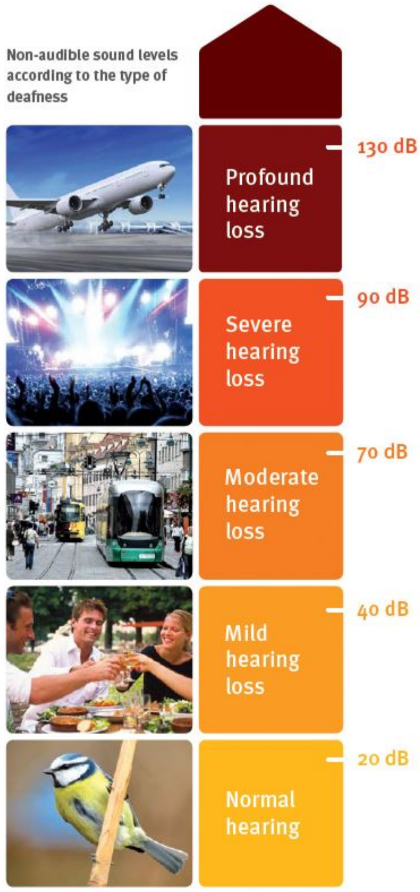


Figure 2.3: The different levels of hearing loss and their equivalent sound levels in decibel [11].

The first level is ***mild hearing loss*** where light whispers and dripping water are usually not perceived. The quietest sound levels heard range between 25 and 40 dBHL.

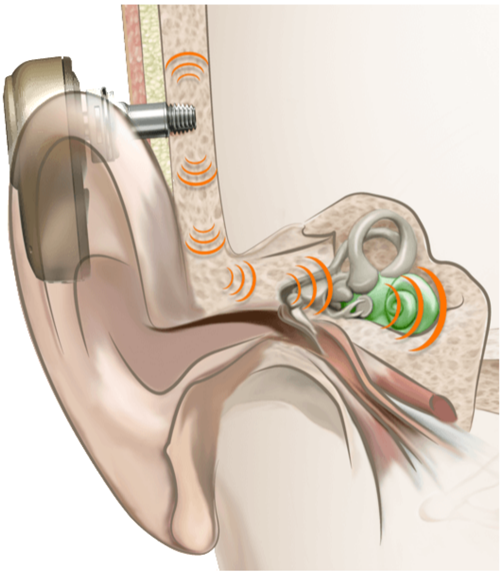
Secondly, what is referred to as ***moderate hearing loss***: normal speech starts to fade, but can be perceived when speaker raises the voice. A person with this level of hearing loss typically cannot hear sounds lower than 40 to 70 dBHL.

The third level, ***severe hearing loss*** heavily affects a person's understanding of speech. Sound levels lower than 70 to 90 dBHL are not perceived.

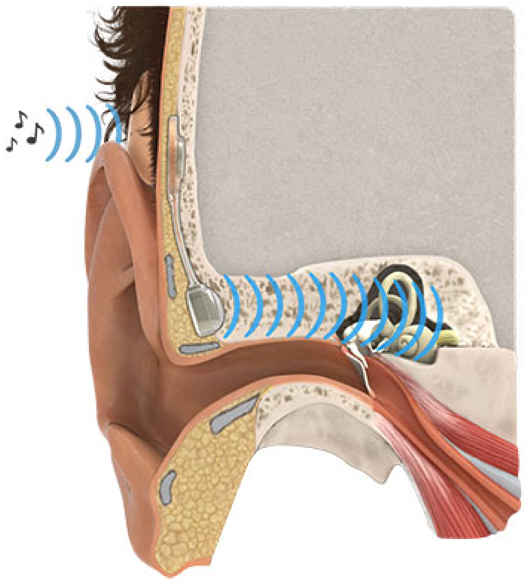
With ***Profound hearing loss***, sounds below 90 to 120 dBHL cannot be perceived and the person would in many cases be considered deaf. Only very loud sounds can be perceived, but not distinguished, and no form of communication in speech is possible. The last level mentioned in this area is ***total deafness***, also known as Cophosis. At this level of hearing loss, nothing is perceived.

2.2 Hearing devices

BC devices bypasses the outer and middle ear and transmits sound directly to the cochlea through bone. In contrast to an AC hearing aid, BC devices are converting the sound into vibrations in a transducer that transmits the vibrations to the bone. There are several different BC devices that are used for different patient needs or preferences. The BC devices can be divided into different types where some requires surgery and some do not, and the biggest difference concerns the attachment of the device. The non-surgical devices are pressed against the skin through which the vibrations passes into the bone, often referred to as skin drive devices. The device is held in place using for example a headband/softband. This type of device can typically be used while evaluating a bone anchored hearing device. It can also be an option for children where an implant is not yet viable, or in other occasions where surgeries cannot be performed.



(a) The percutaneous bone conduction device known as a Bone Anchored Hearing System (BAHS). Courtesy of Oticon Medical AB.



(b) The transcutaneous bone conduction implant (BCI). Illustration by Boid Chalmers.

Figure 2.4: Implanted bone conduction hearing devices, two ways.

The most efficient method of transferring the vibrations is directly to the bone and requires an implant. This method is referred to as direct drive and can be utilised by BC devices, figure 2.5. Most common is the skin penetrating (percutaneous) implant consisting of a titanium screw and an abutment. The screw is implanted in the temporal bone onto which the permanently skin penetrating abutment is fastened. The BC device is then attached to the abutment allowing for the vibrations to go directly into the bone, hence direct drive, figure 2.5.
A recent advancement are the transcutaneous active bone conduction implants, where the transducer together with an antenna is implanted under the skin while the sound processor is retained on the outside of the skin by the means of a magnet, Figure 2.4b. This type of product addresses the lifelong commitment of the percutaneous implant when it comes to skin care around the abutment. Instead, the hearing device is divided into two parts which are the audio processing side and the transducer side, or the outer part and the implanted part.

Figure 2.5: The three main parts of a BAHS, implant, abutment and sound processor (Ponto 4). Courtesy of Oticon Medical AB.

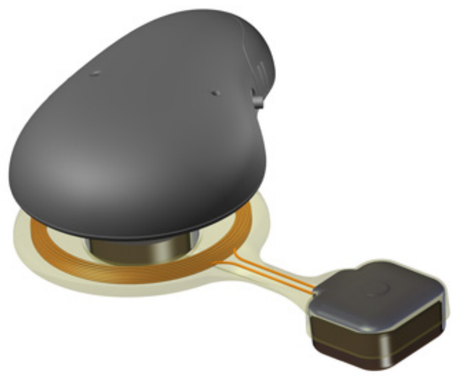


Figure 2.6: The transcutaneous bone conduction implant (BCI) [1].

2.2.1 Transcutaneous Energy Transfer Links

For a transcutaneous system, the wireless transfer of data and energy is one of the most crucial parts of the system. The transducer of active transcutaneous devices are powered from a battery via an radio frequency (RF) link with a transmitter and a receiver coil. Each coil (or inductor) has an inductance determined by factors such as wire material, thickness and number of turns. As a pair, the mutually coupled coils have a mutual inductance (M) which is related to the degree which the coils can be considered to be coupled, known as the coupling factor. The relationship is described with the formula in equation 2.1.

$$Coupling\,factor = \frac{M}{\sqrt{L_1\,L_2}}, \tag{2.1}$$

where $0 \leq Couplingfactor \leq 1$, L_1 and L_2 are the individual inductances of the coils [13], and M is the mutual inductance.
Resonance in a link is achieved with a certain resonant frequency when the links' two impedances act as each others opposites. This can be used to an advantage and a frequently used case is to deliberately cause a "ringing" in the circuit, which then give rise to higher voltages than what was fed to the circuit.
Resonant circuits are often referred to as LC or LCR circuits, referring to its components, resistors (R), inductors (L) and capacitors (C).
The resonance frequency for a circuit can be found by the relation of the components (equations 2.2 and 2.3).

$$\omega = \frac{1}{\sqrt{LC}}, \;\; \omega = 2\pi f \tag{2.2}$$

$$\rightarrow f = \frac{1}{2\pi\sqrt{LC}} \tag{2.3}$$

The resonance frequency is determined by the circuit's Q-factor, which is a function of its resistance. The perfect LC circuit would have an infinite Q-factor and no resistance. However, this is only in theory and not applicable in an actual circuit, since there will always be some resistance. The actual case is better described by the LCR circuits.

The difference between the LC and LCR circuit is the presence of a resistor (or resistance) which generates a damping effect to the oscillatory property of the LC components. This is always the case in an actual circuit, whether there is a resistor or not. There are still naturally occurring resistance in the materials of the circuits.

3
Materials and Methods

This chapter describes the design of the OT-link including which parameters were tested, how they were evaluated and which equipment was used.

3.1 Open toroid link design

The link consists of a primary and a secondary side, with both sides comprising a coil and a tuning capacitor. The primary side also comprise a toroid shaped ferrite core, that is, the gapped toroid which enables the unique positioning of the energy link. Several aspects were evaluated as the parameters were varied between prototypes. Parameters were varied based on theoretical assumptions as well as by exploration of different parameters. By simulating the OT-link and the full system, correlations between simulations and prototypes can contribute to the development process.

3.1.1 Transmitter toroid

The primary coil consists of a gapped toroid ferrite core (Kaschke Components GmbH, Göttingen, Germany), and a copper wire (Copper wire, Dahréntråd, Nossebro, Sweden). In this study, the winding of the wire around the ferrite core was done manually by carefully spinning the OT while feeding the wire through the gap. Multiple parameters affect the behaviour and signal- and power-transferring capability of the OT solution. In this study, prototypes were designed varying the parameters *core material*, *wire diameter*, *number of turns* and *gap size* which all indirectly contributes to the resulting inductance of the coil. The primary coil then needs to be matched with a tuning capacitor to determine the optimal resonance characteristics, according to the formula,

$$C = \frac{(\frac{1}{2\pi f})^2}{L}. \tag{3.1}$$

Essentially, the ferrite core, wire windings and tuning capacitor make up the transmitter side of the OT-link. The full range of prototypes is explained and clarified in Table 4.1.

3.1.2 Toroid ferrite cores

Two different toroid ferrite cores were used building the OT prototypes and compared with each other. The dimensions of the cores were the same, but the materials were different in a way that made them suitable to be used in the frequency range of this application according to the manufacturer (Kaschke Components GmbH, Göttingen, Germany). The two different cores are called K4000 and K10000, where the first one is recommended for a smaller range of frequencies and the latter is more general, but still within the application. Other potential ferrite cores were considered in the study, but due to long lead times it was deemed that focus should be on the two available toroid cores.

3.1.3 Wire diameter

A selection of copper wires with different thicknesses were chosen, $0.15\,mm, 0.25\,mm, 0.30\,mm$ and $0.35\,mm$. A number of receiver coils were constructed from wire of the different thicknesses and manually wound into a coil. The wire was wound around a 3D printed fixture that was designed according to the constraints defined for the receiver coil. The fixture allowed for the copper wire to be shaped into a coil with a conical shaped inner diameter.

3.1.4 Winding pattern

When it comes to the winding of the coil on the toroid ferrite core, it can be done in different ways. To evaluate what difference it makes for performance and efficiency, three patterns of interest were determined and evaluated, according to Figure 3.1. Apart from the fact that the winding pattern may or may not affect the performance of the link, it was also of interest to evaluate in terms of space for enabling different designs of audio processors.

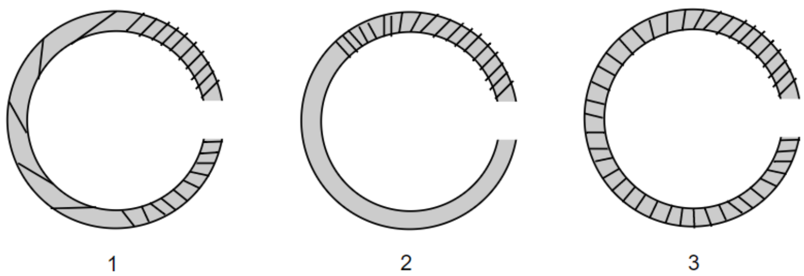


Figure 3.1: The three different winding patterns evaluated in the study.

3.1.5 Receiver coil

The secondary coil primarily consists of copper wire with an air core. Depending on how and with what the coil is wound, it may have a core partially out of plastic. In other words, the coil is either wound around a plastic bobbin which becomes permanent, or around a rod with a diameter of desired inner diameter of the coil. In the second case, the coil is covered in glue to keep its shape and can then be removed from the rod. As for the primary coil, the parameters *wire diameter* and *number of turns* can be altered and in the end yield the resulting inductance. The secondary coil also needs to be matched with a tuning capacitor in the same manner as the primary coil, determining the resonance. In this study, different receiver coil samples were tested in the same manner as the OT coils, however, less focus was placed here. The receiver still needs to be evaluated in terms of wire diameter, turns and preferred inductance since this has a role in the resulting link behaviour, mutual inductance, coupling factor and whether the link has an inductive or capacitive behaviour.

3.1.5.1 Receiver coil winding fixture

The secondary coil is wound with a very thin wire (0,15-0,35 mm in diameter), this can be done professionally where a tool is developed for a specific coil with the possibility to mass produce. This is good if one knows all dimensions and less efficient if there is a need to evaluate a lot of different sizes, also very expensive in relation to the results. To avoid long lead times and enable evaluation of a wider range of prototypes, the secondary coils will be created manually. A prototype coil could potentially be wound on anything, a pen, a metal rod, a piece of paper that is rolled up etc. This works initially while evaluating the extremities of the scope, i.e, should the wire be 0.05 or 0.5 mm in diameter, should it consist of 1 or 100 turns? When this is evaluated and the range has been narrowed, the details get more importance. Such details are the height, the roundness of edges, and denseness of winding. To enable this while still manually winding the coils, it could be useful to have a tool that can be used to wind the coil on, shaping and turning the coil in a controlled manner.

3.1.6 Inductance measurement

An LCR meter (Sourcetronic ST2827A, Bremen, Germany) was used to determine the characteristics of the electrical components, inductors (denoted L), capacitors (denoted C) and resistors (denoted R). The LCR meter can be used in the case of developing coils where the inductance is not known. It can also be used for verifying the capacitance used together with a coil, for example in the case when constructing a resonant circuit. Apart from the component values, the instrument can provide a Q-value as well as be used to determine whether a circuit is of capacitive or inductive characteristics.

3.2 System Overview

Figure 3.2: Block diagram of the five main parts of the device.

Sound transmitted through the air is received by microphones, or alternatively, a generated audio signal is used as input at the microphone input. The digital signal processing (DSP) takes place in software (SW) embedded in the electronics hardware (HW). The input signal (sound from microphones or generated audio signal) is manipulated in different ways to enable the transmission of the signal through the other parts of the system. The DSP constitutes signal amplification in several steps where the signal is amplitude modulated (AM) with a specific frequency, which enables transmission through the OT-link. The two coils of the OT-link (transmitter and receiver coil) are designed to match the AM of the signal. The frequency of the AM signal should be the same or close to the frequency used as reference when designing the OT-link coils. The rectifier circuit is responsible for demodulating the received AM signal. Finally, the transducer converts the signal into vibrations.

3.3 Measurement setups

3.3.1 OT-link efficiency measurement circuit

One of the key factors for the OT-link is the efficiency, i.e. how much power can it deliver with regards to the current consumption. Translating this into a strict method, how high is the quota output over input, and how high percentage of the input power can be transmitted and used in the output.

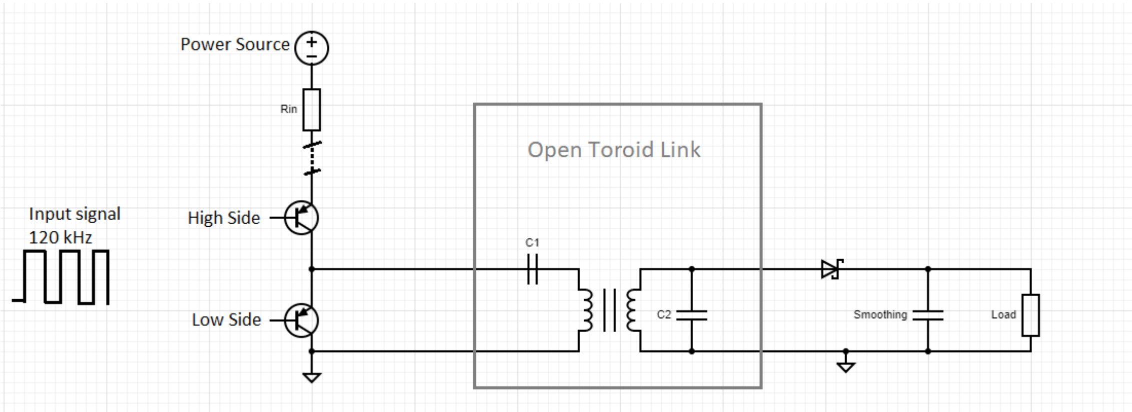


Figure 3.3: Measurement circuit for evaluation of efficiency of the OT-link.

A circuit was designed to be able to measure the efficiency, Figure 3.3. A micro processor generated a 120 kHz square wave signal which was fed to a class-D amplifier operating by switching very fast between its two transistors, generating a pulse train equivalent to an AM audio signal. This signal was transmitted from the primary side of the OT-link to the receiver coil on the secondary side. It was then rectified and smoothed before it could be measured over the loading resistor. The input voltage and current was measured over the input resistor *Rin* and the output voltage over the loading resistor *Load*, Figure 3.3. With an oscilloscope, the voltage was measured before ($V1$) and after ($V2$) the input resistor *Rin*. The current could then be calculated through voltage division ($\frac{V2-V1}{Rin}$) and the power was determined by Ohm's law ($P = U * I$). In the same manner, the output power is determined by measuring the output voltage, and the current was determined ($I = U/R$), where after the power was calculated by Ohm's law ($P = U * I$). Finally, the efficiency is determined by dividing output power with input power
($\frac{output\,power}{input\,power} = \%$).

3.3.2 System level measurements

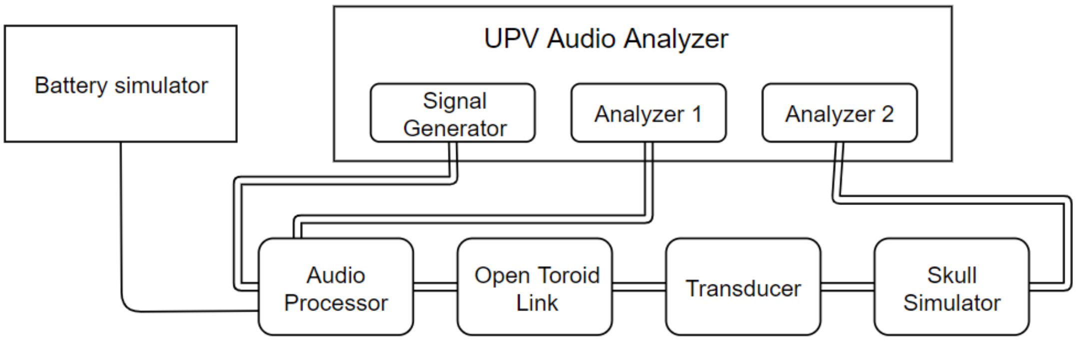


Figure 3.4: The measurement system for evaluation of the efficiency on device level.

A measurement system was designed to evaluate the OT-link in its intended application. This measurement environment includes all parts from a BAHS system and enables comparison with commercially available systems. The environment consists of a UPV Audio Analyzer system (UPV Audio Analyzer, Rohde & Schwarz, Munich, Germany), a battery simulator (Oticon PSU, Oticon A/S, Copenhagen, Denmark), an audio processor designed for transcutaneous systems, an energy link, a transducer designed for transcutaneous systems, and a skull simulator (Skull Simulator, Oticon Medical AB, Askim Sweden), Figure 3.4.

The combined signal generator and analyser UPV Audio Analyzer allows measurements of battery drain simultaniously with force output (FO) while generating a frequency suitable audio-like signal.

The battery generator is a custom made design for Oticon Medical to simulate a zinc-air battery. The simulator can be set to a certain voltage matching a battery (up to 3 volts) and then allows for current consumption up to 40 mA.

The audio processor can generate the audio signal that is to be transferred through the energy link. An audio signal generated from the UPV is amplified to desired voltage level. After amplification, the signal is amplitude modulated to a specific frequency which matches the frequency the OT-link is designed for, $120kHz$, and then it is transmitted to and through the link.

The signal passing through the link is then demodulated before the transducer translates the audio signal input into vibrations. The transducer is of electromagnetic type and consists of an electromagnetic motor with movements based on the frequency of the input signal. The moving assembly of parts are suspended in a spring which counteracts the force of the magnet. The magnet is trying to collapse the moving parts assembly, which results in movement.

The skull simulator enables the measurement of translation of the transducer. A mass is suspended in a construction of springs. Connected to the weight is a sensor which translates the movement of the mass into an electrical signal which is then used to calculate a force ($F = m * a$).

3.4 Simulations

Simulations was used as a verification tool throughout the project. Before building and measuring prototypes, simulations were conducted to verify the measuring environment and the component values to establish a level of expectations for the performance. Electronic circuits and electromagnetic behaviour of the prototype component values was evaluated in LTSpice (Analog Devices Corporation, LTSpice XVII, Norwood, MA, USA). Not only the energy link, but also the surrounding components and circuitry, was included in the simulations, Figure 3.5.

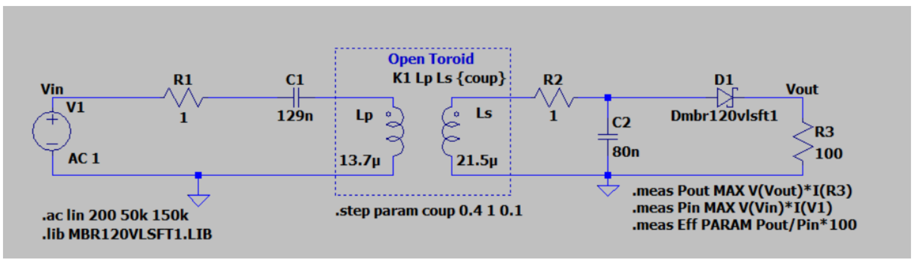


Figure 3.5: Schematic in LTSpice for simulation of coupling factor k.

3.4.1 Efficiency Comparison Factor K

The K-factor is used to compare the efficiency of different OT-links with each other as well as comparing with other systems such as the TET-link or a direct coupling. A quota of output force from the transducer and input power to the sound processor is used to compare different systems. The quota is denoted K and is calculated as per equation 3.2, based on measurements and calculations in equations 3.3.

$$K = (\frac{FO_{Lin}}{\sqrt{P_{in}}}) * 100 \quad where, \tag{3.2}$$

$$FO_{Lin\,[V]} = 10^{(\frac{FO\,[dBV]}{20})} \;\; and \;\; P_{in} = V * I \tag{3.3}$$

3.4.2 Alignment evaluation

The toroid transmitter is meant to be placed over the pinna with a gap of 5 mm and together with a indentation in the center of the receiver coil, this should keep the link in place. As no other restraints for attachment are defined, there is possibility of movement of the toroid transmitter even in its intended position. It can potentially move, turn and twist to some extent, which makes it an important factor to evaluate in terms of efficiency and how this movement influence the energy and the signal transfer of the link. Multiple factors can vary between users, such as thickness of the tissue, how soft the tissue is, but also the surgical outcome of implanting the receiver coil in the ear. The intended indentation in the center of the receiver coil could also vary between users after implantation and should be evaluated for different depths.

4

Results

4.1 Open toroid link samples

This chapter presents all the findings and results from testing and evaluating the OT-link samples in different cases. The link design was systematically evaluated by varying selected parameters and configurations. Several designs were measured in different test environments to evaluate the effects of different alignments, the link performance and the system level performance, which can be compared to other similar devices. The OT-link prototype was divided in two, a transmitter side (transmitter toroid) and a receiver side (receiver coil). First the receiver coil prototypes were evaluated on system level to find the best performing one in terms of efficiency. The evaluation was conducted by comparing all receiver coils together with the same transmitter toroid. The receiver coil found to perform the best was then used to evaluate the transmitter toroid and thereafter also in evaluation and optimization of the OT-link. All measurements were conducted using a power supply with $1.3\,V$ input voltage.

4.1.1 Transmitter toroid samples

The transmitter toroid consists of the toroid shaped ferrite core, isolation coated copper wire of different diameters, and a resonance matching capacitor based on the measured inductance of the coil and the resonance frequency. Toroid cores were modified with a gap of approximately $5\,mm$. Some deviations were found as the gap was made by hand and was not an exact process. The different toroid core gaps were measured and found to be in the interval of $4\,mm$ to $6\,mm$. The size of the matching capacitor was calculated based on the systems carrier frequency, $f = 120\,kHz$. A total of 17 transmitter toroids were evaluated, Table 4.1.

Table 4.1: Table listing the configurations of all 17 Open Toroid prototypes.

Open Toroid ID	Core material	Wire diameter [mm]	Turns [N]	Wire pattern[1]	Inductance [µ]
OT1	K10000	0,35	32	1	13,4
OT2	K10000	0,35	25	1	6,9
OT3	K10000	0,35	15	1	2,4
OT4	K10000	0,35	25	2	11,9
OT5	K10000	0,25	25	1	7,9
OT6	K10000	0,35	25	3	13,7
OT7	K10000	0,25	20	2	6,8
OT8	K4000	0,35	25	1	8,2
OT9	K4000	0,25	25	1	6,4
OT10	K10000	0,35	70	3	96.6
OT11	K10000	0,35	25	1	8
OT12	K10000	0,35	25	1	7,9
OT13	K10000	0,20	22	1	8
OT14	K10000	0,30	22	1	7,9
OT15	K4000	0,30	35	3	22,7
OT16	K4000	0,30	45	3	38
OT17	K4000	0,30	55	3	56,3

[1]Winding patterns, Figure 3.1

4.1.2 Receiver Coil Samples

The receiver coils consist of isolation copper wire of different diameters and a resonance matching capacitor based on the measured inductance of the coil and the resonance frequency. A total of 12 receiver coils were evaluated, Table 4.2.

Table 4.2: Table listing the 12 configurations of the receiver coils.

Receiver coil ID	Wire diameter [mm]	Turns [N]	Inductance [μH]
R1	0.15	70	32.6
R2	0.15	50	17.2
R3	0.15	N/A[2]	N/A[2]
R4	0.15	50	21.9
R5	0.25	52	21.6
R6	0.35	44	21.7
R7	0.15	90	68
R8	0.35	N/A[3]	10.2
R9	0.3	N/A[3]	14.9
R10	0.3	N/A[3]	26.5
R11	0.3	N/A[3]	21.5
R12	0.3	N/A[3]	9.4

4.2 Receiver Coil Parameter Evaluation

4.2.1 Wire diameter

Four receiver coils with different wire diameter, but similar inductance, were used to determine the influence of the wire diameter on the force output and power consumption for the receiver coil. The data showed that the current increases linearly with the increased wire diameter, Figure 4.4). In contrast, the FO increased with increased wire diameter up to 0.3 mm, whereas 0.3 and 0.35 had similar FO, Figure 4.3. Similarly, power transfer efficiency was increased up to a wire diameter of 0.3 mm, whereafter the efficiency plateaued. Consequently, the efficiency of the system, as determined by the K-factor, increased with increasing wire thickness (Table 4.3) up to a wire diameter of 0.3 mm.

[2] Prototype broken before measurements could be performed

[3] Receiver coils were manufactured to obtain a specific inductance, therefore number of turns was unknown

The efficiency thereafter decreased for the coil with 0.35 mm wire diameter. Given the transmitter toroid utilised in these measurements, a wire diameter of 0.3 mm performs best for the receiver coil.

Table 4.3: Measured and calculated data from the performed measurements on receiver coils with different wire diameters.

Receiver ID	Wire [mm] diameter	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
R4	0.15	74	106	85	6	16.7
R5	0.25	73	104.5	83	5.3	14.9
R11	0.30	73.5	106	85	5.7	17.2
R6	0.35	71	103	81.5	5.1	12.2

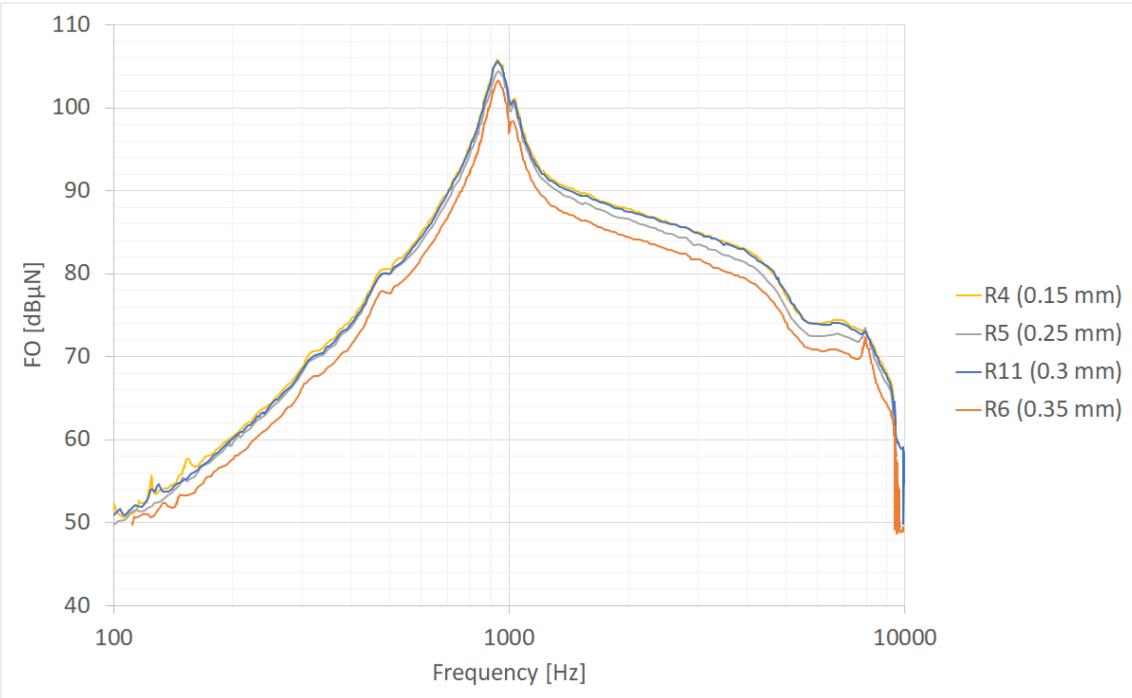


Figure 4.1: Force output measurements from evaluation of influence of wire diameter on the receiver coil together with OT6.

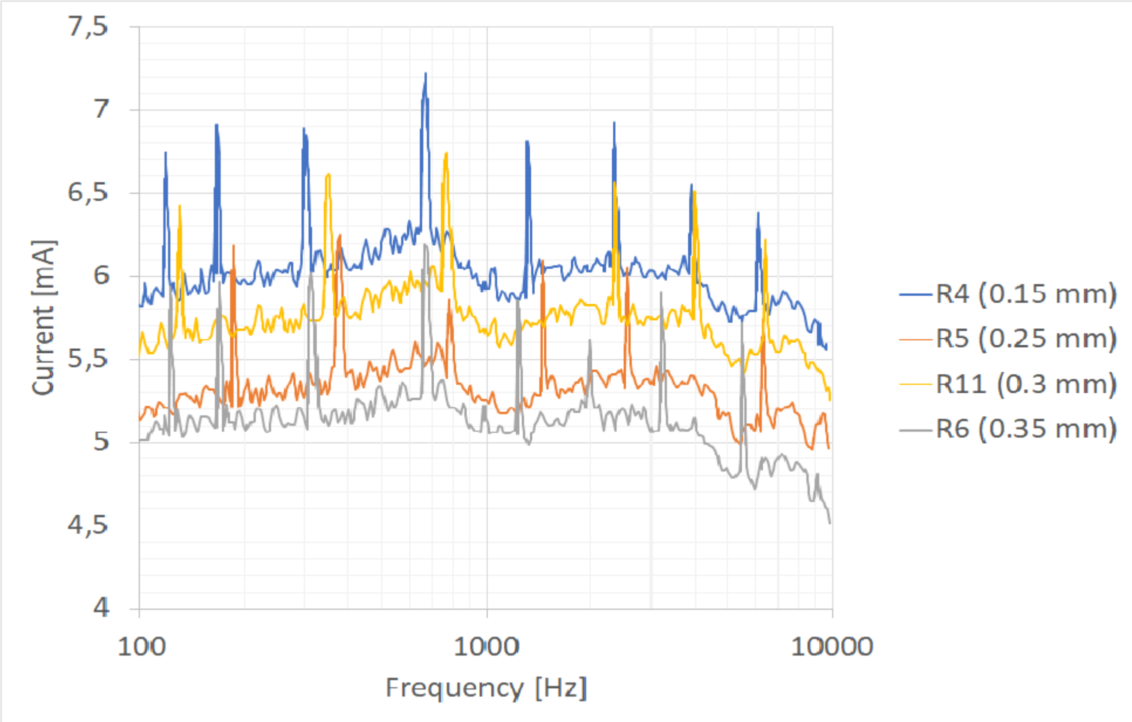


Figure 4.2: Current consumption measurements from evaluation of influence of wire diameter on the receiver coil together with OT6.

4.2.2 Receiver inductance

There is a relationship between number of turns and the inductance, where the inductance will increase with increased number of windings. Based on the evaluation of wire diameter, the influence of inductance on power transfer efficiency was determined using a wire diameter of 0.3 mm. Four different configurations, with inductance ranging from 9.4-26.5 µH were evaluated, Figure 4.3 and Table 4.4. The power transfer efficiency in terms of K-factor peaked at an inductance of 21.5 µH, and was hence not linearly related to the inductance given the transmitter coil used for these specific measurements, Table 4.1.

Table 4.4: Measured and calculated data from the performed measurements on receiver coils with different wire diameter.

Receiver ID	Inductance [µH]	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
R12	9.4	75	106.5	85	6.5	17
R9	14.9	75	106.5	85.5	6.6	16.9
R11	21.5	76.5	108	87.5	6.1	21
R10	26.5	75	107	86	4.5	18

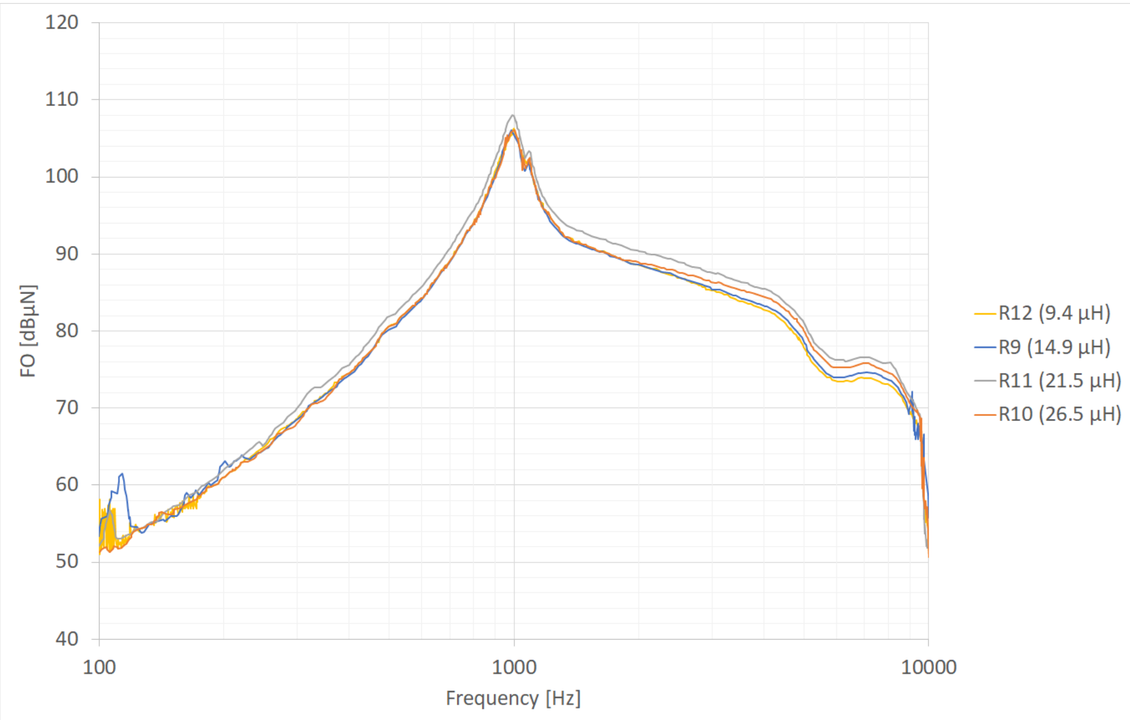


Figure 4.3: Force output measurements from evaluation of inductance of receiver coil together with OT6

4.3 Open Toroid Parameter Evaluation

4.3.1 Wire Diameter

The influence of wire diameter used in the transmitter toroid was evaluated together with the most efficient receiver coil (R11, see section 4.2). The power transfer efficiency was determined for four different transmitter toroids with the same winding pattern, and hence similar inductance. The transmitter toroids with wire diameter of 0.25 and 0.3 mm performed better than the ones with thinner and thicker wires with regards to the K-factor, Table 4.5. The transmitter toroid with the thinnest wire had the highest current consumption whereas the transmitter toroid with the thickest diameter had the lowest, 4.5. However, the low current consumption for the sample with the thickest wire, was not reflected in a corresponding high force output curve and high K-factor, indicating that the capacity of that particular configuration is limited, 4.4.

Table 4.5: Measured and calculated data from the performed measurements on receiver coils with different wire diameter.

Open Toroid ID	Wire [mm] diameter	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
OT13	0.20	67.5	102	81	9.5	8.4
OT5	0.25	75	106	86	6.4	16.3
OT14	0.3	72.5	106	86	6.4	16.3
OT2	0.35	69.5	103	81.5	5.2	12.6

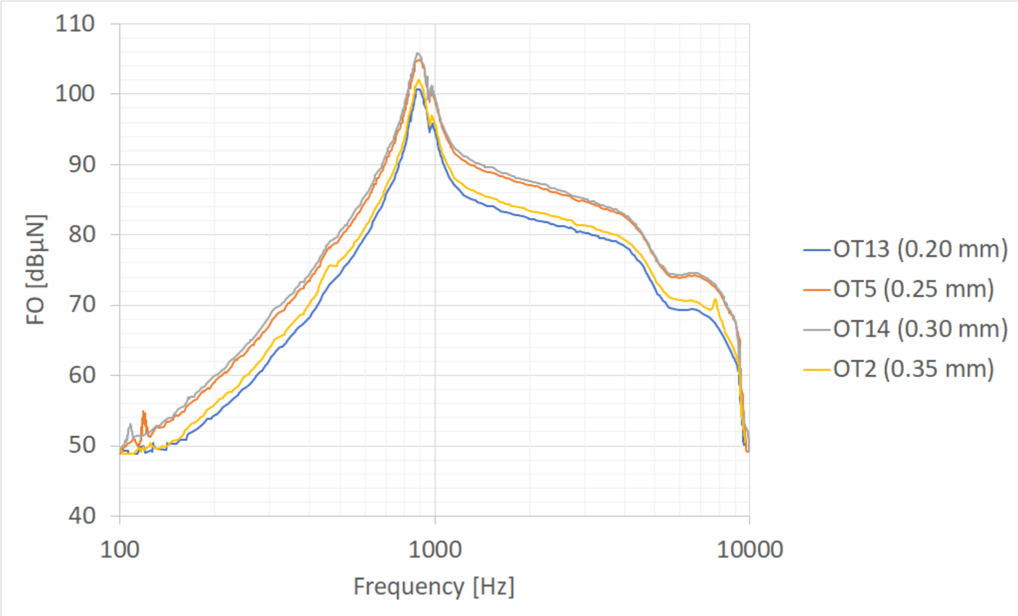


Figure 4.4: Force output measurements from evaluation of influence of wire diameter together with R11, force output.

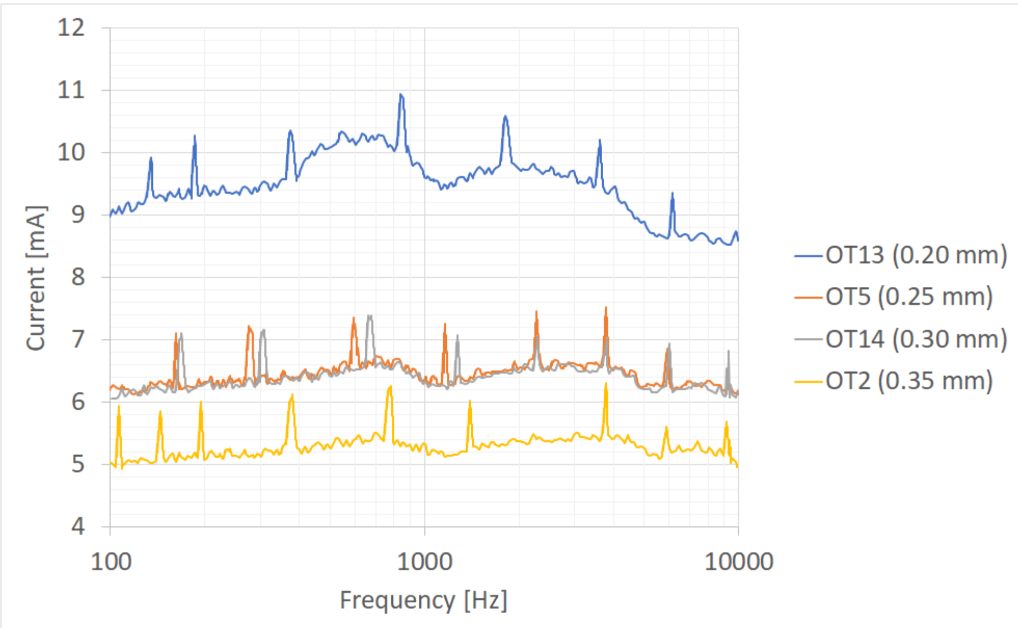


Figure 4.5: Current consumption measurements from evaluation of influence of wire diameter together with R11, current consumption.

4.3.2 Toroid winding pattern

To determine the effect of toroid winding pattern on performance parameters, the current consumption, force output and K-factor were obtained for three different winding patterns while keeping the wire diameter and number of turns constant (0.35 mm and 25 turns). Distributing the windings equal along the whole toroid core resulted in the highest K-factor whereas concentrating them to the both ends gave the lowest, Table 4.6, Figure 4.6. Interestingly, despite that both the wire diameter and the number of turns were held constant, the inductance of the three samples differed. However, the total length of the wire for the patterns differed. Likely, the pattern with equally distributed windings (pattern 3) had the longest wire whereas the pattern with windings concentrated to one end had the shortest (pattern 2). This was however not confirmed with measurements of the wire lengths. Despite this, pattern 1 had the lowest inductance, Table 4.1.

Table 4.6: Winding pattern evaluation together with receiver R11.

Open Toroid ID	Winding pattern	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
OT2	1	73	105.5	85	6.2	15.6
OT4	2	75.5	106	85	5.8	17
OT6	3	77.5	107	86.5	6.5	18.2

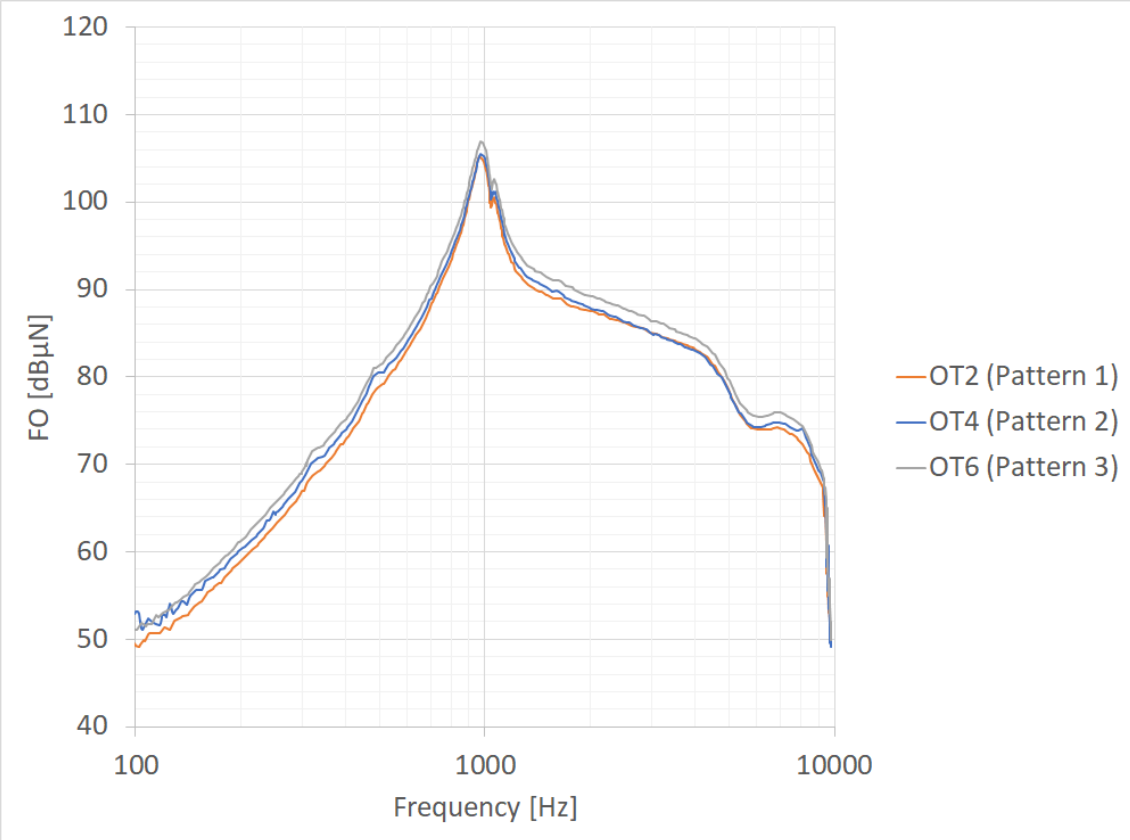


Figure 4.6: Force output measurements from evaluation of influence of winding pattern with R11, force output.

4.3.3 Core Material

To determine the influence of the ferrite core material composition, two transmitter toroid coils (OT8, OT12) with the same configurations except the core material, was evaluated. The inductance differed slightly with difference 0.3 µH (Table 4.1). Both toroid cores are designed for high frequency applications while the K4000 is adapted for a narrower frequency band compared with K10000. The K4000 (OT8) was found to perform marginally better compared with K10000 (OT12) with a mean K-factor of 17.8 and 16 respectively (Figure 4.7, Table 4.7). Current consumption for the two systems were similar, 4.8.

Table 4.7: OT force output and current consumption comparison for different number of turns.

Open Toroid ID	Core material	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
OT8	K4000	75	107	87	6.8	17.8
OT12	K10000	74	106	86	6.7	16

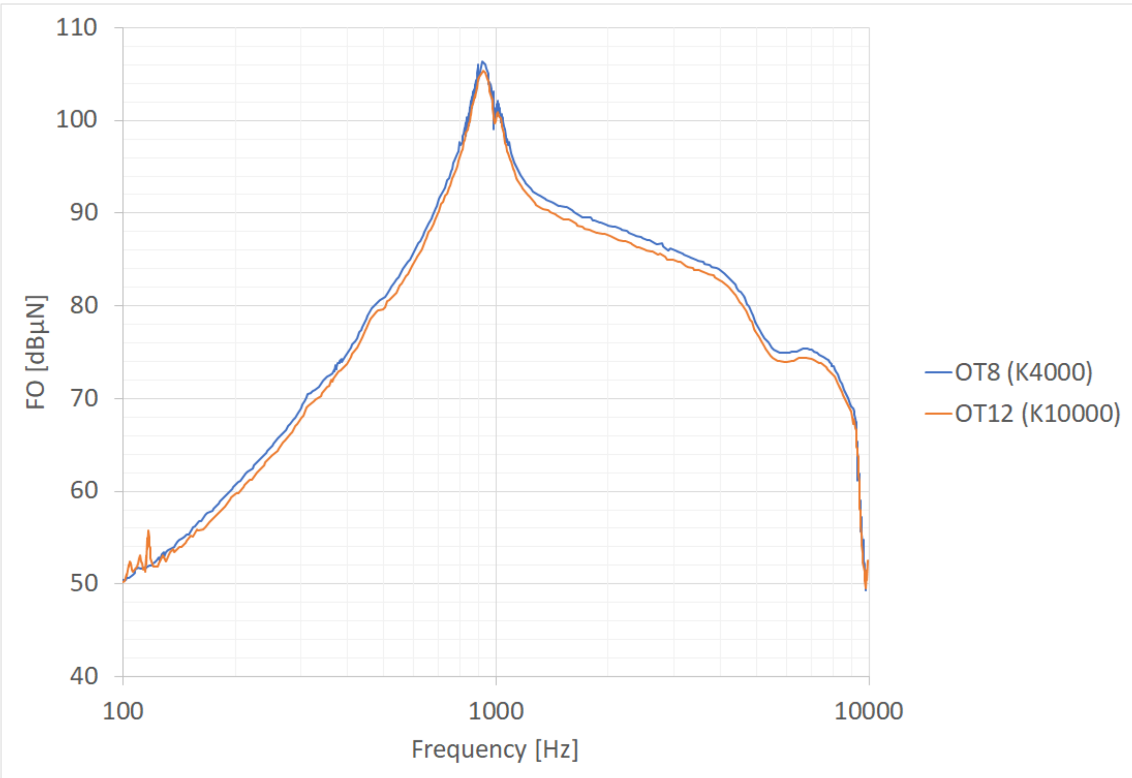


Figure 4.7: Force output measurements from comparison of ferrite core materials K4000 and K10000 with R11.

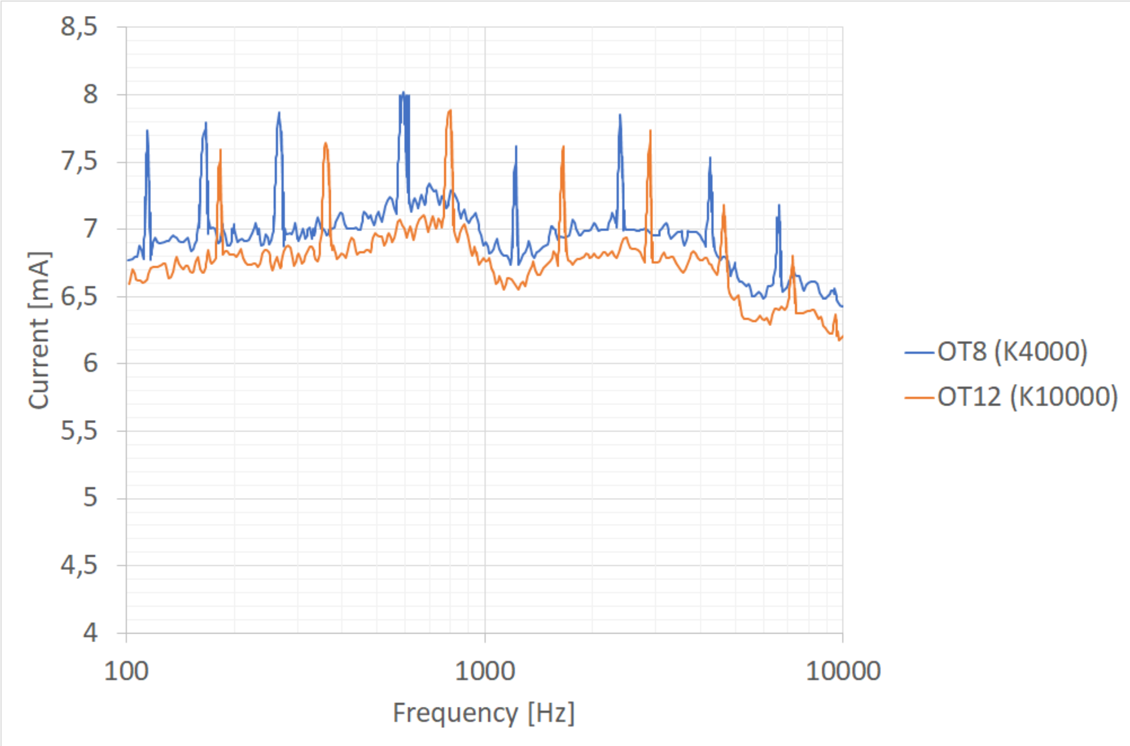


Figure 4.8: Current consumption measurements from comparison of ferrite core materials K4000 and K10000 with R11.

4.3.4 Number of turns

To determine the influence of number of wire turns on the transmitter toroid on the power transmission efficiency, four different configurations were compared (Table 4.8). The result show that the highest K-factors was achieved for the transmission toroid coil having between 35 and 55 turns. The force output and current consumption indicate that the optimal is between 45 and 55, Figures 4.9 and 4.10.

More turns means more capacity and should mean better efficiency but there are several factors that could affect this. The ferrite core will at some point be saturated and the electromagnetic flux will somewhat decrease.

Table 4.8: OT force output and current consumption comparison for different number of turns.

Open Toroid ID	Number of turns [N]	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	K mean
OT6	25	76	107	87	7.4	17.1
OT15	35	77	107	86	6.4	18.3
OT16	45	77	107	85	5.3	19.9
OT17	55	78	105	84	4.3	17.8

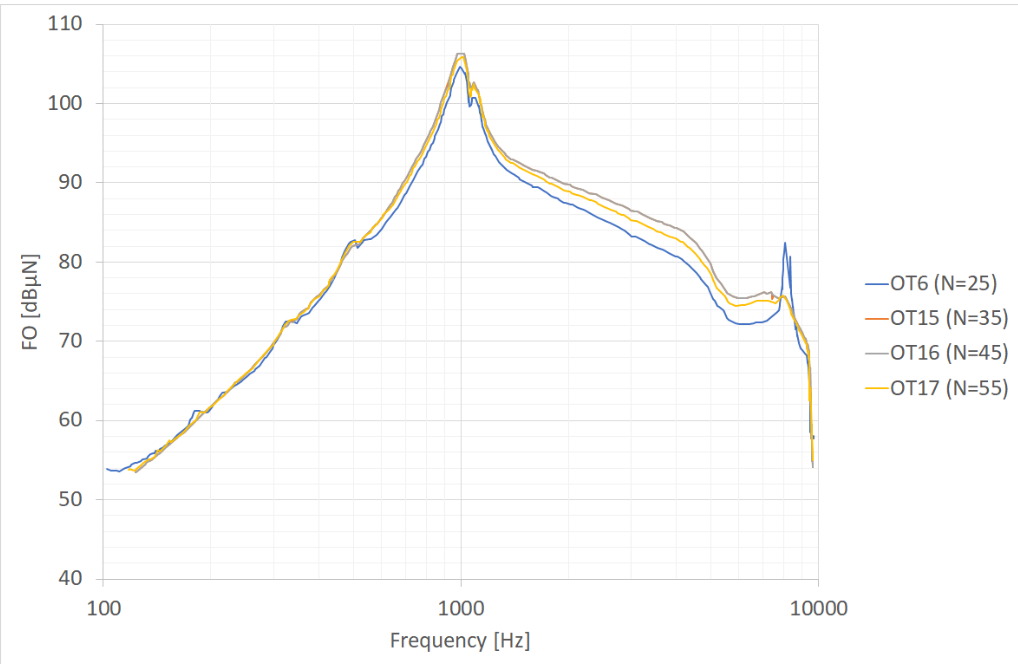


Figure 4.9: Force output measurements from evaluation of influence of number of turns with R11.

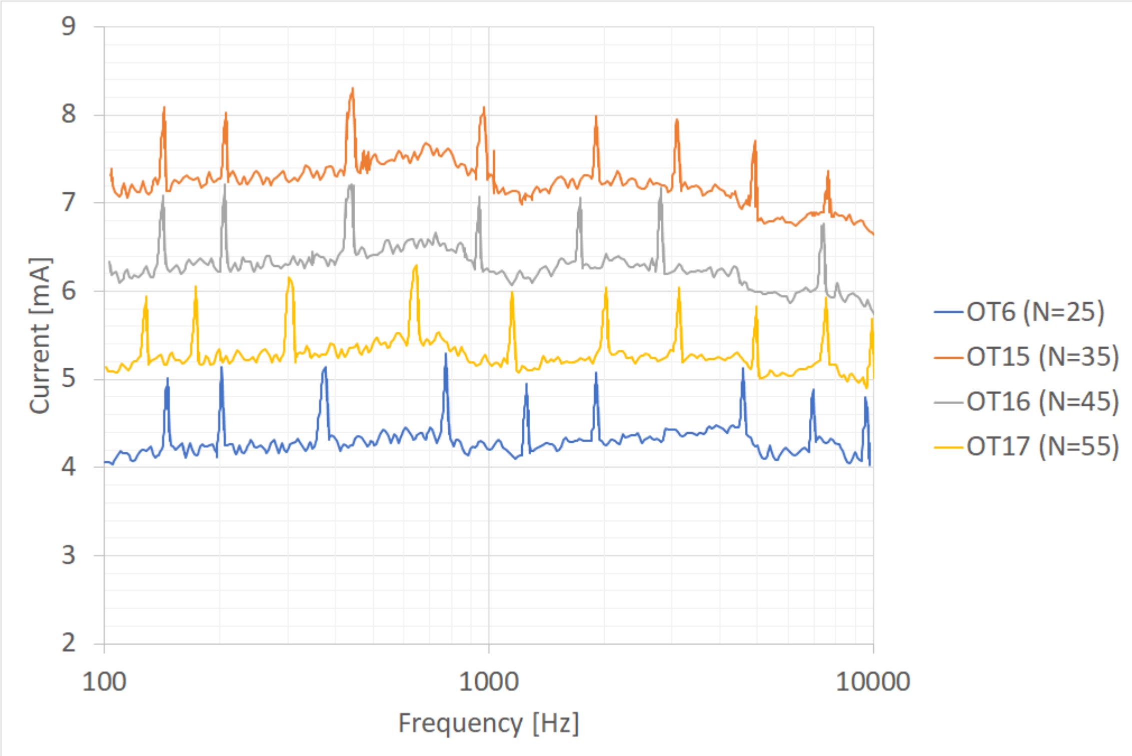


Figure 4.10: Current consumption measurements from evaluation of influence of number of turns with R11.

4.4 Influence of misalignment between transmitter toroid and receiver coil

The performance of the OT-link was evaluated when it was aligned and positioned in various positions in relation to the receiver coil. The design of the link allows for movement in several directions where each selection was evaluated and analysed, Figure 4.19. The different alignment settings were divided into two views, seen from the side and seen from the top. The type of alignment is described based on that particular image of the link arrangement. The results can be seen in Table 4.9 and the measurements conducted on the system level measurement setup can be seen in Figure 4.19.

Table 4.9: Alignment measurements

Open Toroid ID	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumption	Input [V] Voltage	K mean
Position 1	76	108	86	5.5	1.3	21.8
Position 2	77	108	87	6	1.3	21.1
Position 3	77	108	87	6.2	1.3	20.8
Position 4	77	108	87	6.7	1.3	20
Position 5	77	108	86	6.4	1.3	20.3
Position 6	77	108	86	6.4	1.3	20.3
Position 7	77	107	85	5.5	1.3	19.6
Position 8	77	107	85	5.5	1.3	19.6

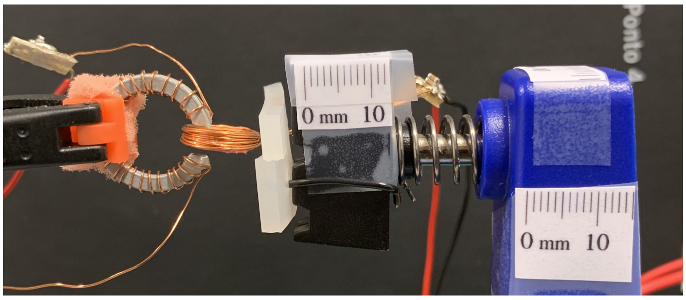


Figure 4.11: Position 1, where toroid is centered in the plane and moved to the left, slightly overlapping the receiver coil.

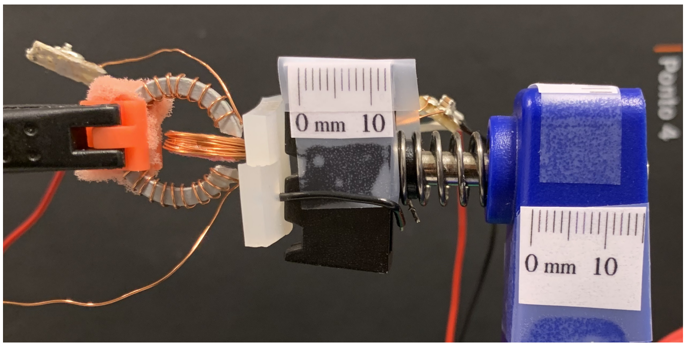


Figure 4.12: Position 2, where toroid is centered in the plane and moved to the right, slightly overlapping the receiver coil.

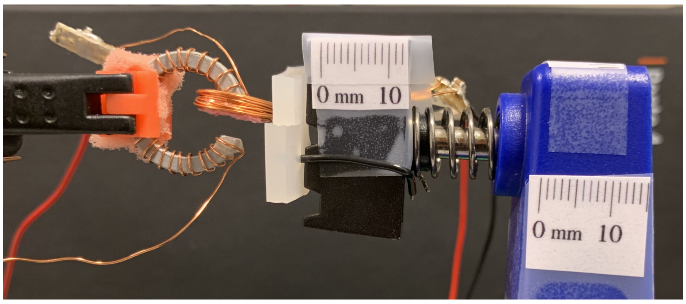


Figure 4.13: Position 3, where toroid is centered in the plane and moved downward to be slightly going through the receiver coil.

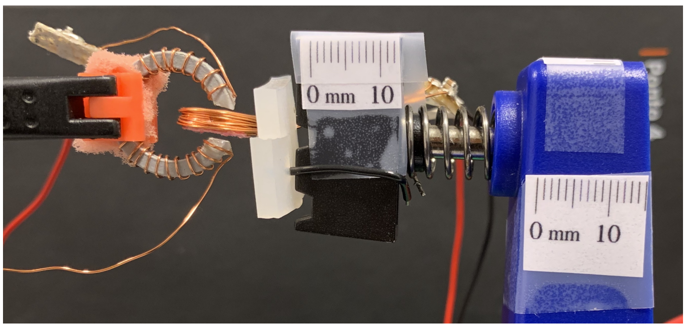


Figure 4.14: Position 4, toroid is centered in all directions in relation to receiver coil.

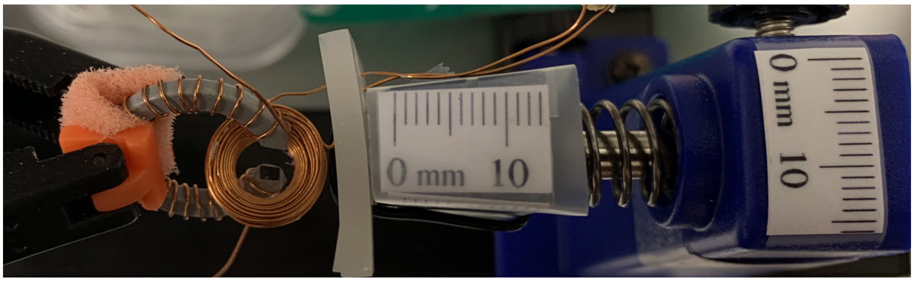


Figure 4.15: Position 5, where toroid is centered in the plane and turned around its axis.

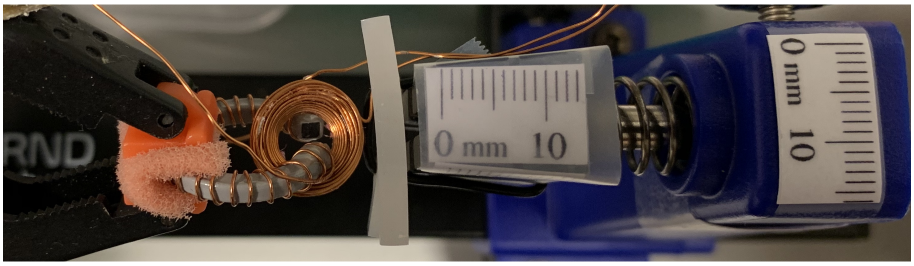


Figure 4.16: Position 6, where toroid is centered in the plane and turned around its axis.

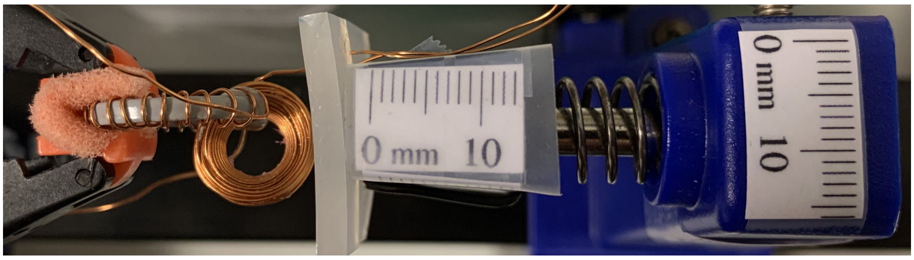


Figure 4.17: Position 7, where toroid is centered in the plane and moved to the side(top in picture), slightly overlapping the receiver coil.

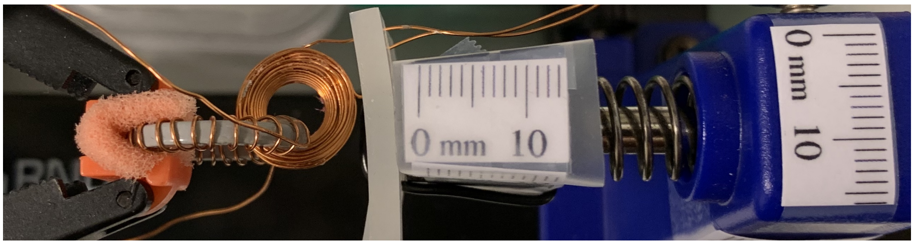


Figure 4.18: Position 8, where toroid is centered in the plane and moved to the side(bottom in picture), slightly overlapping the receiver coil.

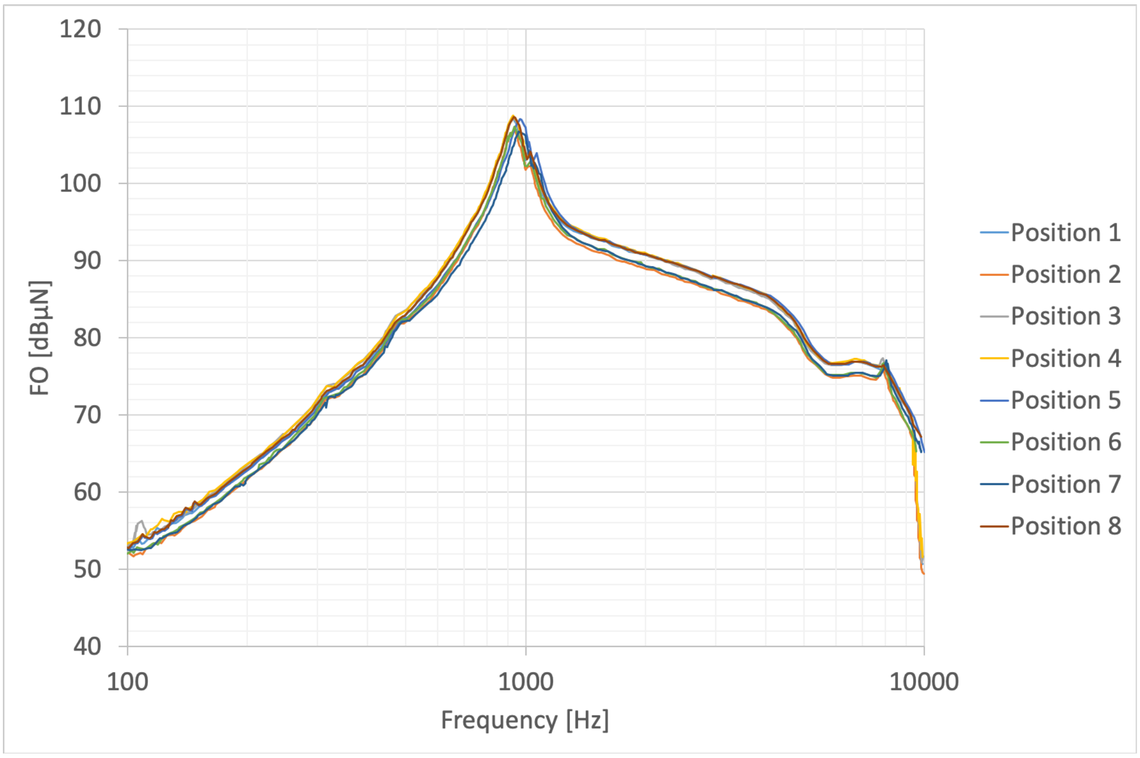


Figure 4.19: Force output measurements of the different misalignment positions.

4.5 System efficiency comparison with TET-link

To establish a good reference, measurements were performed on a TET link using the same audio processor, transducer and skull simulator. The TET link is highly dependent on the skin thickness of the user and was therefore tested with a gap range of different thicknesses. To create the gap, synthetic skin made out of silicone was placed between the two coils of the TET link with a thickness of 3 mm, 6 mm and 9 mm, Figure 4.20, Table 4.10.

In Table 4.21, a direct comparison with an OT-link can be found where the output force was similar in low frequencies, a bit higher at resonance and clearly higher in high frequencies.

Table 4.10: TET versus OT force output and current consumption comparison.

Link	Force [dBµN] @400 Hz	Force [dBµN] @Resonance	Force [dBµN] @3000 Hz	Current [mA] Consumtion	Input [V] Voltage	K mean
TET 3 mm	72	100	-55	5.3	1.3	9.0
TET 6 mm	67	93	-53	4.9	1.3	4.8
TET 9 mm	61	85	-70	4.7	1.3	1.7
OT6, R11	77	107	86	7.7	1.3	16.7
OT16, R11	77	107	85	5.3	1.3	19.9

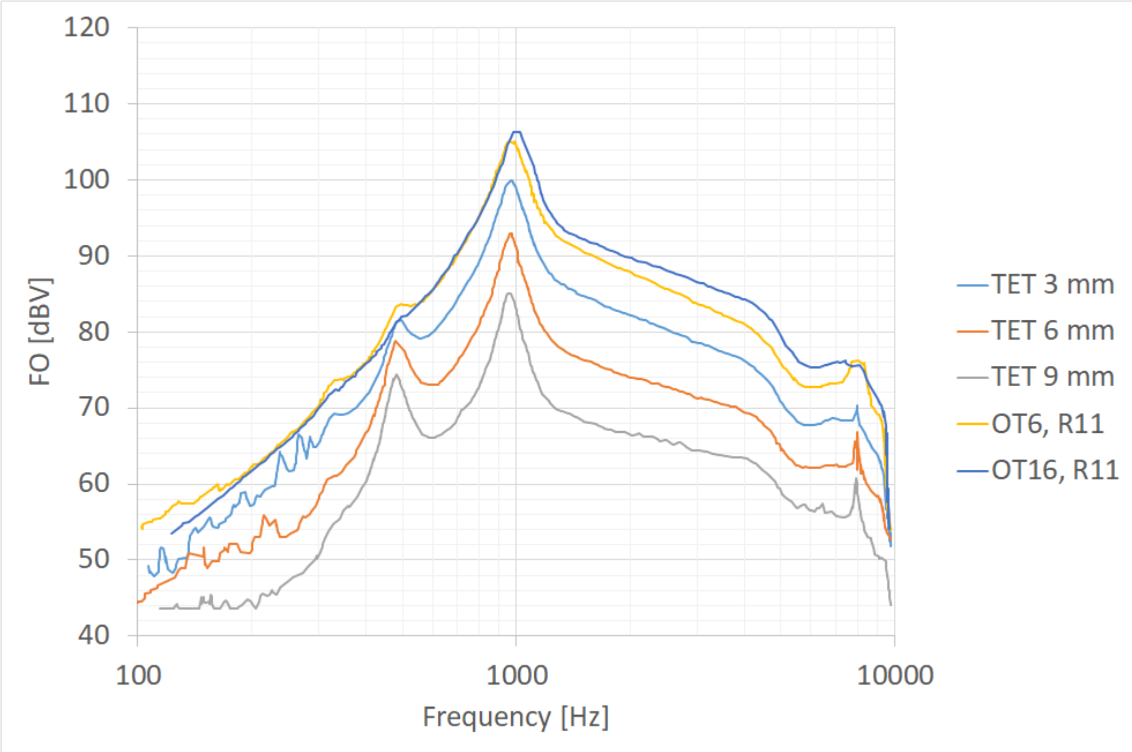


Figure 4.20: Force output measurements of OT-link TET-link with 3, 6 and 9 mm skin imitation.

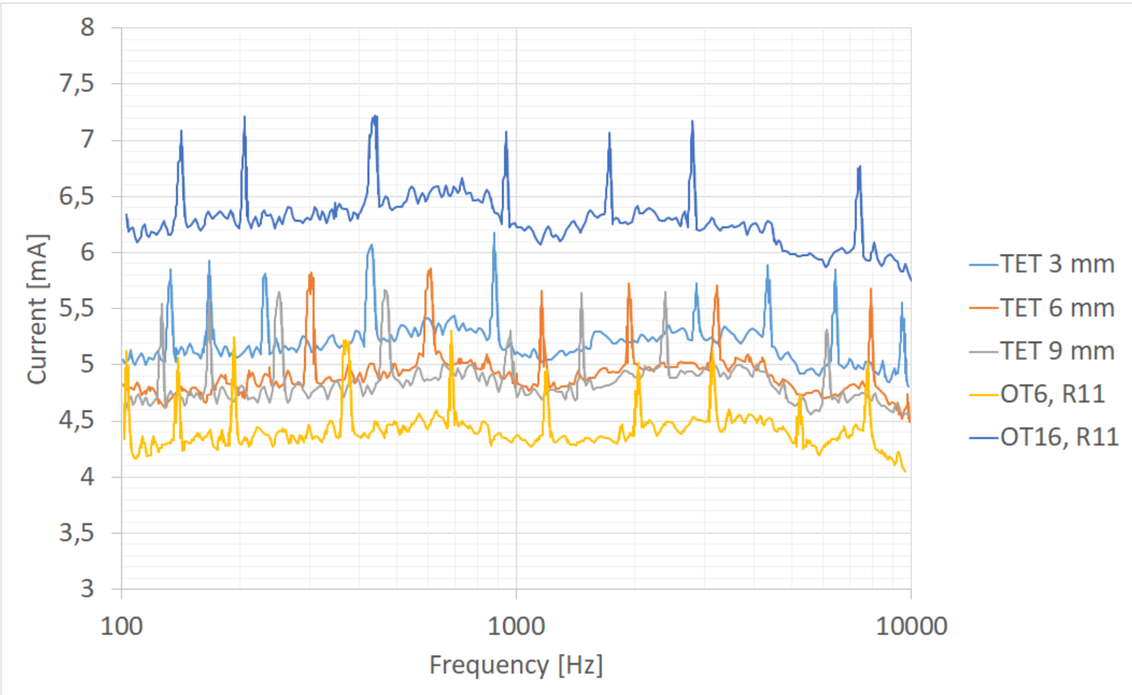


Figure 4.21: Current consumption measurements of OT-link TET-link with 3, 6 and 9 mm skin imitation.

5 Discussion

One main drawback with a conventional TET-link is that the efficiency, and ultimately the output power, is influenced on the skin thickness. To overcome this, a novel link comprising Toroid ferrite cores with two different material compositions designed for different frequency bands was evaluated. The core with the narrower frequency band was found to be more efficient in this particular application. Both cores were of same dimensions, with the only difference being the ferrite material composition. The ferrite cores have a diameter of 2 by 2 mm and could likely be one of the reasons for the limitation of the power transmission efficiency which have been discovered during the measurements. Furthermore, the gap in the toroid core was also made by hand and differed between the samples. To what an extent this affected the result was not determined.

The wire diameter influenced the power transfer efficiency with an increase up to 0.3 mm whereafter it plateaued. The optimal wire diameter was therefore deemed to be 0.3 mm for the toroid system evaluated in the present study. A larger wire diameter would likely improve the efficiency if other parameters such as toroid core material and dimensions as well as windings could be optimised to fit that diameter. The toroid ferrite core limits the capacity of the link as it saturates at some point and cannot deliver more energy. Therefore the bigger wire diameter loses its advantage. Hence, the optimal wire diameter should, among other parameters, be consider for the specific ferrite core used in the specific OT system.

Different winding patterns were evaluated with regards to its impact on the performance. The difference seems to be minor for this application, however an evenly distributed winding pattern is preferable (pattern 3). This minor effect might be important in a final applications where the windings might need to be placed far away from other electronics in a sound processor to avoid interference and potential artefacts. The winding of wires on both the transmitter toroids and receiver coils were made by hand, likely resulting in a suboptimal performance of the samples. The purpose of this study was however not to finetune and optimise the link, instead the objective was to identify and determine what and to what extent various parameters influence the power transmission performance of the link.

Number of turns of the coil and the perceived inductance from the coil is directly related as increasing the amount of turns also increases the inductance. As for the wire diameter, the benefit of higher inductance is limited by other factors such as available power, wire resistance and toroid core saturation. The optimal number of turns in this case (given the toroid core and wire diameter) was found to be between 35 and 55 turns and an inductance of 23 to 56 µH.

Importantly, the variance of efficiency with regards to misalignment was found to be minimal. The evaluation was performed in a rotating, turning and strictly planar positioning manner. It was found that the optimal position is either with one end of the toroid at the same level as the receiver coil or slightly rotated within the receiver coil (one end of the toroid closer to the coil rather than symmetrically placed).

Measurements on the OT-link and the TET-link together with calculations of K-factor show that the OT-link is 2-10 times better than the TET-link with three different skin thicknesses: 3, 6 and 9 mm.

Measurements of only the OT-link were attempted but disregarded due to great inconsistency. The measurements were therefore considered uncertain and the method of measuring the power transfer efficiency had to be revised. Measurements was instead performed on a system level where consistency among the measurements were found to be better. Measurements performed during one session are considered to be consistent, however, results from different measurement sessions can still differ.

The intended position for the OT-link is favourable for optimisation as the skin thickness varies less between users compared to in the position of the TET-link. Less variance between users enables better optimisation for mutual coupling between transmitting and receiving coil and also improved efficiency.

In theory, increasing the amount of wire turns would result in increased efficiency but multiple factors that could affect this. The ferrite core will at some point be saturated resulting in a decreased electromagnetic flux. Hence, there is a pairing and optimisation in terms of toroid core (material and dimension), wire (windings, diameter, position). This have not been fully elucidated in this study.

6
Conclusion

An important finding in this study was that it was possible to use the proposed methods to perform a systematic evaluation of parameters affecting the power transmission efficiency of an OT-link system and to compare that with a conventional TET-link system.

The hypothesis for this project was that the OT-link has the potential of outperforming the TET-link with regards to power transfer efficiency. The results confirmed that the OT-link performed significantly better compared with a conventional TET-link in terms of power transfer efficiency with as much as 10 times.

Parameters winding pattern, wire diameter and ferrite core material were all found to influence the energy transfer efficiency. A more evenly distributed winding pattern was found to contribute more to the performance compared to concentrating the windings both to one end or both ends of the toroid core. A larger wire diameter was also found to be preferred, in this specific case up to 0.30 mm. The material of the toroid core do also influence the setup as the K4000 was found to perform better than the K10000. All these parameter interact so that optimisation of the transmitter toroid and the receiver coil together achieves the best result.

Importantly, the influence of misalignment was found to be small. This is particularly important for the application of this technology for a bone conduction device where the receiver coils needs to be implanted and the alignment to the transmitting toroid have skin in between. Put in relation to the TET-link, which is influenced by misalignment to a larger extent, and also generally positioned in a location where the skin thickness varies more between users, the OT-link is advantageous.

In conclusion, the present study demonstrate that the OT-link provides an efficient alternative for transcutaneous energy transmission for bone conduction devices.

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