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Feedback Analysis in Bone Anchored Hearing Aid (BAHA) and Bone Conduction Implant (BCI)

Master of Science Thesis

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Abstract

The conventional Bone Anchored Hearing Aid (BAHA) is today a common treatment for patients with conductive and mixed hearing losses. It is also increasingly used for patients with single side deafness. Even if the BAHA is quite successful there are some complications reported related to the necessity of a percutaneous implant. To overcome these problems a new generation of a hearing device is under development which is called the Bone Conduction Implant (BCI). The BCI has an implanted transducer and the power and speech signal are transmitted through the intact skin. During this development it has been noted that the new BCI device was less prone to fall into feedback oscillations than the BAHA at higher gain settings especially at higher frequencies. This finding indicates that BCI can allow a higher gain setting than the BAHA without problems with feedback which is something that has been requested for long time and that is in fact an inherent limiting factor for the BAHA gain at higher frequencies. The purpose of this thesis is to investigate the feedback margins in the BAHA and the BCI in some more detail.

In this work, the feedback mechanisms and open-loop gains are defined and measured with the BAHA and the BCI attached to a Skull Simulator and a dry skull. Two different positions on the skull have been investigated named BAHA position (Pos A) and BCI position (Pos B). The devices used were the BAHA Classic-300 and the BCI version 2.0 both adjusted to full on gain.

It was found that the gain margins using the BCI in position B was generally 0-10 dB better at higher frequencies than using the BAHA in position A for a given mechanical output. More specifically, if the mechanical output of the devices were normalized at the cochlear level the improvement in gain margins with the BCI versus the BAHA were in the range of 10-30 dB. One reason for this improved gain margins might be that position B has a higher mechanical impedance than position A and is hence radiating less sound for a given force level. Another even more probable reason might be that the transducer in the BCI is completely encapsulated and is mechanically separated from the microphone in the audio processor. In the BAHA the transducer and the microphone are in the same housing. A possibility of having a higher real gain setting in the BCI than in the BAHA may be of significant clinical importance for the hearing rehabilitation of these patients.

Key words: BAHA, implantable transducer, loop gain, gain margin, sound radiation, stability.

Acknowledgment

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List of Abbreviations

BAHA	bone anchored hearing aid
BC	bone conduction
AC	air conduction
dB	decibel
dryskullA	position A on dry skull
dryskullB	position B on dry skull
HA	hearing aid
HL	hearing level
OL	open loop
CL	close loop
GM	gain margin
OFL	output force level
SPL	sound pressure level

1 Introduction

Hearing is one of the five senses in the human body which is an ability to distinguish sound by transferring sound waves to the cochlea [1]. The sound waves are transmitted through the ear canal and middle ear ossicles to the cochlea or directly via bones [1,2]. Difficulty in hearing is called hearing loss and detecting the sound loudness is called hearing sensitivity which are described in decibels (dB) and are checked for a number of frequencies. The human can hear up to 20 kHz and tests are made between 250 Hz to 8 kHz. Speech understanding exists from 500 Hz to 4 kHz.
One of the solutions to treat hearing losses is sound amplification which is done by hearing aids [3].
Traditional external hearing aids work based on air conduction mechanism to improve patient's hearing level but in some patients, the better solution to increase the hearing level is to use implantable hearing devices such as bone conducted hearing aids and middle ear implants. However, conventional hearing aids are not applicable for patients with ear canal or middle ear impairments. Since the cochlea stimulation is based on the ossicles vibrations, bone conduction hearing devices are developed which stimulate the cochlea directly through the skull bone bypassing the ear canal and middle ear [2].
The Bone Anchored Hearing Aid (BAHA) is a type of bone conduction device which has an abutment surgically implanted into the bone to transmit sound directly to the inner ear. In this study the BAHA standard implantation site is denoted as Pos A. One main drawback is the skin penetration that needs life-long daily care. Also, the bone-anchored fixture can be lost spontaneously or as a result of trauma. Also, BAHA devices are known to have limited gain due to feedback problems. Other drawbacks exist for BAHA such as difficult maintenance, low power, etc. Therefore, the new generation of bone conduction device is developed which is called the Bone Conduction Implant (BCI) system. The BCI has 0-10 dB lower gain compared with BAHA system due to the need for the inductive link. A new position (Pos B) is considered for implanting the BCI implant [4].
This thesis covers two separate issues. We have investigated that the new position (Pos B) has lower sound radiation than the BAHA position and then it was shown that the BCI device gets less feedback problem than the BAHA and has higher gain margin when normalized for the same cochlear acceleration level.
In this report, three main parts will be explained. At first, hearing organ, different mechanisms for hearing and various types of hearing losses will be discussed. Then, the methods, devices under test and specific measurements will be mentioned. Finally, the results will be shown and discussed and conclusions will be made.

1.1 Objective

The aim of this master thesis project was to measure, compare and analyse the results of the loop gain and gain margin measurements with both the BAHA and the BCI devices and show the gain margin improvements for the BCI system.

1.2 Solution Approach

A number of studies have been made to recognize feedback paths and decrease its effect by applying different solutions. One of the factors which has an effect on feedback is the mechanical impedance of the bone. Previous studies done by Eeg-Olofsson *et al.* [5], measured the mechanical impedance of the skull bone behind the ear in eight points. Two positions were chosen to achieve the optimal quality of the sound, traditional position of the BAHA which is 55mm behind the ear canal, in the parietal bone and new position called position B which is 5mm behind the ear canal in the temporal bone [5]. Figure 1 shows these two positions.

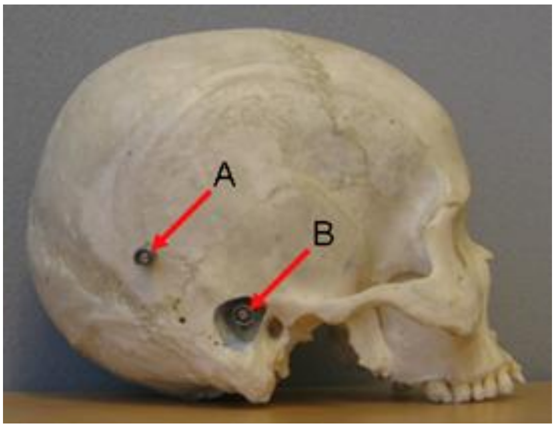

Figure 1: BAHA standard position (Pos A) and BCI implantation position (Pos B) on dry skull.

Two positions with different mechanical impedances on the dry skull bone were studied. One position was the standard BAHA position that is called position A and the other one was the point closer to cochlea which is called position B in this study where the BCI transducer was implanted. The comparison of the BAHA in position A and the BCI in position B can determine which device has lower sound radiation and hence less feedback problems.

2 Background

The principle concepts for development of the bone conducting hearing aids are based on the human hearing physiology and skull bone mechanical impedance. According to this fact, hearing and a number of basic concepts will be discussed in this chapter.

2.1 Hearing Physiology

Hearing is one of the most important human senses which has a significant role to communicate with other people, and ear is the hearing organ in the body. Ear consists of three main parts: external ear, middle ear, and inner ear. Figure 2 illustrates the hearing organ. External ear includes pinna and the ear canal. Pinna amplifies high frequency sounds and distinguishes between frontal and behind sound sources. In addition, ear canal works as a resonator and amplifies sound waves. The outer ear acts as a preamplifier to enhance sound by 15 to 20 dB at frequencies in the range of 2 to 5 kHz. Middle ear contains ear drum and three tiny bones which are known as ossicles: the malleus, the incus and the stapes that all are surrounded by the air. These bones transmit vibration from eardrum across the middle ear. Function of the middle ear is to mimic impedance matching between ear canal and fluid in the inner ear. This impedance matching improves sound transmission from outer ear to inner ear. If the impedance matching doesn't exist, the transmitted sound will be about 25 to 30 dB lower [6,7].

The Eustachian tube equalizes pressure between middle ear and the outside atmosphere. Inner ear contains semicircular canals and cochlea which is a solid bony case and is filled by fluid and tiny hairs cover its surface. Movement of stapes is transmitted as waves in the inner ear, and electrical impulses are generated by the hair cells. These impulses are transmitted to brain by auditory nerve.

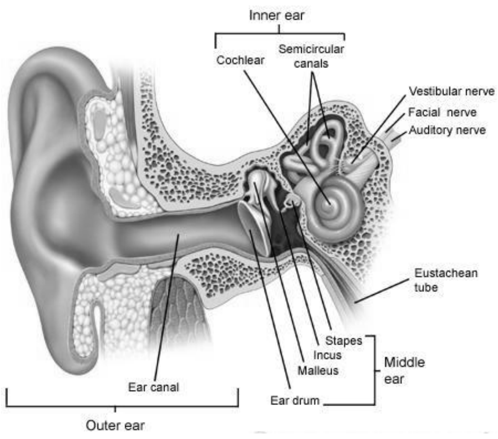

Figure 2: Ear organ consists of three main parts: outer ear, middle ear and inner ear.

2.2 Hearing Pathways

Sound waves can be transmitted via two different path ways to the inner ear: Air Conduction (AC) and Bone Conduction (BC). In the air conduction mechanism, energy of the sound is captured by pinna and is converted to mechanical vibrations across ear canal. These vibrations result in ear drum movements which cause movement in ossicles. According to this movement, the fluid in the cochlea and basilar membrane will move to stimulate hair cells and acoustic nerve. This nerve transmits information to the brain via the cochlear nuclei [1,8].

In hearing by bone conduction, the vibration of the bone is directly transmitted to the cochlea by placing a vibrating device in the mastoid and bypassing ear canal and middle ear [9]. Figure 3 shows two different conduction paths of one’s own voice.

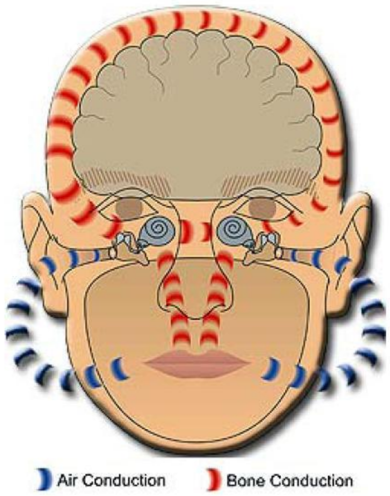

Figure 3: Hearing by air and bone conduction.

2.3 Hearing Loss

Hearing losses are classified into three types based on their origins which are conductive, sensorineural and mixed hearing loss. Impairment in outer or middle ear is caused conductive hearing losses. If the reason of impairment is located in the inner ear or hearing nerve, is called sensorineural hearing loss and combination of these hearing losses is named mixed hearing loss [3].

There are different causes for these types of hearing losses such as chronic infection, holes in eardrum, birth defects which are most common reasons for conductive hearing loss and infection around the brain, viral infection of the inner ear, and disorders of the inner ear bone which are causes for sensorineural and mixed hearing loss. Figure 4 shows conductive and sensorineural hearing loss locations.

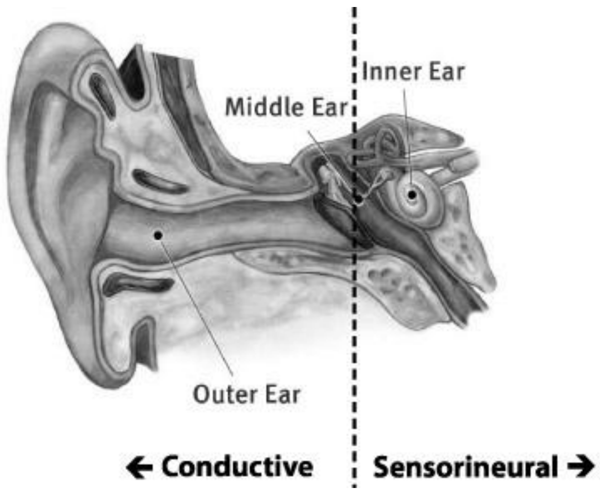

Figure 4: Conductive and sensorineural hearing loss locations.

2.4 Hearing Aids

There are different types of hearing aids based on the sound path. Behind the ear and in the ear canal devices are two types of air conduction hearing aids. For some of patients, traditional hearing aids are not satisfactory. In these cases, bone conduction hearing aids must be used [10].

Conventional bone conduction hearing aids have a number of problems such as variation in speech recognition, skin irritation and headache. These negative aspects led to develop new devices such as bone anchored hearing aid (BAHA) [11].

BAHA consists of a microphone, an amplifier and a transducer which is placed into an external housing and an implanted titanium fixture placed behind the pinna and a skin-penetrating abutment attached to fixture. The microphone captures surrounding sounds and these sound signals are amplified before transmitting to the transducer. This amplified signal vibrates the transducer and this mechanical vibration is transferred to the skull bone [8]. The BAHA (see Figure 5) is now used by a large number of patients in the world.

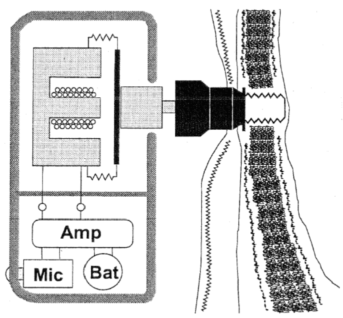

Figure 5: BAHA components.

There are some drawbacks for this type of hearing aid, but one of the most important problems is related to lifelong daily care due to permanent skin penetration of the implant. It has been discussed that a device with a permanently implanted transducer could improve the conditions for users with percutaneous BAHA [4]. However, 10-15 dB of output force will be lost due to the inductive link across the skin. In addition, it has been concluded that sound sensitivity would increase 15-20 dB when the excitation point moves closer to the cochlea. Such a system called the bone conduction implant (BCI) that was studied on cadaver heads [4]. This system consists of an external audio processor and an implanted unit as illustrated in Figure 6. An inductive link is used to transmit the power and signal to the implanted transducer that keeps skin intact and subcutaneous tissue undamaged. The link consists of two coils, an external transmitting coil and an implanted receiving coil. A permanent magnet retention system aligned these coils to each other.

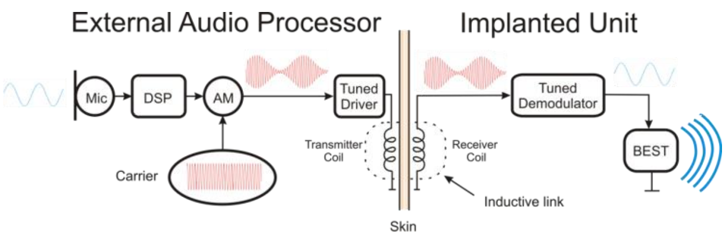

Figure 6: BCI system with external audio processor and implanted unit.

2.5 Feedback

Feedback is defined as returning a part of the output to the input and is generally used in control systems and amplifier designs which a system could be controlled via feedback. There are two types of feedback: negative feedback and positive feedback. When a part of output is in opposition to the input, there is a negative feedback and if the feedback is in the same way as input, positive feedback occurs. Positive feedback is used for designing oscillators and negative feedback is more functional in amplifiers [12]. However, in hearing aids, there are different feedback paths from transducer to the microphone which can cause an undesirable effect of howling sound and oscillations. There are a number of drawbacks for feedback such as limiting the maximum gain of the device. Block diagram of a feedback amplifier is depicted in Figure 7.

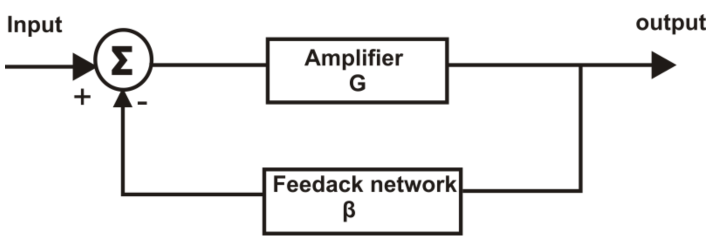

Figure 7: Block diagram of a feedback system.

Closed-loop gain of this system with feedback network can be written as:

$$G_{CL} = \frac{G}{1+G\beta} \qquad (1)$$

G_{CL} is called closed-loop gain since it consists the feedback loop. G is called the open-loop gain because it is the gain when the feedback loop is disconnected and βG is defined as loop gain [12].

The closed-loop gain is less than open-loop gain If G and β are positive and it is the requirement of negative feedback. If the gain of the amplifier is negative and feedback network is positive, 1+βG can be less than unity and the closed-loop gain is greater than unity. In this condition, oscillations occur.

When there is a positive feedback, the magnitude of the close-loop gain increases but a small change in G would cause a large variation in G_{CL} and led to poor stability. Open loop gain of the system is greater than unity and the open loop phase response of the system is a multiple of 360 degrees at that frequency [13].

2.5.1 Stability Conditions

To analyze the feedback effect, it is useful to consider Bode plots of magnitude and phase of the loop gain. According to $G_{CL} = \frac{G}{1+G\beta}$ equation (1), closed-loop gain is a function of frequency. If βG (f_1) = -1, the closed-loop gain goes to infinity and the system becomes unstable. Since loop-gain magnitude is equal to unity and phase is -180 degrees, oscillations would be started. In this study, unwrapped phase diagrams are plotted. Thus, there are oscillations in multiple of 180°. Figure 8 shows this definition. Magnitude of the loop gain is less than unity for a stable system. The amount that the magnitude of the loop gains is below 0 dB is called gain margin. A system with larger amount of gain margin is more stable and has less feedback problems. A minimum gain margin which guaranties stability is defined to be 10 dB in this project. Feedback of the closed-loop gain will increase towards infinity when the loop gain will always be less than open loop gain. The feedback can degrade the sound quality by introducing ringing at low gain margins [12].

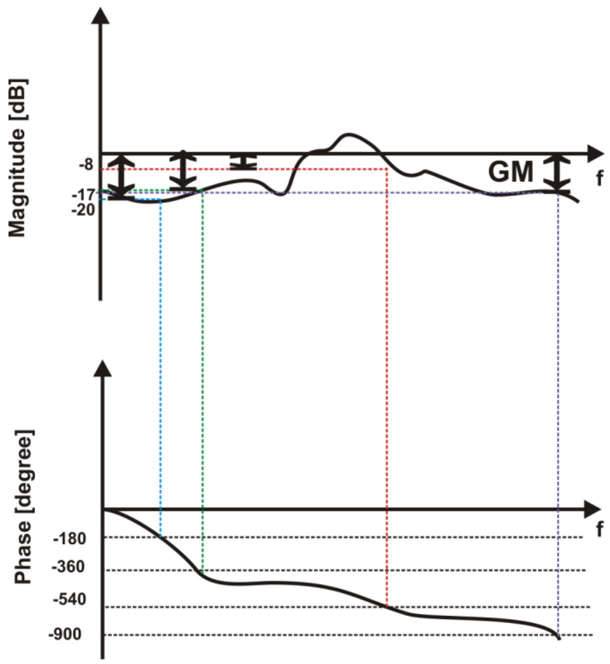

Figure 8: Method to obtain the gain margin (GM).

2.5.2 Types of Feedback in the BAHA

The output of a hearing aid can be returned to the microphone via different paths. Hearing aid is a component of a closed-loop system. System can oscillate, if the gain of hearing aid is raised. A common problem in hearing aids is feedback which causes a howling sound. There are four types of feedback paths in BAHA device:

1. Mechanical vibration of transducer transmitted to microphone via housing that is called structure-borne feedback (S);
2. Voltage from power amplifier can return to preamplifier or microphone via electric path (E);
3. Transducer can have magnetic leakage (M);
4. Hearing aid casing and skull bone sound radiation which transmitted acoustically to the microphone that is named acoustical feedback (A).

The feedback of the output to the microphone is an undesired effect. The hearing aid includes a closed-loop function which the forward path is electro acoustic transfer function and the feedback path is a combination of four feedback types. Figure 9 shows the block diagram of analytical model of the BAHA feedback and Figure 10 illustrates the feedback paths.

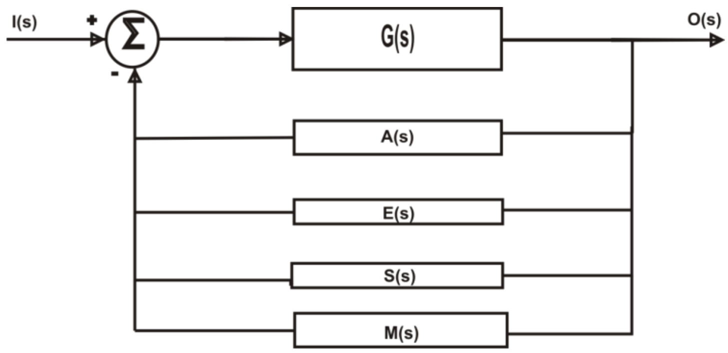

Figure 9: Analytic model of the BAHA considering acoustical A(s), structure-borne S(s), electrical E(s) and magnetic M(s) feedbacks. G(s) is the forward transfer function.

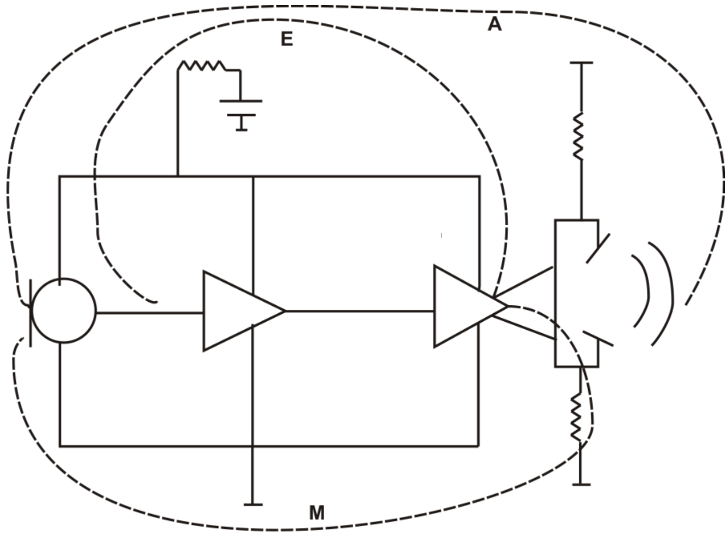

Figure 10: Model of the BAHA device and feedback paths.

In this work, to investigate the feedback effects, connection between preamplifier and power amplifier was cut and the input voltage was applied to the power amplifier and the output voltage was measured at the output of the preamplifier. Figure 11 shows the measurement set-up.

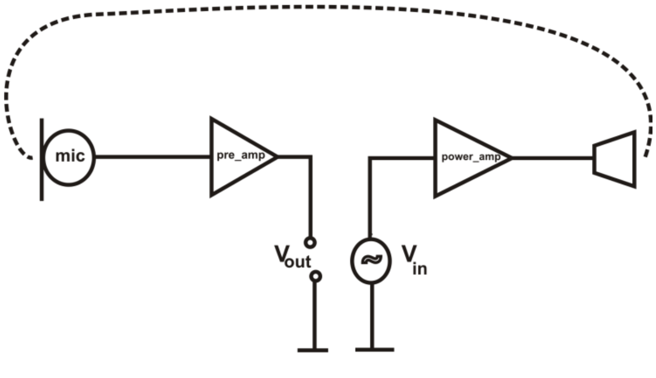

Figure 11: BAHA device measurement set-up.

The closed-loop transfer function of the BAHA with feedback paths can be written as:

$$G_{CL} = \frac{G(s)}{1+G(s)\beta(s)} \qquad (2)$$

where

$$\beta(s) = A(s) + M(s) + E(s) + S(s). \qquad (3)$$

G(s) is the electro acoustic frequency function and $\beta(s)$ is the feedback path function. Earlier studies on BAHA [8] have shown that the acoustic feedback has the most contribution among other feedback paths. To be able to demonstrate the acoustic feedback, microphone inlet was occluded by a sticky adhesive material and loop gain was measured.

For the BCI loop gain measurements, the connection between preamplifier and power amplifier was broken. The input voltage was applied to the power amplifier and the output was measured at the pre amplifier output. Figure 12 illustrate this measurement.

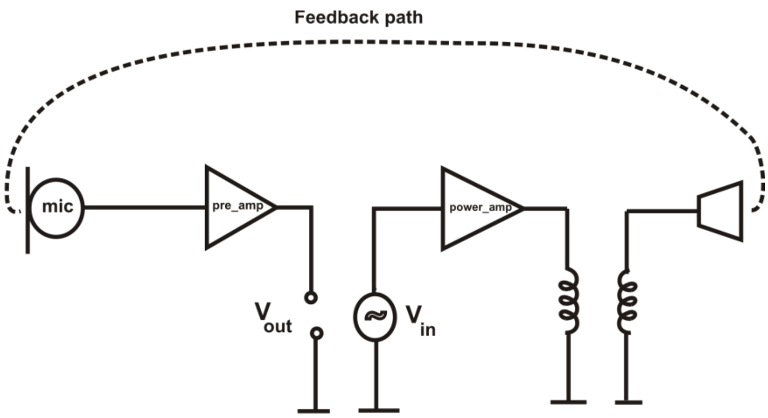

Figure 12: Feedback measurement set-up for the BCI system.

3 Methods

This section is divided into two parts since the scope of the study has two main focuses. The first part covers the methods used for investigating the difference between sound radiation and loop gain by placing BAHA in two different positions on dry skull (Pos A and Pos B). Thereafter the second part describes the methods used for measuring output force level (OFL) of the BCI and loop gain measurements by implanting BCI transducer in position B.

3.1 Devices under Test

During this work, two devices were used to be compared with each other: BAHA Classic-300 from Cochlear (Cochlear Bone Anchored Solutions; Mölnlycke, Sweden) and the BCI version 2.0. In this section brief information will be given about the devices.

3.1.1 BAHA Device

In this study, BAHA Classic-300 was used as a reference to compare the results with BCI version 2.0. BAHA consists of a microphone, an amplifier, a battery supply and a transducer. A percutaneous titanium screw is fixed into the bone behind the ear canal and transducer is snapped into the screw. In this system, the microphone is so close to the transducer which causes the unwanted feedback problem.
There are two potentiometers in the BAHA device called RP0 and RP1. The RP0 and RP1 were changed manually. In this work, RP0 was adjusted to minimum amount to obtain the largest bandwidth and RP1 was set to optimal case to fit the output force level of the device at 80 dB SPL to be similar to Baha® Classic-300 data sheet. In all measurements, maximum volume control was used and tone switch was set to normal position. For analyzing the loop gain, pre-amplifier and power amplifier were disconnected. To mimic the normal case before cutting the loop, impedance corresponding to initial case was put at the end of the pre-amplifier circuit. This is called BAHA-feedback device from now on. Figure 13 shows this device.

Figure 13: BAHA device.

In the first part of this work, output force level and loop gain of the BAHA were measured. For OFL measurements, the BAHA was attached to the Skull Simulator. To measure the loop gains the device was placed on the dry skull (right side) in position A and position B. Figure 14 and Figure 15 illustrate the measurement set-up of the BAHA on dry skull.

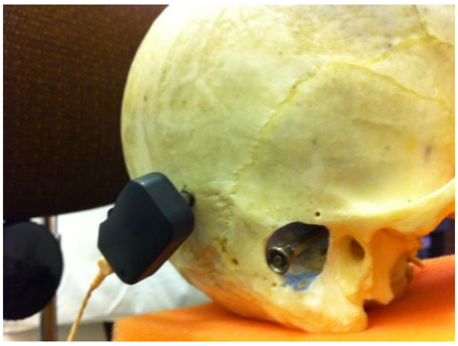

Figure 14: BAHA device placed in position A.

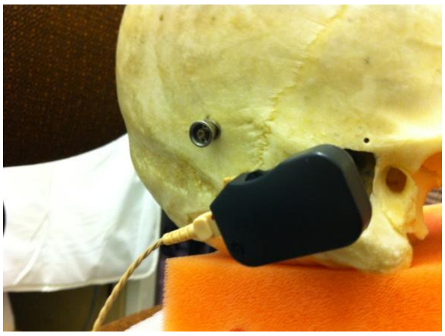

Figure 15: BAHA device placed in position B.

In the second part of this thesis, comparison between the BCI and the BAHA was performed. 4 mm sticky adhesive was used as virtual skin to mimic the real condition. The BAHA device was placed in the standard BAHA position, on the left side of the dry skull. Figure 16 shows the BAHA with virtual skin.

Figure 16: The BAHA device placed in position A with virtual skin.

3.1.2 Bone Conduction Implant (BCI)

The BCI system consists of an external audio processor and an implanted unit that is illustrated in Figure 17. An inductive link is used to transmit the signal to the implanted transducer for keeping skin and subcutaneous tissue undamaged. The link consists of two coils, an external transmitting coil and an implanted receiving coil. A permanent magnet retention system used to align these coils to each other [4].

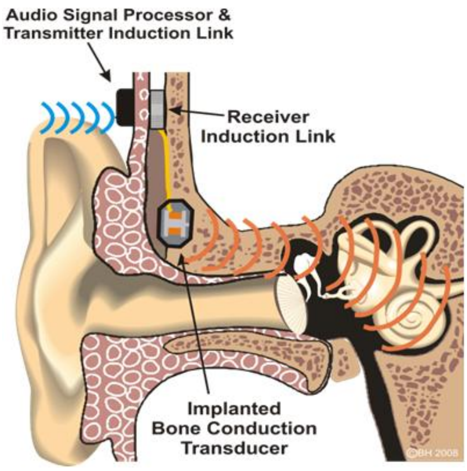

Figure 17: Left: The Bone Conduction Implant (BCI). Right: The BCI version 2.0 that was used in the loop gain measurements.

In this work a proto-type of the BCI device (version 2.0) was used during the measurements. In Figure 18, the BCI device under test is shown. 4 mm skin thickness was used between transmitter and receiver coils. To analyze the effect of the acoustical feedback, microphone was occluded by sticky adhesive.

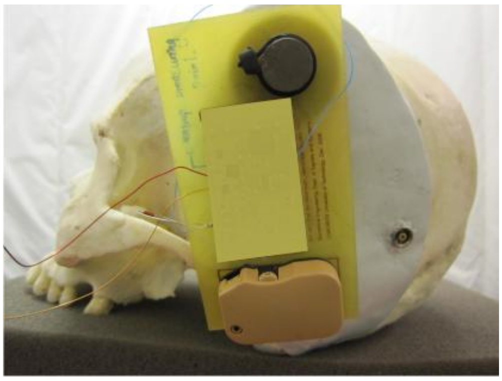

Figure18: The BCI version 2.0 was used in the measurement set-up.

3.2 Equipments

During this study different equipments were used which are described in this section.

3.2.1 Brüel & Kjær Pulse Analyzer

The Brüel & Kjær analyzer type 3560C was used in this work which has five-channel input that allows measurements for different forms of input, two-channel output controlled by a pulse system of version 12.6.
Different methodologies exist to analyze the signals. The method that was used in this thesis was the Steady State Response (SSR) that includes frequency response. In this method, a sinusoidal signal at certain frequencies was transmitted through the analyzer and response at each frequency was measured. This process continued for all frequencies at desired range to obtain frequency response. The frequency range was 100 Hz to 10 kHz.

3.2.2 Agilent Dynamic Signal Analyzer

The Agilent 35670A was used to measure the loop gain frequency responses and the linear spectrum of the output force levels of the BAHA and the BCI.
The FFT mode presents an almost instant frequency analysis of the desired measuring set-up using the Fast Fourier Transform. This mode has the advantage of being fast, but has few possibilities to control the instrument's excitation signal. Therefore, this mode is only applicable for measurements with no demands on keeping a constant signal level at one of the input channel. For these measurements, e.g. measurements requiring a constant sound pressure level (SPL), instead the Swept Sine mode was used allowing more control over the instrument's source level [13].

3.2.3 Skull Simulator

The Skull Simulator TU-1000 was used to mimic the load of the skull. It was used to measure the output force of the BAHA and the BCI in the frequency range within 100 Hz to 10 kHz. This force is converted into voltage which is measured with the Agilent Signal Analyzer.

3.2.4 Dry Skull

Most of the measurements were performed on the dry skull. The BAHA device was attached to Pos A and Pos B and the BCI transducer only implanted in Pos B.
Position A was the standard BAHA position which is placed 55mm behind the ear canal and somewhat upwards in the parietal bone. Position B for the BAHA loop gain measurements was situated 14 mm deep into the temporal bone. Figure 19 shows these two positions on the dry skull.

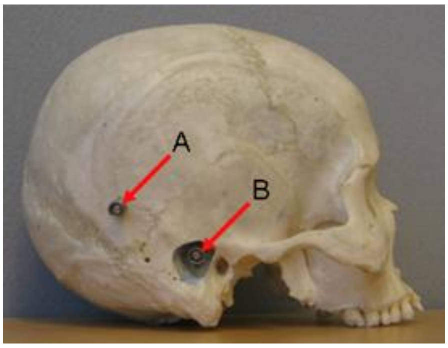

Figure19: Positions A and B on the dry skull that were used for measuring the BAHA loop gain.

3.2.5 Condenser Microphone

This type of microphone converts acoustical energy into electrical energy via a capacitor. During this work, Brüel & Kjær condenser microphone type 4134 and microphone power supply type 2804 were used during output force level measurements.

3.2.6 Anechoic Chamber

An anechoic chamber is a closed environment that is used to stop reflections of either sound or electromagnetic waves. There are different sizes of anechoic chambers. Due to the signal frequency range and size of the objects, size of the anechoic chamber could vary. A Brüel & Kjær anechoic test chamber type 4222 and a sound-insulated room which is called "acoustic room" in this report were used for loop gain and OFL measurements.

3.3 Output Force Level of the BAHA and the BCI

Both devices were mounted on the Skull Simulator inside the anechoic chamber. A condenser microphone was placed inside the chamber to be used as a feedback to the Agilent to keep the sound pressure constant over the sweeps. A swept sine wave in frequency range of 100 Hz to 10 kHz was then sent to the included speaker in the chamber from Agilent. 60, 70 and 90 dB SPLs were used in all sweeps. The signal from Skull Simulator was measured and analyzed with the Agilent. Linear spectrum of the force signal was used as the output. 4 mm skin thickness was placed between transmitter and receiver coils for the BCI output force level measurement [8,14].

3.4 Saturation point of the BAHA Device

According to Figure 20, the power spectrum of the BAHA-feedback device is linear between 60 dB SPL and 70 dB SPL, since by increasing the input sound pressure, the output increases with the same amount, but by increasing the sound pressure level more than 70 dB SPL the device reaches its saturation and is not linear anymore. To obtain the saturation point, the output force level between 60 dB SPL and 90 dB SPL was measured in specific frequencies of 1 kHz and 2 KHz which are shown in Table 1.

Table1: Output force level at 1 kHz and 2 kHz between 60 dB SPL to 90 dB SPL.

Frequency kHz	SPL dB	OFL	Frequency kHz	SPL dB	OFL
1	90	-22.07	2	90	-29.35
1	89	-22.02	2	89	-29.35
1	88	-21.97	2	88	-29.30
1	87	-21.93	2	87	-29.28
1	86	-21.88	2	86	-29.22
1	80	-21.81	2	80	-29.16
1	76	-21.92	2	76	-29.35
1	72	-21.04	2	72	-29.01
1	70	-23.45	2	70	-31.36
1	60	-33.72	2	60	-42

3.5 Loop Gain Measurements of the BAHA-feedback and the BCI Devices

The BAHA-feedback device was mounted on the Skull Simulator, dry skull position A and dry skull position B in different environment conditions: inside a room, inside the anechoic chamber, and inside the acoustic room to measure the loop gain. On the other hand the BCI was mounted on the dry skull in position B and only inside the acoustic room to measure the loop gain of the device.

3.6 Loop Gain without Acoustical Feedback

One of the most complains between users of hearing aids is the feedback problem which is mostly related to the acoustical feedback. In previous parts, three types of feedback were described. The acoustical feedback has the most contribution among other feedback paths. To be able to measure the acoustical feedback, the microphone inlet was obstructed and the loop gain was measured.

3.7 Noise Floor

To measure the noise floor, zero voltage was applied to the input of the loop during the sweep.

4 Results

This part is divided into two main parts, where the first section explains the loop gain measurements of the BAHA in positions A and B and the second part describes the loop gain measurements of the BCI. Finally comparisons between two devices will be performed.

4.1 Output Force Level

The output force levels for the BAHA Classic-300 are plotted in Figure 20. The volume control was set to Full-on Gain in all of the measurements. The output force linear spectrum was measured at 60, 70 and 90 dB SPLs.

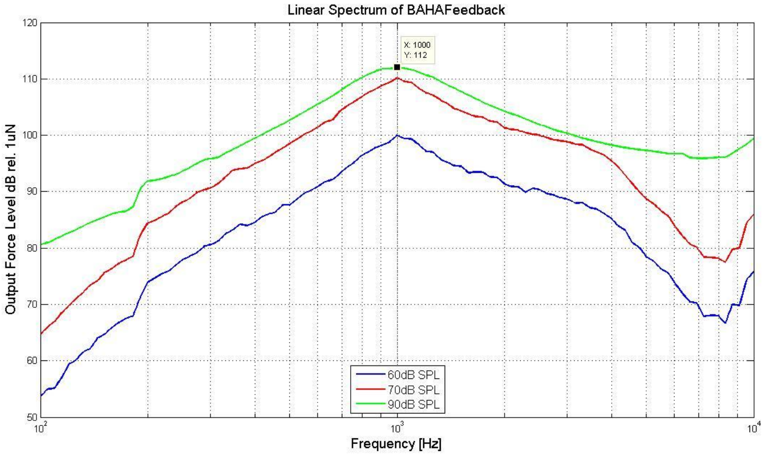

Figure 20: Output Force Levels at 60, 70 and 90 dB SPLs when the BAHA-feedback device was attached to the Skull Simulator inside the anechoic chamber.

The output force levels of the BAHA and the BCI are plotted in Figure 21. The volume control was set to maximum. Measurements were done from 60 dB SPL up to 90 dB SPL. 4 mm skin thickness was used for the BCI measurements.

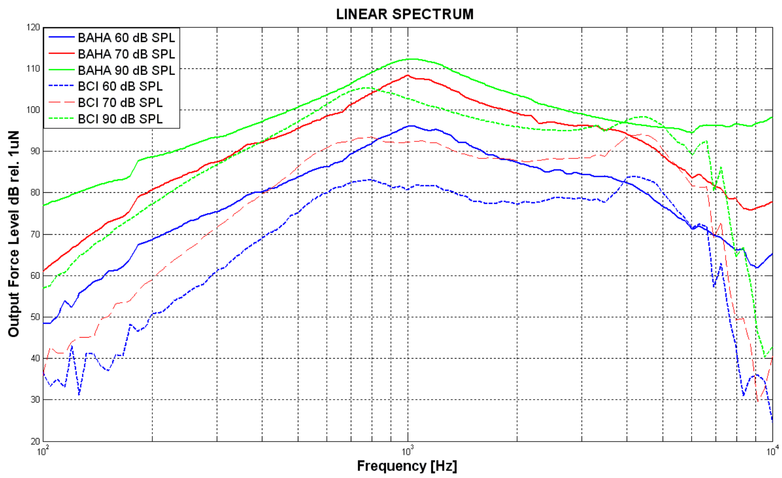

Figure 21: Output Force Levels at 60, 70 and 90 dB SPLs for the BCI and the BAHA when attached to the Skull Simulator inside the anechoic chamber.

4.2 Saturation Point of the BAHA-feedback Device

Loop gains were measured with three types of load, Skull Simulator, dry skull position A and dry skull position B, and the linearity of the device was investigated for different input voltage levels as shown in Figure 22. The figure presents that the device is in its linear range for input voltages of 1 mV_{rms} to 10 mV_{rms}. For loop gain measurements of the BAHA, minimum voltage of 1 mV_{rms} was chosen as input voltage source which corresponds to aproximately 58 dB SPL.

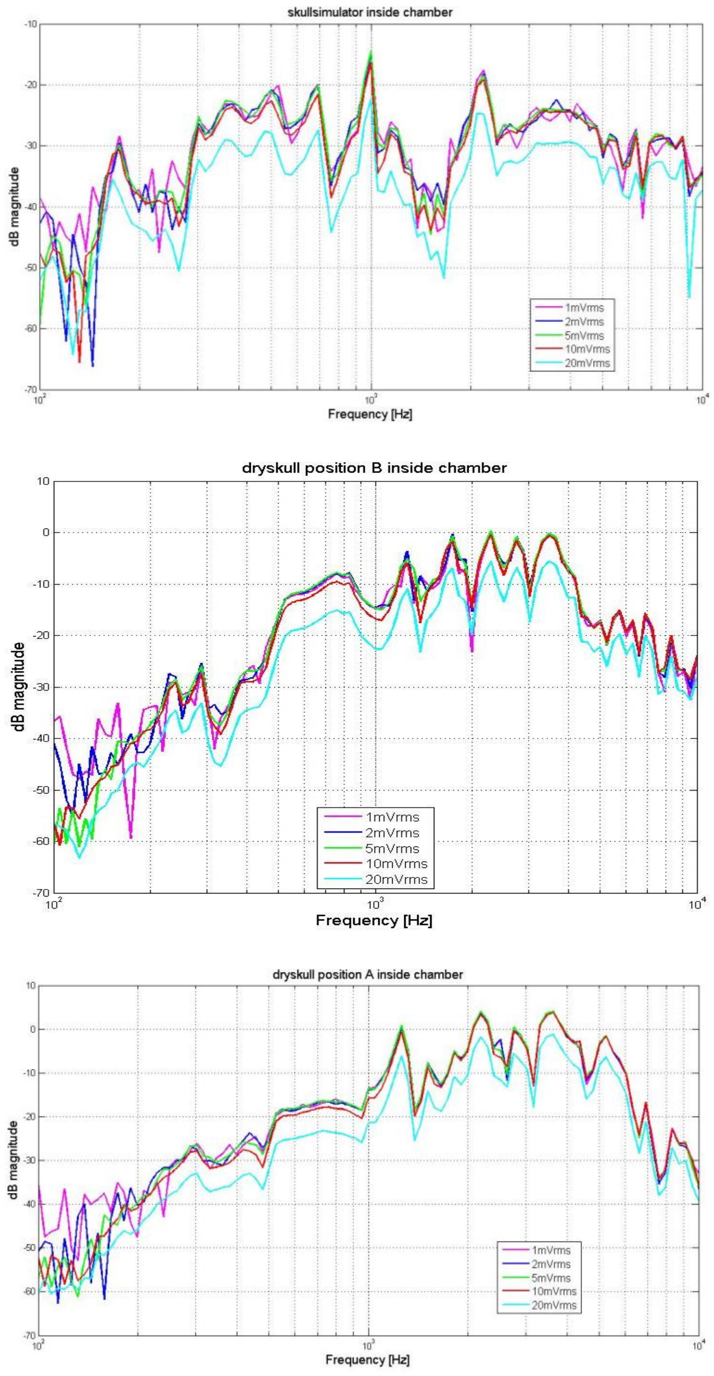

Figure 22: Loop gain of the BAHA-feedback device with different input voltage levels with three types of loads inside the anechoic chamber.

4.3 Loop Gain of the BAHA-feedback Device

Loop gain magnitude and phase diagrams of the BAHA-feedback device were measured in three environment conditions: inside a room, in the anechoic chamber and in the acoustic room by three types of load: Skull Simulator, dry skull Pos A and dry skull Pos B. The loop gains for three loads are shown in Figure 23. In the room, lower amount of the gain margin in position B is 7 dB at 1260 Hz and in position A is 3 dB at 1260 Hz. The gain margin in position B is 1-5 dB higher than in position A in the whole frequency range.

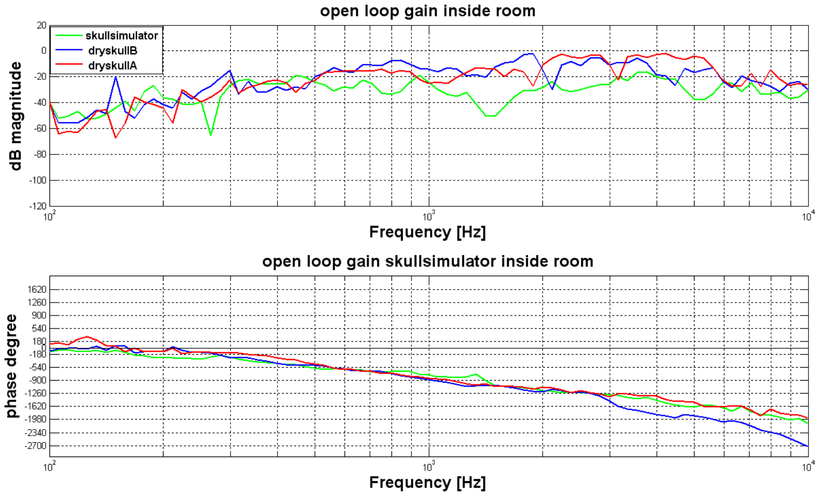

Figure 23: Loop gain magnitude and phase of the BAHA-feedback device when attached to the Skull Simulator, dry skull in position A and dry skull in position B inside the room.

The loop gain of the BAHA inside the anechoic chamber is shown in Figure 24. The smallest amount of the gain margin in position B is 5 dB at 1260 Hz and in position A is 7 dB at 1260 Hz. The gain margin is totally larger in position B rather than position A in whole frequency range. Figure 25 illustrates the loop gain measurements inside the acoustic room.

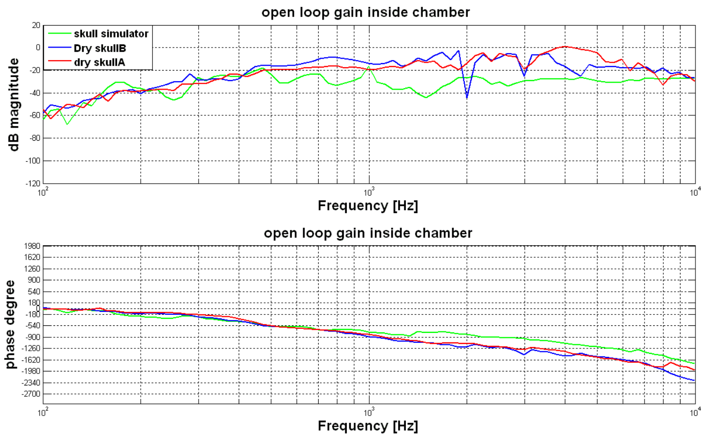

Figure 24: Loop gain magnitude and phase of the BAHA-feedback device when attached to the Skull Simulator, dry skull in position A and dry skull in position B inside the anechoic chamber.

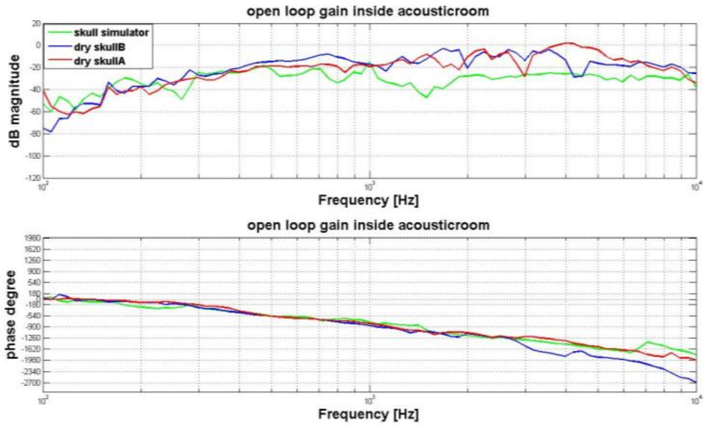

Figure 25: Loop gain magnitude and phase of the BAHA-feedback device when attached to the Skull Simulator, dry skull in position A and dry skull in position B inside the anechoic room.

In the acoustic room, the lowest amount of the gain margin in position B is 7 dB at 1260 Hz and in position A is 7 dB at 1260 Hz, but the gain margin in position B is larger than in position A in whole frequency range.

4.4 Loop Gain of the BAHA without Acoustical Feedback

Figures 26, 27 and 28 illustrate the loop gain magnitude and phase for the BAHA-feedback device when the microphone inlet was occluded. Dry skull in two positions A and B and the Skull Simulator were investigated inside the room, anechoic chamber and the acoustic room, respectively. The loop gain magnitude decreased when the microphone was obstructed in three conditions with three types of loads. In these situations, the effect of the acoustical feedback was investigated.

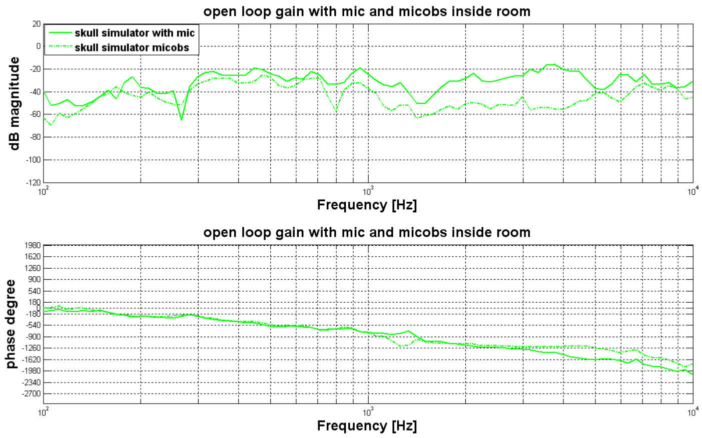

Figure 26: Loop gain of the BAHA with microphone and microphone obstructed on Skull Simulator in the room.

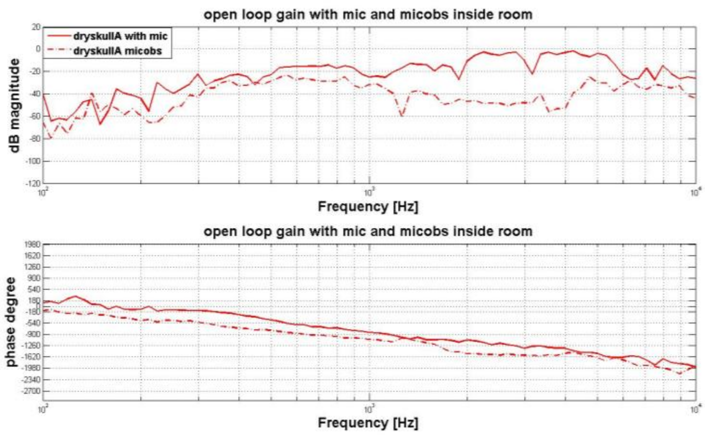

Figure 27: Loop gain of the BAHA with microphone and microphone obstructed in Pos A in the room.

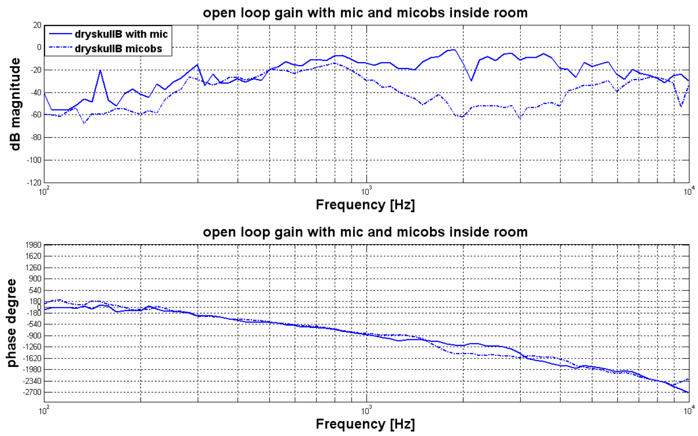

Figure 28: Loop gain of the BAHA with microphone and microphone obstructed in Pos B in the room.

Figures 29, 30 and 31 show the loop gain magnitude and phase of three types of loads inside the anechoic chamber when the microphone was used and when the microphone inlet was obstructed.

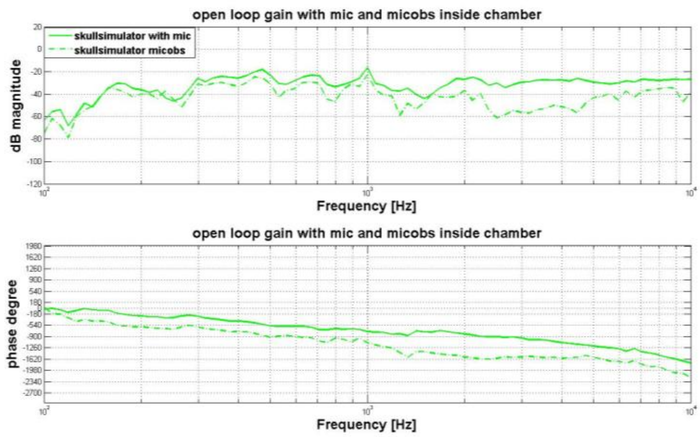

Figure 29: Loop gain of the BAHA with microphone and microphone obstructed on Skull Simulator. inside the anechoic chamber.

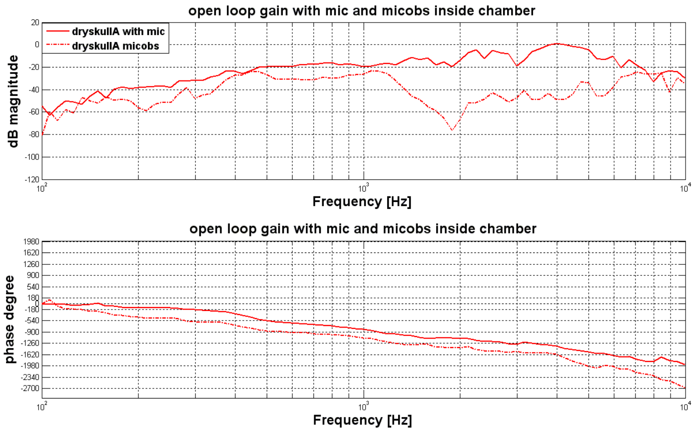

Figure 30: Loop gain of the BAHA with microphone and microphone obstructed in Pos A inside the anechoic chamber.

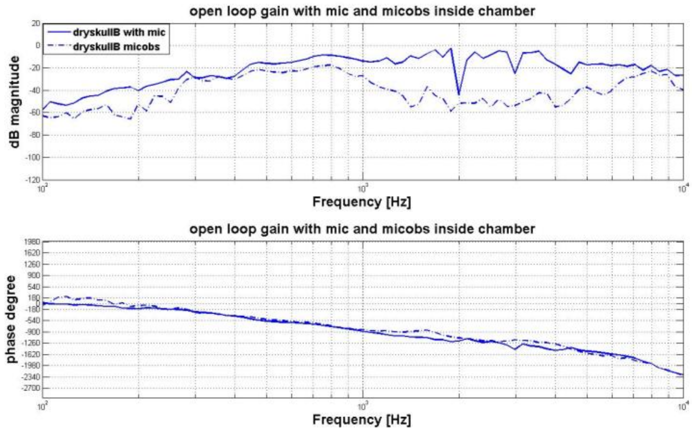

Figure 31: Loop gain of the BAHA with microphone and microphone obstructed in Pos B inside the anechoic chamber.

Figures 32, 33 and 34 present the loop gain magnitude and phase of three types of loads inside the acoustic room when the microphone was used and when the microphone inlet was obstructed.

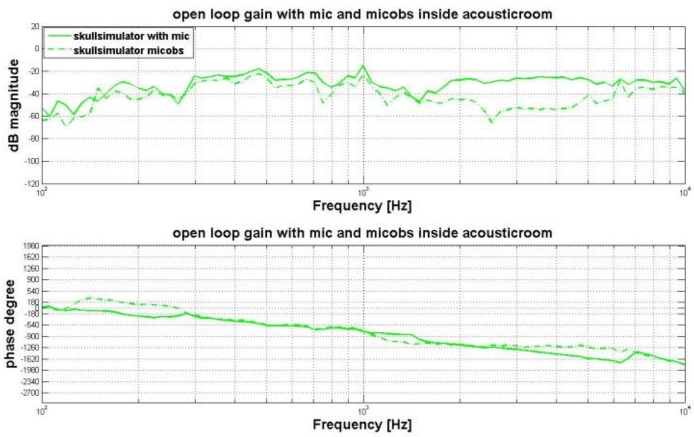

Figure 32: Loop gain of the BAHA with microphone and microphone obstructed on Skull Simulator inside the acoustic room.

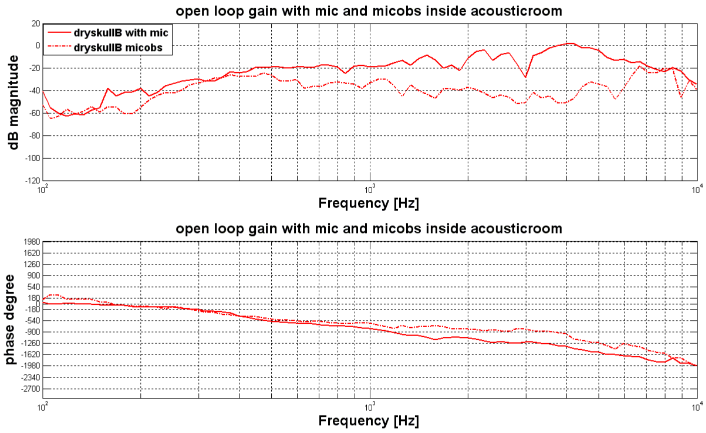

Figure 33: Loop gain of the BAHA with microphone and microphone obstructed in Pos A inside he acoustic room.

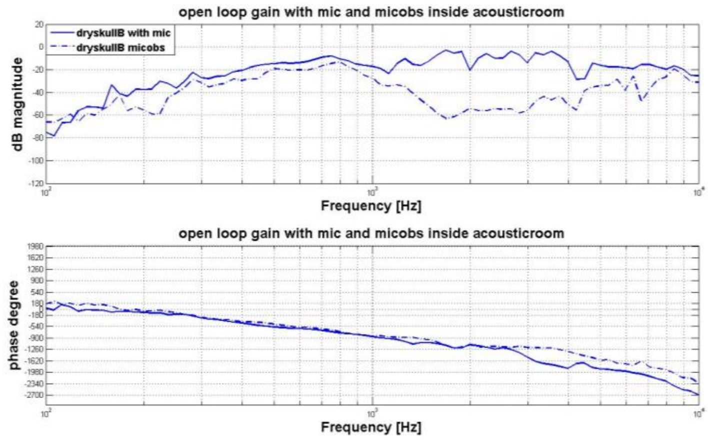

Figure 34: Loop gain of the BAHA with microphone and microphone obstructed in Pos B inside the acoustic room.

4.5 Noise Floor Measurements for the BAHA

In noise floor measurements the same set-up as loop gain measurements were used. The only difference was to apply zero input voltage to the device and measure the noise floor. Figure 35 shows the loop gain and noise floor measurements of the BAHA when attached to dry skull in position A and position B inside the acoustic room.

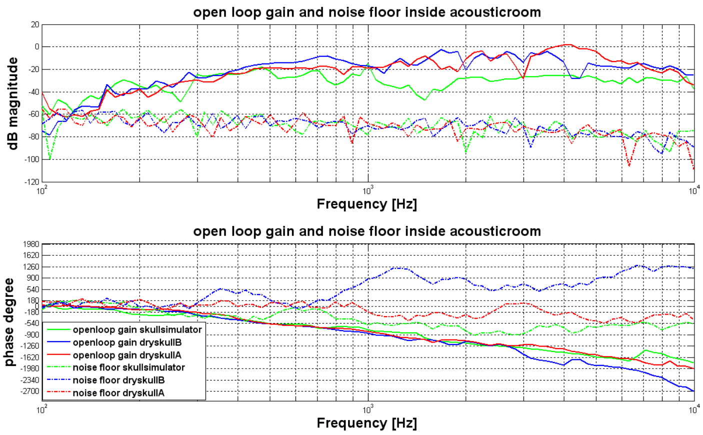

Figure 35: Comparison between loop gain and noise floor when the BAHA was attached to the Skull Simulator, dry skull position B and dry skull position A inside the acoustic room.

Figure 36 depicts the loop gain and noise floor measurements of the BAHA when attached to dry skull in position A and position B inside a room.

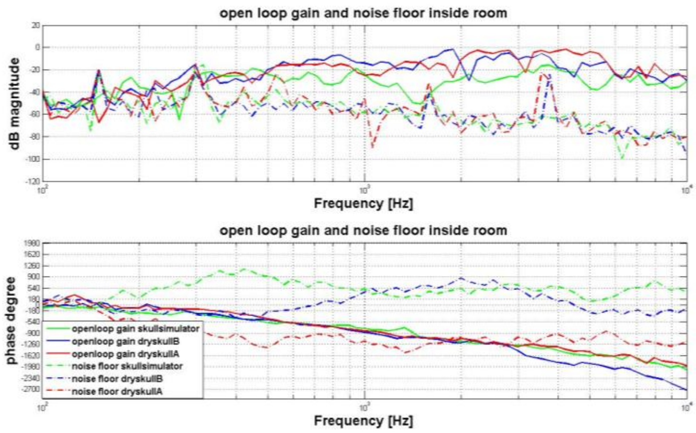

Figure 36: Comparison between loop gain and noise floor when the BAHA was attached to the Skull Simulator, dry skull position B and dry skull position A inside a room.

Figure 37 illustrates the loop gain and noise floor measurements of the BAHA when connected to the Skull Simulator, the dry skull in position A and position B inside the anechoic chamber.

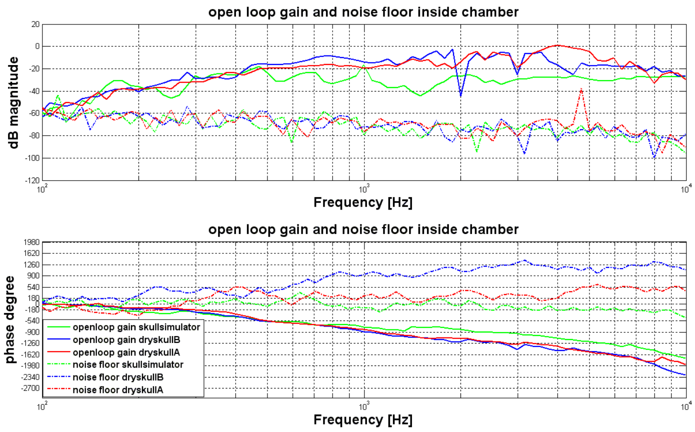

Figure 37: Comparison between loop gain and noise floor when the BAHA was attached to the Skull Simulator, dry skull position B and dry skull position A inside the anechoic chamber.

4.6 Gain Margin Measurements of the BAHA

According to the loop gain measurements, the gain margin of the BAHA was measured in each 180 degrees. This is due to the fact that the positive and negative output pins of the power amplifier can be connected to the transducer in two ways which have 180 degrees phase shift. Table 2 shows the gain margin of the BAHA when mounted on dry skull in position B and position A. In both conditions, loop gain measurement and acoustical feedback measurement with microphone inlet obstructed were performed and the gain margins were measured. The magnitudes were recorded at frequencies which their phase were the coefficients of 180 degrees, in other words, 180*n (for n=1, 2, 3,….). The difference between zero dB and the magnitude at specific frequencies was measured as gain margin.

Table 2: Gain margins - dry skull position B and dry skull position A inside the acoustic room.

Degree	Unstable frequencies	Gain margin Dry skull B	Gain margin Dry skull B mic obs	Degree	Unstable frequencies	Gain margin Dry skull A	Gain margin Dry skull A mic obs
-180	236	32	44.5	-180	291	30	34
-360	350	25.6	32.5	-360	389	24	26
-540	487	15	21	-540	490	18.8	26
-720	793	9	14	-720	878	19	33
-900	1079	21.5	27	-900	1163	16	34
-1080	1327 1604	12 5	38 62	-1080	1526 1813	10 17	44.5 38.5
-1260	2347	10	54.5	-1260	2777 3442	13 7	48 45
-1440	2906	9	57	-1440	4300	10	42
-1620	3117 3737 4374	7 7.8 16	54 45 46	-1620	5741 7203 8152 8602	12 18 22 22	43 23.9 20.5 33
-1980	6082	19	42	-1980	9897	34	38
-2160	7323	17	33				
-2340	8186	18	25				
-2520	8817	19	22				

Similar to previous measurements, all of the gain margins were measured when the BAHA was placed inside a room. Table 3 shows these values.

Table 3: Gain margins - dry skull position B and dry skull position A inside a room.

Degree	Unstable frequencies	Gain margin Dry skull B	Gain margin Dry skull B mic obs	Degree	Unstable frequencies	Gain margin Dry skull A	Gain margin Dry skull A mic obs
-180	281	-20.8	-26.49	180	116 135	-62 -47	-75.6 -62.5
-360	374	-31.6	-26.6	-180	334	-28.5	-34.8
-540	560	-12.8	-20.6	-360	458	-27	-30
-720	802	-7.5	-14	-540	562	-15.9	-23.3
-900	1031	-15.9	-29	-720	819	-16	-27
-1080	1257 1591	-19.2 -8.9	-38.9 -46	-900	1153	-22	-37
-1260	2654	-7	-53.7	-1080	1786	-17	-48
-1440	2954	-9	-60	-1260	2777 3156-3343	-3 -6-(-13)	-49 -48-(-39.5)
-1620	3143	-9	-55	-1440	4265	-3	-34.5
-1800	3800	-13.5	-50	-1620	5286 6032 6715	-4 -23 -23	-30 -32 -34
-1980	5647	-20	-31	-1800	7293 7663 8461	-24 -22 -22	-34 -32.4 -33
-2160	7115	-23.5	-27				
-2340	7986	-27.5	-26.8				
-2520	8964	-25	-40				
-2700	9897	-29	-43				

Table 4 presents the gain margin of the BAHA when mounted on dry skull in position B and position A. In both conditions, normal loop gain measurement and acoustical feedback measurement with microphone inlet obstructed were performed and the gain margins were measured.

Table 4: Gain margins - dry skull position B and position A inside the anechoic chamber.

Degree	Unstable frequencies	Gain margin Dry skull B	Gain margin Dry skull B mic obs	Degree	Unstable frequencies	Gain margin Dry skull A	Gain margin Dry skull A mic obs
-180	199 238 253 266	-40.5 -32.9 -31 -30.1	52.53 45.6 51 38.3	-180	285 298	-32 -31.6	41 48
-360	366	-28	28.5	-360	420	-25.8	26.9
-540	483	-15.5	21.5	-540	501	-19.6	26.7
-720	766	-8.7	18	-720	802	-16.2	29.5
-900	1027	-14	30	-900	1111	-17.8	23.6
-1080	1489	-11	52.3	-1080	1707	-16	62
-1260	2687	-5	48	-1260	2811 3079 3343	-8 -18 -7	51 44 47
-1440	2966 3707 4300 4575	-24 -12.5 -23 -20	54 42.5 50 43	-1440	4248	-1.5	48
-1620	6082	-17.5	36	-1620	5717	-12	45.5
-1800	7353	-21	27	-1800	7293 8152 8890	-18.5 -31 -24	25 25.5 37
-1980	8220	-19	25				
-2160	9001	-22	28				

4.7 Loop Gain of the BCI Device

To measure the loop gain of the BCI device, Agilent dynamic analyzer was used. All of the measurements for the BCI version 2.0 were performed inside the acoustic room. Open loop gain of the BCI with 4 mm skin thickness is shown in Figure 38. These results will be used to compare the BCI device with the BAHA.

Figure 38: Loop gain of the BCI with 4 mm virtual skin.

According to Figure 38, the BCI device is always in the stability region in high frequencies since the gain margin is more than 10 dB which guarantees the stability.
When the BCI device was measured, 4 mm sticky adhesive was used between transmitter and receiver coils instead of skin. Therefore, the BAHA loop gain measurement was also done with the virtual skin in place (see Figure 39). It is obvious that the loop gain decreases around 3 dB in high frequencies.
All of the measurements in the first part of the report were done on the right side of the dry skull. In this study, the implanted position for the BCI was located on the left side of the dry skull. The goal was to compare the gain margin of the BCI in position B versus the BAHA in position A at the same side. Figure 40 shows the difference between BAHA's gain in left and right side of the dry skull.

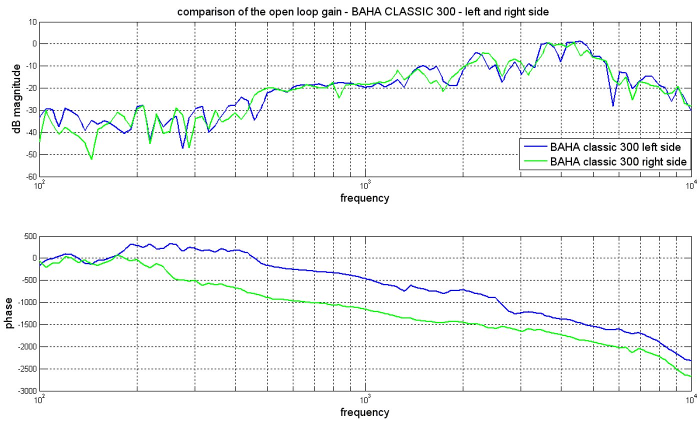

Figure 39: Loop gain of BAHA when placed on left side and right side of the dry skull.

Comparison between the BCI in position B and the BAHA in position A is illustrated in Figure 40.

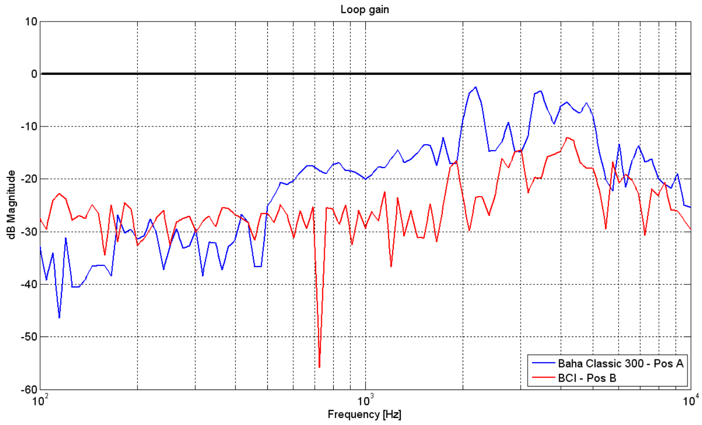

Figure 40: Loop gain of the BAHA and the BCI with virtual skin in place.

5 Discussion

It is obvious from Figure 21 that the maximum output force level of the BAHA device is 112.2 dB rel. 1µN at the transducer resonance frequency which is quite similar to data sheet of the device (113 dB rel.1µN). The output force level of the BAHA is linearly increasing by raising the input sound pressure level to 70 dB but from 70 dB SPL to the maximum OFL increases nonlinearly. According to Table 1 the saturation point of the device can be determined as 72 dB SPL that is corresponding to 1 mV_{rms} input source from Figure 22.

Similar to the BAHA device, the BCI output force levels at 60 dB, 70 dB and 90 dB SPLs were shown in Figure 21. It is also clear that the BAHA's gain is higher than the BCI. Figure 41 presents that the maximum output force level for the BAHA is 112.2 dB rel. 1 µN and for the BCI is 105.5 dB rel. 1µN. It means that the BAHA produces more output force than the BCI on Skull Simulator. Since the compensated case must be considered for the BCI to compare both devices in terms of gain margins.

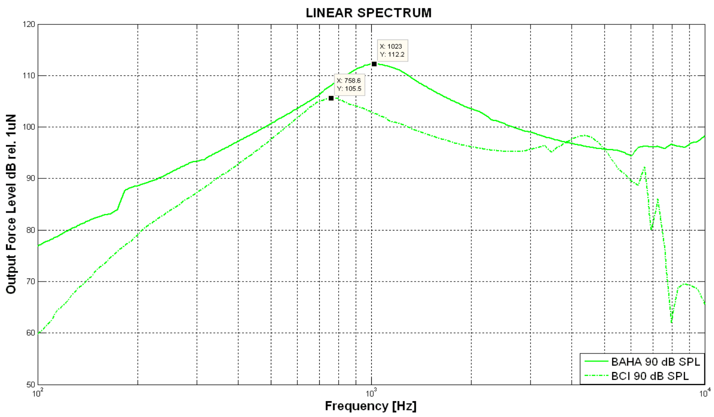

Figure 41: Output force level of the BAHA and the BCI at 90 dB SPL.

Firstly, loop gain of the BAHA device was measured to get information about stability margin of the device in position A and position B. The loop gain diagram of the BAHA system was plotted in Figures 16, 17 and 18 in three different situations and three types of loads. It is notable that the loop gain of the BAHA in position B is 1-5 dB lower than it is in position A which results in higher gain margin in position B than in position A in all measurement environments.

To measure the acoustical feedback which has the highest contribution among different types of feedback paths in the BAHA, the microphone was obstructed and all loop gain measurements were performed. Figures 42, 43 and 44 show the comparison of the loop gain of three loads inside a room, inside the chamber and inside the acoustic room when the acoustical feedback exists and when the microphone is obstructed and there is no acoustical feedback.

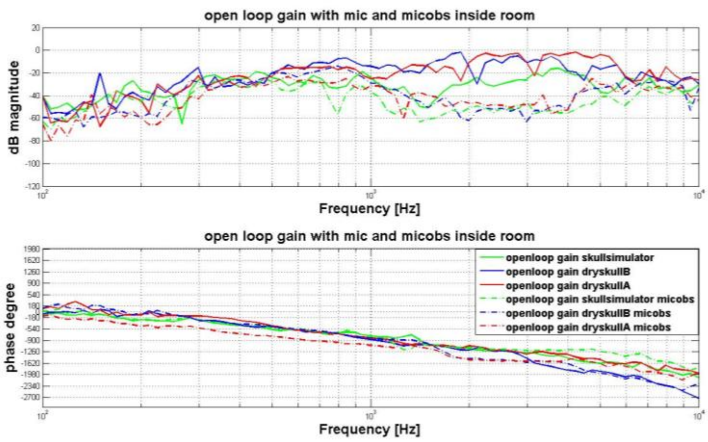

Figure 42: Comparison between the loop gain of the BAHA with microphone and obstructed microphone when attached to the Skull Simulator, dry skull position A and dry skull position B inside a room.

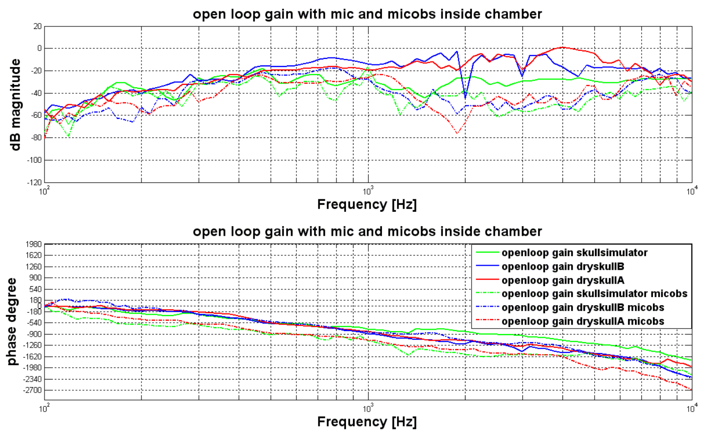

Figure 43: Comparison between the loop gain of the BAHA with microphone and obstructed microphone when attached to the Skull Simulator, dry skull position A and dry skull position B inside the anechoic chamber.

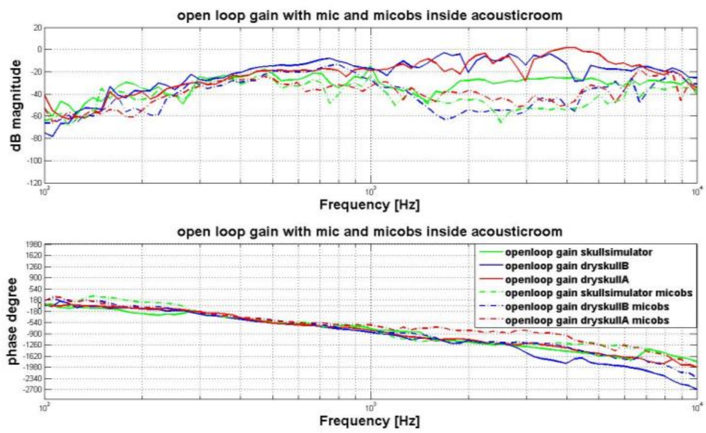

Figure 44: Comparison of the loop gain of the BAHA with microphone and obstructed microphone when attached to the Skull Simulator, dry skull position A and dry skull position B inside the acoustic room.

In all three measurement environments, the gain decreases when obstructing the microphone mostly in high frequencies for three types of loads. That is obvious especially when the device placed on the dry skull in position A and position B.
According to these results, Tables 2, 3 and 4 were concluded. We Consider below 10 dB as the critical condition for reaching instability. It means that the system gets unstable at those frequencies that the gain margin is lower than 10 dB. Therefore, the gain margin points were plotted when the device was placed in position B and position A. In each position, two conditions were considered: microphone was used and microphone was obstructed. If the number of points below 10 dB is high and these especial points are closer to 0 dB, the system has less stability margin. Gain margin points are shown in Figure 45, 46 and 47 when considering 10 dB as a guaranty for stability.

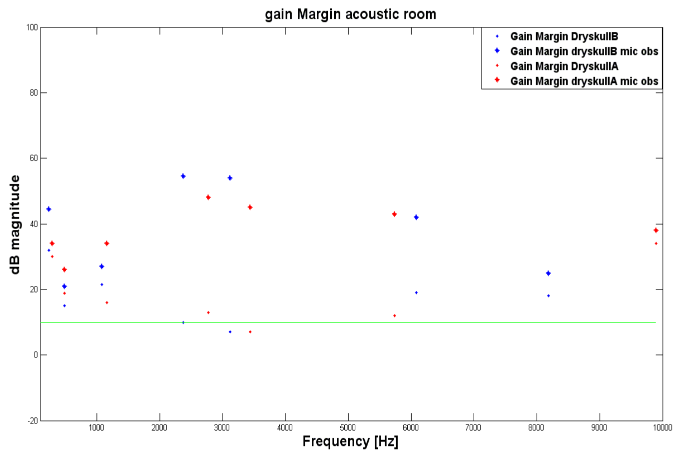

Figure 45: Gain margin of the BAHA inside the acoustic room in position B and position A when microphone was used and obstructed. 10 dB line is shown as the border of instability.

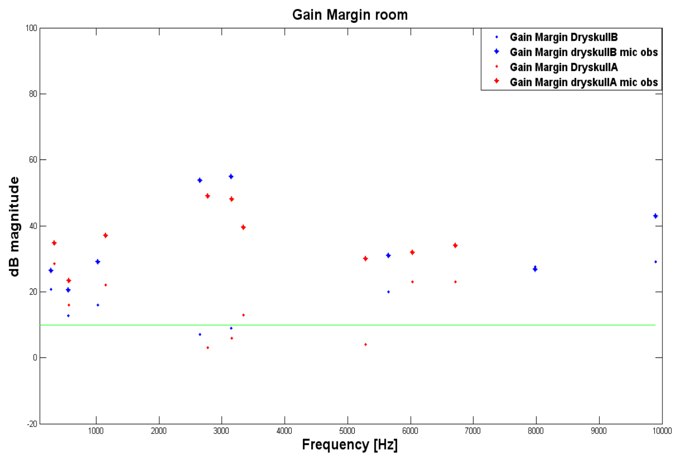

Figure 46: Gain margin of the BAHA inside a room in position B and position A when microphone was used and obstructed. 10 dB line is shown as the border of instability.

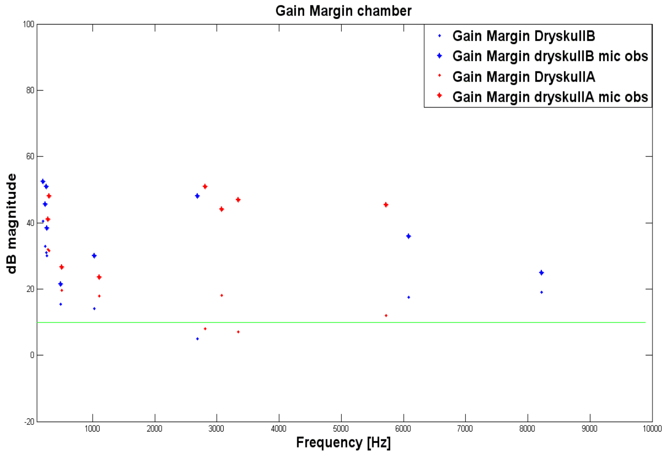

Figure 47: Gain margin of the BAHA inside the anechoic chamber in position B and position A when microphone was used and obstructed. 10 dB line is shown as the border of instability.

It can be seen from figures that the device in position B is more stable than in position A. However, the difference between position A and position B is not so big and is in the range of 1-5 dB. The goal of this work was to show that the BCI which is a new generation of the bone conduction device has less feedback problems than the BAHA. Therefore, the loop gain of the BCI version 2.0 was measured inside the acoustic room using 4 mm spacing between transmitter and receiver coils. According to Figure 40, it is obvious that the loop gain of the BCI is around 0-25 dB lower than the BAHA in high frequencies.

To compare two devices, all of the properties and conditions must be considered to be similar. Therefore, the output force level of the BCI was measured at 60 dB SPL and compared with output force of the BAHA at the same sound pressure level to get the difference in the gains. Figure 48 shows the difference between the output force level of the BAHA and the BCI at 60 dB SPL measured on Skull Simulator. 60 dB SPL is in the linear range of both devices.

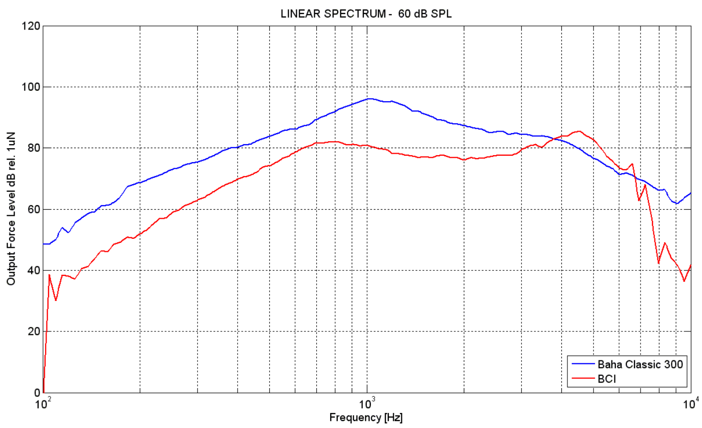

Figure 48: Linear spectrum of the BAHA and the BCI at 60 dB SPL.

Based on the OFL difference between the BAHA and the BCI, loop gain magnitude of the BCI can be compensated to have the same mechanical output as the BAHA device. Figure 49 illustrates the compensated BCI for the same mechanical output as the BAHA device.

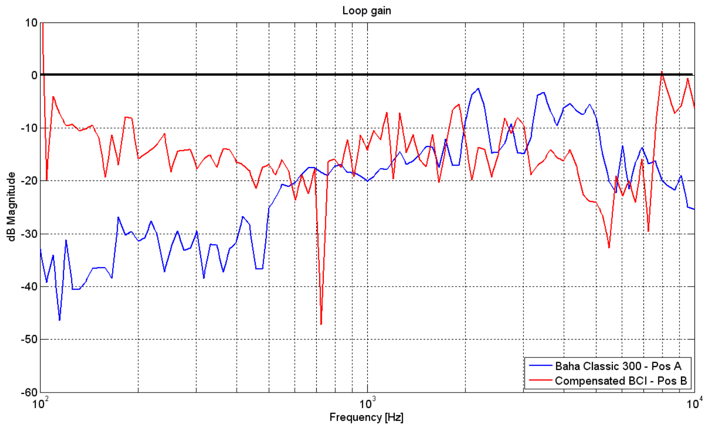

Figure 49: Loop gain of the BAHA vs. compensated BCI.

It has been shown in previous studies [Håkansson, Måns] on dry skull and cadaver heads that the sensitivity to bone-conducted sound will increase if the stimulation point becomes closer to cochlea. In the BCI the stimulation point is closer to cochlea than the BAHA standard implantation point. Therefore, the BCI device can be compensated a second time by the gain difference between implanting in Pos A versus Pos B. This can be made by measuring the Promontory Acceleration Levels (PAL) using a laser Doppler vibrometer (LDV). The same BAHA transducer was attached in both positions on the dry skull. In Figure 50, the PAL for both positions are presented when 1 volt was applied to the transducer.

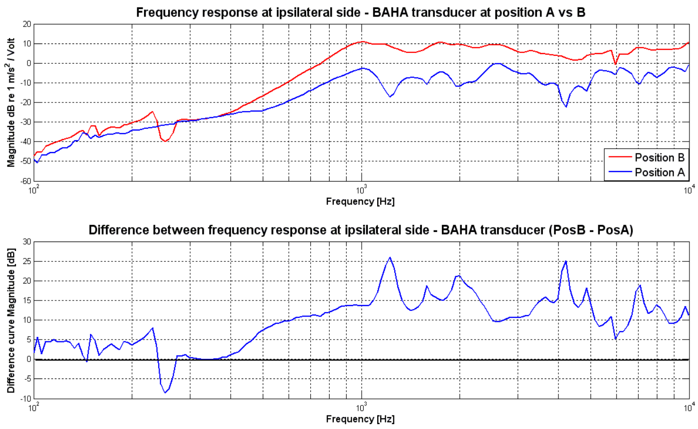

Figure 50: Promontory Acceleration Levels from BAHA transducer @ 1 volt input to transducer measured by LDV on dry skull in position A and position B and the gain difference between two positions.

Based on the difference in the gain between Pos A and Pos B, the loop gain magnitude of the BCI was compensated which is depicted in Figure 51.

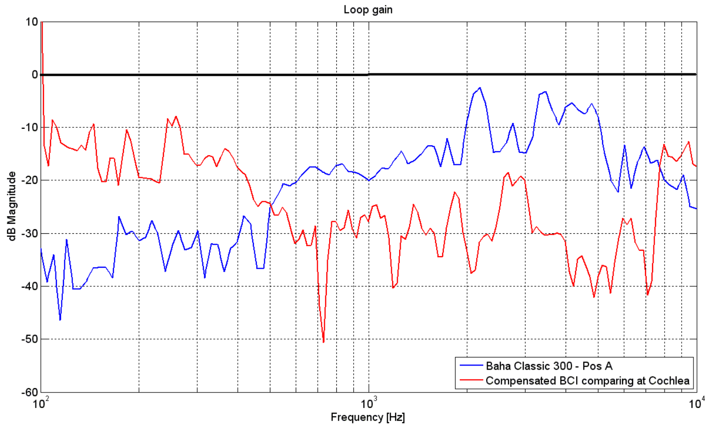

Figure 51: Loop gain of the BAHA vs. compensated BCI comparing at cochlea after two compensations.

The BCI loop gain is now also compensated to have the same cochlear acceleration level as the BAHA. This gives additional 0-25 dB more gain margin as compared with the BAHA. It can be seen that the compensated BCI for the same cochlear acceleration level has 10-30 dB higher gain margin than the BAHA in the range of 600 Hz to 7500 Hz. The improved gain margin shows how much the amplification can be increased with the BCI device, as compared with the BAHA, without obtaining feedback oscillations.

6 Conclusions and Future Work

It is obvious that the new position B for implanting the BCI transducer has lower sound radiation than the BAHA standard position A. This study has investigated if a bone conduction implant could be an option to currently used Baha ® Classic 300 from gain point of view.

It was found that:

- the gain margin with the BCI in position B has been improved 10-30 dB versus the BAHA in position A for the same cochlear acceleration,
- the gain margin has been improved 0-10 dB with the BCI versus the BAHA with the same mechanical output,
- the gain margin has been improved when the BAHA was placed in position B as compared in position A,
- gain margin increases 20-60 dB when the BAHA's microphone is obstructed. It means that **acoustic pathway** is the major contributor to feedback in the BAHA,
- loop gain of the BCI is always in stability region (below -10 dB),
- loop gain at main speech frequency (500 Hz to 4000 Hz) is lower which is allowed to increase the gain of the BCI without unwanted feedback,
- loop gain in the BCI is obviously lower than the BAHA in high frequencies especially at speech frequencies.

Present findings are only based on measurement and analysis of one dry skull and it is of course very important to repeat these measurements on a real patient when such are available.

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