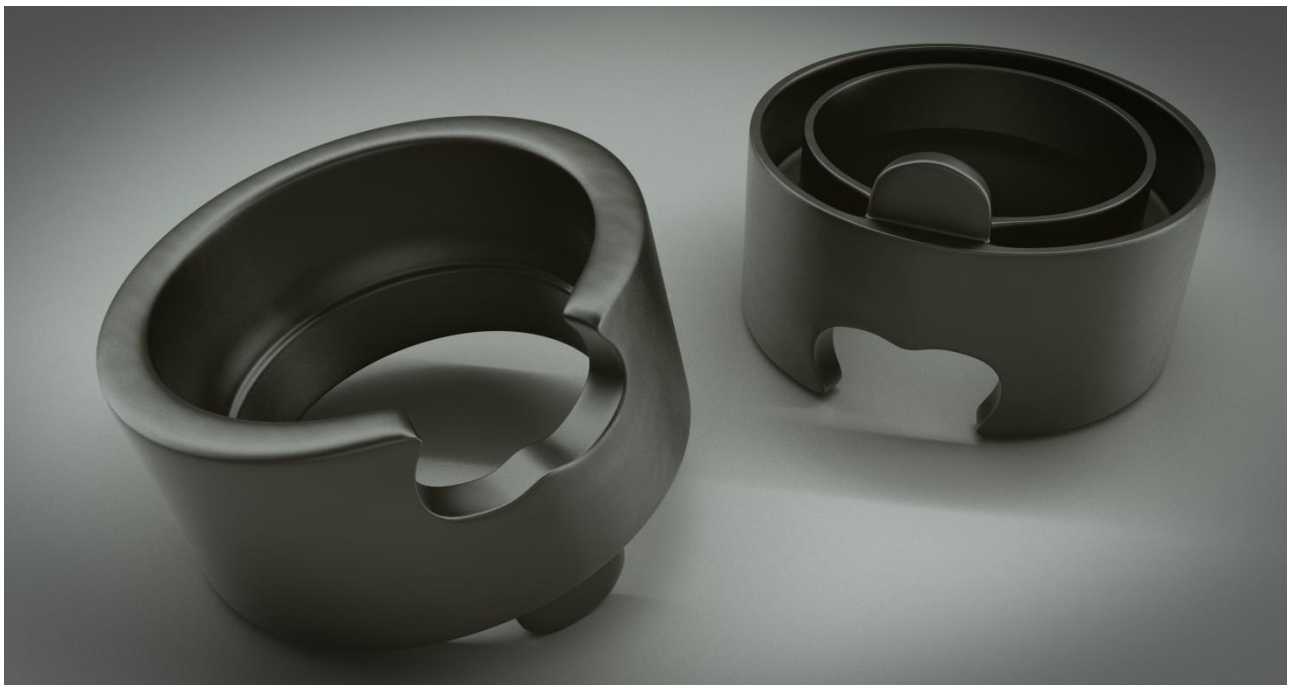
Optimizing design of dual-microphone/speaker probe for otoacoustic emission measurements

Internship



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Preface

This report describes the redesign process of the ear probe used for measuring otoacoustic emissions. The goal of this report is to reduce the noise floor by reducing the size of the dual-microphone probe and investigate if one or two mini-speakers can be added or attached to the probe. In order to tackle the problem the "Design of Biomedical products Reader", by G.J. Verkerke, will be used as a guideline. The report will start with discovering the real main problem and using the synthesis phases to get to the final product.

Acknowledgement:

I would like to give special thanks a few people for helping me during the project to:

A. Maat, for being my supervisor and helping me as much as he could, especially during reverse engineering and during assembling the final concept phases. Also for offering the opportunity to do this project.

Fam. Huisman, for making it possible to make a new PCB within a few days so that we could make this project doable in time.

P. van Dijk, for being helpful, supportive and keeping in touch during the entire project.

Contents

1 Introduction

1.1 What are otoacoustic emissions (OAEs)? [1,2,3,4,5]

Otoacoustic emissions are events where the ear produces sound instead of receiving them. David Kemp was the first describing this phenomenon in 1979. He discovered that the ear produces an echo (~5-10ms later) after hearing a click sound. This sound is produced in the inner ear by a healthy ear. Suggested is that the outer hair cells of the cochlea produce these emissions by influencing the basilar-membrane and set it into motion. There are two types of otoacoustic emissions: evoked and spontaneous, with subclasses for evoked otoacoustic emissions.

1.1.1 Evoked OAEs

Evoked otoacoustic emissions tests are divided into several subclasses, defined by its method. The different classes will not be discussed but the general idea of evoked emissions will be described. These types of emission tests are tested by presenting a click sound to the patient. The response is recorded via a microphone. After applying a filter, the output is a frequency spectrum of the emissions.

Evoked OAEs tests tell something about the healthiness of the inner ear and therefore also about the eardrum and middle ear. If there are emissions present, normal hearing is to be expected. If the emissions are present it does not mean that the person is not deaf. There is still a chance that the hearing nerve fibre is damaged which causes the deafness.

Evoked emissions tests are generally used by infants in order to check the hearing, but it is also used in research.

1.1.2 Spontaneous OAEs

Spontaneous emissions as it says are spontaneous, without a trigger. 'Spontaneous otoacoustic emissions are represented by weak narrow-band acoustic signals generated naturally within the cochlea. They can be measured in the ear canal with a sensible microphone. To reduce the noise floor in the measurement setup a dual microphone is used'[6] Many studies were performed on this topic, and reveals that about a third of the population has SOAEs. The SOAEs tests are similar to the evoked OAEs test, nut now there is no sound presented to the ear. The signal is normally very low compared to the noise. Therefore, multiple techniques are used in order to reduce the noise floor.

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[1] Wikipedia (May 2016). Otoacoustic emission (accessed at April 11 2016) https://en.wikipedia.org/wiki/Otoacoustic_emission

[2] Ototoning, Our ears emits a sound!! It's called Spontaneous Otoacoustic Emissions (accessed April 2016) http://www.ototoning.com/spontaneous-otoacoustic-emissions.html

[3] Probst, R., Lonsbury-Martin, BL., Martin GK. (1991 May), A review of otoacoustic emissions, J. Acoust Soc Am. 1991 May;89(5):2027-67.

[4] Dizziness And Balance, Timothy C. Hain, MD (March 2016), OAE Testing (Otoacoustic Emissions) (accessed April 2016) http://www.dizziness-and-balance.com/testing/hearing/OAE.htm

[5] Audiologieboek, Wit, Prijs, van Zanten (2007), 4.3.2(2). Otoakoestische emissies (accessed April 2016) http://www.audiologieboek.nl/htm/hfd4/4-3-2.htm

[6] Maat, A. (2016). Internship application form: Optimizing design of dual-microphone/speaker probe for otoacoustic emission measurements.

1.2 Optimising the recording

First of all, the tests are done in a place where the noise is reduced to its minimum by doing the test in a highly isolated room, silent room. This room is separate from the main building, leaving the room independent from movement and AC networks. No AC connections are used for any of the equipment, everything is powered by batteries. By minimizing movement and people in the room most controllable noise in minimized. Except for the laptop controlling the measurements, the noise of the fans can be detected in the final output and there is a peak at 8 kHz from an unknown source. A new fan-less with SSD laptop is ordered to reduce the noise in the room even further.

In order to get the best recording, a very sensitive microphone is used. SOAEs are recorded over a longer period of time to average in frequency domain in order to reduce the noise. By using a low noise and high sensitive microphone, one microphone is enough in order to record the signal. By using multiple microphones the noise is reduced by cancellation by a small amount, but the cross-correlation is used in order to reduce the noise floor. The cross correlation will search for similar sound waves and indicates them. Also known is that the smallest probe volume will enhance the small-amplitude sound waves. The ear probe has to fit almost perfectly in the ear with the right ear tip in order to catch the full signal.

The noises which are still present are low frequencies. These are produced by for example the blood flow or breathing. By using a high-pass filter with a cut-off frequency of about 300Hz one can get rid of these unwanted signals.

The SOAEs detection threshold is mainly controlled by the frequency resolution, which can be fixed by longer measurements and better equipment. SOAEs are narrow-bandwidth signal making it necessary to measure longer to get a clear signal.

1.3 Current Designs[7]

1.3.1 Dual ER-10B+ microphone probe

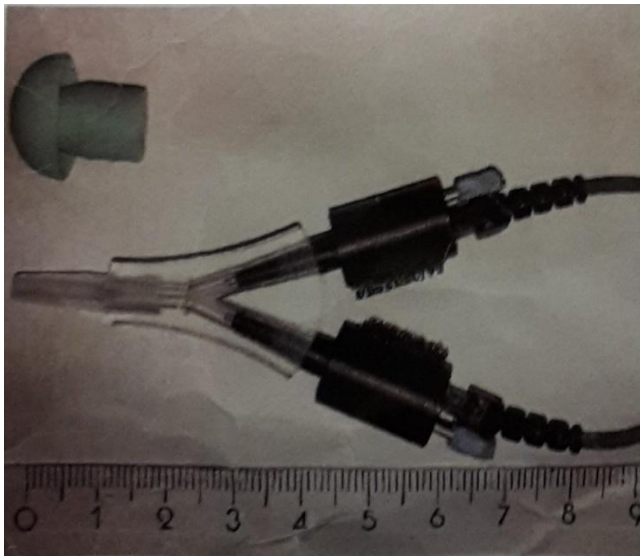


Figure 1: Dual ER-10B+ Microphone Probe [8] From the tip at the left to the micrphones in the black cylinders is aproximately 5cm.

There already exists a dual microphone probe, but this system is pretty little large, see figure 1. This product is made and tested in the UMCG[8] . This system is about 5 to 6 cm from tip to the point where the microphones are placed. It is that long because this system uses two single microphone probes (ER-10B+[9], each cost $1500). The two single microphone probes are connected to each other via a funnel-like tube system in order to make a single entrance for the sound from the ear to the microphones. Each single microphone probe has an entrance tubes for an external speaker. The speakers are connected via rubber tubes. This feature enables all kind of tests.
The problem researchers face is that the ear probe is too long. This can cause the probe to get loose and eventually pop out the ear. Another point is that the microphones should go closer to or even in the meatus in order to get more signals/higher amplitude out the ear itself and less sound of the surrounding. Reducing the length should help reduce the overall noise of the system. The last mentioned problem is that there are too many cables from ear to measurements setup, making it hard to keep the cables clear from one another. If the cables touch each other there will be a higher noise floor.

[7] Etymotic Research, Inc (2016). Low-Noise Microphones for research (accessed April 2016), http://www.etymotic.com/auditory-research/microphones.html
[8] A. Maat, E. De Kleine, P. Van Dijk, Spontaneous otoacoustic emission measurement with dual microphone technique (poster UMCG P3).
[9] Etymotic Research, Inc., ER-10B++ lo Noise[tm] DPOAE Probe System Data Sheet (Accessed April 2016) http://www.etymotic.com/auditory-research/microphones/ER-10B+.html

1.3.2 ER-10X[10]

Figure 2: Representation of the ER-10X taken from the datasheet.

The ER-10X is a new ear probe (figure 2), which is pretty expensive (about €7-10 thousand). The noise level is 1 kHz spot noise, typically below -17 dB SPL. This design has three speakers and one microphone. The ER-10X has a clever design by making it slim, but longer. Assuming that the microphone is put nearby the ear, the three spots left are speakers. Each component has its own tube towards the ear canal. The ER-10X provides an extra hole for the use of a probe microphone or boroscope. A tip with all the individual tubes is placed on the device in order to hold the ear tip.

Figure 3: Complete ER-10C system; Probe and amplifier. This model will be used for reverse engineering.

1.3.3 ER-10C[11]

The ER-10C is an older system (figure 3), having two speakers and a microphone. A complete kit now costs $2000. From the data sheet, one can see that the noise level looks the same as the ER-10X, but this system is cheaper. By peaking into the system two microphones may have been seen. Further investigation is needed to confirm this because the ER-10C is not fully disassembled yet. This system uses special ear tips with foam or plastic with a straw to connect it to the probe.

[10] Etymotic Research, Inc., ER-10X Datasheet (Accessed at April 2016) http://ER-10X.com/downloads/documents/
[11] Etymotic Research, Inc., ER-10C lo Noise[tm] DPOAE Probe System Data Sheet (Accessed April 2016) http://www.etymotic.com/auditory-research/microphones/er-10c.html

1.3.4 Reverse Engineering ER-10C

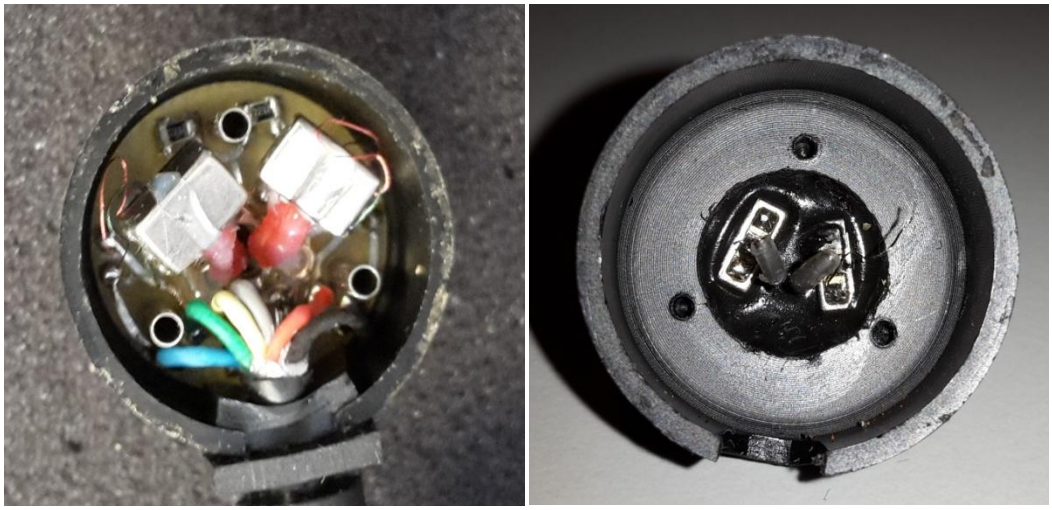


Figure 4a (left): This is the ER-10C probe after lid removal. One can clearly see the speakers on top of the PCB which has seven cables attached to it. Figure 4b (right): After removing the PCB, the microphones are discovered and two tubes where the speakers were attached to via red rubbery tubes.

The ER-10C is fully disassembled in order to know how the probe works. The lid is removed and the first thing found are the speakers on top of the PCB. The remarkable thing was that there were two resistors in parallel (top of the figure 4a) leading to under the PCB. This with the amount of cables (seven cables) led to the assumption there were two microphones under the PCB. After removing the PCB the two microphones were discovered (Figure 4b). Presumably, the microphones are electrets microphones[12] with an active MOSFET amplifier to enhance the signal and get rid of most noise as soon as possible or it is just an ordinary mass connection. More information (e.g. serial number) stays unknown because the microphones are cast into the housing. With the parallel connection of the microphones the manufacturer has reduced the noise floor by a small amount (±3dB). After reinvestigating the circuit board extra components are discovered. It is assumed to be parallel connected resistor and capacitor to the mass, making a resistor-capacitor high pass filter. It was found underneath the coloured cables, connected from the grey cable to the ground. After further research it appears to be a dual switching diode (M5C w) connected to the capacitor (~100-200nF) to make some sort of limiter, to avoid overloading the amplifier.

[12] Profesional Sound corporation, MilliMics (Accessed May 2016) http://www.professionalsound.com/specs/milli.htm

Figure 5: ER-10C PCB, The resistors, and connection points are visible together with the screw and cable holes.

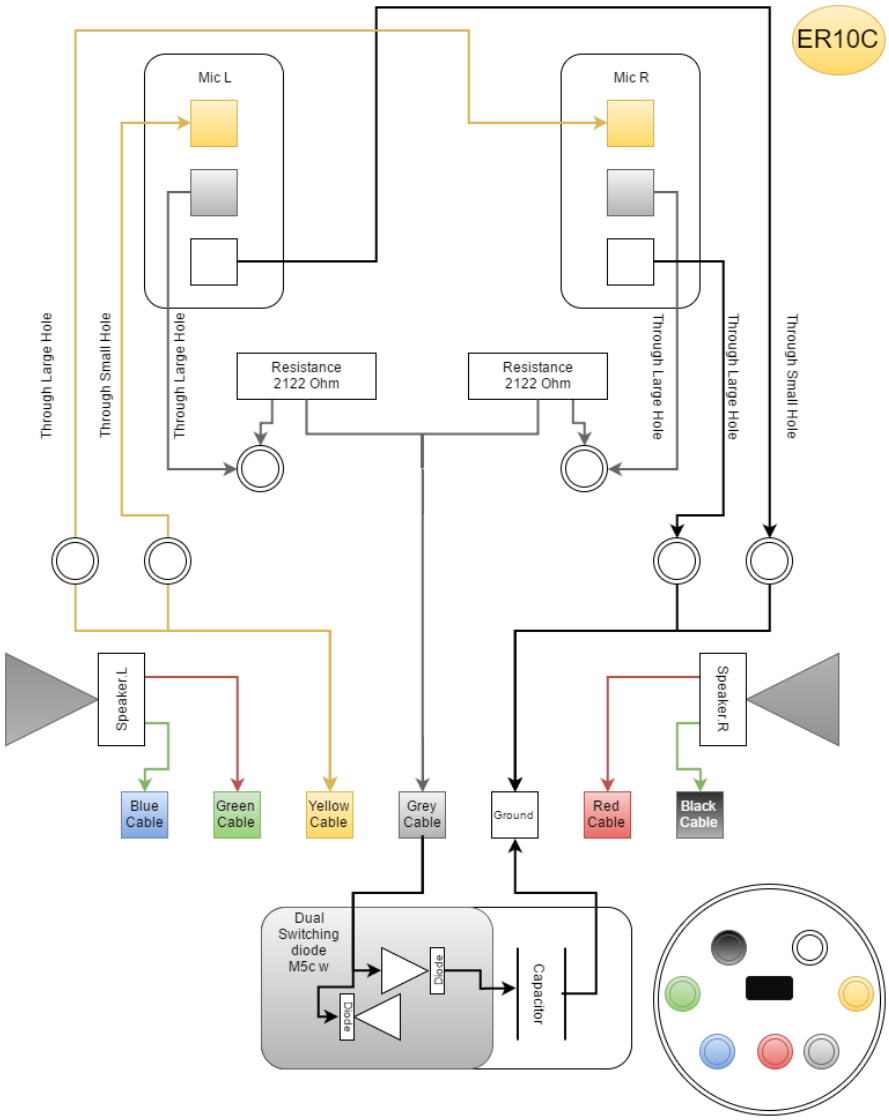


Figure 6: Schematic representation of the circuit board connections with all the components of the ER-10C.

Component	Type	Value	Component	Type	Value
Speaker	Length	6mm	PCB	diameter	19mm
	Width	5mm		Height	1,5mm
	Height	3mm	Resistors (0805)	Length	2mm
Microphone	Length	5mm		Width	1.25mm
	Width	2mm		Height	0,5mm
	Height	?mm		resistance	2212ohm
Tube	diameter	1mm	switching diode (sot23)	Length	2.9mm
Tip straw	Total diameter	3mm		Width	1.3mm
	(big) mic hole) diameter	3mm		Height	1.mm
	(small) speaker hole	1mm	Capasitor (1206)	Length	3,2mm
	Length	~18mm		Width	1,6mm
Casing (cillindrical into conical)	diameter	23mm		Height	1,6mm
	Height	25mm		capacitance	100-200nF

Table 1: List of the ER-10C components with their dimensions and values in found. [13],[14],[15]

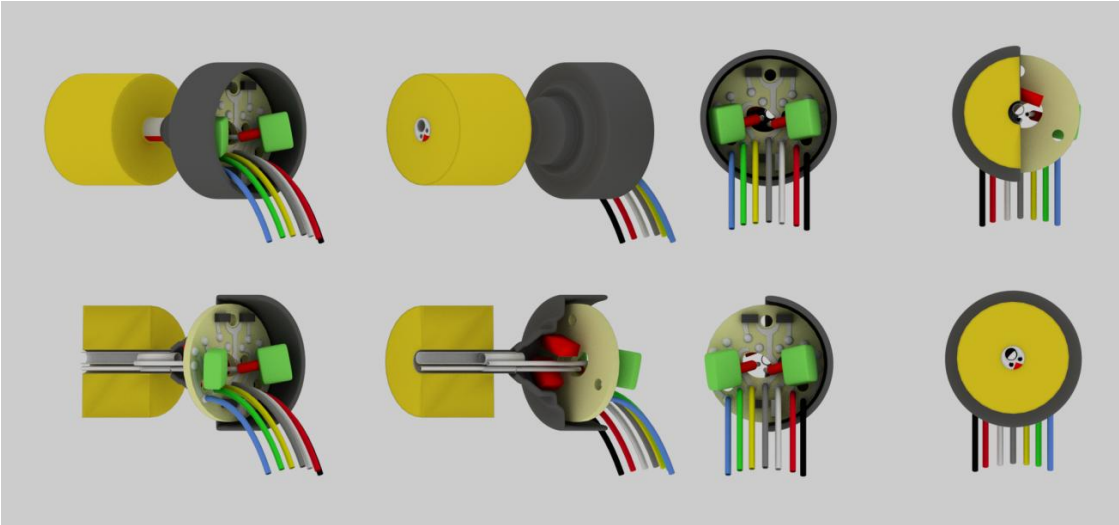


Figure 2: Schematic 3d model of the ER-10C.

With this information gathered a schematic 3d model, using blender[16], is made to prevent replicated labour.

[13] RS (webshop), Surface Mount Resistor 0805 Case 22.1kΩ (Accessed May 2016) http://no.rs-online.com/web/p/surface-mount-fixed-resistors/2153910P/
[14] On Semiconductor, Dual Switching diode (Datasheet) (Accessed May 2016) http://www.onsemi.com/pub_link/Collateral/MMBD7000LT1-D.PDF
[15] Farnell Element 14 (webshop), SMD Multilayer Ceramic Capacitor (Accessed May 2016) http://uk.farnell.com/kemet/c1206c105k3ractu/cap-mlcc-x7r-1uf-25v-1206/dp/9227865
[16] Blender 2.77a (April 2016), opensource 3d computer graphic software, The Netherlands, https://www.blender.org/

1.4 Market Research

Otoacoustic emission tests are performed daily on infants to give an indication of their hearing capabilities. These tests can also assist diagnosing higher level hearing loss, auditory neuropathy. It is mostly used because it is non-invasive and is simple, cheap test.

In research, the focus is more on SOAEs, because of the little knowledge about it and the fact that not all people have it. Having a very low noise floor microphone will definitely help with any of those tests to filter out more SOAEs or with any OAE and give a better signal to noise ratio. If this product passes all the tests it is very likely more people wants this system.

2 Analysis Phase

In this phase, the actual problem and the essential features will be discovered. This will be done by looking at the stakeholders and their perspective on the problem. Using this information a concrete problem definition is formulated. With the help of a cause and effect diagram together with a goals scheme, further clarifications can be given about the main problem which can be tackled to reach the goal. With the stakeholders in mind, a requirement and wish list is made to get the basic functionality of the final product. The analysis phase is a reference for synthesis phases, later on.

2.1 Problem definition

The Dual ER-10B+ microphone probe is too large. This is due to the fact that two single microphone probes are connected via a separate tube system. This tube system raises the tube volume. This extra empty space causes a rise in the noise floor which makes it hard to read or distinguish the signals from the noise especially the weak signals. The real problem is the noise being too high. But using a dual microphone and cross correlation, as already used, the noise can be reduced. The problem left to solve is to reduce the tube volumes to enhance the signal to noise ratio even further.

By removing this connection and making a real dual-microphone probe the signal travel length can be reduced and therefore more signals should be preserved and the noise floor lower. In addition, a smaller probe will hang less, making it less likely to make noise due to movement of the probe.

2.2 Stakeholders

Stakeholders are all those people and groups of who might be involved in this project, direct and indirect. Table 2 lists the main stakeholders with their relation to and possible influence on the project.

Stakeholders	Characteristics	Expectation	Potentials & Deficiencies	Implications for the project
Research group	A better product will lead to better data, which can help with a better understanding of their problems.	A flawless product which fit their need.	The need of a better product to get a better understanding.	Limited freedom, need a specific product. Uninterested if it is not better than the current probe
Audiologist	OAEs test more accurate, better diagnosis	The Proper working device, similar to existent probe.	Improve of workflow and diagnosis.	Uninterested unless tests prove that the product it better.
Technicians/Engineers	Better setup of experiment	Easy to setup/switch between products	Can help improve or can help you down	Knowing the subject and are critical, can help or can help you down
Patients	Has hearing problem or infant hearing test.	Device works properly	Should work on different persons and their characteristics	Should work on different persons and their characteristics
Purchase & Sales	Can sell a final product if better than existent probes.	Tested/proven to be a good product, low cost	Knows potential customer	No marketing potential unless proven that it is better
Industry	Interested in the product if better than current device. Low-cost high profit.	Make profit out of design.	Produce product	Knowledge about market potentials
Health insurance	Low cost for better data, only for evoked OAEs	Enhanced quality for same/less expensive	stimulate the market, by funding hospitals for buying this product	Can cause failure for final product if is not working as expected
funding groups	Better spending of money, if data is better	Fast design, best product will be used	Sceptic about their money spent	None for this report

Table 2: List of stakeholders: Stakeholders are those who are involved in the project and what their relation is with/influence on the project.

2.3 Cause & Effect

Figure 7 describes the origin of noises which affect the measurements.

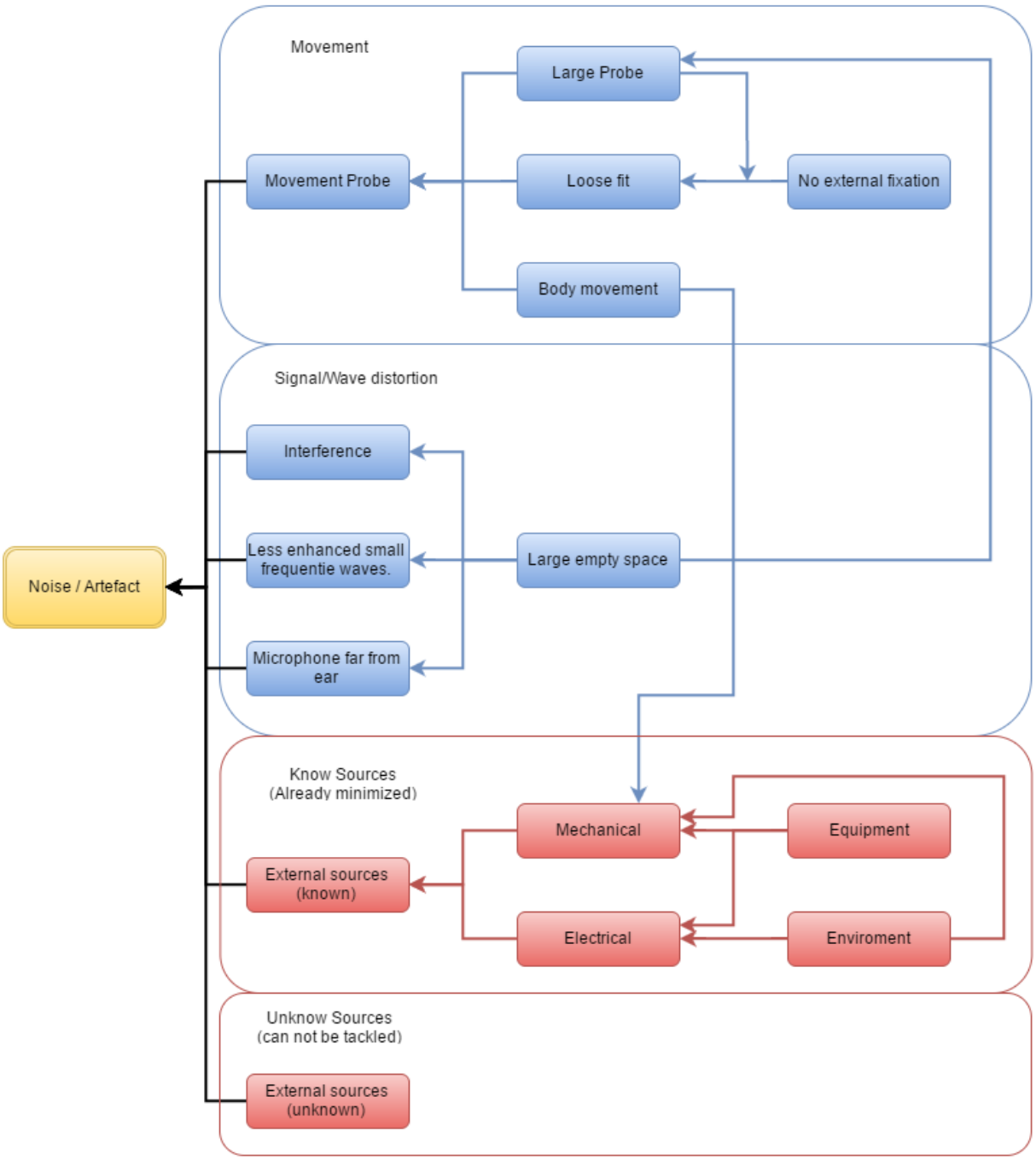


Figure 7: Cause-effect diagram of the problem. Many things can cause additional noise. In this list, some causes are categorized.

There will always be some noise left because some causes of noise cannot be eliminated. Whether it is because the source is unknown or the noise is coming from the test setup / environment. The environmental and test setup noise is minimized.

2.4 Goals

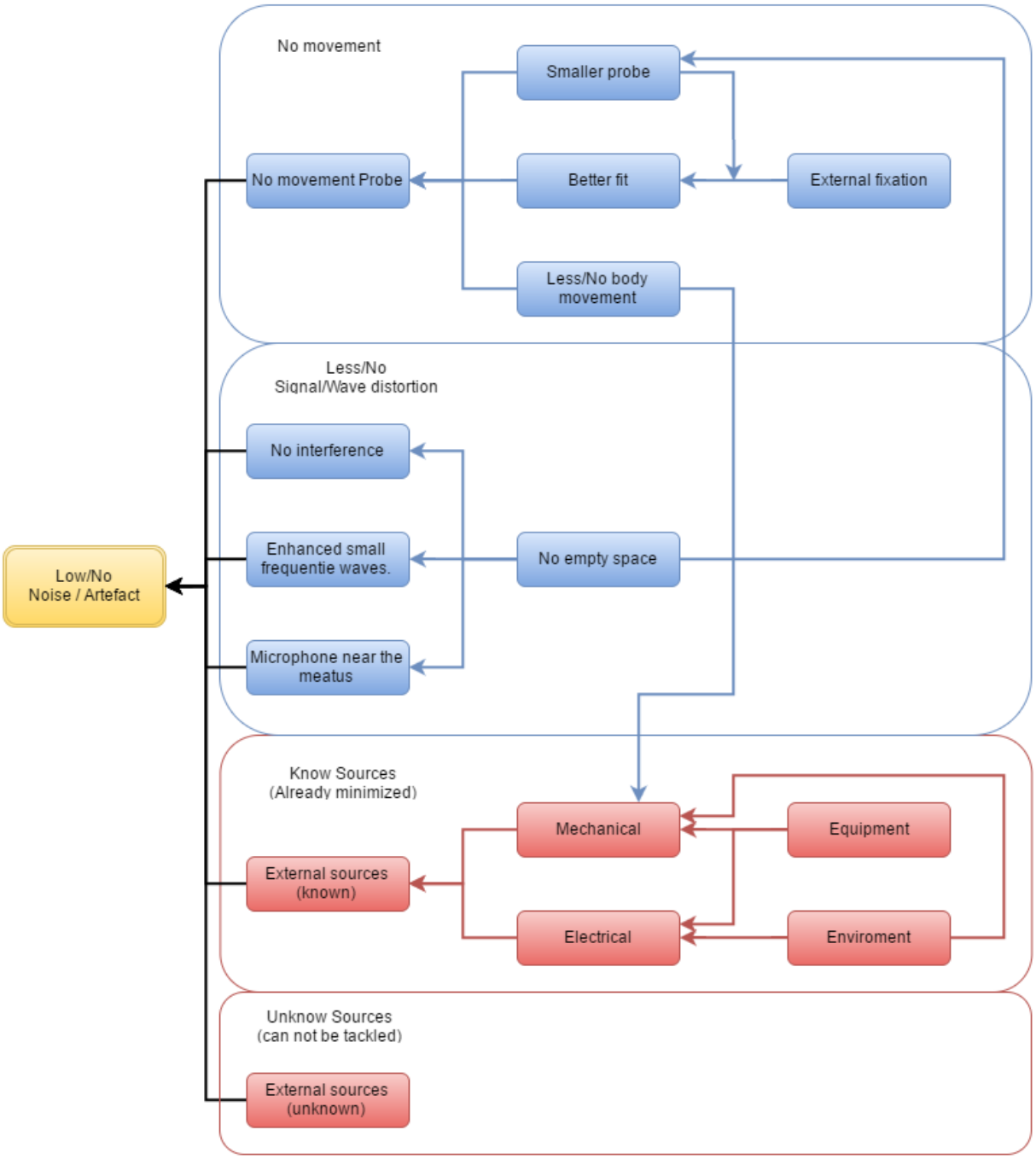


Figure 8: Goal diagram. This is the reverse of the cause-effect diagram. The red part is the already from the sources which are already minimized or cannot be minimized.

Looking at the cause and effect diagram (figure 7), there are plenty of sources which can cause noise and therefore raise the noise floor. Looking at the goal scheme (figure 8) one can see that the problem can be tackled on several levels, but many of them are already used to reduce the noise to its current minimum. The silent room already reduces the external noise source to its minimum. With every newly discovered source action will be taken to cancel out that source. Unknown sources cannot be tackled because the origin is unknown. The things which can help reduce the noise floor is making the ear probe smaller, therefore, less empty space, create a better fit and make movement less likely. If the probe is smaller the momentum (due to its own weight) will be smaller by making the arm smaller, making it less likely the probe will fall out of the ear. It looks like that the size of the probe the part to solve which will affect a number of other noise sources as well. Making the fit better can be considered in the design phases as an addition, but may add noise to the system.

2.5 Design Assignment

To help the OAE research a more suitable probe is needed. Especially for cases where the emissions are very weak, the noise floor is relatively too high. The ER-10C is used as a reference and can be used as a component source. Design an ear probe which volume of the microphone tube is the smallest and additionally try to add speakers in order to make it suitable for all OAE research instead of only SOAE tests. It is preferred to make the probe in such a way that the microphones are as close to the ear as possible and existing ear tips can be used.

2.6 List of requirements & wishes

Requirements	Weight
At least two low noise microphones	1
one speaker	0,7
Smallest tube volume	0,9
(smaller than current design)	
Small overall volume	0,7
(smaller than current design)	
Microphones near meatus	0,8
Least (body) contact	0,6
Low cost	0,7
Recycle ER-10C components	0,8
Use existing ear tips	1
Lower noise floor than current one	1
Cost no more than ER-10C	0,6
Wish	**Weight**
Smallest probe	0,8
One speaker	1
Multiple speaker	0,7
less probe movement	0,4
Easy disassemble	0,5

Table 3: List of requirement & wishes. All musts and nice to haves a listed in this table and given a weight factor to represent their need.

Ideally, the system should contain two microphones and two speakers.
With the absolute minimum requirements, the system should contain two microphones and the probe should be as small as possible. Any addition of a speaker is technically optional, a wish, but the addition of one microphone is highly in demand, and this will make other (OAE) tests possible. Therefore, one speaker with two microphones will be the requirements for the system. The sound waves of the speakers should have their own tube towards the ear. The microphone may have a common tube toward the ear, with the minimum volume. The probe should be compatible with the existent ear tips to make testing the probe easier. This means that the tip of the probe has a fixed length and diameter, depending on the used tips.
Each requirement and wish are given a weight on a scale from zero to one. This weight is the importance of the requirement/wish, where one is the most important. In the least ideal case no speakers are used, making the probe only usable for SOAE tests, but probably the smallest.

2.7 Function Analysis

In the current designs, there are tubes starting from the tip leading sound waves to the microphone, but also from the speakers to the ear. This makes the tubes transporters of a signal. The microphone converts the incoming sound waves into an electrical signal which is transported through a cable to the computer via an amplifier. The computer can generate a signal which can be played by the speakers, making an inverse route possible. The microphone will translate the signal to a sound wave.

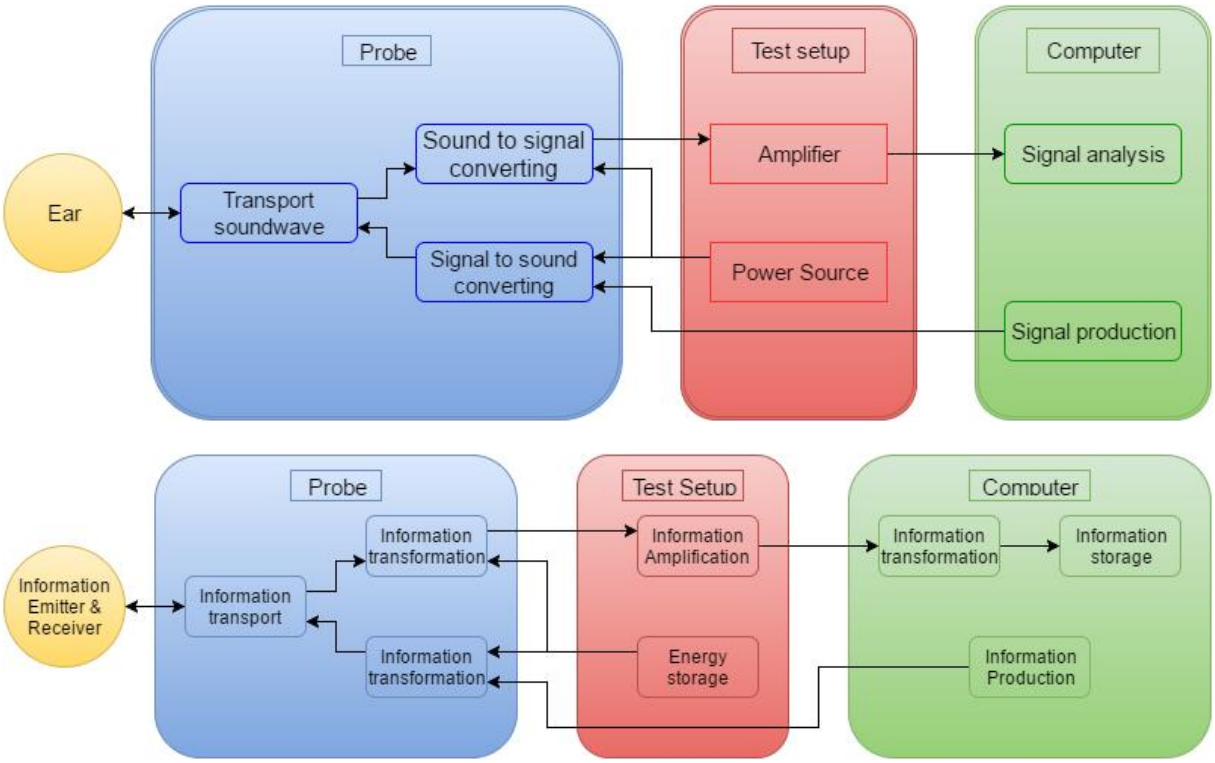


Figure 9: Function analysis of the testing setup. The top represents it component wise and the lower one in terms of information and energy. The setup is divided into components having their own functions. The power source are the batteries on the amplifiers.

3 Synthesis I

This phase is all about obtaining as many solutions as possible. After gathering plenty of general ideas, pre-concepts will be drawn and described. These concepts will be the end results of this section and are obtained after brainstorming and using construction elements. By comparing the pre-concepts and scoring them on the list of requirements and wishes, the best three will be taken to the next phase.

3.1 Brainstorm

The brainstorm began with thinking about all possible arrangements of microphones and speakers to get the smallest volume. Different kinds of geometry are described in order to do the same thing. At last, the recycling of the ER-10C came into the picture. The microphones could be separated and connected in a different way. Also adding more microphones is suggested. But it became clear that this project is very limited by the lack of different ways to accomplish the wanted outcome.

But finding the two microphones in the ER-10C is a huge advantage. This makes it possible to test the dual microphone very quickly. By connecting the microphone each to an individual cable to feed it to separate amplifiers the contrast between the Dual ER-10B+ microphone probe and the altered ER-10C can be measured. Because this system is very small already, while having two microphones and two speakers, two more microphones may be considered. The system will then contain microphone whose two sets of two parallel connected microphones in order to reduce the noise even further by the same technique as already used in the ER-10C. These already are nice ideas to consider further in synthesis 1.

3.2 Construction Elements

The brainstorm session provided a list of components needed to build the system. These components are the same as seen in the ER-10C and the minimum amount of components to make the probe.

Construction Elements
Microphones
Speakers
Tubes
(Electric) Cables
PCB
Amplifier
Resistors (22kOhm)
Capacitor 100nF
Double Diode

Table 4: All components found on the PCB and have to be used to make the duo microphone probe.

3.3 Sketches

Concept 1 (2mic/1sp cylinder):

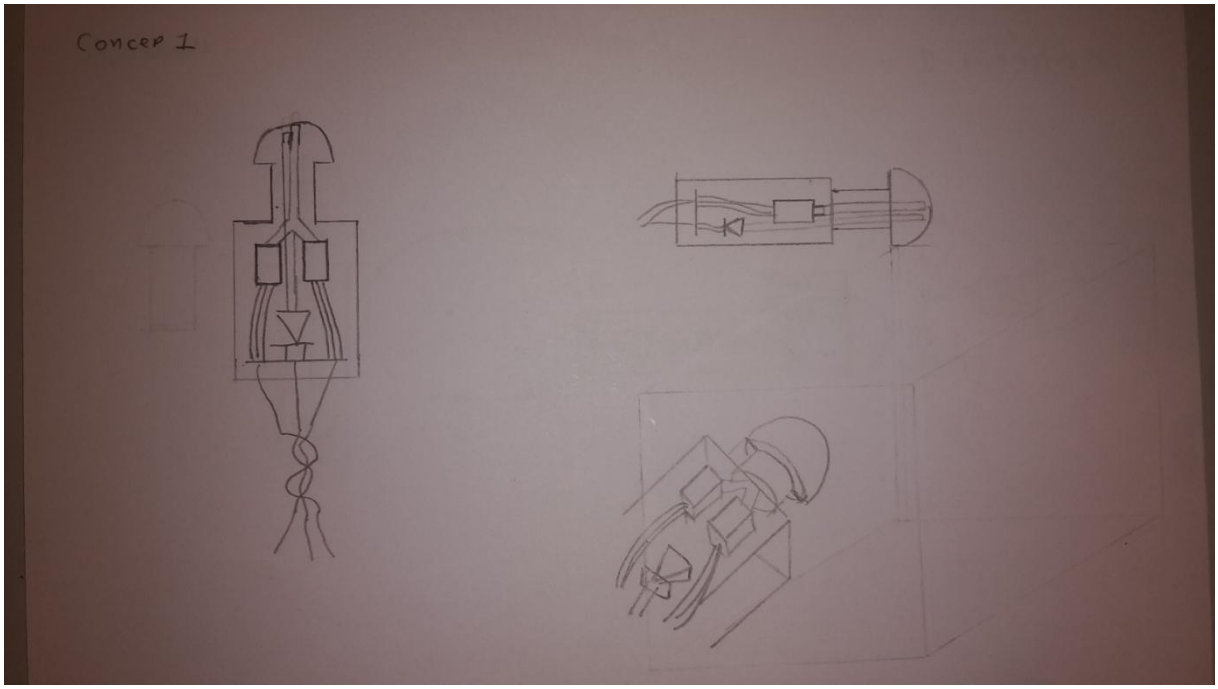


Figure 10: Concept 1, Contains only two microphones and one speaker in a small housing.

By making a small longer tube-like probe the two microphones can be out next to each other via one tube towards the ear. The microphones will receive the same signal. A speaker can be placed via a long tube near the end of the probe. The PCB connecting all the circuit together can be placed on a side or at the back. It is also possible to provide each microphone with its own tube.

Pros & Cons:

This concept will probably make a long small probe but it is quite hard to assemble it. By building the probe in layers it will be easier. This probe should be pretty small compared to the current system.

Concept 2 (ellipse):

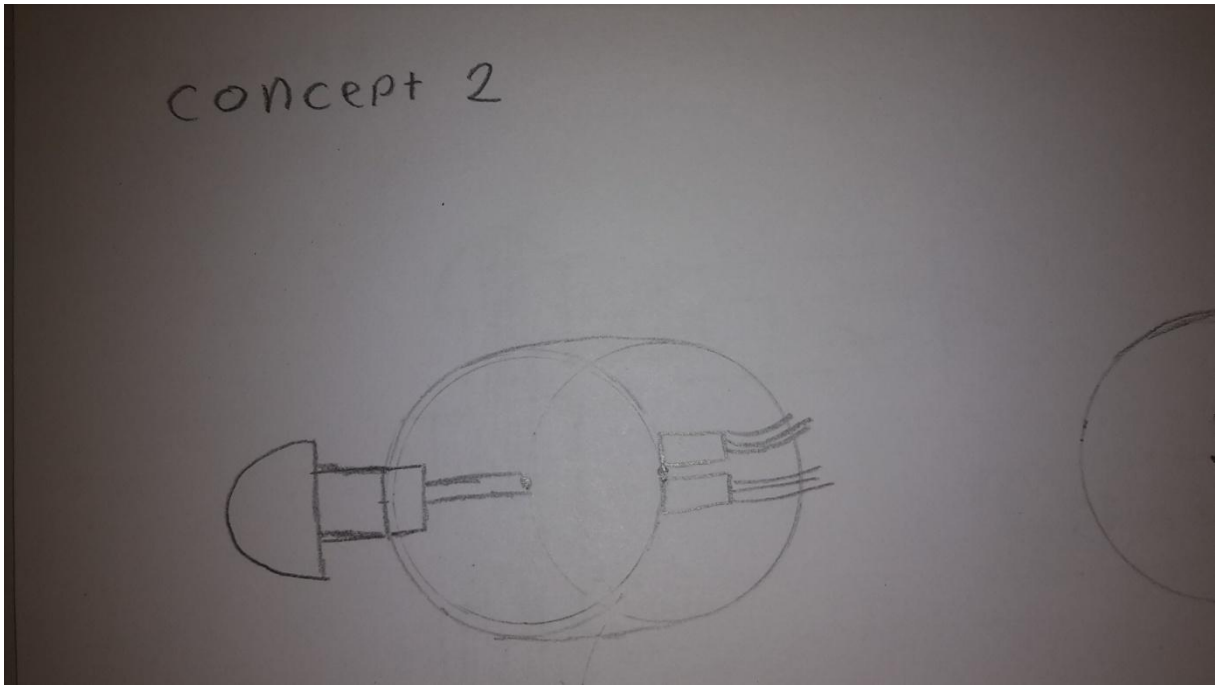


Figure 11: Concept 2 is an elliptical housing. The elliptical shape should focus the sound into the focal point where the microphones are placed.

This concept uses the property of ellipses. By putting sound in one focal point the ellipse will collect the sound in the other focal point. By letting the tube start near the ear and end on a focal point and putting the microphones in the other focal point. A speaker can be added via a tube around the ellipse system.

Pros & Cons:
All the sound will be collected, but the ellipse will consume a lot of space, making the device huge compared to the normal tube system. Another problem is that putting two microphones in on a focal in not doable. In addition, the tube volume will be immense compared the current design, creating more noise.

Concept 3 (Pyramidal/conical):

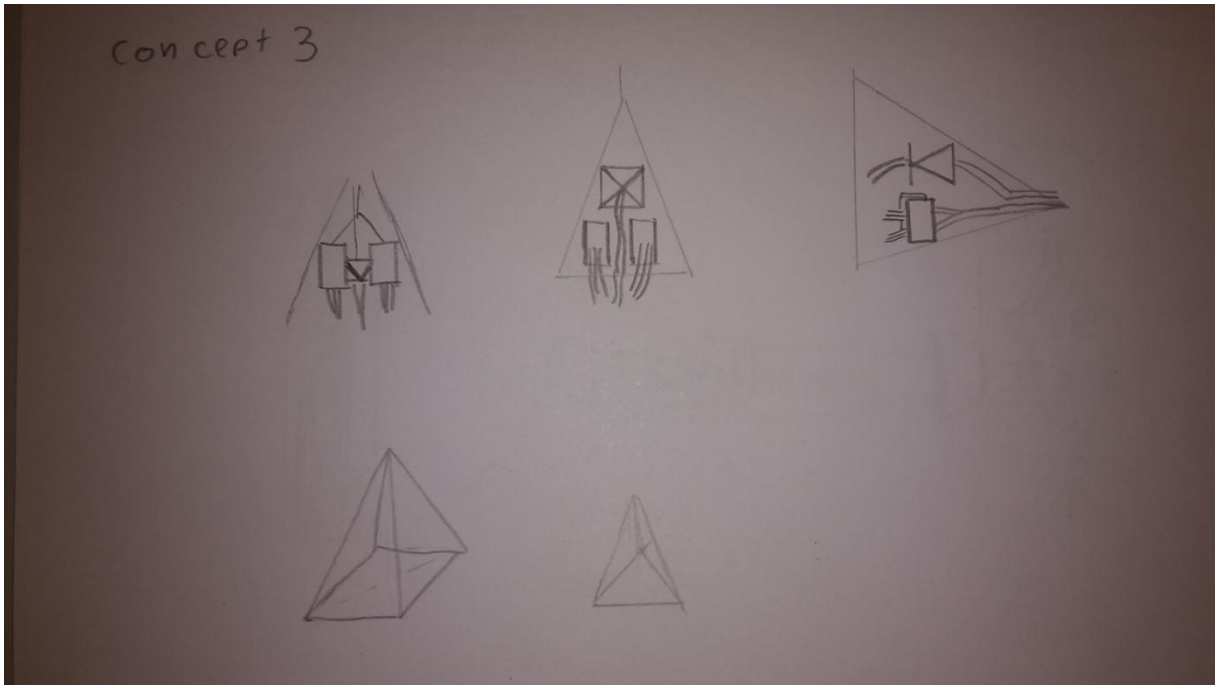


Figure 12: Concept 3 is a pyramidal or conical structure to get the microphones as close as possible near the meatus. The components are stacked tightly in order to reduce empty space.

By making a pyramidal or conical structure one can put two microphones on the base and a speaker on top. This will reduce the overall size of the probe while maintaining space for all the components.

Pros & Cons:

The walls of the probe will be at an angle, making it more difficult to attach or fit the components. But once designed it will be small in volume in overall shape and the tube volume of the microphone will also be quite small because they can be put as much as possible in the narrow tip.

Concept 4 (2mic/1sp wide):

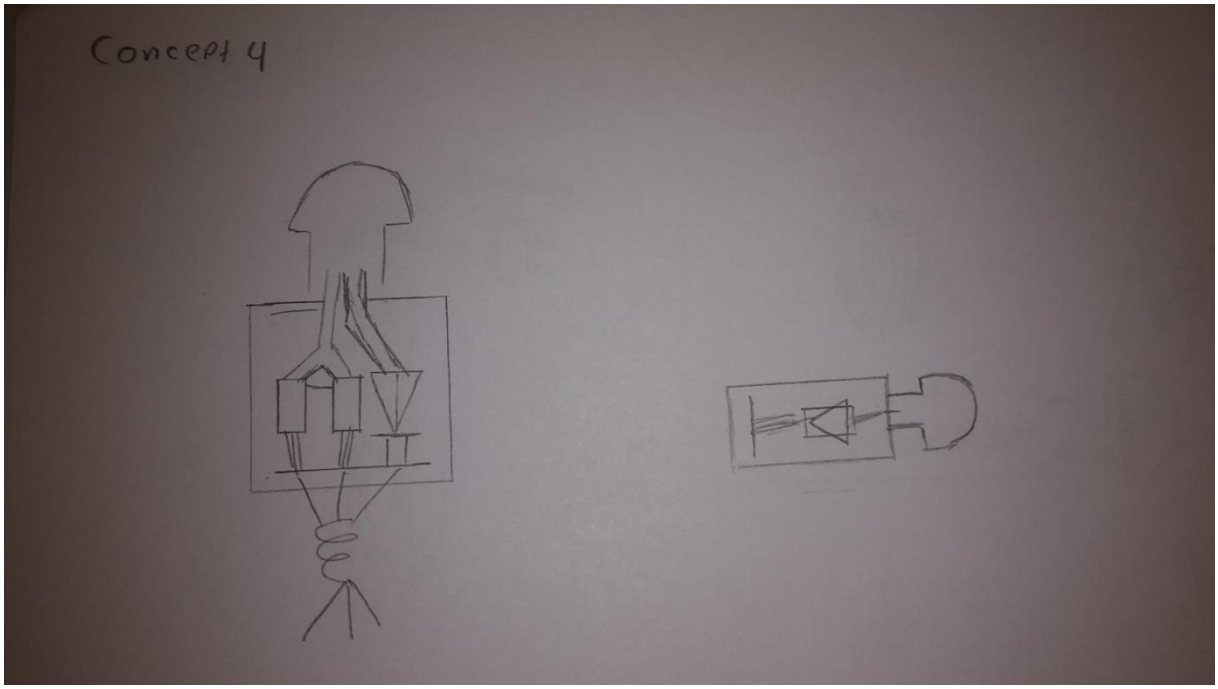


Figure 13: Concept 4, this concept is another arrangement of the components and therefore the shape of the housing. This one is a wide probe. The reduced length may help not popping out the ear.

This concept is like concept 1, but instead of putting the speaker further away, one can put is next to the microphones, making the probe wider but shorter.

Pros & Cons:

By placing the components next to each other, the probe will be shorter. Making the probe shorter will not hang that much, making it less likely that the probe will start sliding and create noise. This concept

Concept 5 (2mic/1sp long):

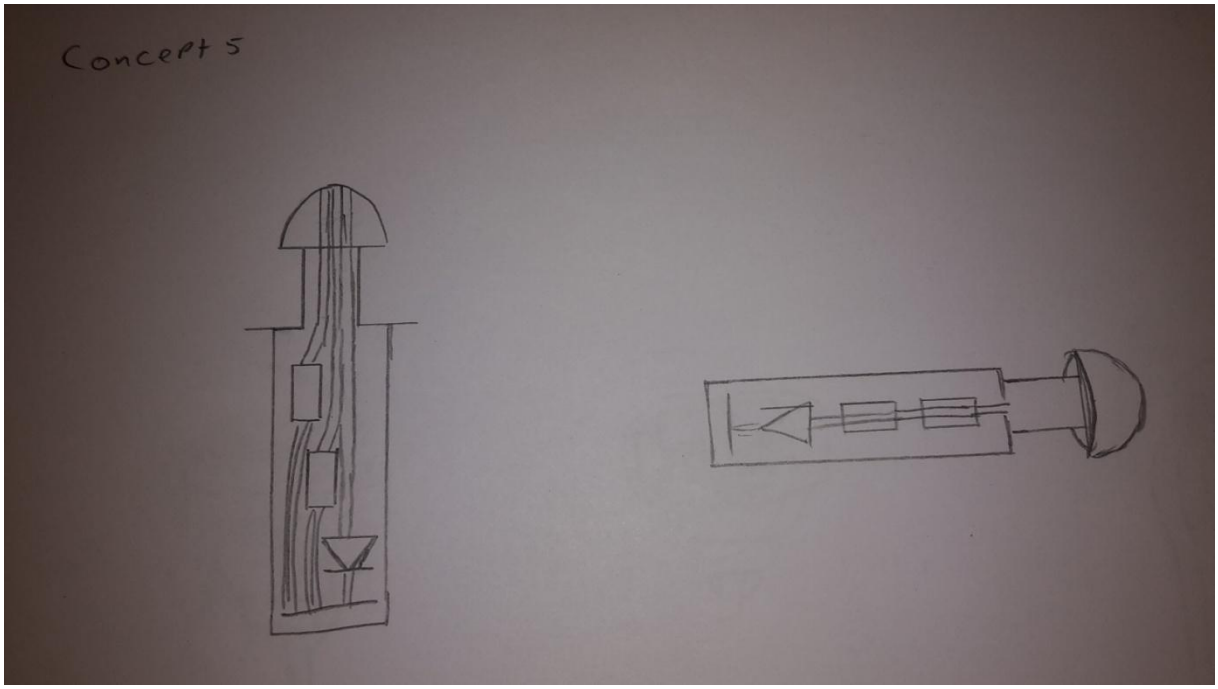


Figure 14: Concept 5 is a long probe to avoid hindrance of the ear. A small long probe may be able to enter the ear a little further to reduce the length from the eardrum to the microphones.

Instead of trying to put the microphones next to each other, one can arrange them in a row. This will make the probe thinner but longer.

Pros & Cons:

This smaller construction is more probable to fit in the ear, but the tube of one microphone will be longer than the other, making the sound in each slightly different, due to noise and phase by arrival. Also, one cable will be longer than the other, which can have an effect on the noise floor or even put the microphones out of phase.

Concept 6 (Recycled ER-10C):

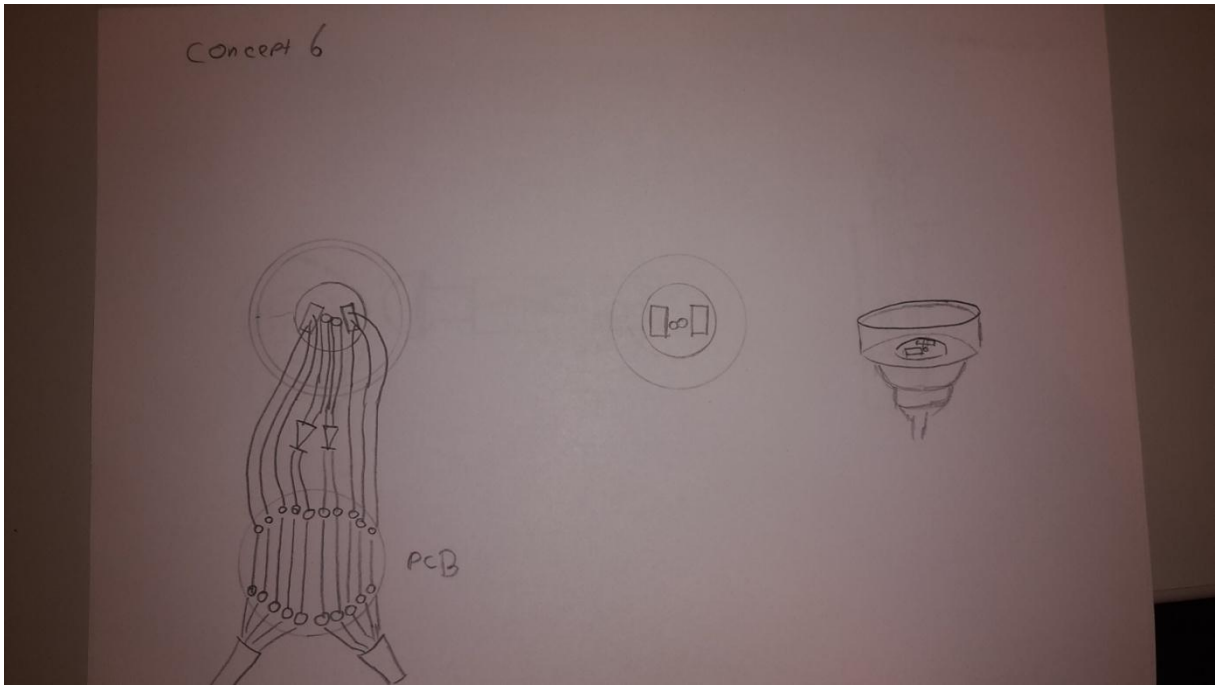


Figure 15: Concept 6 is completely recycling the ER-10C. Only a new PCB is required to achieve the goal.

Partially recycling the older ER-10C. This system is already smaller than the current one which is used. It also contains two microphones and two speakers. By connecting them in a different way the ultimate goal can be accomplished. The microphones should each be connected to a separate amplifier. An extra cable and another PCB are needed to achieve this.

Pros & Cons:

The current system works and it is already smaller, so why changing much of its design. But by recycling this system, the freedom of design is limited by the existing case.

Concept 7 (recycled ER-10C +2mics):

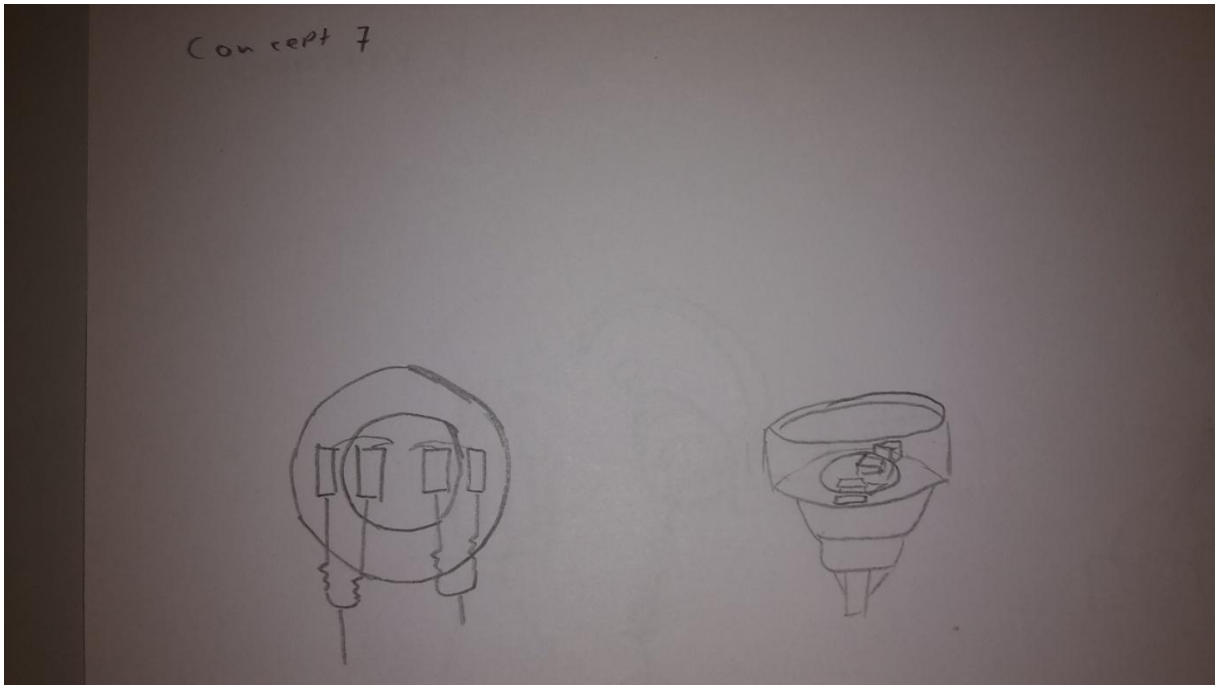


Figure 16: Concept 7, the ER-10C already had two microphones and probably for a reason. In order to make a very good probe, four microphones can be used to create two ER-10C's in one system.

The ER-10C has used two microphones to get a low noise floor. For a dual microphone probe, this system is also usable. Therefore concept 7 is about using four microphones, two sets of parallel microphones. One or two speakers can be added to the system as they already are in the ER-10C. An extended PCB and extra cable are needed in order to implement this concept.

Pros & Cons:

The space needed to fit all the components is larger than any previous concepts, but not necessarily bigger than the ER-10C because there is some space left. Extra tubes to the microphone have to be added. One or two speakers are used to make it applicable for all kind of OAE tests, but these already are in the ER-10C.

Concept 8 (Earplug boom):

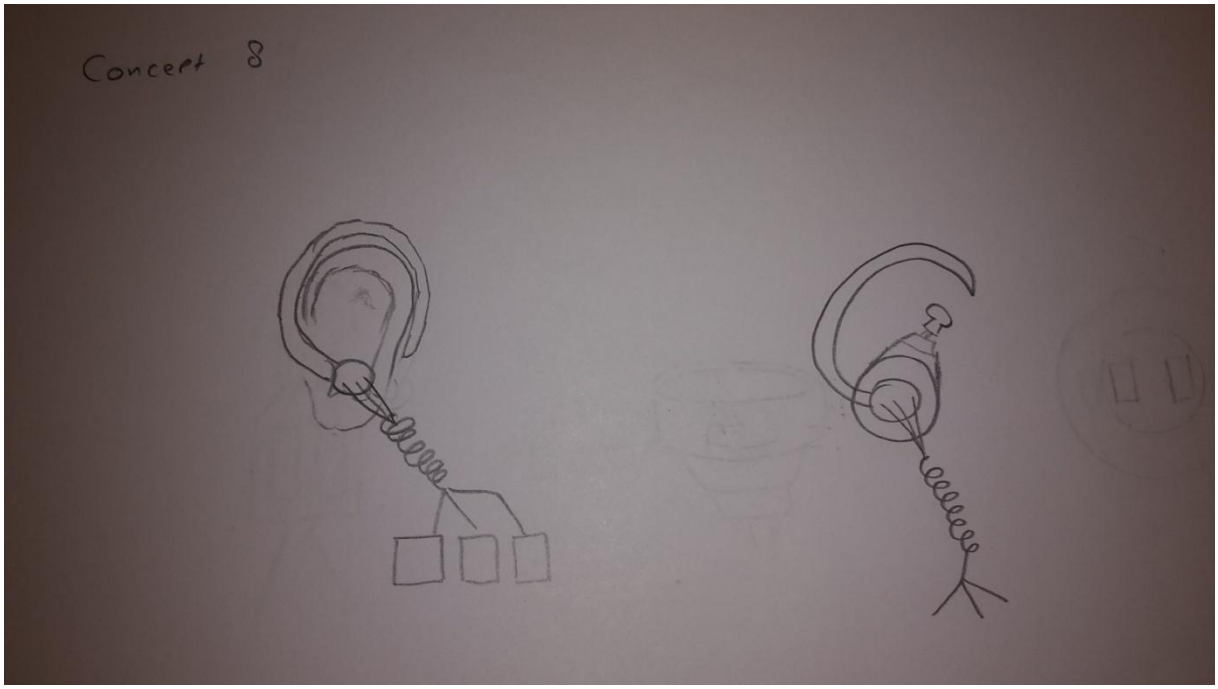


Figure 17: Concept 8 is a boom and not a new probe, but may be a good addition to the probe to reduce movement of the probe.

Adding a boom as already used in Smartphone ear microphones, an ear microphone boom can help with holding the probe in place. The boom may prevent movement and therefore limit the noise, but it can cause additional noise from the skin contact. Also reducing the number of cables and twisting the cables can help reduce the noise. In the current system, there might be 4 separate cables coming out for two microphones and two speakers. These cables may not touch each other, this will add noise to the system.

Pros & Cons:

This will prevent the probe hangs. This will contribute to the fit and reduce movements, but due to the additional contact point, it may introduce a new noise source. This is not a solution for using multiple microphones, but it tries to reduce the noise in another way.

Concept 9 (Minimum requirements):

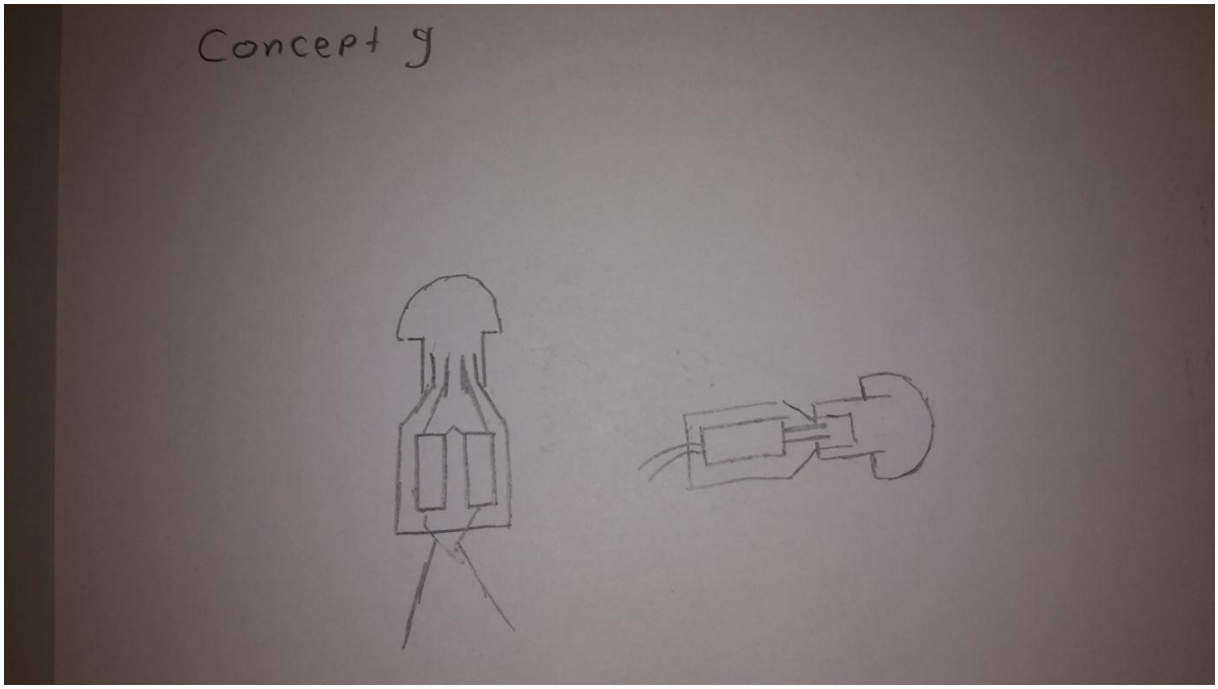


Figure 18: Concept 9 is the smallest probe one can think of, but is only usable for SOAEs, because there are no speakers to give stimuli for other tests.

Using the minimal requirements, the least ideal case: no speakers and only two microphones. This is doable with two microphones, one or two tubes, and three cables per microphone. This will be the smallest probe possible.

Pros & Cons:

Only SOAEs are measurable without speakers. A system without speakers is a waste of resources because it cannot be used in any other kind of OAE tests, making the probe relatively expensive. This concept is exceptionally simple making it suitable for testing. With this design, the difference in signal to noise ratio by volume change can be seen if one compares this system with the current one installed.

Concept 10 (2mics probe external speaker):

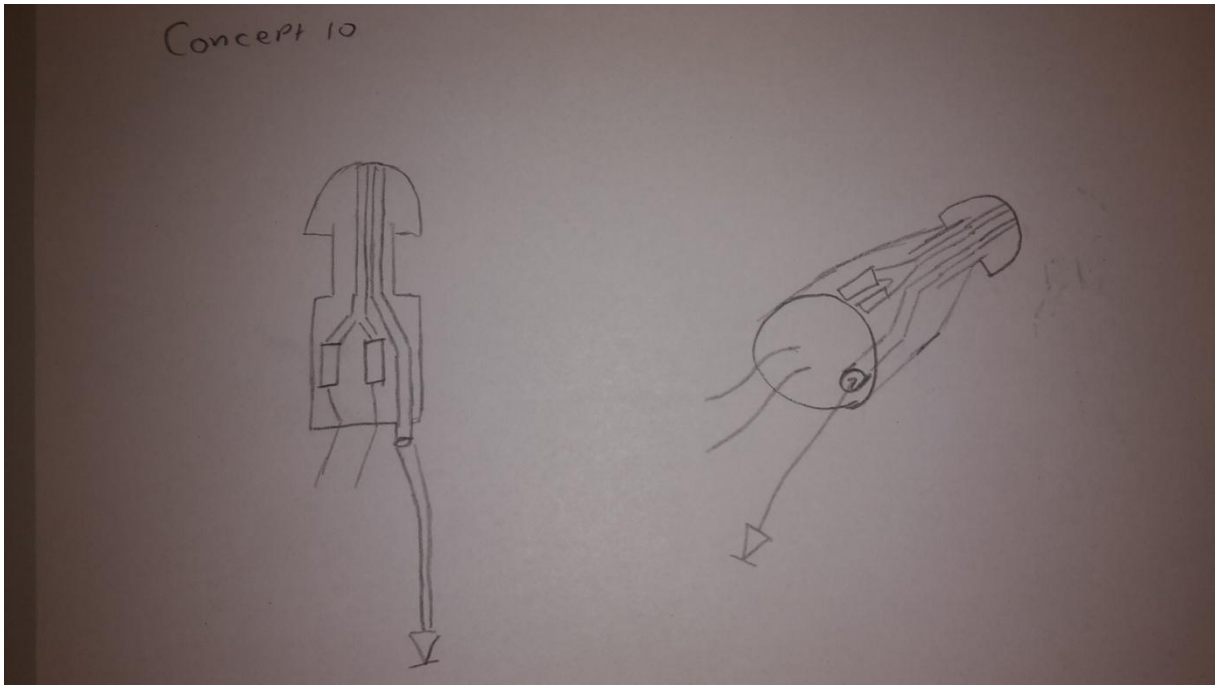


Figure 19: Concept 10 adds functionality to concept 9 by using the external speaker system from the current duo microphone probe.

Using the minimal requirements within the probe (two microphones), but leave a tube or two open for adding a speaker to it. This system is used in the probe currently in used. The tubes are closed by a cap when it is not used.

Pros & Cons:

Probe can be pretty small, but the there will be a very long cable for the speaker to the probe. It makes separating and keeping the cables clear from each other more difficult.

3.4 Pre-Concept Selection

Each concept will be tested against the list of requirements and wishes. On each aspect, a concept can score number between 0 and 5, where 0 is the worst and 5 the best score.

Requirements	2mic/1sp cillinder	ellipse	Pirimidal/conical	2mic/1sp wide	2mic/1sp long	recycled ER10C	recycled ER10C +2mics	Ear plug boom	Minimum requirements	2mic probe external speakers	Weight Factor
At least 2 microphones	5	4	5	5	2	5	5	0	5	5	1.0
Small tube volume	4	2	4	3	2	4	4	0	5	4	0.9
small overall volume	4	1	4	3	4	3	3	0	5	5	0.7
Microphones near meatus	4	1	4	3	3	4	4	0	5	5	0.8
least (body) contact	4	3	4	3	4	3	3	0	5	5	0.6
Low cost adjustments	4	3	4	4	4	5	3	5	4	4	0.7
Recycle ER10C components	4	3	4	4	4	5	5	0	4	4	0.8
Use existing ear tips	3	4	4	4	4	5	5	0	4	4	1.0
Expect Lower noise floor than current one	4	2	4	4	3	4	5	3	4	4	2.0
Cost no more than ER10C	2	4	2	4	4	5	2	5	4	5	0.6
Req. Scores	38	27	39	37	34	43	39	13	45	45	
Req. Weighed Scored	35.2	24	36.2	34.4	29.8	39.2	38	12.5	40.4	40.1	
Wishes	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10	Weight Factor
Smallest probe	4	1	4	3	3	2	3	0	5	4	0.8
at least One speaker	5	3	5	5	5	5	4	0	0	4	1.0
Multiple speakers	3	2	2	4	3	5	4	0	0	4	0.7
Less probe movement	4	2	4	3	3	3	3	5	5	3	0.4
Easy disassemble	4	4	3	4	3	3	3	5	5	4	0.5
Wish Scores	20	12	18	19	17	18	17	10	15	19	
Wish Weighed Scored	13.9	8	12.7	13.4	12.2	12.8	11.9	4.5	8.5	13.2	
Total Scores	58	39	57	56	51	61	56	23	60	64	
Total Weighed Scored	49.1	32	48.9	47.8	42	52	49.9	17	48.9	53.3	

Table 5: In this table each pre-concept will be tested against the list of requirements and wishes. This scoring table ranks the solutions

Table 4 shows that the top three concepts: 2microphone external speakers (Concept 10), Recycled ER-10C (Concept 6) and Recycled ER-10C + 2mics (Concept 7). Concept 10 is the best scoring concept and concept 7 the lowest of the top 3. These concepts are better because they are cheaper, are easy to make and have assumedly a low noise floor. In order to make it easier to refer to each concept, the top three will be renamed.

Concept 10 / External Speaker Probe: Make a small probe with just two microphones and add two tubes for external speakers, like the system currently in use.
Concept 7 / Recycled Probe: Almost recycling the ER-10C but connecting the microphones separately, each to its own amplifier.
Concept 8 / Quadruple Microphone Probe: Almost recycling the ER-10C but duplicating the microphone system in the ER-10C to have two sets of two parallel connected microphones to get as much noise reduction as possible.

4 Synthesis 2

The focus in synthesis 2 will on detailing the top three concepts. Clearer descriptions of the models will be given. 3D and technical drawings will be made to make it more visual. Also, the materials are left to be chosen, so this will also be discussed together with the manufacturing procedure. Another important aspect of this phase is the risk management of the device. The device has to be tested and has to fulfil to a certain amount of criteria.

4.1 Modelling

External Speaker Probe:

This concept uses a solution for the speakers of the Dual ER-10B+ microphone probe and the components of the ER-10C to make a complete new probe. The Dual ER-10B+ microphone probe has two tubes open for using speakers, where external speakers can connect to via long rubber like tubes. By using this system the overall size of the probe can be relatively small because the speakers will not consume space of the probe. The microphones of the ER-10C can be placed very closely to the ear. There is a limit because the tubes of the speakers have to fit in the tip of the probe as well. This concept allows a redesign of the housing, making it possible to determine the spacing between the microphone and the ear and the spacing between the relative spacing of the microphones. A representation of the PCB can be seen below (figure 20). The external speakers are left out of the flow chart because they are external.

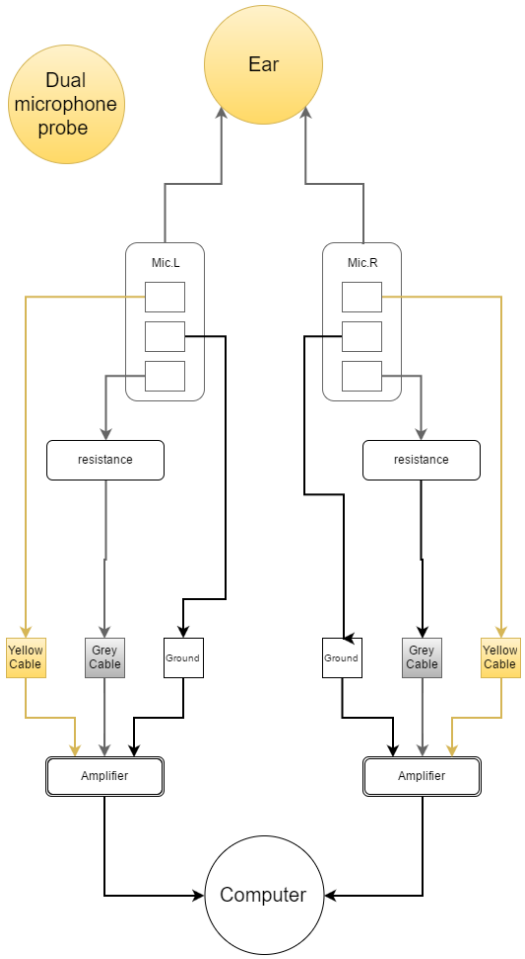


Figure 20: A schematic representation of the new PCB for the recycled probe concept, without the speakers.

Recycled Probe:
During the reverse engineering of the ER-10C two microphones were discovered. These microphones were glued into the housing. Because the housing is relatively small, compared to the Dual ER-10B+ microphone probe, the ER-10C is a very good solution once the microphones are disconnected and hooked up with their own amplifiers, to make an ER-10C dual microphone. In the ER-10C the microphones were places as much as possible to the tip of the probe, making it very close to the ear. This means that the tube volume is reduced compared to the Dual ER-10B+ microphone probe.

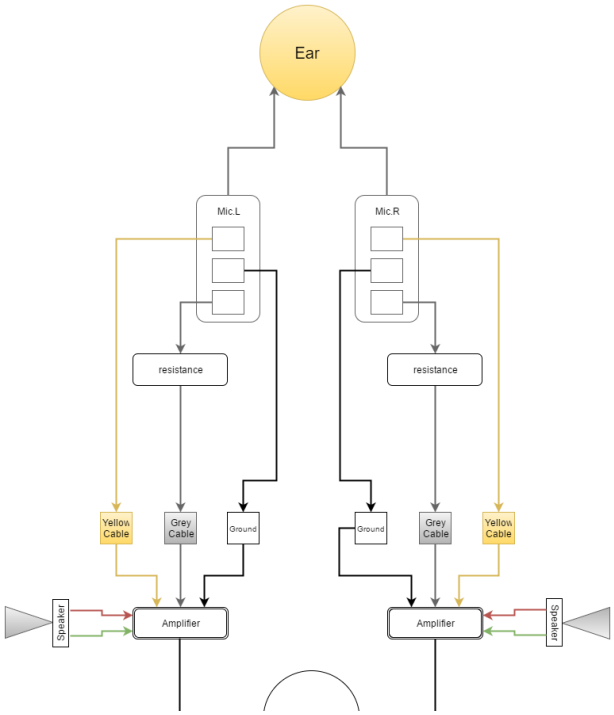


Figure 21: A schematic representation of the new PCB for the recycled probe concept.

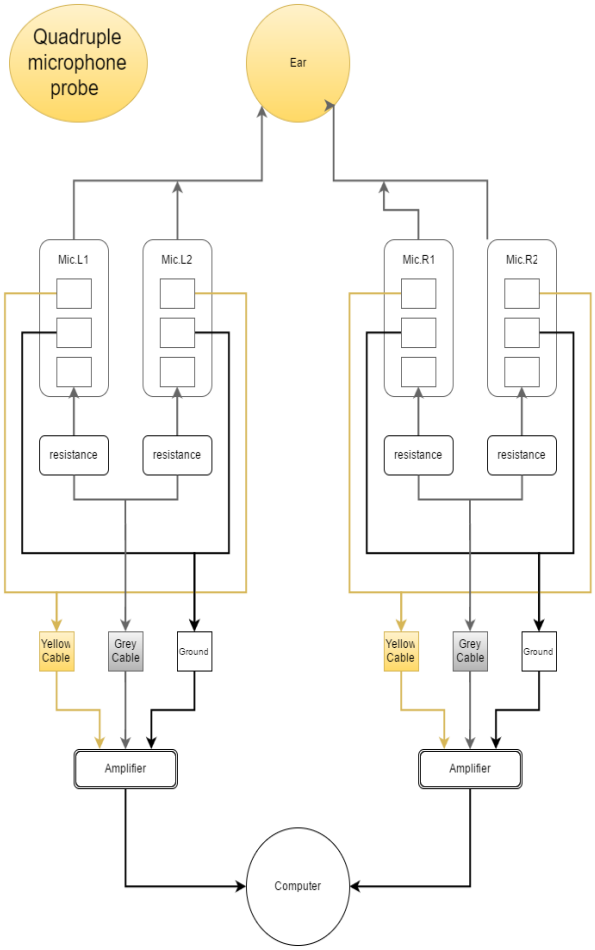


Figure 22: A schematic representation of the new PCB for the Quadruple Microphone probe concept.

Quadruple Microphone Probe:
Why stop after recycling the probe and making it a dual microphone probe? The ER-10C used two microphones to reduce the noise. For a dual microphone probe, four microphones can be used to reduce the noise even further. Two sets of two parallel connected microphones will do the trick. Basically, two ER-10C probes are combined into one probe by rearranging the components or connected via a tube system, which is not the preferred method, like the Dual ER-10B+ microphone probe.

4.2 Materials

The housings will be of any kind of plastic because it's cheap and relatively easy to make a product with. For building a new case compression moulding or 3D printing are perfect for plastics. Other components are prefabricated, such as resistors, PCB's, capacitors and small metal and rubber tubes. For making a new housing abs or pla will be used, because it is cheap and widely available. Otherwise, the housing will be recycled this means that there are no additional materials needed other than an extra cable.

4.2.1 Sterilization of the product

The device itself does not have to be sterilisable because with every measurement a new ear tip can and will be used. The tips are available in different sizes, making the device fit in all ears and keeping it hygienic. If not emerged in a fluid, one can clean the housing of the device using a moist towel or anything similar.

4.2.2 Manufacturing

Depending on the final outcome of the concepts different techniques will be used. By the recycled concepts, there will not be much to fabricate other than a new PCB. For a completely new housing, 3D printing will be used (for testing purposes), because it is easily available and it can make any kind of shape and it is a cheap method. On macro scale injection moulding the housing is a better way of producing. The PCB and other components will be bought to make the product.

4.2.3 Classification of medical device

The product is class 1 with measuring capabilities (class 1m). This is determined with the help of figure 23. It is a non-invasive measuring device. This means that no extra control or certificate is needed to use this device if a new ear tip is used for every measurement. Meaning a hygienic workflow by using clean tips is the standard and must be performed.
The device should follow annex IV, V or VI and VII to be eligible for CE marking[17,18]. For research purposes, the same rules will apply. The product should be in the same, CE qualified, state for research and marketing purposes to eliminate all risks.

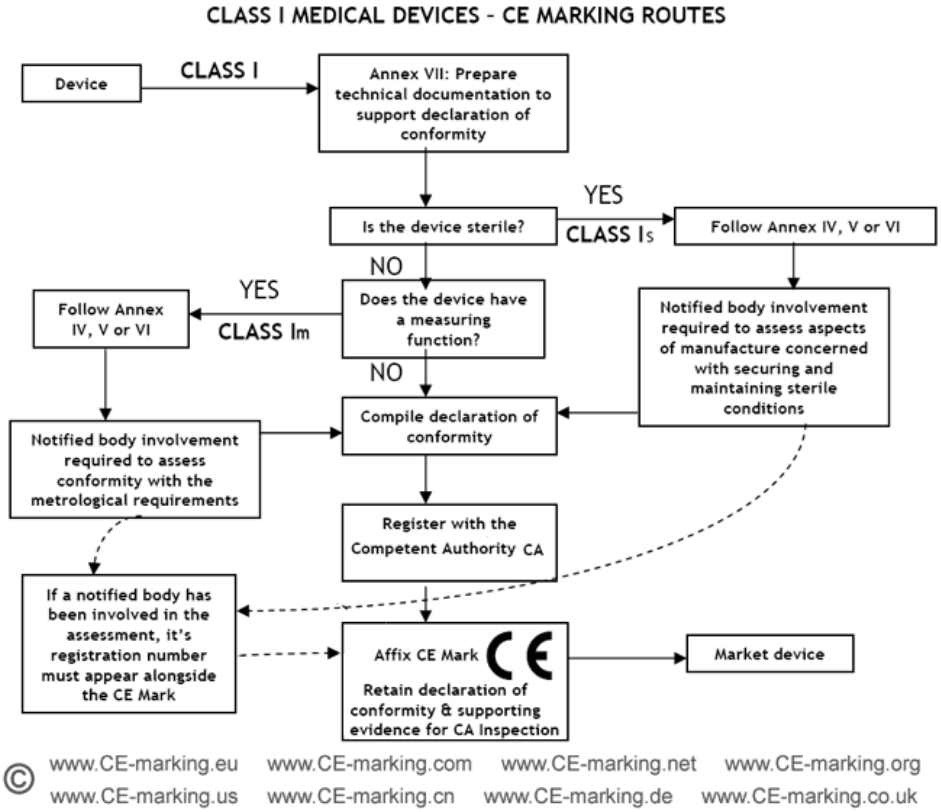


Figure 23: Medical device classification and CE marking route by ce-marking.com

[17] Avan.nl, Richtlijn 93/42/EEG van de Raad van 14 juni 1993 betreffende medische hulpmiddelen, (accessed May 2016) http://avan.nl/wp-content/uploads/2014/10/Richtlijn-Medische-hulpmiddelen-tekst.pdf
[18] CE Marking Consulting Service European Authorized-Representative EU, Medical Devices (Accessed May 2016) http://www.ce-marking.com/medical-devices-class-i.html

4.3 Failure Mode and Effect Analysis

Here all kind of risks will be evaluated. By scoring them by severity and likelihood of the risk, one will see the major problems of each concept. This analysis can help determining the final concept.

Priority = (impact + likelihood) /2		**External Speaker Probe**		**Recycled Probe**		**Quadruple Microphone Probe**	
	Impact	*Likelihood*	*Priority*	*Likelihood*	*Priority*	*Likelihood*	*Priority*
Risk of failure while making the product	80	60	70	20	50	60	70
Project exceeds budget	20	60	40	20	20	60	40
Project exceeds time window	20	40	30	20	20	60	40
Unexpected difficulties	40	60	50	40	40	60	50
Product cannot be realized	80	60	70	40	60	60	70
Speakers generate to loud sound	80	40	60	40	60	40	60
No advantages of using this product.	60	60	60	60	60	20	40
Same signal/noise ratio than current systems	60	40	50	40	50	20	40
Broken after dropping	80	80	80	60	70	60	70
Does not fit all ears	60	20	40	20	40	20	40
Not user friendly	20	40	30	40	30	40	30
Defect in electrical system	80	60	70	60	70	40	60
Shocking the patient	80	20	50	20	50	20	50
Not durable	60	40	50	40	50	40	50
Improper calibration	80	60	70	60	70	60	70
To expensive	60	20	40	60	60	80	70
Total:		49	55	39	49	44	52

Table 7: Risk analysis per concept

From the scoring table, one can see that making a complete new probe has the most risk compared to the others. This is a result of all uncertainties for making the new capsule and its performance of this new probe. The other two concepts are using the ER-10C which has proven to be functional. By altering the ER-10C there will be some risks and uncertainties about its performance but the overall idea stays the same and has low risks. The high risks found in the table are mostly caused by human errors and less about the design of the probe. The least complications are expected by the second concept, recycling and altering the ER-10C to a dual microphone probe.

4.4 Final concept choice

After having gathered more information about the ER-10C and have knowledge of the risks per pre-concepts, recycling the ER-10C seems to be the simplest and safest pre-concept. It might not be the best for the lowest noise floor, but because it is a good way to experiment if this system works because it is cheap and easy to fabricate. With the Pre-Concept selection and Failure Mode and Effect Analysis in mind a new table it made and shown below. From table 8 with the results from the pre-concept selection (table 5) and risk analysis (table 7) in mind, one can see that recycling the ER-10C and rewire it to a new PCB is the best choice for this project.

Requirements	Recycled ER10C	Recycled ER10C +2mics	2mic probe external speakers	Weight factor
Producable in 10 weeks	5	3	5	1
small overall volume	4	3	5	0,5
Cheapest	5	3	5	0,8
Zero risk of failure making the product	4	2	4	1
User friendly	4	4	3	0,9
No extra noise (via extra cables etc)	4	4	2	1
Total:	24,6	16,2	23,7	

Table 8: Final concept selection based on a combination of the list of requirements & wishes and the FMEA.

Factors which played a role are that it is just a test version and it is for research purposes, getting the dual microphone easy, low cost and fast is preferred.
Nevertheless, the other two concepts might perform better once tested. If the recycled probe concept does not work as expected the quadruple microphone probe can be considered. This concept shows fewer risks than designing a completely new system but is assumed to be very expensive because two more microphones have to be bought and embedded. One can add additional microphones to the recycled probe concept, making the fix very easily (new PCB is needed with extra resistors).

5 Synthesis 3

5.1 Detailing and technical drawings

In order to get the probe working two connection cables are needed, each microphone needs its own amplifier. One connection cable will only contain three cables (two signal cables, one ground), but the ground is not connected, to avoid ground loops. The other connection cable consists out of two a 10 core cable connected to the speaker, not all the cores are connected. The ground of this multi-core cables will be connected. The connection has to be in the same as the ER-10C, the ER-10C amplifier cannot be used otherwise.

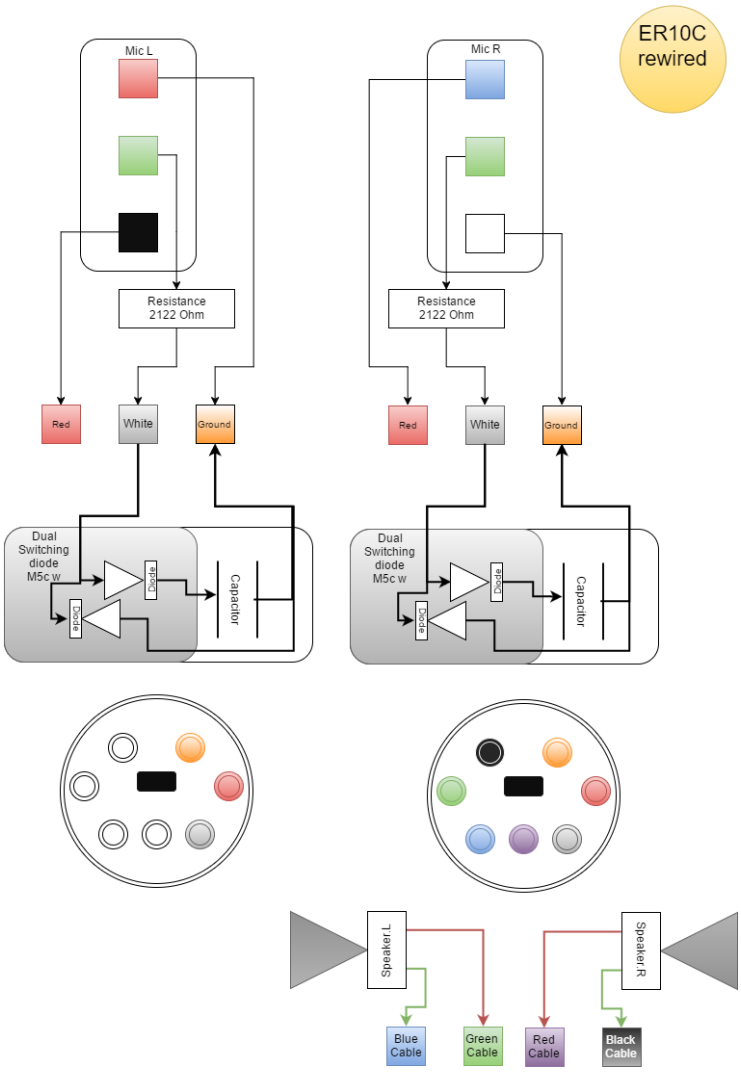


Figure 24: Schematic representation of the PCB for the final concept.

To connect the cables with the components a new PCB had to be designed and made and is shown in figure 25. This PCB is made from the flow chart in figure 24. The components will be soldered to the PCB with the cables connected as explained above. To design the PCB a free version of the program called EAGLE will be used.[19] The PCB should contain almost a double amount of components because

[19] Cadsoftuse, PCB Design software,(accessed May 2016) http://www.cadsoftusa.com/

if acts if it has an extra microphone in it. In reality, the new PCB only contains two more components (making six in total), but it makes the PCB quite full.

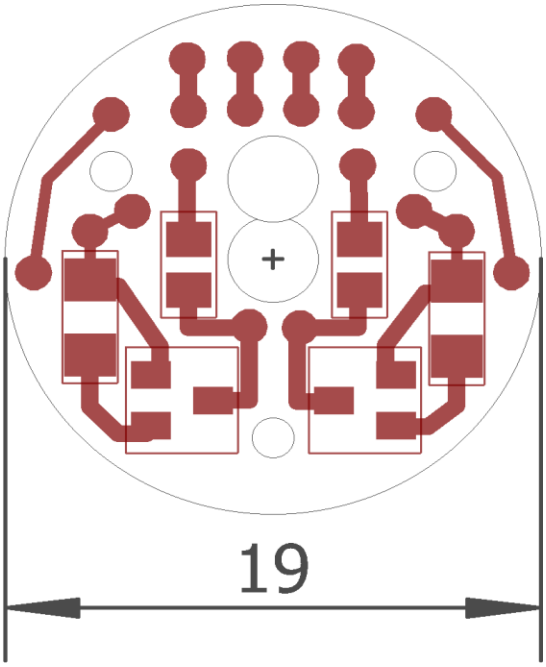


Figure 25: PCB design layout. The PCB is designed in EAGLE with standard components and a line thickness of 0.6096mm. There are four holes, one in the centre to reach the microphones and tube system. The other three are in the same spot as on the current PCB to allow screws through it, to screw the cap on the housing.

Exported from EAGLE with DesignLink								
Quantity	Value	Package	Order code	Manufacturer	Manuf. Code	Availability	Price (from)	Description
2	100nF	C1206	718646	YAGEO (PHYCOMP)	CC1206KRX7R9BI	52969	0,067	YAGEO (PHYCOMP) - CC120
2		SOT23C	1611382	STMICROELECTRONICS	BAR43AFILM	10316	0,172	STMICROELECTRONICS - BA
2	2200Ω	M0805	1469887	VISHAY	CRCW08052K20F	35665	0,0374	VISHAY - CRCW08052K20FK

Table 9: PCB component list exported from EAGLE.

Table 9 lists all the components needed (dual switch diode, resistor, and capacitor) to recreate the PCB with their product information and price estimation. The PCB has the same dimensions as the old PCB to fit it into the new housing without making the current design much different. The housing of the ER-10C will be recycled because the two microphones are cast into it. Also, the speakers and the tube system within the ER-10C will be recycled. This tube system can hold the ear tip to mount the probe into the ear. But to make the device compatible, an extension of the housing has to be designed to hold the PCB and make the cables fit, leaving the original housing intact. The housing mount is designed in blender, which is a 3d modelling software is made in the Netherlands. With the measurements of the attachment was made. A test version is printed in PLA using a Flash Forge Dreamer.

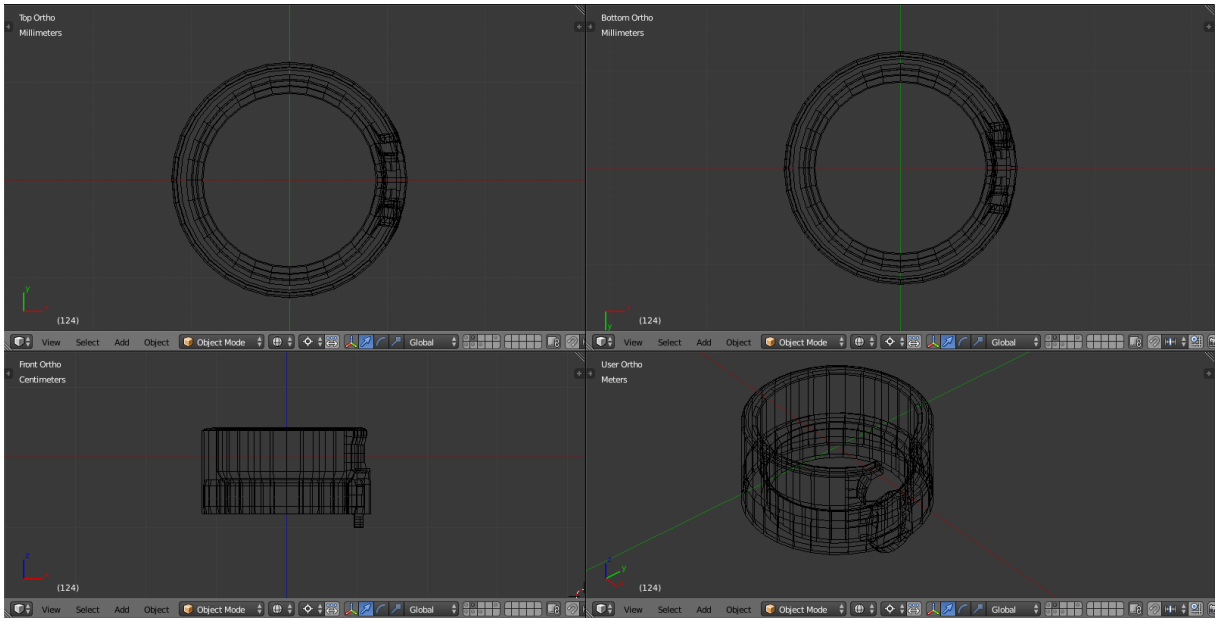


Figure 26: Wireframe views of the cable holder probe attachment, made in blender. Top left: Top view, Top Right: Bottom view, Bottom Left: Front view, Bottom Right: orthographic view.

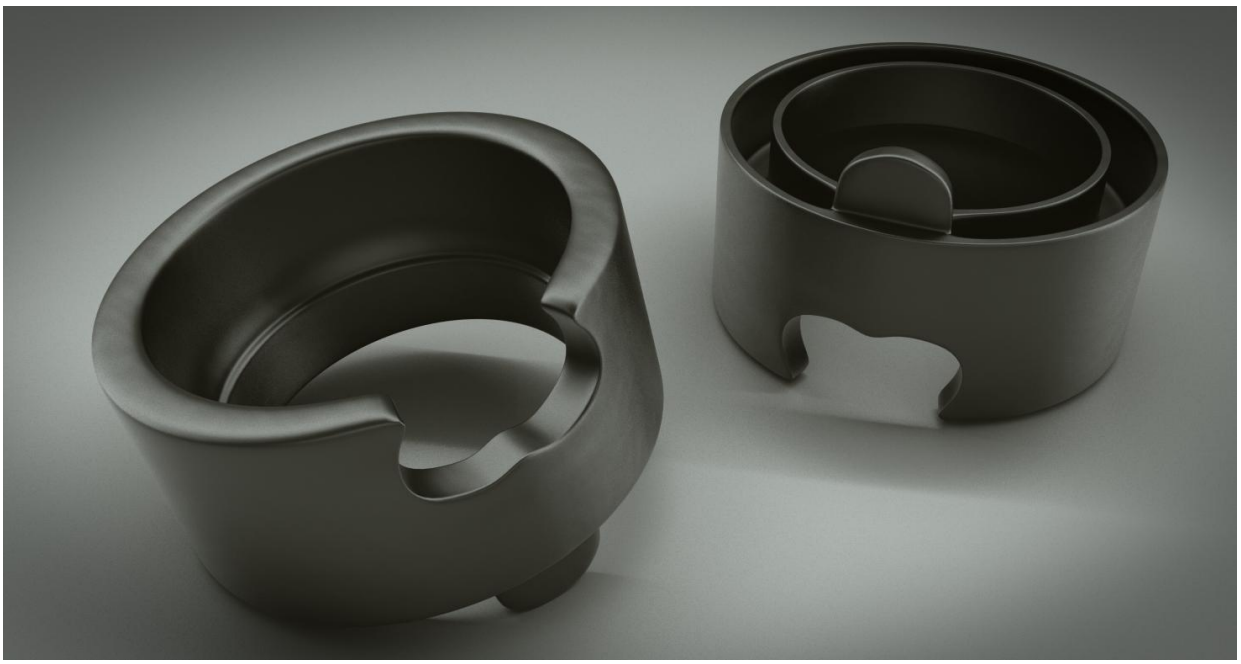


Figure 27: Housing attachment, made in blender

5.2 Material Detailing

A breadboard is used as a replacement of the PCB, for testing purposes but once the final product is defined a well-designed PCB is preferred.
Two cables with isolation will be used to connect the PCB to the amplifiers. These will be two 5 core cables for the microphones and speakers. Each cable will have one speaker and one microphone and will be connected to its own amplifier. The housing is of an unknown type of plastic but susceptible a common type of plastic like pp, pet, abs. The housing attachment will be of pla because it is printable and easily accessible.

5.3 Production methods

To create the test dual microphone probe the ER-10C will be recycled and therefore there almost no production. The disassembled probe will be rewired on a new PCB and connection cables towards the amplifiers.

But if the tests are promising and one will produce it on a macro scale the housing can be printed or injection moulded. For macro scale, injection moulding is a better choice because it can produce a lot in a short amount of time. There are no complicated structures, so there no need to use a 3d printer on a macro scale, because the model is quite simple.

Injection moulding is a process where dies are used. The die is a negative of the product itself. Liquid plastic or metals are poured into the dies. Once cooled the product is pushed out of the die and after some minor cleanup the final product is obtained.

5.4 Cost estimation

In this section two separate cost estimations will be given, one will be focussing on making it for the market while the other will focus on making a product for this project only.

Project cost estimation

For this report one single example has to be made and can recycle a lot of components, e.g. amplifiers, ER-10C as a whole except PCB and cables. The cables, connectors, and component prices will still be there, but the PCB and the housing attachment will be homemade. To make the product without the speakers and microphones is fairly cheap. This estimation is done by adding up the component prices of table 6 (~€0.55), add two 7 pin DIN connector (~€3 Okaphone Groningen) and some wiring (~€10). The 3d printed costs less than 5 euros if a third party is used to print it and even less if one have a printer. The price estimation is done by uploading the print file to 3dhubs[20] and selecting PLA/ABS as materials. Adding it all up to a cost around €15-20.

Macro scale cost estimation

The cost estimation of going macro scale it different, because not only the project cost are present but also the microphones, speakers and amplifiers are also on the cost list and those are the expensive components. No estimations can be done on the speaker and microphones because the specifications are unknown. The components have to be low noise and the microphone has to be very accurate. The price for microphones is about €179 euro's each and up depending on the quality. A millimic can be found here[21]: http://www.professionalsound.com/specs/milli.htm. The price of the speakers is also unknown, but a nice list of speakers for hearing instruments can be found here[22]: http://www.knowles.com/eng/Products/Receivers-and-speakers/Hearing-instruments. Speakers are assumed to be about the same price as the low noise microphones.

Making the housing and the PCB are both calculated, for orders of 100.000 microphones, via online tools. A housing will cost about $0.18 and the PCB $0.04 per probe.

An online tool[23] (figure 28) is used to estimate the costs of injection moulding the housing. The program uses simple size as input, envelope sizes, and knowledge of various products of similar sizes to give an estimate. The model also included batch size and tolerances. For the housing, an estimation is given below for a batch of 100.000.

[20] 3D Hubs, (Accessed June 2016) https://www.3dhubs.com/
[21] PSC, (accessed May 2016) http://www.professionalsound.com/specs/milli.htm
[22] Knowles, list of different speakers for hearing instruments (accessed May 2016) http://www.knowles.com/eng/Products/Receivers-and-speakers/Hearing-instruments
[23] Custom Part net, Cost estimator injection moulding (accessed May 2016) http://www.custompartnet.com/estimate/injection-molding/

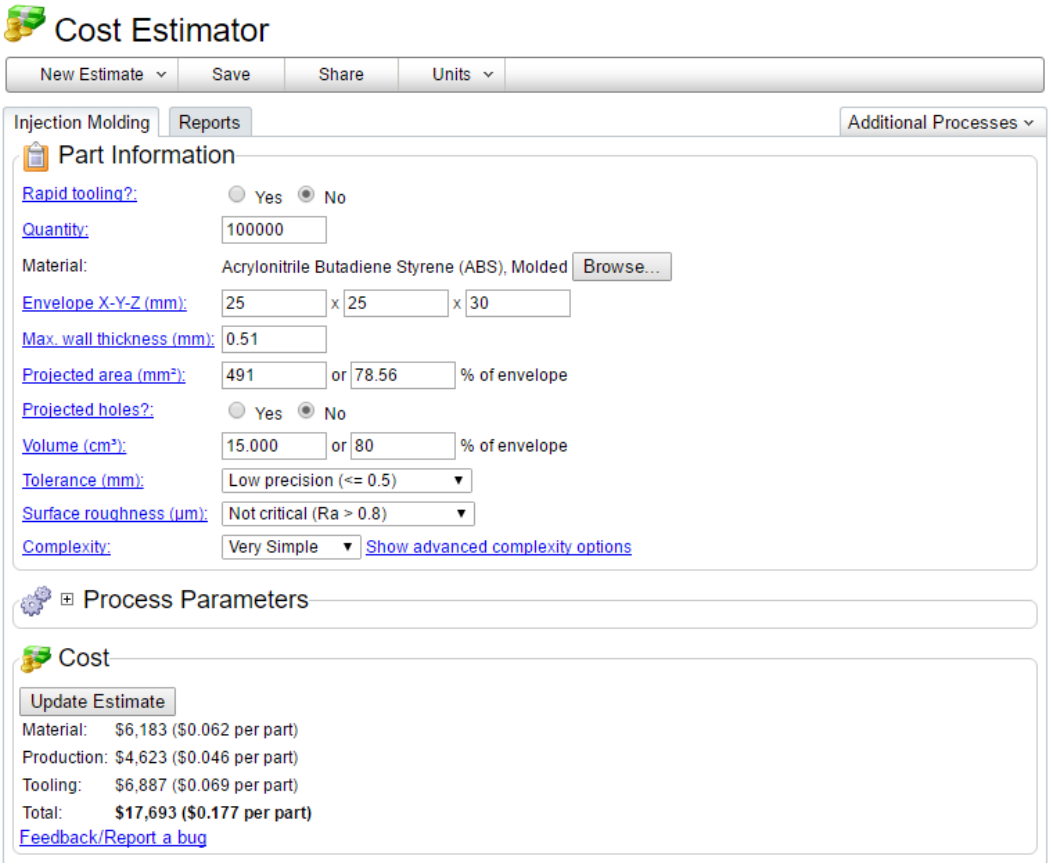


Figure 28: cost estimation Injection moulding of the housing

To estimate the price of a PCB another online tool[24] (figure 29) estimates the costs of the PCB by sizes and features of the PCB, like layers, materials etcetera. The default settings are mostly maintained to give an estimation. Only the amount of layers is reduced to one and the sizes of the PCB (20 x 20mm) are filled in. Also here the price is given per batch of 100.000 pieces. A larger batch will reduce the price per PCB. Making a single PCB is very expensive.

[24] PCB Cart, online PCB cost estimator (accessed May 2016) http://www.pcbcart.com/quote

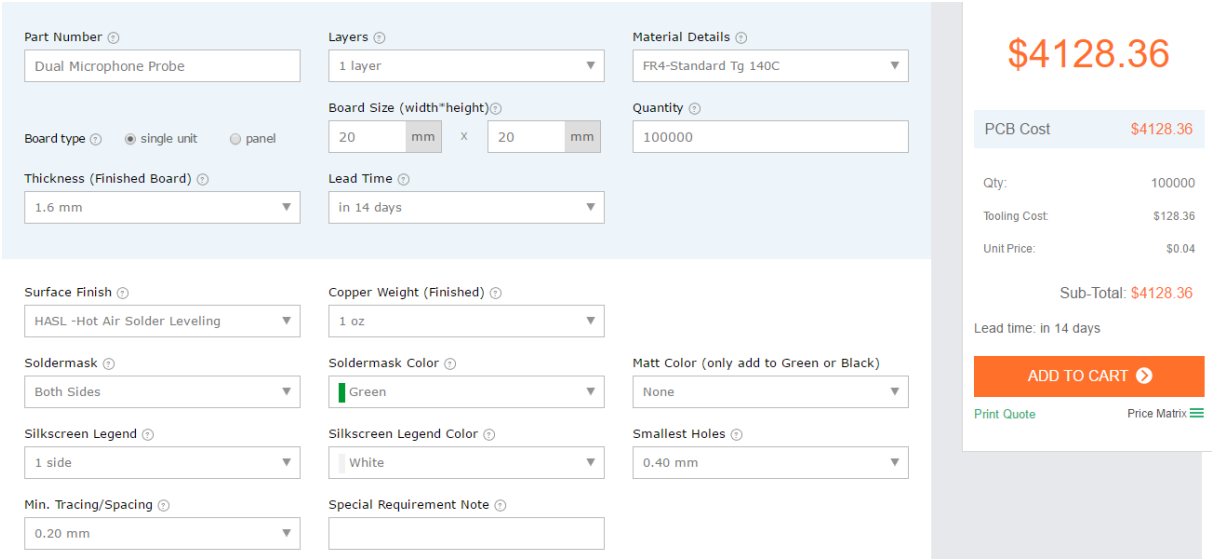


Figure 29: Cost estimation to make 100.000 PCBs.

In addition, several cables are needed to connect it all together, which will cost a few Euros. Some example choices are shown below.

Two connection cables toward the amplifiers. Two 5 core cable, which is about 70 euro cents per meter or less.[25]

Some small wiring for the PCB which is about $7.50 for 200meters.[26]

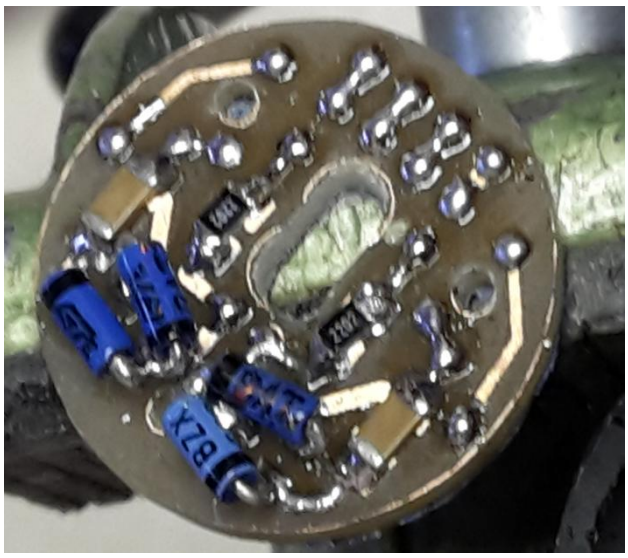
Two 7 Pin Mini-DIN Male Inline Plug Connectors are needed to plug the probe into the amplifiers. They cost about four dollars per set of five.[27]

The total price estimation is hard to make because the most expensive components are unknown. The total price per unit will around €400 and €600 to make a complete new probe from scratch including the microphones and speakers, depending on the quality, without amplifiers.

[25] TLC (webshop), 5core cable (accessed May 2016) https://www.tlc-direct.co.uk/Main_Index/Cable_Index/Flex_White_3/
[26] Adafruit, (webshop), Thin shielded PCB wire (accessed May 2016) https://www.adafruit.com/product/1446
[27] AliExpress (webshop), 7 pin DIN connector plug (5pcs) (accessed May 2016) http://nl.aliexpress.com/item/Sale-5-Pcs-Mini-7-Pin-DIN-Male-Plug-With-Plastic-Handle-Soldering-Cables-Black-Adapter/32560873398.html?spm=2114.48010608.4.2.BMbAeW

5.5 Final Concept model

The final concept made it to a real product. The components of table 6 are mounted to the PCB and an attachment has been made to house the extra cable. It was a very tight fit on the PCB and in the housing, but it is doable.



6 Testing and calibration

6.1 Building separated microphones on breadboard

Test during reverse engineering

Rebuild on breadboard was not successful with the same connections originally on the PCB. Originally the top connection will lead to the yellow cable on PCB (red on the breadboard) and the bottom to the ground but for the left microphone, the mirrored connection has to be used (top to ground and bottom to red). The mirrored connections of the right microphone can be used but is not necessary. Possible connections are shown below. With these connections, the system was responsive for both microphones and had the lowest noise measured on the oscilloscope (Hameg 20 MHz Dual Trace hm203 oscilloscope). It is strange that this differs from the PCB in the reverse engineering section. The breadboard can differ only on a few points. The resistance is a little higher (2.2kOhm), there is no RC filter, or some cables are switched but this is checked multiple times.

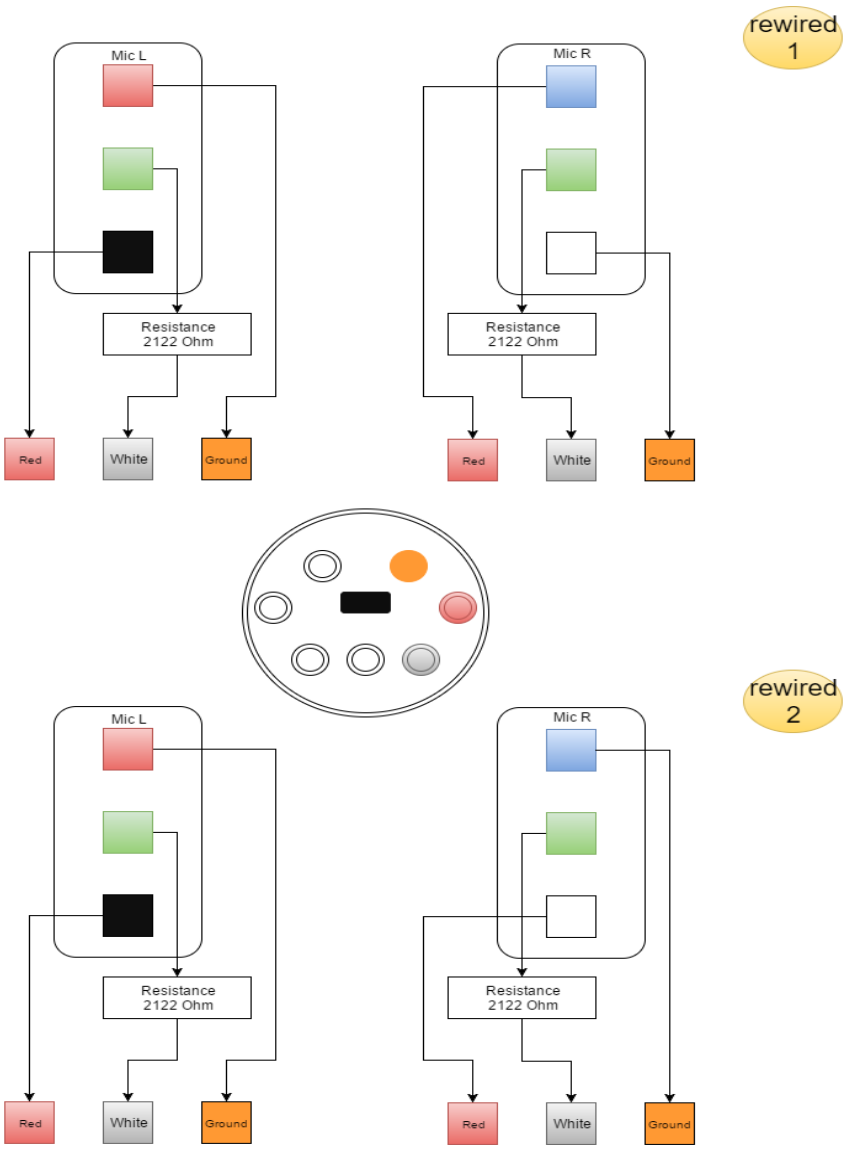


Figure 30: rebuild probe on breadboard can have multiple ways to connect

Rewired 1 will be used further down the road in the following setup (figure 31):

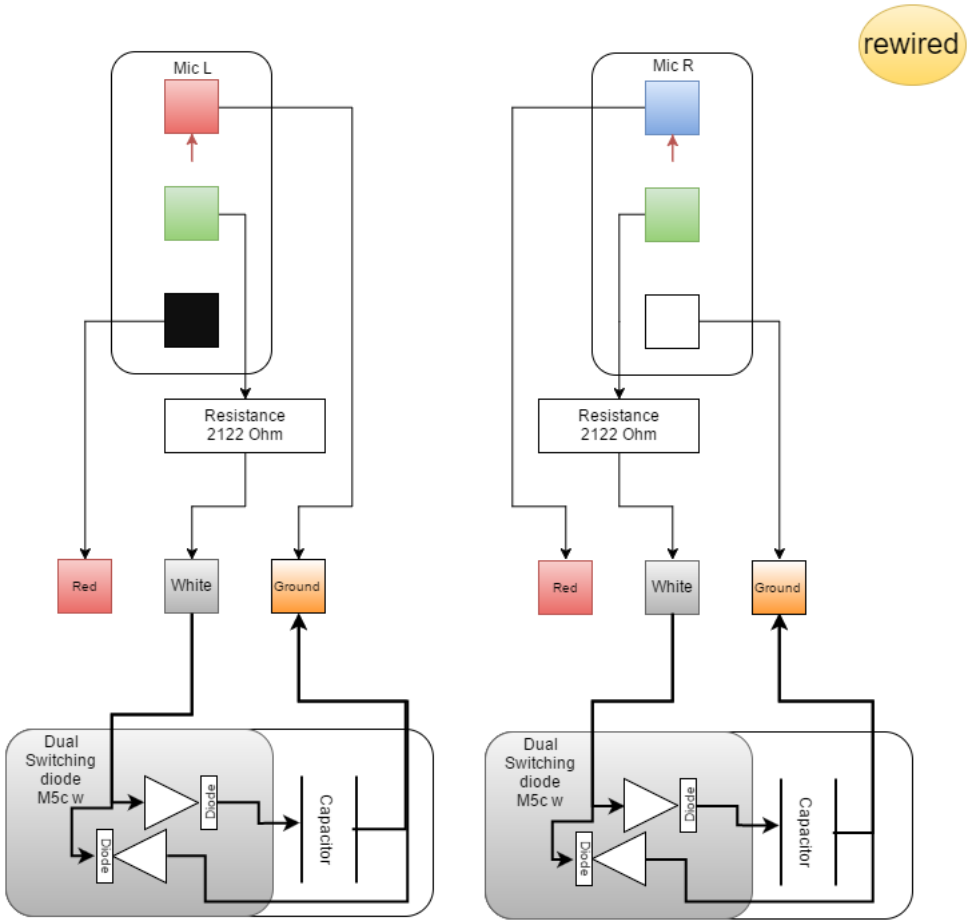


Figure 31: Rewired 1 (figure 30) with dual switching diodes and capacitors.

6.2 Intensity measurement on oscilloscope

Test during reverse engineering

To test the quality of each single microphones are connected on a breadboard with the needed components and will be compared to another ER-10C probe. This test has a very simple setup and is just to give an indication of the performance. A Smartphone (Samsung galaxy S5 mini) produces a sound signal of 1 kHz at 8/15th of the maximum volume straight up into the room at a 10cm distance of the probe. The ER-10C amplifier was set to +40dB. The measurements were performed on a Hameg 20 MHz Dual Trace hm203 oscilloscope. The ambient noise is about 20-30dB. It seems like one individual microphone (on PCB) will give half the signal with about half the noise of the original probe. The reconstruction on the breadboard loses another half of the signal and noise, but this system is not optimized at all.

Model	Amplitude /w signal (mV)	Amplitude w/o signal (mV)
ER-10C Original	100-150	20-40
ER-10C Mic. L on PCB	50-100	20
ER-10C Mic. R on PCB	50-100	20
ER-10C Mic. L on breadboard	60	10-20
ER-10C Mic. R on breadboard	40	10-20

Table 10: Oscilloscope amplitude measurement table while applying a sine wave of 1000hz at 8/15th of the maximum loudness of a Galaxy S5 mini.

6.3 Intensity measurement on oscilloscope

Test during building final concept

The final concept has to be calibrated. This will be done by a three point setup: One calibration microphone and the Dual microphone ER-10C at the same distance and angle from the sound source. But first, the measurement will be done as explained in 6.2 to check if everything works properly.

If these tests are performed, two SOAE test will be done. One with dual ER-10B+ microphone probe and one with the final concept. This test is to see the difference in noise floor and see the gain of the project by doing it this way.

Signal/Mic	Left	Right
Ambient Noise (20-30dB)	<5mV	<15mV
1000Hz sine (8/15 volume)	~15mV	~15mV

Table 11: Intensity test on final concept as in 6.2

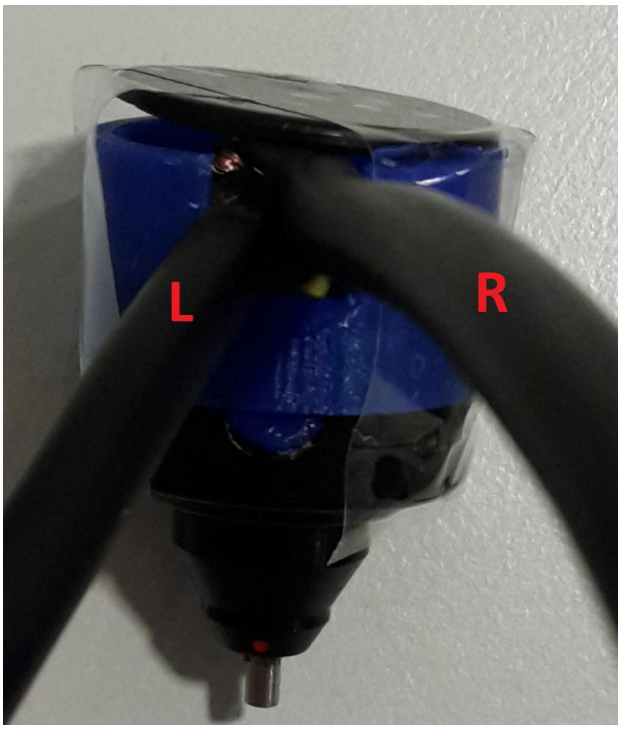
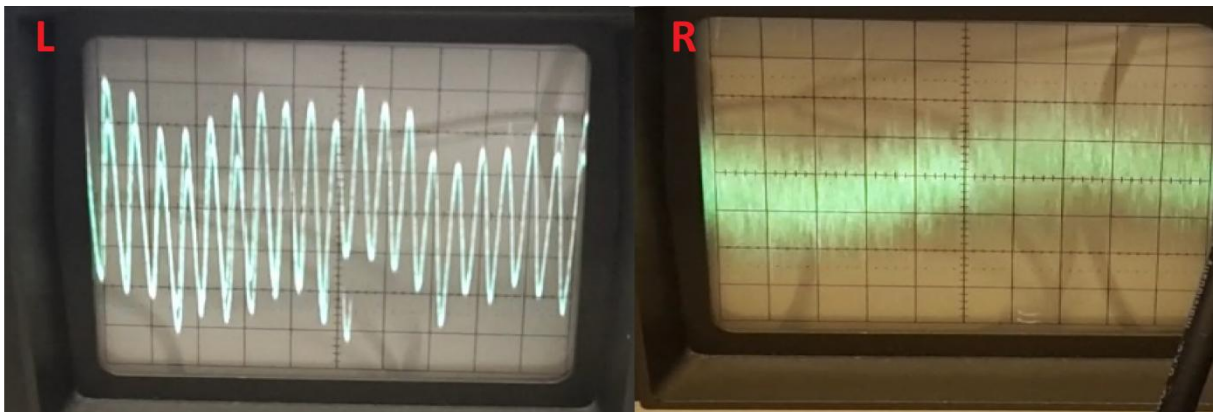


Figure 32: Final concept to distinguish left and right

Table 11 shows the result of the intensity test as described in 6.2 for the final concept. The left cable has a low signal with ambient noise compared to the right cable which let to assume that the left was less sensitive. But after applying the signal was clearly visible when the left cable was connected and disappeared in the noise for the right one, figure 33. The right was unresponsive and is only sensitive to very loud sounds. Only then one can distinguish the signal from the noise. The right connections have to be checked to improve the signal. It turns out that the PCB was made according to figure 21 instead of figure 24. Now the microphone is responsive, but still has more noise than the other.

Figure 33: Intensity response of the different cables on the oscilloscope while test fluting. Left shows the signal clearly,



right shows no signal. (Note: these are frames from actual footage at different times and tones).

6.4 Calibrating, SOAE test

For calibration the new dual microphone ER-10C it will be tested against an unmodified ER-10C and against the current dual microphone probe ER-10B+. First, the tips will be closed such that the microphone will not get any signal. With this test, only the noise of the probe itself will be visible. Then two SOAE tests will be done. The results are plotted in figures 34 and 35.

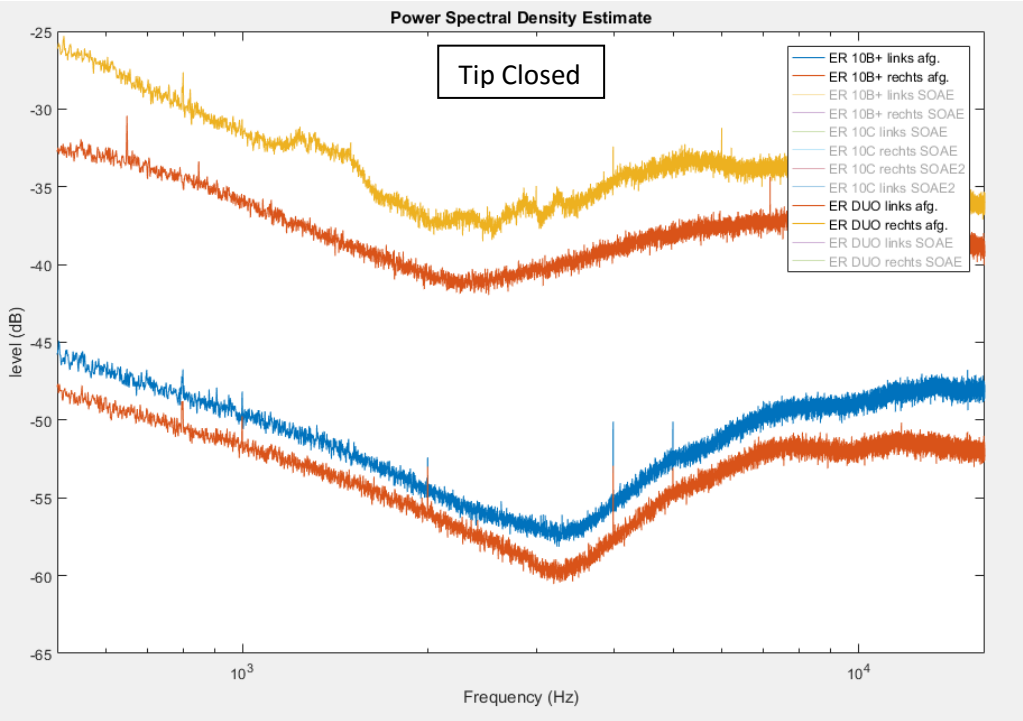


Figure 34: Closed tip, silence measurement results. The difference between microphones and models are clearly visible.

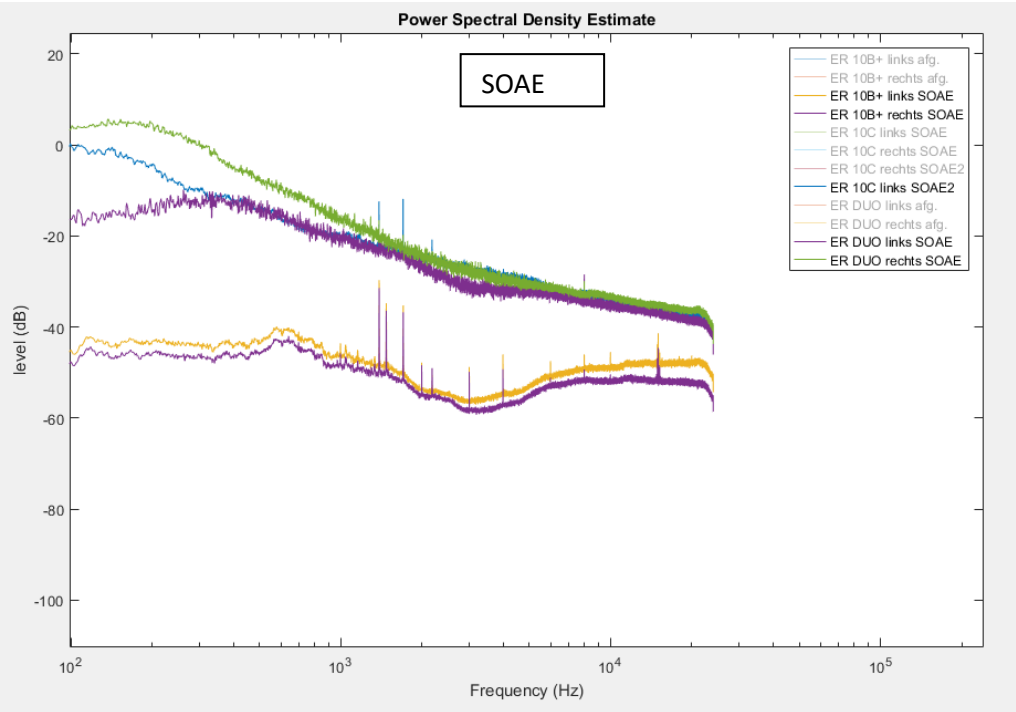


Figure 35: SOAE measurements with three models (Dual microphone ER-10B+, ER-10C, Dual microphone ER-10C (new probe)). Differences are clearly visible.

Figures 34 and 35 showed that there is a clear difference between the current dual microphone and the new dual microphone probe and there is less difference between the unaltered ER-10C and the altered ER-10C. The lower the curve started (more negative) the better the microphone performs, and has a higher sensitivity. Unfortunately, the current dual microphone performs better, than the new one which performs as good as the unmodified ER-10C probe. The microphone of the ER-10B might be more sensitive and different amplifiers are used . In figure 34, one can see a clear difference between the left and right microphones in the dual microphone probes. Also here the difference between the microphones is greater in the new probe and less in the currently used probe. As an effect of the lower sensitivity, the new probe will detect less OAE's than the current probe.

7 Conclusion & Discussion

In the end, the first tests indicate that the new dual microphone probe performs less than the currently used probe, the sensitivity of the microphone is less. Some more testing has to be done to conclude this. Further research is necessary in order to get the best dual microphone probe. The cross-correlation technique can be used to reduce the noise, and may help find the weak signals, but not as weak as one can find with the current dual microphone probe. The question remains: why does the new dual microphone perform less than the currently used probe and performs as good as the unaltered ER-10C? And how can one improve the microphone?

One way to investigate this is to get a probe professionally made. This may reduce noise from the fully packed PCB or from any damage to the cables due to soldering. Another way is to recreate the dual microphone probe from another component source; instead of recycling the ER-10C one could recycle the currently used dual microphone probe made of two ER-10B+ probes. This because it is possible that the microphones used in the ER-10B+ are individually more sensitive than those of the ER-10C.

8 Evaluation

This project started as a normal design process, with following all the steps from the reader, but when we went further and dug deeper into the reverse engineering of the ER-10B+ the more limited we became. The time we had to make a real product and the costs of the components needed to create a complete new ear probe withheld us to make a completely new one and we recycled the old one instead. This was more limiting because now we could not alter the shape of the housing because the microphones are cast into the housing. Every change had to fit into the probe, like the PCB. This was making it difficult and a limited task at one side but at the other, it made the project easy because we only had to adjust the PCB. The difficult part was making it all fit because with the new PCB a double amount of components and were needed making it quite full and hard to solder it all on the PCB. It is very unfortunate that the project did not deliver a probe which performs better than or equally well as the currently used probe.

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