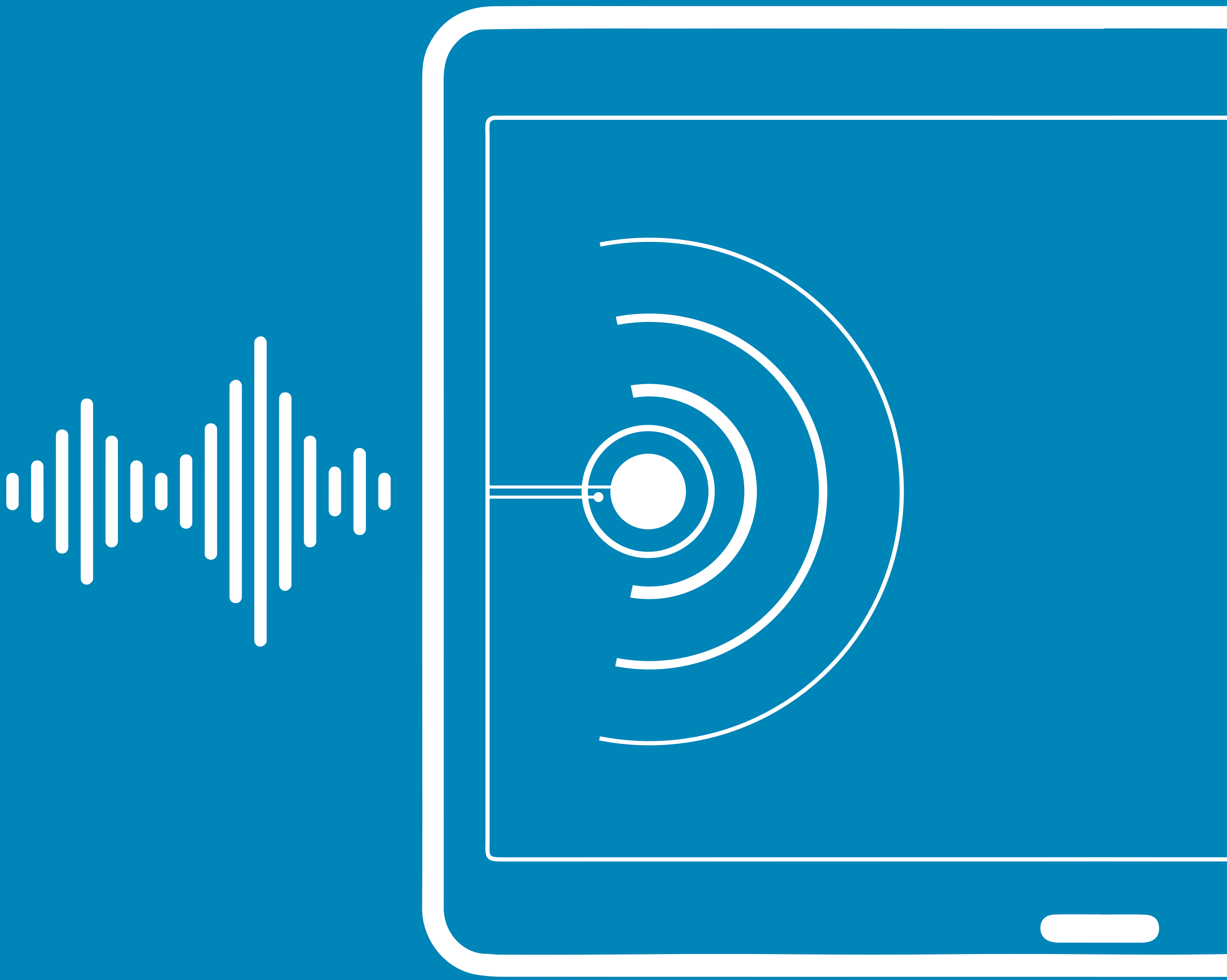
Aito Sound

A proof of concept exploration for haptics and sound with piezoelectrics

Graduation Thesis of Tessa Mellema
MSc Integrated Product Design



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Aito Sound; *A proof of concept exploration for haptics and sound with piezoelectrics*
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Supervisory team

- Chair: Dr.-Ing. N.A. Romero Herrera
- Mentor: J. Bourgouis

In collaboration with:

- Aito B.V. (Mentor: J Lönnberg)

Preface and acknowledgements

My project took place under the circumstances nobody would have ever imagined. I started preparing this project in January and the company, Aito, allowed me to travel to their Finland office to discuss possible directions with the employees there. When I went back home to the Netherlands, the plan was to go back to Finland after the first half of the project was completed to review the new developments. But then, five weeks after I had started my project, Covid-19 caused lockdowns all over the world. For me, this not only meant that travelling to Finland was no longer possible, but also that user testing and prototyping became a lot more complicated. I could no longer work at the university or the office of Aito but was stuck home along with everyone else. Luckily during this period, I was surrounded by people who either helped me with the practical aspects of my graduation or my emotional well-being. I would like to thank these people in this section of my report.

The first two people I would like to thank are my chair Natalia and mentor Jacky. For them, this situation was also completely new, and they had to combine their courses that suddenly became online with coaching in an online format. Both of them have mentioned that "we" would reach a good outcome of the project, and this "we" part has helped me during the times I was struggling with adapting. I was not the only one adapting, but my coaches had to adapt as well. The moments when I felt I was not there and struggled with adapting, they let me know I was on the right track and that it was okay that I did not know all the answers yet. During the project, they have helped me focus on reachable outcomes as this is a project "that could go on for multiple years" according to Natalia, when I first explained my plans to her.

I also want to thank Aito and their employees for the opportunity to work with their technology and the use of their knowledge. Unfortunately I did not spend as much time in the office as I would have liked, because I enjoyed my days there. Fidgeting away in the lab and always being able to ask if I wanted to know something or get feedback were two things I particularly missed. In my project, I got the freedom to explore and try new things, Aito was always involved in decisions, but they never felt restricting.

And lastly, I want to thank my family, boyfriend and friends who helped me with the emotional aspects of a graduation project. Graduating itself is already stressful and chaotic, add Covid-19 to the mix and these things increase drastically. The people in my private life offered an ear when I needed to fend or gave me helpful insights for either my project or the problems surrounding my project. They also helped me to find and create a nice work environment because working from home all the time during your graduation is not ideal. And lastly, they were so kind as to participate in my user test.

Without all these people I could not have finished this project without the minimal delay of three weeks. Looking back, it was quite intensive and might not have gone how I imagined it. However, it will make a great impression during job interviews to mention I managed to graduate during the pandemic. So thank you all who have helped me during this project. I could not have done this without you.

Tessa

Abstract

Aito has developed a technology that can be placed underneath surfaces to give haptic feedback. They make use of piezoelectric discs to sense a pressure difference and actuate a pulse if this difference reaches a certain level. This system is possible because of the piezoelectric crystals in the discs. These crystals create current from movement for the sensing action, and create movement by adding current for actuation action. These properties, combined with the way Aito layers the structure to support the piezoelectric discs, allow for this type of haptic feedback which mimics the press of a button. While the technology of Aito currently focuses on a single pulse to simulate the feeling of a button, it is possible to send a continuous stream of vibrations through the piezoelectric discs. This stream could be a pulse that is being repeated over and over, or it could be a variation of pulses which creates music. This last possibility is explored in this graduation project by a state-of-the-art review, objective measuring techniques and subjective measuring techniques.

With Aito's current structure, it seems possible to create a speaker in which the surface is vibrated to create audio according to the gathered literature in the state-of-the-art review. The literature describes two types of speakers with a similar structure as Aito, which are the distributed mode loudspeakers and multiactuator panels. These speakers use a vibration module (an exciter), to move the surface they are attached to. The difference between these two speakers is the placement and number of exciters. Both these speakers have a different designing approach than the standard design process of coil-based speakers. The design approach for distributed mode loudspeakers and multiactuator panels is used in this project but incorporates some techniques from the usual procedure. The main elements that are adopted from the standard audio engineering approach relate to the validation of the setup with users and measurements.

The traditional approach of audio engineers to involve users into the design process, is by letting participants participate in listening test to define the audio quality perception of the speaker. This approach is adapted in this project into an approach which allows users to define their audio quality expectations; this involves users earlier on into the design process. By letting users participate early on in the process, the audio quality experience can be changed efficiently. The perceptions could improve the experience at the end of the process, while the expectations change it in the beginning. The expectation that is explored during this research involves foldable laptops and tablets. This approach shows that the audio quality of foldable laptops is expected to be higher than foldable tablets. The whole foldable group is expected to perform lower than a laptop, but higher than a smartphone. The expected speaker placement also showed a difference between foldable laptops and foldable tablets, which shows similarities to their non-foldable device group. Therefore, a speaker that is integrated into the surface would ensure that the speaker location is most optimal in both the laptop position as well as the tablet position of a foldable device.

For the measurement validation, various tests were done based on the approach of audio engineers to define how Aito's structure performs for audio functionalities. This approach was chosen to compare the results to the requirements of the industry; these take volume levels and frequency range of the audio into account. When these requirements are combined, a grading system is created to help in selecting the correct speaker for specific experiences. The tests were done with simplified models of a foldable tablet because this product group is the best fit for a haptic and audio combination. In total, there were eight individual models used during the system performance testing. All these models originated from one basic model, which was a simplified foldable tablet structure; this model can be seen in figure 1. Its structure is separated into two identical halves to be able to create stereo audio when both halves are used. In the individual models, changes were made to test the effects of different surface materials, surface edge fixtures, piezoelectric disc layouts and uses of the space behind the system. These changes were mainly based on the design principles of distributed mode loudspeakers and multiactuator panels but were combined with some design principles dictated by Aito and the speaker industry. The results of the tests with the models are the following:

- Size differences on a cm-scale do not improve the audio performance.
- A mix of too many changes in the models does not allow an analysis of the effect of the changes.
- The simplified model does not represent the final product accurate enough.
- With a different piezoelectric disc layout, it is expected to be possible to improve the overall loudness throughout the different frequencies.

This research was a first step in the direction of audio with Aito's current setup. From the performance of eight models in combination with the user expectations on foldable laptops and tablets can be concluded that the technology is not yet there. However, for less demanding products, such as intercoms, the audio quality can be deemed good enough as is with some small improvements. There is also the possibility to use the system only for higher frequencies and haptics and add

another speaker to generate lower frequencies. When this project is continued, four hurdles need to be taken to get satisfactory audio out of the system.

- Aito should increase the loudness of the system to meet the industry requirements.
- The loudness should also be consistent throughout the frequency range, which it is currently not.
- Beside the improvements to the structure, Aito should also develop an amplifier specifically for their system.
- To ensure their current haptic feedback performance is maintained, the software has to be adapted to the audio functionality.

Aito has to find partners and staff to develop the audio technique further. Partners can be found among their clients, as it is preferred to develop this technique further with a real product rather than a simplified version. Staff for the next steps towards an audio functionality should consist of audio engineers, engineers with knowledge about Aito's system and electrical engineers with expertise about amplifiers.

Keywords

Piezoelectric speaker, Distributed mode loudspeaker, Audio expectations, Audio measurements, Haptic feedback

Is an audio feature possible with this system?

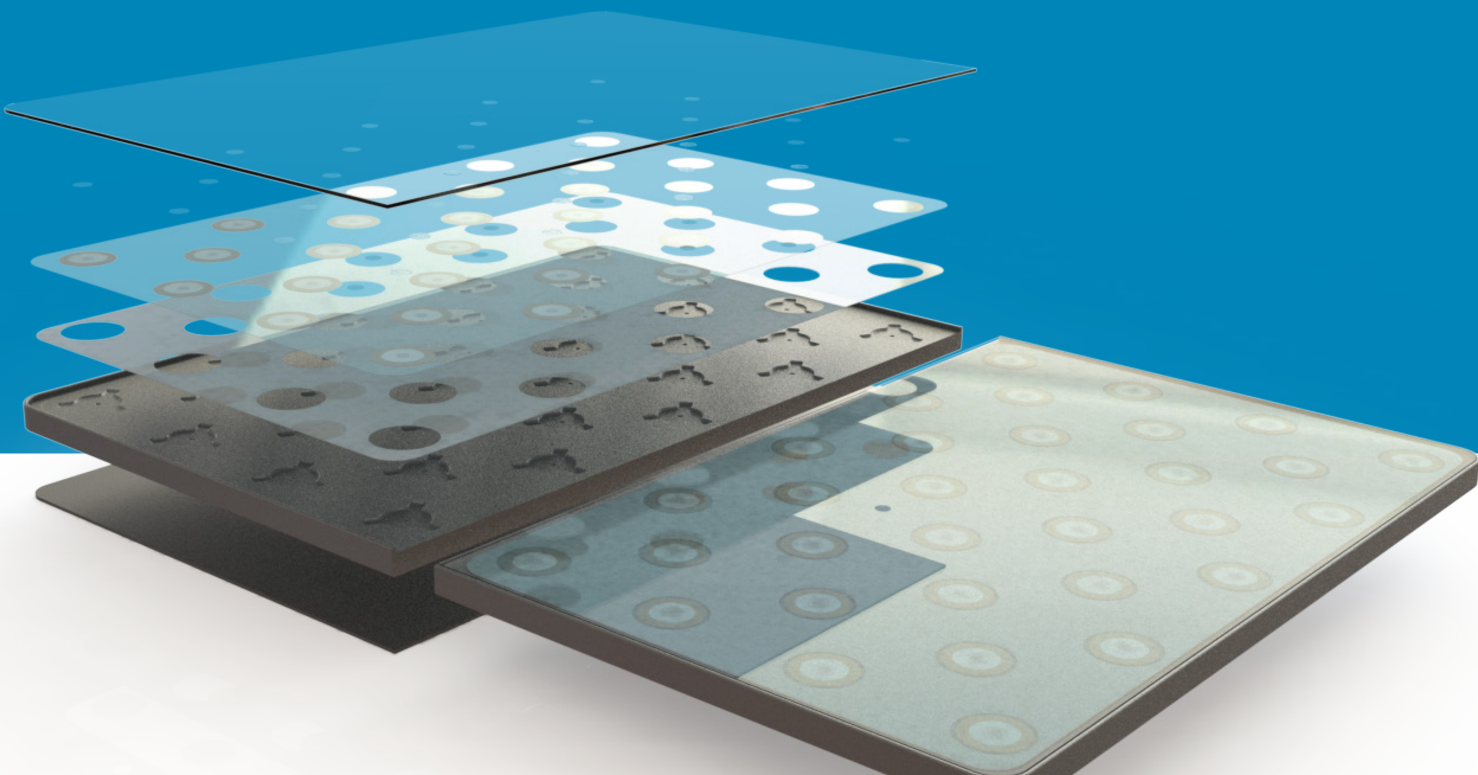

Figure 1, Layout of the overal model for the prototypes

Glossary

Acoustic In audio engineering acoustics describe the sounds that are not preferred. These sounds change the audio, which results in an inaccurate representation of the original input.

Actuator An actuator is an electrical component that gives an output; this output can be many things. For this project, the output of an actuator is a movement which offers either haptic feedback or audio.

Amplifier This is the component in the speaker system that transforms a low voltage signal from the audio device, to the required voltage for the signal for the whole system.

Audio The word audio describes the sounds that are preferred in audio engineering and are achieved with the design, compared to the unwanted acoustics, which is a by-product. The term audio relates to the musical aspects of audible vibrations in this project.

Audio design Audio design is the process of designing speakers to give the correct output. This process is aided by measurements and listening to the audio.

Audio engineer This profession focusses on designing the correct audio response in speakers or other products that generate sounds.

Audio experience The audio experience describes how users perceive the audio related to the use-case of the device and its context. The experience can be focussed on music, or on only supplying voice audio for phone calls.

Audio performance The audio performance describes the audio from the outcome of the measured data in a sound lab with microphones.

Audio quality The audio quality describes the audio from the outcomes of tests in which participants describe the perceived audio.

B2B This is an abbreviation for business to business which is a market strategy. This strategy focusses on selling a product to other companies rather than selling to the end-user of the product.

Cap sense The cap sense technology is used in touchscreens and locates where the screen is pressed and sends this information to the device.

Carrier The carrier is a part of Aito's stack design and acts as the support on which the other components are placed.

Distortion The term distortion is used to define audio that does not represent its input, the distortions can come from acoustic problems, problems with the signal supply or with the speaker design itself.

DML This is the abbreviation for distributed mode loudspeakers, these are speakers which generate audio with a panel to which a vibration module (an exciter) is attached.

Dot The dot is a part of Aito's stack design and focusses the forces of the applied pressure to the piezoelectric discs.

DSP This is an abbreviation for digital sound processing, which is the process of digitally adjusting the input signal input of the speaker system to get a flatter frequency response.

Enclosure The enclosure is the whole structure around the speaker driver and sometimes houses the amplifier. The speaker chamber is considered a part of the enclosure in this project.

Exciter The exciter is the vibration module in a DSP or MAP; it moves the surface to create audio.

Foil The foil is the circuit to which the piezoelectric discs are connected.

Foldable devices With foldable devices, foldable laptops and foldable tablets are described in this report. The foldable smartphone group is excluded from this term.

Frequency A frequency is a specific sine wave vibration which is described with the unit of Hz.

Frequency range The frequency range of a speaker gives the minimum and maximum frequencies a speaker can produce while staying within a certain loudness range.

Frequency response The frequency response is represented in a graph with the frequencies on the x-axis and the loudness on the y-axis. This graph shows how the loudness levels for the speaker change when different frequencies are played.

Haptic feedback The term haptic feedback describes the action of a movement response to indicate an action to the user when they touch or hold that element.

Loudness The loudness is measured in dB SPL in this report and describes the energy of the vibrations of the audio that comes out of a speaker.

MAP This is an abbreviation for multiactuator panel, which is a sub-group of DML's. The multiactuator panels consist of an array or matrix of exciters where DML's often have one exciter.

Objective audio testing In the objective audio tests, the audio is measured with microphones and processed in computers to visually represented the frequency response.

Personal mobile devices The term personal mobile devices is used in this project to describe laptops, tablets and smartphones as one type of device.

Piezoelectric actuator A piezoelectric actuator is a piezoelectric element that is used as an actuator which uses the current to motion properties of piezoelectric ceramic.

Piezoelectric disc A piezoelectric disc is a single layer piezoelectric element that is used in the Aito stack as both an actuator and a sensor.

Piezoelectric element The term piezoelectric element is used in this project to describe a component that uses the properties of piezoelectric ceramic; this can be either for actuation or sensing. Abbreviations for this term are piezo or piezoelectric and the plurals of these abbreviations piezos or piezoelectrics.

Piezoelectric sensor A piezoelectric sensor is a piezoelectric element that is used as a sensor which uses the motion to current properties of piezoelectric ceramic.

Pink noise A pink noise file is used in objective audio testing; it consists of all audible frequencies with the same loudness levels that are played at the same time.

Resonance peaks A resonance peak is one of the elements that cause distortions. These peaks occur when the vibrations correlate with the natural vibration of a material.

Sensor An sensor is an electrical component that gathers data with a digital input signal; this input can be many things. For this project, the input of a sensor is the difference of current. The difference indicates the pressure that is applied to the surface.

Sine wave sweep A sine wave sweet is used in objective audio testing; it consists of all audible frequencies with the same loudness levels that are played in sequence from the lower to higher frequencies.

Sound The word sound is used in this project to describe audible vibrations which can be music, voice recordings or the clicks of the haptics. It differs from the term audio, which only relates to the musical aspects of audible vibrations.

Sound lab A sound lab is an environment in which audio testing is done; this is a room with damping to achieve little to no background noise.

Speaker The term speaker indicates in this project the full product, so enclosure with the speaker chamber and the speaker driver(s).

Speaker chamber The speaker chamber is the area behind the speaker driver in which air is moved with the vibrations of the driver.

Speaker driver A speaker driver is the part of the speaker that creates the vibrations by applying a signal to it with the correct voltage and current.

Speaker system The term speaker system is used in this project to indicate multiple speakers that are connected to produce audio.

Stack (design) A stack or stack design is the layer composition Aito uses to create a structure that can provide haptic feedback. It consists of a top layer, dot, foil and carrier which are stuck together.

Subjective audio testing In the subjective audio tests, the audio is defined by participants by letting them describe their perception or expectations of the audio.

Top layer The top layer is a part of Aito's stack design. Underneath this layer, the piezoelectric discs are placed.

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Project Introduction

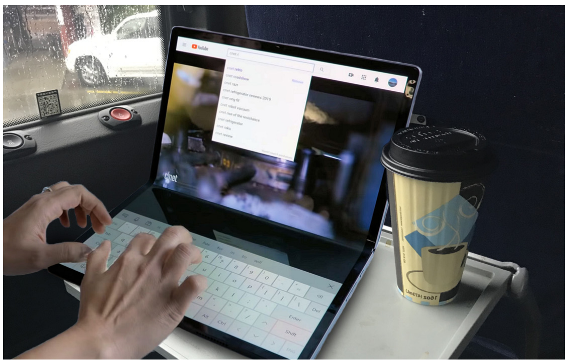
What is it all about?

1.

What if your flat rigid touchscreen had more depth than only the visual effects of buttons with shadows? What if you could also get the feeling of movement when you are pressing these buttons on your screen? Well, this technology already exists and is being further developed by Aito, a company specialised in giving haptic feedback with piezoelectric sensors. They have created a system that sits underneath (seamless) surfaces to detect touch and provides haptic feedback accordingly. But what if we take the previous scenario a bit further? What if this new technology could also create audio? Would it be possible to turn the whole screen into a surface speaker, instead of having small speakers that are not even facing the right direction? We could end up with the scenario below. This scenario shows Aito's innovative technology in combination with another innovative technology, foldable tablets/laptops. However, it is difficult to convey in the scenario with text and images what the experience of audio and haptic feedback is. It is everywhere in this scenario, it is in typing on a flat surface, in drawing on the screen (either with a pen or your finger), in watching a video and in flipping a page in an e-book. Besides the new, and hopefully improved, user experience Aito would also benefit from an implementation in foldable devices. For Aito, an audio implementation would mean that they could offer a two in one solution to their clients. This would create an added selling point beside their already existing selling point of their solution: decreased thickness, local haptic feedback and seamless implementation.

1 This is Frank. He is the father of Lily and works at an advertisement consultancy.

2 Before he leaves for work, he takes his foldable of the charger and folds it, so it fits in his bag.



3 On his way to work, he already answers some emails on the tablet by folding it in laptop modus.

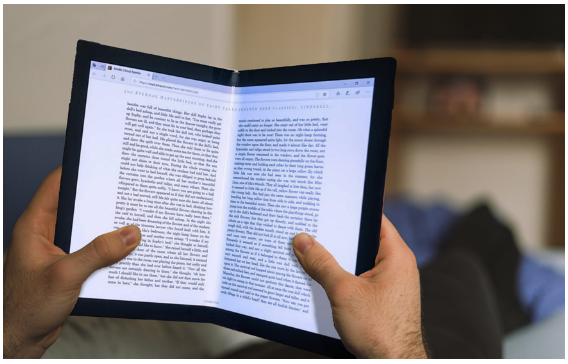
4 During a client meeting, Frank uses his tablet to draw an impression of how the final result will look.

5 When his meetings are over, he goes to his desk where he puts the tablet in the dock to use the full screen as a monitor.

6 In full-screen mode, both halves can function as a speaker, which creates a stereo effect.

7 When Frank gets home, Lily can play a hide and seek game on the tablet. The game implements sound location and touch.

8 Due of the lockdown, Frank has to Skype with his friends to have a game night. He can simultaneously see his friends and the game.



9 Before he goes to sleep, he reads some chapters of his book in bed with the night-time settings on.

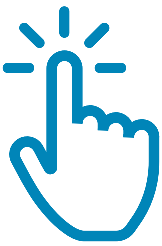
10 When the tablet has reached the end of its life, it will be disposed of. Because of the elimination of speakers and a keyboard, less plastic and critical materials will be thrown away.

1.1 Assignment

To achieve the previously described scenario, Aito needs to further develop their technology to offer an audio solution with their system. Aito has done little research into the audio possibilities of their system in terms of audio quality and voice clarity (appendix 8.1, Aito audio). Where the audio study is under-researched, the haptic feedback received a more thorough approach. That is why this project mainly focused on the needed innovations revolving around audio rather than the haptic feedback part of the system. This project explored the possibilities in the field of audio design and researches how these will integrate into the Aito system with feasibility, desirability and viability in mind (appendix 8.2, Graduation Project Brief). The assignment definition for this project was the following:

"Explore how the current Aito system can be adapted to give a haptic and sound output for a tablet by changing the electronics, software or mechanical structure. The findings of the exploration will need to be shown in a proof of concept prototype for the tablet, which will show the user interactions with the haptic and sound combination."

The choice for the tablet was the first element of the design context; with this context, the audio explorations began. This device was deemed a good fit for the integration of haptic feedback and audio with piezoelectrics and was made based on the following two aspects:



The first aspect is the use of a touchscreen to interact with the device; this interaction relies on touch in which haptic feedback would be beneficial. Aito already works with the technology that tracks the placement of the finger in their Haptile Trackpad, which is called cap sense. A touchscreen would visually support the haptic feedback as an extra part of the experience; the visual elements on the touchscreen are easily altered where mechanical haptic structures need to be rebuilt. For a tablet, this would mean that keyboard layouts can be easily swapped, a qwerty keyboard becomes azerty with a simple setting adjustment. While a touchscreen is not a unique feature of a tablet, multiple devices are implemented with touchscreens nowadays. The tablet was also selected based on another aspect.

This second aspect is the multimedia capability of a tablet; a tablet is a versatile device on which users can take notes, play games, watch videos or browse the internet. Where devices such as elevators, refrigerators, intercoms and car consoles have touchscreens that would benefit from haptic feedback, their use for audio is less prominent. These devices might need a speaker for voice commands or calling purposes, but a tablet will need speakers in a broader range of use cases. Because the tablet relies heavier on audio, the limits of the new system are held up to a higher standard. It might be the case that the system is not suitable for the use cases of a tablet but would fit the earlier mentioned devices better. By aiming for the most challenging standard first, the lesser challenging criteria can already be met in the process; this is easier than doing it the other way around.

This selection does leave some other devices that fit the multimedia capabilities and have a touchscreen. These devices are within the groups of smartphones and laptops. These devices were not selected based on different reasons for each device. The reason for not using the smartphone as the device for explorations is that smartphones are deemed to have a lower demand for haptic feedback. In the use cases where a keyboard is needed on a touchscreen, haptic feedback could improve the experience. A smartphone is too small to implement such a keyboard. A laptop would benefit from a thinner haptic feedback keyboard, but the use cases for a touchscreen are the reason the laptop was not selected. Although some laptops are integrated with touchscreens, the focus of interaction still lies mainly on the keyboard and mouse. In the end, the tablet is large enough to fit a qwerty keyboard for ten-finger typing and relies on touch interactions, which makes it the best device for explorations with haptic feedback and audio.

1.1.1 Process

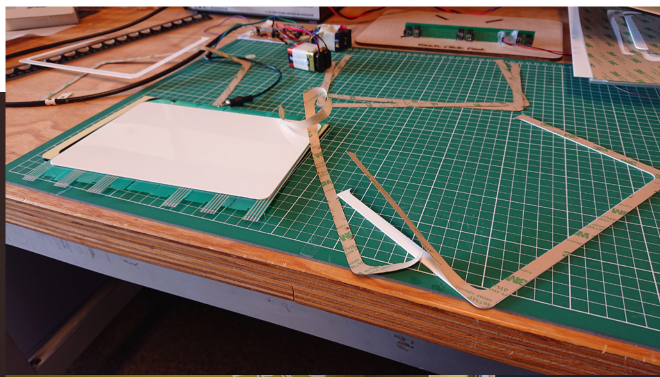
Gathering information was the first step in this graduation project; this was done to identify already existing solutions and define the methods that were used to design these solutions. This research was done by finding relevant literature, meetings with audio engineers and gathering information online. Besides the speakers, new developments on the tablet market were researched as well. To better understand the tablet market, interviews were conducted with companies that develop these products. The found information with all the interesting findings can be found in chapter 2, State of the art.

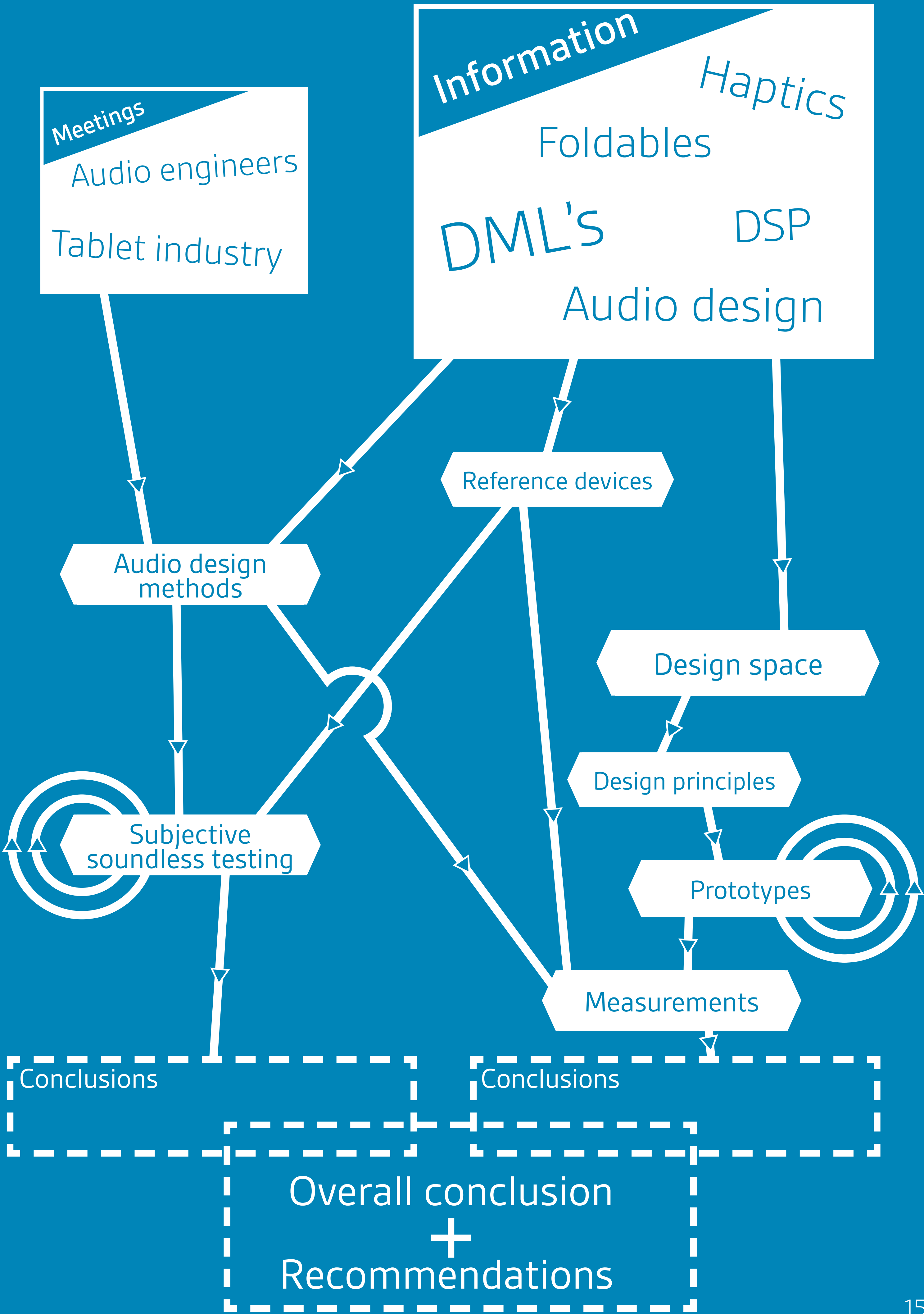
The next step in the process was to use the found methods to design and test the new speaker setup. This part is where the process splits into the user focussed part and the technology focussed part of creating a speaker (chapter 3, Approach). The user-focussed section (chapter 4, Subjective method) describes how the user was involved in the exploration of the new speaker system. This part of the process needed multiple iterations due to the influences of Covid-19. The traditional methods that were found in the research did not fit with the quarantine restrictions in the Netherlands, because they required testing with participants in real-life. So an online approach was adopted to still get user input and feedback for the project. The other part, the technology part, describes the technology exploration that was done to validate the audio quality of the new speaker system. This part is explained in chapter 5, Objective method; where various prototypes are validated by doing measurements according to the found methods during the information gathering. In this part of the process, there were also multiple iterations. These were based on results of the various tests.

The last step of the process was to combine both the user and the technical parts to compare the measured results of the prototypes with the gathered user input. This comparison, which is made in chapter 6, Discussion, concludes if the new technology is feasible and would be desired by users. Furthermore, future recommendations were made based on the limitations of this graduation project and the overall results comparison.

The full process is visualised on page 15; this visualisation shows how each exploration links together to get to a conclusion if the technology would be something Aito can achieve with their technology. Figure 2 shows the activities that were done regarding testing, measuring and prototyping.

Figure 2, Testing, measuring and prototyping




Meetings
Audio engineers
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Information
Haptics
Foldables
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DSP
Audio design
Reference devices
Audio design methods
Design space
Design principles
Subjective soundless testing
Prototypes
Measurements
Conclusions
Conclusions
Overall conclusion
+
Recommendations

State of the art

What is already explored?

2.

To define a design space for this project, the three different technologies that play a role in this project were analysed. The design space, paragraph 2.4 Design space on page 42, details the possible directions which can be researched to explore the audio functionality with the Aito setup. The three technologies that are involved in this project are:

- **Tablets** and the innovations surrounding these devices. The analysis for this topic is discussed in paragraph 2.1 Tablets innovation on pages 17 to 19.
- **Haptic feedback** and the approach Aito and their competitors have to achieve this. The information regarding this topic can be found in paragraph 2.2 Aito and haptics on pages 20 to 27.
- **Speaker** and their design principles to develop a well-performing product. This topic is explained in paragraph 2.3 Speaker design on pages 28 to 41.

2.1 Tablets innovation

The first personal mobile device is the personal digital assistant, abbreviated to PDA as a term for these devices. The purpose of this device was to message other people, store events in the calendar and make notes. The PDA did not focus on audio, which can be concluded from the manual of the MessagePad. In this manual, there is no description of audio and only on message notifications. Before the tablet looked as we know it nowadays there was a mobile phone and tablet hybrid period; in this period the Nokia 770 was released in 2005. On this device, the user could browse the internet and listen to the radio or watch videos. With audio being one of the features of this device, it had a large bezel where the front-facing speakers were placed. Nokia later updated the 770 with the N800, which also had an audio focus. Both of these devices can be seen in figure 3. The first tablet in the shape we are familiar with is the Apple iPad which was released in 2010, and shortly after that came the Samsung Galaxy Tab. With this new design, the speakers were moved to the sides of the device. This move created a screen without a large bezel for the speakers.

The uses for tablet range from watching videos to making notes and from playing games to reading an e-book. Netflix has released data on how many of their customers use a tablet for streaming their video's, the percentage of tablet users is 5% which is the device with the lowest rate. Most of their users watch Netflix on television, which is 70% and after the TV, the laptop has the second-highest percentage with 15% (Richter, 2018). Not only Netflix shows a lack of interest in tablets, but the total tablet market is also decreasing in sales. This decrease might be because the tablet is an in-between device. It is not as portable as a smartphone while they are nowadays almost equal in performance, but a tablet is by far not as powerful as a laptop (Richter, 2015). Another possibility for this decline is the less frequent model update compared to smartphones. Where smartphones are offered when the customer gets a new cell phone plan, the tablets cannot be obtained via such offers; they have to be bought in (online) stores as a single purchase.

Figure 3, N800 (left) and Nokia 770 (right)

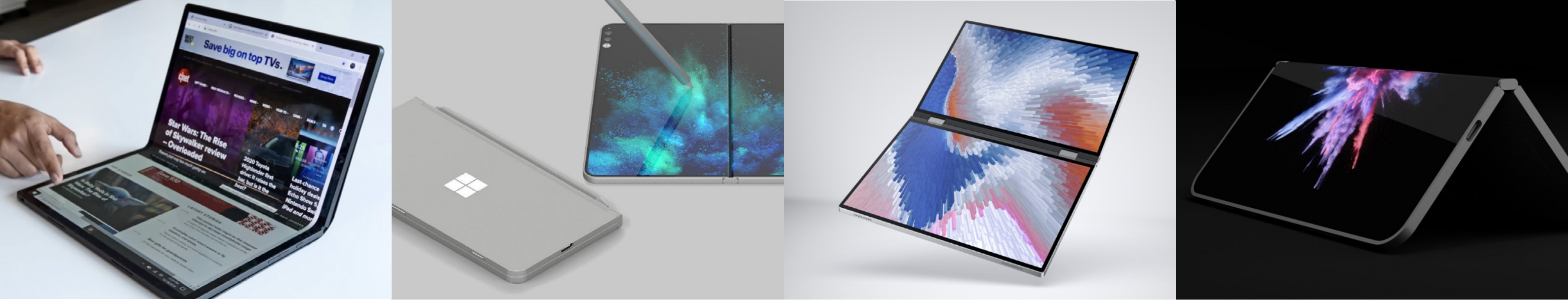


Figure 4, Foldable concepts from left to right: Intel, Microsoft, Dell and Microsoft

With a saturated tablet market and the main difference from smartphones being the size of the screen, companies are trying to take a new approach with their tablets. The current tablet designs are updated to try and compete with laptops, which is the approach of Apple with their iPad Pro (appendix 8.3, Tablet speaker collage). Others strive to innovate by making foldable tablets to create a new experience for tablet use. Several brands have released their concepts for the approach of a foldable tablet which are: Microsoft, Lenovo, Samsung and Dell. The designs of these concepts can be seen in figure 4. Only Lenovo has released a foldable tablet which is ready for purchase, which is showed in figure 5. There seem to be several approaches to design a foldable tablet.
There is a group of concepts which use the two separate screens connected by a hinge while others use a new technology in which an Oled screen is foldable. Foldable Oled screens differ in two ways from the commonly used screens in tablets or laptops. The first difference is the lack of a backlight, which is necessary for LCD screens. This elimination of a component means that Oled screens are thinner than their predecessor, the LCD screen. The second difference is the elimination of glass in the structure of the foldable Oled screen, which allows the screen to fold. The lack of glass does mean that the screen is more prone to scratches, but you get a flexible thinner screen in return. It is estimated that foldable Oled displays will be between 1mm and 0.5mm thick. It is unclear what the support structure needs to be for these foldable screens. Each company is secretive about the development because most are still in the concept phase. (appendix 8.4, Oled screens)

Besides the foldable tablets, there are also concepts for foldable laptops; the differences between them can be found in the hardware inside and possibly the size of the screen. It is difficult to make a black and white separation between these groups; it is more of a greyscale on which these devices can be pinned down. The presentation of both concepts shows that companies try to mix the large screen of tablets and the work experience of a laptop. For the last use case, the concept devices come with a separate keyboard, which is either a loose accessory or attached to a flip-case. Not only foldable concepts offer a separate keyboard, but Apple is also doing the same with their iPad pro. They offer a separate stand with an integrated keyboard for 400 dollars. The keyboard attachment allows the user to use the whole screen while typing. The need for separate keyboards indicates that a pleasant typing experience cannot be guaranteed when the user must type of a smooth surface.

Findings

- The current design for tablets focusses on as much screen space as possible.
- Tablets have a prominent multimedia purpose, but their use and purchase numbers are declining.
- The tablet market is trying to innovate by leaving their saturated market and focussing more on the laptop market with high-end tablets.
- There are two ways to separate the types of foldable devices. The first would be a separation on screen, where there is the option of a double screen device or a foldable one screen device. The second separation can be made in terms of performance, which can be on the tablet or laptop side. However, the difference between tablet and laptop is more of a greyscale rather than black and white.
- The use of a separate keyboard accessory indicates that the typing on the screen lacks in the foldable devices. With haptic feedback inside the screen, this accessory could be eliminated, which means lesser components are needed.
- The Lenovo ThinkPad X1 Fold is the only foldable device that can be used for size specifications. There, is no information on the Oled thickness, so it is estimated to be under 1mm, which is the size on the higher end of the spectrum.

Figure 5, LenovoThinkPad X1 Fold

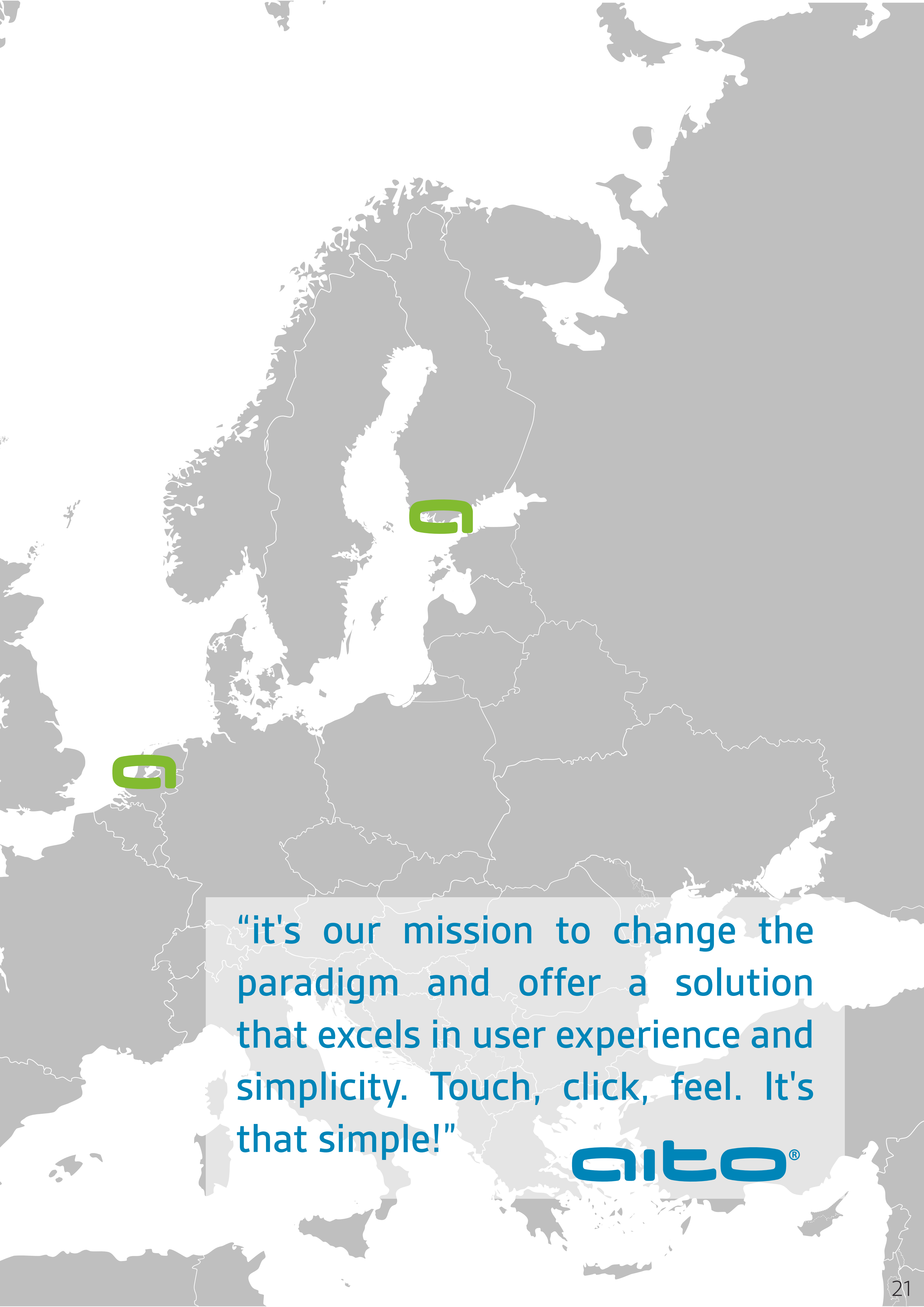
2.2 Aito and haptics

Aito, a company located in Amsterdam and Helsinki, was created in 2012 when the Dutch company d-Switch and a team of Nokia engineers merged to combine their knowledge for piezoelectric sensors and actuators. One team had an expertise for sensing pressure differences with piezoelectrics, while the other group was more familiar with the actuating side of piezoelectrics. Both these specialities combined allowed Aito to create a system which could both sense pressure and respond with haptic feedback accordingly. The advantages of this system are primarily the design freedom to implement buttons and limiting the mechanical components; the last advantage results in a possible decrease in the overall thickness of the system. But the main advantage is a richer interaction with a surface that first was rather stiff. With this system, such a surface gets the perception of much more depth.

Currently, Aito is still a start-up with a focus on growing and scaling up. Their focus has shifted over the years from automotive and house appliances to personal electronic devices, such as computers, laptops, phones and tablets. The business model of Aito can be split into two parts. The first is the licensing of their software to their clients; this is a business to business (B2B) selling approach. The second part is the service Aito provides when developing, together with the client, a proof of concept prototype or working product. In this second part, Aito positions themselves more as a design agency with specific knowledge about one technology, namely their own. Helping a client to build a proof of concept prototype was mainly done for the automotive industry. Unfortunately, these products often stayed just that; proof of concept prototypes. For their new clients in the personal electronic devices industry, Aito is trying to develop ready to build in testing kits, an example of such a product is the Haptile Trackpad in figure 6. If a client is interested in using Aito's technology in, for example, their laptop. They could build in this Haptile Trackpad test kit in their laptop prototype. So instead of having multiple products with each their own design and details that will influence the mechanics of Aito's system, Aito has set the system boundaries themselves, which allows use by multiple clients. These boundaries enable their clients in prototyping faster on their own. If they would like to implement the solution, then they can approach Aito to make a production-ready product.

But of course, clients always want more than what you are offering, so a question that is often raised by clients in the personal electronic devices industry is whether Aito's system could also produce sounds such as music or voice recordings. While Aito has done some research about the audio possibilities with their system (appendix 8.1, Aito sound research), they have not tested how good the audio quality is and how to improve this. The next paragraph explains why it could be possible to use Aito's technology for audio as well by explaining how their system works.

Figure 6, Haptile Trackpad demo



"it's our mission to change the paradigm and offer a solution that excels in user experience and simplicity. Touch, click, feel. It's that simple!"

aito®

2.2.1 Technology

To explain how Aito's technology works, it is essential to explain the principle of piezoelectric elements. Piezoelectric sensors or actuators are made from two, or multiple layers of a metal and a piezoelectric ceramic. In Aito's case, they use a two-layer piezoelectric disc that consists of one layer of brass and one layer of the piezoelectric ceramic; this piezo type can be seen in figure 7 on the right. The standard size Aito uses in their systems is 15mm in diameter and 0.23mm in height. The smallest size they use in their system is 10mm and the biggest around 25mm.

Figure 7, Two layer piezoelectric disc

The most important properties of a piezoelectric element are located in the piezoelectric layer; this layer transforms a current into movement or movement into a current. The first mentioned option, turning a current into action, is displayed in figure 8. When the positive is connected to the ceramic, and a negative to the brass, the ceramic will stretch. When this is reversed, the ceramic will shrink. By controlling the current, switching the negative and positive directions, you can create an in and outwards movement with the disc. This in and outwards movement, is the principle of a speaker, which will be further explained in chapter 2.3 Speaker design on page 28. So in theory, this disc could be used for the audio purpose of this project.

The second mentioned option, transforming movement into a current, is used to sense the change in pressure. The same principle of shrinking and stretching the ceramic is used, but now a current is created from the movement. To make use of the creation of a current, a circuit is made that can detect the changes in this current and can calculate the amount of deflection of the piezoelectric disc. The current can be as low as only a couple of millivolts (mV), so the detection must be accurate enough to measure these types of changes. A well-known example of measuring pressure with piezoelectrics, and in this case, air pressure differences, is the microphone. The vibrations of the sound will let the piezoelectric element vibrate, which creates current differences which can be transformed into a digital audio signal.

Aito makes use of the piezoelectric by continuously switching between the current to motion and the motion to current properties of the ceramic (figure 9). This switching creates a sensor that can be an actuator and an actuator that can be a sensor; this results in a similar type of principle as a standard mechanical button. However, instead of a lot of mechanical components in Aito's system, it is only the piezo and where the mechanical button needs a redesign to change the feeling of a click Aito can do this programmatically. By merely altering the voltage that is used for the pulse or changing the pulse itself, you can create a whole different feeling and sound. This changing allows for multiple variations in feeling by switching between a softer or stronger click and between a smooth click or a very sharp click. In the software of the chip is determined how the pulse should look like for specific values, smooth/sharp are one value, and soft/strong are another value. This pulse is then created by the electronics system which can boost a current of 12 volts up to 200 to 400 volts, based on the settings for the preferred pulse. This pulse has to be designed by continuously testing it with users to ensure the feeling that is aimed for is achieved because a rating on the smooth/sharp and soft/strong scale is not descriptive enough to eliminate experiencing the sensation.

The sensing and actuation performance is not only influenced by the capabilities of the software and electronic setup of Aito's technology, but the

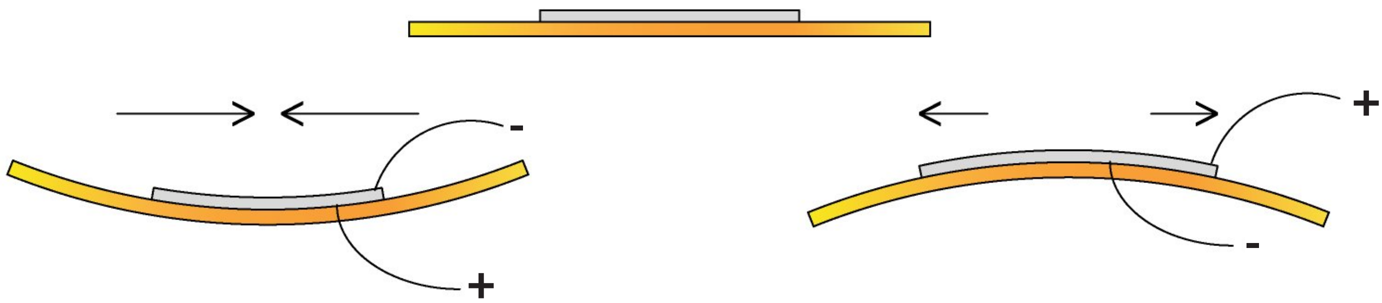


Figure 8, Bending principle of a two layer piezo disc mechanical structure is also just as important. For example, the wrong material selection can dampen the vibrations, which limits the intensity of the haptic feedback. An example of the mechanical structure, or stack design as Aito refers to it, can be seen in figure 10. For each new implementation, this stack design has to be adjusted to give the best possible haptic feedback. The general structure of a stack consists of the following elements: a top layer, glue dots, foil with piezoelectric discs, glue layer to fixate the foil, carrier onto which everything is assembled. Each component of the stack has its own set of design rules which are the result of the research Aito has done over the years. These rules will be applied in the design process to achieve a well-performing mechanical structure. This structure will be found through multiple iterations in which each of the earlier mentioned elements can be changed.

Top layer
For the top layer, the primary design constraint is how the edges transition to other possible surfaces. Aito has determined that fully fixing the edges in both the x and y direction decreases the haptic feedback drastically. Fixation in only one of the axis still allows enough bending for proper feelable feedback. The top layer can be made out of a wide variety of materials. Yet, as earlier stated, the material choice will impact how the vibrations will react inside and along the surface of the material. A less stiff material, such as plastic, could mean that entirely fixated edges will have less of an impact because the surface can still bend in between the edges. For stiffer materials, such as glass, bending between the edges would not occur and thus limiting the haptic feedback.

Dot
The most common design for the dot is 5mm in diameter and 0,15mm in thickness. Both these dimensions are not set in stone and can be altered to find the optimum in performance. The dots redirect the downward pressure to the middle of the piezoelectric discs to improve the sensing. The smaller the dot, the more focussed the pressure is on the individual piezoelectric discs. The dots are placed underneath the top layer and onto the foil in the middle of each piezoelectric disc.

Foil
The foil can be designed freely and can be made to fit most shapes. However, the foils are single-layered, meaning that power lines cannot overlap. Each piezoelectric disc needs a separate power line to control all piezoelectric discs in the circuit individually. The ground line can be connected to all piezoelectric discs. For a foil of 24 piezoelectric discs, this means that 24 individual power lines will run through the foil which should not overlap

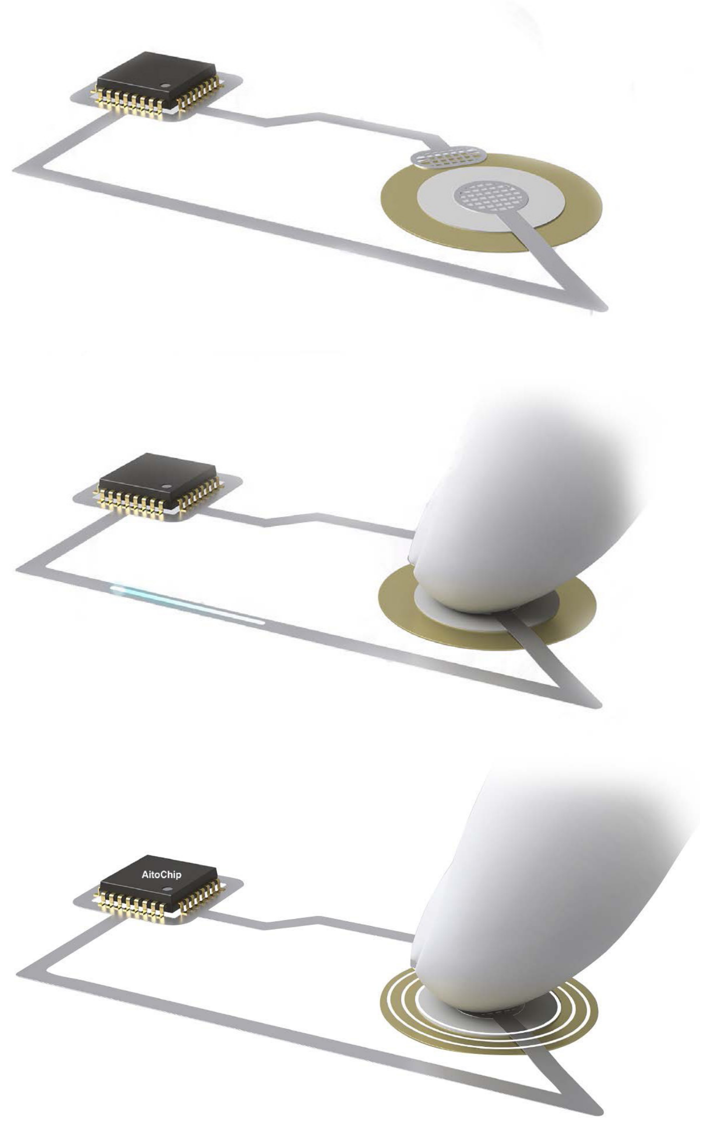


Figure 9, Working principle of sensing and actuation

with each other or with the ground line. For the prototype of haptic integration into a tablet, Aito used a matrix setup with rows in the x and y-axis. Their Haptile trackpad uses a diamond-shaped matrix where the rows run diagonally. Both these types of matrixes are depicted in figure 10.

Foil adhesive
The foil adhesive layer is needed to keep the top layer and carrier connected; it is attached to the foil and the carrier. The piezoelectric disc itself should not be fixated because this would limit the expansion of the ceramic and thus restrict the bending. Therefore, the glue layer should leave a 2mm space around the piezoelectric discs to connect the foil but not the disc. This type of fixation of the piezoelectric discs will cause a pre-pressure on the piezoelectric discs, which will improve the sensing.

Carrier
For the carrier, the structure must not bend when pressure is applied. This pressure can be created by the press of a finger or with the activation of the

discs. The bending will influence the sensing accuracy and will heavily impact the haptic feedback because some of the energy of the discs will go into bending the surface of the carrier rather than bending the surface of the top layer. Therefore, the carrier should be stiffer than the top layer. By using either a rib structure or more rigid material by substituting metal for plastic, for example, this increased stiffness can be achieved. Another essential design feature for the carrier is the area in which the piezoelectric discs can bend. This area is 2mm smaller in diameter than the piezoelectric discs with three extra cut-outs to allow space for the connection between the piezoelectric discs and the foil circuit. The additional cut-outs also provide some stability to the discs due to their triangular positioning. Aito has determined that a thickness of 0.25mm would be enough space not to limit the movement of the piezoelectric discs when the haptic feedback pulse is applied. However, they have never tested if 0,25mm would restrict the movement when an audio pulse is applied.

Figure 10, Stack design of the Haptile Trackpad and the possible matrices

Findings

- The best way to determine if the haptic feeling is correct is by testing with users, rather than looking solely to the measurements.
- The edges of the top layer should have a minimal fixation to ensure well-performing haptic feedback.
- Between the top layer and the piezoelectric discs, dots should be placed for better sensing.
- The carrier should be stiff enough to limit the piezoelectric discs from bending the carrier.
- The carrier should allow a minimum movement of 0,25mm, but audio might need more movement space.
- The cut-outs in the carrier to allow the piezoelectric discs to move should be 2mm smaller in diameter and have three extra cut-outs for the foil connections and stability.
- The piezoelectric disc themselves should not be glued; they should only be attached to the foil
- The foil design has to account for a single layer circuit; lines cannot overlap each other.

2.2.2 Competitors and partners

Aito is not the only company that sees value in adding haptic feedback to our primarily static surfaces. There are a lot more, and each of these companies have their approach to achieve a haptic feedback sensation.

When looking at the market for haptic feedback incorporated in screens, there is quite a wide variety of possibilities to find with a simple Google search. Some companies use electrostatic to simulate texture, such as the company Senseg. While others, Tanvas for example, use vibrations to achieve the same feeling of texture. There are even more innovative solutions which use gels that can harden based on the desired feeling, the company that has developed this solution is GelTouch Technologies. Although these companies also operate in the haptic feedback market, they are not deemed Aito's primary competitors. The primary competitors for Aito lie in the markets for haptic feedback with piezoelectrics and audio with piezoelectric speakers.

For the first competitor market, haptic feedback with piezoelectrics, there were two main competitors defined along with one outlier that is still an interesting competitor. These competitors are:

Redux/Google

Redux is an interesting competitor. The reason for this is that they no longer exist; they have become a part of Google. The takeover by Google has resulted in Redux's technology no longer being available for public access or for other companies to use this technology in their products. For Aito, this would mean that their technology would not be competing with Redux's technology to get deals with clients to implement haptic feedback in their products. But Aito's technology would compete when it is implemented in products which could be

Figure 11, Redux actuators

compared to Google products that are implemented with Redux's technology. Another scenario would be that Google would start to offer their technology to clients of Aito, but because the takeover was so secretive, this seems unlikely. The still available data about Redux shows that their technology will be placed on the edges of a screen rather than directly underneath the spot where haptic feedback is wanted. Figure 11 shows one of the first modules of Redux, which uses a coil-based actuator, and figure 12 gives an impression of the haptic feedback. In the later stage of their development, Redux revised their module to one that used a piezoelectric based actuator. With their software, Redux could let the surface vibrate with hotspots in the areas where haptic feedback was needed. Besides creating these hotspots, the vibrations could also be used to turn the whole surface into a speaker. It is not clear how well their module performed in terms of audio or haptic feedback, but good enough to attract Google's attention.

Boreas

The technology Boreas has developed is more similar to Aito than Redux. Boreas has developed software that can sense and actuate at the same time, but the placement of the piezoelectric element is more localised compared to Redux's approach. Boreas suggests a structure for their technology where the components are placed underneath the

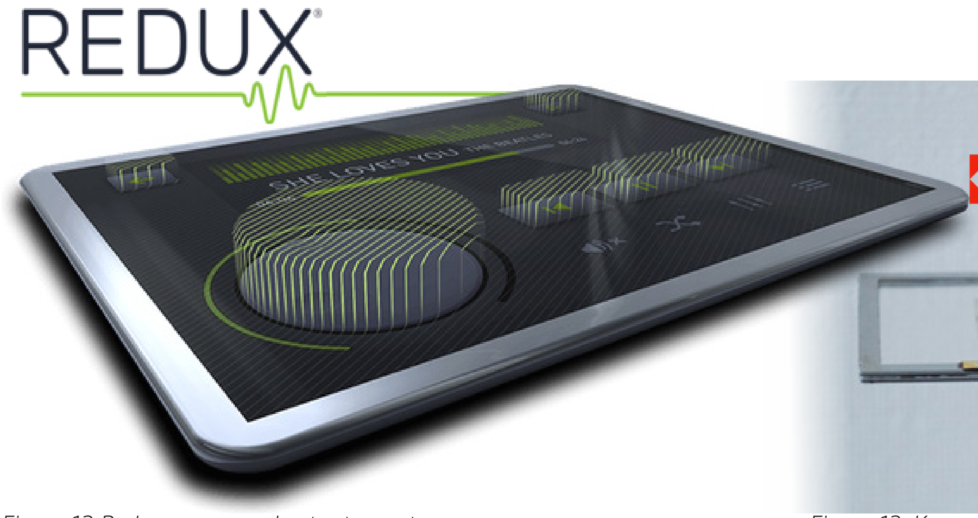


Figure 12,Redux sensor and actuator system

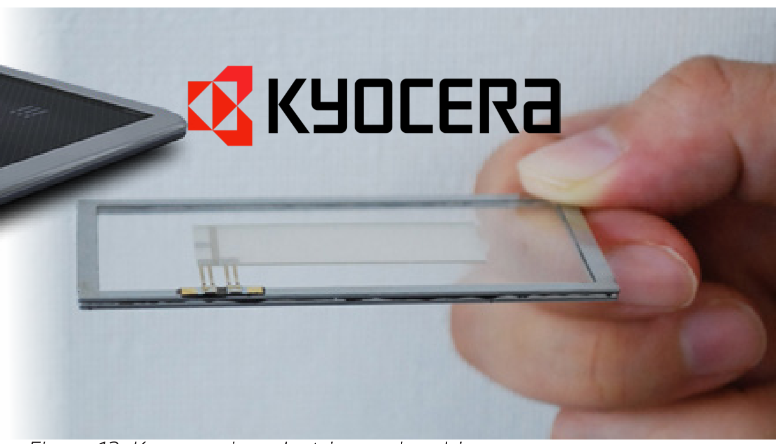


Figure 13, Kyocera piezoelectric speaker driver surface and not at edges. The difference with Aito's structure is the use of different piezoelectric elements, where Aito uses discs Boreas uses plates. A good comparison would be the demos for trackpads of both companies. Aito uses eight piezoelectric discs to get even haptic feedback and sensing across the surface, and Boreas uses one piezoelectric plate to do the same thing (figure 14). The chip and structure Boreas has developed is only usable for playing a haptic pulse and not an audio pulse.

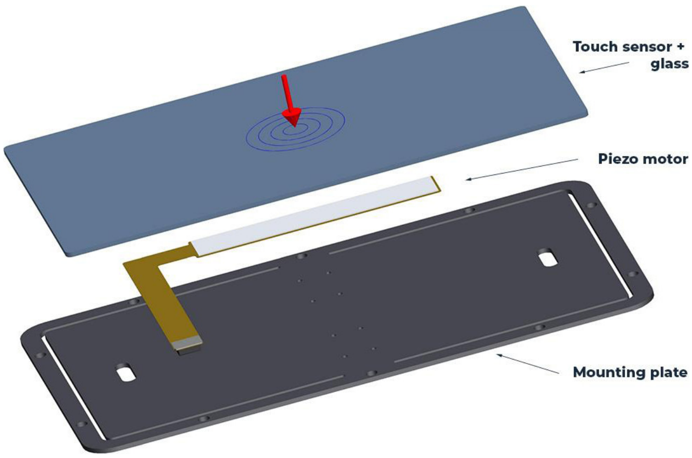


Figure 14, Design Boreas trackpad

Apple

Apple is a bit of an outlier in this list with their Apple Force Touch trackpad (figure 15) because it does not use piezoelectrics for the haptic feedback. Instead, their system uses a magnet to move the whole surface of the trackpad to give the impression of a downward press. However, this type of system will be competing with the piezoelectric approaches of trackpads and is, therefore, still a competitor to acknowledge. When comparing Aito's Haptile Trackpad with the Force Touch trackpad, Aito's solution is thinner, cheaper and uses fewer mechanical components. It seems that Aito's technology does not need to worry about Apple's technology, but this technology still needs some development before it can be entirely accepted into the laptop market.

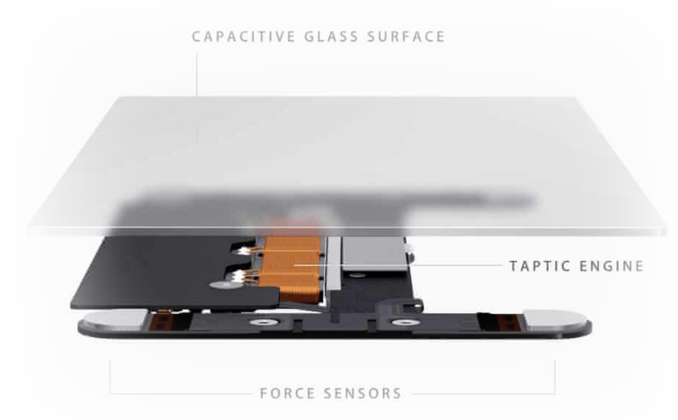


Figure 15, Apple Force Touch trackpad

For the second competitor market, audio with piezoelectrics, there were three main competitors defined. In this chapter, the specifics of the different piezoelectric speakers are not discussed; this is done in paragraph 2.3.2 Coil versus Piezoelectric on page 30. One of the defined competitors is currently a partner of Aito, so the term competitor does not quite fit. The identified companies are:

Sonitron

This Belgian company is specialised in audio with piezoelectric elements. They have created buzzer and alarm components as well as a piezoelectric speaker driver. The piezoelectric speaker driver consists of a plate of metal onto which the piezoelectric ceramic is attached (figure 16). When a current is applied, the ceramic will bend, which causes the metal to bend as well. Sonitron advertised the speakers as environmental proof due to the resistance to water and dust after being installed. The speaker needs to be placed into a cut-out and can be secured with either glue or screws. These speakers are specifically designed for audio and cannot be used for any haptic feedback purposes.

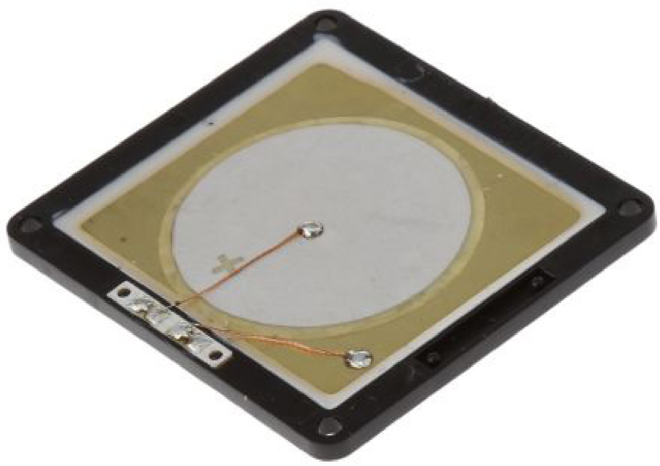


Figure 16, Sonitron piezoelectric speaker driver

Kyocera
Kyocera has developed a similar type of speaker as Sonitron in terms of installation; the speaker has to be placed into a cut-out. However, the design of the speaker itself has a different approach. The speaker consists of a plastic film in which the piezoelectric components are placed. When a current is applied this film will vibrate with the piezoelectric elements (figure 13). The film in Kyocera's speakers is 1mm thick, which is significantly smaller than the commonly used speaker drivers. Kyocera's piezoelectric speaker drivers are used in the curved Oled tv from LG, which can be seen in figure 17. These speakers are also not suitable for haptic purposes.

Figure 17, LG 55EA9800 with Kyocera speakers

TDK
TDK is one of Aito's partners; they offer the type of piezoelectric discs Aito uses in their stack design. TDK offers a wide range of different piezoelectric elements, which range from elements for haptic purposes to parts for transmissions in automotive. They also have piezoelectric audio components in their portfolio, the PiezoListen line (figure 18). The PiezoListen has a different type of attachment; it is secured on the back of the surface instead of being a visible speaker outlet. If a current is applied to a PiezoListen component, it will bend and therefore also bend the surface. This approach allows for a seamless surface in which the speaker is not visible. This solution could be suitable for haptic feedback, although this use case seems to never been tested by TDK.

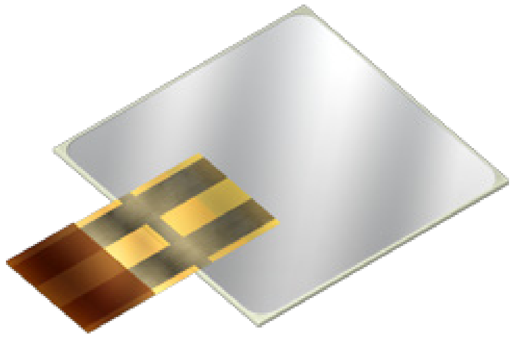


Figure 18, TDK's PiezoListen component

Other suppliers of piezoelectric discs do not seem to focus on piezoelectric speakers and mainly focus on the current products they have. Therefore, a collaboration with TDK seems the best choice if Aito wants to further develop a technology with haptic feedback and audio. With the knowledge of TDK on piezoelectric manufacturing and audio engineering, Aito could design together with TDK an improved piezoelectric disc that fits with the haptic and audio solution. For the new audio approach, Aito can, and maybe even should, partner up with possible clients to use their knowledge about audio and get information about real product structures. The product structures are needed to adjust the stack design to fit the real-life scenario. Otherwise, it will be a lot of guessing. During this project, the tablet industry was contacted to gather insights into their audio approach. The industry stated an interest in the approach of audio and haptic feedback within the same structure, so they seem to be willing to invest in this and start a partnership. Possible partners could be found in the previously mentioned companies (figure 19) that are developing foldable laptops and tablets.

Figure 19, Possible partners to develop the audio functionality with

Findings

- To further develop audio, possible clients could give useful insights with their approach to designing a speaker system.
- A collaboration with a possible client is needed to get details of the mechanical structure from which limitations and possibilities can be determined.
- The partnership with TDK could be used to design a piezoelectric disc that would better fit a combination of audio and haptic feedback.
- There is currently no solution freely available to companies which can be used for both haptic feedback and audio.

2.3 Speaker design

Before we go deeper into some of the more experimental or new speaker solutions, we will first cover the most used speaker setups and the principles behind these. Commonly used speakers are speakers such as your home cinema set, Bluetooth speakers or the speakers in most of your portable devices. The difference between speakers and speaker drivers is that the term speaker is used for the whole system and speaker driver is the electrical component that produces the sound. So, the previously mentioned speakers all have a speaker driver, which uses the principle of moving a cone back and forth to create vibrations in the air. One vibration consists of a compressed section of air, due to the forward movement of the cone, and a decompressed part from where the cone moved backwards. When these air vibrations reach your ear, they will vibrate your eardrum and allow you to hear sounds (Müller, 2015). The spectrum of the human ear has a minimum of 20 hertz (Hz) and a maximum of 20 kilohertz (kHz), the amount of hertz indicates how many vibrations there are within a second (Müller, 2015). Standard speaker drivers use a coil and a magnet to create these vibrations by changing the current in the coil. The coil can either be attracted to the magnet or be pushed away by it. In figure 20, a standard speaker driver is cut in half to show he inside components; in this figure, you can see that the coil is connected to the cone. So when the coil is attracted or being pushed away, it will also move the cone and created the vibrations earlier discussed.

Speaker drivers can be divided into groups according to their response to frequencies. As mentioned, the human ear can hear frequencies between 20 Hz and 20 kHz, but this does not mean any speaker can produce these frequencies. To create a system which can provide as much of the frequency range as possible you will often need multiple speaker drivers, with each their speciality in a specific frequency range. The speaker driver specialised in the lower frequencies, which range from 20 to 100 Hz, are called subwoofers. These speaker drivers produce sounds that are described as the bass portion of the audio. The speaker drivers one step above, which are used to create frequencies around 50 Hz up to 2 to 5 kHz, are the woofers. The frequencies that lie in the frequency range of the woofer is called the mid-range. And lastly, the higher frequencies, 2 kHz and up to 20 kHz are produced by tweeters (JL Audio, n.d.). These higher frequencies, mainly the ones between 2 and 4 kHz, are perceived well by the human ear, this means these frequencies are more noticeable than the other frequencies such as the lower bass frequencies (Müller, 2015) and (Scherz, 2013). To recreate the sound that was recorded or created as accurately as possible, the whole frequency range is needed, this means that the signal must be split between the three speaker drivers. This split is done with a crossover system; this system switches the incoming voltages to the correct speaker driver. In figure 21, such a crossover system can be seen along with the frequencies corresponding to the three speaker driver groups. This crossover can be a single standalone device, or it can be integrated into the amplifier (Benton, 2018).

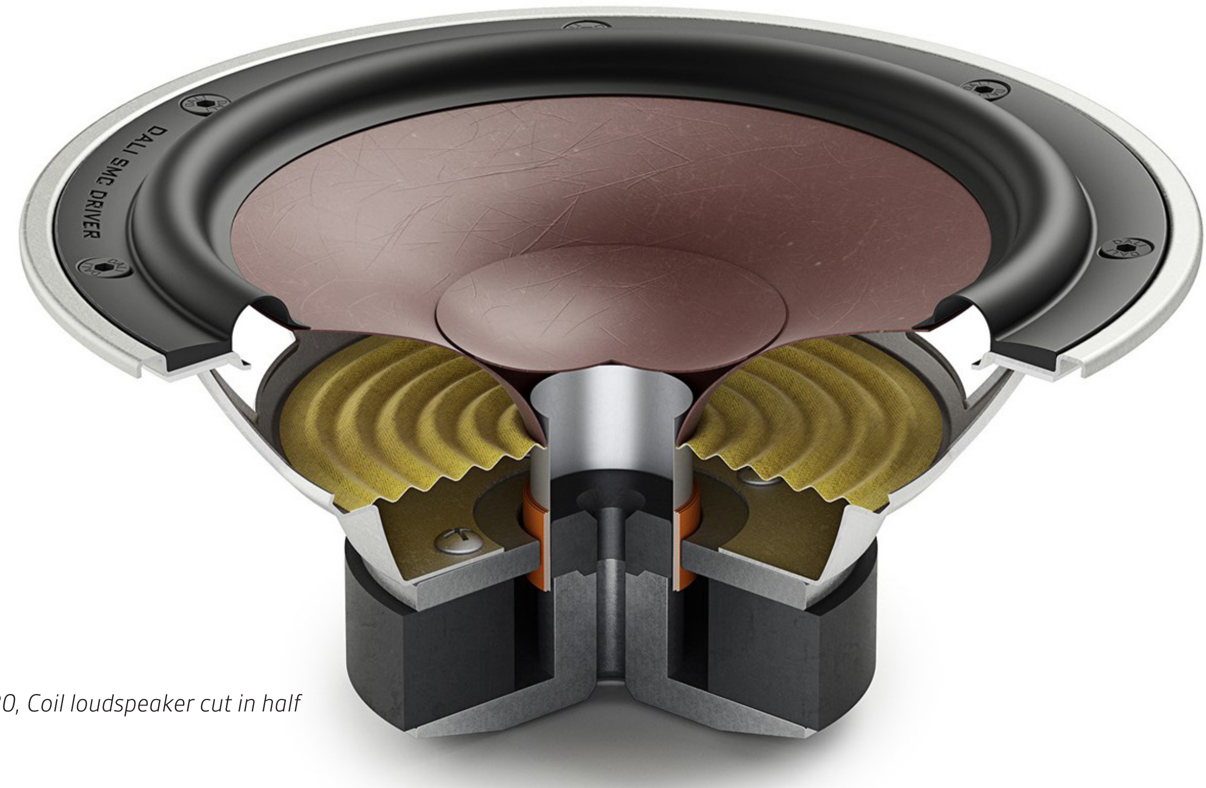


Figure 20, Coil loudspeaker cut in half

An amplifier is needed to amplify the input current to an output current that is suitable for the speaker drivers of the system. The five most used types of amplifiers are the: A, A/B, D, G and H class amplifiers, each with their pros and cons. The difference between these amplifiers lies in how the system controls the input signal to create a higher output signal and the efficiency in which it does this (Munz, 2018). When currents are being switched, heat can be generated as an unwanted effect. If you combine a precise analogue amplifier circuit with a digital sound processing (DSP) circuit, you can get more out of an amplifier. The process of DSP is further explained in paragraph 5.3.1.1, DSP on page 88. Such an amplifier can be called a “smart” amplifier, because it can be adjusted to the speaker driver where it filters the frequencies into two streams. One stream is the frequency range that can be produced by the speaker driver safely, and another one that needs sound processing before it can be played through the speaker to prevent overpowering it (Pickering, 2016). This type of amplifier makes it possible to get much more out of a single speaker driver. It could eliminate the use of multiple speaker drivers, in some instances, if the bass is not necessary. For that type of application, you could only use a woofer/tweeter combination and get close to a system with a subwoofer. Besides the separation in signals for the different frequency, there is also a separation for left and right speakers. This configuration is called stereo sound, where the sound “moves” between the left and right ear. In the case of no separation between left or right the audio is called mono, all the audio out of the speakers has the same signal input. In next paragraph, the amplifying system is further explained in terms of implementation in this project.

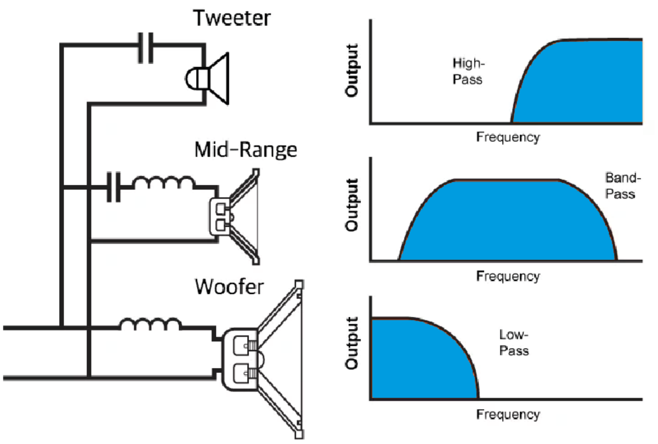


Figure 21, Crossover of the three speaker driver groups

Beside suitable electronic hardware, it is also vital to create a professional design enclosure for the speaker drivers. Good enclosure design is needed to eliminate resonance peaks, to increase volume and to decrease the current, which is necessary to power the speaker drivers. Why it is so important to eliminate these resonance peaks will be explained in chapter 5 Objective Method on page 68. This paragraph will explain how speaker design can help to reduce these if they occur. One way to lower resonance peaks is to change the material of the enclosure; it might be that the material that is being used absorbs too many vibrations and acts like a speaker itself. These vibrations will interfere with the sound coming from the speaker driver causing resonance peaks and inaccurate sound recreation. Another option to limit the vibrations of the enclosure, is to use foam to damp the vibrations inside the enclosure. Thin layers of foam have a minimal effect, so it is best to fill the complete enclosure with foam, especially on places where the air has the highest velocity which is right after the speaker driver (Horvath, 2016). There is a lot of software available online to help with designing enclosures for speakers; they give a prediction of the outcome based on the variables with which the designer can work. For this project, however, these tools cannot be used because they are all focused on coil-based speaker drivers and this project analyses the use of piezoelectrics as speaker drivers.

Findings

- If a speaker (system) needs to emulate the whole spectrum of the human hearing, it would need to produce frequencies between 20 Hz to 20 kHz. A single speaker alone cannot deliver this entire range of frequencies.
- If a speaker is louder in the higher frequencies, this will be more noticeable because humans have a better perception of frequencies between 2 and 4 kHz.
- An amplifier is needed to get the correct current to the speaker system because the internal voltage in most devices is not enough to move the speaker.
- The needed performance, budget, size, and thermal properties have to be taken into account when selecting an amplifier.
- A smart amplifier could help to get the best performance out of a speaker.
- The design of the enclosure can ensure the correct damping and guiding of waves; this can be done by adding foam or making tracks where the air can move through.

2.3.1 Coil versus Piezoelectric

In terms of the basic principle, coil speaker drivers, and piezoelectric speaker drivers work in the same way. Both drivers create a movement to displace air which causes the vibrations in the air. The difference between them lies in the way this movement is created. The movement in coil speaker drivers is created by a coil and a magnet where for piezoelectric speaker drivers it is created with an alternating current through the ceramic. Both types of speaker drivers have their advantages and disadvantages; these lie in the following areas:

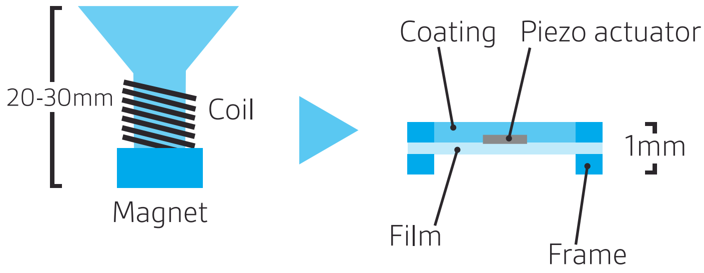


Figure 22, Kyocera thickness comparison for medium sized TV speakers

Materials

Material wise the piezoelectric speaker drivers are more favourable than coil speaker drivers because they use both fewer materials and no critical raw materials. More parts are needed to make the coil speaker drivers, which results in more material overall. For the piezoelectric speaker driver, only the piezoelectric element itself is required along with a structure to attach it to either a surface that is already there or install it the same way as a coil speaker driver. Using a piezoelectric speaker driver instead of a coil speaker driver also means the elimination of neodymium; the magnet in the driver is made from this material. The EU declared neodymium in 2017 as a critical raw material (Mathieux, 2017), so eliminating it is preferred. The metals in both piezoelectric speaker drivers, brass, and in the coil speaker drivers, copper, don't differ much in terms of sustainability or cost. So, there is no advantage or disadvantage in this part.

Thickness

As earlier stated in the competitor and partners paragraph, the piezoelectric speaker driver of Kyocera is 1mm thick. This is significantly thinner than a small coil speaker driver, which are around 20mm thick in televisions (figure 22). This thickness is still thin, but in the personal mobile device industry 1mm is a lot. In the case of Kyocera, it is not clear if the speaker still needs some type of enclosure behind the speaker. This enclosure could add a couple of millimetres which takes its advantage away. The speaker driver of Sonitron does require an enclosure space; they have tested their speakers with an enclosure of 40 x 15 x 5 cm. The Sonitron speaker is not intended for a personal mobile device but rather as a standalone speaker. So in terms of speaker driver, the piezoelectric speaker driver has an advantage over the coil speaker driver, but it is unclear if the same can be said for the enclosure.

Frequency range

In the area of the frequency range, the coil speakers drivers take the lead; they can produce a broader range of frequencies than piezoelectric speaker drivers. Especially in the lower spectrum, the piezoelectrics struggle to reach lower than 200 Hz (Kyocera, 2013), (DigiKey, n.d.) and (RS Components, n.d.), where coil drivers can reach the needed 20 Hz for a full human spectrum. The reason why piezoelectric speaker drivers struggle with the lower frequencies is that they cannot retain their charge and are limited in their maximum movement. Where a woofer can move the cone a total of approximately 9 millimetres, a piezoelectric disc for their haptic feedback moves a maximum of 40 micromillimeters. This minimal movement impacts the low frequency range of the driver because not enough air is pushed to create the power that is needed to hear the tone. With their frequency range, piezoelectric speaker drivers are seldom used on their own in a speaker setup; they are used as a tweeter (Soundbrigde, 2019) along with a woofer and possibly a subwoofer.

As a tweeter piezoelectric speaker drivers excel, they perform better in the higher frequencies compared to the coil speaker drivers. This excellent performance is because piezoelectric speaker drivers can switch their movements fast based on the current, where a coil speaker driver has a higher moment of inertia due to the coil or magnet which is not that easily stopped. Another reason why they perform better is that they have their resonance peak often around 1000 to 5000 Hz, which means that they need less power to play audio in this range. Both of these factors make the sound that comes from these discs mostly consists of high tones, making it unpleasant to listen to. Sometimes the piezoelectric speaker drivers are used on their own despite the lack in lower frequencies, an excellent example of this is its use in a birthday card. The design requirement for a birthday card is that the speaker driver should be thin, which is the case for a piezoelectric speaker driver. Still, the downside is that the audio sounds unnaturally high and sometimes even distorted. Another use for piezoelectric speaker drivers lies in the field of alarms because the human ear is more receptive for frequencies between 1000 and 2000 Hz (Scherz, 2013), piezoelectrics are perfect for situations in which the sound should not be missed. This high-frequency range is not practical in an everyday speaker to listen to your favourite music on. Still, companies such as Kyocera, Sonitron and TDK are trying to change this by creating piezoelectric speaker drivers with a broader frequency range.

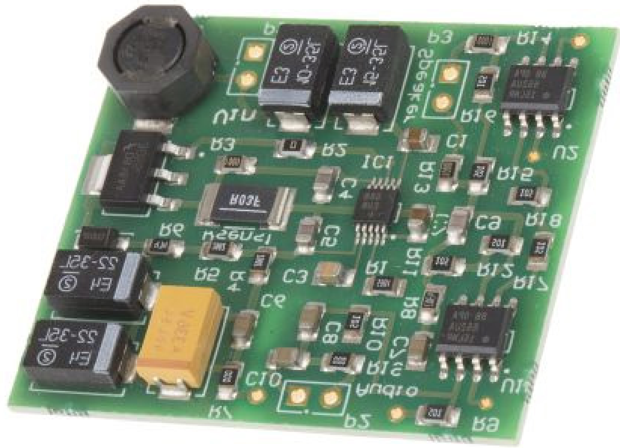


Figure 24, Sonitron amplifier for piezoelectric speakers

Electrical circuit

As earlier mentioned, a speaker system would require an amplifier to get the correct voltages and current to the speaker driver(s). Most amplifiers are designed with the coil speaker drivers in mind because these are more common. For piezoelectric speaker drivers, these amplifiers can struggle in providing the correct voltages and current for a setup with piezoelectrics. Some amplifiers can start oscillating when driving a capacitive load instead of an inductive load; an inductive load is used for the coil speakers. The difference between these loads comes from the phase difference between voltage and current. In a capacitive load, the current is behind the voltage with it peaks while the current in the inductive load peaks before the voltage has reached its peak (figure 23). The oscillations will result in distortions of the sounds or will damage the amplifier (Soundbridge , 2019). Distortions can also be created due to the conversion of the audio signal. If this is done in small steps rather than a smooth transition, the piezoelectrics will not bend accurately enough. The small steps can cause the piezoelectric speaker drivers to bend the wrong way or stop the bending midway causing a vibration that does not represent the soundwave that is needed. This step conversion is what prevents Aito to use their current haptic circuit for the audio use; their amplification system makes use of the small step approach. However, Aito is developing a new amplification system which might be usable for audio as well, instead of a programmed pulse an audio signal can be sent via the chip to the piezoelectric discs. This solution would save components, space and therefore, money. An example of a piezoelectric amplifier can be seen in figure 24.

The minimal thickness is one of the reasons why companies in the personal mobile device market are trying to implement piezoelectric speaker drivers into their products. Two examples of companies who work to innovate their products with this technology are Xiaomi and LG. LG has collaborated with Kyocera to create a speaker system for the curved Oled television of LG. This television was released in 2014, but LG has not implemented a Kyocera speaker in any of their later televisions. Xiaomi is not specialised in televisions but operates on the smartphone market. They have implemented in their first version of their

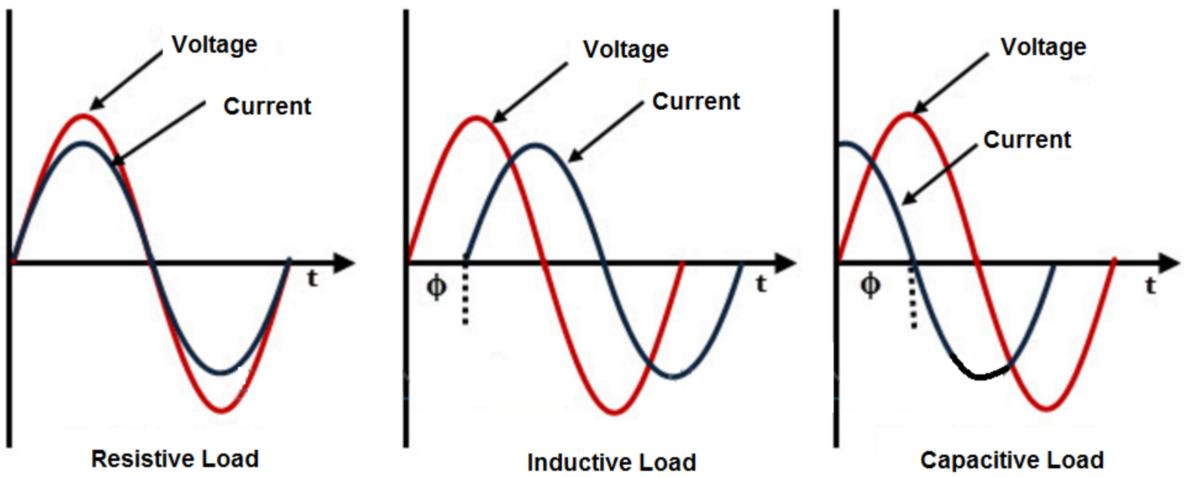


Figure 23, Differences between load types

Mi Mix smartphone the "cantilever piezoelectric ceramic acoustic technology". This technology was based on letting the metal phone frame vibrate, which amplifies the audio. This use of piezoelectrics did not need an air vent or outlet, and therefore a continuous screen design could be achieved. However, in the second version of the Mi Mix, the cantilever was substituted for a coil-based speaker to improve the audio quality (Stiwe, 2017). Where Xiaomi gave up LG tries it again in 2019 with their "Crystal Sound OLED" technology based on distributed mode loudspeakers (DML's). This technology is implemented in their G8 Thing smartphone and is based on letting the screen of the phone vibrate (figure 25). To get a good audio quality, LG has also decided to add their so-called "Boombox" speaker beside the Crystal Sound Oled; this combination ensures that the audio is pleasant to listen to (Byford, 2019).

With the setup Aito has created for their haptic feedback, the piezoelectric discs would not transfer their vibrations to the frame as what Xiaomi's technology did, but it would let the screen of the tablet vibrate. Therefore Aito's approach is more similar to the LG technology, so the design approach of this project should be focused more on distributed mode loudspeakers (DML's). In the next paragraph, these type of speakers are further explained along with their own design rules, which cannot be compared to those of the most common loudspeakers.

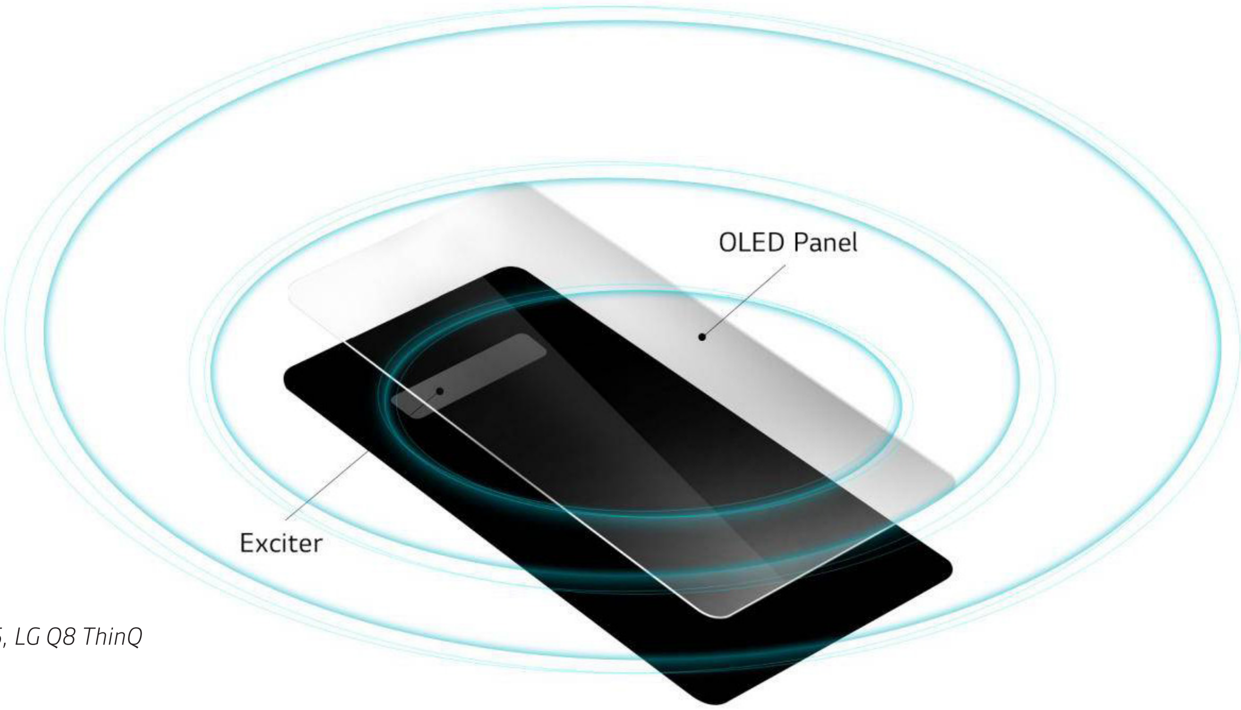


Figure 25, LG Q8 ThinQ

Findings

- The design approach of piezoelectric speaker drivers is different from coil speaker drivers, but some design elements can still overlap.
- The limitation in lower frequencies could result in a less pleasant sound compared to current solutions.
- The minimal thickness and lesser (critical raw) materials are two main advantages of the piezoelectric speaker.
- The standard amplifiers are not suitable for piezoelectric speakers, so these might need to be specially made.
- The amplifier system could be combined with the current electrical circuit of Aito to drive the piezoelectrical discs. This combination would save components, space and costs.
- Piezoelectric speakers are already scarcely used in mobile phones to create a screen without bezels, but they still need an extra speaker to perform well or are excluded in the next version. So the solutions are not perfect yet.

2.3.2 DML & MAP speakers

Where LG uses distributed mode loudspeakers in their phone, which is abbreviated to DML's, Sony has implemented this technology into their televisions with their "Surface Audio" and "Surface Audio+" technologies. They use two or three coil speaker driver modules, exciters in this use case, on the back of the Oled screen to vibrate the whole surface (appendix 8.5, Sony Surface Audio). Their technique is still aided by a subwoofer which is placed on the back of the television. LG and Sony are examples of the DML implementation for screens, but there are companies which have developed solely a speaker system that makes use of the DML technique. These companies are Soundwall, NXT and Room One. They have created frames with a raw material or artwork look that can be placed on the wall. All these companies prove that using this technique in consumer products is feasible. However, it is not a straight forward design process.

The previous sections already briefly mentioned that the principle of DML's lie on the vibration of a surface. The upwards and downward bending of the panel will create the airwaves that are needed to produce sounds. Because the whole front surface of a panel or screen acts as a speaker and the airwaves are not guided by a cone the dispersion of audio is much wider spread out. Figure 26 displays the difference in sound dispersion. The cone loudspeakers projects sound with an angle, while the DML projects the sound like half a sphere. However, it is quite challenging to get a uniform spatial dispersion of the sound for DML's. The spatial dispersion does not often represent an actual sphere (Anderson, 2015). Another difficulty in DML's is to achieve a flat response Anderson and Boco state; this is due to the presence of isolated low-frequency panel bending modes. This presence means that the panels will damp the lower frequencies, which results that these frequencies will be less audible than the mid or high frequencies. A flat response means that all the frequencies will have the same loudness level; this is further explained in chapter 5, Objective method on page 68, along with the definition of good audio and how to measure this. A flat response is preferred because the audio from the speaker will represent the audio file as accurately as possible without changing it. The bending of the panel is created with so-called exciters; these components create vibrations which they transfer to the surface when they are attached to the back of a surface. Companies that are specialised in the

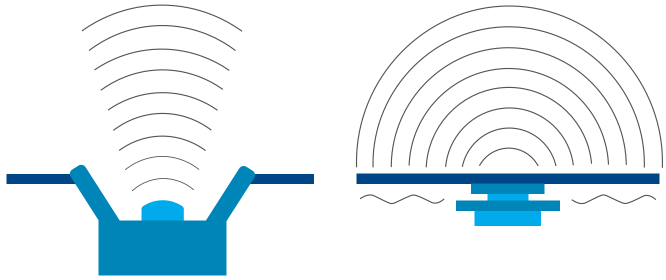


Figure 26, Sound distribution difference between coil speaker and DML speaker

production of these exciters are Dayton Audio and Tectonic Elements; these are well-known suppliers for these type of speakers. Most exciters are using coils to create the necessary vibrations, but a piezoelectric exciter example would be the PiezoListen from TDK. Roughly summarised, a DML can be described as a system where a vibration module is attached to a bendable plate.

Designing such a system is unfortunately not straight forward, the reason being that every change to the overall design has a direct influence on the audio performance. Where a conventional loudspeaker is confined in a box which can be placed in various other devices, a DML is fully integrated into the whole device. For example, in a laptop the speakers are plug-and-play components. Plug-and-play means that you buy the full speaker as a part and adjust your design to fit this speaker. Adding the existing speaker will slightly impact the performance of it, but for a DML, every component of this laptop contributes to the sound performance. When the design for a DML laptop speaker is almost finished, and changes must be made to the material of the frame, the whole system changes acoustically.

In situations where a flat panel DML is used, it is often floating in a room from wires in the ceiling. This setup makes it easier to predict panel vibrations and acoustic radiation. These predictions can be made with an electro-mechanical analogy, finite element analysis and fast Fourier transform (Baia & Huang, 2001). But when a DML is incorporated into a system such as a laptop, these methods are not accurate enough to fully predict the outcome. Another approach, in that case, would be to experimentally test what works best for that specific system by making several models. There are a couple of techniques known which have proven to positively affect the response in terms of flatness or how low the frequency range can go, to design such a system. For experiments, these techniques can be used as guidelines to define where to look for possible changes to improve the response of the DML. These techniques can be found in the following areas:

Materials
When using certain materials, the way they handle internal vibrations should be known. They should have good internal damping to separate peaks from each other, high compressive strength and moderate to high bending strength. The bending strength of the material influences the mid and lower frequency efficiency of the panel speaker (Dayton Audio, 2014.). Materials that should be avoided are solid materials, such as metals, thick beams or concrete, because they could continue ringing after the exciter has stopped vibrating. This ringing happens because there are still internal vibrations moving inside of the material. Dayton Audio (2014) suggest the following materials for panels: Aluminium, Kevlar, resin impregnated paper honeycomb sandwich composite, structural or syntactic foam sandwich composite, fabric reinforced phenolic plastic, fibreglass reinforced resin panel or corrugated/honeycomb cardboard sheet. They also identified materials that are less in performance but still suitable for a panel; these materials are unreinforced plastics, Plexiglas, glass, acoustic drop-ceiling tile, wallboard, plywood, MDF or OBS.

Panel shape
The panel shape plays a part in the amount of bass the panel can produce, and the shape influences the distortions in the audio. The amount of bass is linked to the size of the panel, with an increase in size the panel can produce more bass.(Canton, 2018). DMLspeakers.com has a tool on their site which lets you roughly predict the frequency range of the panel; with this tool, you can see what the influence of size is. It is not possible to give a correlation between the lowest frequency and size because a lot of other factors play a role in determining the frequency. Only measurements can show what the effect in size will do for a specific project. How these measurements work will be explained in chapter 5, Objective method on page 68. The impact of shape on distortions can also only be identified by doing measurements. However, some common shapes are known to limit distortions and improve audio quality. The main shape for DML's is a rectangle with a width that is 4/5 of the height of the panel and rounded corners. The rounded corners help in reducing long-decay reflections; these reflections cause audible distortions and decrease the audio performance of the system. Long decay reflections are vibrations that will continue to move or "bounce" within the material after the source for the vibrations is removed. The bouncing happens because they get trapped in a sharp corner. There are a lot of possibilities to experiment with because DML's design is so intricate. For example, a video on YouTube "soundboard speaker" shows the option of shaping the back of the surface into a cone-like shape. It could be a possibility, but there are no measurements that show that this design approach improves the audio quality of a DML.

Exciter placement
For exciter placement, Dayton Audio, a producer of exciters for DML's, suggest placing a single exciter 3/5 from the top and one side. This placement should prevent spikes in resonance because the length of the waves to each side of the panel has a different length and will, therefore, bounce differently from the sides of the panel. The 3/5 approach will reduce the build-up of standing waves on the panel. Dayton Audio states that it is possible to attach multiple

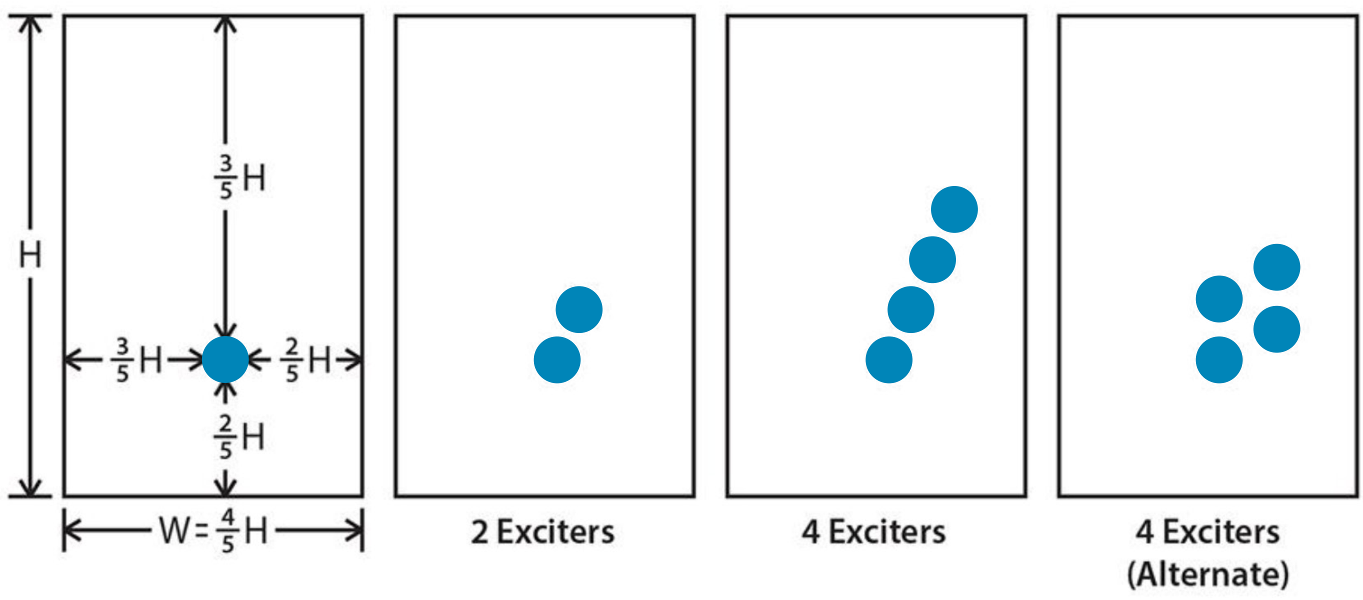


Figure 27, Suggestion by Dayton Audio on panel dimensions and exciter placement (Dayton Audio, 2014) exciters to a panel, but these should not be spaced evenly. The uneven spacing has the same reason as the 3/5 placement; it should prevent the overlap of different waves. By placing multiple exciters to one panel, a left and right speaker setup can be created. However, it is difficult to control the waves and especially in the middle, where two different waves overlap. Figure 27 shows suggestions made by Dayton Audio how to place multiple exciters on one panel.

Fixation

The type of fixation of the DML can either negatively impact the sound or positively. For home-made DML's it is suggested to hang the panel from the ceiling with a wire, this allows the panel to move freely without obstructions of the vibrations. If the edges were to be fixated, the material would absorb some of the vibrations, causing distortions. In the case edge fixation is needed, it can best be done in the form of a compliant suspension with either foam tape or a silicone adhesive. These materials do not transfer vibrations to the attached material and absorb some vibrations of the DML without reflecting them into the DML. Full baffling of the panel helps in extending the low-frequency response of the system. However, this may not be a practical proposition in many applications (Azima, 1999). Figure 28 gives examples for fixating the panel to another structure.

Enclosure

A standard DML does not have an enclosure; it is only a flat panel suspended in the air. But if such a panel is placed close in parallel to a wall (Azima, 1999) suggest taking special care. The reason for this is that the vibrations of the panel will bounce back from the wall, causing interference issues. Interference is when vibration waves overlap and cancel each other out; this is the basic principle for noise cancelling headphone to give an example of the effect it can have. Sony also takes the placement of their television into account when giving instructions for installation to their customers (appendix 8.5, Sony Surface Audio). Their suggestion is to not place the TV under an overhanging wall or cabinet; the assumption is that the airflow is obstructed by this and could cause distortions in the air vibrations to produce audio. To create a system that would be easier to predict a small enclosure can be used states (Azima, 1999), this is due to limiting the factors that influence the system. This setup will make the DML independent

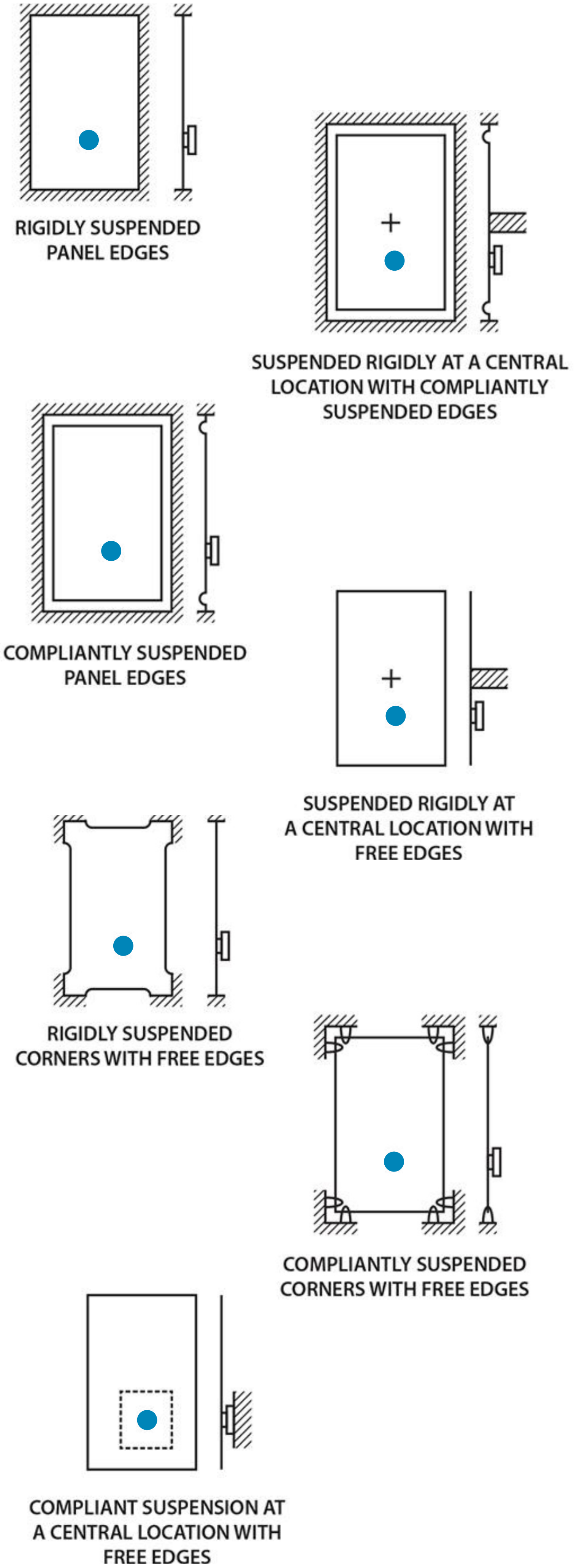


Figure 28, Types of suspension suggestions for DML's by Dayton Audio (Dayton Audio, 2014) of its immediate environment, which could be beneficial when implementing it in a device where there are all sorts of components which could impact the system.

Total setup

The whole DML setup can consist of multiple panels which each have their combination of the previously mentioned aspects. For example, you can have a setup of two DML's where one panel has a different rectangular shape than the other. Each panel will have their frequency curve with both likely some flaws in it, but when both DML's are appropriately designed, it is possible to cancel out these flaws. Where one panel has a spike in volume, and the other is lacking in volume, this will be balanced out to a level closer to zero, which is needed for a flat response. Figure 29 shows an example in which multiple panels are layered to achieve a flatter response. In the figure, each response for a DML is shown, and if these responses were to be added together, it would be a flatter line than only one single DML.

MAP

In some cases, it can be challenging to have multiple DML's, in that case, the same overlapping of responses can be achieved by adding multiple exciters, as earlier mentioned in the exciter placement section. This category of DML's are called multiactuator panels (MAP's), instead of one exciter per panel MAP's have an array of multiple exciters. How the exciters are positioned in MAP's can be seen in figure 30. The previously mentioned Sony television makes use of this category of DML, where they have placed two exciters on each side of the screen. Other examples for this category are mainly found as topics for research purposes rather than implementations in a consumer product. Both the research of (Anderson, 2017) and the research of (Pueo, 2008) about MAP's suggest that to improve the audio quality of the system each exciter that has its unique distances to the edges of the panel should be controlled separately. Unique distances mean that a position cannot be mirrored in either the x-axis or y-axis, a mirrored position in either axis will give the same vibrations but in a different location. Controlling is done by creating a signal that is digitally sound processed for that individual exciter; this process will be further explained in paragraph 5.3.1.1, DSP on page 88. In a small array of three exciters, this is still manageable; you need to create three different signals to control the system. But for the setup Aito wants to create, this means there should be individual control for at least six exciters and possibly even for 24 exciters per panel if 24 piezoelectric discs are used. Individual control means that the signal must be processed for a particular case and that there is an amplifier needed to increase the signal to the correct voltage. Trying to fit 24 amplifiers into a device means an increase of volume or a limitation for other components in the device. The need for 24 amplifiers should be minimised to avoid this problem, preferably to only one to keep the total volume of the amplifiers as small as possible. Another theory for MAP's, beside the individual control, is that each exciter should drive its part of the surface without influencing the vibrations of other exciters. To achieve this, the material of the panel should be able to damp

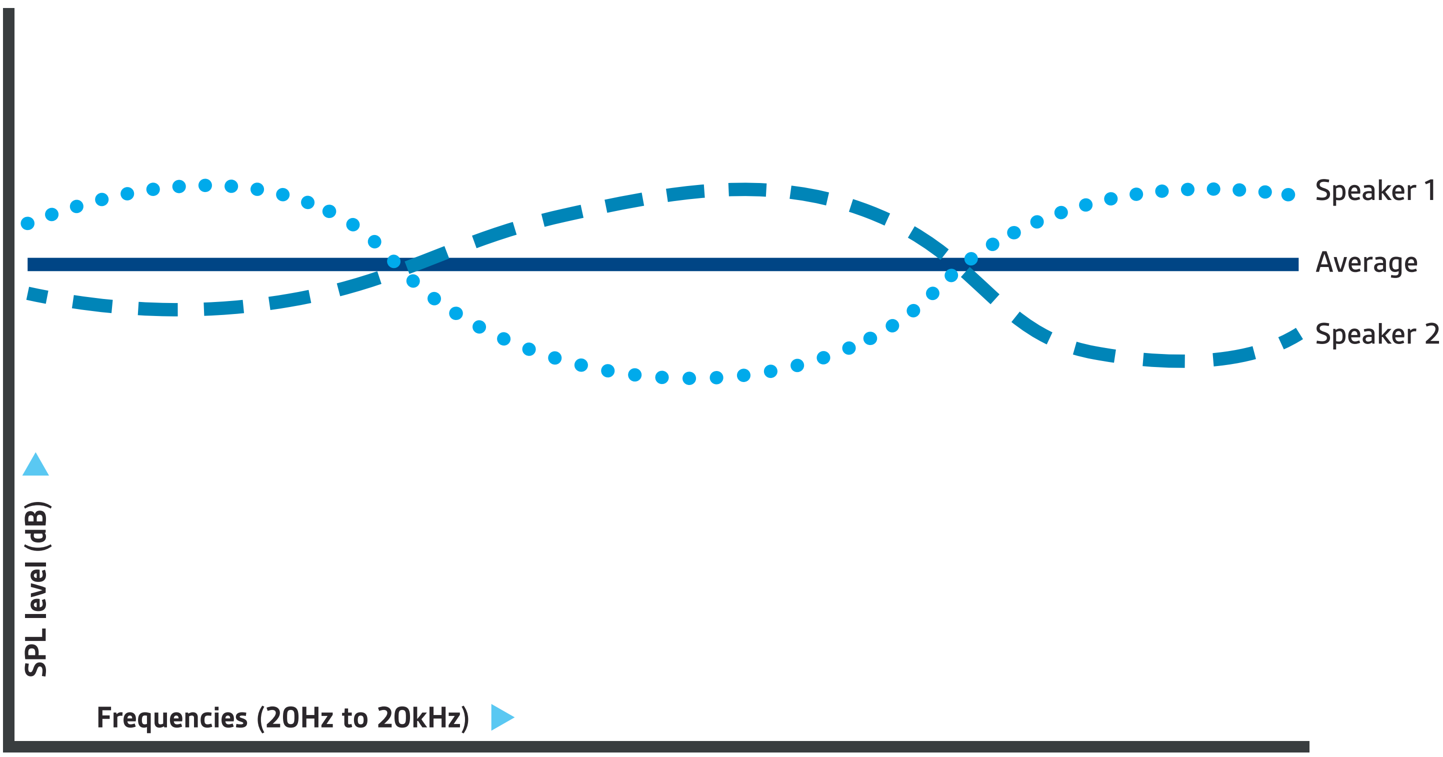


Figure 29, The effect of layering multiple panels to get a flat repsonse these vibrations internally (López, 2007). So, this again suggests that material selection is an important design factor, not only for the frequency range and distortions but also for the possibility to add multiple exciters. In the example of the Sony television, it is unclear how their "Surface Audio" and "Surface Audio+" technologies control the exciters. From online reviews can be determined that the audio can "move" around on the screen where a traditional setup uses a left and right speaker to create the effect of sound movement. The technology of Sony likely creates hotspots in vibrations in certain areas, which gives a much louder sound in that specific spot.

Previous examples showed an exciter placement in the middle of a panel, but there are other examples where the exciters are placed on the sides of a panel. Redux, one of the previously mentioned competitors, made use of the edge placement. DeNoize is a start-up located in Delft, another company example, makes use of custom piezoelectric elements in window frames for noise cancelling. DeNoize is developing a technology that can detect the vibrations in the window and give counter vibrations to block the outside sounds; this will then result in a much quieter indoor space. The reason for DeNoize to use this setup is that it allows hiding the piezoelectric elements in the window frame. Another reason for placing the exciters at the edges is the maximum bend that can be achieved; this is easier in this case.

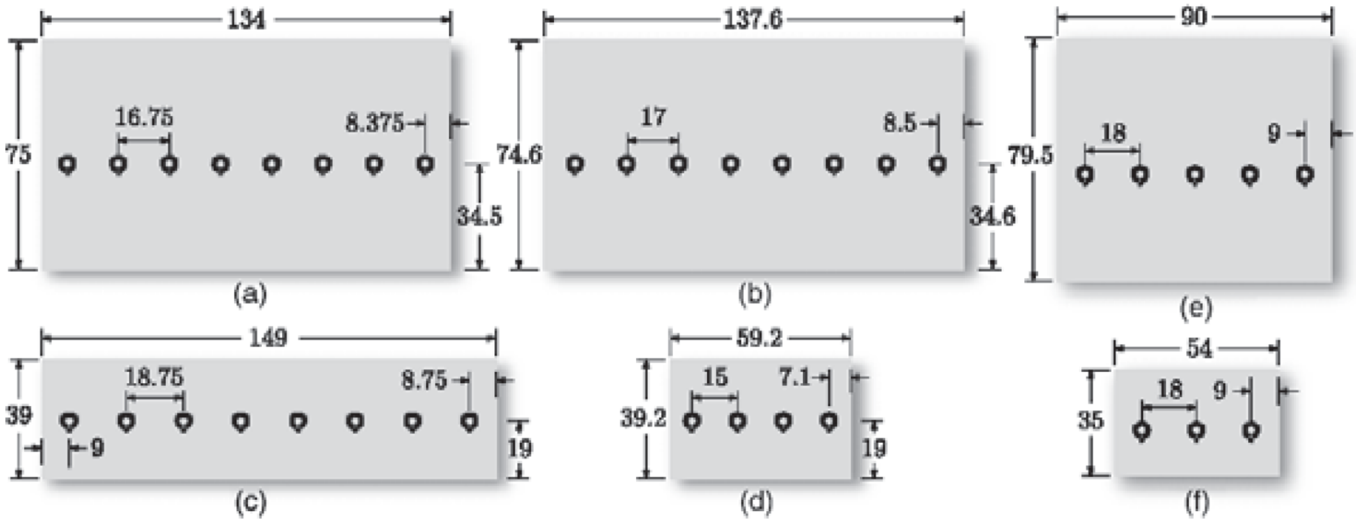


Figure 30, The designs of several MAP designs from various researches (Pueo, 2008)

Findings

- DML's are applied in consumer products, but in most cases, an extra speaker was needed to ensure a full frequency range
- DML's have a wider spatial dispersion which is beneficial because this creates a broader audio field for the user; they do not have to sit in one specific spot.
- Most materials can be used for DML's, although some work better than others. However, metal or stone should be avoided.
- The shape of the panel or screen should be rectangular where the width is smaller than 4/5 of the length, the edges are rounded, and the overall size should be as large as possible.
- The exciter should be placed ideally at 3/5 from both one side and the top of the panel, and when other exciters are placed, these should not have the same distances to edges.
- A flexible suspension or even no suspension at all, making the panel free-floating, will prevent vibrations from transitioning to the frame or surrounding parts.
- Making an enclosure for the DML might make it easier to predict the outcome because its surroundings do not influence the audio.
- Multiple panels can help to get a flatter response by overlapping each response.
- Digital sound processing for MAP's has to be done for each unique exciter location to get the best result. This method could mean that each unique exciter needs an amplifier and filter which should be kept at a minimum.

2.3.3 Tablet speakers

As previously mentioned, the most common type of speaker driver is the coil version; this also applies for speaker systems in tablets and other personal mobile devices (laptops and smartphones). Although Redux tried to introduce their surface speaker to the personal mobile device market, this is not yet adopted by manufacturers of these products due to the takeover by Google. With the coil driver setup, each company has their approach to implement the speaker system in their tablet. When going to an electronics store (appendix 8.3, Tablet speaker collage) to look at the different tablets and what speaker system they use a couple of differences are noticeable.

Firstly, the variation placement of the speaker is noticeable. Where some companies have decided to place the speaker outlet at the sides facing backwards from the screen, others have put them behind the screen with a small slit in the screen for the speaker outlet. All setups need an outlet for the air vibrations the speaker driver produces, due to the use of the coil speaker driver. There is also a difference in placement when it comes to which side the speakers are placed on. This placement can either be the shorter side of the tablet or the longer side. The differences in speaker placement in tablets can be seen in figures 31 and 32.

Secondly, there is a difference between the number of speakers on the tablet. Where some only have one speaker, others might have four. The number of speakers depends on the price of the tablet and its purpose. For high-end tablets such as the newest iPad Pro, it is more common to have a total of four speakers. This number of speakers is also the case for the Samsung Galaxy Tab S6, where the speakers are placed in each corner (figure 33). Both companies also mention this speaker setup in their product advertisement; it is assumed this setup is created to compete with the systems some laptops have. As earlier mentioned, the iPad Pro is presented as a laptop substitute, and to comply with this, it should come with the same audio quality as a laptop as well. For the mid-end standard iPad, only two speakers at one side are deemed enough. The placement on one side means that there is no stereo possible for this setup.

Thirdly, there is also a differentiation between the software that is used to drive the speakers. Some tablets advertise themselves as having speakers with Dolby Atmos, which means that the audio is enhanced with the Dolby software. The first tablet to use this software was the Kindle Fire HD of Amazon, but lately, more brands are using it such as Samsung, Apple and Lenovo. However, this software is not applied to all their products; only the higher-end models seem to implement Dolby Atmos. This implementation in only the higher-end models makes sense, because the higher-end models have more speakers to work with and are already more focused on delivering a higher quality audio experience.

Figure 31, Examples of speaker placement in iPads

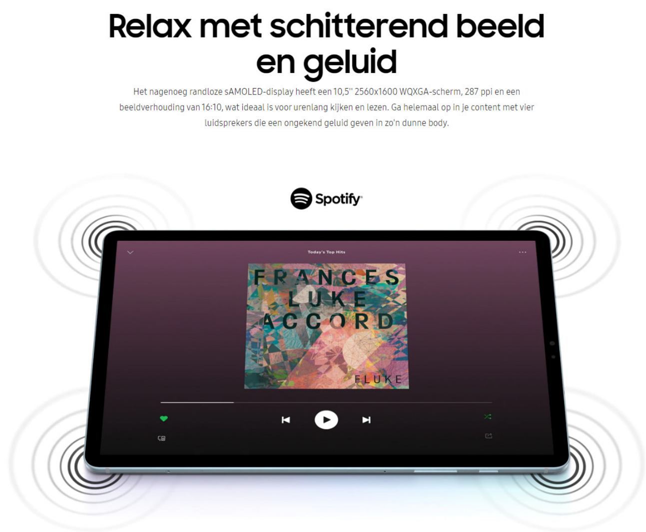


Figure 33, Speaker placement Samsung Tab S6

To get to know more about how these differences occur and what the process is of designing a speaker system for a tablet, audio engineers and project managers in this industry were contacted (appendix 8.6, Industry contact). The following information in this paragraph is based on these meetings. During these meetings, a three-step approach came forward as the primary design process of speakers in tablets and laptops. The first step is to determine the type of experience the user should have with the device; this step is not only for the speaker system but for the whole device as well. The choice could be made to design a device that is more mobile for on the road or a device that is excellent for watching movies on the couch. The suggestion is that the price range, high-end, mid-range or low-end, will also contribute to the type of experience users will expect. For a low-end device , the audio quality might be a bit lower graded than the higher-end version, because the expectation of users does not require perfect audio quality for the cheap tablet. The industry uses a grading system to determine what the audio quality of speakers from multiple manufacturers is; this scale has four levels which are: "acceptable", "okay", "good" and "excellent". To be able to grade the speaker based on the system, they have to be tested in the correct setup developed by the industry. This grading system is the same for tablets and laptops. When comparing the experience with the grading system, the industry can determine which level needs to be scored by the speaker and what specifications are required in terms of audio quality. For the speaker, the specifications include the frequency range, loudness and power consumption. To give an example for the frequency range of a high-end tablet, the iPad Pro 2015 has a frequency range from around 120Hz to 20kHz (Mabumbe, n.d.). This range means the iPad Pro would be graded with an "excellent' by the grading system, solely based on frequency performance.

The second step in the speaker design process is when the design team is ready with the detailing of the tablet and state how much room there is left for the speakers. The team of audio engineers get this information as a requirement to which they must comply. The speaker design is, in most cases, a bit of an afterthought and gets assigned the spaces that are left. Design-wise this means that speaker outlets


Figure 32, Speaker placement of the Surface Pro

are often placed on the back because the designers did not want cut-outs in the screen. However, the audio engineers would prefer front-facing speakers over back-facing, because front-facing means more direct and louder audio. So here there is an opportunity for DML's where a seamless surface is needed with still front-facing audio. For the iPad Pro, you can see in figure 34 that audio was not an afterthought; there was space created which resulted in a smaller sized battery package. The audio engineers who worked on the iPad Pro designed four foam-filled speaker compartment in the frame of the tablet; they did this intending to get the best audio experience possible for a tablet.

The third step in the process is designing the speaker setup while staying within the budget. During one of the meetings, an example is given of two scenarios, where two almost identical speakers need to be developed. The difference between these speakers is only their size; one has to be smaller than the other. Both speakers will sound the same in the end, but the smaller speaker will be more expensive to meet all the requirements of the bigger speaker. This rule also applies to speakers in phones when comparing them to tablets and tablets when comparing them to laptops. You could get the same performance, but depending on the budget you might have to make some concessions. As a rough estimation, "good" graded speakers have a budget of around five dollars in total; this includes the speaker driver(s), amplifier and digital sound processing system. When comparing speaker drivers designed for tablets, the prices range from 0.15 to 3 dollar per speaker driver (Alibaba, n.d.) and (Powerbookmedic, n.d.). Of course, the price will also depend on whether the speaker driver must be custom made or if it is an off-the-shelf component and in what amount these speaker drivers are bought. The industry standard for tablet and laptop speakers in terms of power consumption is around 2 Watt per speaker, for a stereo setup, this will result in 4 Watt total for all the speakers. Although some smartphones have multiple speakers to create a stereo effect, due to the small distance between these, you do not get an actual stereo experience. Most of the times, a dual speaker setup in smartphones is used to increase the overall loudness of the total speaker system. But in laptops and tablets, stereo audio is feasible due to the distance and is preferred over mono audio.

This three-step approach is likely the same for the foldable devices. However, it can be maybe a bit trickier. This difficulty has to do with the greyscale between laptop and tablet, which make decisions on speaker location more difficult. The first step in the speaker design approach is selecting for which experience is aimed. For the foldable devices, it is difficult to determine the type of audio based on the unknown experience. Should it be a high-end performing device with similar performing speakers or is the primary focus on foldability with slightly less advanced speakers. And then there is also the labelling because the device can be compared to a laptop and a tablet. Where on the scale should this device fit in terms of audio? In the industry, this label does not make a difference. In their grading system, a tablet or

Figure 34, iPad Pro speaker compartments laptop are equal. For customers, however, their expectations for a laptop or tablet might be different based on the label it gets. Where tablets have their speakers mostly side facing, laptops have them placed underneath the screen facing the user. From the concepts, it is not entirely clear where the speakers are positioned in the foldable devices. Still, from the product images and information Lenovo has released for their device (Low, 2020) it appears the speakers are placed on the sides of the device. In figure 35, the device of Lenovo can be seen; on the rendered image, there are holes in four places on the tablet, suggesting that the device will have a maximum of four speakers. These speakers are all placed on one part of the device, which indicates that the foldable device can be used in only one position as a laptop. The number of speakers and whether they adjust to the positioning of the device cannot be concluded from the available information. Making the speakers adjustable would make sense because the foldable devices can be used in a wide range of positions, to ensure good audio quality in all of them requires some changes. For example, one part of the device can lay flat on the table while the other half stand up with an angle from the table. Another possibility is to fully unfold the device to create a large screen which is set on a table with a stand. In these situations, the audio should come from different places. Otherwise, some part of the speaker may be blocked. For regular tablets, there is already a difference in holding positions, horizontal or portrait (Reddy, 2017), which varies per device in preference. Still, with an added angle in the foldable devices, you have even more possible positions.

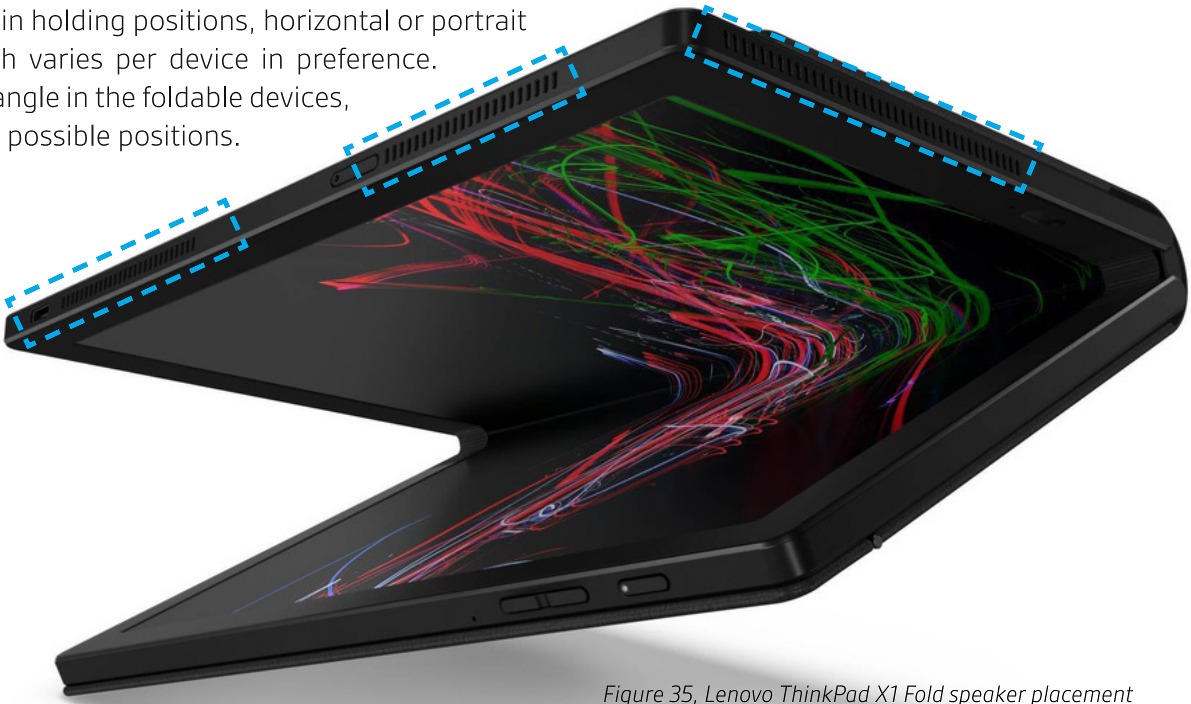


Figure 35, Lenovo ThinkPad X1 Fold speaker placement

Findings

- The most common speaker type for a tablet is the coil speaker driver, but the industry is looking into piezo-based DML's.
- Placement is generally based on where there is space left; this causes a lot of differences between tablets and mostly results in side-facing speakers.
- The number of speakers is linked to the price range of the tablets. The price range also influences experience, the higher the price, the better the experience should be.
- Software such as Dolby Atmos is used to control the speakers and get more out of them. Other types of software are used to adjust the speaker output based on the position.
- There are three main steps in the selection of speakers: Experience, Confinement and Budget.
- Front-facing speakers are preferred over side-facing or back-facing speakers because this allows the user to experience the sound the clearest and loudest.
- A stereo setup is feasible in laptops and tablets due to the space between speakers. Otherwise, the distance is too small to distinguish the direction in the audio.
- A "good" graded speaker system costs roughly 5 dollars for the whole system with amplifier and has a power rating of 4 Watt for a stereo setup.
- The experience for audio in foldable devices is not clear but appears to be outshined by the other functions of the device, which results in less attention for the speakers in the design
- The speakers should change their output based on the position for foldable devices; this is even more important than the changes in audio for tablets.

2.4 Design space

From all the findings in this chapter, a design space can be determined with all the possible exploration directions. The design space is visualized on page 43, where the links between the areas are displayed. During the state of the art research, four main areas for exploration were defined. These areas are the basis for the new audio functionality of Aito's system; they are the beginning of the design process in which decisions have to be made on the approach or design features. The decisions are briefly stated in this paragraph but are made in paragraph 5.1, Design principles on page 72; here the reasoning behind the chosen approach can be found.

Type of device

While the focus of this project lies on an exploration for the tablet, the foldable tablet is an interesting direction as well. If the foldable tablet is chosen, there has to be made a distinction between the term foldable tablet and foldable laptop.

Speaker type

In "State of the art", three types of speakers were defined which all had their own design approach and rules. The traditional speaker is already partially excluded based on its design features; this is not possible with the limitations of piezoelectrics. However, design principles from this traditional approach, such as a foam insulated chamber or air vents, are still an option for the new design. The MAP and DML types are still feasible with the Aito stack design, and their principles could be applied.

Stack design

The stack design is the area in which most of the decisions have to be made. These decisions can again be split into multiple areas based on the earlier defined components of the stack design. Each decision for the stack design should take the haptic feedback, audio quality and overall thickness into account. An optimum between these three aspects has to be found.

In the top layer, or panel in the case of a DML or MAP, decisions have to be made for the material, shape, type of edge fixation and left and right speaker separation. For the materials, the options are glass, plastic, foam, wood or an Oled screen. This decision will be based on the availability of materials and which material fits the chosen device. The options for the shape take into account some design principles for DML's which are: the 4/5 width rule, rounded corners and keeping the size of the panel as large possible while keeping the thickness to a minimum. For the edge fixation, the options are between no fixation at all for a free-floating panel, a more flexible fixation with either foam, silicone, rubber or a fully fixated edge with glue. The last decision for the top layer is if a stereo setup is needed or if mono is sufficient enough. If stereo audio is preferred, the structure has to be designed with this intent. This structure can be created by making a separate panel for the left and right channel, separating the panel with a glue division or having no division and using half of the piezoelectric discs for the left channel and the other for the right.

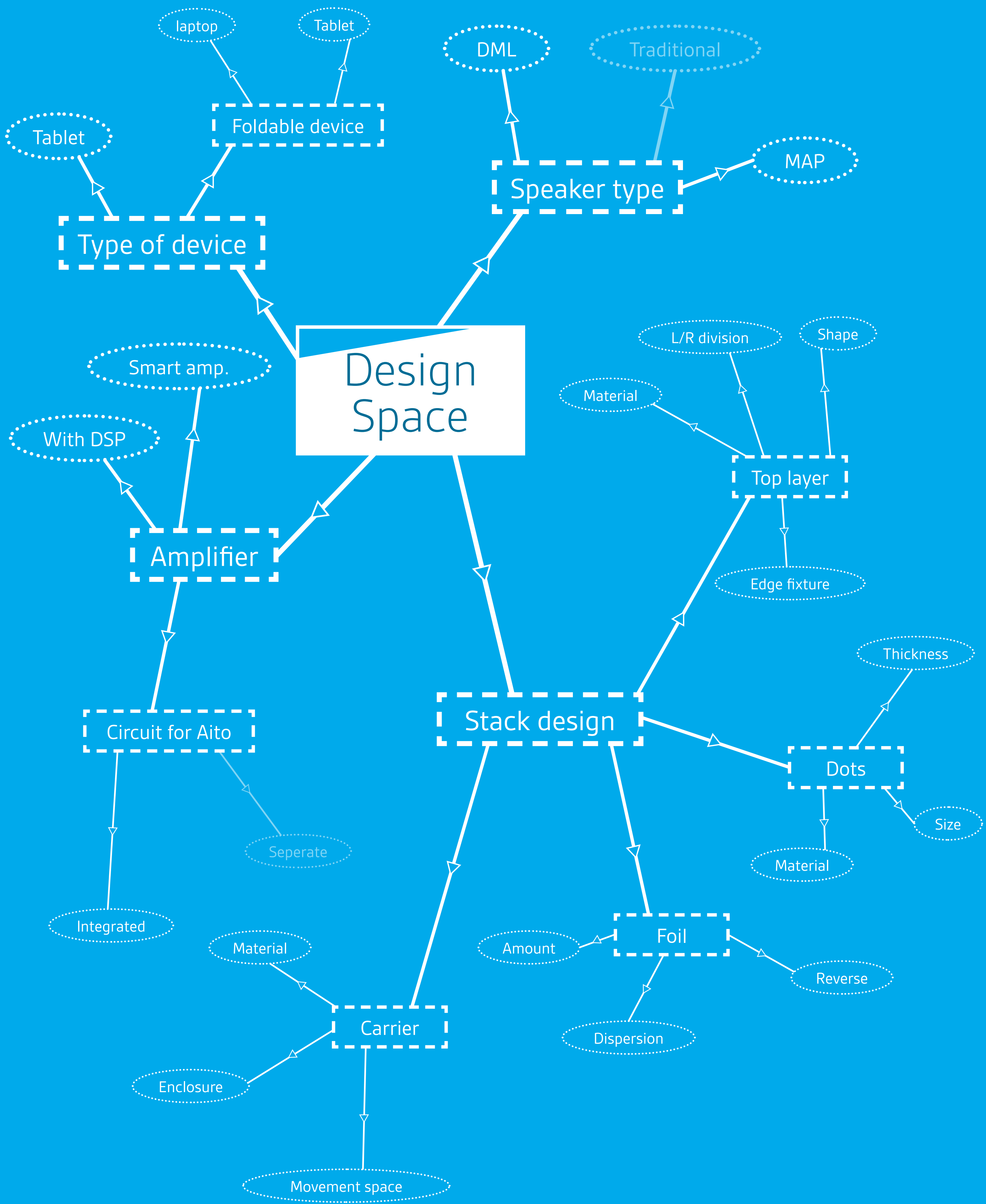
For the dot, choices have to be made on the size, thickness and material. The standard option is a dot with a 5mm diameter, 0,15mm thickness and is made out of an adhesive.

The options for the foil also consist of a standard option, from a previous project that are still some foils left. Aito has used this foil layout underneath a tablet screen. This layout consists of 24 piezoelectric discs placed in a matrix with several rows. Besides the standard foil the other option is a custom foil which allows a variation on the placement of the piezoelectric discs and the number of discs. The placement can then be based on the 3/5 rule and unique positions. Another option with a custom foil is to design the layout in reverse; this would result in a system which does not use the screen but plates inside the device. This system could have airports side or back facing in the same way current tablets designed their speaker outlets.

The choices for the carrier are the type of material, which should result in a stiffer structure than the top layer, and the possibility of a speaker chamber. For the speaker chamber a decision has to be made to create a chamber with that includes the electronic components or to separate these areas. A separate chamber should ensure a better predictable speaker and could be as small to only allow space for the piezoelectric discs to move.

Amplifier

The area of the amplifier combines electronics and software components, but this part of the new system will not be designed in this project. However, this project does include suggestions for the design of these components for the new system to be feasible. Suggestions include the possible implementation of a digital sound processing chip or smart amplifier setup. Besides these suggestions, another recommendation will be developed regarding the integration of an amplifier into the current Aito circuit. A separate amplifier is excluded based on the added costs and extra difficulties to let the haptic and audio functionalities work together.



Design Space
Type of device
Tablet
Foldable device
laptop
Tablet
Speaker type
DML
Traditional
MAP
Amplifier
Smart amp.
With DSP
Circuit for Aito
Integrated
Seperate
Stack design
Top layer
L/R division
Shape
Material
Edge fixture
Dots
Thickness
Size
Material
Foil
Amount
Reverse
Dispersion
Carrier
Material
Enclosure
Movement space

Approach

What will be explored? And how?

3.

In the previous chapter, the design space consisted of a lot of possible directions to explore for this research. Especially in the area of the stack design, a lot of variables can be tested to find out which design principles would work best for a haptic and audio solution. The research questions helped to make a selection on which directions to explore; they were formulated to incorporate both the user side as well as the technological side of audio design. These questions were used to find interesting topics for both these sides in the state of the art analysis. The sides combined should make for a valuable outcome of the project by not limiting the possibilities to only one area.

3.1 Research questions

This project was done to explore whether Aito can make use of piezoelectrics to provide an audio feature to their clients besides their already existing haptic and sensing features. The overall question for this project was:

What opportunities lie in the implementation of audio with piezoelectrics?

The possible opportunities are stated in the design space in the previous chapter. Whether these opportunities can help Aito to develop an audio feature still has to be explored in the upcoming sections. The overall question for these chapters is a variation on the main question for the project, namely:

What opportunities lie in the implementation of audio with Aito's stack design?

The design space shows that it could be possible to use Aito's current design structure for audio purposes by using the principles of DML and MAP speakers. Where the main question is still open to other design structures with piezoelectrics, the next chapters focus on solutions with Aito's stack design. This overall question can be split into multiple smaller questions which together answer this main question. These questions reflect both the user and technical side and partially stem from the possibilities in the design space.

- **How do users experience audio quality in personal mobile devices?** In the current audio engineering field testing of speakers is often done by the audio engineers themselves. If tests are done with participants without knowledge of audio design, this is to test speakers for home setups. The industry likely excludes users in the audio design process because they rely on the fact that audio engineers know best, and it would be costly to use users with little knowledge and only their own opinions. However, this project does try to incorporate these users more into the design process by taking into account their views on the audio quality. It is suspected that users can only identify either low audio quality setups or high audio quality setups; anything between these extremes will be neutral territory. Users will not have strong opinions in this neutral area, but when the audio quality exceeds the lower limit, it is noticed negatively. The hypothesis is that the neutral area for each device will be based on the expectations users have for these products. The three sub-questions that are used to further define users thoughts on audio quality are the following:
    - **How is audio quality involved in purchase decisions of new personal mobile devices?** This question originated from the hypothesis that audio quality is rarely the decisive factor in the purchase of a new personal mobile device. If this is indeed the case, it further strengthens the hypothesis for overall audio quality in these devices. It can also indicate that audio might not be necessary in most use cases of the devices, or peripherals are excepted to take over the audio features for better quality, such as headphones or portable speakers.
    - **What level of influence does the audio quality have on the use of personal mobile devices?** To verify if peripherals are expected, the use of the devices can be analysed to determine if the users approach a device differently if the audio quality is better. The hypothesis is that peripherals are mainly used to increase audio quality in use cases that require audio. For example: if the audio quality of a personal mobile device is excellent, the users might not be interested in peripherals. However, another possibility could be that the peripherals are not used to improve audio but for a whole different reason than the need to increase the audio quality.

- What are user expectations for the audio quality in foldable devices? Because foldable devices such as tablets and laptops are not yet on the market, and a lot of companies are still developing concepts, the audio quality cannot be tested in real-life by participants. The hypothesis is that there is a greyscale in expected audio quality for laptop and tabled foldable devices as well.

- What are the effects on the audio performance of Aito's system by changing: (layer) layout, used materials, shapes, hardware setup? The findings showed that the best speaker type for Aito's structure would be a MAP. These type of speakers are still in the experimental phase, although some companies have implemented this technology into their products. The limit in design rules for these type of speakers is because each setup is different and should go through multiple iterations. The design rules for Aito have to be created with the findings on speaker design as the basis for iterations. How some identified principles for DML's, MAP's or normal speakers would impact the audio performance, positively or negatively, is uncertain and should, therefore, be researched. The two sub-questions to answer this question are the following:

    - What are appropriate prototyping methods to use to create models to test the previously mentioned effects? Because this research was done without any other companies involved beside Aito, there was no accurate knowledge available for the structure of a specific tablet. Some details about the structure could be found by opening up a tablet, but the structure of foldable devices could not be obtained this way. Due to the high level of secrecy surrounding these devices, there was no possibility to integrate the new system into a real device. Therefore, a model had to be created from the limited amount of information to represent an actual product as close as possible. A defining constraint for the prototyping will likely be time and available materials such as foils and top layers.

    - What are the correct testing methods to use to conclude how well the audio is performing? The methods will likely be found in the current approach of audio engineers. In this approach, the requirements or definitions for well-performing or "good" audio are stated. However, these methods are likely based on traditional speaker and non-foldable devices. So adjustments might be necessary to either the methods or the definitions.

- Can the user expectations and client requirements be met in Aito's system by applying the proposed design principles? Both the user expectations and audio requirements should be translated into one definition that tests audio quality and performance for foldable devices to validate the performance of Aito's system in terms of audio. The hypothesis is that the system will fit some of the requirements and expectations, serving as a demonstration for further development.

    - What is needed to further develop to improve Aito's system, making an audio functionality feasible? As earlier stated in the design space paragraph, the amplifier will not be designed. However, some changes for further development can still be identified. Also, the results of the audio test could help to define which design principles can still be developed further or are considered not to improve the audio performance.

3.2 Methods

Two different methods were used in this project, the subjective and objective methods, to answer the research questions. Both methods are conventional in the field of audio engineering, but this project uses them differently.

In the subjective method, the audio quality is tested either by a trained audio engineer or with a group of untrained participants. The testing is done by listening to an audio recording via the speakers that need to be tested. This way of testing takes the different types of human perception into account that currently cannot be analysed by a computer. The outcome of a subjective audio test is a written description of the audio performance, which can make it quite complicated due to the number of words available. Another part of the complexity is the difference between trained listeners and un-trained ones; they each have their own set of words to describe audio. Due to Covid-19, this approach of subjective audio testing could unfortunately not be used. The subjective part of the audio testing was transformed into an online version in which users participated in an exercise/survey style test. This test was developed to incorporate the users more in the first design step, defining the experience participants envision for foldable laptops or tablets. This experience needed clarifying because there is still little known about what this should be. The experience was defined by letting the participants firstly rate the sound quality of their own devices while also explaining their approach to several day to day use cases, to get an idea of what audio quality meant to them. After rating their devices, they had to define their expectations for both foldable tablets as well as foldable laptops. This approach to the subjective method should give answers to the previously stated research questions regarding the user aspects in this project.

The objective method was used to define the effect different design principles have on the sound performance of Aito's system. This approach was used to answer questions regarding the technical aspects. While a different approach was needed for the subjective method, the objective method for testing was still possible. For this method, no participants were required because the audio coming from the speakers was recorded in a closed-off sound lab, and these recordings were transformed into a visual representation of the audio to analyse it. Testing was done with various model prototypes instead of testing with a mathematical model, which was a possibility that was found during the state of the art research. The model making approach, or experimental approach, was chosen because the mathematical approach would better fit a physics graduation project and would not reflect every aspect that might influence the audio performance. Some audio designers have already experimented with both the mathematical approach and the model-making approach. They found that their mathematical model did not represent their real-life model. It seems that it is still too complex to calculate or predict how vibrations transition between components and what the influence of airflow inside of the model is.

The various models that were tested in this project were based on one overall model design that used Aito's stack design. For each model, the overall model design was changed to test one or two design principles from the design space. Testing and analysing these models was done according to industry standards which are used for developing speaker systems for their tablets and laptops. Aito's system would have to comply with the requirements the industry has defined, to get a grading-label. Another part of the testing involved measuring the power consumption and performance of the several amplifiers to give recommendations for future changes to Aito's technology.

Subjective method

What do the users say?

4.

What is subjective? The Cambridge dictionary describes it as the following "influenced by or based on personal beliefs or feelings, rather than based on facts". For audio testing, this means that the audio quality is described on a deeper level than only on performance; it takes the preferences of the listener into account as well. Where computers can analyse data very well, and new algorithms are developed every day, the human hearing is currently far too complex to define with any code. It is impossible to predict with a model if users will approve of the audio quality of a speaker, you need actual people to test this.

The participants in these objective tests can be divided into two groups; the audio engineers who trained their hearing to detect most variations in performance and the users of the speaker systems who want good audio based on their preferences and definition of audio quality. The two groups, audio engineers and users, have a different approach to validate the audio quality. Audio engineers listen to see where there is an imperfection and know what causes it and how to change this; they roughly identify where the peaks and troughs are. A typical user will experience these as distortions less precise, and base the audio quality on the lack or abundance of certain sounds. For example, they can say the bass is too loud or the audio sounds too high without really knowing what the problem is. Another part of the user experience is the preferences towards audio, where a user would like more bass the audio engineer might label it as well balanced due to the industry standard. These descriptions of the audio are the most important outcome of a subjective test, and they can consist of a wide range of terminology that is used in the audio design field.

In the field of audio design, there are a lot of different terms to use when describing sound subjectively. A study of (Wilson & Fazenda, 2015) tried to analyse what type of words are used to express positive and negative audio aspects. This research included both professionals in the industry and people with little knowledge about audio. Wilson and Fazenda found that a single participant only ever used 62 % of the words. From all the words, a top 20 of terms was created, and each word had its quality score (figure 36). The quality score was related to a 5-point scale, where 5 was the highest score. The outcome of the research showed, besides the commonly used words, also the difference between professionals and people with little knowledge. The five words that professionals used more than the other group are dynamic', 'muddy', 'cluttered', 'compressed' and 'tinny'. Where people with lower audio expertise used the words: 'busy', 'messy', 'mellow', 'brittle' and 'light' express their audio perception.

Word	Quality score
Clean	4.10
Full	3.91
Strong	3.88
Clear	3.86
Spacious	3.79
Deep	3.75
Smooth	3.69
Punchy	3.61
Wide	3.54
Aggressive	3.50
Bright	3.33
Synthetic	3.13
Crunchy	3.07
Loud	2.90
Narrow	2.59
Thin	2.54
Dull	2.43
Fuzzy	2.43
Harsh	2.31
Distorted	2.30

Figure 36, 20 most used words to describe audio (Wilson, 2015)

"The best test will always be a song you are familiar with and have heard in as high a resolution format as possible so you'll hear where the performance excels and/or misses a trick"

CAMBRIDGE AUDIO

The study of Wilson and Fazenda showed a relation between words and audio quality where the study of (Gagge, 2014) suggested a relationship between prominent frequencies in audio and wording to describe the audio aspects. The word thick (grötigt) was used for audio with a higher volume in the frequency range between 150 and 500 Hz. The word nasal (nasalt) for frequencies between 600 to 2000 Hz. Airy(luftig) for frequencies between 2500 to 8000 Hz. Sharp (skarpt) had an overlap with airy in the 2500 to 8000 frequency range but sharp was also used for frequencies between 8000 to 16000 Hz. The study Gagge did was done in Swedish; it might be the case that the same words translated into different languages might not give the same results. The same applies to the rating (Wilson & Fazenda, 2015) has assigned to the 20 most common words to describe audio aspects. There are multiple other studies done to get a better understanding of wording used to describe audio aspects. Examples of these studies are a study by Staffeldt in 1974, and the study by Gabrielsson in the same year. A more resent study on terminology in audio was done by Zacharov. A visual representation of how these words are related to each other are shown in figure 37, which is the Letowski mural. The mural shows the different “layers” there are when describing audio aspects. The study of Wilson and Fazenda was chosen to use to maintain consistency for this project, due to the fact this was done relatively recently while others date back multiple years.

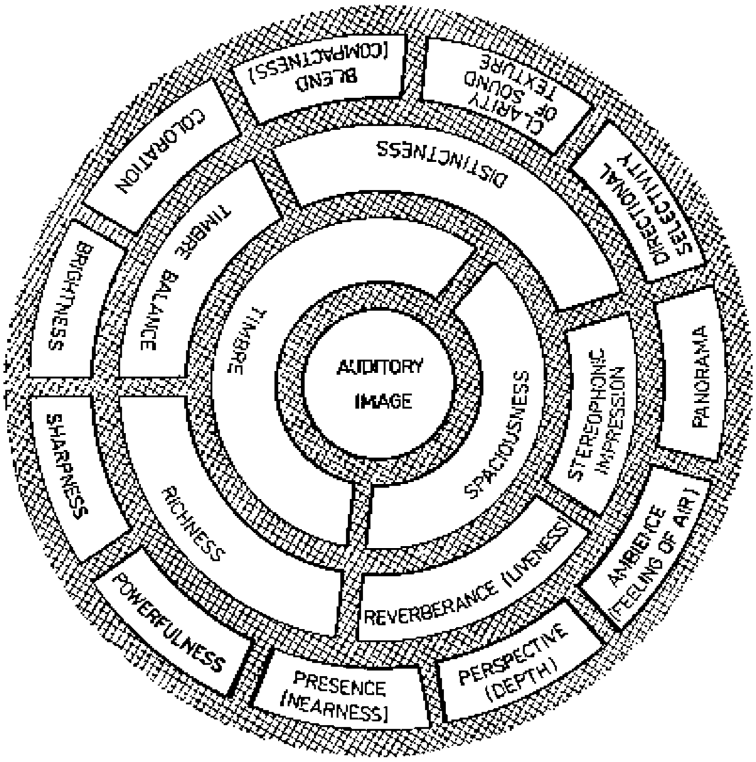


Figure 37, Letowski mural

Testing with an audio engineer happens most often, without verifying with users. An example of this is the company Kien; they stated that their speakers have a more limited bass than most speakers. They expect that their customers will get used to it, but they have never tested this with an actual focus group to verify their assumptions. Testing happens by just listening to songs via the speaker and trying to find unexpected deviations. Cambridge Audio, a speaker design company, states on their website that they test their speakers with a list of various songs. They have picked out well-recorded audio files that come as close to real-life experience as possible. The songs should also consist of a variety between highs, lows, fast and slow parts in the songs. Cambridge audio says that an audio engineer will use songs he or she knows by heart to spot the possible differences if they occur. (Wilson & Fazenda, 2016) suggest that the song familiarity also influences the quality rating of a speaker during a subjective test. Where most speaker producers have their testing facilities inhouse, there are also options to test this independently. SenseLab is an example of a company that is specialised in perceptual sound quality testing with professionals in the field of audio design or potential customers. An outcome of a test performed by SenseLab can be seen in figure 38; in this figure, there is also a different approach to terminology compared to the earlier described researches. For the subjective approach, the vocabulary should be taken into account as an influence on the results.

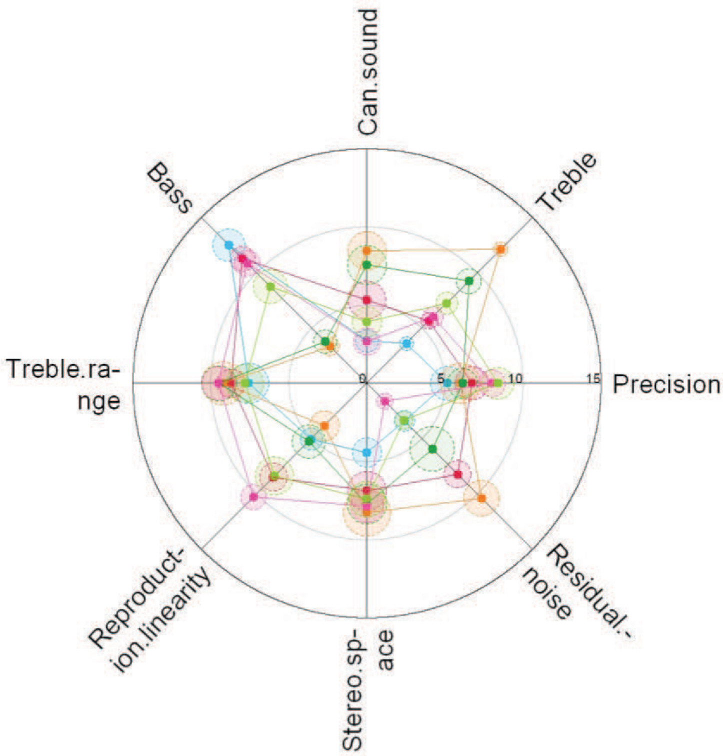


Figure 38, SenseLab perceptual sound quality test outcome

4.1 Soundless audio testing

The main question for the subjective part of this project was: How do users experience the audio quality in personal mobile devices? The original technique would be to let participants listen to several devices and possible some prototypes of Aito's approach of audio to define the perceived experience. However, due to Covid-19 in the world during the time this graduation project took place, in-person testing was no longer possible. The audio testing had to be done in an online setup via either a videocall, online exercise or survey. But how can you still test audio from a speaker when you cannot listen to it in real life? Because if you were to send a recording of several speakers to participants, they would listen to it on their speaker system. This system can either be a high quality one or the limited speakers on their phones.

To still be able to answer the research question about the audio experience in personal mobile devices, a type of soundless audio testing method had to be created for this project. Creating this method was not a straight forward process, and multiple iterations had to be done to get to a final approach that could be used to gain insight into the experience of personal mobile devices. Initially, the traditional audio testing method was explored (appendix 8.7, Initial user test approach), but no possibilities were found to turn this method into an online variant. The restrictions of Covid-19 did not allow in-person testing because thise would need to happen in the same sound-proof room. This room was required to have the same controlled environment, which would not impact the perceptions between participants. Letting multiple participants travel to this room and interacting with them felt like making concessions on safety and health during the Dutch peak of Covid-19. Because the traditional method focusses on the perception of audio quality, and there was no possibility to let the participants listen to models, an online solution was briefly investigated. However, as earlier mentioned, a recording of a model played to a speaker that participants would have at home gives inaccurate data about the real perception of the audio quality. Therefore, the traditional method was no longer a possibility.

After the traditional method failed, the option for an online test setup was the next best thing. This new approach would no longer focus on the perceptions of audio quality, but on the expectations on audio quality. The initial setup of this approach was an online survey to map the trade-offs during the purchasing devices to see what type of expected impact audio quality has on making decisions. Participants would get a choice between two components each time, and they had to pick their most favourable one. Figure 39 shows in light blue all the choices the participants would have to make. When further detailing this survey, multiple problems arouse which turned the survey towards another area for studying expectations on audio quality.

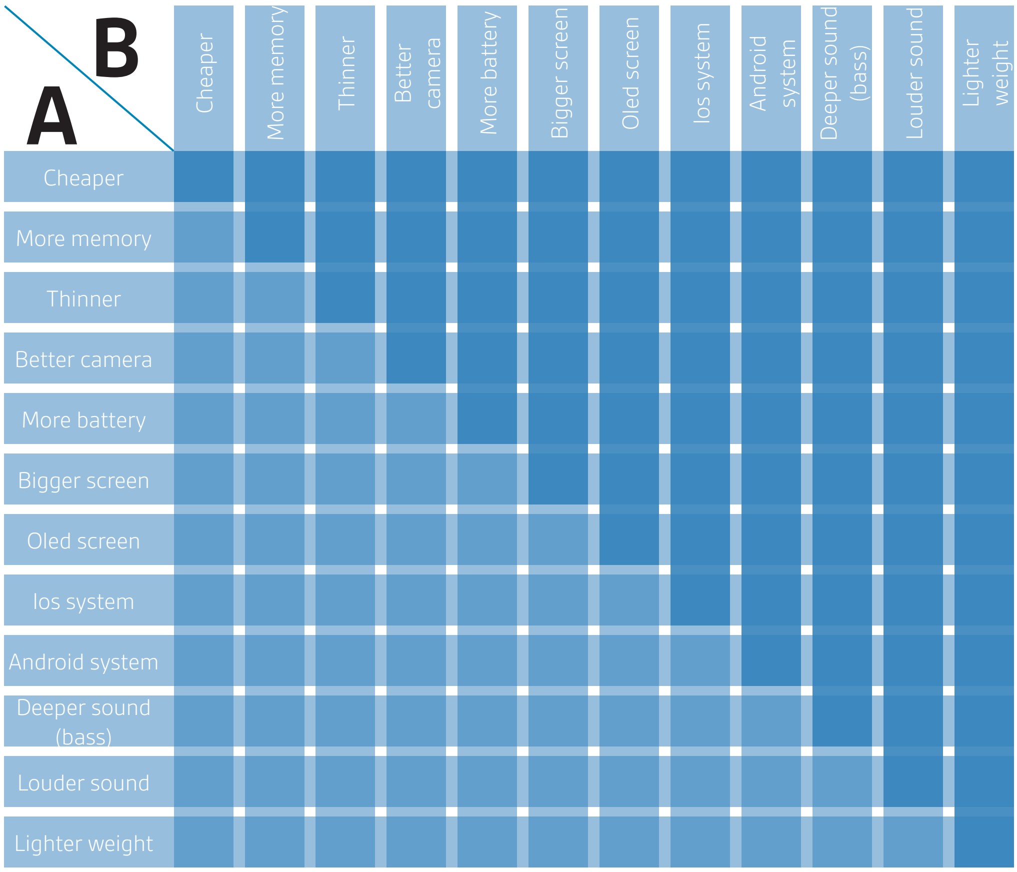


Figure 39, Purchase decision matrix

The first problem was related to giving value to different components and if this should be done at all. A comparison of two vague components is not as valuable as a comparison where a more precise decision can be made. The difficulty of setting a real value is that for some elements there could be a tipping point where before this point, one component is favoured but when this point is reached, the other becomes more favourable. The two components storage and price are used to illustrate this. In this example, participants have to choose between 250 Gb of storage or a 60 euro/dollar discount. Participants show to have more interest in the larger storage in the device rather than the discount. But a tipping point, where participants choose the discount, might be if the price is raised to 150 euro/dollar. From this example, the conclusion cannot be drawn that storage is favoured over a discount because this is true until a certain discount level.

The second problem that would influence the results can be found in the previous example as well. The personal preferences of the participants cause this problem. In the example, some participants would value storage more compared to other participants because they like to keep as many photos and videos on their device as possible. This preference results in them being willing to accept the discount in a later stage, which results in an increased tipping point. A large group of participants should be used to level out these differences or to be able to divide the participants into multiple groups based on their favouritism for specific components to combat the personal variation. Here the problem that is created is that reaching a large group of participants that would be willing to fill in 87 questions is difficult for a graduation project. Either it would take a long time to gather these participants, or it would cost quite some money to find willing participants, neither of which were available for this project.

The third problem is created with the choice of device to base the models on; the foldable tablet or laptop. Because this type of device is not currently on the market, yet participants might not recognize the component "foldability" as a favourable one. Or if this component is not tested, and the test is based on which components participants would like to have in a foldable tablet or laptop, the participants might not imagine the full range of use cases for these new devices. This lack of imagination would result in an inaccurate outcome. Some useful components will be discarded, while later on, when participants are more familiar with these devices, they will value them more.

The solution for these problems was found in a new area of audio quality expectations, namely expectations on foldable laptops and tablets and the decisions that participants already made when buying their devices. These expectations on foldable laptops and tablets would help in validating the audio functionality feasibility of Aito's system. An outcome on purchasing decisions would be useful, but as for now, the result is too uncertain because participants are not yet familiar with foldable laptops and tablets. The element of lack of knowledge was used as the main inspiration in developing the soundless sound testing method that was used in this project. This approach also consisted of an online survey, which tried to involve users in the audio design process. But how capable are participants to imagine the audio quality for a non-existing product? How can you guide them through this process?

4.1.1 Setup

The defined method of soundless sound testing helps to understand better the context in which the speakers will be used. An internal laptop speaker with good audio quality might not be deemed to give a good performance when compared to the audio system that is installed in a cinema. It is important to know what the intended use for the audio is to say more about how well the audio is performing. For mobile personal devices, it is accepted that they lack bass and will perform better in the higher frequencies due to their small size. The same definition for foldable devices has to be explored to be able to validate if the results of the objective method match with the context of foldable devices. This context was defined by a survey in which several participants had to rate their own devices and state their expectations on foldable devices by making a comparison between their own devices. The structure of the survey can be seen in figure 40, and the full study with all the questions can be found in appendix 8.8, Online survey design. Figure 41 gives an insight on how the survey was visually presented. As seen in figure 40, the research consisted of three main parts in which smaller sub-parts were positioned. To get a better insight on the purchase decision another analysis was done by looking at online electronic stores and reading reviews and their acknowledgement of the audio quality in the device (appendix 8.9, Tablet purchase collage). The analysis was based on audio quality in tablets, and more specifically the Samsung Tab S6 and the Apple iPad Pro. These tablets were chosen because both brands advertise with their speaker setup which they claim gives the best experience. On the website of BestBuy the reviews were gathered that contained the keywords "audio", "speaker" or "sound".

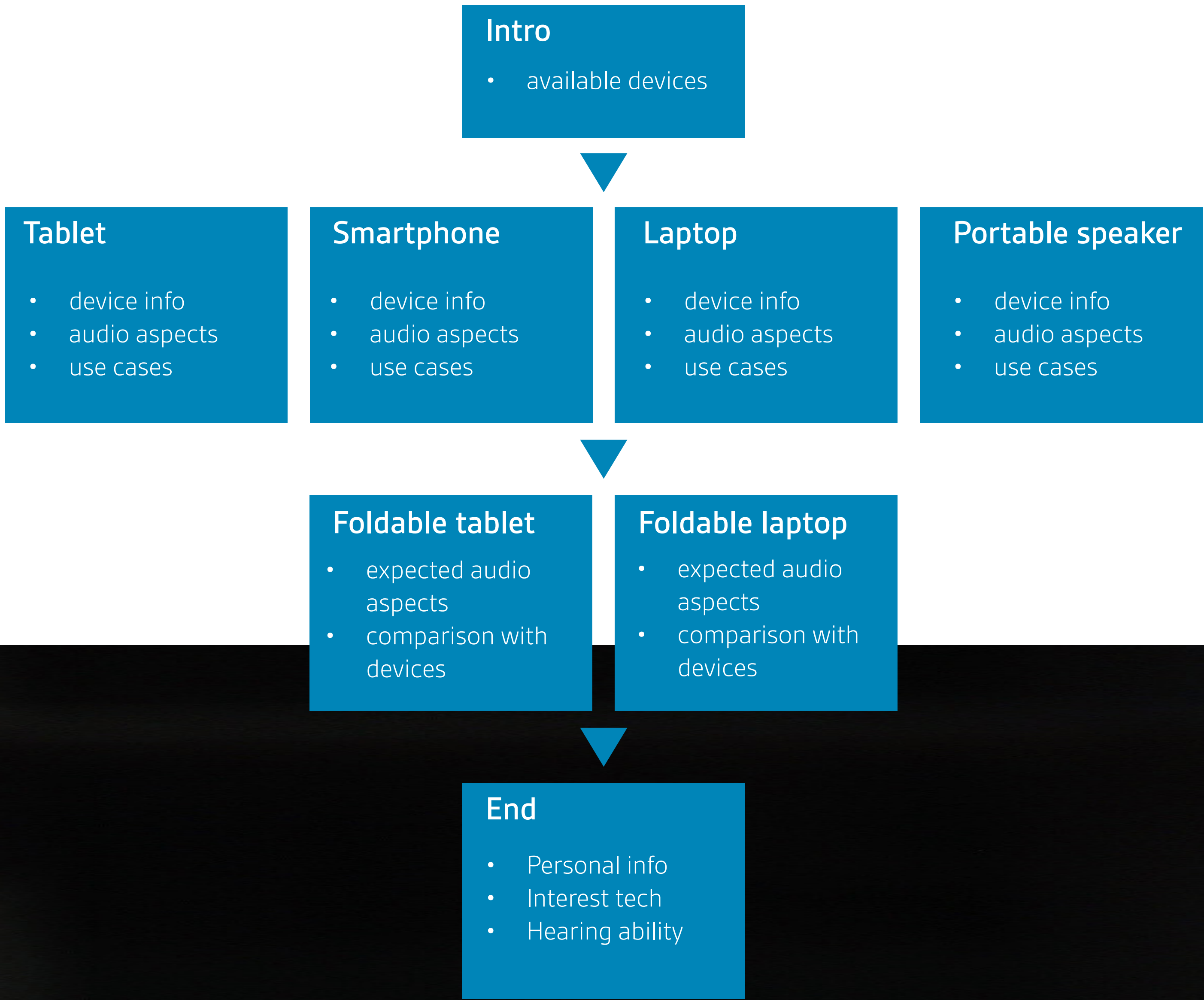


Figure 40, Survey structure

First part

The first part of the survey explained the purpose of the research and how participants should test the audio quality of their devices, the topic of foldable devices was later introduced to the participants in the third part. The participants had to state with which devices they would be using to do the audio testing. The survey adjusted the questions automatically to the devices that were used and hid the questions related to the devices that the participant would not be using. The devices participants could use during the survey were: a smartphone, a tablet, a laptop and a portable speaker. The first three devices are personal mobile devices which lie within the field Aito might implement the new technology, so the context of these devices would be valuable to know. The portable speaker is a bit of an outlier, but because this is still related to audio in a mobile way it was included. Headphones were excluded from this research due to the distance to the ear; all other speakers could have a distance that is larger than 10 centimetres. The survey prevented participants from participating in the test if they used less than two devices for the audio test. This threshold was set to ensure the comparison at the end of the survey contained enough variables to get a richer outcome. Before the participants went into the main part of the study, they were asked questions related to the devices they were going to use to get some insights on the brands that were used, in which price class these devices were positioned and how old they were. This information could later be used to group several data sets for analysing purposes.

- What is the brand and type of the device?
- Was it a high-end, mid-range or low end device at date of purchase?
- In which year was the device bought?

For the first nine participants, the order of the sub-parts, about their current devices and foldable devices, was not yet randomized. The survey was adjusted after these nine participants to randomize in which order these sub-parts needed to be answered.

Second part

The sub-parts about their current devices were answered in the second part of the survey. This part was created for two reasons. The first reason was to let the participants get a feeling for audio quality and make them think about how they experience it. The second reason was to gather insights on the audio quality in current devices and how participants approach this topic. The assumption was that letting participants firstly rate their own devices before giving the expected rating for the foldable devices, they could better imagine the experience they would want and compare it with their current devices. This exploration for the participants regarding audio quality was guided by the following questions, which were mainly the same for all devices:

- What is the amount and placement of the speakers in the device on a generic device drawing?
- Is the audio coming from one or multiple directions?
- How they would rate the audio quality on a scale from 1 to 5?
- What positive and negative words they would use to describe the audio quality?

This part should stimulate the participant in starting to think about certain decisions on audio in personal mobile devices. The portable speaker did not include the question about placement due to the wide variety of shapes in these products. Smartphones, tablets and laptops have a more uniform design language per device, so to creating a generic drawing for these types was possible. In describing the audio quality with words, the participant was also guided by a list of example terms. These terms were the twenty most used words found by Wilson and Fazenda (2015). These terms should help participants to imagine words, but they were allowed to use other words to describe the audio as well.

During the exploration, participants already provided information about their current experiences with the audio of their devices. Another part was added to get more information regarding what role audio has in purchase decisions and how audio influences day to day use of devices to get a better inside on these experiences. This expansion consisted of the following questions:

- Was audio taken into account in the purchase decision of the device?

- What type of audio setup, device speaker or peripherals, is used in various use cases and why?
- What would they change in terms of audio to improve their experience with the device?
- What is the accepted increase in price and thickness to get better audio?

Third part

The third part firstly stated the foldable devices as interest for this research. Each sub-part had its introduction regarding either the foldable laptop or foldable tablet with specifications of the specific device. The differences between devices were based on the screen size, the performance of the system and their example image. The image for the laptop depicted the foldable device in the laptop position to focus on this type of use, and the tablet was shown folded fully open. These two depictions should guide the participant to focus on different use cases rather than sticking to one type of use. The two sub-parts were used to take the possible grey scale between foldable tablets and laptops into account because this might also apply for audio quality aspects. The difference between the non-foldable and foldable devices were discovered by asking the same questions for both device groups. However, in the questions about the foldable devices were based on expectations.

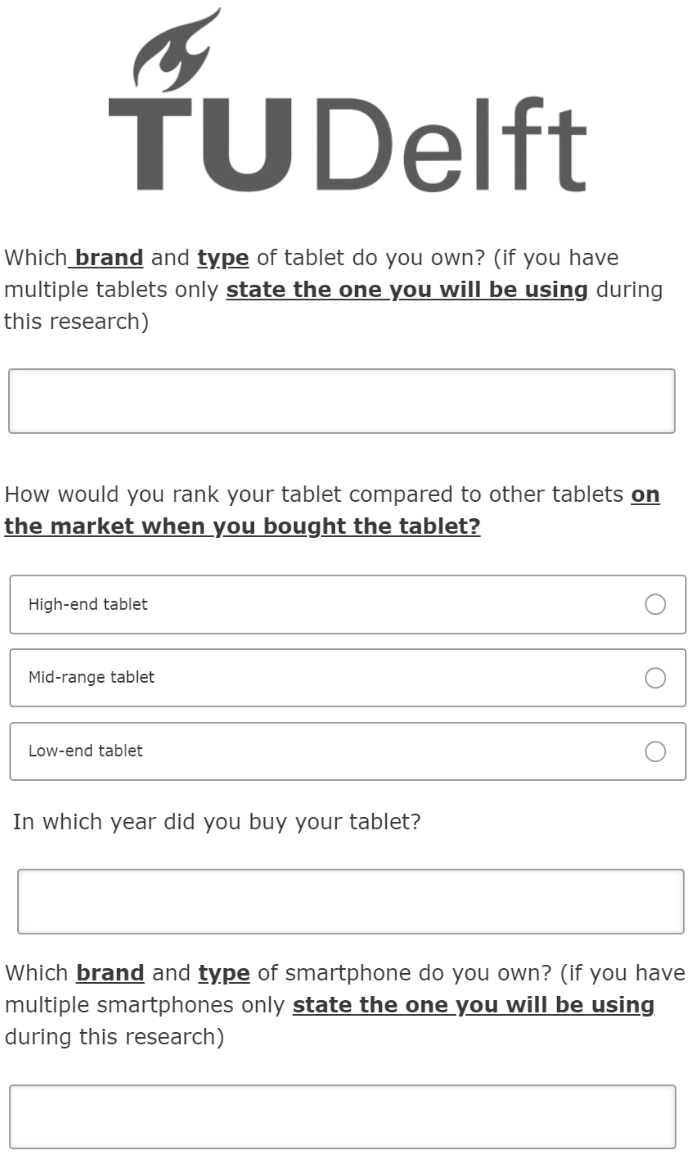
- What would be the amount and placement of the speakers in the device on a generic device drawing?
- Would the audio be coming from one or multiple directions?
- How would they expect the audio quality on a scale from 1 to 5 based on the current devices?
- What words would they use to describe the expected audio quality based on the current devices?

Besides discovering the differences between the two types of foldable devices, another goal of the third part was to see how foldable tablets and foldable laptops would be classified compared to existing personal mobile devices. The following questions were asked to get information about this topic:

- What would they expect the advantages of a foldable device to be compared with its non-foldable device type?
- How would they score the device compared to current devices by giving them an order from best to worst audio quality?

Fourth part

The last section was added to get background information about the participants to filter out some of them or group participants based on gender, nationality, age, hearing capacity and technology interests. The hearing capacity was added to exclude participants who would have trouble hearing because their perception of audio quality will differ from normally hearing participants.


TUDelft

Which **brand** and **type** of tablet do you own? (If you have multiple tablets only **state the one you will be using** during this research)

How would you rank your tablet compared to other tablets **on the market when you bought the tablet?**

High-end tablet

Mid-range tablet

Low-end tablet

In which year did you buy your tablet?

Which **brand** and **type** of smartphone do you own? (If you have multiple smartphones only **state the one you will be using** during this research)

Figure 41, A section of the online questionnaire

4.1.2 Benefits and limitations

The online survey had to be used instead of the ideal test setting, and this change brought some limitations; it proved to be relevant. This paragraph discusses these limitations and benefits and explains why this survey was deemed a good substitute for its real-life version.

The main benefit of this approach is access to insights on the expected experience before the speaker design process has fully started. In the traditional method, the speaker is already fully designed, and the input from the user is the last step in the process. By flipping this around and allowing the user to help with the design process, less effort is invested in creating an experience that the user might not see fit for the context. In the design field, the changes that are made at the beginning are still flexible where at the end they are more rigid because changing something, in the end, might mean discarding the whole product and starting over. For this project, this flipped process was not fully incorporated because the design is in such a beginning stage that changing certain elements would not mean a waste of effort. This approach meant that while the survey was online, the model could be developed further.

Having the survey running while working on other aspects saves time. While developing the study itself took some effort and time, remotely running the survey made it worthwhile. Following the traditional approach would mean that the researcher would be busy with conducting multiple tests spread out over several days. Because the participants did not have to have to travel to the testing space and could participate in the survey in any spare time they had, they also saved time. However, this type of independent remote testing can come with some downsides as well. The first being the situation in which the participant runs into a problem, they have no contact person to ask questions. This lack of contact might result in them incorrectly filling in the questions, or they will stop filling in the survey. The second downside is that participants can also end with the survey any time they want due to lack of interest. One of the reasons for stopping is because the survey takes too long. According to Qualtrics, which is a company specialized in online questionnaires, a survey should not exceed the 10-minute limit to keep participants engaged. Stopping a test midway is less likely in the traditional setup because there is a personal connection, which is lacking in the remote version. The most obvious way of limiting the number of participants that will stop the survey is to stick to the 10-minute norm. If this is not possible, there are two other options. The first one is to ask familiar people to be a participant; this brings back the personal connection. The second one is to set a reward as an incentive; this can be a price, discount or money. There are platforms available that work on this reward principle; familiar ones are Amazon Turk, SurveyMonkey and Clickworker. These sites have a database of possible participants that fill in a questionnaire and get money in return. If these sites are used to look for participants, the target audience can be selected for an increase in price. When the target audience is not chosen, unemployed people might fill in the questionnaire. For some studies, they do not represent the correct audience. These unemployed participants might also use the surveys as their job and will fill in the surveys as fast as possible, which results in less accurate results. In the setup of the study for this project, these downsides were tried to be kept at a minimum. The solution to the first one downside was to run a pilot test to filter out possible problems that could occur. Besides the pilot test, an open comment section was placed at the end of the survey in which the participants could share their thoughts on the survey. A solution to the second downside was to ask family and friends to participate in the research. This option was chosen because they would be more willing to fill in the 87 questions which were estimated to take around 30 minutes to answer. The length was not shortened to keep the exercise element in it, participants needed to start thinking critically about audio, and this takes time. Besides reaching out to familiar people, the survey was also posted online to attract a wider audience possibly. However, it was published without a reward because this would cost too much money for too little people. The number of participants that was aimed for during this project was above 25; this should allow a quantitative analysing approach to base strong conclusions. It was suspected that if most of the familiar people filled in the survey, this threshold of participants would be met.

Another benefit of having an online survey also relates the participant audience; this audience is no longer restricted to the area of the testing facilities. An online test allows gathering participants from all over the world. Two conditions for this are the availability of an internet connection, and the participants should be able to understand the language in which the survey is written. If the language is the second language of a participant or if multiple surveys, all with different languages, are combined, the terminology might influence the results. As earlier stated the same words could have a different interpretation in different languages. Before the survey went online, this possible influence was acknowledged, but English was the only language that allowed a broader range of participants. Dutch would also have been an option because this was the first language of most familiar people that were asked to participate.

4.1.3 Data processing

As described in the previous paragraph, the assumption was that the number of participants who filled in the questionnaire would exceed the 25 participant threshold. This threshold was set to get enough data to analyze the data with quantitative methods. After the deadline of the survey 12 participants had filled in the survey, meaning that the threshold was not met. Because the number of participants was lower than 25, the quantitative analysis approach was no longer feasible. Instead, a qualitative analyzing approach was chosen to get insights from the data. The gathered data is divided into four sections: demographic, purchase decision, influence and expectations. For each of these sections will be explained how the data was analysed qualitatively. The demographic section will discuss who filled in the questionnaire and what data was excluded based on this information. In the purchase decision section, the relevant data about buying is grouped. For the influence section, the data on the influence of audio quality on the use of personal mobile is grouped. And the last section, expectations groups the data about expectations of foldable laptops and foldable tablets. The complete results of the survey can be found in (appendix 8.10, Survey results).

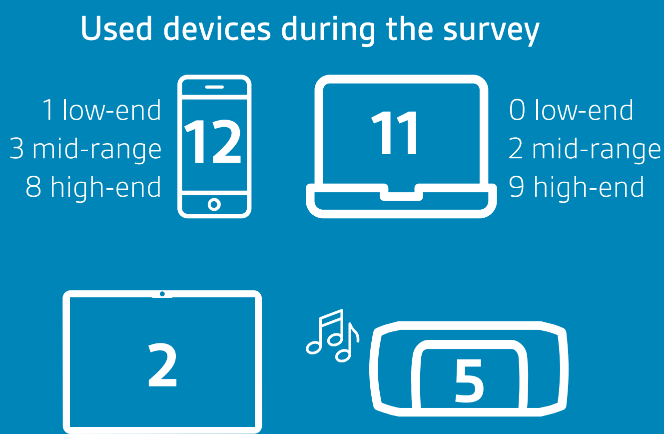
Demographic

None of the participants were excluded based on hearing, all rated their hearing “average” or higher. If they would have scored their hearing “poor” or “terrible” they would have been excluded because they could not give an accurate definition of their device’s audio quality. The low number of participants resulted in a group that showed a limited mix of nationalities and used devices. The primary devices that were used were smartphones and laptops in only the mid and high price categories. There was a more even mix in genders and previous knowledge about foldable devices. Due to the low number of tablets and portable speakers, their results were only used in the analysis of terminology for positive or negative audio qualities.

The participants

22 to 65 years old

- 66% between 20 and 30 years old
- 83% Dutch
- 91% with interest in new technologies
- 41% with previous knowledge about foldable devices
- 0% has to urge to buy the latest devices.

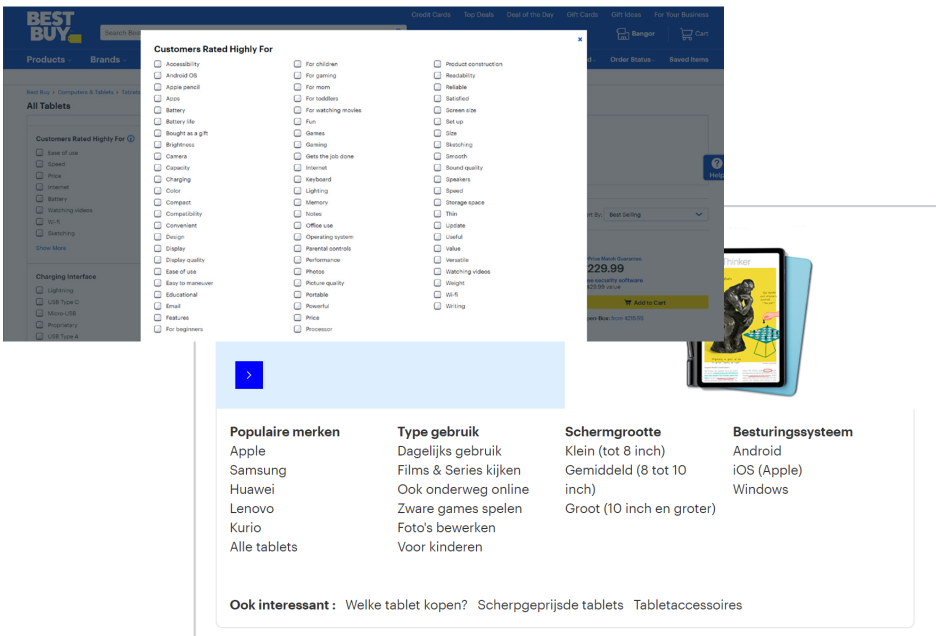


Purchase decision

For the purchase decision, the smartphone and laptop are analyzed to give an insight into the purchase decisions of the participants. The majority of the participants did not take audio quality into account when purchasing their devices. The number of participants that did take the audio quality lies higher for laptops compared to smartphones. The three participants who took the audio quality into account had a laptop in the upper price range. As earlier mentioned no quantitative analysis could be performed to conclude whether there is a difference between the price range of the device and the attention on audio quality. The primary reason was the low amount of participants, but there were some other reasons for this specific data set. It was not possible for the smartphone because none of the participants took this into account, and for the laptop, there was a too small mix of different price ranges.

As mentioned previously, besides from the survey information was gathered by looking at online stores and tablet brands as well. The collected information shows that online stores offer few filters to pick tablets based on audio quality, the only store which had filters related to audio was the American website Best Buy. Bol.com, a large Dutch online department store, did offer a filtering selection based on the use case (figure 42). For the use case "watching videos" the filter to look for devices with good audio quality might be included, but this cannot be said for sure. The specifications of the speaker system are limited in online websites. Some online stores state only the amount or the software that is used to drive the speakers. Information about audio quality is also not stated on the website of the brands who offer the devices. It often says where the speakers are positioned and what the experience will be. The online reviews, of two leading tablets currently on the market who focused on the audio aspects more than others, were analysed to see how many buyers acknowledge the audio in their tablets. For the Samsung Tab S6, 604 reviews were analysed, and for the Apple iPad Pro, this number was 1359 reviews. The outcomes of this analysis can be seen in the infographic on the right.

The infographic on the right also shows what participant would be willing to give up, in terms of thickness and price to get better audio quality; the details of this quality increase are depicted in the word cloud. These averages do not show the number of participants who did not want any changes for increased audio performance. For the smartphone, three participants did not want to increase the thickness, and six participants did not want this for a laptop. For the price increase, three did not want this for a smartphone and six did not want this for a laptop. In total, six participants did not wish an increase in either thickness or price for a laptop and only two for a smartphone.



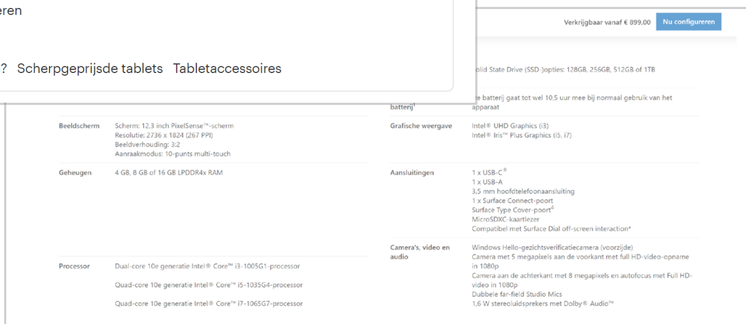


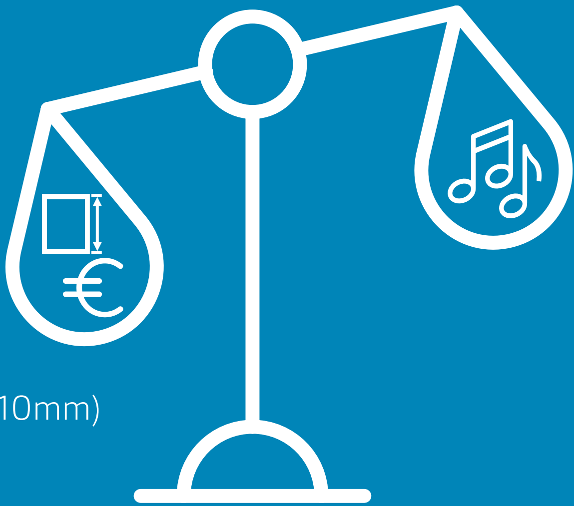
Figure 42, BestBuy, Bol.com and Microsoft screenshots of audio specifications and filtering options

0% takes audio quality into account when purchasing a smartphone

37% takes audio quality into account when purchasing a laptop

Audio quality online

- Lack of filters for audio quality in online stores
- for the Samsung Tab S6 11.8% acknowledged the audio quality or said something about the audio.
- Apple iPad Pro 3.8% acknowledged the audio quality or said something about the audio.

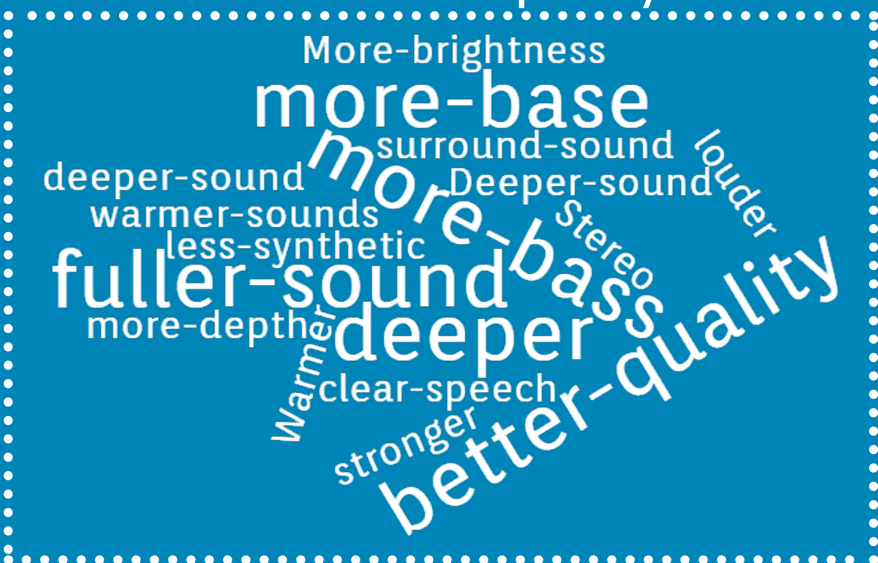


What are they willing to give up?

- 2.17mm thickness increase (min: 0mm, max: 6mm)
- 26 euro/dollar (min: 0, max: 80)

- 2.3mm thickness increase (min: 0mm, max: 10mm)
- 36 euro/dollar (min: 0, max: 172)

The increased audio quality



Influence

In this section, the results regarding the influence of audio quality on the use of peripherals such as headphones and external speakers are shown. While participants used devices in different price ranges in this survey, no data could be extracted to see the effect of quality on the type of audio use. The number of devices in the different price ranges was too small, and the statements regarding the positive and negative elements of the audio quality of the devices could not be translated into a statistical analysis.

The words used to describe the audio quality did show some differences compared to the research of Wilson and Fazenda. The words "synthetic" and "loud", which are graded relatively negative by Wilson and Fazenda, were used to describe positive aspects of the audio quality. There was also some overlap in positive and negative because the word "spacious" was used in both cases. As the study of Wilson and Fazenda already suggested, there are a lot of words to describe audio. Besides the twenty example words that were stated in the question, the participants filled in their own words as well. These new words are "Okay", "Warm", "Complete", "Detailed", "Lack bass", "Empty", "Bad stereo", "soft". In the created word clouds (figures 43 and 44), the descriptions for all four devices were used. The size of the word in the word cloud indicates how many times that word was used, the bigger the word, the more it was mentioned by participants. Some words were more frequently used for specific devices, meaning that of the total uses of the word, the particular device had a total of 50% or more of these uses. These words were selected if they were mentioned more than three times by participants, and these terms are:

- "Thin" 4 out of 7 to describe smartphones
- "Strong" 3 out of 6 to describe portable speakers and 2 out of 6 to describe laptops
- "Clean" 3 out of 5 to describe smartphones
- "Clear" 2 out of 5 to describe laptops and 2 out of 5 to describe smartphones
- "Dull" 2 out of 5 to describe laptops and 2 out of 5 to describe smartphones
- "Deep" 2 out of 4 to describe portable speakers
- "Bright" 2 out of 3 to describe laptops
- "Full" 2 out of 3 to describe portable speakers

The data shows general audio uses, instead of a more specific use which is determined by the device's price range as earlier explained. The data shows that the main reason to pick the internal speakers over the use of peripherals is that getting either a headphone or external speaker is too much of a hassle and the internal speakers are a more accessible option. Another reason is that the quality is deemed good enough for that specific use case. For the laptop, this reason is stated more frequently in the social media scenario compared to the same situation with the smartphone. The top three of the scenario's in which the internal speakers are accepted can be seen in the infographic on the right. In the situation regarding music, the participants stated that getting a peripheral is no longer too much of a hassle; these options were never picked as a reason for both the laptop and the smartphone. The main reason for chosen either a headphone or an external speaker is to increase the audio, 8 participants give this as a reason for the smartphone and 6 for the laptop.

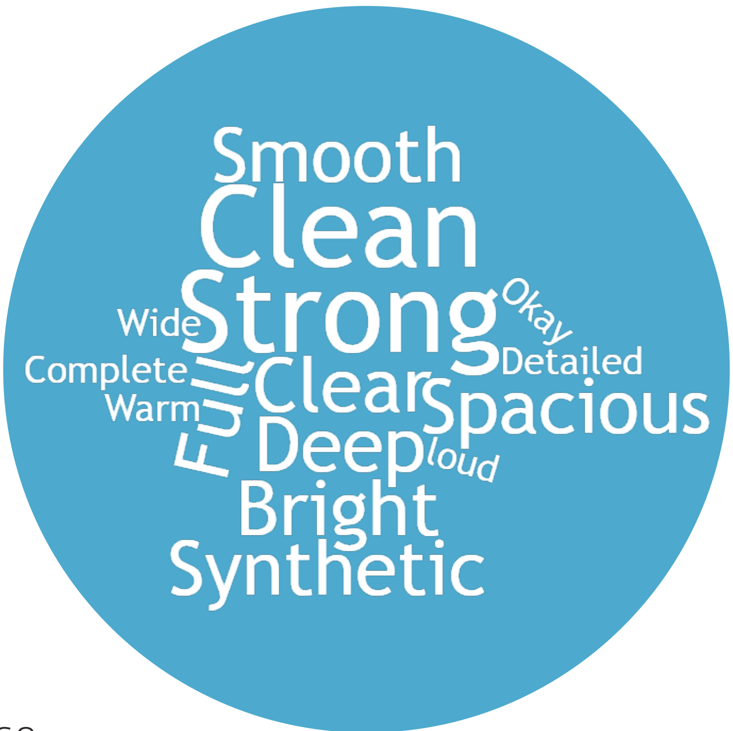
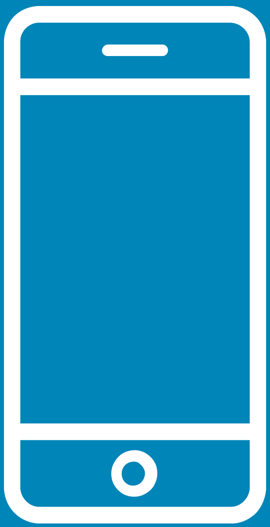


Figure 43, Positive discriptions of audio

Figure 44, Negative discriptions of audio



Top 3 of smartphone speaker uses

1. Browsing social media (9 participants)
    - Easiest option (8 participants)
2. Watching Youtube (6 participants)
    - Easiest option (4 participants)
    - Quality good enough as is (2 participants)
3. Video calling (5 participants)

Top 3 of smartphone speaker uses

1. Browsing social media (7 participants)
    - Easiest option (4 participants)
    - Quality good enough as is (3 participants)
2. Watching Youtube (6 participants)
    - Easiest option (4 participants)
    - Quality good enough as is (2 participants)
3. Watching Netflix (5 participants)
    - Quality good enough as is (3 participants)

What about music?

When listening to music via their smartphone....

- 6 participants use headphones
- 5 participants use external speakers
- 0 participants use the internal speakers

When listening to music via their laptop...

- 5 participants use headphones
- 3 participants use external speakers
- 3 participants use the internal speakers

Main reason is that the audio quality is increased with these devices (6 participants for the laptop, 8 participants for the smartphone)

Expectations

From the questions regarding the speaker, there are three types of data gathered; data regarding the expected speaker setup, data about the expected audio quality and expectations about the advantages of foldable devices. This last group is visualized in the infographic on the right.

The first type of data, regarding the speaker setup, is visually represented in figures 45 and 46. These images show hotspot locations where the participants expected the speakers to be located. The closer the colour is towards the colour red, the more participants selected this area. From the hotspot images, there are differences visible between the foldable laptop and the foldable tablet. For the foldable laptop, the speakers are placed more on the sides and the "top" part of the screen, the hotspots show a clear focus area. This area is less prominent in the image of the foldable tablet. The speakers are placed more on the edges of the device, along with some expected places on the side. Both the laptop and tablet show that some participants put the speakers on or underneath the screen of the devices. Another expectation regarding the speaker setup is that the majority of the participants expected the audio give a stereo output; 10 out of 12 participants selected this for the foldable tablet and 11 out of 12 for the foldable laptop. Some of these participants also stated that they expect the audio to change according to the orientation of the device; this number of participants was 2 for the foldable tablet and 3 for the foldable laptop. When participants were asked in the open question to state their assumptions about the audio quality multiple of them mentioned a stereo output in this question as well. Three participants also mentioned the importance of the location of the speakers; the three following quotes are from these participants:

- "No bass as this would make the tablet too thick to fold, more speakers to provide a good experience in every position, The speakers at multiple positions."
- "But the location is different from my laptop, because in the foldable laptop the screen is at the location of the speakers of my normal laptop."
- "Sound coming from different locations, so the orientation of the laptop makes no difference."

The second type of data, regarding the expected audio quality, shows that both foldable devices score higher in quality than the smartphone but do not score higher than the laptop. The ratings can be seen in the infographic on the right, which also shows the results of the comparison between the devices. This comparison also shows that the foldable devices are expected to have a better audio quality than smartphones and balance around the laptop. The data also shows a difference in rating between the foldable devices; the foldable tablet is rated slightly lower and is lesser put before the laptop in the comparison. When analyzing the comparison, the quality of the compared devices is not taken into account.

The answers to the open question regarding the expected audio show three groups of participants; one group expects the device to perform worse compared to their non-foldable sibling: "Comparable to a smartphone" and "Good volume, but worse sound than the laptop". The second group expects the device to perform similar to their non-foldable sibling: "Same as a regular tablet" and "I don't expect them to be better than a laptop... Around the same". And the third, and last group expects an audio quality that exceeds the non-foldable device: "Close to that of a laptop, probably a bit more bass as I guess the device is a bit thicker compared to most other laptops".

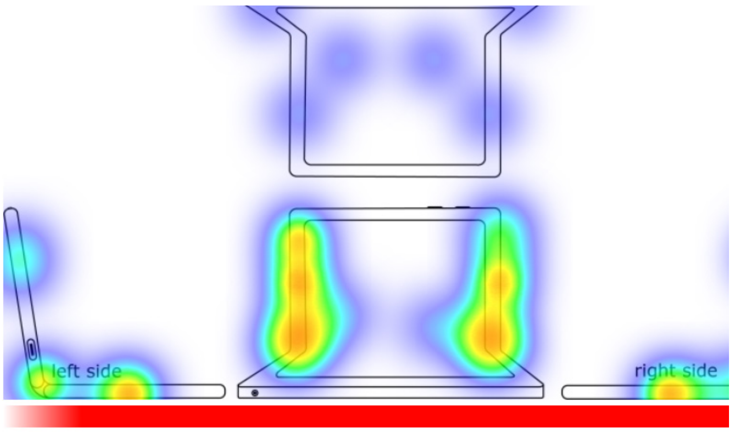


Figure 45, Hotspot image of expected speaker placement in foldable laptops

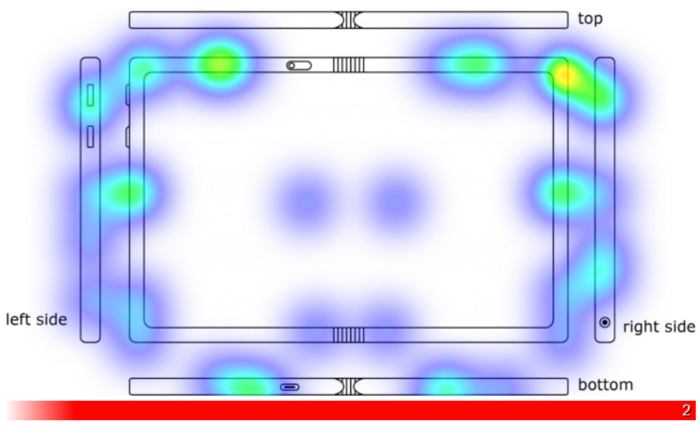
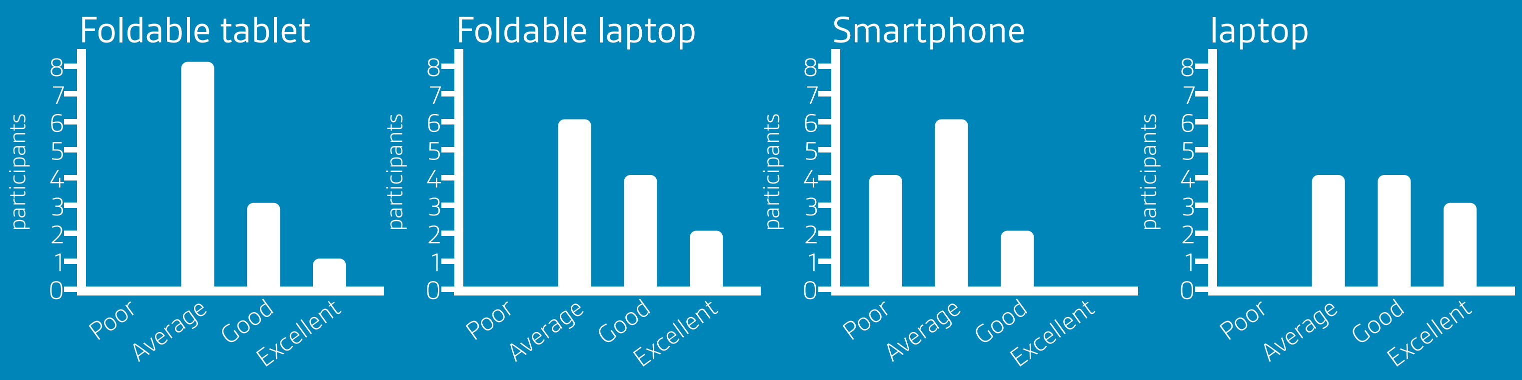
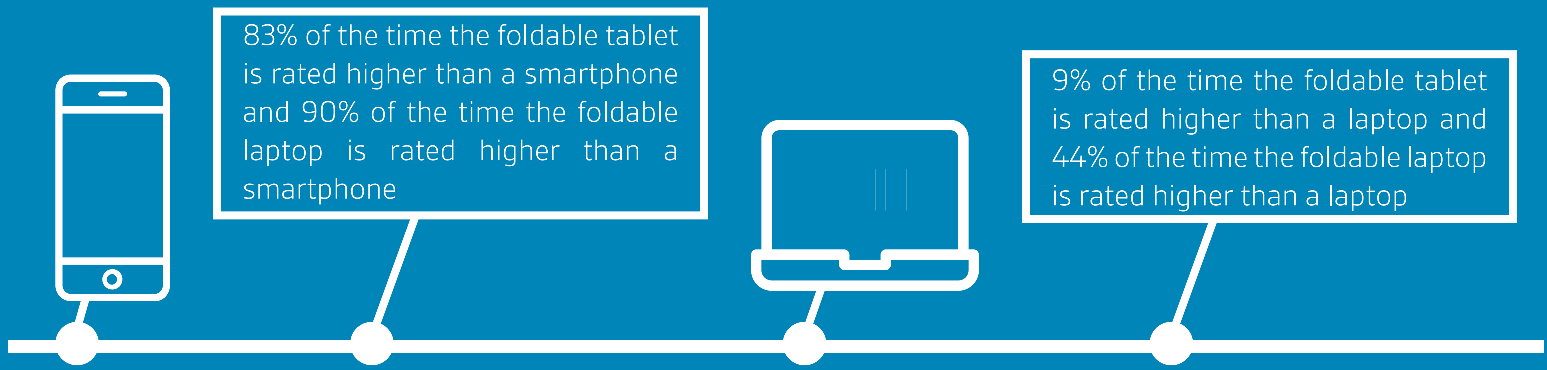


Figure 46, Hotspot image of expected speaker placement in foldable tablets

Audio quality rating





Interesting quotes

Regarding the advantages of foldable devices

Foldable tablet

"Same as a regular tablet"

"You probably dont need a standard to put it upright"

"Not damaging the screen"

"Portability, Looks cool"

"Bigger screen and easier to carry - because it is smaller when folded than an unfoldable tablet"

"larger display in same package"

"Space efficient. Screen is protected when folded. Half of the screen can be used as keyboard."

Foldable laptop

"I think might be lighter. and easier to watch series in bed when you want to hold it and lay on one side.. Also easier to walk with, with a laptop you have to close is because it is bad for you screen if you walk with it open. And with a foldable it could be easier. Also when cooking and you want to read recipice, you can put it easier in a holder and take up less space."

"That it's a combination with a tablet and small to carry around"

"possibility for multiply open views..."

"Nice to watch movies, as you can use the full screen. Disadvantage would be that the experience of the buttons disappears."

"You can impress others with a cool new gadget."

4.1.4 Conclusion

Overall the study was filled in by fewer participants than the wanted number of 25, which made it unable to draw well-founded conclusions. It is suspected that the 30-minute average it took to fill in the questionnaire was deemed too long by participants, and by sending an invitation online, the social pressure to participate was low. Mainly the younger group of the people who were asked to participate, likely study friends, filled in the survey. This effect might be since they also have experienced how difficult it is to gather participants for these type of studies. Overall the approach of gathering participants has to be adjusted. An incentive has to be offered to participants to keep the survey in its current form; this can either be a payment to participate or a price. Another approach would be to shorten the survey; it might be interesting to see if participants would give different ratings and expectations if the first exercise part is eliminated. This approach could be tested in a new user test and compared with the data set from this research. If there are no significant differences, it means that the guided approach is not necessary.

One of the effects of the low participant number was a low mix of devices, mainly laptops and smartphones were used to fill in the questionnaire. To get a better insight into foldable device expectations, it would have been better if more participants would use tablets as well. In the current data set, the foldable devices are only compared with laptops and smartphone. Still, a comparison with tablets would give a better insight where a foldable device is placed in a ranking of personal mobile devices. The tablet is preferred because this device in its use is similar to foldable devices. The tablet could, therefore, give better insights on audio quality than a smartphone, which has different use cases compared to tablets and laptops.

Although the number of participants was too small for quantitative analysis, the participants who filled in the questionnaire did this quite complete. Some of the open questions were not required to fill in, but almost all of the participants did fill these in. This indicates that the participants took there time to fill in the survey, and they have likely thought well about their answers instead of quickly filling everything in. Even though the participants have probably filled in the survey with the best intentions, the question about rating their hearing might not be reliable. Assessing your hearing based on no further information is prone to overestimation; it would have been better to let users participate in a hearing test. However, this would mean an increase in time on top of the already long 30 minutes.

Purchase decision

From both the user test and the online analysis can be concluded that audio quality is rarely taken into account when purchasing a device. In the user test, participants stated that in the case for smartphones, they never thought about audio quality when buying their device. For laptops, this is a bit higher and might be related to the different types of use cases of the laptop compared to the smartphone or the expectations related to its size. There seems to be an indication that audio quality is more important in high-end devices. The participants who stated that they took the audio quality of their device into account all purchased a high-end device. However, due to the small number of participants, this could have been a coincidence. In the online analysis, there was a lack of filters or information for customers about the audio quality of devices. The filters Best Buy offers regarding audio quality are hidden away inside the filter settings. The lack of filters and difficulty to find them if they are provided suggests that there is no demand from customers to know more about the audio quality. Otherwise, companies would offer these specifications to accommodate their customers. The little information and filters that are provided are likely for the small group of customers that is knowledgeable enough to know what this information means. The typical buyer will not understand what this information means and is not interested in it. They likely trust the audio engineers of the device to provide them with acceptable audio quality.

There is an industry-standard for audio quality, and only if a device performs less or better, this is noticeable. If the device performs within these boundaries, the user will likely not acknowledge the quality. The online analysis of the two tablets shows this; only a small percentage of the reviewers acknowledge the audio quality. Even though these tablets pride themselves in audio quality better than most tablets, it is still not recognised by the users. This might have to do with the fact that the audio quality does not exceed their expectations of the tablet or that they compare the audio quality with that of a laptop. The comparison with a laptop is made based on the advertisement of the brand, which is focused on selling the tablets as a substitution for a laptop. In the online analysis of reviews, only tablets were analysed to get more information about these devices because of the lack of tablets in the user test. It would have been interesting to look at how laptops are advertised and reviewed in terms of audio quality, but the user test provided enough information to analyse this.

Participants mentioned that they see an increase in audio quality as providing more bass and louder audio; this was the common result for tablets, laptops and smartphones. The participants were willing to accept an increase in both money and thickness to get this increase. The averages give a general maximum for these increases, and the new system should not exceed this. However, the fact that in the case of the laptop 6 participants and the case of the smartphone 3 participants would not want an increase in both money and thickness does not make these averages reliable. Therefore, the increase in money and thickness should be kept to a minimum to stay as far from the maximum as possible. The survey causes another inaccuracy in the averages; in a real scenario, participants might pick differently. It is easy for the participant to say what they would do in a particular situation, but doing it is something different. Also, the aspect of thickness is difficult to grasp when there is no possibility to experience this. Because an increase in thickness also means an impact on the design and handheld feeling of a device, which is also an essential aspect of buying a device. It is not solely about technical specifications; often, it is mixed with personal preferences that are not based on facts but more on emotions.

Influence

The user research shows that in day to day life the use of peripherals, such as headphone and external speakers, is too much of a hassle. Therefore, the device itself should provide an audio quality that makes it possible to use the speakers in typical daily activities. The users still have the option to use peripherals if they want to increase the audio quality further, but not meeting the minimum audio quality will make users feel limited in their use of the device. Therefore, the industry standard for audio quality is set, and the users know they can expect that level of quality. For music purposes, the use of peripherals is not an inconvenience and is accepted as a solution to increase the audio quality. This increase in quality, as mentioned in the purchase section, means an increase in lower frequencies and louder audio. In the user research, the participants could only select one reason for their choice on speaker setup. It might have been the case that some decisions were made with a combination of multiple reasons; these could not be discovered in this research. Another limiting factor in the research was the low mix in both devices and their price range. If the data set had been more extensive, influences of the audio quality on uses cases could have been analysed. This analysis could be interesting for further research.

The words to rate the audio quality of the devices varied based on the device. Where the term “thin” was mainly used for the smartphone, the words “strong” and “deep” were used for the portable speaker. These words describe the amount of bass or describe when there is no bass at all. The terms can be linked to the quality of the device; the smartphone generally scored lower than the other devices and had the most negative words. The negative and positive words can be used in further research to define how well the Aito setup is performing. However, these words might not fully represent the audio quality due to a mix of negative and positive words. The term “spacious” was used positively and negatively, and the words defined negatively by Wilson and Fazenda were used positively. These differences in meaning might be due to translation issues. The survey was entirely in English, and the nationality of most of the participants was Dutch. Even though all of them spoke English, some words have a different meaning or feeling in the other language.

Expectations

When analysing the results of the audio quality of the devices of the participants, there is a difference in context for these devices. This conclusion is made on the ratings of smartphones and laptops, in some cases, both the smartphone and laptop were rated the same while the smartphone was still placed last in the comparison. This indicates that the rating “average” means something else in the context of a smartphone and the context of a laptop. These rating differences might be caused by the order in which the questions had to be answered, even though the participants could go back to previous questions. The smartphone had to be rated before the laptop; this was the case for the first 9 participants. After these 9 participants, the order was randomized, but no analysis could be done on these last three participants if the order had any influence. But this influence is deemed not significant as participants still had the option to rate the laptop higher than the smartphone, as they never reached the maximum rating in the smartphone.

The effect or the question order could also have played a role in the ratings of the foldable devices. But again, the grading could be adjusted as the maximum or minimum ratings were rarely reached, and the participants could go back if they wanted to change their rank. The group of participants showed a mix of participants with previous knowledge about foldable devices and participants who did not have this. The differences in answers were not analysed in this research due to the qualitative approach. It is suspected that this mix ensured that the ratings and comparisons would balance each other out to show an average expectation. From the statements on audio quality for foldable devices can be concluded that the expectations are quite diverse. There is not one uniform expectation on the audio quality for these devices. However, from the rating and comparison results can be concluded there are some differences between the foldable devices and the current personal mobile devices.

The foldable devices are expected to perform better than smartphones audio-wise, but lower than a laptop. The comparison for the laptop was mainly made with high-end laptops in mind. So for low-end or mid-range laptops, a comparison might give different results. In the comparisons with the smartphones, the audio quality influence on the results was not analysed. The foldable devices were, in some cases, rated lower than smartphones, the audio quality of the smartphone could be a reason. However, due to the small number of participants, this could be a coincidental result.

The foldable devices show differences in both expected audio quality and the placement of speakers. The foldable laptops are rated slightly higher in audio quality than the foldable tablet; this does confirm that the terminology determines the expected quality and speaker setup. Due to the limited amount of participants, and the lack of randomization, the results can be caused by chance. But because two different results show a difference between these devices, it is assumed that this result does represent the expectations accurately. For the new system, this would mean that if it underperforms for a foldable laptop; it might still be usable for a foldable tablet. The different terms and positioning also cause a difference in expected speaker placement, which could be solved by creating a screen speaker; this ensures that the users get front-facing audio in every position of the device. Some participants also mentioned they would prefer a speaker system that would adjust according to the position, and all participants deemed a stereo setup as a must. Therefore, the new system should be able to provide in at least one position this stereo audio output.

Figure 47 visualizes the difference in expected audio quality based on the context of the devices. The dark area indicates the audio quality that is negatively noticed by users; this area should be avoided in the device. The light area indicates the expected audio quality in which users will not acknowledge the audio, and they feel not limited by the audio. The slightly darker area after the "neutral" area indicates the positively noticed audio quality. When the audio quality reaches these levels, the users will be positively surprised by the audio quality, and users with interest in audio will look for these types of devices. As indicated by the figure, each device has unique transition areas. A laptop with audio quality in the "neutral" area is not acknowledged while a smartphone with the same audio quality is likely noticed positively. Further research needs to be done to validate this assumption about audio quality and the influence of context.

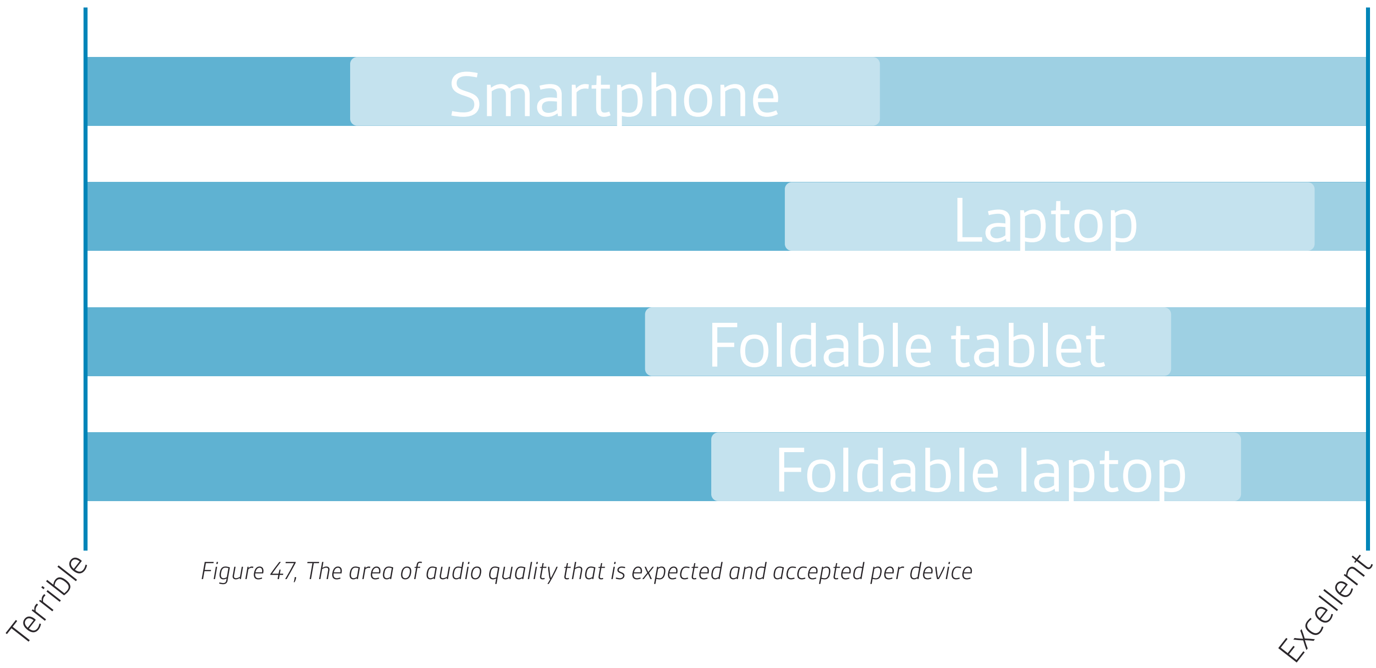


Figure 47, The area of audio quality that is expected and accepted per device

Findings

- Context matters to determine audio quality. A laptop is expected to have a different audio quality compared to a smartphone.
- Audio is not taken into account when purchasing a smartphone or laptop, and the industry acknowledges this.
- Some customers accept an increase in price and thickness if they get better audio quality in return.
- If customers want better audio, they accept the fact they have to use a different setup. For example, using headphones or a portable speaker when listening to music.
- “Thin” and “dull” are words to avoid and “strong”, “clean”, “clear” and “deep” are words to aim for in an audio setup.
- The label “tablet” or “laptop” influences the expectations about audio quality. Foldable laptops are expected to have a better audio quality compared to foldable tablets.
- A front-facing speaker setup in the screen of a foldable device would ensure audio in every position of the device. Otherwise, speakers might be blocked if they are placed on the sides of the device.
- The device should provide a stereo audio output in at least one position as this expected by users for this type of device.

Objective method

What do the measurements say?

5.

Where the subjective method is based on personal beliefs or feelings, the objective method is the complete opposite. The Cambridge dictionary states the following explanation: "based on real facts and not influenced by personal beliefs or feelings". This testing is done by playing an audio file through the speakers, which is recorded by a microphone to analyse how close the speakers represent the actual signal input.

Test setup

The testing for objective analysis is done in a soundproof room so that the microphone does not pick up any other noises; only the audio from the speaker system itself should be recorded. Every small change can influence the outcome of the recorded quality, even the setup of the room itself. While measuring, there could be soundwaves that do not come directly from the speaker system but are waves that have bounced off either a surface behind the speaker or the floor. Figure 48 shows how a measuring setup can be created to counter soundwaves that bounce off the ground. Figure 49 shows what happens when soundwaves bounce back from the surface behind the speaker in such a way it will cancel out the soundwave that comes directly from the speaker. These problems often occur in larger speakers which are more powerful compared to the smaller speakers in personal mobile devices. Hence, the bouncing effects are likely less significant to happen for personal mobile devices. The position of the speakers and microphone in the room differs per person or company; each has their own approach. However, it is crucial that testing is done in the same setup each time to be able to compare the results. If the microphone is moved or if the speakers are placed at a different angle, the recordings will change significantly. For example, if the microphone is moved from the centre axis of the speaker. This movement changes the polar pattern, which measures how spatial the audio is, and could show inaccurate results. There is a difference in setup for MAP's to record their performance; this setup is designed by Pueo (2008). The setup requires multiple microphones placed at each exciter position and one microphone in the middle of the whole panel. This measuring setup can measure the effects of each exciter individually and can record the overall impact of all exciters combined.

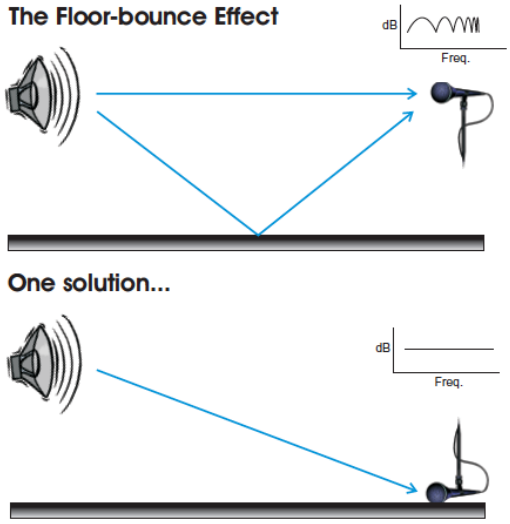


Figure 48, Floor bounce effect and possible solution

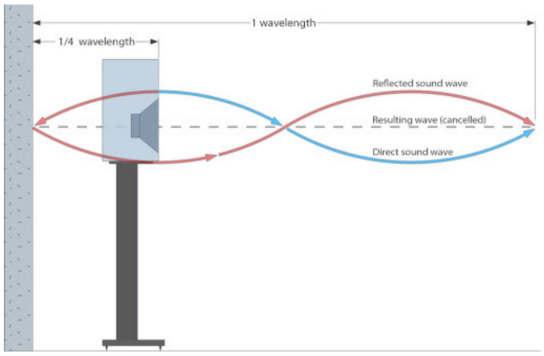


Figure 49, Speaker boundary interference response

Another essential aspect of the testing setup is the audio that is used; this is a music file for the subjective method. For the objective method, the audio file consists of all the frequencies in the audible spectrum. Two types of frequency audio files can be used for testing; pink noise or a sine wave sweep. A pink noise file plays all the possible frequencies within the audible range at the same time, and these frequencies all have the same intensity. A sine wave sweep plays these frequencies also with the same intensity, but plays them one by one. Because all these frequencies have the same energy, they should be picked up by the microphone with the same sound pressure level (SPL), another way to express SPL is in decibel (dB). The sound pressure level is the variable which represents the volume of sounds. However, the sound pressure level does not say anything about the perceived volume; this is why the units phon and sone are created. These units take the sensitivity of the human ear for frequencies into account; figure 50 shows how these units correspond with decibels. The definition for one phon is that it is equivalent to 1 dB at 1 kHz. For different frequencies, the phon might change while the dB level stays the same. The sone scale is based on the fact that observations show

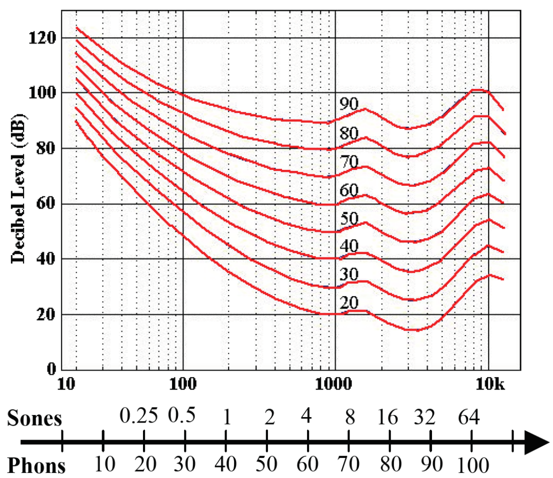


Figure 50, Phon and sone scale compared to the dB scale (Physics classroom, n.d.)

that if there is a 10 phon increase, there is a perceived doubling of loudness (Physics classroom, n.d.). While phon references the loudness to a reference point of 1 kHz and sone also takes the perception of loudness doubling into account, dB is still the preferred term in audio engineering to analyse the audio performance. The decibel scale is logarithmic, which means for decibel that if the number of speakers doubles the number of decibels is increased by 3 (JL Audio, n.d.). An increase or decrease of 3db is deemed inaudible (Dicomo, 2005) and therefore, the intensity levels should not decrease or rise above this level within a specific frequency range.

Analysis

After the recording process is done, the files can be analysed with various programs to determine how well the speaker is performing. The professional programs offer a wider range of analysis possibilities than the free programs. However, most of the freely available programs can be used to do a spectrum analysis, which is needed to determine the frequency range (Zlatic, 2017). Some of these programs can only be used in combination with a sine wave sweep or vice versa.

The programs analyse the recording and present it visually. This type of data makes the objective analysis easier than the subjective method; the problems are easier recognizable. The visual representation after the analysis can either be a spectrogram or a filtered frequency response graph. For audio engineering purposes, the frequency response graph is the most important one. This graph plots the loudness on the y-axis against the frequency on the x-axis; the result can be seen in figure 51. The frequency response graph is often smoothed with a 1/n octave filter; the

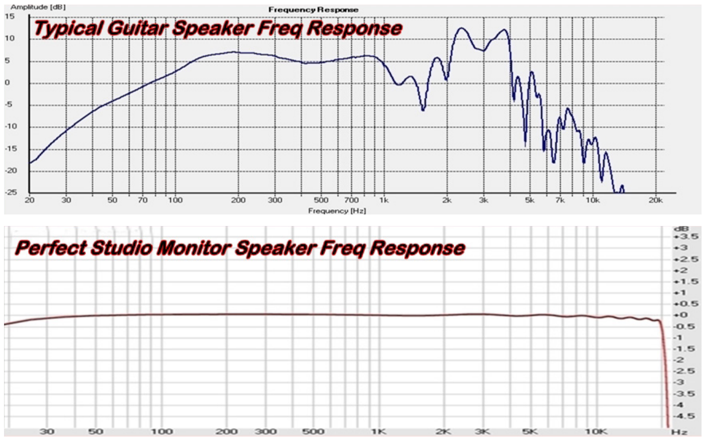


Figure 52, Real and perfect frequency response

“n” stands for the level of filtering. If “n” gets smaller, the graph becomes smoother, the problem that could occur is that valuable data gets lost in the process. Where a 1/12 octave filter shows more peaks, the 1/3 octave filter could show half the peaks, which results in the expectation of a better performing speaker.

The performance of a speaker can be determined from these frequency response graphs. The ideal response would be a straight line, as is shown in figure 52. This straight line means that the audio is played as its recording or digitally generated file; it is a perfect translation from data to real-life. However, this is never the case, and there are always frequencies with a different intensity level, even in the best speaker system due to physical and electrical limitations. Rises in SPL are called peaks and declines are called troughs; these can occur due to resonance or interference between waves. A peak in the lower frequency range results in louder bass which might overpower the other frequencies, some people have this as a preference, as earlier mentioned in the subjective method. In general, this is not aimed for by audio engineers. A trough in these lower frequencies

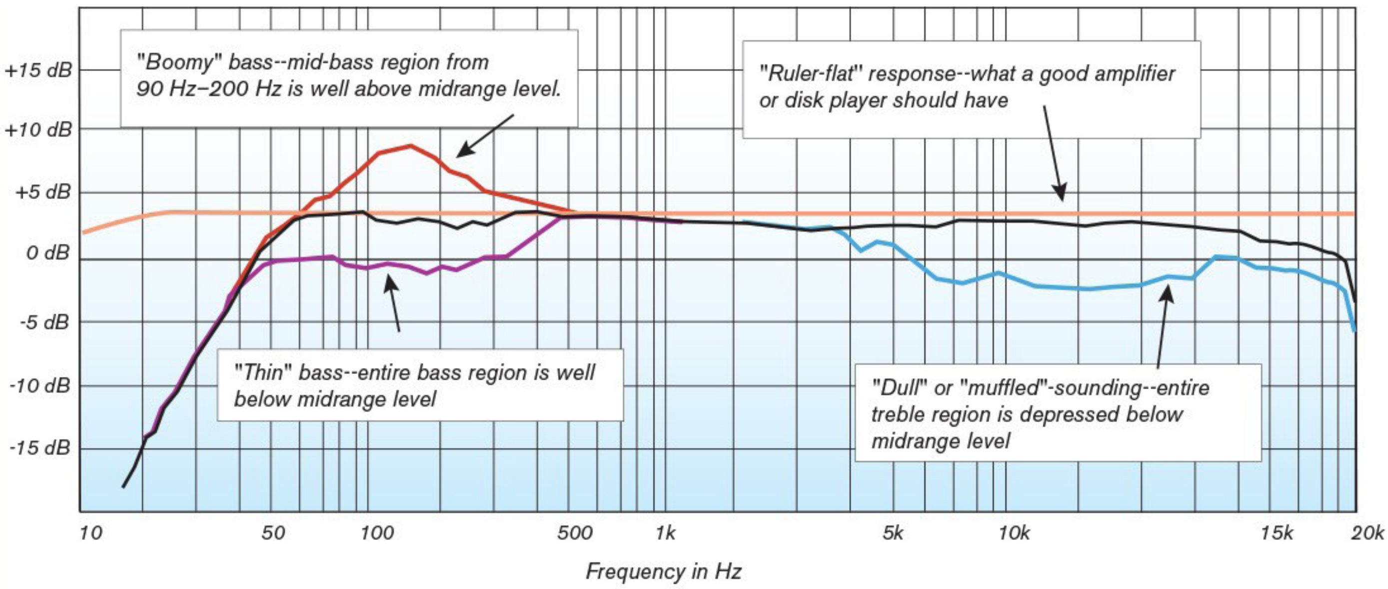
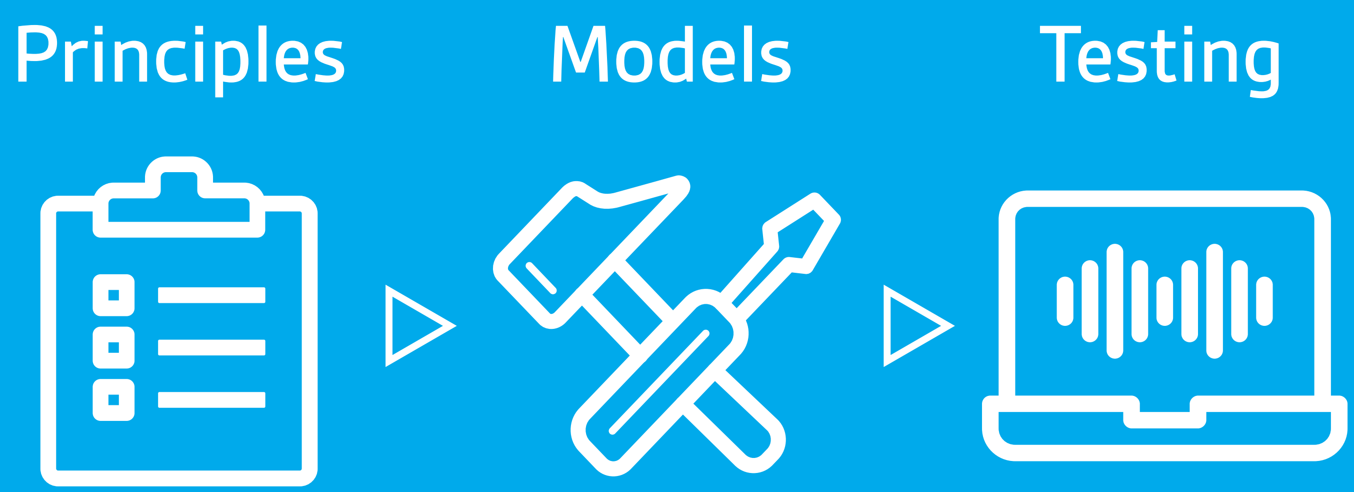


Figure 51, Audible perception of the measured effects means the speaker system is lacking bass. Instead of a trough in the lower frequencies, the graph can also show a steady decline when moving from the higher frequencies to the lower frequencies; this transition shows the cut-off or minimum frequency of the speaker system. Where this cut-off is deemed, reasonable depends on the use case. A tweeter can have a cut-off after 1000Hz, but when a sub-woofer cannot reach below 150Hz; this means that the speaker is not properly designed. Peaks in the higher frequencies will be more noticeable due to the higher sensitivity human ears have that was earlier mentioned. To combat these effects, first, the structural design of the speaker system must be adjusted before trying to fix it with a digital approach. If these peaks and throughs are within the 3dB limit compared to a set reference point, the speaker system can be concluded as having a flat response; often, this reference point is 1 kHz. Beside staying within this limit the peaks and troughs should also show gradual changes compared to a lot of quick changes throughout the frequencies. A gradual transition is less noticeable compared to a fast one, but the gradual change should still not exceed the 3dB limit (Dicomo, 2005). Another element that determines the performance is whether the speaker is ringing after stopping the audio. Ringing means there is still some energy in the speaker, which causes audible vibrations.

For this project
This project tries to follow the approach which is described above, as this is the industry standard. Following the standard industry approach for measurements allows the results to be compared with their requirements. If another setup is used, these results could not be compared, as explained earlier. Besides the audio testing to determine the performance, another element of performance that was tested in this method was the power consumption.

The steps in the objective method for this project are the following:

- Determining which elements to test to improve the audio quality (paragraph 5.1 Design principles)
- Making various models for conducting the performance tests (paragraph 5.2 Prototyping)
- Defining the test setup with the models in mind (paragraph 5.3 Test setup)
- Analysing the results from the tests (paragraph 5.4 Conclusions)



5.1 Design principles

Because the design space offered a lot of possible elements to incorporate, some had to be discarded to keep the project concise. Some elements could also be eliminated on the basis that there was already evidence that supported their negative influence. Others could be excluded because they would not fit the design of a foldable device. For the four main areas, these decisions are explained in the following sections.

Type of device

The basis for the model is based on a foldable device. This group of devices was chosen over the tablet because the use case of typing on a flat surface is more prominent in foldable devices. Because the Lenovo ThinkPad X1 Fold is the only device with known specifications on its size, this specific device will be used for the dimensions of the model. The structure itself will follow the stack design and not the real structure of the device because this is not known. The inside of the Lenovo ThinkPad X1 Fold needs to be estimated with the information on existing devices. From the results of the subjective method and the objective method combined can be concluded if the system would be a better fit for a foldable tablet or a foldable laptop. This choice is left open for now.

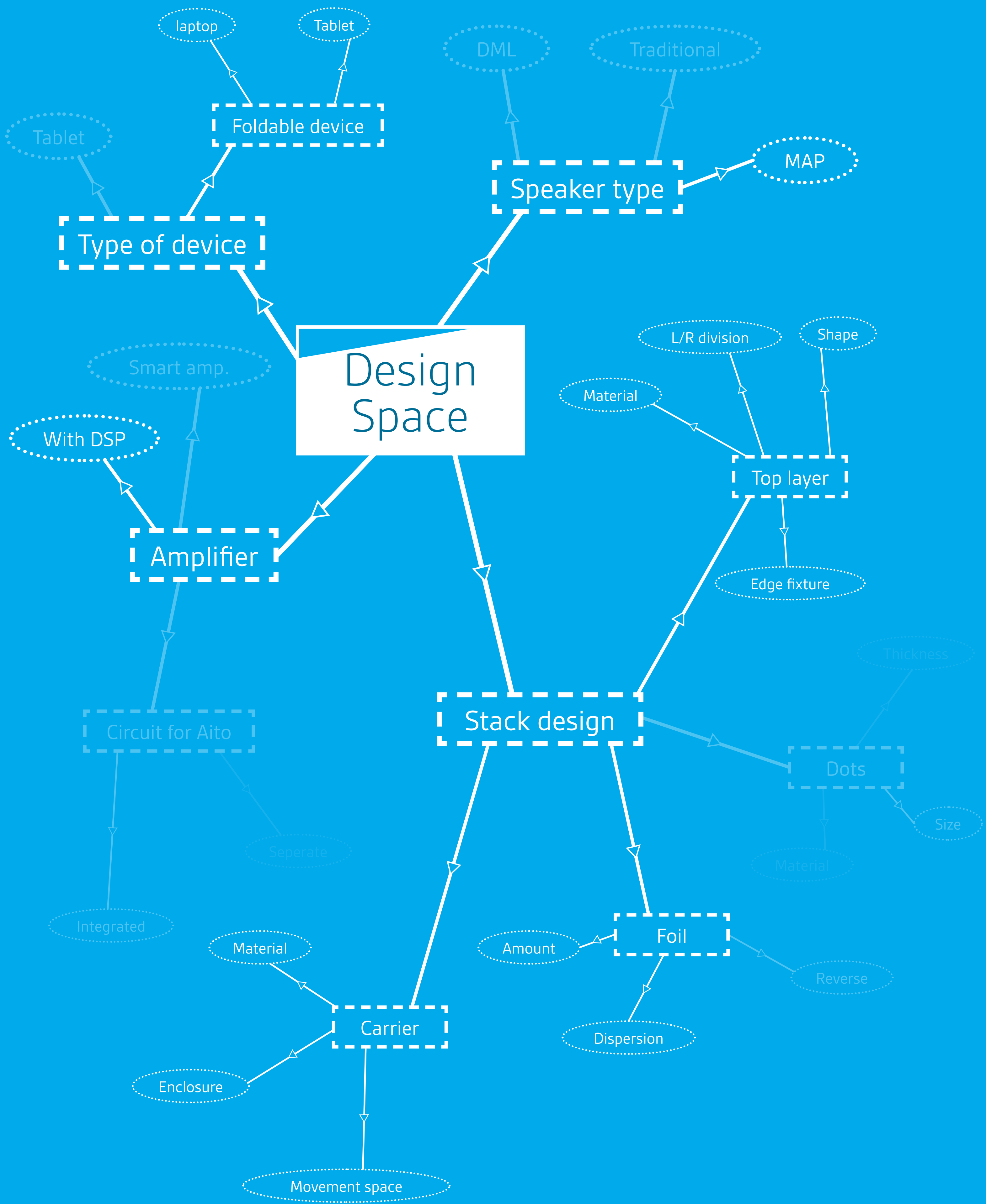
Speaker type

This new speaker system is designed with the intention of it being a MAP type speaker; this is the most logical approach due to the current design Aito is using and would mean no rigorous changes would need to be made. The current stack design is based on connecting the piezoelectric discs to the back of the top layer in a matrix, which is the principle of a MAP. An advantage of not making significant changes to the stack is that the haptic feedback will be less impacted. Although the MAP type is selected as a starting point for the model exploration, the principles for DML's and traditional speakers are not entirely discarded; this can be seen in the design principles for the stack design.

Stack design

The choices that needed to be made mainly involved the stack design, and were made based on whether they would work with the MAP setup, minimizing the thickness and maintaining the haptic feedback. The minimum thickness demand resulted in an elimination of the option for a reversed design, with audio coming from the sides or back of the device. One of the reasons was that this would not minimize the thickness of the overall stack design but only increase it. If the current structure does not work, this approach can be further explored if companies would be willing to accept the thickness increase that comes with it. Another reason for discarding a reverse design was to try to create a front-facing speaker design, which is preferred in the industry.

- For the top layer, or panel, in this case, the decisions that were made are the following:
- Wood, foam, Oled screens and glass are excluded from the exploration. Wood and foam are eliminated because this material is not suitable to apply in personal mobile devices. Although Oled screens and glass are suitable, these were excluded due to them not being available during this project; this left the options of plastic and metal as materials for the top layer, even though metal is not deemed a proper material for a DML. Metals were still included as a substitution for glass and to test if this material is also not fit for a MAP.
- The design of the top layer should be a rectangle where the width is 4/5 of the length, the corners are rounded, and the total surface should be as big as the dimensions of the device allow.
- The user research concluded that a foldable device should have a stereo speaker setup. There should be multiple panels rather than trying to emit stereo audio with one panel to get well-divided stereo audio. Although the literature suggests stereo with one panel would be possible, it is expected to be more difficult than two panels. The foldable device easily allows a two-panel approach, so this is the more straightforward approach to explore first.
- For the edge fixture, the options stay open. Individual models should show if a free-floating edge, a suspension edge or a rigid edge is the best solution; this means that adhesives such as rubber, silicone or foam can be explored for the suspension edge.


Design Space
Type of device
Foldable device
laptop
Tablet
Tablet
Speaker type
DML
Traditional
MAP
Amplifier
Smart amp.
With DSP
Circuit for Aito
Integrated
Seperate
Stack design
Top layer
L/R division
Shape
Material
Edge fixture
Dots
Thickness
Size
Material
Foil
Amount
Dispersion
Reverse
Carrier
Material
Enclosure
Movement space

Decisions for the dots were made based on the current structure Aito uses. The existing structure is accepted to be the best solution, and no changes will be made to it; this means that the adhesive dots will be 5mm in diameter and 0,15mm thick.

The decisions for the foil layout were made on the availability of foils that could be provided by Aito for prototyping purposes. The available foils had a set distance between them on the y-axis, but the x-axis distance could be altered; this allowed for a more flexible implementation into the prototype. However, the number of piezoelectric discs, 24 in total, was fixed by using these foils. This fixed number is why, later in the project, a different prototyping approach for these foils was used to be able to change the layout and amount of piezoelectrics. The maximum distance between the piezoelectric discs was set at 40mm; this should ensure that there is still sufficient haptic feedback in between the piezoelectric discs. This number is based on the distance between piezoelectric discs of the pre-made foils. In both cases, the 3/5 rule for exciter placement for DML's, which was suggested in the literature, was discarded. This elimination was done because the rule could not be combined while still ensuring an even layout for the haptic feedback and because the MAP approach was used, which required a different placement than the DML approach.

In the design of the carrier, two main areas were defined that could impact the audio quality; these were the space underneath the carrier and the cut-out for the piezoelectric disc movement. For the area underneath the carrier, the options stayed open to implement either a speaker chamber or fill this space completely. If a speaker chamber would be used, this could be isolated with foam to create a damping effect. The cut-outs should be a minimum of 0,25mm thick to allow enough space for the haptic feedback, and the edges should be rounded not to cause a build-up of waves in the corners.

Amplifier

Not integrated into the design as there was not yet a need to test the haptic feedback and audio at the same time, the first step was to define if the audio was even possible with the system. Another reason for not integrating the system yet is that the correct requirements for an amplifier had to be defined. To define these requirements multiple amplifiers were tested and used to play audio with, all these amplifiers were per-build some were specifically design for piezoelectric speakers while others were standard amplifiers used in standard speakers.

Because the chosen amplifiers were standard of-the-shelf products they did not have the smart amplifier functionality so in this project this approach was not further researched. The digital sound processing approach could be explored as this was a separate module that could be attached to any amplifier. The device that was chosen to explore the digital sound processing could only be used on the total system and not for each individual piezoelectric discs, which was on option suggested in the literature. The main amplifier (A-303) that was used in the project, along with the digital sound processing module (miniDSP 2x4), can be seen in figure 53.

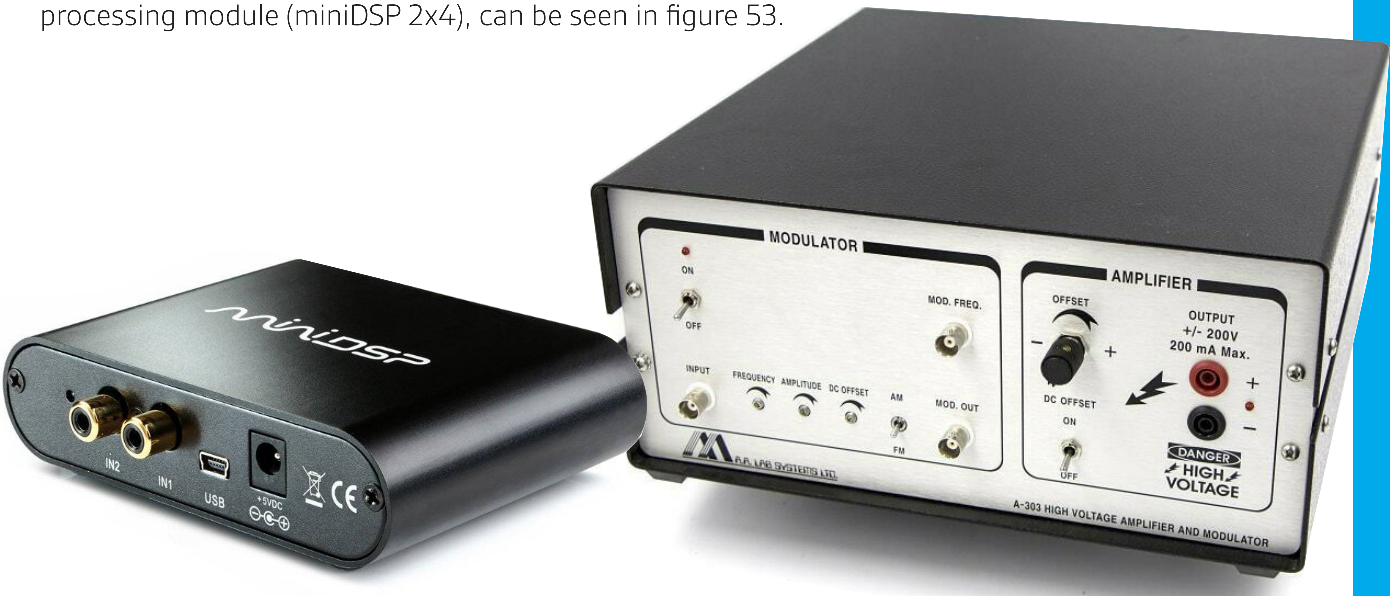


Figure 53, The digital sound processing device (left) and on of the used amplifiers (right)

Design principles

- The Lenovo ThinkPad X1 Fold is the base for the model design and is not yet labelled as a laptop or a tablet.
- The total stack design should be as thin as possible and should not go over the tolerated increase that was the outcome of the subjective method, which is 2mm for both the laptop and smartphone.
- Plastic or metal can be used as top layers in the stack design.
- The top layer is a rectangle with a width of 4/5 the length, with rounded corners and as large in size as possible
- The dot size is fixed to the Aito “standard”.
- The foil layout is based on pre-existing foils to give ensure a good haptic feedback.
- The edge fixation can be varied to explore, which has a positive influence on the audio performance. The variations that could be explored were adhesive glue tape, foam tape and no fixation at all.
- The cut-outs on the carrier should allow a minimum movement of 0,25mm and all the corners should be rounded
- The enclosure can be varied to open, partially filled, insulated with foam or filled, to explore which has a positive influence on the audio quality.
- Different amplifiers can be used to determine what the effects are on the audio quality.
- DSP may be used to flatten the frequency response of the models.

5.2 Prototyping

In the previous chapter, multiple design principles were stated that can be used during the development of a speaker system with Aito's technology as a base. To test these principles, a general model was created. With various variations of this model, the principles could be tested. This resulted in multiple individual models that were created using two types of techniques. The first was a 2D layering approach in which a laser cutter was used to create cut-outs which could be placed on top of each other to create a 3D model. The second technique was using a 3D printer to eliminate the 2D layering and allow for even more of a 3D shape. Both methods had their limitations and benefits related to the project, which can be seen in tablet 1.

Laser cutting	3D printing
+ Time efficient: 1.5 hours	+ High accuracy
+ Easily accesible	+ Uniform material
+ Cheap, around 15 euro per model	+ Low chance of errors
- Mixing of materials	- Time inefficient: 14 hours minimum
- High chance of errors	- Expensive: around 50 euro per model

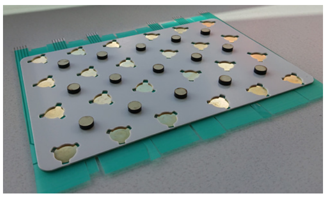


Table 1, Differences between the prototyping techniques

5.2.1 Overall design

The overall concept model, in which several adjustments will be made to test the effects of the different design principles, can be seen in figure 54 and 55. The numbers correspond to the following parts of the design:

1. Top layer/panel
2. Dots
3. Foil with piezoelectric discs
4. Adhesive spacer
5. Carrier and frame
6. Backplate
7. Electronics compartment

The idea behind the model is that the area of the plate is as large as possible to achieve a lower frequency. For the middle of the model, the two halves should meet in the middle to prevent a dead spot in the middle where haptic feedback would not be possible. Because both halves should connect in the middle, the hinging system requires some engineering. The companies which have shown their concepts already designed hinges that could achieve this. For this project, such a hinging system did not need to be developed. The sizes for the overall conceptual model were based on the Lenovo ThinkPad X1 Fold, which has a size of 11.8 x 9.29 x 0.30 inches (30 x 23.6 x 0.76 cm) when unfolded and a size of 6.23 x 9.29 x 1.09 inches (15.8 x 23.6 x 2.76 cm) when folded. The screen on the device has an aspect ratio of 4:3 and is 13.3" (Hackman, 2020). Figure 56 gives a representation of how the real product should look if both halves are connected with a single foldable screen.

The two halves mean that in the unfolded tablet position, each half can function as a separate left or right speaker, while in the laptop position, the top half can function as a mono speaker. There is still a possibility that one panel could also emit stereo sound but is suspected the quality is not good enough. Therefore, a mono configuration is expected to be more suitable. The effects of a flexible Oled screen instead of separate plates is uncertain. The foldable part in the middle of the screen might damp vibrations travelling from one half to the other, but no statements can be made for this. The only assumption that can be made about Oled screens is that the thickness will likely lie around 1mm (appendix 8.4 Oled screens). The overall design intends that the Oled screen will be glued on top of the stack design. Again, the impact of this connection is uncertain. Another assumption

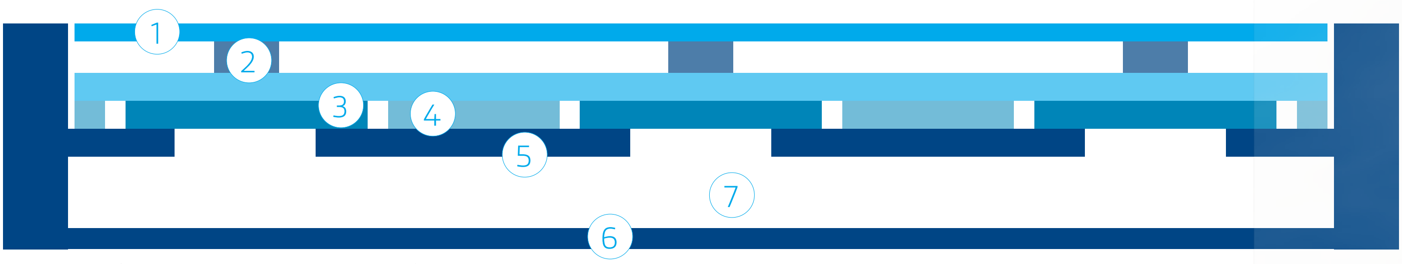


Figure 54, General stack layout as basis for the explorations about the screen is that the edge is close to 1cm thick. This means that the area of this edge does not need haptic feedback. It would also be ideal if this area does not vibrate when audio is being played, as this is expected to be uncomfortable for users.

In the general model, there is space left for either a speaker enclosure or for the electrical circuit and the battery. How much space the electrical components will take is undefined, but it is assumed the whole area will be filled to pack as many battery cells in as possible. In the individual models, this space is changed to analyse the impact. The focus on designing the models was in the first place to create a structure with a good audio quality and performance, but there also was another focus point. The focus in creating these models lied also on minimizing the thickness, which is one of Aito's selling points that should be maintained. The thickness was assessed by taking the current thickness of Aito's stack design and comparing this with the stack design in the models to get the thickness increase for audio. The screen and carrier are not taken into consideration when defining the thickness as these components are a part of the structure of the device. From the user test the average accepted increase was determined to be 2mm, and this is used as a maximum increase in the stack design.

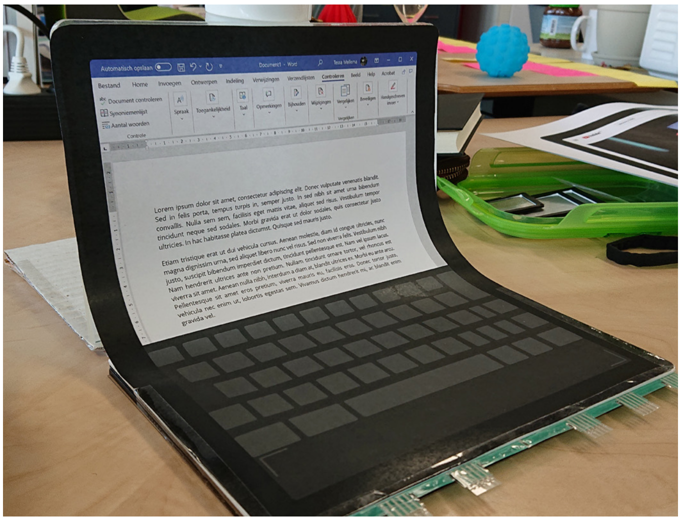


Figure 56, Paper prototype of overall concept

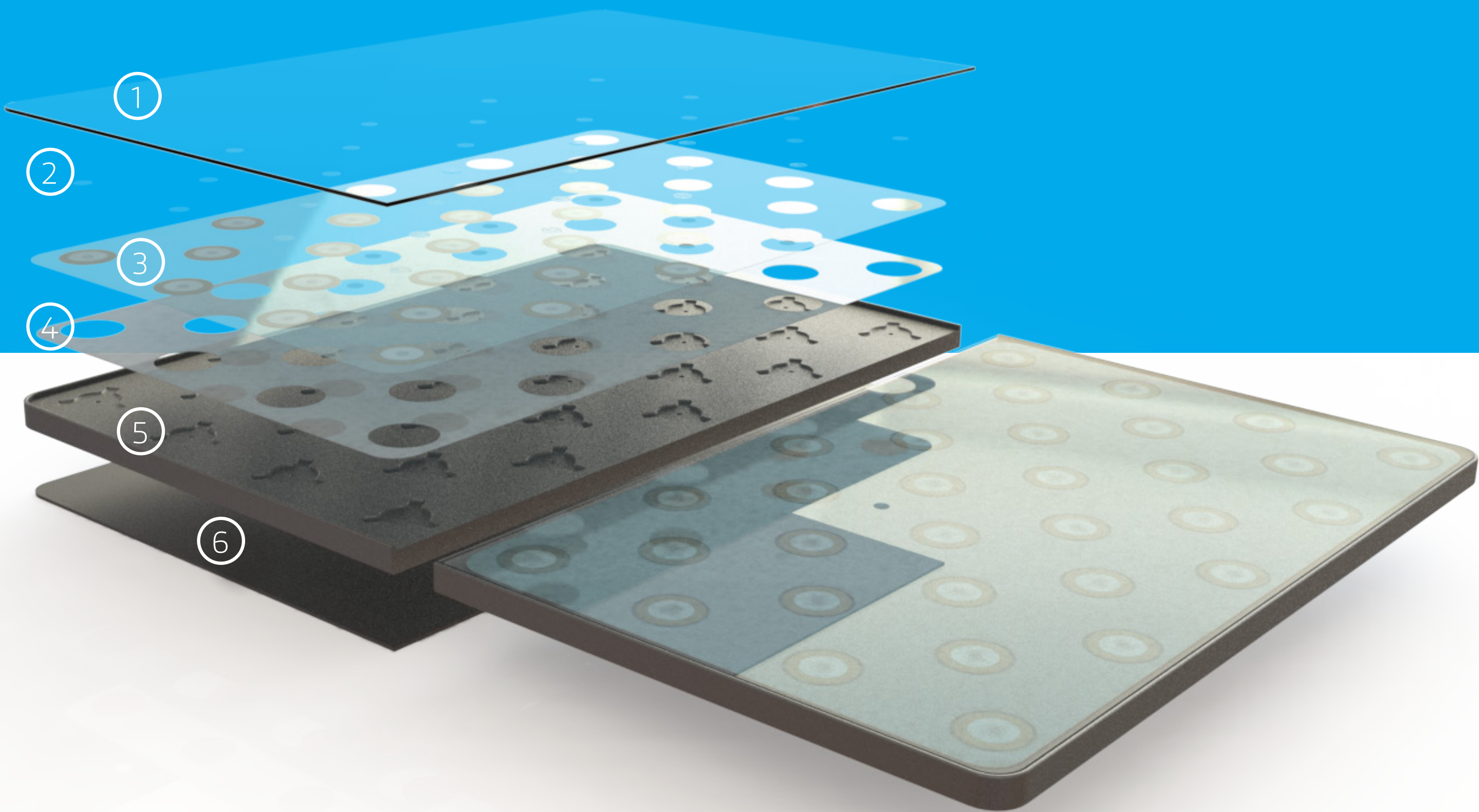


Figure 55, The tablet frame with carrier structure integraded

5.2.2 Individual designs

The individual models were created in three iteration rounds. The models were designed by incorporating the earlier stated design principles. The thickness of the carrier was either 1mm or 0,5mm. In the prototyping process of the models in round 1 and 2, a mistake was made with the foil glue. Instead of an area around the piezoelectric discs to let them move, the area was underneath the discs. The result was a fixation on the edges of the discs, which restricted the movement. This error was corrected in round 3 of the prototyping process. The difference between the two types of fixation can be seen in the figures on the right, and more detailed information can be found in appendix 8.11, Models.

Round 1

Both these models (figure 57) had an open speaker chamber which was created with support beams to keep a stiff structure. These beams were rounded to allow the waves to bounce off easily. The models were built with a thick outer edge which would represent the area where there is no interaction with the touch screen. Separating this edge from the moving panel should result in an area where the user can hold the device while playing audio and not feel the vibration. The difference between these two models was that model 1 (figure 60) had a foam insulated chamber, and model 2 (figure 61) had a foam suspension edge. The hypothesis was that model 2 would emit fewer vibrations to its frame with the implementation of the foam edge. The assumption for model 1 was that the foam layer directly behind the piezoelectric discs would prevent airwaves from bouncing into the open chamber.

Round 2

In round 2, the models (figure 58) were adjusted to better represent the electrical components which would be inside the space underneath the carrier. There was a difference between model 6, which had a filled compartment and models 3, 4 and 5, which all had partially filled compartments. Another difference between these models was the size of the panel; this was increased in model 5 (figure 64). Model 5 had a free-floating edge, which is preferred for the haptic feedback, and was increased in size, which should positively impact the lower frequency range. Model 3 (figure 62) was based on Aito's current Haptile Trackpad, which also had a filled back and a stiff glass top layer. The Haptile Trackpad showed in the first round of testing that it had a flatter response than models 1 and 2, and was therefore used as a reference to change the new four models. In model 3, a metal top layer was used to mimic the stiffer top layer, and the speaker chamber was filled only allowing air in between the back of the carrier and the piezoelectric disc. Model 4 (figure 63) had a fully glued edge which should result in no vibrations in the fixed area. It is suspected that the fully glued edge will give more distortions overall.

Round 3

Both model 7 and 8 focus on improving the accuracy of the prototype by using 3D printing. Both models (figure 59) have a foam edge, because in round 2, this model was performing the best. These models also have a thinner edge to maximize the panel size. This decreased thickness does result in possible vibrations in the edge, which might not be pleasant for users. The difference between the models is that in model 8 (figure 67), the piezoelectric disc layout and amount is changed. Model 7 (figure 66) uses the layout of the already existing foil provided by Aito, and model 8 uses the diamond matrix layout mentioned on page 24. The number of piezoelectric disc in model 8 follows the layout because there should be no piezoelectric discs in the middle, and there should be no greater distance than 40mm between the discs.

Figure 57, Models of round 1

Figure 58, Models of round 2

Figure 59, Models of round 3

Figure 60, Model 1 with a foam insulated open speaker chamber and thicker outer edge

Figure 61, Model 2 with a foam suspension edge, open speaker chamber and thicker outer edge

Figure 62, Model 3 with a metal top layer, parially open speaker chamber and thicker outer edge

Figure 63, Model 4 with a adhesive ridge edge, parially open speaker chamber and thicker outer edge

Figure 64, Model 5 with a free floating top layer, parially open speaker chamber and no outer edge

Figure 65, Model 6 with a free floating top layer, fully filled speaker chamber and thicker outer edge

Figure 66, Model 7 with a foam suspension edge, partially filled speaker chamber and thinner outer edge

Figure 67, Model 8 with a foam suspension edge, partially filled speaker chamber, different layout, number of piezoelectric discs and thinner outer edge

5.3 Test setup

In the objective method, the audio performance was measured along with the power that is needed to produce audio. Measurements to analyse the haptic feedback quality were not performed; this was tested at the end with only the last two models by one person, the researcher of this project. The haptic feedback was tested in a small area with four piezoelectric discs that were closest to the edge. The testing was done by pressing the area around these discs to see where they would be activated and how well the pulses could be felt. Another part of the haptic test involved playing audio on all the piezoelectric discs, and feeling on the sides and back if the vibrations were noticeable in these areas.

Audio testing

The audio testing was done to determine which grade the models would get according to the industry standard and which principles would give the best results. While the industry focusses on various requirements to provide a grade for the speaker, this project only focussed on the frequency range and loudness. The reason for this selection are the limitations of the software, which was the free program Room EQ Wizard, and the available tools. Room EQ Wizard uses a sine sweep instead of pink noise, which is more commonly used by audio engineers, and therefore not all requirements could be tested. The settings for the measurements with Room EQ Wizard were the following:

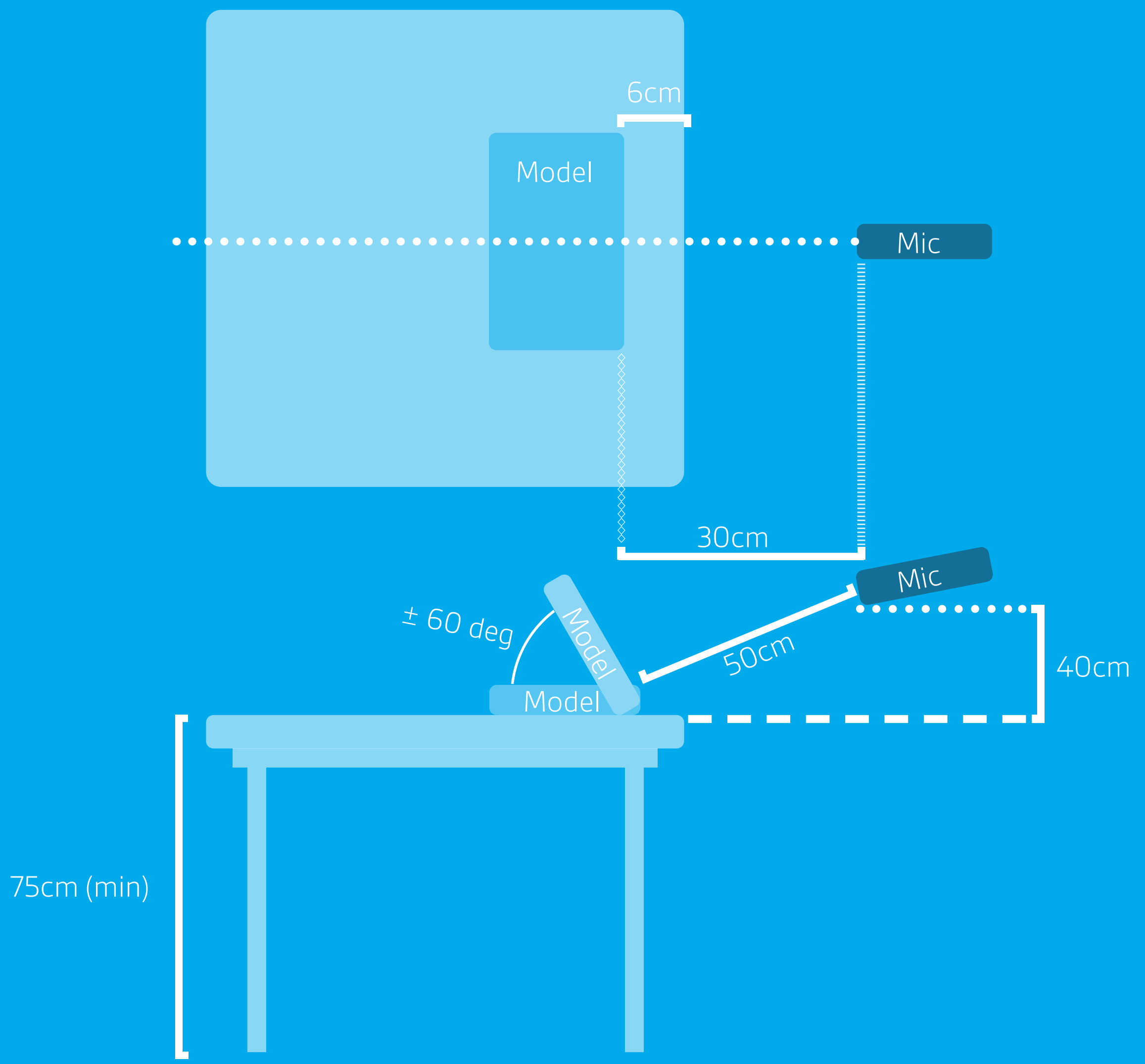
- The computer volume was 42% as a higher percentage gave too many distortions. It seemed as if the piezoelectric discs could not cope with these vibrations; they started clicking and buzzing at higher volumes. For some models the volume was set at 84% to get close the maximum loudness, in the industry standard, the volume should be 100%.
- The start frequency of the sweep was 20 Hz and end frequency 20 kHz to cover the audible frequencies.
- The level was set at -30 dBFS
- The length of the sine sweep was set at 1M, to test with as many frequencies possible.
- The number of sweeps was set at two, to limit the influence of accidental distortions.

The measurements were conducted in the sound lab of the TU Delft; this room offers a low-noise chamber with a microphone (the ecm8000 designed by Behringer). The setup for the measurements can be seen in the infographic on the right. Because the amplifier could not produce a stereo audio output, and the models represented one half of the total model, the measurements were done with mono audio. The models were tested in both an upright position and a position flat on the table; this positioning is a mix of industry standards for measuring laptops and tablets. The mixture between positions was necessary because the model represents a laptop as well as a tablet due to its foldability. The earlier mentioned bounce effects and interference problems are avoided with this setup, as this setup is developed by professional audio engineers. This setup tested the overall performance of the model, unlike the study of Pueo, where besides the overall performance, every single exciter was measured as well. This type of measurement was not possible due to the number of available microphones. Even if the measurement with multiple microphones would have been possible, the results could not be used to apply various filters. The various filters could not be applied because this would require multiple amplifiers, and only one well-performing amplifier was available for this project.

Besides the eight models, a piezoelectric speaker of Sonitron and the Haptile Trackpad were tested as well. Information regarding these speakers can be found in appendix 8.11.9, Haptile Trackpad and 8.11.10, Sonitron speaker. The PiezoListen speakers of TDK were considered for testing as well, but listening to the speakers already excluded them. The PiezoListen speaker was not pleasant to listen to, which is likely the result of the construction. However, TDK did not offer information on how to improve the structure, and most of the effort went into creating the models with Aito's setup. So, no further time was invested in creating a well-performing PiezoListen speaker.

All the speakers in the test were compared with the grading system of the tablet and laptop industry. The requirements of this system that were used in this project can be seen in the infographic on the right. The full requirement list can be found in appendix 8.6, Industry contact. The frequency range is determined by measuring at the 1/12 octave points; if the difference is less than +/- 3dB, the response is considered "flat" by the industry. The min and max frequencies in the grading system, reference the points in which the difference is larger than the +/- 3dB requirement. The maximum loudness is the average over the whole frequency range. The enclosure volume is a guideline rather than a limiting requirement and is only based on standard coil speakers. So, it is less applicable to DML's and MAP's.

Test positioning



* this image is not drawn with the proper proportions

Grading system

Acceptable	Okay	Good	Excellent
Min freq: <500Hz	Min freq: <400Hz	Min freq: <250Hz	Min freq: <160Hz
Max freq: >10kHz	Max freq: >12.5kHz	Max freq: >16kHz	Max freq: >20kHz
Loudness: >74dBSPL	Loudness: >74dBSPL	Loudness: >77dBSPL	Loudness: >77dBSPL
Enclosure size: 6cc	Enclosure size: 8cc	Enclosure size: 10cc	Enclosure size: 25cc

Power consumption

The power consumption was measured to get a better insight into the required power for different frequencies. The results from this measurement will be used to set requirements for the amplifier that needs to be made if Aito decided to continue with an audio feature for their system. Besides the use for requirements, power consumption is also interesting for possible clients. It might be the case that the new setup consumes less power than standard coil speakers, which lies around 2W per speaker.

Figure 68 shows the test setup to measure the power consumption for multiple frequencies. The power source is the large amplifier that gave the best audio performance; this amplifier was connected to a laptop with a volume setting of 24%. Besides the large amplifier, several other options for amplifiers were tested as well but were discarded for various reasons. Standard amplifiers could not be used because they did not provide high enough voltages to produce audible audio. The amplifier designed by Sonitron was tested with Aito's system, but this amplifier was not able to generate the power for the lower frequencies. Lastly, a driver of PiezoDrive was used as an amplifier, but this module was not created for this purpose. The result was an audio output that sounded unpleasant. However, it could be possible to get better performance by adjusting some components. But if this will reach the level of the larger amplifiers is uncertain.

The audio systems were model 2 and model 6; more models were not tested because these models gave similar results. It was expected that almost all the models would show the same results, except model 8. Model 8 had more piezoelectric discs which changes the needed power to control them all.

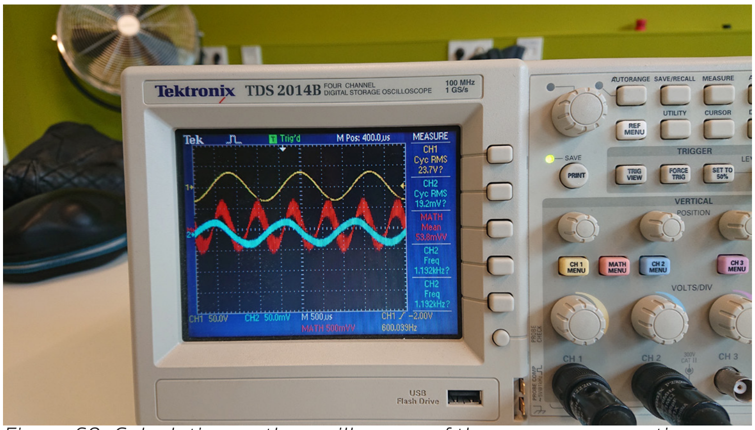


Figure 69, Calculation on the oscilloscope of the power consumption

In between the connection between the previously mentioned elements, the oscilloscope is connected with two channels. The first channel measures the current by connecting both probes on either side of a 10ohm resistor. The resistor does change the current a little, which makes the measurement not completely accurate. However, the change is expected to be small enough to get a rough estimation, which is needed to set general requirements for a new amplifier. The second channel measures the voltage by connecting the probes to the positive and negative side of the power supply.

The math function on the oscilloscope calculated the power (figure 69), taking the capacitive load of the amplifier into account. The calculation needed a continuous voltage, which meant that every frequency required to be played individually. The frequencies that are measured started at 130Hz, because lower frequencies were unlikely to be achieved by the system, and ended at 20kHz. These frequencies were measured using an audio file with the sine wave of the measured frequency. The steps in frequency were done according to a logarithmic scale; this meant steps of 10 below 200, steps of 100 below 100 and steps of 1000 below 10000.

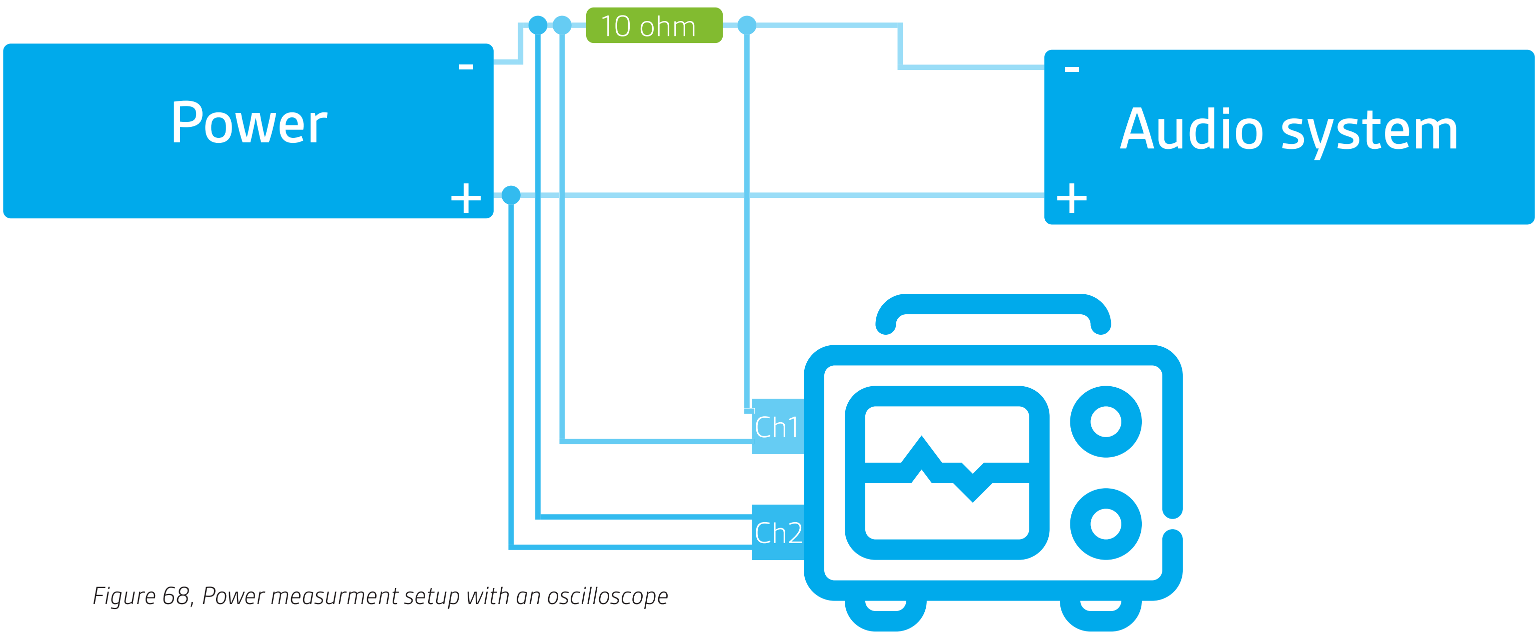


Figure 68, Power measurment setup with an oscilloscope

5.3.1 Audio measurements

The data of the measurements were visualized in the program Room EQ Wizard. This visualization applied a 1/6 octave filter to smooth out the lines of the graphs to make it easier to analyze. The 1/6 filter was chosen as a balance between a smooth graph but not eliminating too much data.

The frequency response graphs of all the models show they do not meet the +/- 3dB requirement to get the label “flat”. Even the Sonitron speaker does not give the same outcome shown by the manufacturer, figures 70 and 71. Because the models do not show a flat response, the minimum and maximum frequencies are determined another way. The estimation roughly finds the places on the frequency response graph where the audio shows a significant drop; this drop does not include gradual changes over multiple frequencies. The meaning of a “significant drop” is different for every graph, and is not based on the standard analysis procedure of audio engineers. The loudness is determined the same way; it is a rough estimation based on the earlier defined frequency range. The loudness is determined by finding the minimum and maximum loudness in this range and creating a general average. Because the volume on the computer was set at 42%, this is not the maximum volume of the models. However, it is the maximum volume that still sounds relatively pleasant. Figure 72 shows the estimated frequency range and the roughly determined loudness. In appendix 8.11, Models, all the models' details can be found, along with their frequency response graphs.

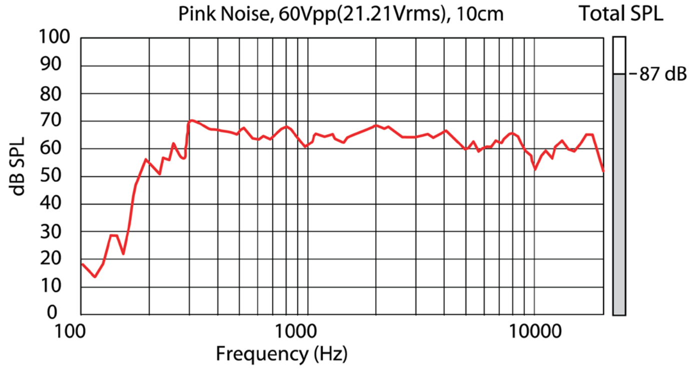


Figure 70, Sonitron frequency response provided by manufacturer

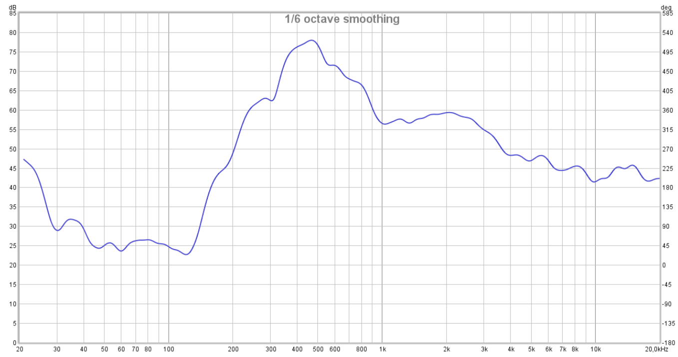


Figure 71, Sonitron frequency response measured data

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Haptile	Sonitron
Min freq.	600 Hz	290 Hz	756 Hz	1 kHz	460 Hz	470 Hz	480 Hz	480 Hz	470 Hz	280 Hz
Max freq.	20 kHz	20 kHz	20 kHz	8 kHz	20 kHz	20 kHz	20 kHz	20 kHz	20 kHz	10 kHz
Loudness	52 dbSPL	51 dbSPL	53 dbSPL	58 dbSPL	50 dbSPL	51 dbSPL	40 dbSPL	40 dbSPL	46 dbSPL	60 dbSPL
Thickness incr.	4mm	4.2mm	0mm	0mm	0mm	0mm	0.2mm	0.2mm	0mm	-

Figure 72, Results of all the tested speaker systems

Amplifier

Audio tests with the Sonitron amplifier and the big a-303 amplifier show that if the same model is used, lower frequencies can be produced with the big amplifier. The differences between the audio output of these amplifiers can be seen in figure 73. Besides the measured data, the difference between the amplifiers could also be perceived when listening to the audio. The smaller amplifier produces more distortions compared to the big amplifiers.

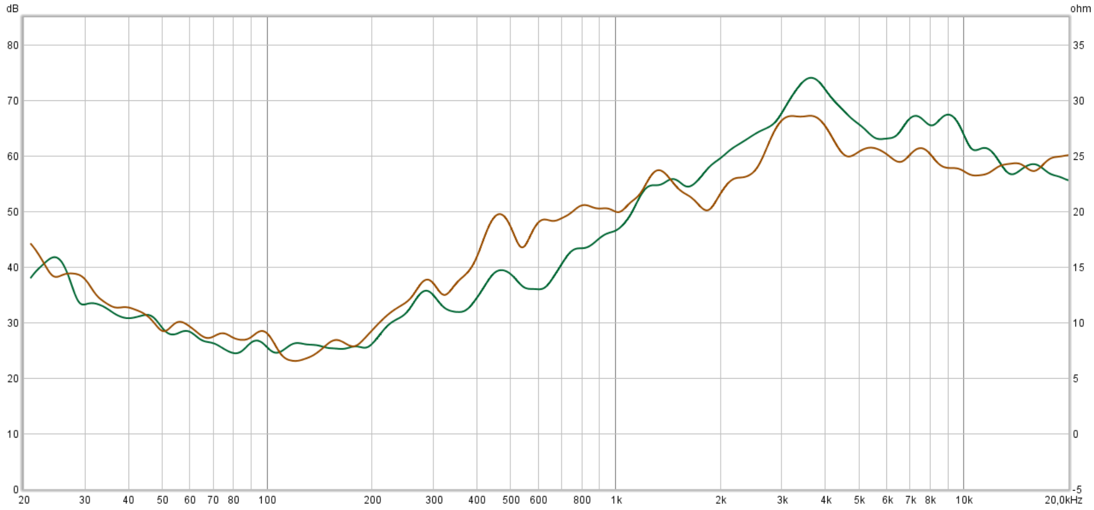


Figure 73, Model 2 with the Sonitron amplifier (green) and the A-303 amplifier (brown)

Angle

The different positions of the model seem to change the measured audio, as can be seen in figure 74. However, the changes of the measurement can also be caused by other elements. Model 8 shows a different response graph after it is measured two separate times (figure 75).

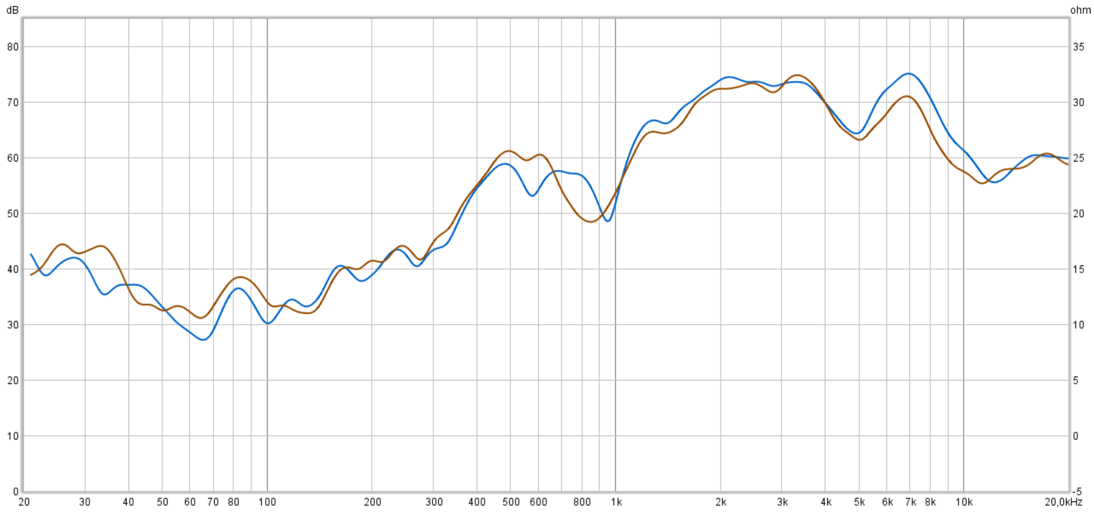


Figure 74, Model 8 in the flat position (blue) in the angled positon (brown)

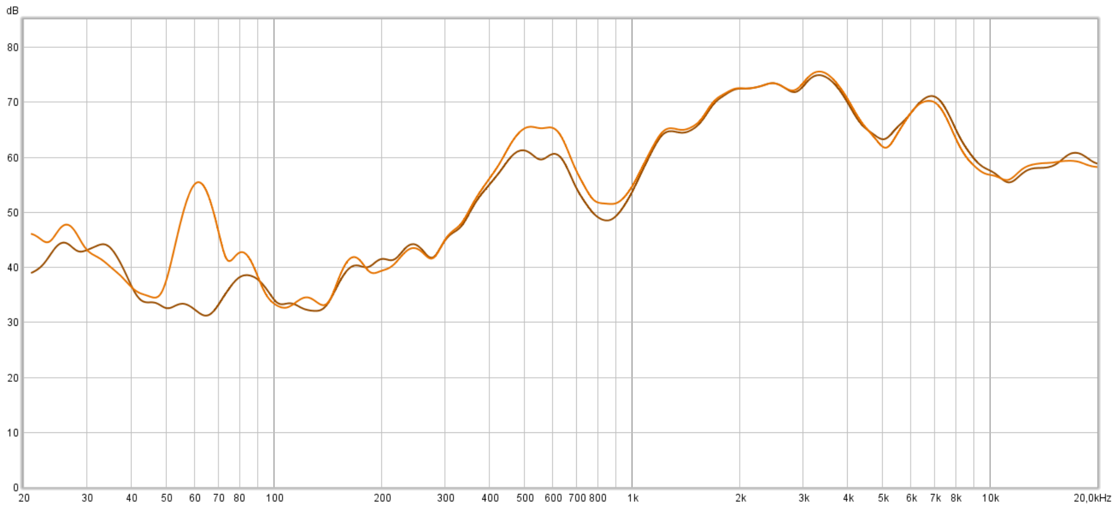


Figure 75, Model 8 the first measurement (brown) and the second measurement (orange) in the angled postion

Piezo layout
In models 7 and 8, the influence of the piezoelectric disc layout was analysed. Figure 76 shows that the differences between these models can be found in several frequency areas. Model 8 produces louder frequencies in the higher range, and model 7 does the same in the lower frequency range. There is no significant difference between the frequency range of both models; only the peaks and throughs are different for both models.

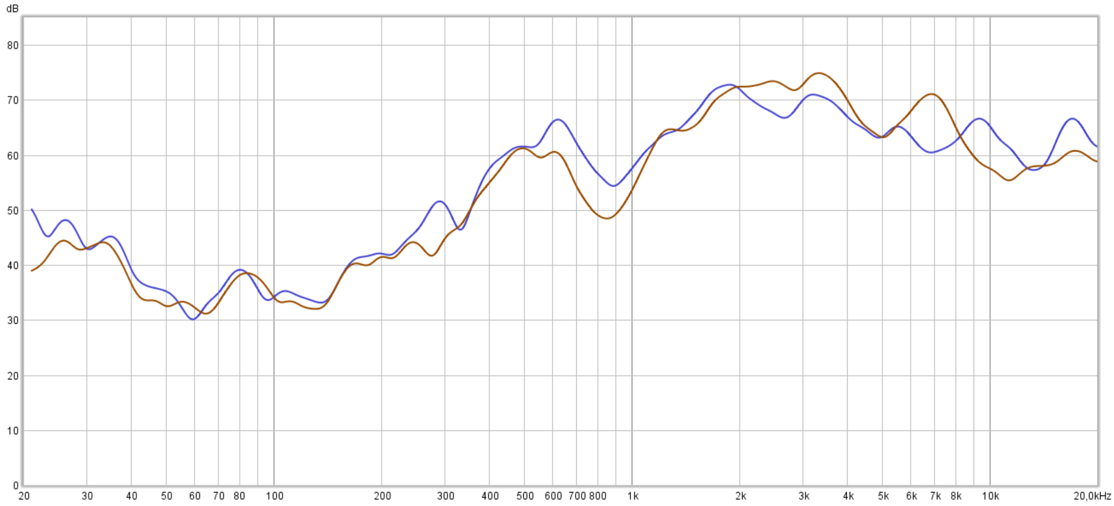


Figure 76, Model 7 (dark blue) and model 8 (brown) in the angled position

Piezo fixation
As mentioned earlier, in the models 1 to 6, the piezoelectric discs were fixated by mistake. The effects of this mistake can be analysed with models 2 and 7, as these have the same layout and general structure. The two differences between these models are the enclosure behind the carrier and the fixation of the piezoelectric discs. In figure 77, the different frequency response graphs of these models can be seen. Model 7 shows a response with a more even loudness throughout its frequency range. Model 2 shows a peak in the higher frequencies that is not present in model 7. Both models show a small peak around 200 Hz. In model 2, this peak represents its minimum frequency cut off because there is a gradual transition. Model 7 shows a significant drop before the 200 Hz point, resulting in a different minimum frequency. As mentioned previously, the enclosure of the models also shows differences. The enclosure can also cause some of the mentioned effects.

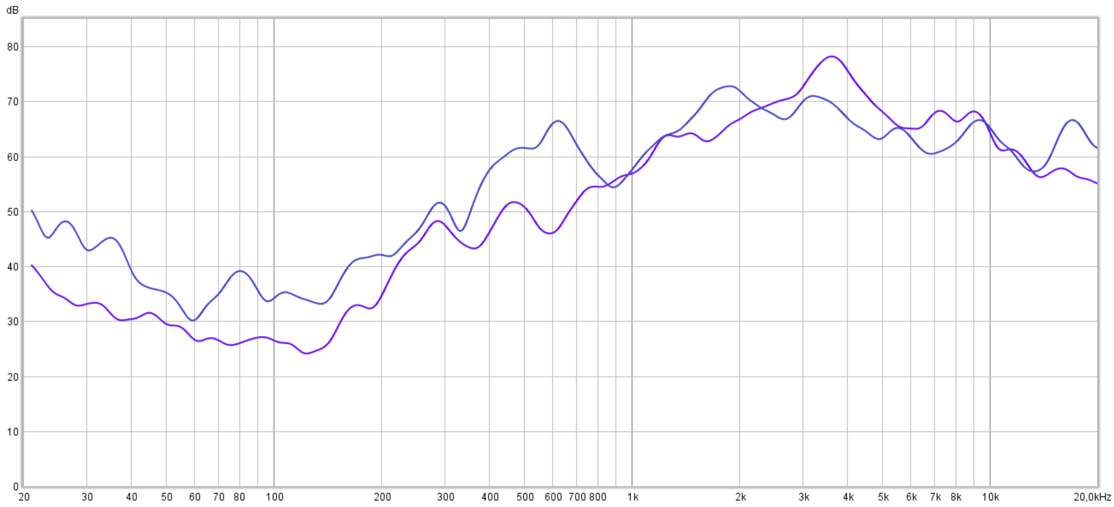


Figure 77, Model 2 with fixated piezoelectic discs (purple) and model 7 with free piezoelectric discs (blue)

Enclosure
Instead of using model 2 and 7 for analysing the effects of a open or closed enclosure, model 1 and 6 were used. The only difference between these models was the different enclosure. Because both of these models were made with the same error, they are better for the analysis of enclosure effects. Figure 78 shows both graphs of model 1 and 6. Model 6 shows a peak around 3 kHz where model 1 shows a flatter response. However, model 6 has a larger frequency range compared to model 1. The effect of a partially filled enclosure could not be analysed due to too much differences between the models.
Another effect on the enclosure was analysed using the Sonitron speaker, the speaker was measured with foam insulation and without the foam. Figure 79 shows that there is a minimal difference between foam or no foam.

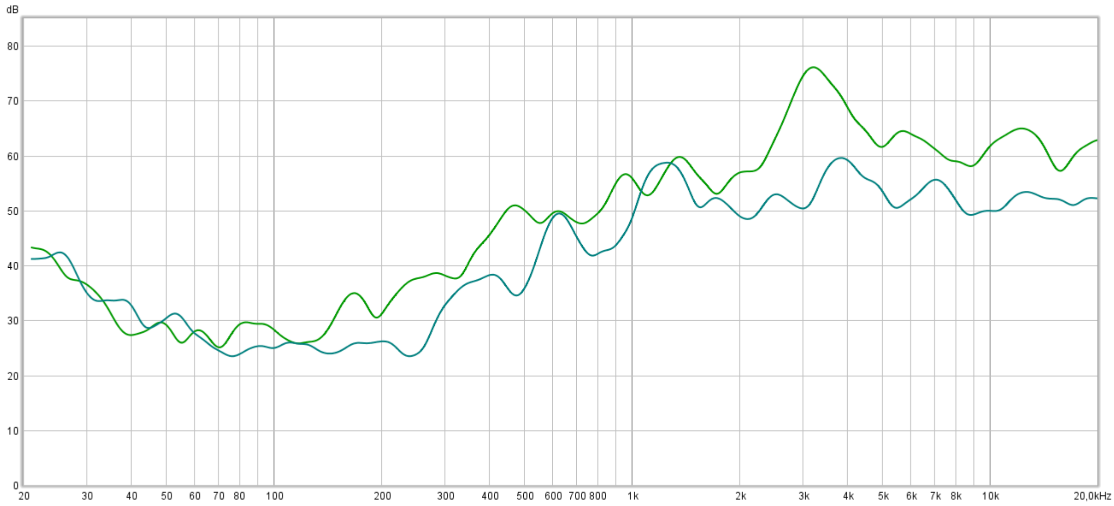


Figure 78, Model 1 with foam enclosure (dark green) and model 6 with filled enclosure (light green)

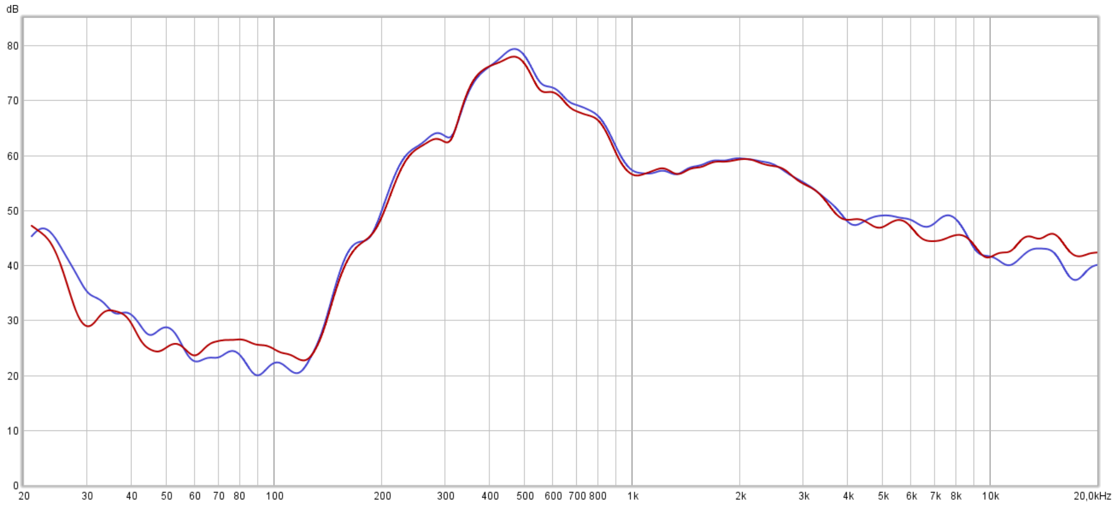


Figure 79, The Sonitron speaker with foam (blue) and the same speaker without foam (red)

Size

Even though models 5 and 6 have two differences between them they show a relatively similar frequency response graph (figure 80). The differences between these models are top layer size and enclosure filling. The main difference between the models is the reduced peak in the frequencies around 3.3 kHz.

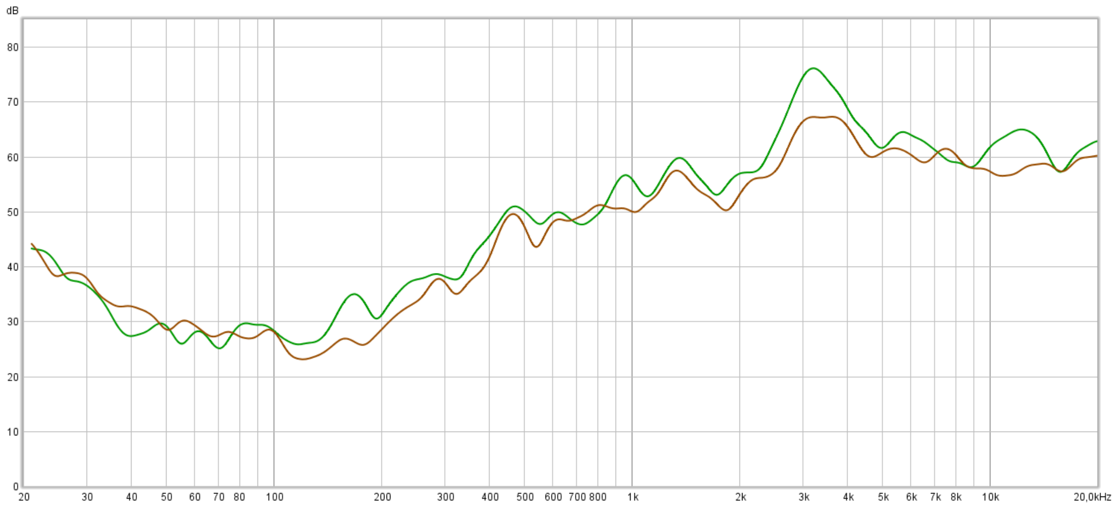


Figure 80, Model 5 with a larger top panel (brown) and model 6 with a smaller top panel (light green)

Edge suspension

The effects of different types of edge fixture were analysed with models 4 and 5. Even though these models do not have the same top layer size they were deemed rather similar. Figure 81 shows that a fully fixated edge results in a higher minimum frequency. The effects of a suspension fixation with foam adhesive could not be analysed. The models showed too many differences between each other to make a comparison.

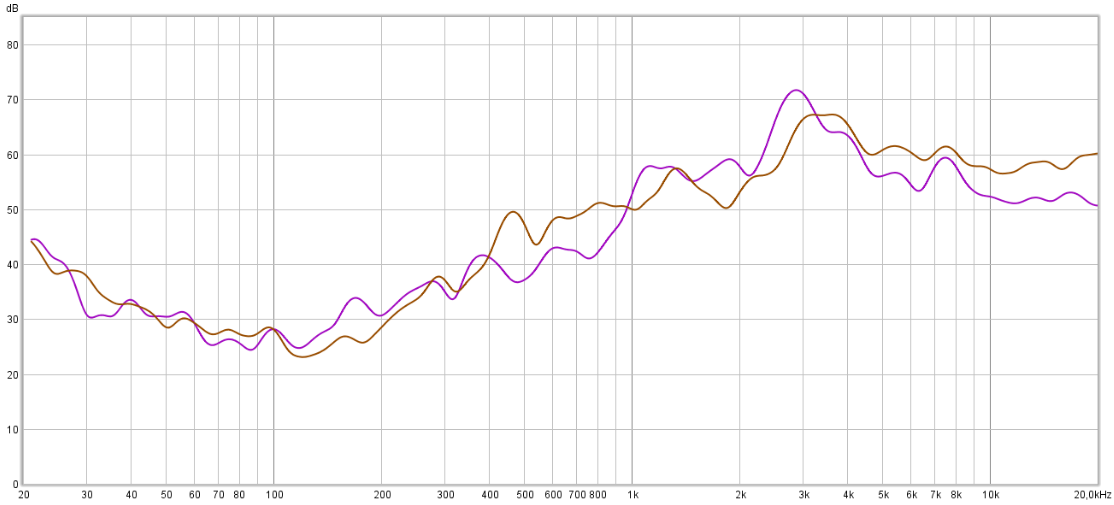


Figure 81, Model 4 with a fixated edge (purple) and model 5 with a free floating edge (brown)

Material

The comparison between model 3 and 5 in figure 82 shows that the metal plate causes less peaks in the higher frequencies. But in return the minimum frequency is increased along with the overall loudness as well.

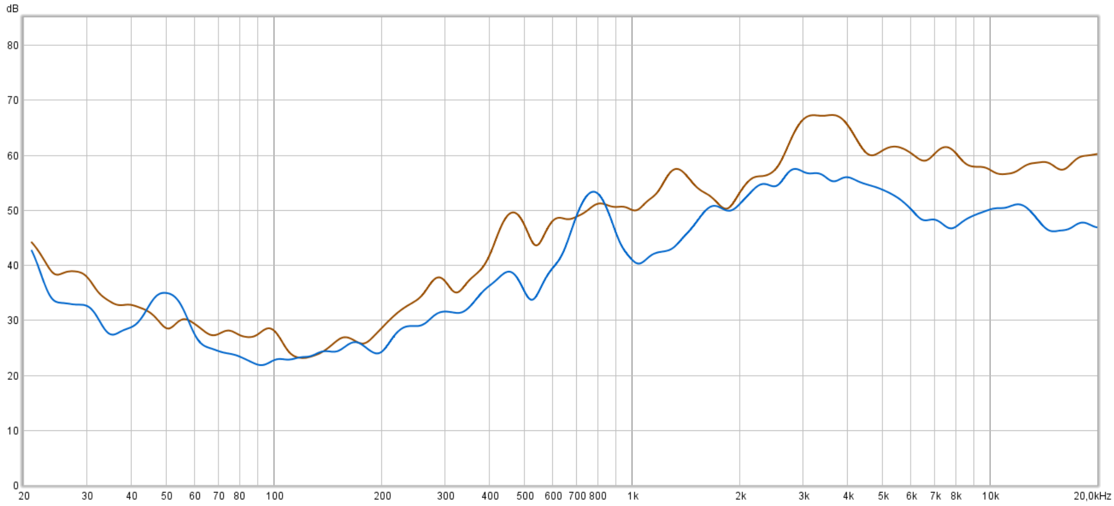


Figure 82, Model 3 with a metal top plate (blue) and mode 5 with a PMMA top plate (brown)

Although the models did not show flat responses it was expected this could be improved with digital sound processing. The process of digital sound process is explained in the next paragraph along with the approach in this project.

5.3.1.1 DSP

Digital sound processing (DSP) is done after the structure of a speaker does no longer needs improvements and only needs some small adjustments. The adjustments are done based on the measurements and hearing, because the measurements cannot show all the effects of the DSP effects. The basis for DSP is to adjust the gain in the areas where there are peaks or troughs, the gain is responsible for the volume. A higher gain means a higher volume, so to combat a trough the gain can be increased in that area. The gain adjustments are controlled by a designated chip which can integrated into a stand-alone device for larger speaker setups or directly integrated into an amplifier board. The adjustments happen in real time by checking the input signal and adjusting this with the filter that is created for the digital sound processing. This filtering has to be done quick in order to prevent audible delays in the audio, if you were to watch a movie you would not want the speech to be out of sync with the actors mouths. To speed up the filtering process the chip does not have a gain adjustment for every frequency but makes calculations based on a formula for a graph. An example of such a graph can be seen in figure 83.

There are two possible filtering techniques, the FIR (finite impulse response) and IRR filters. The difference of these filters lie in how these filters are implemented (Iowa Hills Software, 2013) FIR filters can be implemented with integer math instead of floating point math, because integer math is easier and quicker it is more common to find the right components for this type of filter. The IRR filter cannot use integer math because its coefficients cannot be scaled down, thus you need more heavy duty components to make these calculations. It depends on your requirements for the system and the price you are willing to pay which filter is the best way to go.

In the previous paragraph 2.3.2, DML & MAP speakers, the influence of individual filtering for each exciter was discussed. Individual filtering would mean that for each exciter DSP components are needed which drives up the cost of the whole system. Another problem that might occur is if there is a different delay for each exciter filter, this would mean that the exciters do not move all together to vibrate the surface. A possibility with the delay would be that one exciter moves up while another moves down, this has to be prevented. Therefore, if individual filtering is applied, the system needs to be adjusted to combat individual delays.

Another approach to DSP would be to change the signal input rather than trying to change the input after it is received by the speaker system. This means that before an audio file is exported for use the file is adjusted to sound better on smaller speakers. Music producers often adjust their music by listening to it on their high-end speaker or headphones, but most users will listen to it with crappy headphones or their bass-limited device speakers. One technique that is described to counter the effect of lacking bass is to add fuller tones to the midrange frequencies (Recordingrevolution, 2017). Dolby also has processing software to enhance the audio performance of a smartphone, tablet or laptop (Dolby, n.d.). Because Dolby protects this software to prevent other companies from copying it, it is unclear how this filtering is done and if it would be suitable for a DML or MAP.

The model that was chosen to tests the effects of DSP, was model 7. This model was chosen because it showed a roughly flat response compared to the other models. The first step in DSP for this project was calculating the filter settings for the model. The calculation was done with Room EQ Wizard, the settings for this calculation can be seen in figure 84. This figure also shows the predicted outcome if

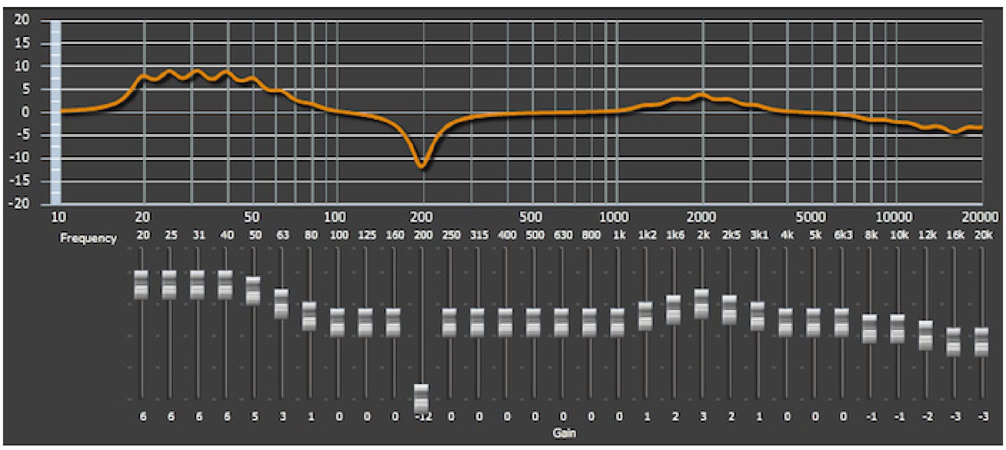


Figure 83, Standard DSP filtering graph this filter is applied. The settings for the calculation were set by looking at the prediction and seeing how this was effected by changing the settings. Audio engineers will likely have a different approach to determining the settings, but a lack of knowledge in this field resulted in this changed approach.

The second step in the process was putting the filter in the DSP module. The module that was used in this project was the miniDSP 2x4. This module allowed a total of 5 filters, other modules can handle up to 200 different filter settings.

The third step was to validate if the filtered result came close the predicted outcome by measuring the model with the DSP module on. Figure 85 shows this final measurement, which was done with a volume setting of 88% on the connected computer. The figure shows a flatter response with less prominent peaks in the higher frequencies. However, the model does not meet the +/- 3dB requirement even with the DSP.

Besides the results from the measured effects, there was also a noticeable audible effect. The audio did sound "muffled" compared to the audio before applying the filter. The explanation for this would be the elimination of the higher frequencies, which resulted in a loudness decrease and the "lack" of the higher frequencies.

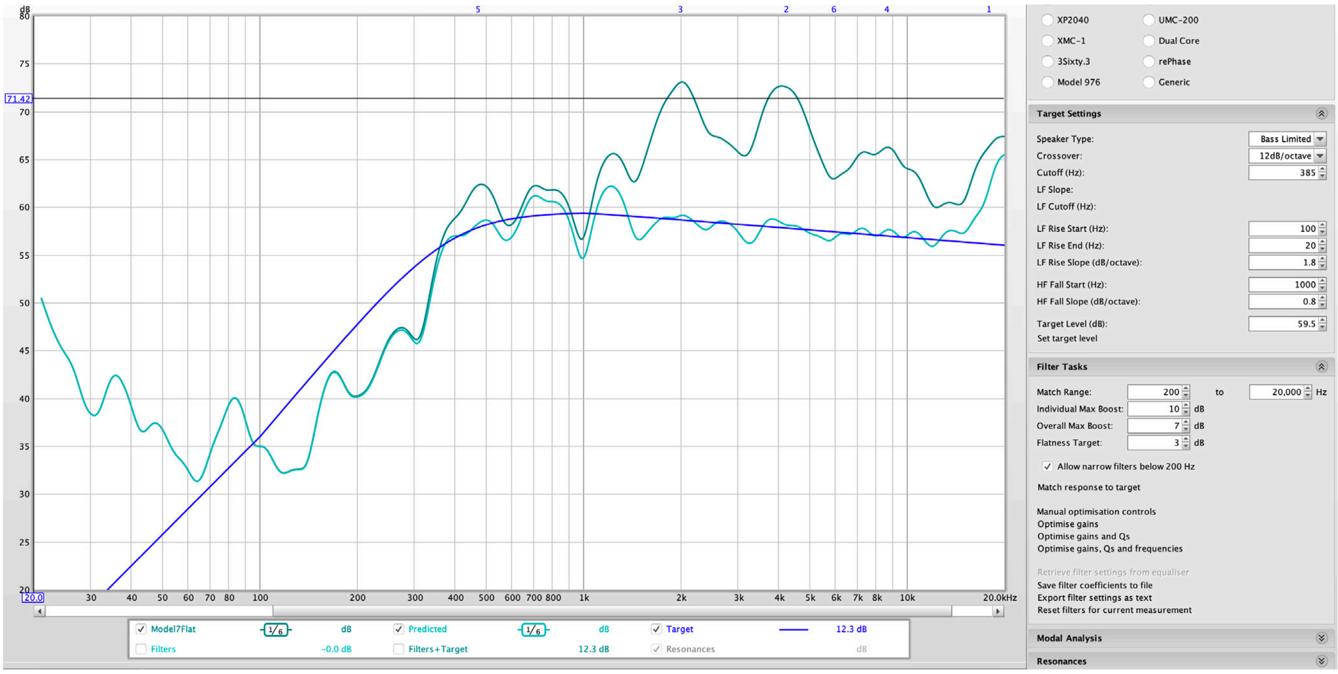


Figure 84, Outcome for model 7 with DSP predicted by Room EQ Wizard

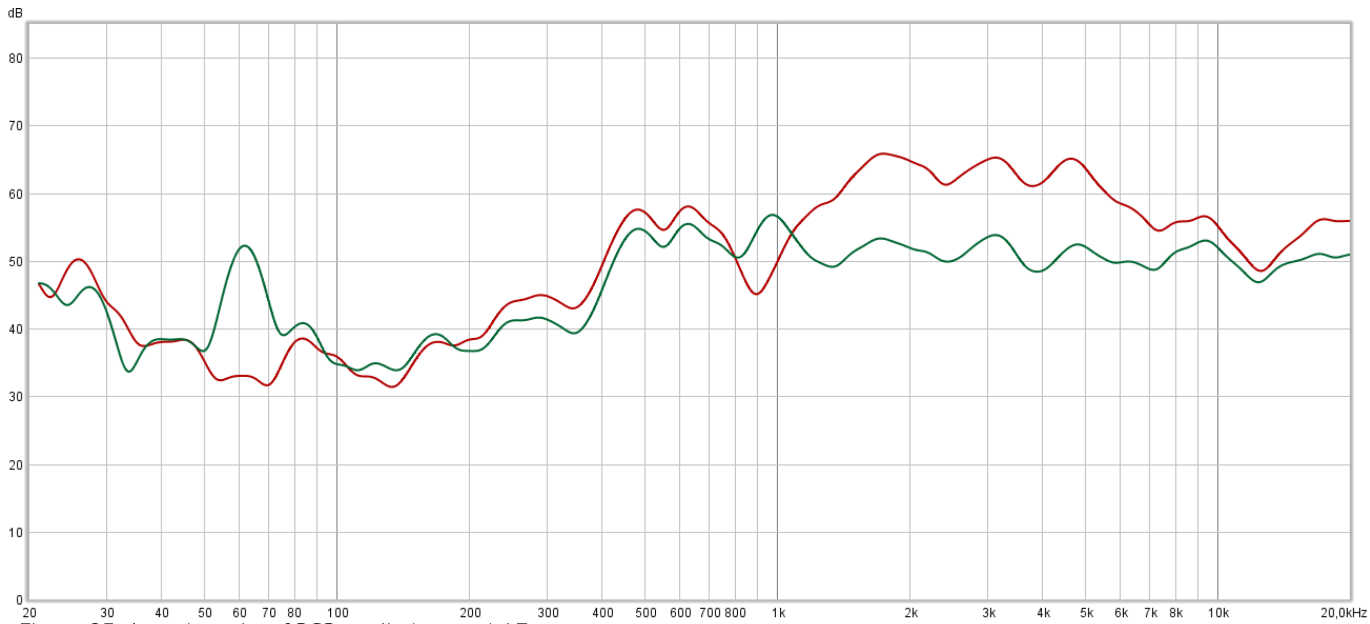


Figure 85, Actual results of DSP applied to model 7

5.3.2 Amplifier measurements

Figures 86 and 87 show in a graph the results of the power measurements with the big amplifier. These figures, as mentioned before, show many similarities. Based on these figures can be concluded that in the lower frequencies more power is needed. There are two areas in these lower frequencies. From 20 to 200 Hz and from 500 to 900 Hz. This last area is more interesting as most of the models have their minimum frequency lying in this area.

The maximum power consumption can be seen around 800 Hz for model 6 (190mW) and 500 Hz for model 2 (75mW). The area before is not taken into consideration as none of the models produced audible audio in this area. The maximum voltage measured in the test was 63V (needed for 140Hz) and the maximum current 584 mA (needed for 14000Hz)

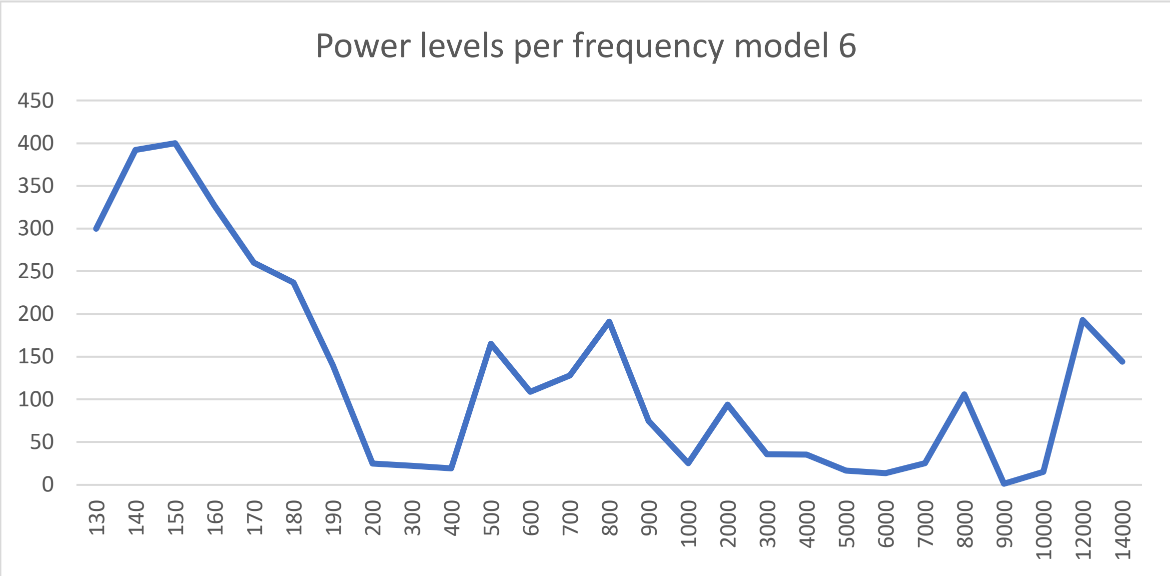


Figure 86, Power levels of model 6 (x-axis the frequencies, y-axis the power in mW)

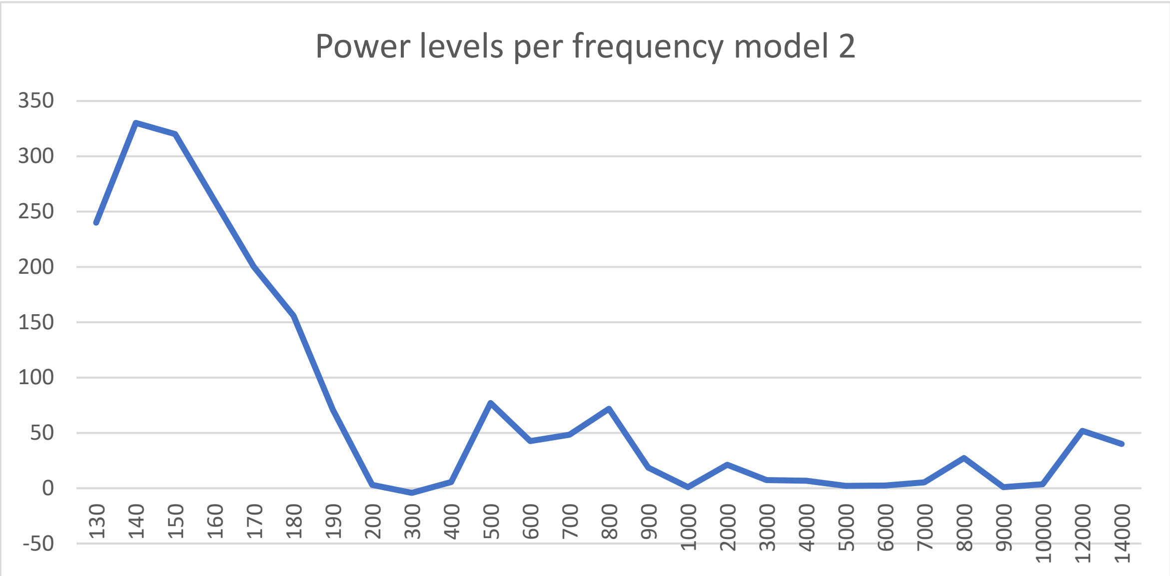


Figure 87, Power levels of model 2 (x-axis the frequencies, y-axis the power in mW)

5.4 Conclusions

Because both the audio and amplifiers tests were rather new; it took some time to get accustomed to them. In the process of learning to work with the test setups, errors were made, which contributed to a less accurate measuring result. In the audio measurements and amplifier measurements sections of this paragraph, the errors specific to these tests are explained.

The overall conclusion for the objective method is that designing and testing should include audio engineers and electrical engineers with knowledge of amplifiers. This will eliminate most of the errors made during prototyping and testing; thus saving time because tests go much fasters and do not have to be redone. Another part of this conclusion involves the model making process; if this project is continued, the model should be based on a real product. A real-life scenario and product will ensure that the prototypes are guided by the set requirements for that product or scenario. In this project, there were too many design principles, and some could have been excluded if more details about the structure of foldable devices were known. The last part of the overall conclusion also focusses on the model making process. This should be done more accurately compared to how it was done in this project. Accuracy can be improved in the assembly and the structure of the prototypes. As the models were made by hand, some piezoelectric discs were slightly misplaced, or the glue stuck together in some places. The process of assembling could be improved by making assembly rigs that guide the placement. An automated process for these types of models is too advanced, as they are only prototypes. For the structure, it would be ideal if it consisted of one material, and all the components were created with their final material. This ties in with the use of a real product and the details on the used materials. In the models for this project, several materials were mixed in the structure to get to the right dimensions. This mixture consisted of several layers of glue and PMMA stuck together. In the third round, this mixture was replaced by a 3D printed model as it was more accurate and was suspected of giving a better audio performance. It is suggested that for future models, the 3D printing approach is continued. This approach will ensure the prototyping is not limited by the available materials for laser cutting and improve accuracy.

5.4.1 Audio measurements

Looking at all the results of the audio measurements; it can be concluded that there is not yet a well-performing model that can be implemented by the industry. However, the measurements did show which principles and methods had a positive or negative effect on the models. The information about the effect can be used to explore further the possibilities of Aito's system for audio purposes.

DSP

The effect DSP had on the overall system was positive. Although the +/- 3dB requirement was not met with this approach, and the loudness was decreased, it shows potential. The problem of the reduced loudness in all models can be an issue, as this lies far from the required 72 dBSPL that is required by the industry. Another requirement issue that occurs with the use of DSP is that the frequency response should be flat without applying any filters. However, because the requirements are intended for coil speaker drivers, they are not fully representable for DML's or MAP's. Therefore, DSP is acknowledged as a viable solution to improve the audio performance of Aito's system. In further tests, the current DSP module can be substituted with another module with more filter options. The current module allows a total of 5 filter settings, but this can go up to 200 with other modules.

Size

From the measurements can be concluded that a size increase of 2cm in length and 1cm in width does not result in a better audio performance. The scale of the increase is likely too small, as literature only mentions sizes larger than a meter. The effect can be seen best in the Haptile Trackpad and the created models, the trackpad does perform the same as the models in terms of minimum frequency.

Edge suspension

For the edge suspension, Aito stated that fully fixated edges should be avoided to give proper haptic feedback; this also applies for audio performance. The model with the glue edge performed the worst of all models. The effects of a foam edge were less conclusive as there was a mix of too much design principles per model. The models with a foam edge, models 2, 7 and 8, did show a peak around 200 Hz, which might indicate that the foam edge improves the lower frequency reach. In model 2, the foam edge could not be accurately applied, and this might have resulted in some undetermined effects.

Material

The steel top layer in model three had negative effects on the frequency range but did improve the peaks around the higher frequencies. Prototyping issues likely influence the results of this model. The top layer was made by cutting the top plate out of a plate of steel; this causes some errors in the corners and the overall dimensions. The corners are not perfectly rounded due to the cutting. The other models were produced by either laser cutting or 3D printing, which is more accurate. When this model was assembled, the top layer slightly overlapped with the surrounding edge of the model. This means that when the plate is vibrated, it will collide with the surface of the edge, causing distortions. Which distortions came from the material use, and which from the prototyping inaccuracies could not be determined from the measurements.

Enclosure

The measurements with the Sonitron speakers regarding foam or no foam showed that insulation in the speaker chamber of a DML would likely have no impact. However, an audio engineer might conclude differently. Examples showed that foam is used in the industry, even in the small speaker chamber of the iPad Pro.

Other measurements regarding the enclosure showed that a speaker chamber does not necessarily have a positive effect on the lower frequencies. However, the difference could also have been a result of other design principles due to the mix of different principles in each model. Another possibility for the measured result is that the foam glue used to insulate the foam chamber attached itself to the piezoelectric discs. The mixture in design elements also made it impossible to determine the effect of the partially filled enclosure. Even if these results could have been determined, it would have to be seen if these were useful. The partially filled enclosure was not based on actual components, as there was no example product to work from. The filling was estimated, which might give different results if done differently in a real product.

Piezoelectrics

The differences between model 7 and 8 are mainly based on the different layout and number of piezoelectric discs. However, inaccuracies in both models cannot be excluded. Model 8 is louder in the higher frequencies, which is also perceived during the research. The model sounds louder due to the sensitivity of these frequencies. The differences occur because the panel is vibrated differently in both models. The different results show that it could be possible to adjust the layout to position the peaks an throughs. However, this would need a lot of prototypes. It would be better to first do rough estimations on placement with mathematical analysis before building the model.

Even though the piezoelectric disc fixation was not intended, it did provide useful information. Fixating the piezoelectric disc results in a large peak in the high frequencies. Letting it move freely is advised as this gives an overall flatter response. The enclosure behind the carrier should not limit the free movement. In this project, the maximum displacement of the piezoelectric discs was not measured. This measurement should be done to determine the minimum thickness of the carrier if the audio feature is further explored.

Testing setup

As mentioned before the test setup is based on testing laptops and tablets rather than foldable devices with a screen as a speaker. The adjustments made to the setup can be revised by an audio engineer to get more accurate measurements. That the setup influences, the measurements can be seen from the differences between positions and measuring the same model twice. The differences in the measurements of Sonitron speakers also indicate that creating the right setup is more than placing a speaker in a box. Sonitron likely adjusted their speaker with multiple tests, and this process has to be done for Aito's setup as well.

5.4.2 Amplifier measurements

The A-303 amplifier showed the best results of all tested amplifiers. This amplifier should be used as a benchmark to test amplifiers for Aito's system both for its power supply as well as its lack in distortions.

Because the piezoelectric discs showed high sensitivity for small changes in the input the current booster of Aito cannot be used. Aito's booster uses a stepwise conversion, but a smooth increase and decrease in voltage is necessary. The power measurements can act as guidelines to select the right configuration for the amplifier. This means that the new system should provide a minimum voltage of 63V and minimum current of 584mA. The power source should be able to provide around 190mW per half of the speaker. In a stereo setup this should then be 280mW, which is significantly lower than the 4W stereo setup in current devices. However, the volume setting on the laptop was set at 24%. So, the measured values will be higher to get louder audio. The maximum values that the piezoelectric discs can endure are unknown. From tests with full volume can be determined that the discs struggle with the supplied input. This struggle can come from the maximum in power supply, lack of movement space or collision of the top layer with the edges.

Findings

- Use real products instead of simplified models to get more accurate data and useful results.
- The accuracy in the prototypes should be improved to limit distortions caused by these imperfections.
- DSP shows promising results to flatten the frequency response, and should be looked into further.
- Size differences on the cm scale do not improve the audio performance.
- Edge suspension and enclosure effects should be further explored with models that consist of a low mix of design principles
- The effects of design changes can best be analysed by only changing one element at the time.
- Small design changes to the models can have a significant impact, even the position itself changes the measured results. So, the measuring setup should stay the same and has to be adjusted for the to be tested device.
- Piezoelectric layout should first be predicted with a mathematical analysis before models are created.
- Aito should make their custom amplifier based on the performance of the A-303 amplifier.
- The cause for the clicking and buzzing noises should be determined before the loudness can be improved.

Discussion
How can this exploration help Aito?

6.

At the end of this project, the subjective method and objective method were combined to validate the audio. The results from the survey of the subjective methods were used to select a grade in the grading system of the objective method. The expected grade is then compared with the actual grade the various models got. This comparison should give an insight into whether Aito's system would be suitable for foldable laptops or foldable tablets. Paragraph 6.1, Overall conclusion, discusses this comparison along with points of improvement.

As this approach of designing speakers is rather new, the insights on improvements can be helpful in future projects. Both the subjective method and objective method show potential, but still need to be further developed. The necessary steps in applying these methods are based on problems within this project, and promising results of some of the tests. The approach is focused on further improving Aito's system but could help other projects in finding the right direction. The recommendations for further development can be found in paragraph 6.2, Further development.

6.1 Overall conclusion

In the survey, the participants graded the foldable laptop and foldable tablet with mainly an "average" and in some cases a "good" or an "excellent". The grade of the industry grading system that would fit with this overall expectation is an "acceptable" or an "okay". Some participants expect the higher grades for the foldable devices, but the general expectation fits better with the previously mentioned grades. There is a difference in expectations between the foldable laptop and foldable tablet; the foldable tablet scores lower than the foldable laptop. So, the devices could be graded with different grades. It is a possibility that the foldable tablet is graded with an "acceptable", and the foldable laptop with an "okay".

However, the measured result from the objective method shows that the current system does not meet the requirements of the grading system. Aito's system is not ready yet to be implemented in either the foldable laptop or the foldable tablet. Whether it is possible to improve the system to meet the requirements is unclear, but there are still some exploration areas left. The audio possibilities are definitely something for Aito to explore further before writing it off. In meetings with the industry, it became clear they would be quite interested in this type of speaker system, as it provides front-facing audio. Another reason to continue is the added value Aito would add to the current system. The audio feature would be an extra selling point besides the seamless surface and the decreased thickness selling points. To make the audio feature a reality, Aito has to overcome four hurdles. These are loudness increase, the flatness of the frequency response, integration of the amplifier, and the combination with haptic feedback. In the next section, these hurdles are explained with the explorations that are needed to overcome them.

Loudness

The current structure cannot reach the 72dBSPL requirement while simultaneously showing a flat frequency response without any distortions. The loudness of the models lies currently between 40 and 58 with an input of 42% volume. There are three areas for improvements of the loudness: structure, power supply and amount of piezoelectric discs. The enclosure design did not seem to make a difference in the loudness of the different models.

The structure adjustments to increase the loudness would focus on the approach of Sonitron. They use a bendable surface with one piezoelectric element, and the surface bends as one. Because the surface can bend with a larger displacement, due to the larger piezoelectric element, a louder volume is created. This approach is less feasible for Aito because the current haptic feedback system would no longer be possible with this setup. A completely different system is not advised as there are other options to explore that could increase the loudness.

Another option for the loudness increase is applying more power over the piezoelectric discs. However, when this was done in the project, the models would produce "clicking" and "buzzing noises. In further development, the reason for these noises should be explored. It is suspected that these noises could originate from distortions that are already present and become more noticeable with louder volumes. Another reason for these distortions could be the power is too much for the piezoelectric discs; if this is the case changing the discs could be a solution. The distortions could also come from limitations in movement, caused by either the carrier or the top layer. The restriction in motion by the carrier can occur when the piezoelectric discs hit the surface behind the carrier because the displacement of the piezoelectric disc is larger than the thickness. A solution to prevent this would be to increase the thickness of the carrier to be able to increase the loudness. The limitation can also come from a collision between the top layer and the edge. If the distance between these components is smaller than the displacement of the piezoelectric discs, the parts collide. The solution to this problem would be to increase the dot thickness. Measurements need to be done to explore which of these areas cause the distribution. For the possible movement obstructions, these measurements would be with a laser to determine the maximum displacement of the piezoelectric discs. For the power limitations, the specifications of the piezoelectric discs should be compared with the power settings from the amplifier. The power settings can be measured with an oscilloscope. If the result is that neither the movement nor power is an issue; it can be assumed that the distortions were already there and originate from the structure.

Flatness

To create a flatter frequency response the issues with the structure should be tackled first. The placement of the piezoelectric discs are expected to give the most significant impact on the flatness. In the process of finding the balance in piezoelectric discs placement the throughs of some piezoelectric discs should combat the peaks of other discs. The peaks and throughs should cancel each other out. What steps need to be taken to achieve this are explained in paragraph 6.2.1, Process steps.

After the structure can no longer be improved, DSP should be used to further improve the frequency response. It is unlikely that DSP will be possible for each individual piezoelectric discs, which was the suggested method for MAP's. This is not possible due to the large number of amplifiers that would be needed. Therefore, a filter should be created that works for the complete system in order to be able to use one amplifier. The measurements did show that this process could decrease the loudness of the audio; this effect should be taken into account when determining the overall loudness before applying DSP. The "muffled" audio perception can be avoided by letting an audio engineer create the filter settings for the DSP; they have the knowledge that is needed to create a pleasant audio experience. The industry does not acknowledge the use of DSP to determine the grade; this should be determined without DSP. However, as this technique is new; it is expected that these requirements need to be adjusted to be applicable for DML's and MAP's.

Amplifier

Beside the structural hurdles, the electronic design for an amplifier can cause some problems as well. In this project the A-303 amplifier was used because of its abilities to generate high voltages and large currents with limited distortions. These specifications are needed in an amplifier that would fit in personal mobile devices. The difficulty in creating such an amplifier is the size. Electrical engineers of Aito should determine if it is possible to create a reasonably sized amplifier within the price range the industry is willing to pay. Recommendations for this system are made in paragraph 6.2.3, Electronics.

Haptics

The last hurdle lies in the user experience area and partially in the software area. In this project, the haptic feedback performance was not extensively tested. At the end of the project, models 7 and 8 were tested to see how limiting the foam edge would be on the haptic feedback. The conclusion from this test was that the foam edge gave a dampening effect until roughly 5mm from the side. However, if this setup is used in a foldable device, this area does not contain the screen. In the Lenovo ThinkPad X1 Fold, for example, the screen starts around 1cm away from the edge of the device. The haptic feedback can also be influenced by the combination between audio vibrations and haptic feedback pulses. It might be the case that by mixing these, the haptic feedback is less prominent. A solution for this problem is discussed in paragraph 6.2.4, Software.

Beside the haptic feedback, a new vibration can be felt as well, namely the vibrations of the audio. It is suspected that these vibrations can be a discomfort for some users. Therefore, in areas where users hold the device, these vibrations should be kept to a minimum. The effect of the audio vibrations was also tested on a small scale by the researcher of this project. The result was that if the edges were separate from the vibration top layer, the vibrations were minimally noticeable. The vibrations were more prominent on the back of the models but were not deemed uncomfortable. The vibrations could be compared with the vibrations that could be felt when a phone is playing audio at full volume. However, this small test takes only one opinion into account. Tests should be done with multiple users to get a better result and to conclude whether the vibrations are uncomfortable in use.

Implementation

When these hurdles are all resolved, the outcome might be a system that would be graded with an "acceptable" or even an "okay". The measured results in the objective method showed that a minimum frequency of 400Hz could be achieved, which would result in at least an "acceptable" grade. When these grades are achieved the system would be good enough for a foldable tablet or possibly a foldable laptop. It could be possible that the industry has a higher standard for the speaker system in foldable devices. In this case Aito's system could still be usable as an audio system, but with a different focus.

The first of two options would be to acknowledge the lack in the frequency range and use the system as a tweeter rather than a full range speaker. If Aito's system is used in foldable devices for its haptic feedback an audio feature would be an added bonus, even if it is only a tweeter. The design of the foldable devices already reserved room for other speakers, and this space can be used for speakers that only focus on the lower frequencies. The result would be a front-facing speaker for the higher frequencies, and side-facing speakers for the lower frequencies. An advantage of the front-facing speaker is that higher frequencies are perceived with direction. This means that the human hearing knows where the sounds are coming from, this effect is less for lower frequencies. Therefore, the lower frequencies do not have to be directed towards the user. Another solution to get an audio system with lower frequencies is to place the foldable device in a charging dock with (sub)woofers. This could be an added option, just like Apple sells their iPad Pro with a 400 euro case. However, this would mean that without the dock the audio quality might limit the user too much in their use.

The second option would be a different device for the implementation of this system. There are other products where the audio is less demanding compared to the tablet or laptop industry. Instead of products that are used for music purposed, Aito's system can be implemented in products that are used for voice audio. This group of products could be intercoms, elevator screens, navigation systems or any other device with a touchscreen and voice feature. Voice audio needs a minimum of 500Hz and up, which can be produced by the current models. Even a smartphone could still be an option, as the Haptile Trackpad showed that even in a smaller size the 500Hz frequency could still be reached. The use of haptic feedback, although more obvious in tablets and laptops, can still be a disruption in the smartphone or touchscreen industry.

6.1.2 Result limitations

As this was the first step towards audio for Aito and myself, the process that was followed was not yet optimal. There were some mistakes made, and certain things can be improved; these should be addressed in future development phases. To learn from the mistakes, they are described in this paragraph. How these mistakes can be avoided, or how the process can be optimized, as detailed in section 6.2, Further development.

Model making

During the model making process, various mistakes were made. The first mistake that made it difficult to analyse the effects of the design principles was mixing too many variables. The second mistake was creating models that were too simplified; these models will not represent the actual product accurately. The accuracy of the models was decreased by assembly mistakes, as they had to be assembled by hand. As earlier described, the piezoelectric discs were fixated with adhesive or not positioned correctly. An improvement in the model making process would be to add a mathematical analysis to roughly estimate the piezoelectric disc layout and the effect the design changes will have. This approach will result in more iterations, which are necessary for the development of panel speakers. Overall the system has to be improved in small steps.

Electronics

The amplifiers that were used during this project were standard amplifiers or drivers for piezoelectric elements. Although the A-303 amplifier had a pre-amplifier that was designed by Aito employees, it was not specifically built for the individual models. There were some adjustments possible, but due to a lack of knowledge about amplifiers, this option was not used to its full potential. An electrical engineer with expertise in amplifiers should be involved in the testing of the complete system, to create an amplifier specific to the system.

User test

As the user test approach was completely new, it was not the most optimal setup. The randomization was later added, and the number of participants was too low. The randomization issue is already fixed, and there are some solutions to gather more participants. As discussed a price or small amount of money should help in gathering more participants. However, this type of research would fit better with Aito's clients than Aito itself. The traditional user tests for speaker are more useful for Aito.

Audio test

The measurements showed that the test setup for the audio performance tests could influence the results. Therefore, one setup has to be created that can be applied to all prototypes to be able to compare the results in the end. An audio engineer could help in this process, and he or she would be of value in applying DSP as well. The audio engineer can identify much more quickly in which areas the audio needs improvement, and predict what the influence of the DSP filters will be. In this project, the data was analysed with the gathered knowledge, but this cannot compete with multiple years of expertise.

6.2 Further development

In this project, questions regarding waterproofing, lifespan, durability or assembling were not researched. However, if Aito has the goal to implement their haptic and possibly audio technology into devices, these should be answered. This paragraph details the necessary steps and gives recommendations for the prototyping, electronics and software processes.

6.2.1 Process steps

This approach is based on the different phases in this project and the mistakes that were made and should help Aito to develop the audio functionality. This plan consists of a total of 7 steps, as can be seen in the infographic on the right. The seven steps are not based on any specific product, as it unclear in this stage what this product should be.

Step zero

Before the process of designing a product can be started, the minimum size of the needed amplifier should be determined. This is the hurdle regarding the decrease in size of the amplifier while maintaining a low noise signal. It might be the case that the size will never get small enough to implement this into personal mobile devices. If so, the development of the audio feature should be stopped. The development of the amplifier in itself should not solely focus on audio. It should also focus on improving the signal for haptic feedback because if the amplifier never gets small enough, the experience gathered in this project could help to improve the haptic feedback circuit. Another advantage of an amplifier approach for haptic feedback is described in paragraph 6.2.4, Software.

A good starting point would be the PiezoDrive module, as this is designed for piezoelectric elements. This module should be altered to act as an amplifier rather than a single pulse driver. It is suggested that Aito assigns electrical engineers with knowledge about amplifiers to this project. If the quality of the amplifier reaches a certain level, an audio engineer is involved in this project as well. This audio engineer will likely have now knowledge about DML's or MAP's, but it would be beneficial if he or she has this knowledge. Instead of an employee, Aito could also partner with companies with an expertise in DML's and MAP's, Tectonic Elements, for example. They have researched DML's since 1996.

First step

The haptic feedback and audio implementation begins by selecting an already existing product. It is recommended that Aito finds a parentship with a company that has an interest in the combination of haptic feedback and audio. The partnership is needed as the integration is not as easy as that of the Haptile Trackpad; this system will need to be fully integrated into the product. A simplified version of the product will never perform the same as the real product, and therefore, the prototypes should be made as close to the final product as possible. This means that Aito and the partner company should work closely together in the design process.

Second step

After the product is chosen, it should be mathematically analysed to roughly predict the audio performance. This analysis will not give accurate results about the real-life audio performance, but it is expected to provide a general piezoelectric discs layout. In the project, this layout was selected based on haptic feedback performance and measured results from the Haptile Trackpad. The model making would be more efficient if certain layouts can be discarded based on mathematical analyses. How detailed this calculation will depend on the capabilities of the used software.

Third step

If a satisfactory result is achieved with the mathematical analysis, the next step is to make a prototype based on these calculations. The model should be made with the materials and dimensions of the actual product, and assembling should be done as accurately as possible. The approach for creating these prototypes is further discussed in paragraph 6.2.2, Prototyping.

Fourth step

The prototype or prototypes that were created in the previous step have to be tested to determine their audio performance, audio quality and haptic feedback performance. For these last two measurements, it is suggested to do the tests this with a mix of users and professionals. The setup for the audio performance should be kept identical and should be determined based on the product that is being tested. The setup for the audio tests, both performance and quality, can be designed by an audio engineer or an independent testing lab.

Fifth step

From the measured data areas for improvement can be defined. For the audio performance and audio quality, the improvements will likely focus on an increase in loudness, getting a flatter frequency response or decreasing the distortions. These areas can be defined by analysing the frequency response graphs and terminology that is used to describe the audio. For the haptic feedback, areas for improvement could involve limiting the dampening effect on the haptic feedback pulses or adjusting the interference effects between audio and haptic feedback with software updates.

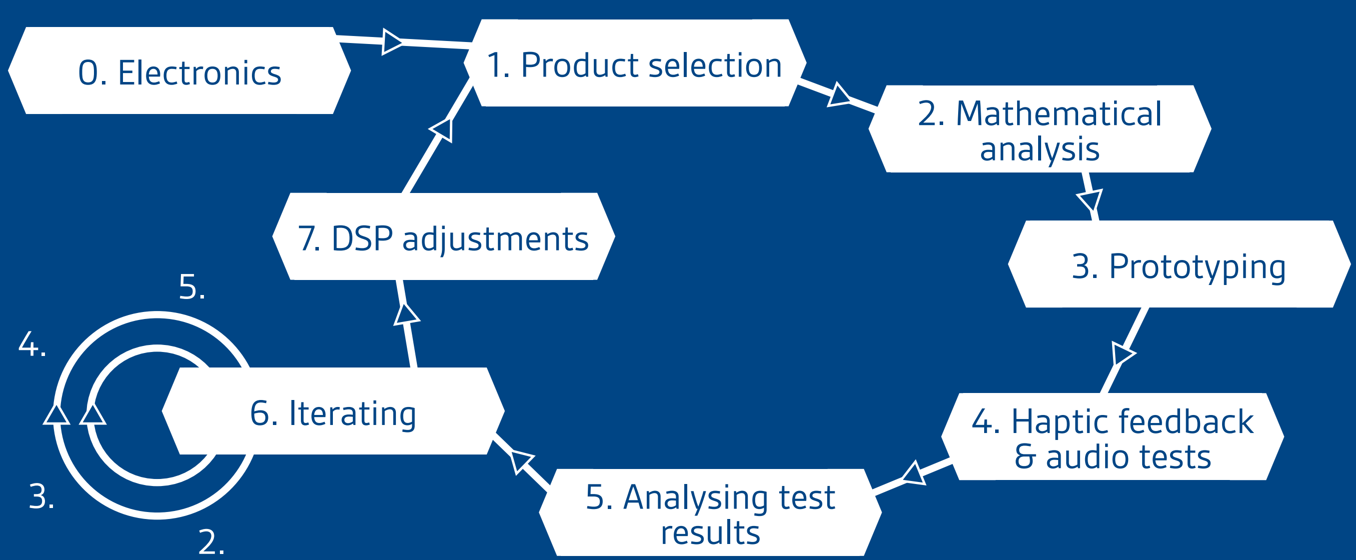
Sixth step

When areas are defined for improvement steps two, three, four and five should be repeated until a satisfactory result is reached. These iterations have to be done in small steps, not to mix too many design changes. If the design is changed too much, the effects of these changes cannot be linked to a specific change. Over time the effects will become easier to predict and pinpoint to one specific change as more iterations are done.

Seventh step

This is the last step in the process as the structure can no longer be improved. DSP can help to smoothen the frequency response of the system and should be done by an audio engineer. One filter will likely be applied instead of a filter for each piezoelectric position. Multiple filters would mean multiple amplifiers, which will mean a larger volume and an increased price.

Recommended process steps



6.2.2 Prototyping

This project showed that making the right model for testing can be quite a challenge. So based on this experience, several recommendations can be given to Aito. As described in the process step one, finding the right client is vital in developing the audio feature. All the data on the structure of the product should be accessible to create prototypes that accurately represent this product. This also means that material selection for the prototype will play a role as well. However, this project could not conclude the level of the impact of material changes of the frame on audio performance.

It is advised the frame itself is 3D printed to represent the final product accurately. A structure that is created with laser cutting can only be a 2D representation that will not represent the actual frame. The parts should be assembled or attached to this frame to save on components. The electrical components should be able to be taken out of the prototype if the system is not performing well; they can be reused in the next iteration phase. The recycling of components cannot be done for the top layer, as the piezoelectric discs have to be glued to this surface. So, if the top layer is an OLED screen, this results in unnecessary waste of electrical components. For this specific case, it might be an option to deviate from the actual material and find something that represents the mechanical properties of an OLED screen.

6.2.3 Electronics

As mentioned before, the amplifier is one of the first hurdles that needs to be taken towards an audio feature with Aito's system. The PiezoDrive module would be a good starting point for an exploration of the possibilities for amplifiers. This exploration needs to be done with an electrical engineer that is familiar with both amplifiers and piezoelectric drivers. It is suggested to integrate the amplifier into the Aito haptic feedback circuit to save components and money. The advantages of such a system are further explained in paragraph 6.2.4, Software.

No requirements for the amplifier are set, as it would depend on the product what speaker system is needed. The specifications that would vary based on the product are:

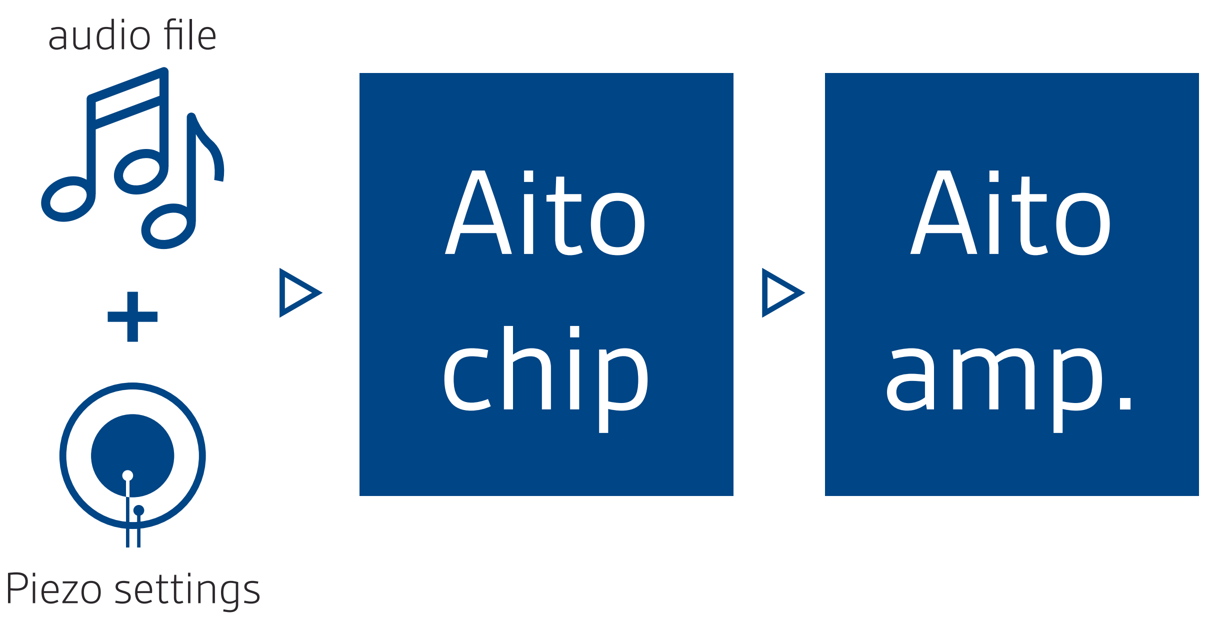
Size/volume

For personal mobile devices, where the thickness is kept to a minimum, an amplifier should be thin and small. While in an intercom, a part could be integrated into a wall, which would allow a setup that is larger in volume.

Loudness

This project looked at specifications for tablets and laptops. These devices need a minimum loudness of 72dBSPL, which could not be achieved with the current models. A suggestion to increase the loudness was to increase the voltage and the current. The design for the amplifier should be able to handle these voltages, which will exceed 60V. It is expected that the voltage will even exceed the 100V mark. However, other products might not require the same volumes as tablet and laptops. This means that the needed voltage and current might be lower.

Another possibility to increase the loudness would be to use a smart amplifier. The details about this specific



type of amplifier have to be researched to determine if this could be used for piezoelectric speakers. These amplifiers are likely designed with the standard coil speaker drivers in mind.

Amount

The speaker setup for foldable devices should provide stereo output, based on the results from the user test. This means that the amplifier should be able to send a signal to two channels with a DSP filter for both sides. For the setup for the foldable devices, each half consisted of 24 piezoelectric discs, which gives a total of 48 discs for the whole device. The amplifier should be able to provide power to all these discs, but again, this will depend on the product.

Frequency range

Based on the measuring results with the A-303, the frequency range will depend on the maximum power the amplifier can deliver. A new amplifier design should take this into account. If a specific minimum frequency is needed, the amplifier should provide the required power

Budget

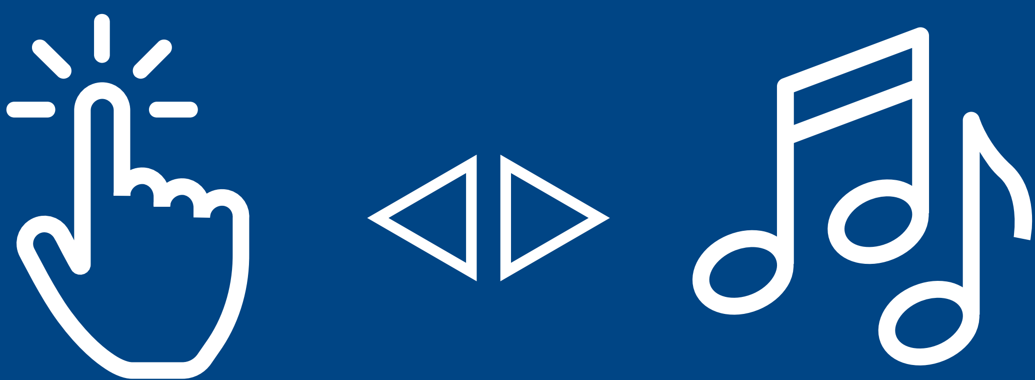
The last factor that influences the amplifier design is the budget. A “good” graded speaker system with an amplifier should cost around 5 dollars according to the industry (appendix 8.6, Industry contact). For Aito’s system, this means that the piezoelectric discs, combined with the amplifier, should be around this price. However, as this system is also used for haptic feedback; it is expected that the industry would allow a more expensive solution.

6.2.4 Software

On the software side, the use of an amplifier system that can play mp3 or other music files could be beneficial for haptic feedback. Currently, the pulse that is needed is set on Aito’s chip and cannot easily be changed dynamically. When Aito’s technology is installed in tablets or laptops, it would be easier for developers to create an audio file for the haptic feedback instead of changing the pulses on the chip. The data about the designated piezoelectric discs that are required for haptic feedback should still be sent to the chip.

The control of the individual piezoelectric discs could also offer a solution in giving haptic feedback while still playing music. It is uncertain if the haptic feedback can be played over the music and still give the impression of a button, or if the specific area for the feedback should stop playing music. The last solution might result in a distortion in the audio when no longer all the piezoelectric discs are used. Another effect of the combination of functionalities is the disturbance of the sensing capabilities. The vibrations of the audio can trigger the sensing threshold and inaccurately detect a pressing event. Cap sense technology could help to limit the effects of the audio vibrations. The suggested method would be to use the cap sense layer to detect a pressing event. When this is registered, the piezoelectric discs in this area will no longer play audio, which should result in a more accurate sensing area. Whether this would work will have to be researched. These problems show that it is beneficial to have one software solution to control both the audio and haptic feedback to minimize the negative effects.

Audio and haptic feedback trade-off



6.3 Reflection

My intention for this graduation project was to show my skill set that defines me as the industrial design engineer I am. I see myself as the connecting element between the creative side of the designer and the technical side of the engineer. The engineering side, for me, consists of software and electronics rather than mechanical engineering. I wanted to show my ability to balance between these two sides in this project.

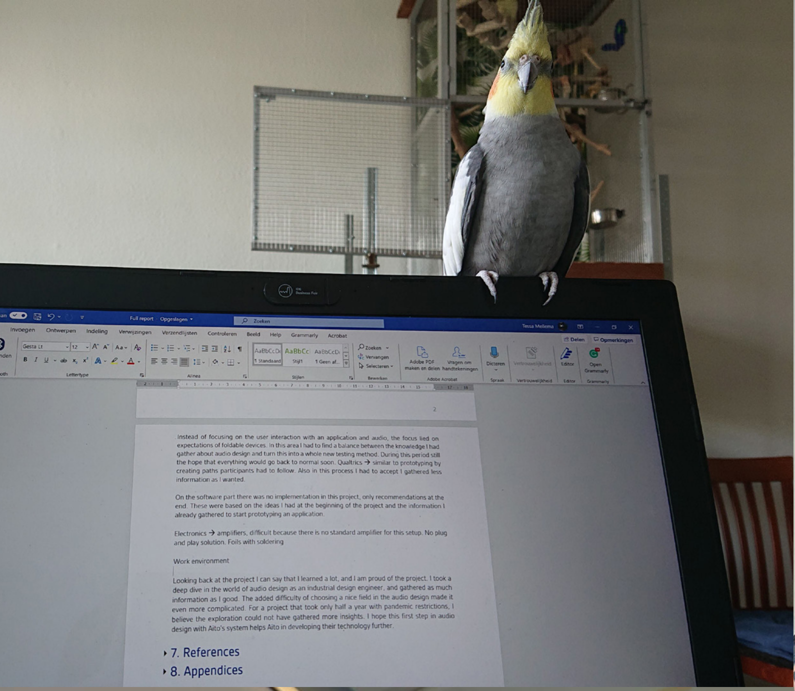
The initial planning for this project was to build and test various models in the first half of the project and pick the best model to integrate this into a tablet with an Aito audio application. Looking back at this original plan, it was ambitious to create and a new technology and try to implement it immediately into a product. The audio measurements of this project show that the technology is not yet there, so trying to create an application would be too soon. I think due to the lack of knowledge about audio design it seemed natural to create a speaker, but a deep dive into the field of audio design showed that a lot goes in designing a well-performing speaker. It was quite difficult to accept that I, as an industrial design engineer, did not have all the answers to create a well-performing model as a final prototype. The more information I found, the more difficult the process became. The gathered information showed me there was still is so much more to know about the field of audio design. I tried to find help from various audio engineers, but because this approach is new, they did not have many answers. So in the end, I had to be the expert on this topic.

Another element that made the already ambitious plan even more difficult was Covid-19. The initial planning could no longer be achieved due to the restrictions by the Dutch government. Testing and prototyping took a lot of planning and time, and some tests could not be done at all. I found it challenging create other methods because I was set on my planning. I wanted to create a final prototype in which I could show my programming skills. Over the course of a couple of weeks, I slowly began to accept that the new methods I had to use were just as valuable for Aito as a well-performing prototype.

On the software side, there was no use for it in this project; this part was only addressed for recommendations in further development. These were based on the ideas I had at the beginning of the project and the information I already gathered to start prototyping an application. So the interest in programming is still slightly present in the project.

Because there was no application, the initial user research also needed to be changed. This change led me to an area I am not entirely familiar with as a more technical designer. Testing applications was a part of my bachelor, but gathering "fuzzy" details about expectations was utterly new. The added difficulty in exploring this new area was making decisions based on the restrictions due to Covid-19. In the beginning, I was still quite optimistic that I could do the initially planned tests after the restrictions were over, but as the project progressed, this was no longer an option. The transition of audio design into the online world felt unnatural, as audio is something you experience in real-life. It was also quite challenging to create a method that would fit in with the objective method, instead of doing two separate kinds of research. Finding the right online tool was another hurdle, but fortunately, the TU Delft offers a subscription to Qualtrics. With other online survey software, I was limited in the type of questions. Qualtrics however, provided all the features I was looking for, and I enjoyed working with this software. In the end I was able to connect the user test with the measurements, and I believe this new approach could be beneficial in the field of audio design.

Looking back at the project, I can say that I learned a lot, and I am proud of the project. I took a deep dive in the world of audio design as an industrial design engineer and gathered as much information as I could. The added difficulty of choosing a niche field in the audio design and the restrictions of Covid-19 made it even more complicated. However, this allowed me to learn things I would not have expected as working with Qualtrics, specifications of amplifiers and creating foils with copper tape. For a project that took only half a year with pandemic restrictions, I believe the exploration could not have gathered more insights. I hope this first step in audio design with Aito's system helps Aito in developing their technology further, and that I can use the experiences of this project to further develop myself as an industrial design engineer.



Instead of focusing on the user interaction with an application and audio, the focus lied on expectations of foldable devices. In this area I had to find a balance between the knowledge I had gather about audio design and turn this into a whole new testing method. During this period still the hope that everything would go back to normal soon. Qualtrics → similar to prototyping by creating paths participants had to follow. Also in this process I had to accept I gathered less information as I wanted.
On the software part there was no implementation in this project, only recommendations at the end. These were based on the ideas I had at the beginning of the project and the information I already gathered to start prototyping an application.
Electronics → amplifiers, difficult because there is no standard amplifier for this setup. No plug and play solution. Foils with soldering
Work environment
Looking back at the project I can say that I learned a lot, and I am proud of the project. I took a deep dive in the world of audio design as an industrial design engineer, and gathered as much information as I good. The added difficulty of choosing a nice field in the audio design made it even more complicated. For a project that took only half a year with pandemic restrictions, I believe the exploration could not have gathered more insights. I hope this first step in audio design with Aito's system helps Aito in developing their technology further.
7. References
8. Appendices

Refferences

Where does the information come from?

7.

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Images

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Appendices

Where can I find more?

8.