Design Investigation of Passive Radiators in Loudspeakers

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MASTER THESIS

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Abstract

Passive radiators are components that can be integrated into loudspeakers to amplify the bass frequencies. To ensure good sound quality, the passive radiator, the speaker driver, and the loudspeaker enclosure must all be well-dimensioned and fine-tuned in relation to each other. This master's thesis, written at the Department of Design Sciences at Lund University, aims to deliver a set of general design guidelines to consider when designing loudspeakers incorporating passive radiators.

The report consists of theory and background to give a deeper explanation of how loudspeakers function. It further explores different parameters concerning passive radiators, drivers, and enclosures. Moreover, it investigates several utilities and test methods that allow measurements and determination of relevant parameters needed for designing optimised loudspeakers. Prototypes of loudspeakers as well as in-house made passive radiators were developed to perform sound measurements, the results of which were analysed and compared to simulations.

The project findings brought about a selection of important parameters to be considered when developing products with passive radiators. The project also resulted in defined test methods for measuring these parameters and detailed procedures for analysing the collected data information. Furthermore, the comparison between measured values and simulations led to reflections regarding tuning adjustments and the trustworthiness of above-mentioned test methods.

Conclusively this thesis acts as a helpful tool to potentially facilitate and streamline the design process when creating good sounding loudspeakers incorporating passive radiators.

Keywords: passive radiator, loudspeaker, speaker tuning, Thiele/Small parameters, frequency response

Sammanfattning

Passiva radiatorer är komponenter som kan integreras i högtalare för att förbättra basfrekvenserna. För att försäkra god ljudkvalitet måste den passiva radiatorn, högtalardrivaren och högtalarinneslutningen alla vara väl dimensionerade och finstämda i relation till varandra. Den här masteruppsatsen, skriven på institutionen för designkunskaper vid Lunds universitet, syftar till att leverera en uppsättning av allmängiltiga designriktlinjer att ta i beaktning vid designandet av högtalare som inkorporerar passiva radiatorer.

Uppsatsen består av teori och bakgrund för att ge en djupare förklaring av hur högtalare fungerar. Den utforskar vidare olika parametrar beträffande passiva radiatorer, drivare och inneslutningar. Därutöver undersöker den flera hjälpmedel och testmetoder för att möjliggöra mätningar och fastställande av relevanta parametrar som behövs för att designa optimerade högtalare. Högtalarprototyper samt egentillverkade passiva radiatorer utvecklades för att utföra ljudtester, vilkas resultat analyserades och jämfördes med simuleringar.

Projektresultaten ledde till ett urval av viktiga parametrar att ta hänsyn till vid utvecklandet av produkter med passiva radiatorer. Projektet resulterade också i definierade testmetoder för att mäta dessa parametrar och detaljerade procedurer för att analysera den insamlade datainformationen. Därtill ledde jämförelsen mellan uppmätta värden och simuleringar till reflektioner rörande stämningsjusteringar och tillförlitligheten av de ovannämnda testmetoderna.

Avslutningsvis agerar denna uppsats som ett hjälpfullt verktyg att potentiellt förenkla och effektivisera designprocessen vid skapandet högtalare med god ljudkvalitet som inkorporerar passiva radiatorer.

Nyckelord: passiv radiator, högtalare, slavbas, frekvenssvar, högtalaroptimering, Thiele/Small-parametrar

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Lund, January 2024

Fabrice Dufberg and Valter Hamberger

Table of contents

1 Introduction

This chapter describes the background, purpose, and general structure of the project. It further highlights the delimitations of the project, the project plan, and report disposition.

1.1 Background

An industry leading technology company within the field of network video surveillance and security solutions offers their products to businesses and organizations to enhance their security infrastructure. In order to expand their offerings, the company started a new division which focuses on audio products, access control, and intercom products. This project is focused on loudspeakers and the company which the project was conducted with will hereon be referred to as 'the company'.

There are several ways of designing loudspeakers, one of which makes use of so-called passive radiators (PRs), a vibrating membrane without a driving unit. This technology has several advantages, one of which is allowing for a sealed enclosure making the whole product more resistant to its surrounding environment. At the time of writing, none of the company's current offerings use this technology.

This project aims to investigate the implementation of passive radiators into future audio products.

1.2 Purpose

Loudspeakers have a wide range of use cases, both indoor and outdoor. Some of the company's product offerings are intended to outdoor use where they are exposed to the environment. A fully sealed enclosure prevents any water, dust, or other unwanted particles to enter the speaker but pose restrictions on bass output, whereas an open (vented) enclosure amplifies the bass sound but is more difficult to make resistant to the environment. Passive radiators sit in the middle ground between these two design choices offering a good balance between bass amplification and weather resistance. Like many other audio technologies, passive radiators are quite complicated to implement successfully and have many parameters which affect audio quality. The company wishes to investigate how passive radiators can be implemented in future audio products.

1.3 Goals

The overall goal is to deliver guidelines of relevant factors to take into consideration when designing a loudspeaker which incorporates passive radiators. This goal can be divided into the following subgoals below:

- Investigate how passive radiators operate and how they are implemented in loudspeakers. Identify which materials are commonly used in passive radiators and which material is appropriate for different intended use cases.
- Find and analyse significant parameters involved when designing passive radiator loudspeakers and understand how they correlate to the audio output.
- Develop one or several prototypes designed to achieve selected parameter values.
- Test and analyse the prototypes to see if they perform as predicted.
- Identify which attributes are important and possible to predict when designing passive radiator loudspeakers, and the largest hurdles.

1.4 Delimitations

A few delimitations were set to simplify the project and keep it within the intended time frame. These were:

- Analysis and evaluation were made from experiments on existing passive radiators rather than theoretical derivations.
- Cost and manufacturability were taken into consideration, but no complete cost analysis was done.
- Only simple implementations of passive radiators were considered e.g., no fourth order bandpass boxes.

1.5 Time plan

This project was conducted during the autumn semester of 2023 which was 20 weeks long. A time plan was created during the first week in the form of a Gantt chart, which is included in Appendix A. Furthermore, a second Gantt chart which documented the actual outcome was created and updated over the course of the entire project and is included in Appendix A. Workload was divided equally, and all steps were conducted in tandem.

1.6 Project process

Given the exploring and experimental characteristics of the project, the Double Diamond was found as a suitable design process for the assignment. It was chosen above other methods such as Ullrich and Eppinger's product development method (2012) Lean Startup (Ries, 2011), or Scrum (Schwaber & Sutherland, 2020) as this project did not aim to develop a product, and includes following four steps: Discover, Define, Develop, and Deliver. The Double Diamond does not follow a chronological straight line but is rather an iterative process in which the four steps can be reevaluated several times (Design Council, 2024).

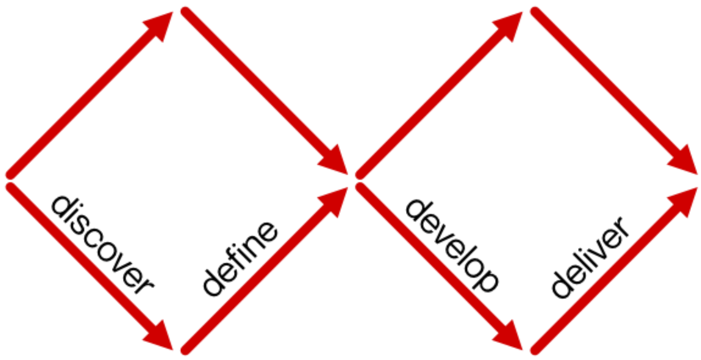

Figure 1: Double diamond

1.6.1 **Discover**

This phase aims to acquire a deeper understanding of the project definition. In this project it included research on loudspeaker fundamentals and passive radiators through literature, online courses, and discussions with experienced audio engineers at the company with the purpose of getting an understanding of which passive radiator parameters affect bass output. It also involved an explanation of why these research methods were chosen and how they impacted the project. To give context, an investigation of the technical description of complete speaker systems and human sound perception was carried out.

1.6.2 **Define**

In this step the information collected at the previous phase was narrowed down to define a challenge. In this project the define step resulted in an investigation of existing passive radiators by identifying important parameters and realizing their measurements. The measurement methods were based upon our acquired knowledge from the Discovery step, interpretation of industry standards, iterative testing and through discussions with audio engineering experts at the company and their educated assumptions. Thus, the methods consist of adaptation, combination, and practical implementation of previously known methods and validation of these methods. Thereafter a testing strategy and setup was decided by using available resources at the company, and the measurements were carried out. This phase constituted a larger part of the project than initially planned due to difficulties in establishing the measurement methods.

1.6.3 **Develop**

The Develop phase involves an exploration of possible solutions to evaluate and investigate the effects of the parameters chosen in the Define phase. In this project it included the construction of three small modular loudspeakers which were tested with different passive radiators. These tests measured both the loudspeakers' objective and subjective performance and the contributing effects of the PRs. Additionally, this phase also included a short development process of PRs constructed in-house.

1.6.4 **Deliver**

This phase involves analyses regarding the performance of the loudspeaker prototypes when integrating passive radiators, by interpreting and quantitatively evaluating their frequency response which is a way of representing bass output in a chart, further explained in section 2.2.1. By using Design of Experiments an examination regarding the measured parameters' internal importance was conducted. There were also comparisons made between simulated and measured results as a mean of verifying the measurement methods developed in the Define phase. Ultimately a concise measurement guide and a set of design guidelines, including relevant aspects to consider, hurdles to avoid, and helpful tools to utilize when creating a PR incorporating loudspeaker is presented.

2 Discover

This chapter involves background, theory, and history of loudspeakers and aims to derive a relationship between bass output and certain parameters. It also includes the methods used to reach a deeper understanding of loudspeakers, and why they were chosen for this project.

2.1 Research method

In order to get a better understanding of PRs and how they operate, it was vital to first understand how loudspeakers work in general before focusing on PRs specifically. The goal of the research phase could thus be summarised as *"getting a general understanding and overview of loudspeakers systems and components with specific focus on passive radiators"*. This research purpose had two reasons, to guide the project by not investigating irrelevant physical properties, and to make sure that any potential mathematical calculation would be based on accepted models of physical systems.

As this topic is based on mathematical models of physical systems, it was decided that the most suitable methods of conducting research was to find and read textbooks and articles, watch online lectures and courses, and to discuss with experienced audio engineers at the company. The first two methods were chosen as they were similar to how physics courses at Faculty of Engineering LTH are taught, and the last one as it could give the authors insight into how the company views and values audio and loudspeaker theory in their product development processes, as well as a guideline for how relevant different areas of loudspeaker theory were for this project. Another benefit of discussions with experienced audio engineers was that they could provide information on where to find relevant and appropriate resources covering the specified topics.

The process of finding and selecting textbooks, journals, and online resources was done in three different ways. Firstly, by recommendation of company experts, such as textbooks available in the company library. These were seen as reliable resources as the company had in at least some capacity used them in their product development processes or employee training. Secondly, some textbooks on audio and sound in general were found by searching in the online LUBcat library and in the Google Scholar database. The resources from LUBcat were seen as reliable, and the resources from Google Scholar were evaluated based on their publisher. The ones found and used were published by the Journal of Audio Engineering Society which is a well-established audio-centred publication. Thirdly, many of the textbooks referenced other sources, such as other textbooks or articles published by the Journal of Audio Engineering Society. Finding and evaluating different resources was done in tandem with reading and analysing them. Discussions with audio engineers in were carried out on an on-need basis in an unstructured and informal manner, without making any recordings.

The research stage was conducted until the specified goal of the research stage was reached and the findings are presented in sections 2.2-2.4.

2.2 Loudspeaker fundamentals

2.2.1 **Sealed enclosure**

The simplest form of a loudspeaker system is a sealed enclosure with a driver element, shown in Figure 4. The driver consists of a cone with a dust cap, a motor system, and a suspension system. A representation of the components in the driver can be seen in Figure 2.

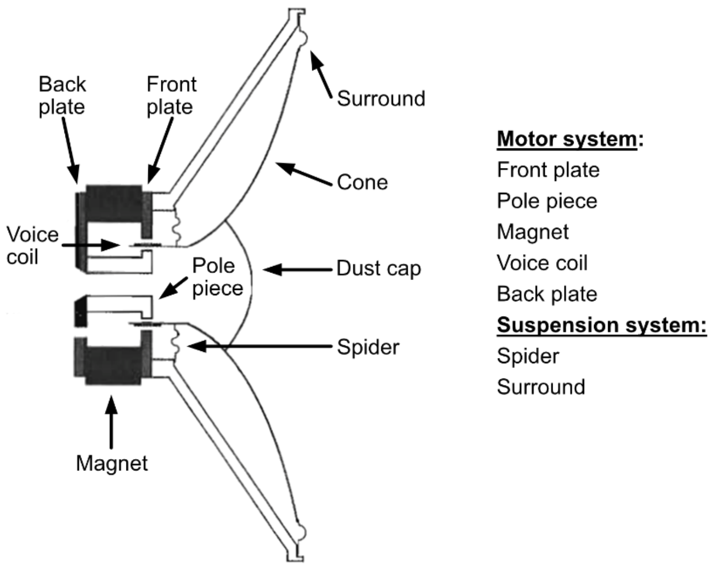

Figure 2: The components of a loudspeaker driver (Dickason, 2006, p. 3)

As alternating current enters the driver, the voice coil generates a magnetic field that shifts in polarity as the current alternates. The magnetic field interacts with the permanent magnet causing an attracting respectively repelling force which subsequentially activates motion of the voice coil (Dickason, 2006, pp. 3, 29). As seen in Figure 2 the voice coil is connected to the cone and the movement of the cone generates soundwaves.

Apart from small changes in material and the introduction of the dust cap, few modifications of the driver setup have been made since it was first invented by Rice and Kellogg in 1924 (Beranek & Mellow, 2019, p. 279) and (United States of America Patent No. 1,795,214, 1925) and (United States of America Patent No. 1,707,570, 1925)

A driver generates soundwaves from both the rear and the front parts, shown in Figure 3. These soundwaves are 180 degrees out of phase. If the driver operates without any type of enclosure these soundwaves cancel each other out (Tanasescu, 2020a) discussed in (Section 7, Video 18). To prevent this from happening the driver is incorporated into a sealed enclosure (Beranek & Mellow, 2019, p. 332).

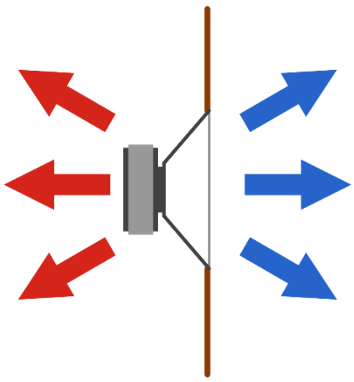

Figure 3: A representation of the soundwaves emerging from the front and back of the driver

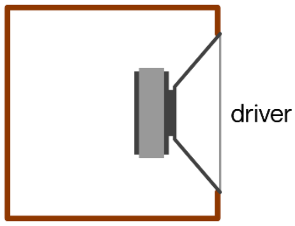

Figure 4: Sealed speaker box

During the first half of the 20th century the construction of many sealed loudspeakers showed that the volume of the enclosure appeared to affect the frequency response (FR) of a loudspeaker (United States of America Patent No. 2,775,309, 1956). The FR is a representation of sound pressure contra frequency. Ideally a speaker should have a flat FR, which means that the sound pressure remains constant for all tones. However, there was no scientific or standardized method to demonstrate and optimize the relationship between the FR and the enclosure volume. Instead, loudspeaker designers relied on try-and-error procedures and listening tests, which is a rather inefficient method that depends on the subjective experience of the individual. In 1972, Richard Small published the articles *Direct-Radiator Loudspeaker System Analysis* (1972a) and *Closed-Box Loudspeaker System* (1972b) in which he scientifically explained the relationship between the volume of the enclosure and FR.

Small's publications together with the publication *Loudspeakers in Vented Boxes* (1973) by Neville Thiele resulted in the identification of a set of relevant parameters for speaker drivers influencing the performance of a loudspeaker, called the Thiele/Small parameters.

The Thiele/Small parameters for a driver:

- R_E – Resistance of voice coil
- Q_{ES} – Electrical quality factor. Describes the electrical damping of the driver
- Q_{MS} – Mechanical quality factor. Describes the mechanical damping of the driver
- F_S – Resonant frequency of the driver
- S_D – Effective area of the diaphragm

- V_{AS} - Equivalent suspension volume. The volume of air having the same acoustic compliance as the suspension of the driver

When designing a sealed loudspeaker, these parameters as well as the linear extrusion limit of the driver, x_{max}, need to be considered (Beranek & Mellow, 2019, p. 289).

Figure 5: Statues of R. Small and N. Thiele

2.2.2 **Vented enclosure**

Another type of loudspeaker design is the vented enclosure. It is essentially the same setup as the sealed enclosure except it has an open port between the inside of the box and the surrounding. The reason for using a vented enclosure is to enhance the FR and decrease distortion at low frequencies. This can be described as improving the bass output of the speaker (Beranek & Mellow, 2019, p. 333) and (Liljencrants & Granqvist, 2004, pp. 9-16).

The vent has a low resonant frequency, and at this frequency the air inside the port vibrates intensely making the port act as a second speaker. (Beranek & Mellow, 2019, pp. 374-376) and (Dickason, 2006, p. 61)

Designing a well-tuned vented enclosure is more complex than creating a sealed enclosure. When designing a vented loudspeaker, you must consider not only the parameters mentioned in 2.2.1, but also the area and length of the port. Vented enclosures are often discussed in terms of alignments, which is a predetermined combination of parameter relations to achieve a desired FR, usually a flat one with a low cut-off frequency. The cut-off frequency is defined as where the FR curve dips below 3 dB in relation to the nominal level (Beranek & Mellow, 2019, p. 441).

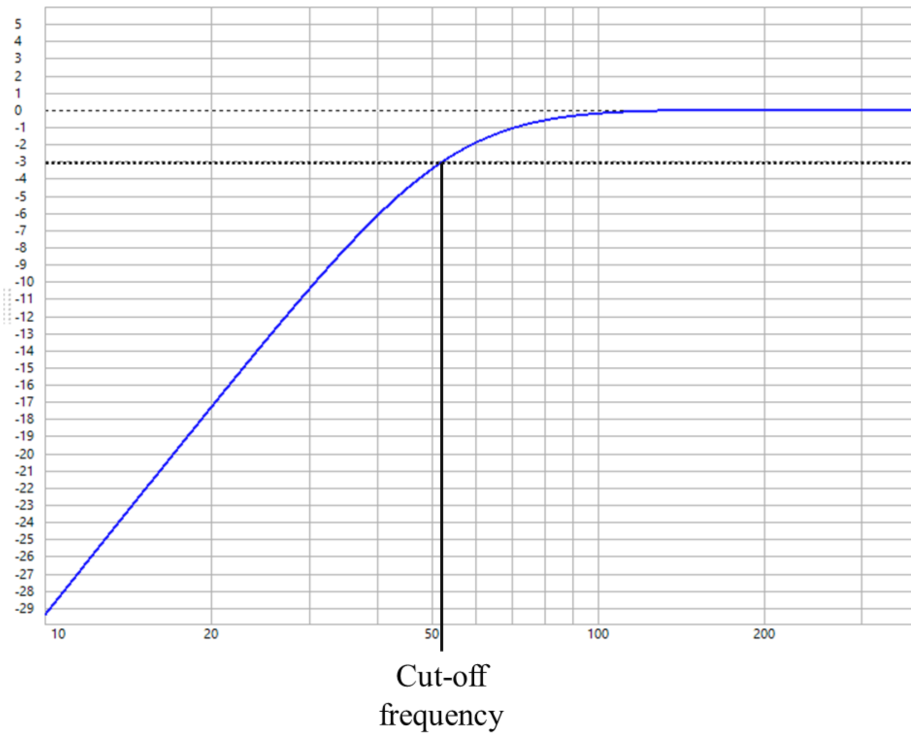

Figure 6: Cut-off frequency of a FR

After adjusting the enclosure parameters to match a desired alignment, the designer must consider the vent dimensions. A larger port area generally produces a more linear FR; however, a large port area requires long vent length, which can cause resonance distortion and be difficult to incorporate in the enclosure design without making it awkwardly large (Dickason, 2006, pp. 61, 69-73).

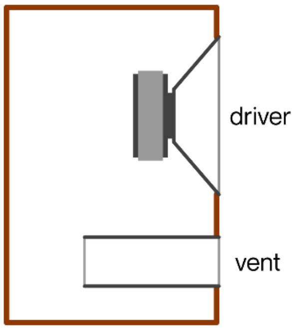

Figure 7: Vented speaker box

2.2.3 **Enclosure with passive radiator**

A third type of loudspeaker design is one using a PR. A PR is essentially a driver unit without a motor system, thus a diaphragm connected to a suspension system. In its simplest form, this is just a rigid plate surrounded by a suspension. Two types of PRs are presented in Figure 8. PRs have the same functionality as ports since they also enhance the FR at low frequencies, due its resonant frequency lying in the bass region. The main reason for using a PR instead of a port is that it occupies less space making the overall loudspeaker more compact and has the added benefit of keeping the enclosure sealed, making a waterproof solution possible such as with the UE Hyperboom Bluetooth speaker (Ultimate Ears, n.d.). However, PRs are usually more expensive than ports and have a slightly higher cut-off frequency than vented enclosures, meaning that they cannot produce as low frequency sounds (Tanasescu, 2020b) discussed in (Section 5, Video 19).

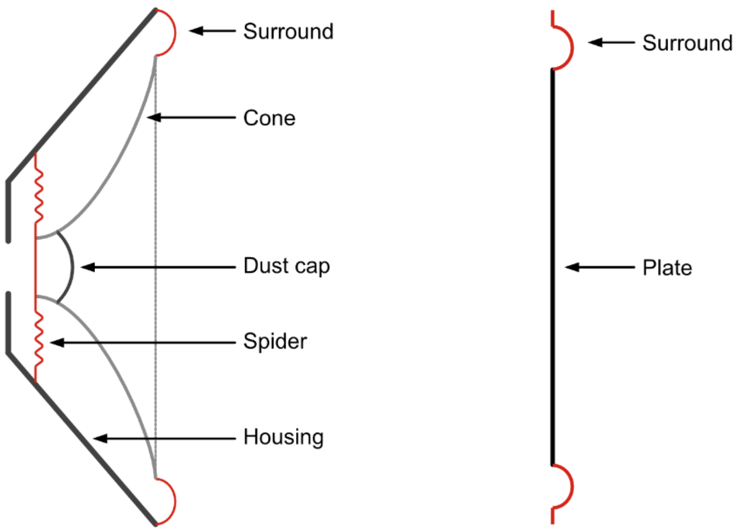

Figure 8: Passive radiator types

A loudspeaker incorporating a PR can be designed following the same procedure as for designing a vented enclosure. In addition to the Theile/Small parameters for drivers in section 2.2.1, the following Theile/Small parameters for PRs should be obtained:

- f_p – Free air resonant frequency of the PR
- S_{dp} – Area of the PR
- V_{ap} – Acoustic compliance volume: volume of air with equivalent acoustic compliance of the PR
- Q_{mp} – Mechanical quality factor of the PR.

(Small, 1974)

The maximum linear extrusion of the PR, x_{maxp}, is also considered a relevant parameter to be obtained, likewise as for a speaker driver.

These parameters are almost identical to the Thiele/Small parameters for speaker drivers minus the electrical parameters as PRs do not have any electrical components.

The tuning of a passive radiator enclosure is regulated by adding and subtracting weight to the PR and the size of the PR's area, rather than for a vented enclosure where adjusting the length and area of the port are the tuning factors (Dickason, 2006, p. 88).

The resonant frequency, f_p, and the quality factor, Q_{mp}, are not parameters which are included in the suggested guide in *Loudspeaker Design Cookbook* by Dickason

(2006). However, since they are parameters which are needed to accurately simulate the FR of a PR incorporating loudspeaker they were included in this project.

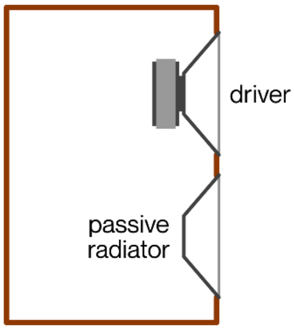

Figure 9: Speaker box with PR

2.2.4 **Frequency response comparison**

In Figure 10 the FR of typical examples of a sealed enclosure, a vented enclosure and an enclosure with a PR are represented in the same chart. An interesting characteristic of a PR incorporating loudspeaker is its dip in FR which can be observed between 30-40 Hz in Figure 10. This happens at the resonance frequency of the PR and is due to the PR being 180 degrees out of phase in relation to the driver (Small, 1974, pp. 592-601). This is however not an audible characteristic, as the difference in sound pressure level is too great. Generally, a 10 dB difference is perceived as a doubling in loudness, and a 3 dB difference is an easily perceived difference in loudness (Toole, 2018, p. 61), which is why the cut-off frequency is an important factor.

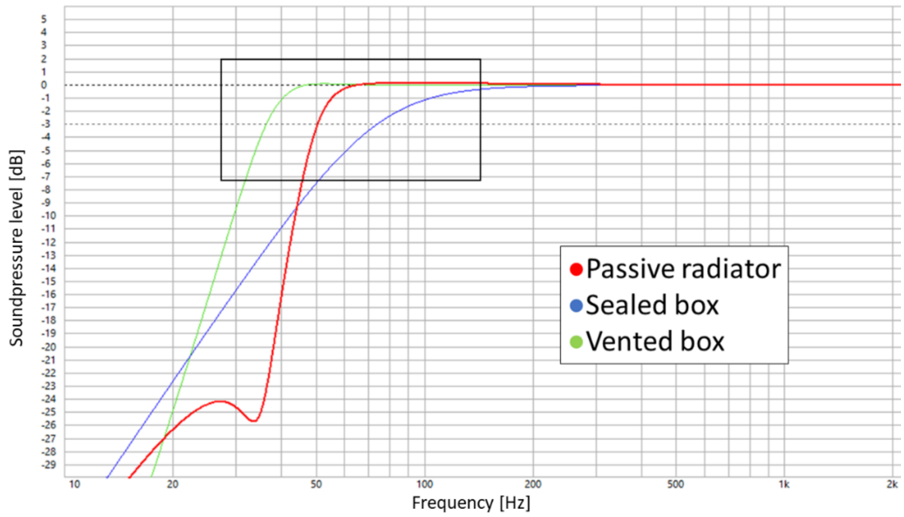

Figure 10: Typical frequency responses of loudspeaker designs. The rectangle highlights the area where bass amplification occurs

2.2.5 **Electromechanoacoustical circuit analogy**

Loudspeakers include electrical, mechanical, and acoustical phenomena. Traditionally vibrations, and henceforth soundwaves, have been represented with the setup of differential equations. However, this did not give a clear overview of the complete system. In 1954 Beranek introduced a schematic representation of the loudspeaker by using an electromechanoacoustical circuit analogy (Beranek & Mellow, 2019, pp. 81-82) and (Small, 1972b) which unifies the mechanical, acoustical and electrical systems into an equivalent electrical circuit. This has the benefit of simplifying three different systems which are based on different physical phenomena into one but relies on linearisations of complex equations which do not always reflect the actual state of a loudspeaker system.

2.2.6 **Computer Simulation Program**

Nowadays there are computer simulation programs that can calculate and display the FR from the Thiele/Small parameters and additional parameters regarding a passive radiator or a port. However, these programs are based on the electromechanoacoustical analogy (Liljencrants & Granqvist, 2004, pp. 9-28). The simulation programs used in this project are WinISD and VituixCAD.

2.2.7 **Measuring the Thiele/Small parameters of driver**

Driver manufacturers normally provide the Thiele/Small parameters. However, if they are not available or if they need to be verified, there are measurements that can be done to acquire these parameters. In the book *Acoustics: Sound Fields, Transducers and Vibration* by Beranek and Mellow (2019) there is a detailed description of a procedure of how to take these measurements.

2.3 Sound perception

What defines good sound quality? This question has been asked by many audio experts throughout the years, and there are still various opinions regarding this matter. Since the early development of loudspeakers, researchers and innovators have been trying to describe sound perception in terms of charts and engineered models (Toole, 2018, pp. 107-110).

Sound is a three-dimensional phenomenon, meaning that it propagates in all angles of a room. Therefore, the perceived sound is affected by the room and the reflections created by the surroundings as well as the loudspeaker and the individual listener. These complex characteristics makes it impossible to represent sound quality in one single chart (Toole, 2018, p. 111).

However, most experts nowadays can agree that there are certain measurements made on loudspeakers which strongly corresponds to the perceived sound quality. The most impactful factor is the FR. People tend to prefer speakers that generate a flat FR and even dispersion (Toole, 2018, pp. 25, 61).

In this report the main focus lies on the measured audio values, while the perceived sound quality is of little importance. Although desired FRs may have been reached during the tests of prototypes made in this project, there is no guarantee that these are well performing in the perceived senses.

2.4 Discussion

Through the research it became evident that sound and loudspeakers are complex concepts, meaning that the learning curve of understanding and connecting ingoing characteristics was very steep. Although, more research could have been conducted to reach even further comprehension of the topic it was decided to move on to the Define phase in order to investigate the phenomena through a more practical and explorational point of angle.

Some key take aways from the Discover phase follow below:

- Amongst loudspeaker engineers there is a rather unified perception of which parameters impact the FR and a vast majority of works refer to the Thiele/Small parameters as crucial.
- The electromechanoacoustical circuit analogy from which the Thiele/Small parameters are derived is based on simplifications and do not completely accurately reflect reality but are nonetheless the best way of representing loudspeaker systems.
- Factors other than the Thiele/Small parameters are barely if ever mentioned, e.g. material, shape, mass, construction.
- Due to the complexity of analysing sound quality as a whole, it was determined to limit the focus to examine the bass output primarily through FR charts which can be analysed quantitatively.
- The individual impact of each Thiele/Small parameter and their internal significance were not mentioned.
- There are limited in-detail publications of how to conduct measurements to determine the Thiele/Small parameter values for passive radiators.

3 Define

After reaching a better understanding of how loudspeakers and specifically PRs work, the next step would be to decide which parameters to investigate and how these should be investigated. The goal of this step was to measure the parameter values for different PRs to be able to evaluate their individual impact on frequency response. It was discovered that measuring these parameters was not as simple as initially thought, and that methods for measuring these had to be developed from existing standards. This chapter describes the process of developing these measurement methods by adapting the standards, and the results of the measurements.

3.1 Parameter selection

Due to the limited amount of Thiele/Small PR parameters affecting bass output presented in section 2.2.3 and not knowing their individual impact on frequency response, a decision was made to investigate all the Thiele/Small parameters as well as x_{maxp}:

- f_p – Free air resonant frequency of the PR
- S_{dp} – Area of the PR
- x_{maxp} – Maximum linear extrusion of the PR
- V_{ap} – Acoustic compliance volume: volume of air with equivalent acoustic compliance of the PR
- Q_{mp} – Mechanical quality factor of the PR

Other factors such as material choice, shape, and attachment method were not explored at this stage due to the limitation of using a set of bought passive radiators, not allowing these factors to be uniquely controlled. For instance, two different PR might have different materials, shapes, and attachment methods making it difficult to see how changing only one of these factors affect sound. Additionally, in contrast to the chosen parameters, these factors are not always able to be characterised by a numerical value, e.g. shape, adding additional complexity to the project.

3.2 Method for determining the measurement methods

From the Discover phase, suggestions on how to measure the selected PR parameters were encountered, e.g. Dickason proposed methods which are further explained and used in section 3.3. However, many suggestions were discovered to be rather fragmented and difficult to interpret, and no in-detail guide was provided of how to explicitly conduct all the steps when measuring all the parameters. Because of this, a process which combined adaptation and interpretation of published measurement methods with own iterative explorations was initiated. Further explanations regarding the specific adaptions, interpretations and own explorations are discussed in sections 3.4-3.5.

The resulting measurement methods are initially presented in section 3.4 whereas the process of reaching those methods is discussed in section 3.5.

3.3 Investigation of existing passive radiators

Before the start of this project, the company was already in possession of a few PRs, two models of which had technical specifications listed such as their Thiele/Small parameters. For the sake of this step in the project, more PRs were purchased and it was decided to buy many cheaper PRs that did not have any data sheets rather than fewer more expensive ones, mainly due to a few reasons. Firstly, having more PRs with a wider range of parameter values would mean that the future analysis of individual parameter impact on FR would contain less uncertainty. Secondly, the type of PR which comes with a data sheet is almost exclusively a cone shaped one rather than a flat one, as illustrated in Figure 8, which may be too big and expensive for the type of products the company would like to offer in the future. Thirdly and lastly, due to the long delivery time, the extra PRs were purchased quite early in the project during the Discover phase at which point it was unknown that determining the parameter values would be so complex and not straightforward.

To begin the investigation of existing PRs, a PR with known parameter values provided from the manufacturer was used. Tests, further described in section 3.4, were then conducted on the PR and the values from the test results were compared with the provided data sheet. After verifying the results, the test methods were used for measuring and determining parameter values for PRs without provided data sheet.

Figure 11: Purchased PRs and their labels

The free air resonant frequency, f_p, is derived by exciting the PR through playing a frequency sweep from a driver and simultaneously measure the amplitude of the PR's excursion.

The area, S_{dp}, is the addition of the cone/plate area and a third of the suspension area. For the most general form, a circular PR, the area is calculated using the following equation:

$$S_{dp} = \frac{\pi \times D^2}{4}$$

Where D is the total PR diameter, which is the diameter of the cone/plate and one third of the suspension at both ends (Dickason, 2006, p. 37). The IEC (2020) defines the effective area S_{dp} as the area of the cone/plate and half of the suspension area. This project used Dickason's definition. D was calculated by measuring the outer suspension dimension, D_o, and the inner suspension dimension, D_i, through the following equation:

$$D = \frac{D_o - D_i}{3} + D_i$$

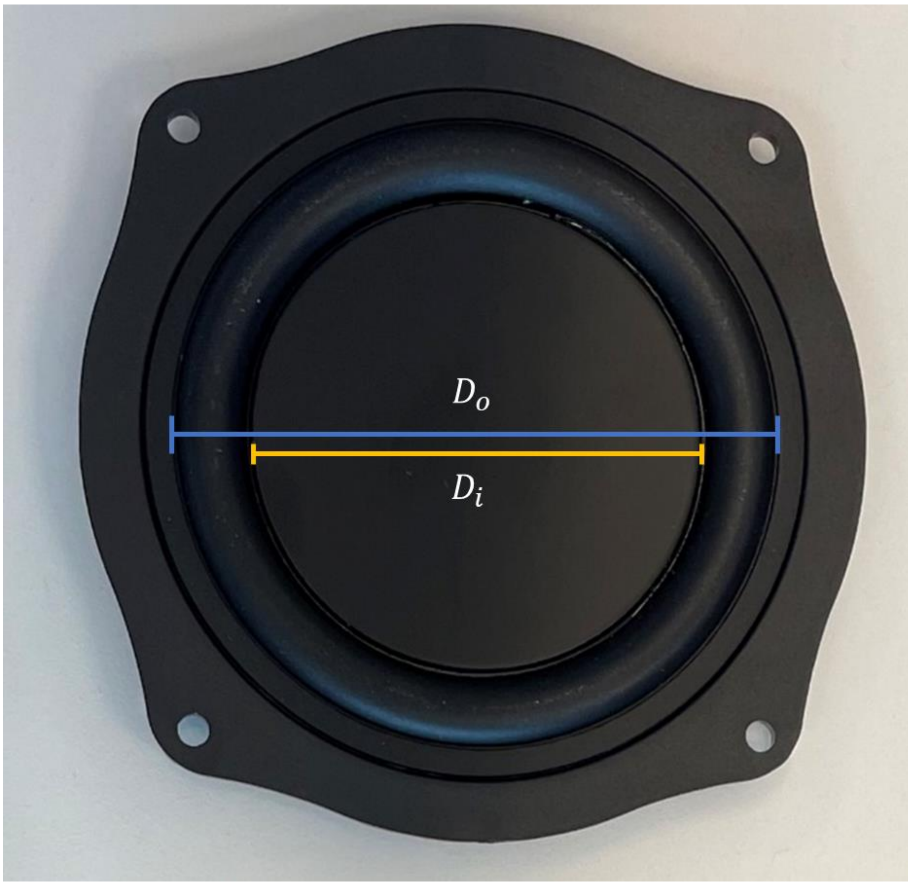

Figure 12: Measurements made on PR to calculate S_{dp}

The maximal linear extrusion, x_{maxp}, is measured by exposing the PR to excessively greater force while measuring its extrusion.

V_{ap}, the volume of air with equivalent acoustic compliance to the PR, is calculated according to the following equation (Dickason, 2006, p. 87):

$$V_{ap} = C_{ap} \times 1.42 \times 10^5$$

where C_{ap} is the acoustic compliance of the passive radiator, which can be calculated according to the following equation (Dickason, 2006, p. 87):

$$C_{ap} = C_{mp} \times S_{dp}^2$$

where S_{dp} is the area of the PR, and C_{mp} is the mechanical compliance of the PR. The mechanical compliance is defined as the displacement for a given force acting upon the PR.

The mechanical quality factor of the PR, Q_{mp}, is slightly more complicated to calculate, and there are different means of deriving an answer. Two separate methods are suggested by Dickason (2006, pp. 204-205), however one is incomplete and the other one is based on measuring the internal voice coil resistance of a transducer which is not possible for a PR. In the International Electrotechnical Commission's (IEC) standard *IEC 62459 Sound system equipment – Electroacoustical transducers – Measurement of suspension parts* (IEC 62459 standard) (2010), the following equation for calculating Q_{mp} is provided:

$$Q_{mp} = H_{peak}(f)$$

Where H(f) is the transfer function measured in dB, normalised around f_{dc}, defined as:

$$H(f) = \frac{X(f)}{F(f)}$$

Where X, F and f are extrusion, force, and frequency respectively. This standard was written with drivers in mind, which makes f_{dc} unachievable since the PR is driven by sound waves and not electric signals. Instead, H(f_{dc}) was interpreted as the minimum value of the transfer function below the resonant frequency. The quality factor can then be written as:

$$Q_{mp} = \frac{H_{peak}(f)}{H_{min}(f < f_{pr})}$$

3.4 Methods for measuring passive radiator parameters

The complete guide for measuring PR parameters is presented in Appendix B and will be referred to as "*the measurement guide*". This subchapter explains how the guide was practically implemented, i.e., what setup was used.

The methods have been developed using the IEC 62459 standard as a foundation. Although the standard provides mathematical derivations and general suggestions of how to measure and calculate the different parameters, there were no explicit description of what specific tools and steps to use and take when setting up the measurement rigs. This section presents the devices and the ultimate methods used for performing the parameter measurements, as well as describes to what extent the standard has been adapted and interpreted in each parameter measurement method.

3.4.1 **Components needed for measuring passive radiator parameters**

3.4.1.1 Modular subwoofer

The IEC standard only requires "*means for exciting the suspension part by the stimulus (for example, a loudspeaker mounted in a sufficiently large test box for acoustical excitation…*" but provides no details about any practical implementation.

At the time of beginning this project, two audio engineers at the company had constructed a modular loudspeaker with a Dayton Audio RSS315HFA-8 driver and an interchangeable panel on the backside. On a given panel a certain passive radiator could be mounted. This allowed for a flexible and effective procedure of incorporating different PRs in the subwoofer while keeping the driver and remaining loudspeaker parameters constant. The loudspeaker incorporated internal braces and had certain dimensions, following the "golden ratio" recommendations introduced by Small, which help to minimize standing waves (Dickason, 2006, p. 113). It also had a built-in connector for use of an internal microphone.

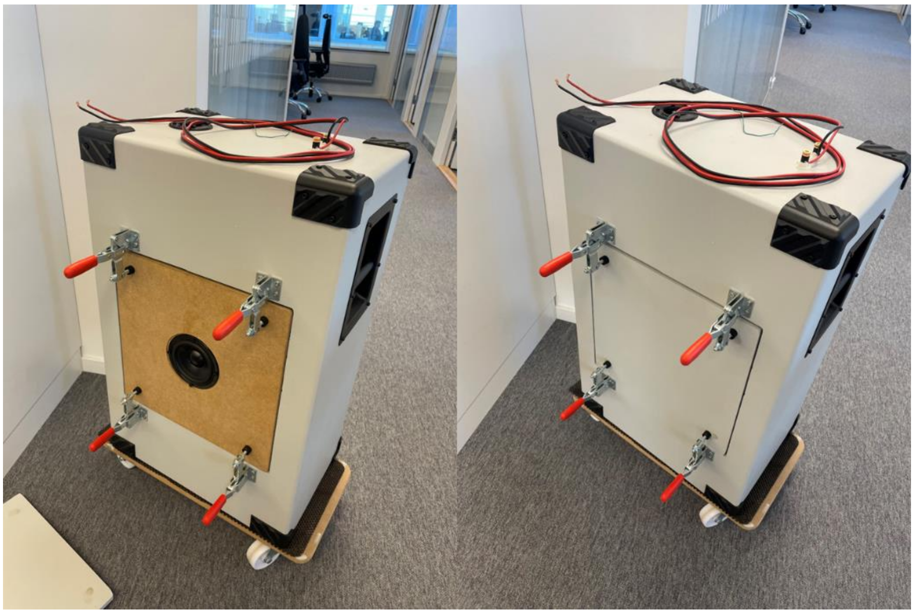

Figure 13: Backside of the modular subwoofer with two different panels attached

Figure 14: Frontside of the modular subwoofer

3.4.1.2 Laser measuring device

The IEC 62459 standard requires a way to measure the extrusion of the suspension part.

In this project, a MicroEpsilon optoNCDT 2300 laser sensor mounted to an aluminium frame was used to measure the excursion of the PRs over time and the data was recorded with the sensor's associated software.

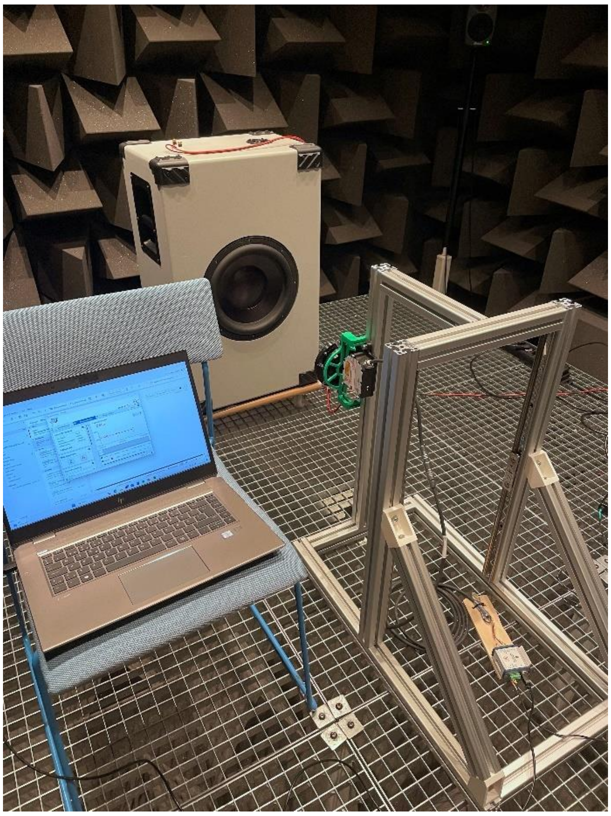

Figure 15: Typical setup in the anechoic chamber

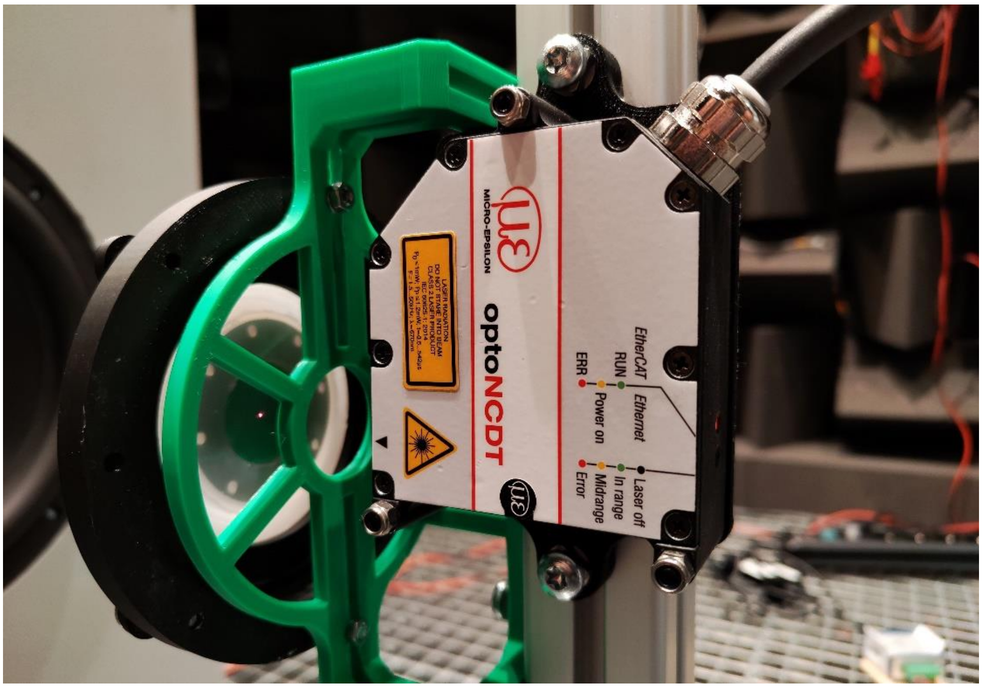

Figure 16: MicroEpsilon laser and PR mount attached to the frame

3.4.1.3 Passive radiator mounts

The same frame which the laser sensor was mounted onto was also used to mount the PRs to minimise the effects of vibration on the results. Figure 15 and Figure 16 show the frame with the laser sensor and a PR mounted.

Since the PRs varied in shape and size, many different mounts were designed and 3D printed, to enable attachment onto the aluminium frame. Some of these PRs (PR3-PR10) did not have any frame to which their suspension was attached, so they were attached to 3D-printed frames with Blu Tack.

Figure 17: Some of the 3D printed PR mounts.

3.4.1.4 Audio software and hardware

Installed in the anechoic chamber at the company is a computer, connected amplifier, and a few other peripherals related to sound reproduction and recording, together with Audio Precision software which is used to generate, record, and analyse audio. For the tests conducted in this project, logarithmic frequency sweeps and fixed frequencies with varying power were mainly used, similar to other tests conducted at the company.

MicroEpsilon provides software to record data from the laser.

3.4.1.5 Python Script

The output files from the laser and the Audio Precision software are in the .CSV file format which can be analysed using custom Python scripts.

3.4.2 **Free air resonant frequency of passive radiator**

The IEC presents a method for measuring the resonant frequency of the PR in the IEC 62459 standard (2010). In short, the method involves a set-up where the PR is attached 10 cm from a speaker driver. The driver runs a frequency sweep that excites the PR, and the amplitude of the PR's oscillations, measured at its centre, is measured over time.

To practically implement this set-up the writers of the report made use of the laser measuring device, referred to in section 3.4.1.2, attached to an aluminium frame which was available at the company. A custom PR mount was also attached to the PR in front of the laser. This rig allowed for amplitude measurements of the oscillations of a PR.

In this case the standard was not adapted, but only practically implemented by using available resources at the company.

The standard does not particularly explain how to attach the PRs to a stable rig, so there could be other options than using 3D-printed mounts and an aluminium frame. It is possible that the choices regarding the set-up can influence the result.

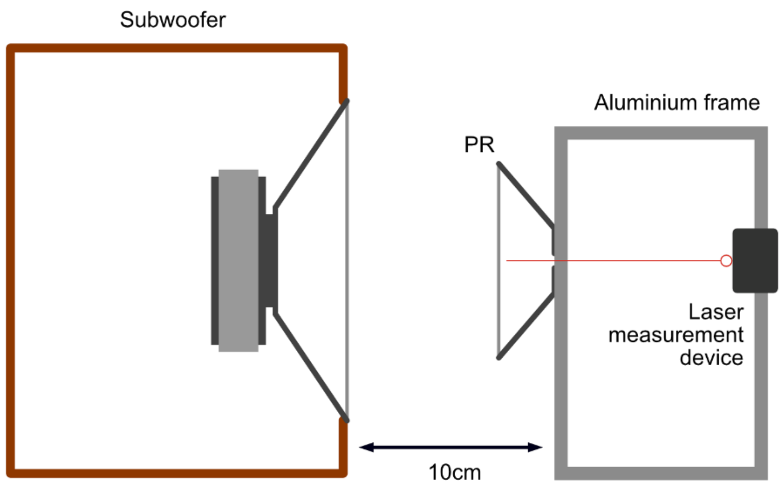

Figure 18: Free air resonance frequency measurement setup

3.4.3 **Compliance**

The IEC 62459 standard (2010) also presents a method for measuring dynamic stiffness. Since compliance is the inverse of stiffness (Klippel, 2007), this same method was applied for the PRs.

The project's practical implementation of this method consists of attaching a PR to a subwoofer and exciting it through playing a short frequency sweep with varying power while measuring the extrusion amplitude with a laser device and the sound pressure level inside the subwoofer with a microphone.

The IEC 62459 standard suggest using a metal rod to guide the oscillations of the suspension part; however the standard assumes that the suspension part has no cone and dust cap/plate. This is problematic as it would require making a hole in the PR to fully follow suggested step in the standard. Therefore, the set-up used in this project did not include a guiding rod.

The standard does not explicitly specify whether a laser measuring device and a microphone inside the enclosure should be used to measure the amplitude of the

PRs oscillations and measure the sound pressure respectively. An interpretation of the standard was necessary in order to practically perform the measurements, but it is however possible that the use of other tools and measurement devices would have resulted in a different set-up and different results. For example, an alternative way of deriving the force acting upon the PR (which can be calculated from the sound pressure inside the enclosure) would be to measure the acceleration of the PRs oscillations and weigh its moving mass, and by extension use the following equation:

$$F = ma$$

However, this method involves complexities of determining the moving mass and the acceleration in an accurate way.

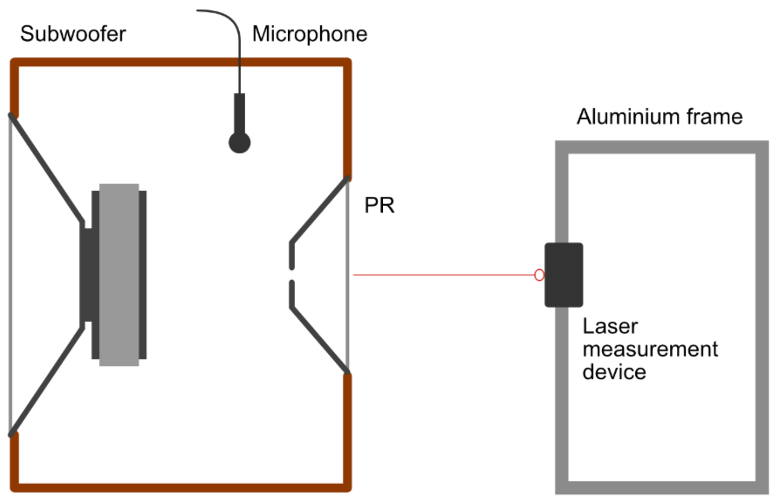

Figure 19: Compliance measurement setup

3.4.4 **Quality Factor**

The IEC 62459 standard (2010) provides a method to derive Q_{mp} using the same setup and test procedure as when measuring C_{mp}. As such, the adaptation and practical implementation is identical as when measuring C_{mp}, described in section 3.4.3.

The standard makes use of the magnitude in a transfer function for low frequencies to calculate the value of Q_{mp}. There is no specified information on what is meant by low frequencies and how to derive this magnitude. The project involved several exploring measurements and scripts to reach, what is assumed to be, reasonable results for this magnitude, discussed further in section 3.5.3.

3.4.5 **Maximum extrusion**

The IEC 62459 standard only mentions maximum extrusion briefly but provides no details on how to measure it. In this project, the maximum linear extrusion was measured in two different ways, one acoustically and one mechanically.

For the acoustic measurement the setup, test procedure, and practical implementation was identical as for measuring C_{mp}, described in section 3.4.3, except that no microphone was needed inside the subwoofer. The maximum extrusion could then be determined by when the peak amplitude no longer linearly correlated with the force applied to the PR.

The mechanical measurement was conducted using an adapted version of measuring the static displacement of a suspension part in the IEC 62459 standard which uses a hanging mass. Because of the difficulties of attaching relatively large masses to the PRs in this project, a static compression machine of the model ZwickRoell ProLine Z005 which was available at the company was used. The machine has a probe which pushes the PR with a constant speed while measuring force and distance. The force was increased in small steps until a predetermined limit which was based on the acoustic measurements.

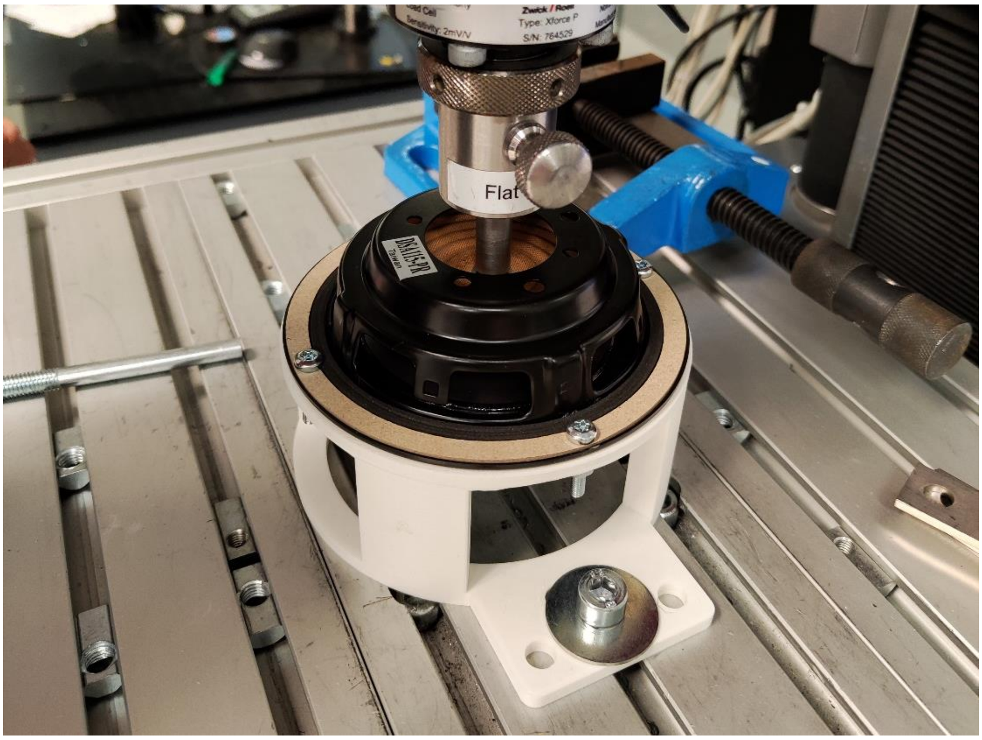

Figure 20: ZwickRoell probe

3.4.6 **Verification of measurement methods**

To ensure that the measurement methods were valid it was decided to perform a set of verifications to evaluate the measurement methods' possible sources of error. These means of verification were entirely developed by the writers of this report in collaboration with audio engineers at the company. Due to limited time, resources, and knowledge it was impossible to evaluate all potential sources of error through verifications.

3.4.6.1 Free air resonant frequency

Initially, tests were conducted on a PR with a provided data sheet from the manufacturer as a way of comparing measured and specified values to ensure that a reliable test method had been achieved. Specifically, the DSA115-PR from Dayton Audio was investigated using the test setup mentioned in the preceding section. As can be seen in Table 3 the specified and measured values vary quite significantly.

Since the laser measured no noise when the PR was not stimulated or other vibrations caused by the room or aluminium frame, the reason for this variance could be caused by errors in the script analysing the raw data or by a manufacturing error. In order to evaluate the script, a new .CSV file was manually generated consisting of a mathematically calculated sine wave at 40Hz with a time interval identical to the measuring rate of the laser and fed into the Python script.

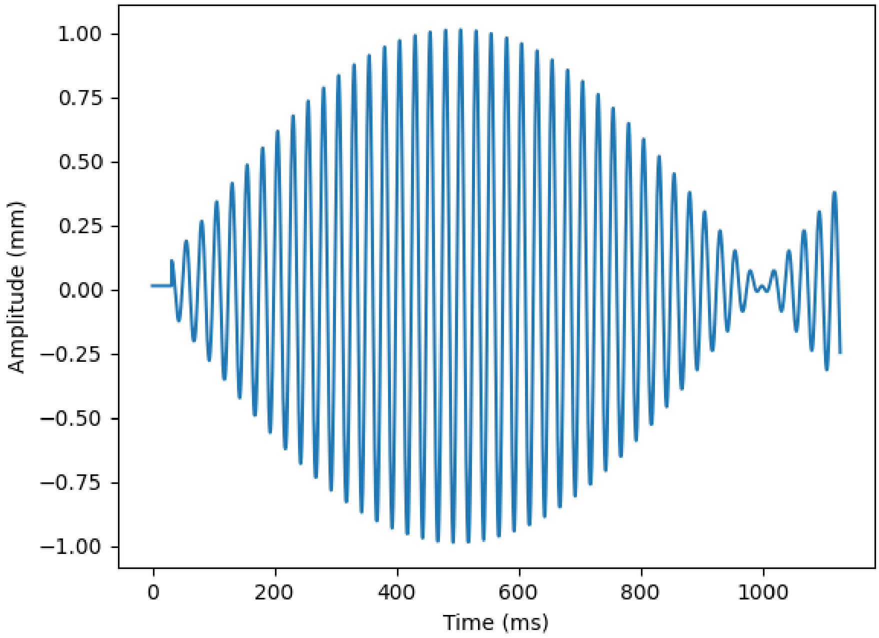

Figure 21: Generated 40 Hz wave pattern

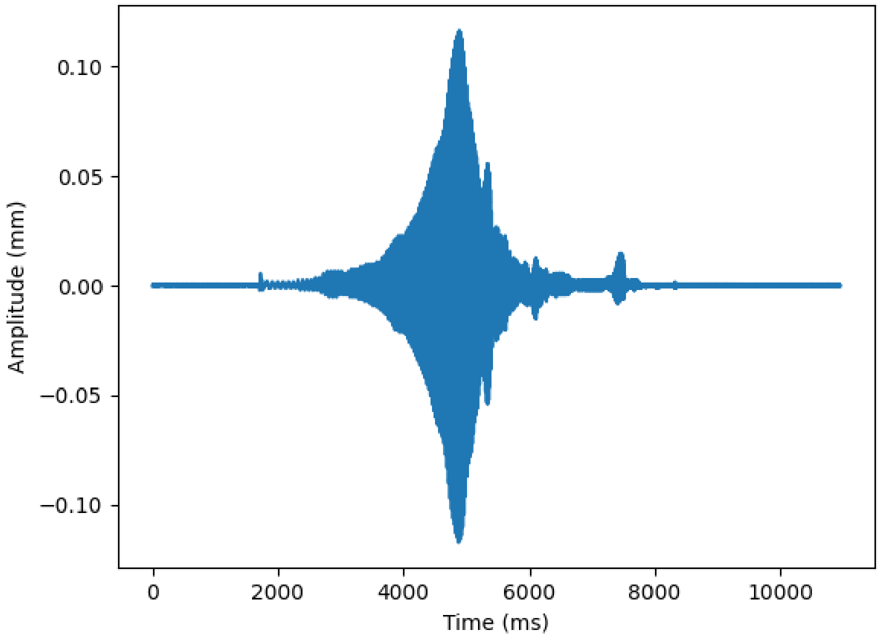

Figure 22: Oscillations of a PR (DSA115) suspended in free air excited by a frequency sweep

Table 1: Calculated free air resonance frequency

	Generated 40 Hz wave pattern	*DSA115 suspended in free air*
Calculated free air resonance frequency	39,37 Hz	43,65 Hz

Figure 21 and Figure 22 show the output plots of the Python script and Table 1 the measured resonance frequencies. As the script yielded a result very close to the true value for the generated wave pattern, it could be seen as accurate and valid. However, just to be certain, a second test was conducted with a loudspeaker driver which was attached to the aluminium frame, passively excited, and measured with the laser. The same speaker driver then underwent an impedance test using a frequency sweep, conducted with a Dayton Audio's DATS V3 impedance measurement device and software, which is another way of determining the resonance frequency (Dickason, 2006, p. 196). These results could then be compared with the provided data sheet for the speaker driver. Since the results, presented in Table 2, were nearly identical and within the manufacturer specification, the script was considered as accurate and valid.

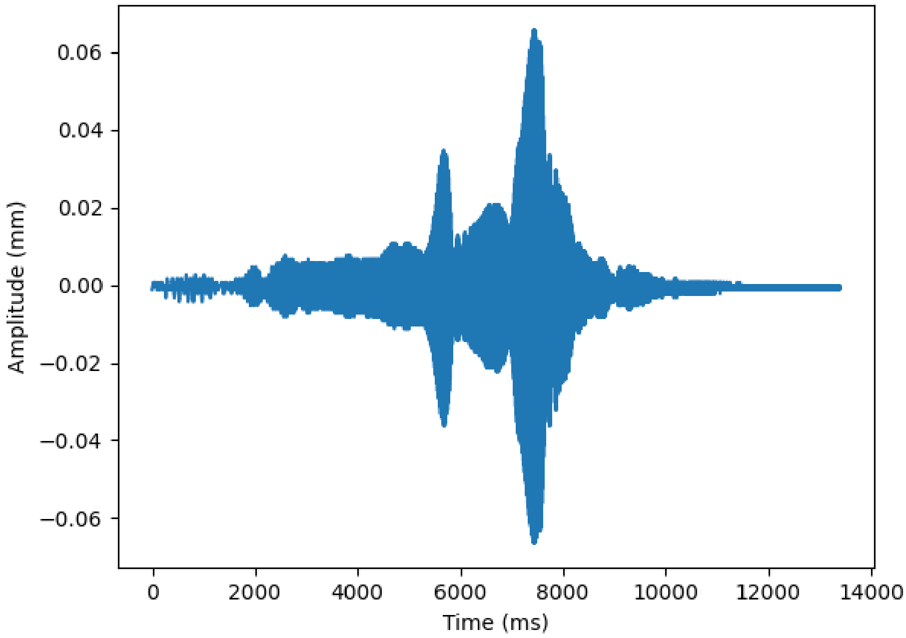

Figure 23: Free air resonance measurement of 4 inch speaker driver

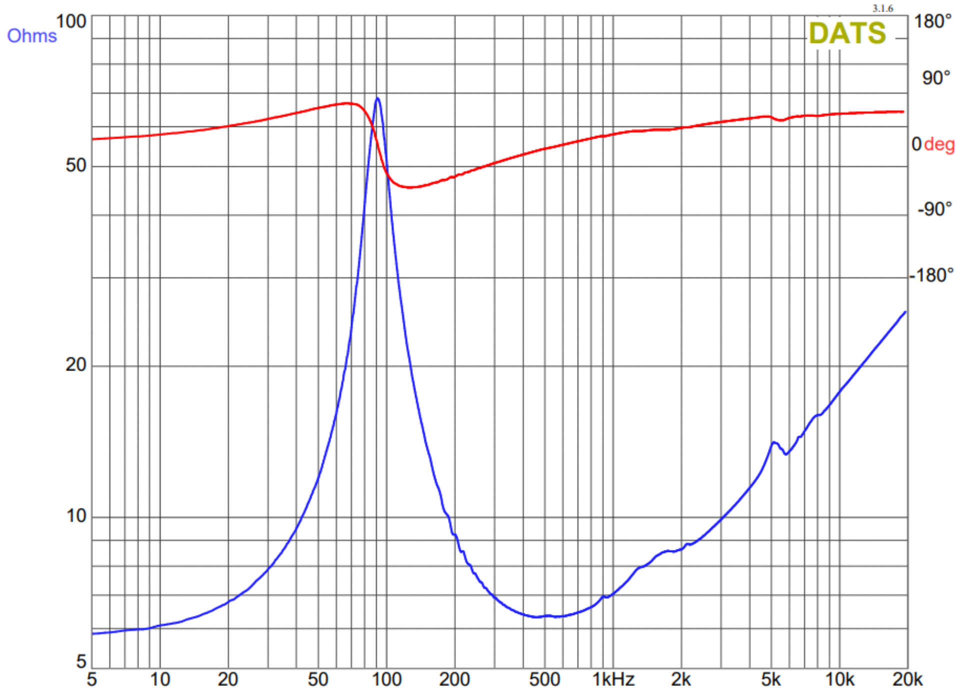

Figure 24: DATS impedance test of 4 inch speaker driver

Table 2: Free air resonance values of 4-inch speaker driver

Source	***Resonance frequency (Hz)***
Free air passive measurement	91,66
DATS impedance test	91,52
Data sheet	90 +/- 20%

3.4.6.2 Compliance

An additional measure to check whether the measured results are reliable was to conduct a static compression test method equal to the one mentioned in section 3.4.5. However, as static compression and dynamic oscillation are not equivalent due to resonance, these values cannot directly be compared. Instead, it is more interesting to compare the shape of the graphs from each test.

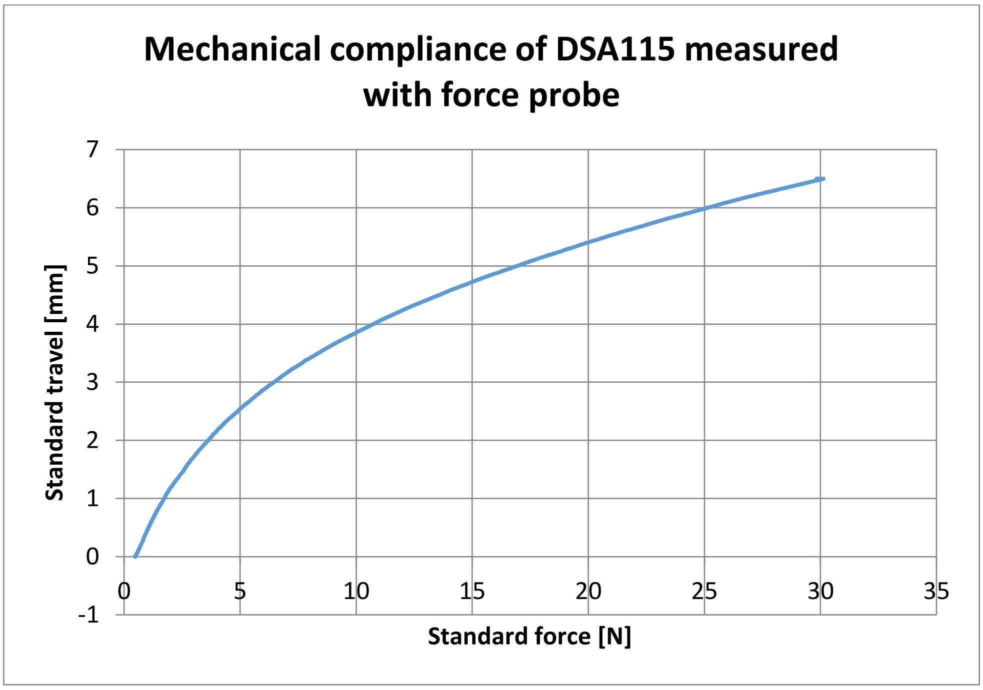

Figure 25: Mechanical compliance of PR DSA115 measured with a force probe

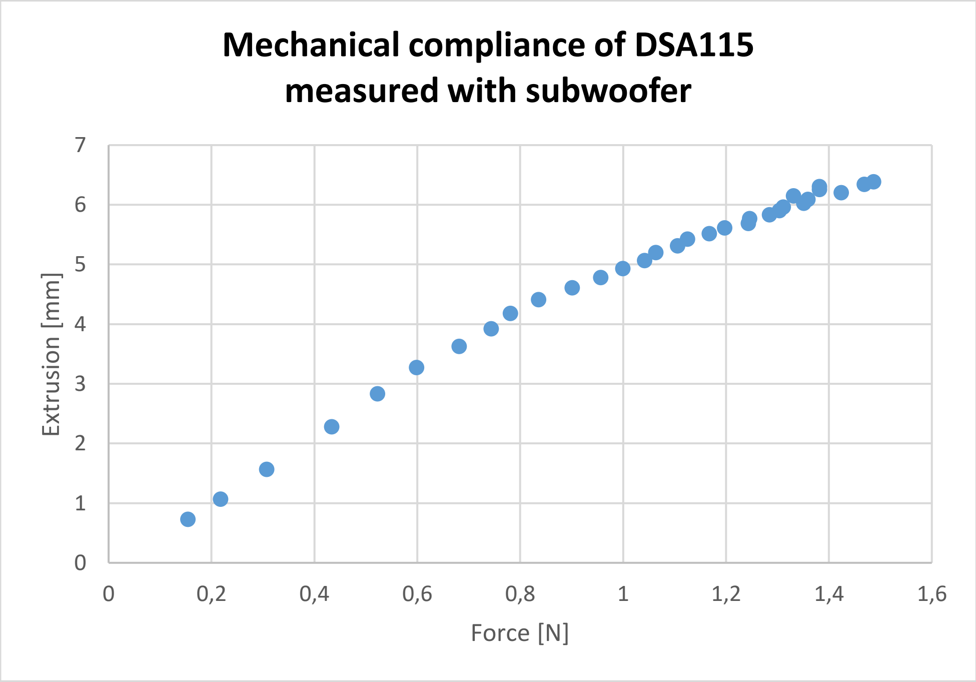

Figure 26: Mechanical compliance of PR DSA115 measured with a subwoofer

From the two graphs Figure 25 and Figure 26 it is apparent that the compliance is more linear in an oscillatory system than a static one. Since compliance is given as a single value in the data sheet and accepted as a single value in simulation programs, a more linear relation between extrusion and force makes it easier to find such a value. Using linear regression without intercept, i.e., specifying that the relation pierces the origin, the value in Table 3 can be calculated. Compliance comparisons of more PRs can be found in Appendix C. During the force probe compliance measurements, the PR's attached with Blu Tack experienced shearing which made them somewhat unreliable. While this could have been rectified, the results showed that the PRs behaved similarly in both static and dynamic extrusion which was the main purpose of these tests. As the static compliances differed significantly from the dynamic ones, using more reliable clamping methods would not have yielded any more valuable information for this project.

3.4.6.3 Quality factor

The measured value was compared to the one specified in the data sheet for both the DSA115-PR and the SD175-PR. As can be seen from Table 3 there is a variation between the values, however no further alternative test method of measuring the quality factor was investigated due to time limitations. The measured values presented in Table 3 are averages across different levels of power.

Only one other method of finding the quality factor was found and is further discussed in section 3.5.3.

3.4.6.4 Maximum extrusion

The extrusions measured are how far the PR extruded when excited in the subwoofer or by the compression machine. However, there were no indications that a maximum limit had been reached such as failure or a clear deviation from the expected behaviour, which is why the values are given as lower limits in Table 3.

3.4.7 **Python scripts**

The data collected involved immense amounts of measurement points, and the only reasonable way to handle and manipulate them was to use dedicated and automated scripts. Parallel to determining test methods, specifically those for measuring compliance and quality factor (discussed further in sections 3.5.2 and 3.5.3), several python scripts were created, developed, and improved in order to get the desired results. This step took a lot of time, not only due to the nature of programming and debugging, but also as every step and misstep taken in creating a reliable test procedure required revamping or creating a new script to make sense of the data.

3.4.8 **Parameter measurement results**

In following parts of the report there will be many comparisons between measured and manufacturer provided values. Below is a brief clarification of what is meant by the two terms.

- Measured values – The PR parameter values that have been measured in the audio lab.
- Provided/specified values – Values that the manufacturer provided with the PR in a data sheet.

For many of the measured parameters, it is difficult to assign a single fixed value as these vary, sometimes depending on power and sometimes just between measurements. In those cases, an average value has been calculated. The results from these tests are not very interesting by themselves, but for the PRs with data sheets they can be compared. For some parameters these values differ significantly. Further analysis is discussed in section 3.5.

Table 3: Measured parameter values for all PRs

PR	Q_{mp}	*C (mm/N)*	V_{ap} (m^3)	f_{pr} *(Hz)*	S_{dp} (m^2)	x_{max} *(mm)*
BIGA	1,30	0,84	0,047974	72,01	0,020023	>4,69
DSA115	3,05	4,38	0,018197	43,25	0,005085	>6,38
DSA115 + 10g	2,80	6,61	0,024257	31,84	0,005410	>6,80
DSA115 + 5g	3,08	6,86	0,025180	34,29	0,005410	>6,55
DSA115 Data sheet	3,48	2,27	0,0094	30,9	0,005410	>6
PR10A	2,68	6,22	0,011648	35,24	0,003632	>6,50
PR10B	2,99	7,00	0,013118	-	0,003632	>6,82
PR11B	2,42	1,58	0,014498	52,73	0,008031	>4,01
PR1A	3,26	6,98	0,007887	41,80	0,002821	>5,95
PR1C	3,29	7,01	0,007926	41,17	0,002821	>6,27
PR2A	2,26	3,16	0,008093	36,94	0,004244	>4,98
PR2B	2,20	2,85	0,007285	38,21	0,004244	>4,61
PR3A	3,69	8,06	0,003620	43,2	0,001778	>4,58
PR4A	3,02	4,02	0,002346	52,93	0,002028	>2,33
PR5A	2,71	4,24	0,001433	51,44	0,001543	>2,41
PR6A	3,06	7,51	0,001686	54,01	0,001257	>3,18
PR7A[a]	-	-	-	-	-	-
PR8A	2,67	11,91	0,000877	54,16	0,000720	>2,78
PR9A[a]	4,58	2,55	0,000286	85,22	0,000888	>0,90
SD175	3,65	2,27	0,053434	28,71	0,012242	>12,1
SD175 Data sheet	5,57	1,15	0,0271	24,5	0,01287	>8

Note: Letters A, B, C indicate specific sample of duplicate or triplicate
[a] PRs 7 and 9 had inconsistent values and were not included in the remainder of the project.

3.5 Discussion

3.5.1 **Free air resonant frequency**

The method for measuring free air resonant frequency, presented in section 3.4.1, could be conducted as planned and the noise level from the laser was negligible compared to the oscillations measured. There were some initial worries that the aluminium frame or the 3D printed attachment would resonate and affect the measured values when performing the sweeps, but after reviewing the results it was concluded that this influence was negligible.

The IEC 62459 standard did not provide any indication for with which power to drive the loudspeaker when exciting the PRs. To verify that power has no effect on the free air resonant frequency a PR was measured at different power levels, the results of which are presented in Figure 27. As can be seen, power has little to no effect on the free air resonance frequency.

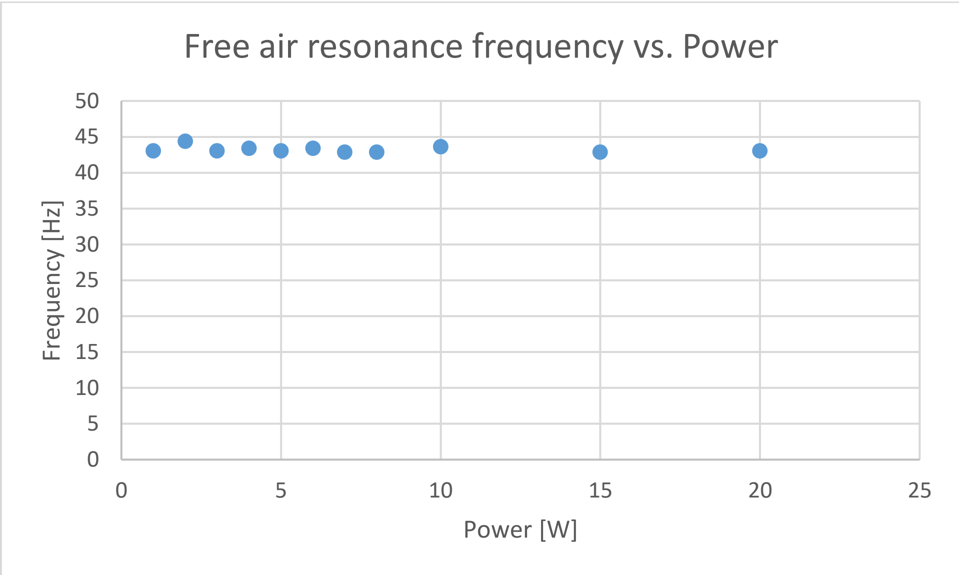

Figure 27: Free air resonance frequency vs. Power

3.5.2 **Acoustical compliance volume (V_{ap})**

3.5.2.1 Alternative compliance volume measurement method

Before conducting the compliance measurements according to the method described in section 3.4.3, another method was explored. The method is introduced by Dickason and calculates V_{ap} by the following equation (Dickason, 2006, p. 87):

$$V_{ap} \approx V_T\left(\left(\frac{f_c}{f_p}\right)^2 - 1\right)$$

where V_T, f_c, and f_p are the box volume, resonant frequency of the closed box, and resonant frequency of the PR in free air respectively.

The box resonant frequency of the closed box can be measured using the following equation (Beranek & Mellow, 2019, p. 368):

$$f_c = f_s\sqrt{1 + \frac{V_{as}}{V_b}}$$

where f_s, V_{as}, V_b are the speaker driver resonant frequency, equivalent acoustic volume of the speaker driver, and box volume respectively.

The resonant frequency of the closed box can also be determined by measuring the impedance of the driver when incorporated in the closed box. This was done with a Dayton Audio's DATS V3 in a similar manner as described in section 3.4.6.1, however with the difference that the driver was now integrated in a sealed enclosure. The resonant frequency of the enclosure is where the impedance curve has its peak (Small, 1972b).

After measuring the resonant frequency of the closed box, which in this case was a subwoofer intended to play low frequencies, and the free air resonant frequency of a couple of PRs, it was evident that the equation for calculating V_{ap} could not be used, since it yielded a negative answer. This was because the PR's had a higher resonance frequency than the closed box according to our measurements. One could theorise that as the purpose of a PR is to boost lower frequencies, and as the effective region of a PR in a loudspeaker lies above its resonant frequency as indicated by Figure 10, the equation "assumes" that f_c is greater than f_p. Though, as no audio expert at the company knew more or any material included in the discovery phase dives deeper into this problem, this method of finding V_{ap} was abandoned. Instead, the volume of air with equivalent acoustical compliance was calculated using measured mechanical compliance.

Another issue that was encountered when trying to find another method for measuring the equivalent acoustical volume through the mechanical compliance was that the IEC 62459 standard presents five different stiffnesses but makes no comment regarding which should be used. Three of them seem to rely on static stiffness which would not be relevant when the PR is implemented in a loudspeaker where it would experience dynamic forces. One of them relies on a mathematical calculation which could introduce consequential errors should other measurements have been done incorrectly. The stiffness, and by inversion compliance, chosen was selected as the one where measurements would be done inside a subwoofer box, i.e., the environment which most closely resembles what the PR would experience in a loudspeaker.

3.5.2.2 Frequency sweep

Initially when measuring the compliance, it was assumed that the resonant frequency of a PR attached to the subwoofer does not change when varying the power. The reason for this assumption was that the free air resonant frequency of the PR does not change when varying the power.

Therefore, a tone of a fixed frequency equalling the PR's free air resonant frequency was played at varying power to excite the PR. The results from these measurements were inconsistent and did not match the expected behaviour. Figure 28 show these preliminary results.

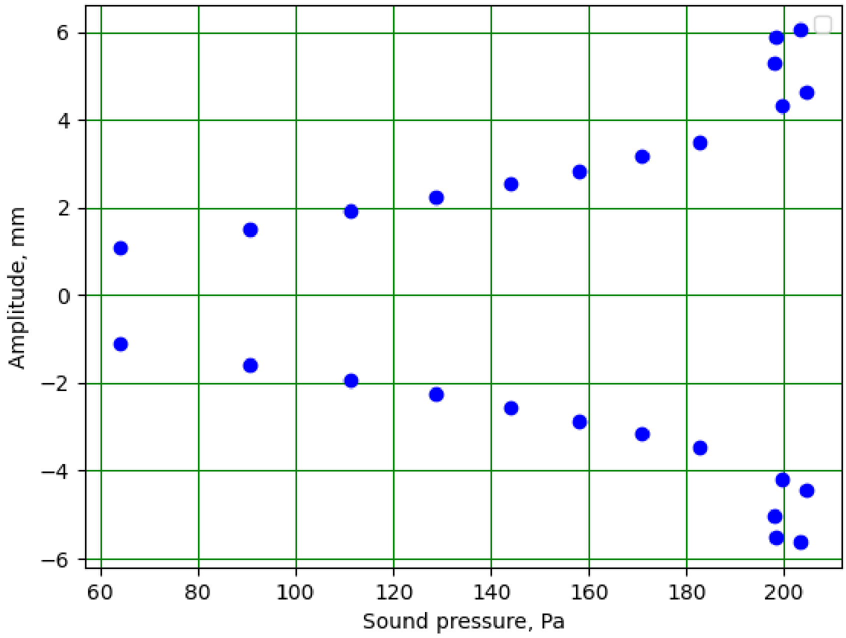

Figure 28: Bad compliance measurements

After lots of discussion with supervisors and audio experts, further understanding of the IEC 62459 standard (2010), as well as additional testing with slightly varying test methods, e.g. playing a "warm up" tone to break in the PR, it was discovered that the resonant frequency of the PR in a loudspeaker was not the same as when suspended in free air. Additionally, the same resonant frequency was discovered to be dependent on power which was not the case when the PR was suspended in free air. In actuality, the resonant frequency was lower when attached to the subwoofer than in free air, gradually increasing with power. This proved to be the cause of the inconsistency of the preliminary measurements, and the sudden increase in amplitude can be explained by the resonant frequency at that power being close enough to the frequency of the played tone. The problem was rectified by playing a narrow frequency sweep instead of a fixed tone.

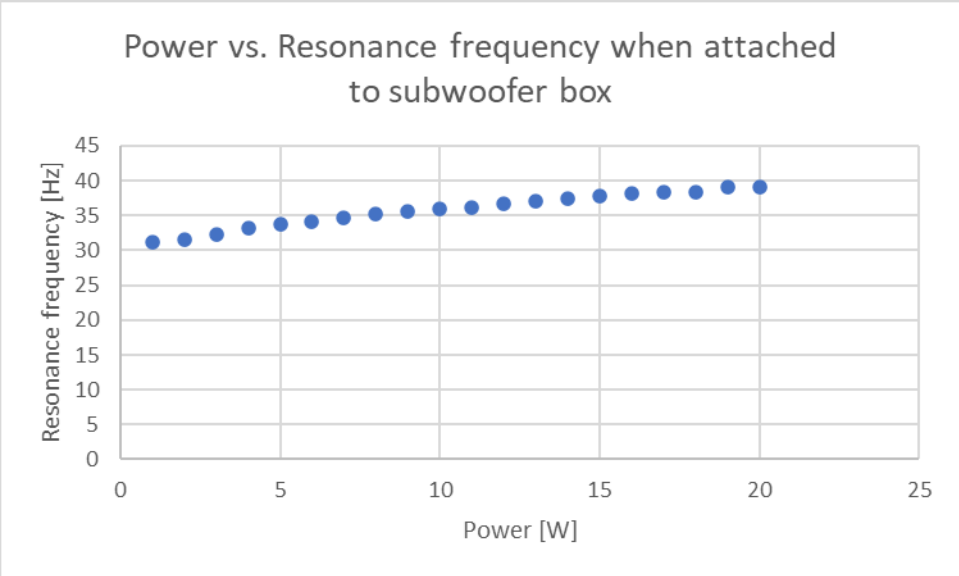

Figure 29: Power vs. resonance frequency when attached to subwoofer

Another potential source of error were the different modes of vibration of the PRs, e.g. the pill shaped PRs used in this project could run the risk of "wobbling". To check if this was the case, an oblong PR's oscillations were measured three times, in the middle and on each side with all other setting being identical. The results showed that any other mode of oscillation was negligible.

3.5.2.3 Compression machine

The test of measuring static compliance by using the compression machine, introduced in section 3.4.5, could be performed as planned.

3.5.3 **Quality Factor**

In the document *Parameter Measurement of Passive Radiators* provided by Klippel (2022) there is the following equation for calculating Q_{mp}:

$$Q_{mp} = \frac{f_p}{\Delta f_{3dB}}$$

Q_{mp} equals the resonant frequency divided by the frequency bandwidth of which the amplitude of the displacement is at least half of the peak amplitude i.e., Q_{mp} describes the pointiness of the resonant frequency displacement curve peak. The extrusion of the PR can be measured using the laser measuring device from section **Error! Reference source not found.**. This is called the bandwidth approximation (Green, 1955) and was the first method used in this project to calculate Q_{mp}.

After consideration and discussion with the company supervisors this method was abandoned in favour of the method described in section 3.4.4, which meant the quality factor would be calculated using the transfer function. Because it required the data for both extrusion and force, the PRs would be measured attached to the subwoofer instead of being suspended in free air and data from the microphone would be needed. At this stage, two problems were encountered. Firstly, the data from the microphone was given as sound pressure at time points and was not synced with the laser. This meant that converting sound pressure from a function of time to a function of frequency was a difficult and time-consuming task. Secondly, since the IEC method is designed for speaker drivers and not necessarily PRs, the transfer function is normalised around a DC signal which isn't possible for a PR. Instead, the lowest value of the transfer function for frequencies below the resonant frequency would be used as a normalising point. Due to limitations of the Audio Precision software used it was at first not possible to generate a signal under 10 Hz which meant the normalising point could not be determined. However, after some help reconfiguring the software to a specific mode, sound pressure data could be read as a function of frequency starting at 1 Hz which meant the calculated values of Q_{mp} were more accurate. Unfortunately, a lot of time had already been spent on this step and it was decided that the project as a whole had to move on instead of spending more time making sure the Python script and calculations were completely error free.

The provided data sheets do not include any information on how the manufacturer's measurements of the quality factor were conducted. Since comparing the measured and provided values is the only mean of verifying the test method, and these values differ significantly, it is hard to tell whether the measured values of the quality factor can be trusted.

Furthermore, the measured values varied slightly with power. An average of these were used to arrive at a fixed value.

Figure 30 shows the relevant graphs for a single measurement of a PR. While difficult to see, noise is a problem which makes finding an accurate value of the quality factor difficult.

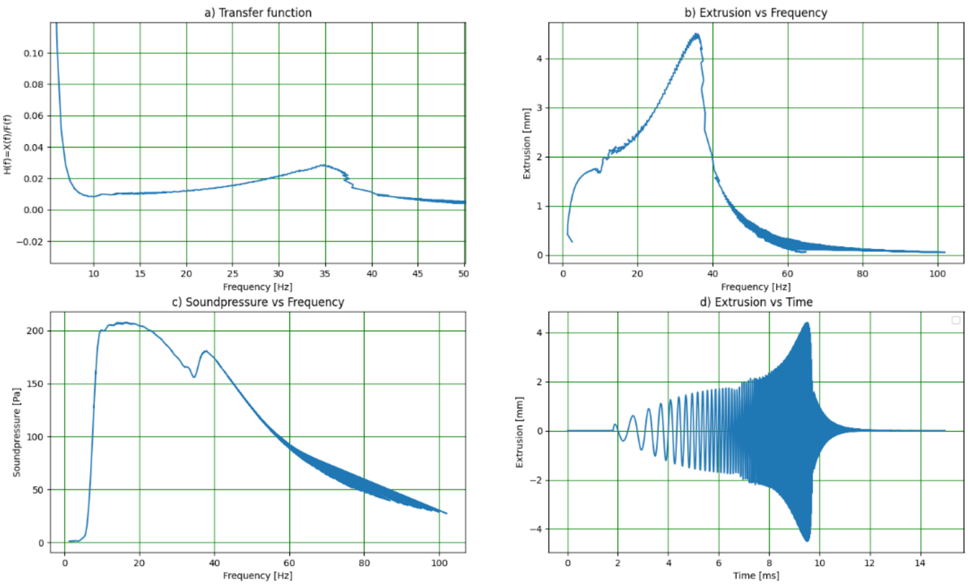

Figure 30: a) Transfer function vs frequency (zoomed for clarity), b) Extrusion vs frequency, c) Soundpressure level vs frequency, d) Extrusion vs time

3.5.4 **Maximum extrusion**

Given that the PRs were to be incorporated in speaker box prototypes after undergoing all tests there was a trade-off between measuring extrusion until failure and keeping the PRs whole and functioning. Because the products offered by the company consume up to a maximum of 14W, and no PR neither broke at powers up to 30W when attached to the subwoofer nor started behaving unexpectedly, finding the maximum extrusion may not be as interesting as initially thought. Furthermore, there could be a distinction between maximum mechanical extrusion and maximum effective extrusion, which could be indicated by distortion in sound reproduction (Beranek & Mellow, 2019, p. 289). However, this was not investigated in this project.

When it came to the mechanical static testing, none of the PRs were tested until they physically tore apart. Instead, the maximal extrusion of the oscillations when attached to the subwoofer driven at 30W was used as an upper limit reference distance when tested in the compression machine.

A problem in deriving a fixed value for x_{max} is the difficulty to determine a definitive point where the extrusion quits being linear, which can be seen in Figure 25 and Figure 26.

3.5.5 **Understanding IEC standard**

A large amount of time was spent on understanding the IEC 62459 standard and its measurement methods. The descriptions were often difficult to interpret, which led to many iterative test-rounds as well as long discussions with supervisors at the company to isolate what specific measurements and set-up needed to be performed.

3.5.6 **Key takeaways**

The Define phase turned out to be more complex and time consuming than initially believed. As opposed to what was planned, the phase turned out to be more divergent rather than convergent, resulting in exploring, developing, and verifying several measurement methods iteratively instead of just performing them and using the results in the succeeding phases of the project. As these difficulties and uncertainties in the measurement methods were encountered, the company supervisor expressed their wish for the project to put additional focus on this phase as it would be beneficial to the company. The key takeaways are listed below.

- This process took more time than expected and more time would be required to fully explore, implement, and verify all methods.
- There was a lot of difficulty to implement the abstract measurement guides presented in the IEC 62459 standard and to know if it was done correctly.
- It was difficult to find possible sources of errors and the evaluate them.
- It would have been beneficial to have more PRs with data sheets.
- Some results might have been incorrect, but it was impossible to evaluate them without continuing with the project.

4 Develop

After determining the relevant PR parameters and measuring their values for the obtained PRs, the following step was to explore their actual performance when incorporated in loudspeakers. There are several ways of measuring performance which depends on the specific goals of the loudspeakers. Bass response was the main objective of this project, but as sound cannot be fully represented by a single value, this could also be accomplished in different ways. This chapter presents which methods were used to evaluate the PRs' performances and why. It also explores the possibility of constructing own PRs and predicting their behaviour.

4.1 Building loudspeaker boxes

To allow for evaluation of the PRs impact on bass output, several loudspeaker boxes of relevant size incorporating adequate drivers needed to be constructed. The reason for building new loudspeakers rather than using the existing modular subwoofer described in section 3.4.1.1 is that it is designed for reproducing low frequencies, and therefore the attaching of a PR does not expand its FR. Additionally, the size of the PR would be almost insignificant in relation to the driver and box volume. The subwoofer is a great tool for determining the parameters of the PRs, but not for evaluating their addition to the bass audio output. The scenario when a PR effectively affects the FR is when incorporated in a smaller loudspeaker with a driver that cannot reproduce very low frequencies.

To keep the prototyping process rather simple and allow for different fast adjustments along the way, it was decided to construct loudspeaker boxes using a 3D-printer. Otherwise, it is common to use MDF as building material since it is relatively cheap, robust, and simple to work with (Tanasescu, 2020a) discussed in (Section 10, Video 34).

The prototype boxes were designed to enable modular and facile attachment of many different PRs. In a sense they were miniatures of the modular subwoofer.

4.1.1 **Driver selection**

The quality factor of the driver, Q_{ts}, affects which type of enclosure the driver is suited for (Tanasescu, 2020a) discussed in (Section 10, Video 34). When evaluating the FR of the prototype, there would be comparisons made between a sealed enclosure and an enclosure incorporating a PR. Because of this, drivers with a Q_{ts} close to 0,5 were selected, since they work well both for sealed enclosures and enclosures involving a PR.

Another aspect that was taken into consideration was the type of future product that could implement a PR at the company. Because of the advantages offered by PRs different types of loudspeakers will experience different amounts of benefit from implementing PRs. For instance, IP classification benefits may not be important to a speaker designed for indoor use. By looking at the current product offerings at the company and determining which ones would benefit the most from PRs, drivers with similar properties to the ones implemented in those products were chosen.

Figure 31: Selected speaker drivers, 4 and 3 inches respectively

4.1.2 **Box dimensions**

To keep the design and manufacturing simple it was decided to create rectangular speaker boxes of different size. Small introduced a "golden ratio" for rectangular enclosures which is 2,6:1,6:1 for the inner relations between the height, width, and depth. This ratio helps to minimise standing waves in the structure. Inside the enclosure bracings were added to increase robustness and disperse the energy of the noise (Dickason, 2006, pp. 113-114). The wall thickness of the first two boxes was determined to 19 mm, which is recommended for speakers that will be driven with powers up to 500 W (Tanasescu, 2020a) discussed in (Section 10, Video 34). When creating a third box, the wall thickness was reduced to 12 mm to reduce manufacturing time, and because the thickness of the first two boxes seemed exaggerated in relation to the relatively low power levels of which the speakers were driven with.

By using the simulation program WinISD it was possible to quickly find suitable box volumes that theoretically would generate a relatively differing FR depending on if the enclosures were sealed or incorporating a PR. Other aspects to consider when determining the box volumes were whether the volumes were reasonable for potential future product offerings by the company, if the boxes would fit in the available 3D-printers at the company, and if they had a surface large enough to fit the larger PRs.

The box volumes were ultimately decided to 1,97 litres, 8,18 litres and 1,91 litres for the speakers BlackBox, BigBox, and Liquorice Allsort respectively. The two smaller ones each integrate the 3-inch driver and the larger one integrates the 4-inch driver.

Figure 32: The three in-house made loudspeakers from the front: BlackBox, BigBox and Liquorice Allsort

Figure 33: The three in-house made loudspeakers from the back, with the PRs that fit in their respective cavity.

4.1.3 **Material**

The purchased PRs had a suspension made from rubber. However, it was impossible to extract any further information on exactly which type of rubber they consisted of. The same thing applied to the specific metal used as the middle plate or material used in the spider and the cone.

Since the box was 3D printed, it consisted completely of polylactide, PLA.

4.1.4 **Leakage**

To check whether the boxes were airtight an impedance test was conducted using Dayton Audio’s DATS V3.

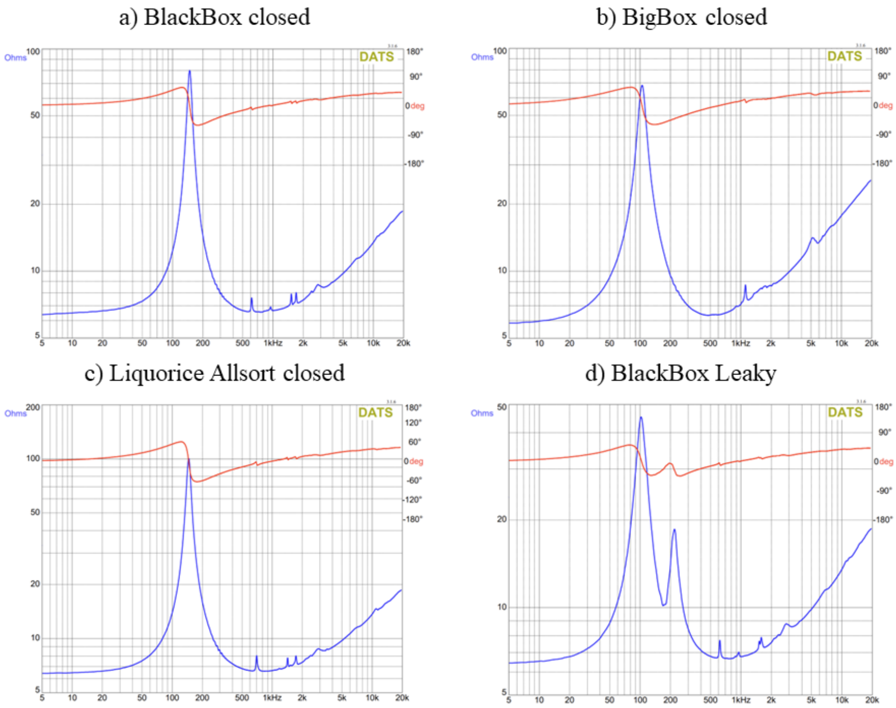

Figure 34: Impedance tests of speaker boxes

Figure 34 shows the results of the impedance tests of the different speaker boxes when closed as well as one with a leakage, which was simulated by not fully covering the modular opening. As can be seen, the leaky impedance test has a distinct second peak at a higher frequency which the others lack, a conclusion supported by an audio engineering expert at the company. The red curve indicates phase.

4.1.5 **Driver parity**

Another set of impedance tests using Dayton Audio’s DATS V3, shown in Figure 35, was conducted on the drivers in free air before they were incorporated in the boxes. Since the BlackBox and the Liquorice Allsort have the same type of driver, the impedance test allowed for a comparation between the two drivers and see if they performed equally.

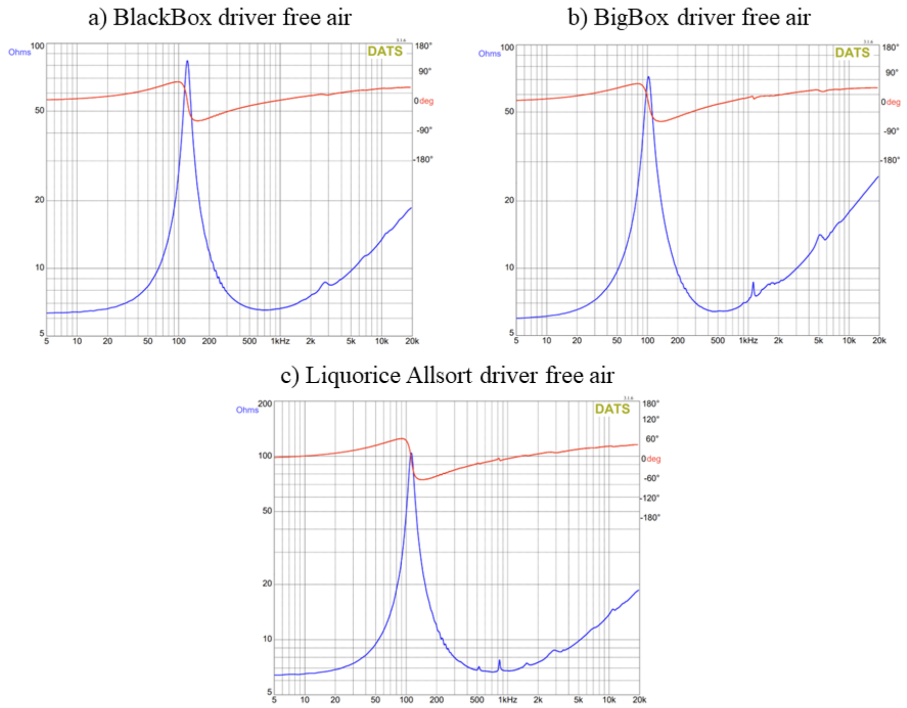

Figure 35: Impedance tests of speaker drivers in free air

4.2 Measuring passive radiator performance

Passive radiator performance can mean different things depending on the specific application. In this project bass was the main goal but even that can mean different things. Because of the uncertainties encountered when measuring the PR parameter values, it was especially interesting to compare the real sound that the loudspeakers would output with their simulated output, which could give an indication whether the measured parameter values were correct or not. The main aspect that simulation programs evaluate is the frequency response of a loudspeaker, which is also the main aspect of evaluating sound output (Winer, 2018, p. 42). There are other ways of evaluating sound output, such as total harmonic distortion, clarity, or spatial propagation (Toole, 2018). However, many of these depend on the specific implementation and construction of the loudspeaker and not necessarily the Thiele/Small parameters. Because this project looked at the general implementation of PRs as opposed to a specific one, these methods of performance evaluation were not considered to be as relevant. The frequency response is more of a quantitative measurement of audio output, whereas, for instance, clarity is a more qualitative measurement (Toole, 2018, p. 164). While the initial FR measurements were being conducted, the seemingly low impact from incorporating PRs gave rise to the idea of conducting subjective listening tests to see whether or not the measured FRs would correspond to the perceived audio output, both as a way of verifying the measured FRs and to get a more qualitative way of evaluating the PRs' performances.

Another possible way to evaluate PRs would have been to look at their mechanical performance such as their resistance to impact or waterproofing. While these are important criteria for a finished PR incorporating loudspeaker, especially since IP classifications are one of PRs' main advantages over vented loudspeaker designs, sound is still the most important factor. If a PR does not improve the bass response of a loudspeaker, there is little reason to chose it over a sealed box design which is both simpler to manufacture and has better IP classifications. Again, as this project did not focus on a specific implementation of a PR but rather a general one, it was considered more important to evaluate sound performance than mechanical performance. Furthermore, the Thiele/Small parameters did not seem to have any correlation with factors such as weather resistance or durability according to the authors of this report or the supervisors at the company.

4.2.1 **Measuring frequency response**

A common way to represent speaker driver and loudspeaker performance is through a FR chart, similar to the one in Figure 10. In order be able to compare different charts, FR measurements are usually conducted at one watt of power one meter from the loudspeaker or driver. Because these measurements should not include any influences from their environments or other sources of noise or inaccuracies, they should ideally be conducted in completely a silent and echo-free environment. However, creating such an environment poses a myriad of challenges. An infinite space is completely echo-free but would realistically only be achievable outdoors where wind and other sources of noise are unavoidable. The anechoic chamber available at the company eliminates echo, but only down to frequencies above 200 Hz. This means that in order to accurately measure bass frequencies these need to be measured "near field", only a few millimetres away from the driver. Because the loudspeakers that were tested in this project incorporated PRs, the near field measurements of the both the speaker driver and PR needed to be measured. Additionally, a far field measurement needed to be conducted. The reason is because within the near field of a speaker the sound source is a mix of propagating and circulating waves and not only propagating waves which causes unreliable measurements at higher frequencies (Klippel, 2012). A far field measurement at 1.78 meters away and 1.5 meters above the floor can reliably measure frequencies above 200 Hz due to the time difference between the direct and bouncing wave. The lower end of a far field measurement range is dictated by $f = 1/T$ (Begin, 2021).

The far field and near field measurements were then merged using software to create an accurate FR curve of the measured system. Figure 36 - Figure 38 show how far and near field measurements and merging of the two through a merger tool in a free software called VituixCAD.

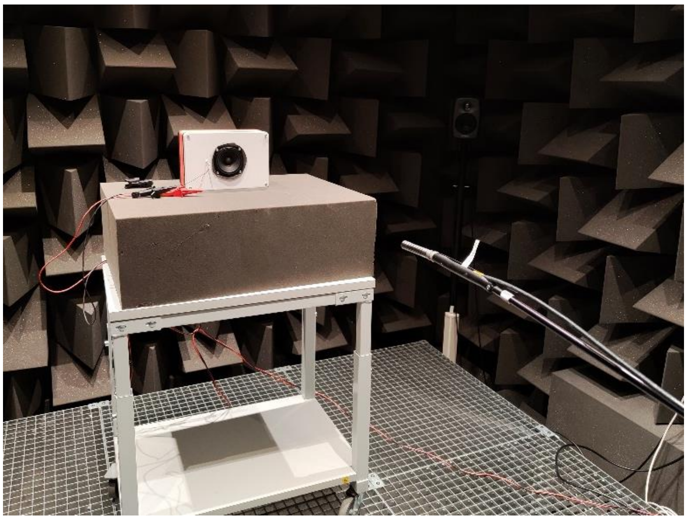

Figure 36: Far field measurement

Figure 37: Near field measurement

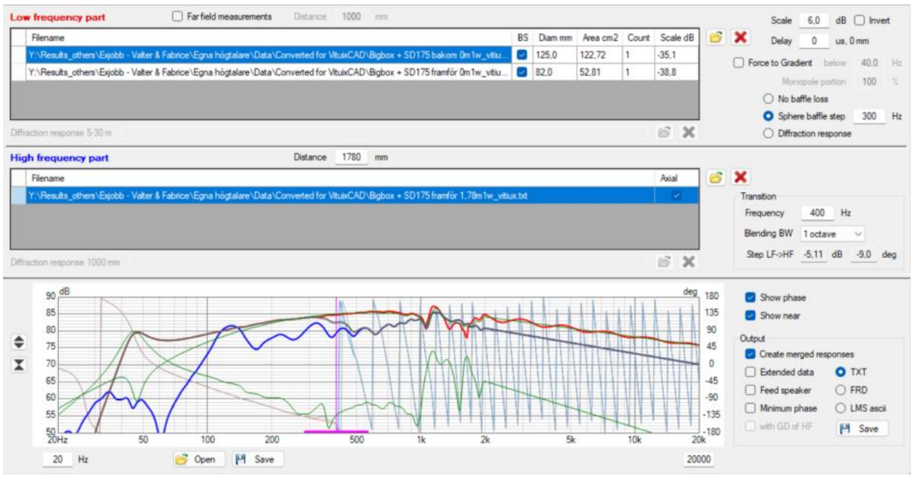

Figure 38: Merger tool in VituixCAD

4.2.1.1 Results

Resulting merged FR curves are shown in Figure 39 and Figure 40. The characteristic dip of a PR loudspeaker is present, which occurs due to the resonance frequency of the PR being 180 degrees out of phase with the speaker driver resulting in destructive interference (Small, 1974). A selection of remaining results is included in Appendix D.

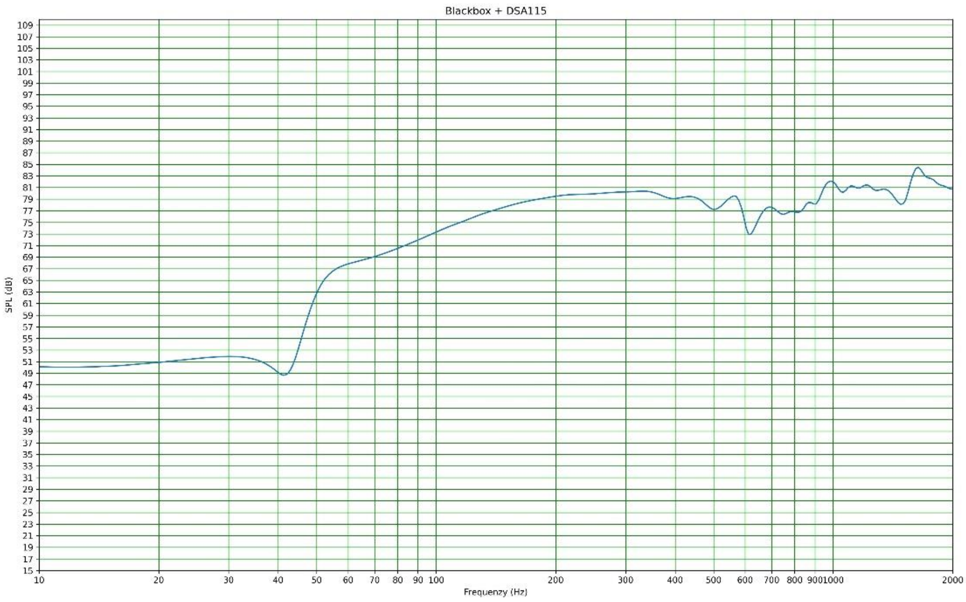

Figure 39: Frequency response curve of BlackBox with PR DSA115

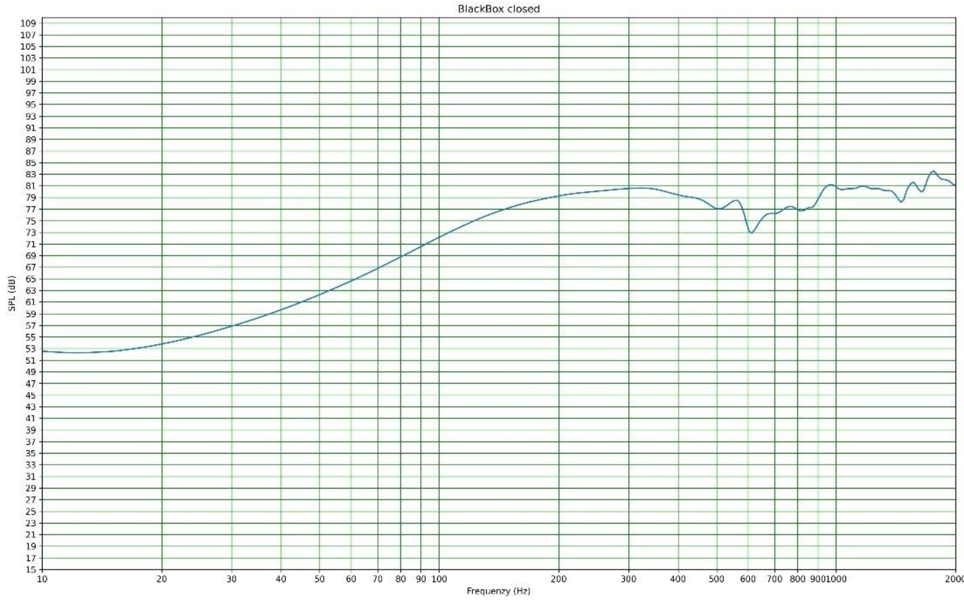

Figure 40: Frequency response curve of sealed BlackBox

4.2.2 **Simulations**

Simulations were performed using the program WinISD as a way to evaluate the measured FRs. After introducing all relevant parameters for the driver and the specific PR, as well as the box volume, a theoretical FR of said set-up could be derived. These simulations were to be compared with the actual measured results from the prototype speaker box. Figure 41 shows a simulation of the FR of the PR SD175 incorporated in an enclosure with the equivalent volume as the BigBox with the ACP 4-inch driver.

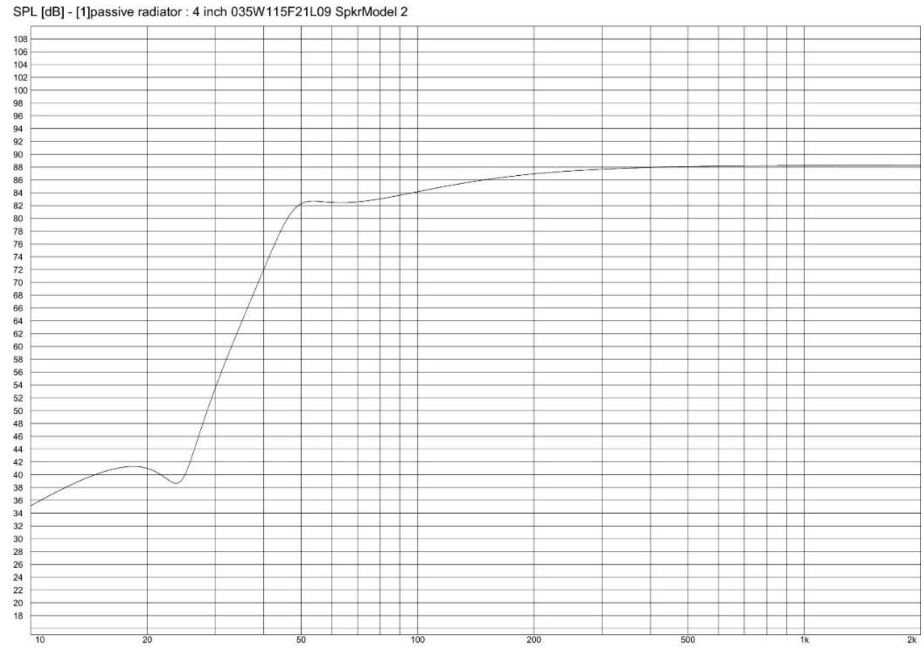

Figure 41: Simulation of PR SD175's frequency response when incorporated in an enclosure of 8,18 litres with the ACP 4-inch driver.

4.2.3 **Subjective listening tests**

As a complement to the measured FR charts, it was determined to perform a set of blind listening tests to evaluate the perceived bass amplification. One relevant reason for deciding to conduct these tests was that the anechoic chamber often was booked for other projects, not allowing for making FR measurements whenever desired. Thus, to use the project time efficiently these tests were seen as an appropriate alternative method of assessing the PR's impact on bass output aiming to achieve a qualitative evaluation aspect and subsequently compare that with the measured FRs. However, these tests had low priority in relation to the FR measurements throughout the whole project.

Due to time limitations these tests were mocked-up rapidly in an exploratory way, include a small number of participants, and can only be viewed as a supplement to measured FR charts. Because of this, they are unreliable, and limited conclusions can be drawn from the results. Yet they are included in the report as a first draft and starting point of further studies of similar type. However, to be scientifically valid the tests would have to include statistical planning and be conducted through a scientifically proven method, such as a crossover study (Bose & Dey, 2009, pp. 1-

4). In such case they may be useful in comparing FR charts with perceived bass amplification.

4.2.3.1 Test setup

The speakers BlackBox and Liquorice Allsort have the same proportions and contain the same type of driver. Therefore, they are well-suited for comparing audio output.

The test was set up by placing the two speakers under a cover sheet. They were both connected to an amplifier that allowed for quick transition between which speaker was reproducing sound. This fast switch was essential since the audio memory of humans is very time limited (Thaut & Volker, 2014, p. 311). The test participant was seated in front of the two speakers. They were told that two speakers, speaker A and speaker B, were placed under the cover sheet. The test leader played snippets of three different songs with varying bass characteristics. During the reproduction of each song, the test leader switched the sound reproduction between the two speakers several times, telling the participant whether speaker A or B was playing. In the meantime, the participant was asked to grade the speakers' bass pressure relatively to each other on a degree seven Likert scale on a questionnaire (Preece, Rogers, & Helen, 2002, pp. 280-281). The test leader informed the participant that the grading should be performed individually for each song, i.e., the participant could rank speaker A having more bass pressure in the first song, and then rank speaker B having more bass pressure in the second song.

Figure 42: Pictures of the test room. The left picture is from the test leader's perspective, and the right picture is from the participant's perspective.

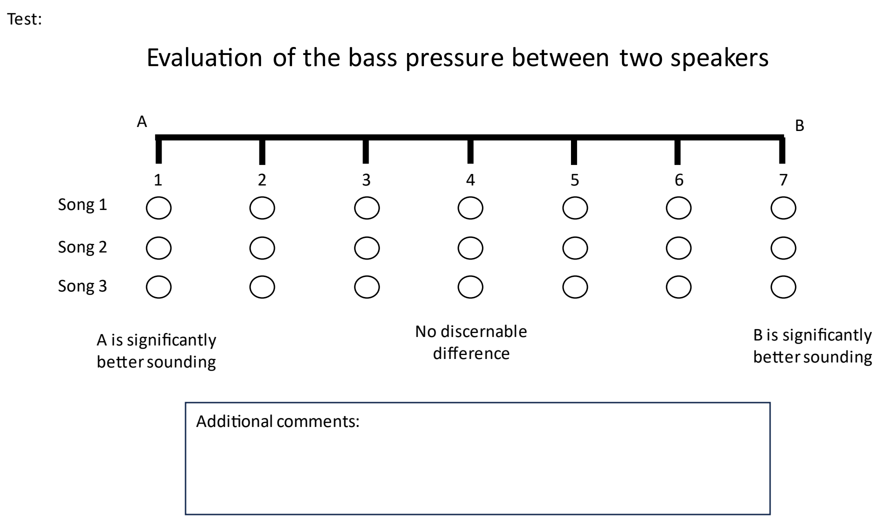

Figure 43: Listening questionnaire

4.2.3.2 Results

In total five sets of listening tests were conducted. In four of them one of the speakers had a PR mounted, and in one test both speakers were completely sealed. In each set seven employees of the company were asked to perform the test and answer the questionnaire. The average values of all participants grading were calculated for each song and are shown in Table 4.

Table 4: Results of subjective listening tests

Speaker test configuration	*Song*	*Average result*
A: BlackBox closed B: Liquorice Allsort closed	1	6,00
	2	4,00
	3	4,71
A: BlackBox + DSA115 10g added weight B: Liquorice Allsort closed	1	2,14
	2	4,00
	3	3,86
A: BlackBox closed B: Liquorice Allsort + PR11B 5g added weight	1	4,00
	2	4,88
	3	5,50
A: BlackBox + PR2A B: Liquorice Allsort closed	1	5,00
	2	4,00
	3	3,14
A: BlackBox closed B: Liquorice Allsort + PR6A	1	2,29
	2	4,00
	3	4,43

Note: A low score indicates loudspeaker A is favoured.

As can be seen by the results, there was no speaker pair where participants unanimously favoured one above the other. Even when no PR was present in either box, participants still favoured one speaker by a similar amount compared to tests where a PR was present. One reason for this may be that the tested PRs' impact on bass sound is not significant enough to be clearly perceivable. Another reason may be the lack of references, how much better sounding does one speaker have to be for participants to grade it on the far end of the Likert scale?

4.3 In-house development of passive radiators

Regarding the purchased PRs, the only variable that can be altered in a controlled manner is the addition of weight. This alteration was made by attaching Blu Tack onto the PR. However, to be able to control more variables, such as shape, material, and thickness of both the suspension and the plate, it was decided to construct self-made PRs. Another motive of developing in-house PRs was to present a proof of concept for the company, as inspiration of a potential way forward to manufacture their own PRs in the future. Like the subjective listening tests described in section 4.2.3 this process was rather low prioritised in relation to conducting FR measurements and carried out in a rapid and exploratory manner.

After discussing with an expert at the company it was determined to mould suspensions using silicone, as it was a resource available at the company. A first test round of moulding was performed using three different 3D printed moulds with varying thickness. Two of the moulds were designed for over-moulding, which allowed for a steel plate to be attached directly to the suspension in the moulding process. The third mould was designed to only create the suspension, which later was attached to a steel plate using a primer and double-sided tape.

Figure 44: Self-made PR's consisting of silicone suspensions and steel-plates. The two white 3D printed parts are the moulds for creating the suspension.

After the first test round it was determined that creating own passive radiators using steel plates and silicone moulding was a suitable method, and it was decided to proceed with a more advanced product development process. Some key takeaways from the initial run were that the PRs would have to be over-moulded as the double-sided tape did not stick to the silicone, the plate would be made of aluminium instead of steel, and the suspension thickness would be set to 1,5mm. The continued process was influenced by the book *Product Design and Development* by Ulrich and Eppinger (2012). The three specific steps used were the following:

- Concept generation
- Concept selection
- Concept testing

4.3.1 **Concept generation**

Given the explorational characteristics of this project, it was decided to strive for a wide variety of concepts instead of creating several relatively similar concepts. This may not have led to an optimised design, but was rather aiming to give a broad understanding of which general design options may and may not be suitable when constructing a PR.

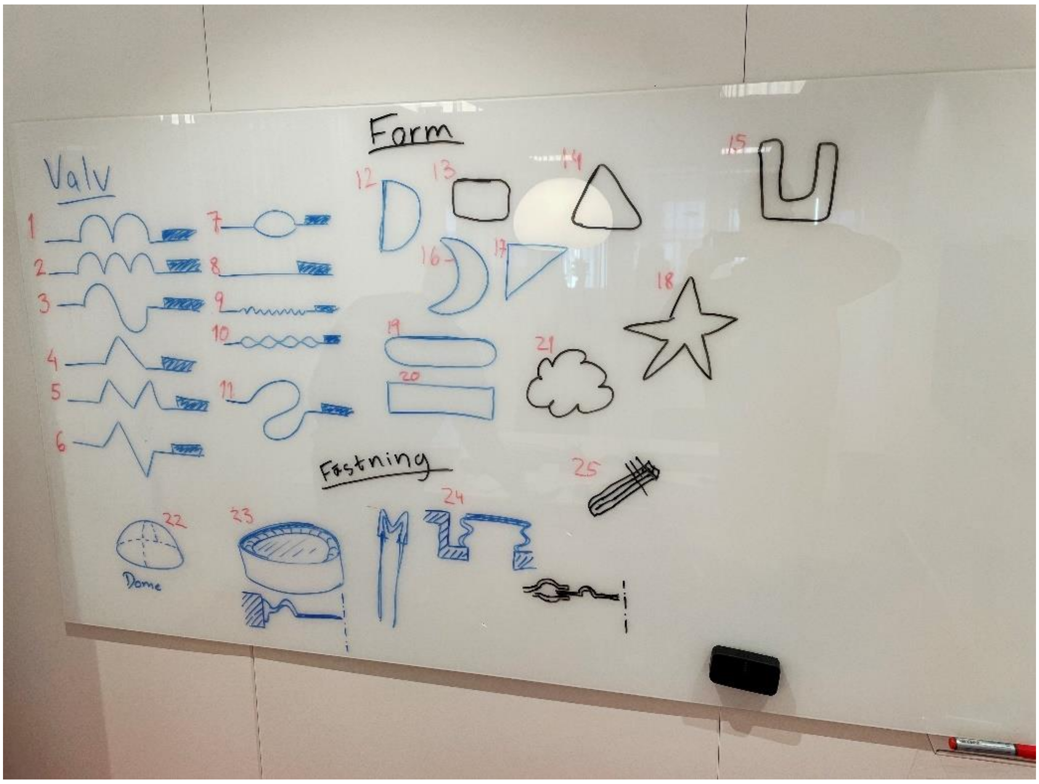

Figure 45: A total of 25 ideas from the concept generation

4.3.2 **Concept selection**

Due to the relative simplicity of design of passive radiators, only one round of concept selection was performed consisting of a concept screening matrix, evaluating different concepts by giving them scores in several criteria (Ulrich & Eppinger, 2012, pp. 150-153). These criteria were selected with the limited resources available in mind as well as how the results could be used by the company for future development of PRs. Furthermore, since the plate shape and suspension and attachment method are independent of each other, they may be combined to create even more concepts. Table 5 presents the criteria and their meaning. The scores presented in Table 6 are based on the authors' estimations.

Table 5: Selection criteria

Criteria	***Explanation***
Complexity	The technical complexity of the PR, which would affect the ability to create an effective prototype, and manufacturing cost.
Size	Is the size reasonable for the type of loudspeaker this project focuses on?
Stiffness	Will the stiffness be similar to other PRs, i.e. not too loose or stiff? Relates to thickness and shape of PR suspension.
Innovative	Does the idea differ from other existing PRs?
Form	The shape of the plate. Affects how the PR can be incorporated in a loudspeaker with limited surface available.
Weight	The weight of the PR's moveable part. Relates to resonant frequency?
Fragility	Is the PR susceptible to breakage under normal operating conditions?
Wobble	Will the PR have any modes of oscillations other than the normal mode?
Time	Manufacturing time.

Table 6: Pugh concept screening matrix

Concept	*Complexity*	*Size*	*Stiffness*	*Innovative*	*Form*	*Weight*	*Fragility*	*Wobble*	*Time*	*Total*
Reference	0	0	1	0	0	0	0	0	0	**1**
1	0	0	1	1	0	0	0	0	0	**2**
2	-1	-1	1	1	0	0	-1	0	0	**-1**
3	0	0	0	1	0	0	0	0	0	**1**
4	0	0	1	1	0	0	0	0	0	**2**
5	0	0	1	1	0	0	0	0	0	**2**
6	0	0	0	1	0	0	0	0	0	**1**
7	0	0	0	1	0	-1	1	0	0	**1**
8	1	0	-1	-1	0	0	0	0	0	**-1**
9	-1	-1	0	1	0	0	-1	0	0	**-2**
10	-1	-1	0	1	0	0	0	0	0	**-1**
11	-1	0	-1	1	0	0	0	0	-1	**-2**
12	0	0	1	0	1	0	0	0	0	**2**
13	0	0	1	0	1	0	0	0	0	**2**
14	0	0	1	0	-1	0	0	0	0	**0**
15	-1	-1	1	1	-1	0	0	0	0	**-1**
16	-1	-1	1	1	1	0	-1	0	0	**0**
17	0	0	1	0	1	0	0	0	0	**2**
18	-1	-1	1	1	-1	0	-1	0	0	**-2**
19	0	0	1	0	1	0	0	0	0	**2**
20	0	0	1	0	1	0	0	0	0	**2**
21	-1	-1	1	1	0	0	0	0	0	**0**
22	-1	-1	-1	1	0	-1	0	-1	0	**-4**
23	-1	0	1	0	0	0	-1	0	0	**-1**
24	-1	-1	1	1	0	0	-1	-1	0	**-2**
25	-1	-1	1	1	0	0	0	0	-1	**-1**

Initially 12 concepts were selected. However, after some discussion with the company supervisor, it was decided to limit the scope of the development of PRs to just shapes, i.e. suspension shape and attachment method would not be altered. The main reason for this was that different shapes may allow for different disposition of a PR and a driver in a loudspeaker if surface area is a limiting factor. After this limitation five shape concepts remained.

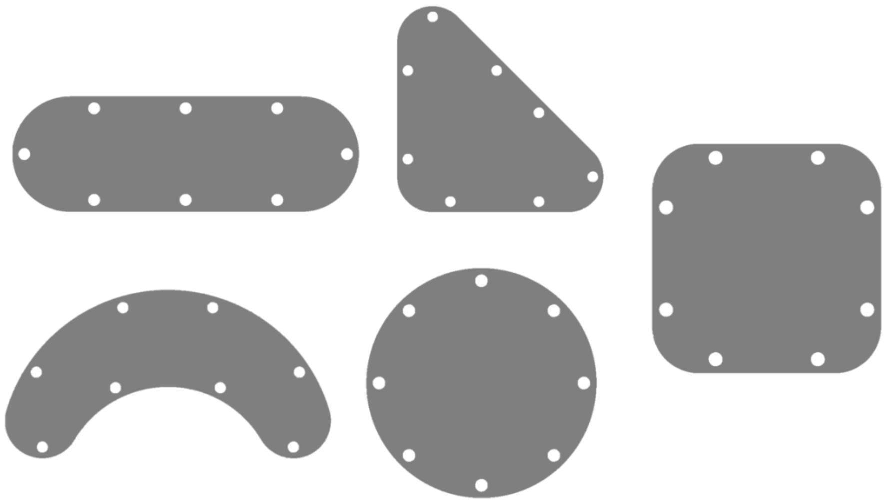

Figure 46: The five selected PR concepts

To get an indication of whether and how the plate shape influences the bass output, it was decided to keep the plate area constant for all the five selected concepts.

The idea was to have these metal discs produced by a workshop foreman at the company, but he was unable to do so. As a second option the production would be outsourced to a local metal workshop, but the offer was deemed too costly by the company supervisor. The third option would be to purchase sheet metal and cut it according to the drawings, but due to the lack of laser cutters able to cut sheet metal this option was deemed too time consuming and thus the in-house development of PRs was abandoned.

4.3.3 **Concept testing**

While no PRs of varying shapes were produced, one of the PRs produced in the initial trial run was fastened to a rigid 3D printed surrounding suspension and then underwent the same parameter measurements as for the purchased PRs, described in section 3.4.

4.4 Discussion

4.4.1 **Loudspeaker boxes**

The construction of the three boxes were relatively time consuming since it included much 3D modelling and 3D printing. To ensure robustness of the boxes and minimise the risk of air leakage, the infill level of filament in the BlackBox and the Liquorice Allsort was set to 85%, which led to long 3D-printing sessions. For the BigBox the infill level of filament was set to 50% to reduce the printing time. This turned out to be a bit excessive but did not cause any other issues. All three loudspeakers were airtight and robust. With respect to this project the prototypes performed well in reproducing sound although, other qualitative aspects such as distortion were not evaluated.

From the impedance tests in section 4.1.5 it can be concluded that the drivers in the BlackBox and in the Liquorice Allsort differ slightly, which may have affected the sound reproduction.

4.4.2 **Measuring frequency response**

Initially, measurements at 1 watt and 1 meter from the loudspeakers with different PRs attached were conducted in the anechoic chamber. After completing measurements of all PRs and plotting the resulting data, very little if any difference between the PRs and even whether the box was closed or had a PR could be noticed. This led to some discussions with the company supervisor who realised that the measurements that had been made were unreliable since the anechoic chamber is only echo-free at frequencies above 200 Hz. Only after this fact was it discovered that in order to achieve an equivalent FR curve at 1 meter and 1 watt, several measurements at different distances had to be made and then be combined using special software. While some near field measurements of the PRs had already been made as a potential point of evaluation, the exported results did crucially not include phase shift, which is required when merging the two near field measurements of the PR and the speaker driver. As a result, all measurements had to be remade. Added to this predicament, the audio lab was heavily booked due to end of year delivery deadlines, making it difficult get all measurements done in time.

Figure 47 shows a measured FR curve of Liquorice Allsort with PR 10A. A selection of more measured FR curves can be found in Appendix D.

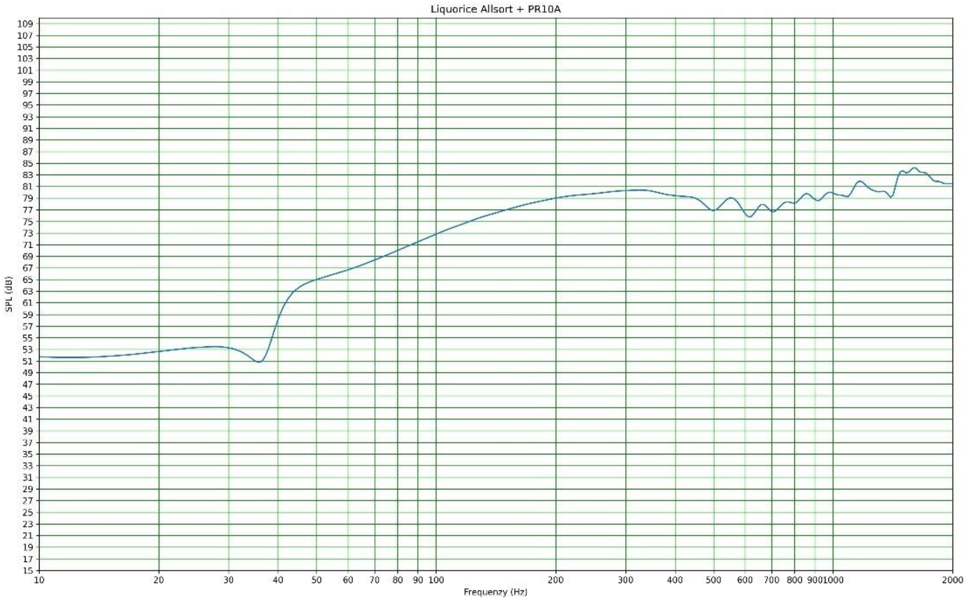

Figure 47: Measured frequency response of Liquorice Allsort + PR10A

4.4.3 **Simulations**

As mentioned in section 2.2.5, loudspeakers are complex systems. To create simulation models, it is necessary to do slight simplifications of reality by using approximations and linearisation. However, the underlying calculations and approximations in WinISD are unknown to the writers of this report. It is therefore difficult to know to what precise extent the simulations represent reality.

Using simulations as reference when analysing measured values is of great help when evaluating trendlines, curve shapes and general magnitudes, but may involve a degree of uncertainty when comparing absolute numbers.

One example of when the simulation program shows odd results is a when adding weight to the PR in the simulation program versus adding weight to the PR in reality. In the program it seems like all the PR parameters, except f_{pr}, remain the same. However, when measured in reality the mechanical compliance, and by extension acoustic compliance volume, and the quality factor change. The two simulated FRs are displayed in Figure 48 and Figure 49, and it can be seen that they vary significantly.

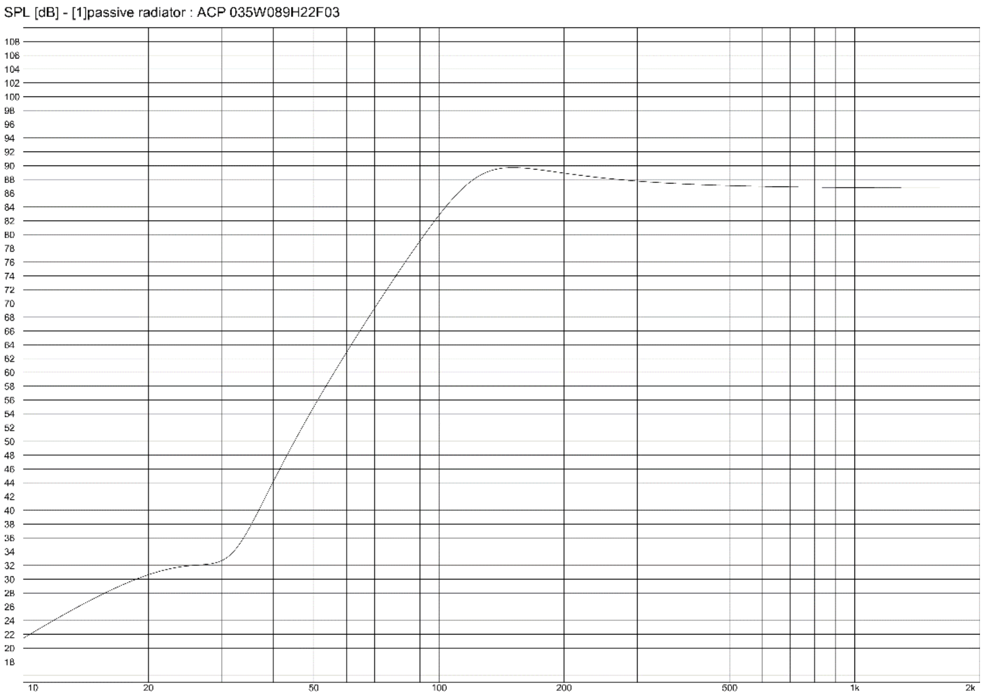

Figure 48: Simulation of DSA115 with adjusted measured parameter values after adding 10g in reality

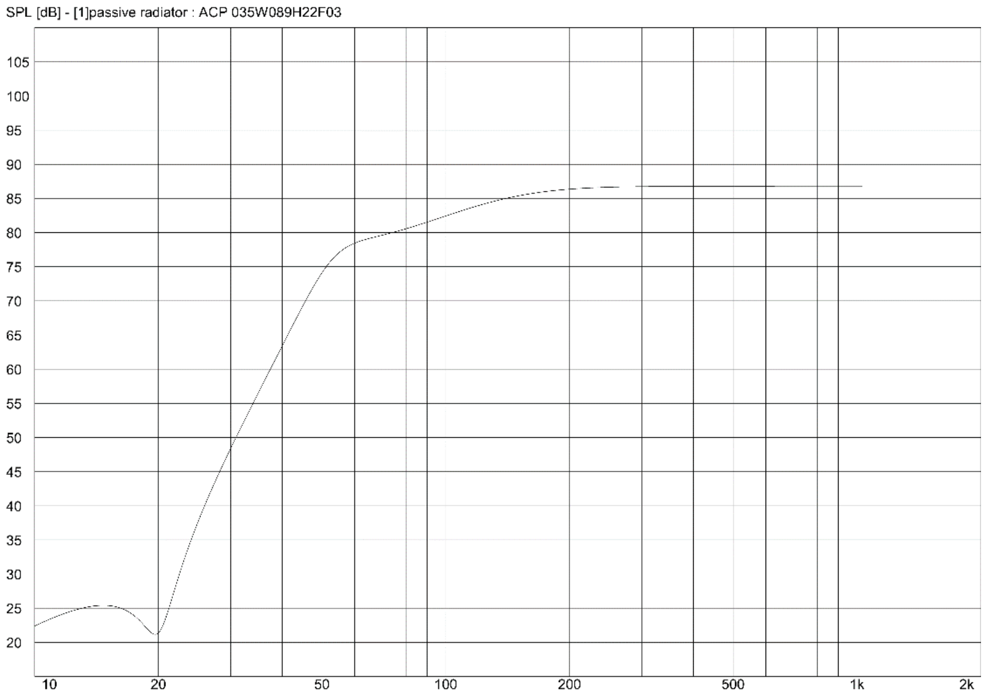

Figure 49: Simulation of DSA115 adding 10g of weight in the simulation program

In following parts of the report there will be many comparisons between measured FR charts and simulated response charts of two types. Below is a brief clarification of what is meant by the different terms.

- Measured FR – The measured response from merged near and far field measurements.
- Simulated FR with measured parameter values – Simulations of FRs using the measured PR parameters.
- Simulated FR with provided parameter values – Simulations of FRs using the manufacturer data sheet PR parameters.

4.4.4 **Subjective listening test**

As mentioned in section 4.2.2 these listening tests have many flaws, which make them unreliable and incapable of deriving useful conclusions. Not only was the method unscientific and the test group very small, but there were also a few unclarities regarding the definition of bass sound. For example, the expression "better bass pressure" was possibly interpreted differently by the participants and may have led to varying grading e.g., one participant may have focused more on the loudness of the bass whereas another participant may have focused more on the clearness of the bass. Another aspect of evaluating bass pressure in songs is that the distinction between the bass pressure and the general sound experience is of highly subjective character. Comments added by participants support this notion, some of which are presented in Table 7.

Table 7: Comments by participants of subjective listening test

Original comment	***Translated comment***
B hade mer djup men A hade mer snärt ("punsch"). Med för mycket "ensam bas" blev A lite rasslig (7 nation army) men B blev lite grötig/dimmig med för mycket annat.	B had more depth but A had more kick (“punch”). With too much “lonely bass” A was a little rattle-y (seven nation army) but B was mushy/hazy with too much else.
Grötig B. Mer volym generellt i A. Man kan "känna" A.	Mushy B. Generally more volume in A. You can “feel” A.
Vänster bas bättre tryck höger mer rent.	Left [A] bass better pressure, right [B] more clean.
A lät något "djupare" på låt nr 1. A lät något burkigt på låt nr 2. A hade mer "snärt" i basen på låt nr 3.	A sounded somewhat ”deeper” during song no. 1. A sounded somewhat more canned during song no. 2. A had more “kick” in the bass during song no. 3.
Det låter nästan som att A distar lite. A låter lite "burkigt"	It almost sounds as if A distorts a bit. A sounds a bit more “canned”.
Förlåt	Sorry

An additional factor to consider is that the three songs reproduced in the test have varying characteristics and play different bass tones, thus the results may have differed if three other songs were selected. In order to compensate for differences between the selected songs, one of the listening tests compared two closed speaker boxes against each other which have a negligible difference in their FR, shown in Figure 50. The results from this listening test could then be used to calibrate the other tests, some results of which are presented in Figure 51. However, the statistical validity of this calibration is in question.

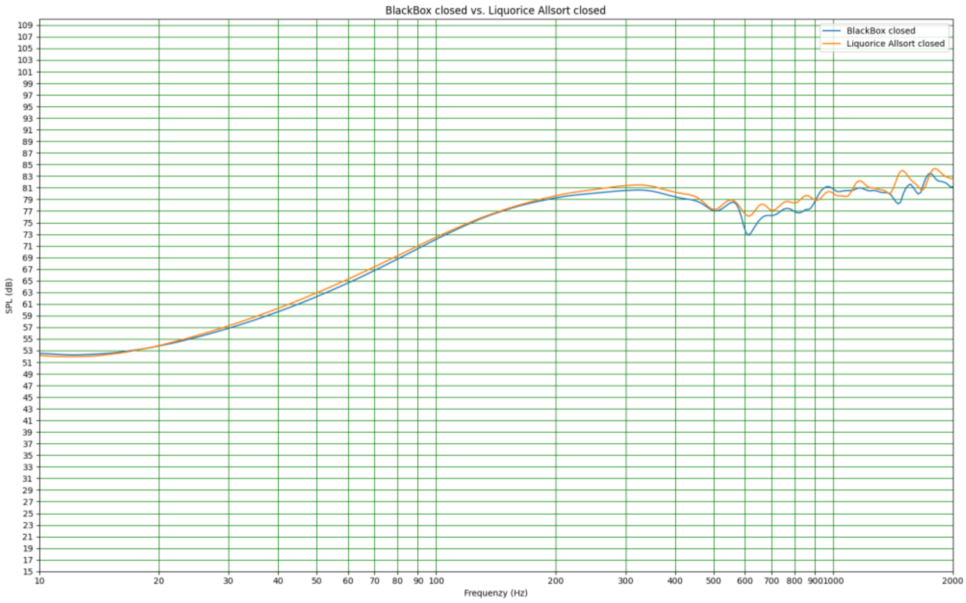

Figure 50: Frequency response of BlackBox closed and Liquorice Allsort closed

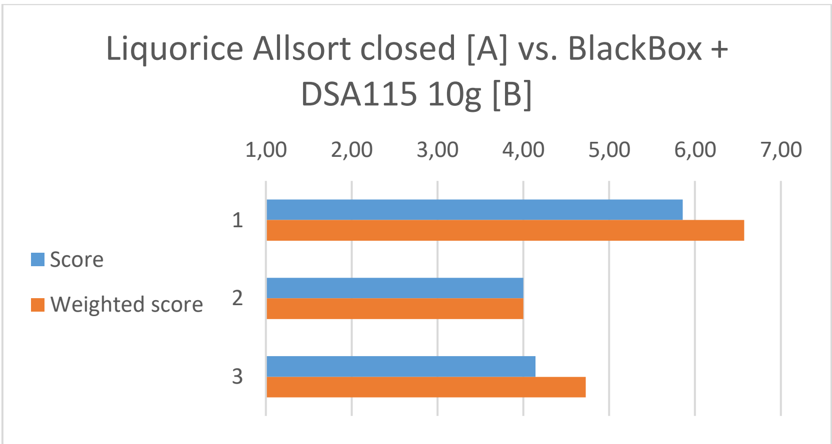

Figure 51: Weighted and unweighted scores of a subjective listening test

4.4.5 **In-house development of passive radiators**

It would have been interesting to create in-house passive radiators and be able to control factors such as plate shape, suspension thickness, and suspension shape individually in a controlled manner. It could potentially develop a deeper understanding to what extent each parameter from section 2.2.2 individually affects the FR, as well as their internal relationships, i.e. does a change in compliance affect the quality factor?

Yet it is a time-consuming task and the decision to give up the development of own passive radiators was necessary to be able to finish the measurements of existing PRs within the given time frame.

The parameter measurements made on the PR from the initial trial round could be conducted as planned and the results resembled the ones for the purchased PRs.

4.4.6 **Key takeaways**

Because of length of the preceding phase, Define, this phase suffered a bit from time restrictions. Many of the ideas initially planned had to be either scrapped or altered to fit the project timeline and to leave room for the final step. Furthermore, end of year delivery deadlines for other project at the company meant that the audio lab where the most important measurements were being made, was heavily booked leaving little time for exploring different evaluation methods. An initial error in when conducting FR measurements further exacerbated the time pressure. Because of this, the Develop phase felt somewhat more convergent than planned. Key takeaways are listed below.

- The 3D printed loudspeaker boxes were over dimensioned with regards to wall thickness and material infill, which could have shortened their development time.
- Developing PRs in house was an interesting part of the project and could lead to useful conclusions had it been explored further. It could provide the possibility of isolating specific parameters which was not possible with the PRs used in this project. Perhaps this could be an avenue for another future thesis project.
- Adding weight to some PRs yielded interesting FR results and it would have been interesting to investigate adding masses to more PRs.
- While the subjective listening test did not result in much valuable information by itself, it did confirm the initial FR results and provided more context for the complex and subjective nature of sound. This can be a good way of evaluating two loudspeakers with similar FR curves for finished products.
- The seemingly low impact of the PRs as seen in the FRs was seen as a slight issue for the next phase of the project. Had there been more time available, iterating the process of developing loudspeaker boxes tuned differently and conducting new FR measurements could have yielded more interesting FR results, but this was difficult to evaluate before the next phase.

5 Deliver

This chapter analyses the results from the Define and Develop phase and discusses the outcomes. An initial section describes how the measured FR charts are interpreted and how they were compared quantitatively in relation to cut-off frequency. Afterwards, there is a section discussing the PR parameters' individual impact on the FR using Design of Experiments with the goal of identifying the relevance of each parameter. Moreover, there is a section examining the differences between measured and provided parameter values and which of whose simulated charts better correspond with the measured FRs as a mean to evaluate the validity of the measurement methods developed in the Define phase. These sections are related to the goals of the project introduced in section 1.3. Ultimately, this chapter also delivers a set of final design guidelines to consider when designing a loudspeaker containing a passive radiator.

5.1 Analysis of measured frequency response

The frequency responses can be interpreted in many ways, both quantitatively and qualitatively. The shape and patterns of a FR are compared to ideal FRs to evaluate if they perform as expected according to certain alignments. The point on the lower frequency end at which the FR dips below 3dB compared to the nominal level is called the cut-off frequency and is another key aspect of the FR. In this report, the FRs are analysed both by their cut-off frequencies and their general shapes, and conclusions are drawn from these analyses.

Looking at a measured FR curve and comparing it to a typical FR curve as shown in Figure 52 it is clear that these differ significantly, something which holds true for many of the measured FRs.

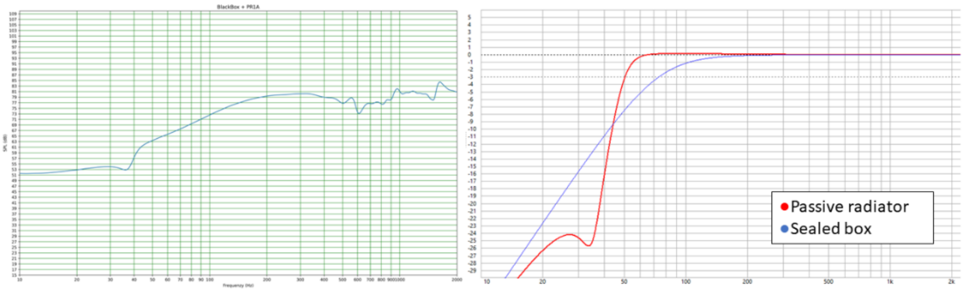

Figure 52: Measured (left) vs. typical (right) frequency response curves

The first key difference is the lack of a plateau in the measured graph which is caused by an imperfect driver. A totally flat response curve is an unrealistic expectation of a speaker driver, and thus some level of tolerance is required when designing a loudspeaker. Since this project focuses on bass frequencies, the fluctuations which are present above 400 Hz are of little interest. However, they do complicate things when trying to find the cut-off frequency, f_{3dB}.

The second key difference is the magnitude of effect of the “bump” caused by the presence of a PR. In the typical FR, this bump extends the curve to lower frequencies at a similar sound pressure level as the rest of the curve, however for the measured curves this bump occurs at much lower sound pressure levels. At these lower levels, which lie below the nominal sound pressure levels, the audible difference becomes much harder to perceive as it is drowned out by the much louder middle range frequencies, which then defeats the purpose of incorporating a PR in the loudspeaker. This is consistent with the results from the subjective listening tests which showed that the loudspeakers with PRs in this project were not clearly favoured over their sealed counterpart. It should be noted that neither the loudspeaker boxes built nor drivers chosen for this project were optimised and tuned for a specific PR, which affects both the placement and shape of the “bump” and is a requirement when trying to achieve a flat FR curve for a loudspeaker, also known as alignment (Dickason, 2006, pp. 62, 85). It was deemed more important to try to find general conclusions regarding PRs rather than optimising the FR for a specific loudspeaker. As such, the volume of the loudspeaker box was chosen with potential future product offerings for the company which could benefit from implementing PRs in mind.

These two factors, together with the fact that audio cannot be fully represented by a single value or graph, make it difficult to perform a quantitative analysis of the measured FR curves. And since the PRs were purchased and all have different parameter values, it is impossible to isolate a single parameter to investigate its effect on the FR.

Nonetheless, the cut-off frequency can be found for all merged FRs. The nominal sound pressure level is taken as the average of the sound pressure level between 300 and 2000 Hz. The resulting cut-off frequencies are presented in

Table 8. As can be seen, the presence of a PR does not significantly affect the cut-off frequency for most loudspeakers when compared to the closed loudspeaker. In the case of *BigBox + SD175*, presented in Figure 53, the FR curve almost has a cut-off frequency around 45 Hz which is significantly lower than *BigBox closed* whose cut-off frequency is 143 Hz. However, the size of the SD175 PR is somewhat unsuitable for the type of products the company aims to produce.

Table 8: Cut-off frequencies of PRs in loudspeakers

Loudspeaker box and PR combo	***Cut-off frequency, f_{3dB} [Hz]***
BigBox + BigB	114,8
Bigbox + SD175	119,9
BigBox closed	142,5
BlackBox + DSA115 10g added weight	125,2
BlackBox + DSA115 1g added weight	125,2
BlackBox + DSA115 2g added weight	130,7
BlackBox + DSA115 3g added weight	128,8
BlackBox + DSA115 5g added weight	125,2
Blackbox + DSA115	130,7
BlackBox + In-house PR	128,8
BlackBox + PR1A	132,6
BlackBox + PR2A	127,0
BlackBox + PR2B	128,8
BlackBox closed	136,5
Liquorice Allsort + PR10A	146,7
Liquorice Allsort + PR11A	106,8
Liquorice Allsort + PR11B	116,5
Liquorice Allsort + PR6A	153,2
Liquorice Allsort + PR8A	151,0
Liquorice Allsort closed	146,7

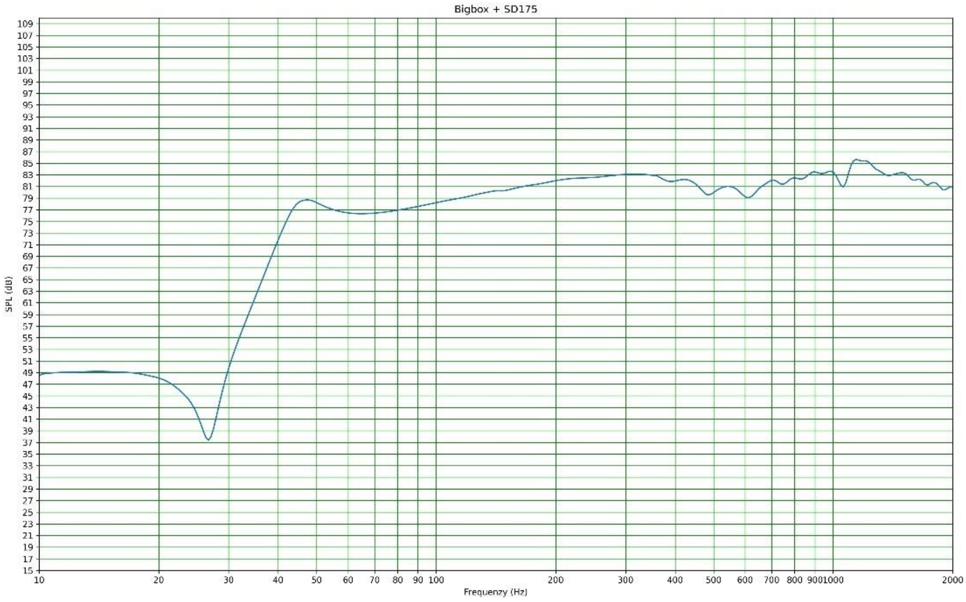

Figure 53: BigBox + SD175 measured frequency response

5.2 Analysis of parameter impact on frequency response

Design of Experiments (DOE) is a method of conducting experiments to create robust products by identifying and varying control factors, identifying noise factors, and observing and analysing the results (Ulrich & Eppinger, 2012, p. 314). In a normal DOE process, the control factors are set to one of two values and each sample to be tested has a different combination of control factor values. This way each control factor's impact on the result can be calculated. Depending on how many control factors and the cost of running the experiments, the number of samples to be tested can be decided to cover all or some of the possible control factor combinations. Full coverage is referred as a full factorial matrix and yields the highest result resolution, but partial coverage can be cleverly designed to still yield reliable results, illustrated in Figure 54. However, since the PRs for this project were purchased, there was no possibility to set the control factors to a specific value. Instead, they were for each control factor characterised as belonging to one of two equally large groups depending on their value. Furthermore, it was also not possible to ensure that the experiments were balanced. The control factors were set as the parameters investigated in section 3, and their grouping is presented in Table 9.

Full factorial matrix

		A1		A2	
		B1	B2	B1	B2
C1	D1	x	x	x	x
	D2	x	x	x	x
C2	D1	x	x	x	x
	D2	x	x	x	x

Half factorial matrix (balanced)

		A1		A2	
		B1	B2	B1	B2
C1	D1	x			x
	D2		x	x	
C2	D1		x	x	
	D2	x			x

Half factorial matrix (unbalanced)

		A1		A2	
		B1	B2	B1	B2
C1	D1	x	x	x	x
	D2				
C2	D1		x		x
	D2		x		x

Actual matrix of performed experiments

		A1		A2	
		B1	B2	B1	B2
C1	D1			x	xx
	D2	xx	x		
C2	D1	xx		x	
	D2		x		xx

Figure 54: Design of experiments example and performed matrices

Table 9: Passive radiator parameter grouping

PR	***C_{mp}* (mm/N)**	***Q_{mp}***	***f_{pr}* (Hz)**	***S_{dp}* (m^2)**	*C_{mp}* ***group (A)***	***Q_{mp}* group (B)**	***f_{pr}* group (C)**	***S_d* group (D)**
BIGA	0,84	1,30	72,01	0,020023	2	2	1	1
DSA115	4,38	3,05	43,25	0,005085	2	1	1	1
DSA115 + 10g	6,61	2,80	31,84	0,005085	1	1	2	1
DSA115 + 5g	6,86	3,08	34,29	0,005085	1	1	2	1
PR10A	6,22	2,68	35,24	0,003632	1	2	2	2
PR11B	1,58	2,42	52,73	0,008031	2	2	1	1
PR1A	6,98	3,26	41,80	0,00282	1	1	1	2
PR2A	3,16	2,26	36,94	0,00424	2	2	2	2
PR2B	2,85	2,20	38,21	0,00424	2	2	2	2
PR6A	7,51	3,06	54,01	0,00125	1	1	1	2
PR8A	11,91	2,67	54,16	0,000720	1	2	1	2
SD175	2,27	3,65	28,71	0,012242	2	1	2	1

Measuring the FRs of the PRs in their respective loudspeaker boxes were the experiments of this project, and the cut-off frequencies were used as basis for the objective function. Since the PRs were not incorporated in the same loudspeaker box, using the absolute value of the cut-off frequency would not be a fair comparison. Instead, the target objective function is the difference between the cut-off frequency for a PR incorporating loudspeaker and the same loudspeaker but sealed. Noise factors were considered insignificant as the FR measurements were conducted in an anechoic chamber and with high quality instruments.

With the groupings in place and the results of the objective function calculated, the impact of the individual parameters on cut-off frequency were calculated using the following equation (Tavčar, n.d.):

$$\overline{A_1} = \frac{Y_1 + Y_2 + \ldots + Y_n}{n}$$

Where $\overline{A_1}$ is the average impact of a parameter group and Y_i is any result (cut-off frequency delta) of a PR belonging to the same parameter group.

The results are presented in Figure 55. Group 1 indicates a higher value for all parameters.

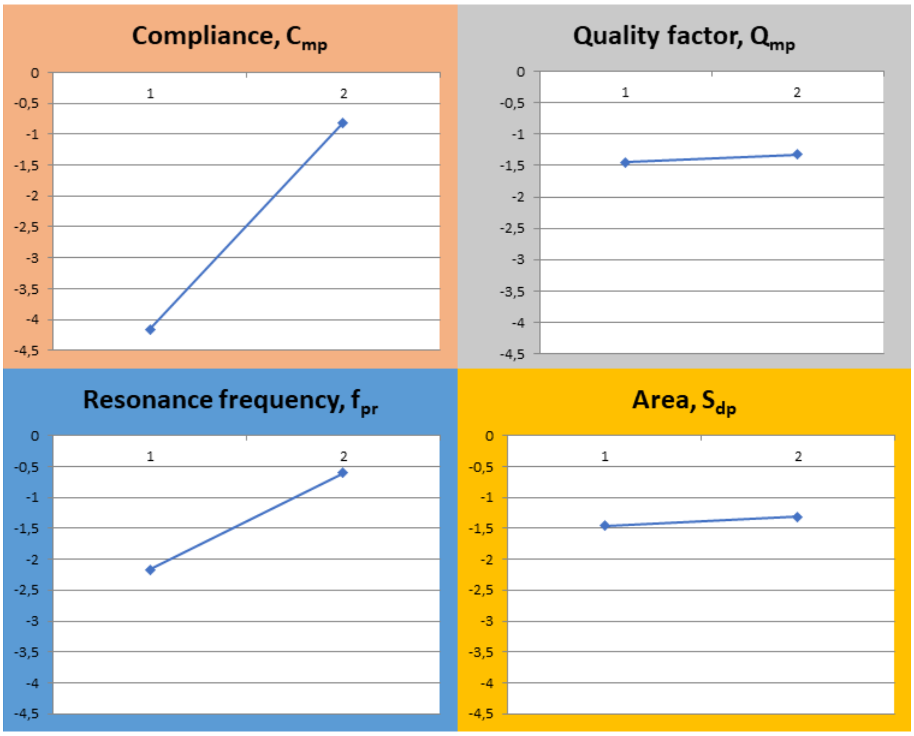

Figure 55: Parameter impact on cut-off frequency delta

The results indicated that none of the investigated parameters had a significant impact on lowering the cut-off frequency compared to an otherwise identical sealed box. Interestingly, for all parameters a higher value correlated with a lower cut-off frequency, even a higher free air resonance frequency of the PR. However, due to the limitations discussed earlier in this section as well as those discussed in section 5.1 these results should not be relied upon too heavily. Furthermore, no statistical analysis such as ANOVA (analysis of variance) was conducted due to project limitations.

5.3 Reflections from comparisons between measured and provided passive radiator parameter values

For two of the analysed PRs, DSA115 and SD175, the manufacturer had provided parameter values in a data sheet. As can be seen from Table 10, some of the measured and provided values differ quite significantly. However, at the project stage right after having conducted these measurements, it was impossible to determine which of the values, if any, were accurate.

Table 10: Comparison between measured and provided PR parameter values for SD175 and DSA115

PR	Q_{mp}	C (mm/N)	V_{ap} (m^3)	f_{pr} (Hz)	S_{dp} (m^2)
SD175 Measured	3,65	2,27	0,053434	28,71	0,012242
SD175 Data sheet	5,57	1,15	0,0271	24,5	0,01287
DSA115 Measured	3,05	4,38	0,018197	43,25	0,005085
DSA115 Data sheet	3,48	2,27	0,0094	30,9	0,005410

It was not until the end of this project when the PRs' FRs were measured and compared to simulations, that it could be seen that the simulations with provided parameters correlated more accurately with the measured FR charts than the simulations with the measured parameters. See Figure 56-Figure 61.

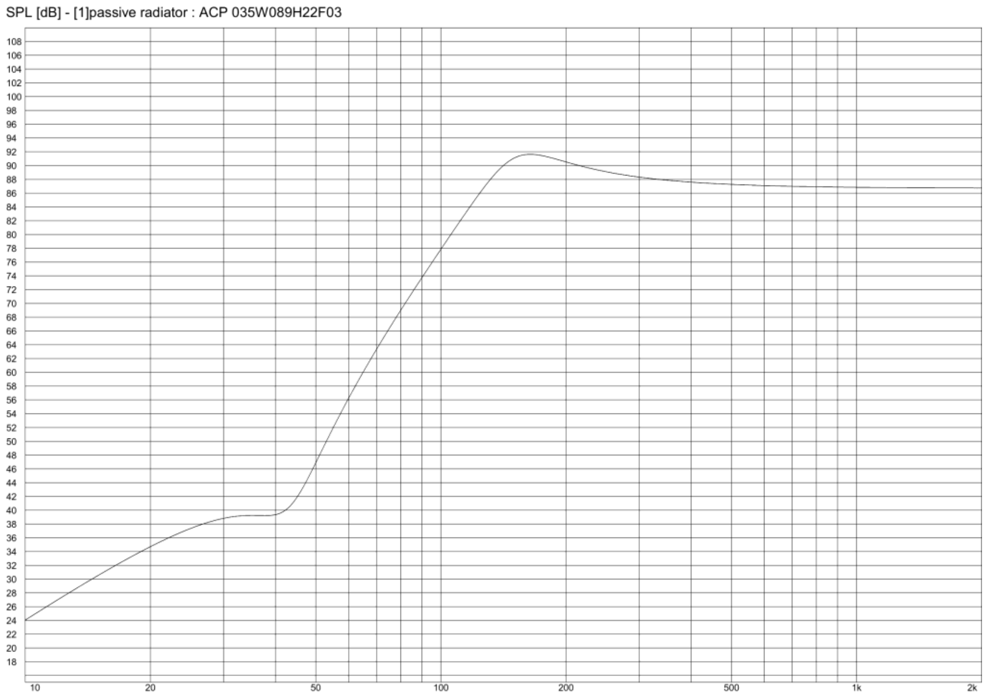

Figure 56: Simulated frequency response with measured PR parameter values for DSA115

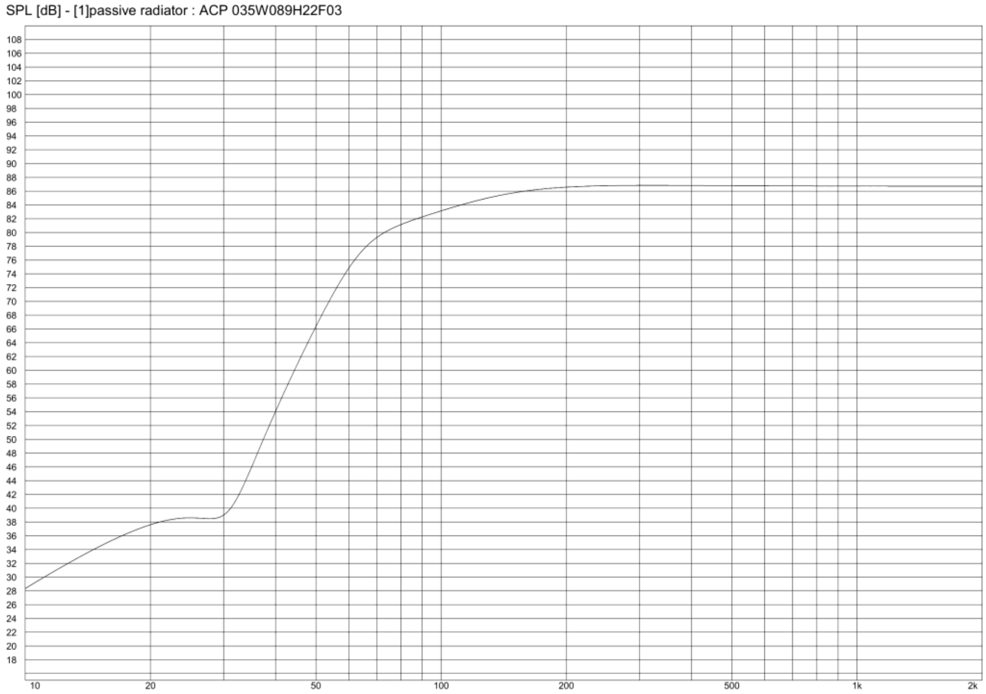

Figure 57: Simulated frequency response with data sheet provided PR parameter values for DSA115

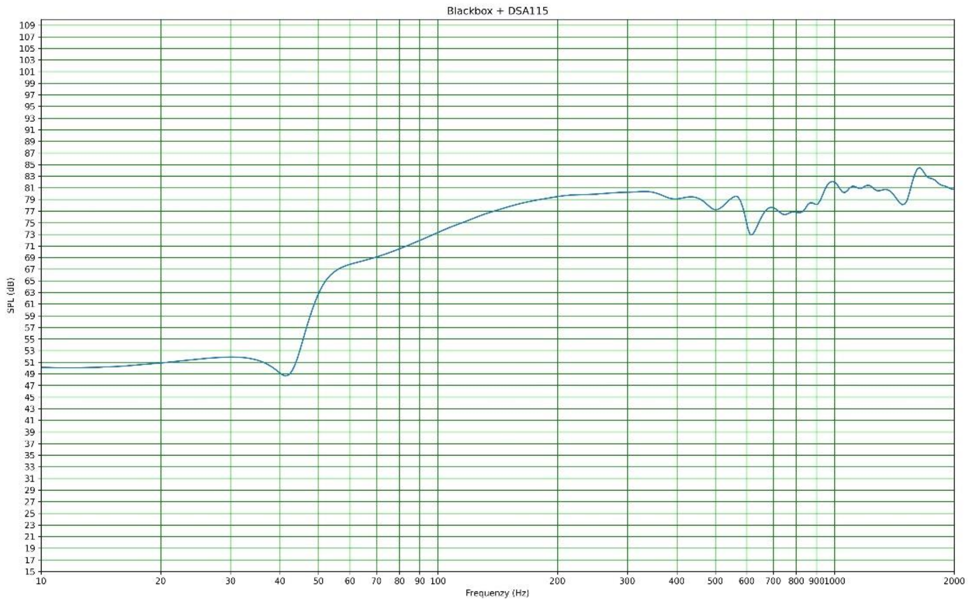

Figure 58: Measured frequency response for DSA115

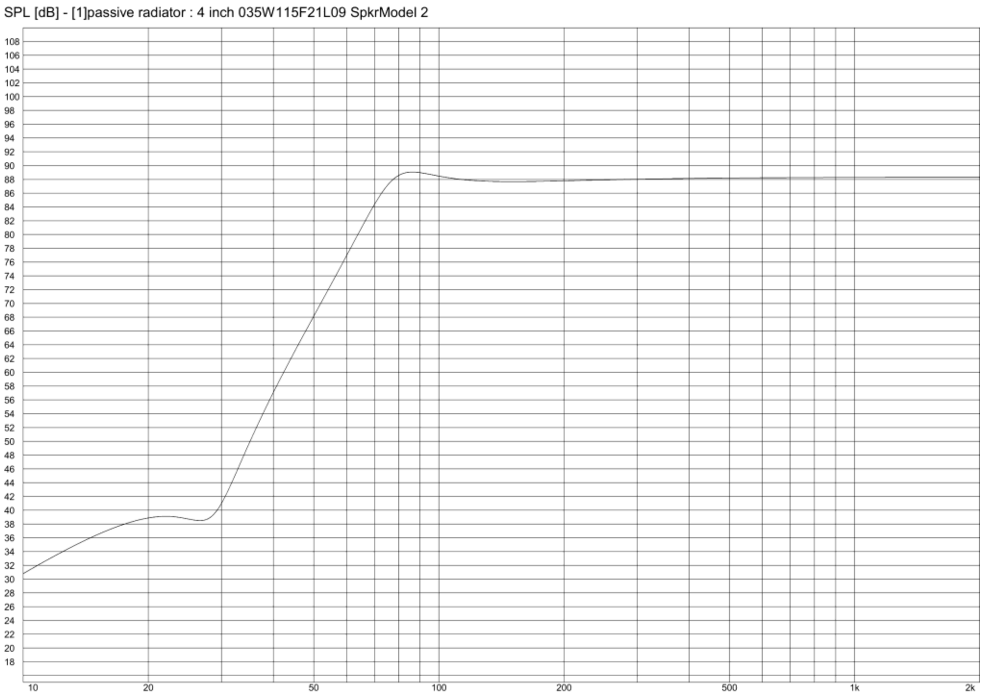

Figure 59: Simulated frequency response with measured PR parameter values for SD175

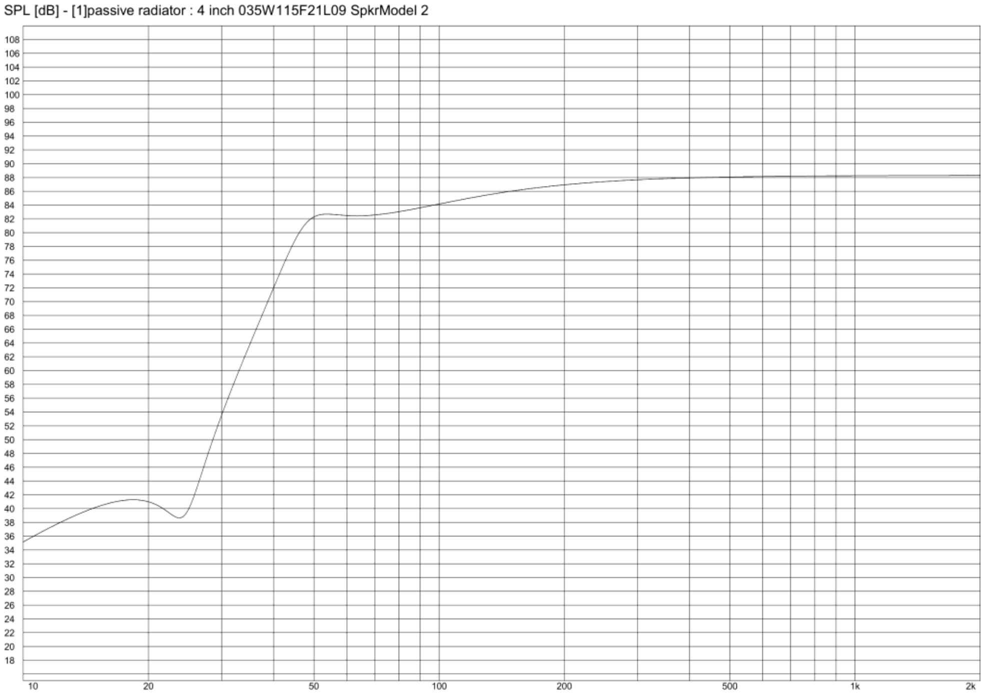

Figure 60: Simulated frequency response with data sheet provided PR parameter values for SD175

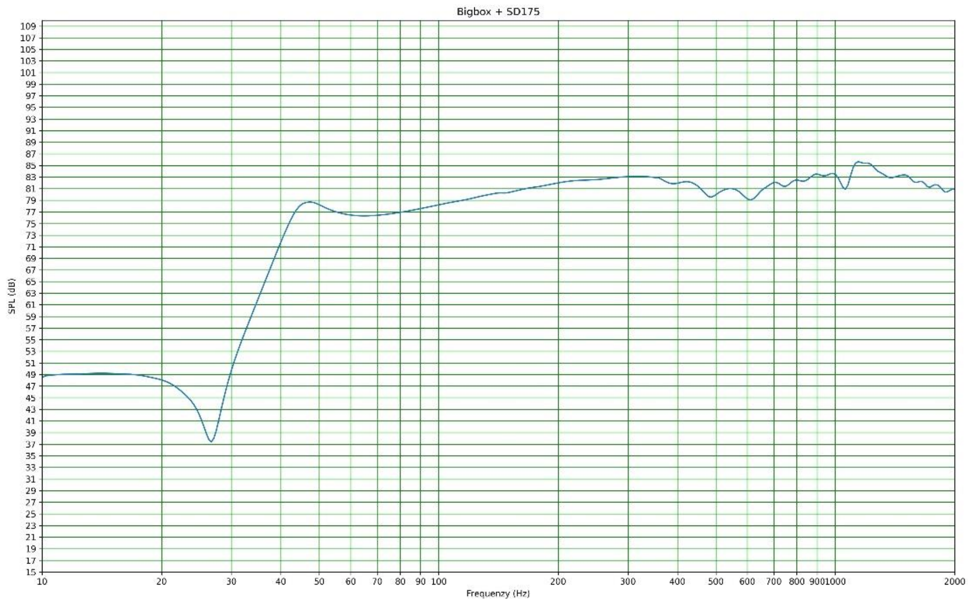

Figure 61: Measured frequency response for SD175

These results implied that there is something wrong with the method of measuring the PR parameters. However, no certain conclusions were able to be drawn of what specific step is performed incorrectly or if the errors follow a general trend, since there are only two samples.

Regarding the compliance and quality factor measurements, one possible source of error could be that the microphone inside the subwoofer does not experience the same sound pressure as the PR. Another factor that may have influenced the results was using Dickason's definition of measuring S_{dp} introduced in section 3.3. When using IEC's definition, the measured value was identical to the provided value for both the PRs DSA115 and SD175. The effect imposed on V_{ap} of using Dickason's definition to measure S_{dp} resulted in a less than 10% decrease in difference between the measured and the provided value for both PRs, compared to using IEC's definition.

Concerning the measurements of the free air resonance frequency two possible reasons for the differing results could be that the subwoofer is not transducing a perfect frequency response, which may affect the PR's oscillations and that the PRs' suspension characteristics may change over time after have being "played in" for a certain number of hours.

5.4 Guidelines

5.4.1 **Measurement guidelines**

Appendix B presents a step-by-step guide of how to measure all relevant PR parameters as well as how to measure their FR when incorporated in a loudspeaker.

5.4.2 **Design guidelines**

One of the goals of this project was to create a guideline to be used when designing a PR incorporating loudspeaker by identifying which PR parameter impact the resulting sound the most, important factors to consider, and hurdles to avoid. Because of the weak results from the FR analyses, it was difficult to identify and rank the importance of each parameter and to pinpoint important factors. Furthermore, this project was limited to FR measurements and did not include other aspects of sound evaluation. Nonetheless, the other findings of this project can be applied as guidelines.

5.4.2.1 Important factors to consider

The Thiele/Small parameters all seem to affect the frequency response. Looking at the FRs of BigBox the area of the PR seems to be an important factor, even if the quantitative analysis does not necessarily support this claim.

PR loudspeakers need to be carefully tuned and should ideally be evaluated iteratively to achieve the desired FR. Due to the limited possibility of tuning a PR (adding mass), several PRs can be evaluated to find optimal characteristics.

5.4.2.2 Individual parameter importance

For resonance frequency, compliance, quality factor, and area it was difficult to rank their internal importance. In section 5.2 a DOE was preformed to evaluate the parameters against each other. The problem was that the parameters of the tested purchased PRs could not be controlled individually. Another problematic aspect was dividing the parameters into two distinctive groups when the values were of transcending character. To set up a proper DOE it would have been necessary to develop own in-house PRs allowing each parameter to be controlled individually.

Regarding maximum extrusion, it was during the project eventually deemed out as a less relevant parameter when analysing PRs. The reason for this was that a physical extrusion limit was never reached, even when the subwoofer was driven with a power of 30W. Since the company's products will not be driven with more power than 14W, the risk of reaching physical extrusion limit is non-existent in the intended use case. Although, as discussed in section 3.5.4, there may be a certain level of extrusion when distortion starts occurring in the PR. However, this was not further investigated in this report.

5.4.2.3 Useful tools

Simulation tools seem to accurately simulate the real frequency responses of PR loudspeakers and can be a useful tool when designing a loudspeaker.

5.4.2.4 Hurdles to avoid

Tuning a PR can be done by adding mass to it, but when this is done new measurements need to be made as some of the Thiele/Small parameters change which is not reflected in the WinISD simulations.

6 Evaluation

6.1 General reflections on the project

The project has been of an exploratory character. The whole purpose was to delve into different paths of analysing and examining PRs. It is therefore natural that some tracks led to dead-ends and many unexpected hurdles appeared along the way. One major hurdle was the development of measurement methods for PR parameters, which required a lot of work. Though not planned as a major part of the project, it became apparent that having a reliable way to measure PRs was important for the future development of PR incorporating audio products for the company. Thus, more work and time was spent on this part than initially planned which caused other parts to be time limited.

At times the project has been developing into different directions simultaneously. During the second half of the project, the available audio lab at the company was often booked for other projects which led to waiting times for performing measurements. To use these waiting times effectively, it was decided to proceed with other processes, such as making own PRs and performing subjective listening tests. However, these two tracks were always relatively low prioritised in relation to performing measurements. With that said, it was still a challenge to constantly adapt to the current situation and prioritise which task to perform at different times.

The double diamond structure used in this project was in hindsight not optimal, mostly due to the divergent nature of developing the measurement methods which was expected to be convergent. This development process almost followed another double diamond structure itself because of its length and iterative process. This meant that not as much focus could be put on the remaining phases, making the full process somewhat imbalanced. Furthermore, since the project did not focus on developing a specific loudspeaker product, the Development phase was not as comprehensive and iterative as one would expect in other projects applying the double diamond structure. The wider focus may also have caused difficulties of prioritisation as the project lacks a centralised goal or product to anchor and rank tasks in relation to, making time a limiting factor for throughout. This meant that the iterative aspect of the double diamond process was not fully utilised. It should be noted, however, that while not optimal the double diamond structure divided the project into succinct parts which helped the authors understand and get an intuitive feel for the natural flow and connections between the different phases.

The conclusion that the PR parameter measurement methods had flaws could not be drawn until the FR measurements were made, which was rather late in the project. This meant that there was no time left to return and continue developing the measurement methods, which seemed reasonable and reliable at the time due to multiple iterations and verifications. Although it causes a disturbing feeling to not have found out the reasons behind why the measured parameter values differ from the provided data sheet values, this project can function as a set off point for further investigations.

All in all, accomplishing this diverse project has been highly educational and fascinating, constantly resulting in new reflections and speculations of how different aspects of PRs can affect the bass sound.

7 Conclusions

7.1 Key findings

This project investigated and explored how several passive radiator (PR) parameters can be measured and how they affect bass sound in loudspeakers. By following and adapting industry standards, methods for measuring the mechanical quality factor, mechanical compliance, free air resonance frequency, and area have been developed to suit the specific needs of the company. PR performance was investigated by constructing modular loudspeaker boxes in order to measure the PRs' FR and analyse the results which indicated that the free air resonance frequency of the PR has the greatest impact on lowering the cut-off frequency f_{3dB} compared to an equivalent sealed box, albeit not by much. However, due to the nature of loudspeakers which need to be individually tuned with regards not only to the PR, but the driver and the box itself, the results were not significant enough for the conclusions to be reliable. Furthermore, the parameter values which were measured differed significantly from the given values for the PRs which had data sheets. When comparing FRs, the simulated FR which was based on given parameter values more closely resembled the measured FR than the simulated FR which was based on measured parameter values. This indicates that there are flaws in the measurement methods developed and requires further investigation.

7.2 Further investigations

As this project focused on general applicability and did not reach any definitive conclusions, there are many avenues that could be investigated further.

The main avenue would be to continue to develop the PR parameter measurement methods as they seem to yield incorrect values. This could be achieved in multiple ways. For instance, analysis of the physics and mechanics of the PRs the could enhance understanding of individual parameters and give indication of how they should be measured correctly. Further testing of different PRs with known parameter values could have to be carried out to explore if there are any trends regarding the difference between provided and measured values. Further measurements of PRs with given values may also give indications of how the measurement methods could be modified to generate results that better correspond with the provided values.

Another interesting investigation to proceed with would be the creation of own in-house passive radiators, experimenting with shape, material, and thickness of both the suspension and the middle plate. It could give a deeper understanding to what extent each parameter individually impacts the FR and may also lead to indications of what the sources of error could be in the parameter measurement methods.

It would also be exciting to perform elaborated and large-scale listening tests to see if the perceived hearing results correlates to the FR charts. Preferably the tests would be designed to eliminate as many subjective interpretations as possible, e.g. asking the participants to rate more specific aspects of bass sound rather than the general experience.

This project never aimed to construct any optimised loudspeakers. However, it would be interesting to see if the findings in this report could contribute to building an optimised loudspeaker and see if it performs as expected. An optimised loudspeaker would presumably show a significant lowering in cut-off frequency and be unanimously perceived to reproduce better bass in blind listening tests compared to its sealed equivalent. In the case of creating many optimised loudspeakers generating significantly distinguishable results, more definitive conclusions could have been drawn.

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Appendix A Time plan and work distribution

A.1 Work distribution

All work was evenly divided among the two authors of the project. While for the most part tasks were performed in tandem, there were a few exceptions such as when one of the authors had a potential workplace interview, was sick, or was on holiday. Furthermore, at times, focus was spread on different areas of the same part of the project. For instance, during measurements in the audio lab, one author would focus on performing the actual measurements while the other would focus on programming the scripts which would handle and interpret the data, or during report writing where one author might write and the other would create presentable figures and tables. In all these instances the pair discussed and evaluated the individual work together either during or after the specific task was completed.

A.2 Project plan and outcome

During the first week of the project a project plan in the form of a Gantt chart was established listing all predicted activities and their estimated time requirements. The resolution was set to days as to not be limited to entire weeks, however, such a highly detailed plan was not entirely necessary.

The outcome of the project was a bit different from the plan, the main difference being the define stage, which took a lot more time than expected. The iterative process of configuring a test setup, running tests, programming scripts to handle and interpret the data, analysing the results, and discussing them with audio engineering experts was extremely time consuming and a lot more difficult than anticipated. As a result, all consequent steps of the project were delayed, and time became a limiting factor at the end. Another thing to note is that the project took a slightly different course than initially planned. The company supervisor wanted the project to focus more on the development of PR measurement methods to make sure that these could be fully utilised in the future rather than the implementation of PRs in loudspeakers and their effect on audio output. As such, while the latter parts of the project became limited, it was not due to lack of work being done during the define stage but rather extra work. Both the planned and actual outcome Gantt charts are presented in Figure A1 and Figure A2 respectively.

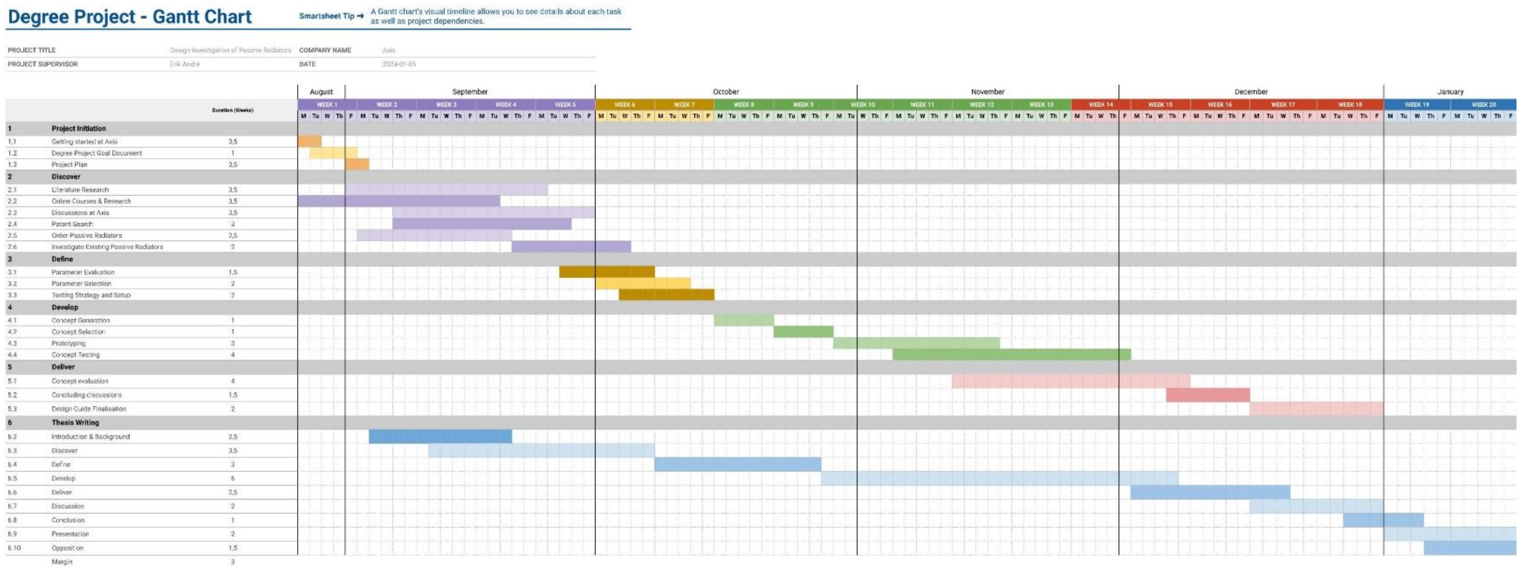

Figure A1: Gantt chart of planned activities

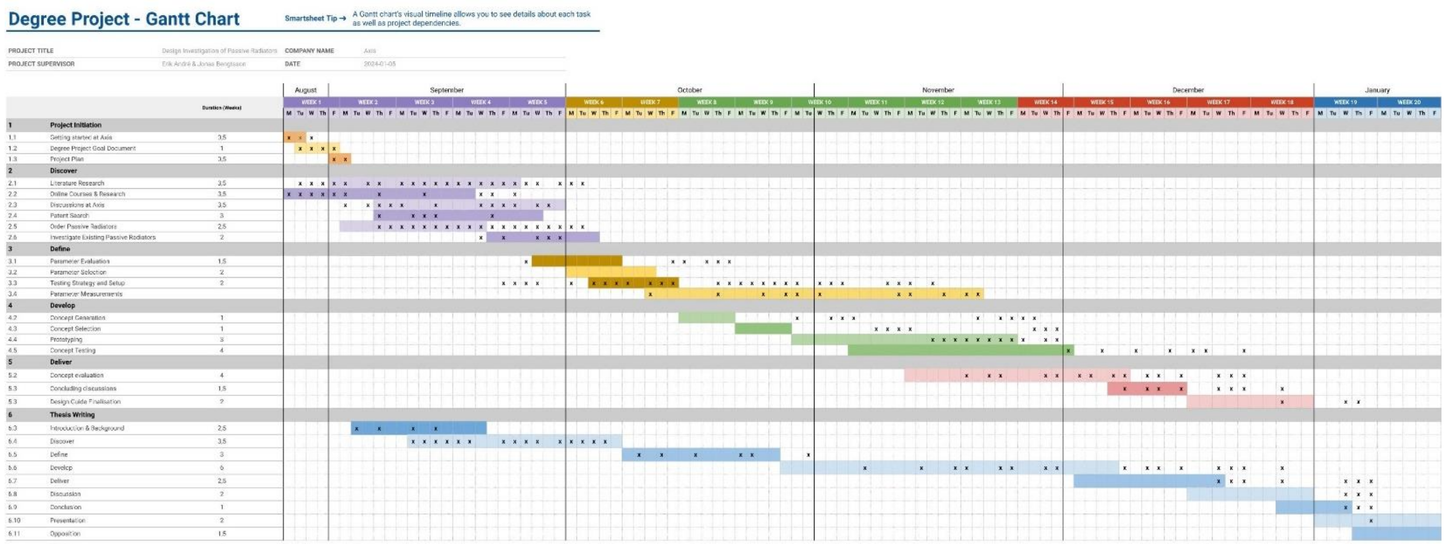

Figure A2: Gantt chart of planned and actual activities

Appendix B Guide for Passive Radiator Parameter Measurements

Some parts of the guide are redacted.

Guide For Passive Radiator Parameter Measurements

Introduction

This guide is a product of the master's thesis of Fabrice Dufberg and Valter Hamberger. For further information about the measurement methods, see the full degree project report available at [redacted].

Components

The following components are required when measuring parameters:

- Subwoofer
- Wooden panel to mount PR onto subwoofer
- ¼ inch microphone
- Co-axial cable adapter (1/2 inch to ¼ inch)
- Aluminium frame
- Micro-Epsilon OptoNCDT 2300 laser (laser, power cable, power adapter, USB cable)
- PR holder to mount PR onto aluminium frame
- Audio Precision Audio Analyzer and software
- Micro-Epsilon SensorTool software (available for free at Most Advanced Laser Displacement Sensor | Micro-Epsilon)

The following components are required for measuring frequency response:

- Speaker box which incorporates the PR
- Cart with foam mattress

- ½ inch microphone
- Microphone stand
- Audio Precision Audio Analyzer and software
- VituixCAD

Free Air Resonance Frequency

The free air resonance frequency measurements are based on the IEC (International Electrotechnical Commission) 62459 standard.

Components

- Subwoofer (closed, no PR)
- Aluminium frame
- Micro-Epsilon laser (laser, power cable, power adapter, USB cable)
- PR holder to mount PR onto aluminium frame
- Audio Precision Audio Analyzer and software

Setup

1. Mount the PR onto the aluminium frame using a custom holder which can be designed and 3D-printed. The laser has a working range between 40 and 60mm, so make sure the holder keeps the PR at a distance within this range. Generally, the free air oscillations are <1 mm so there is no need for the PR to be at exactly 50 mm distance from the laser.
2. Place the subwoofer such that the driver 10 cm from the PR.
3. Adjust the height of the PR and laser such that the PR is directly in front of the subwoofer driver.
4. Make sure that the aluminium frame is stable.
5. Connect subwoofer to audio output and laser to power and PC.

Picture of setup

Method

1. Open the AP template SpeakerPassiveMeasurements_xW_yOhm_laser available at NBAudio ("Y:\Measurement_templates\Speaker passive measurement\SpeakerPassiveMeasurment_xW_yOhm_Laser.approjx")
2. Set the frequency range 1-1000 Hz over 15s. The power output has no effect on resonance frequency, however multiple measurements at different powers can be a good idea to reduce uncertainty.
3. Run the sequency and name it appropriately.

4. The template exports three files. Disregard all but the laser response file.
5. Run the python script *resonance_frequency_free_air.py* ("Y:\Results_others\Exjobb - Valter & Fabrice\Script_for_laser_measurments\resonance_frequency_free_air.py") and observe the output.

Mechanical Compliance

Mechanical compliance measurements are based on the IEC (International Electrotechnical Commission) 62459 standard.

Components

- Subwoofer
- Wooden panel to mount PR onto subwoofer
- ¼ inch microphone
- Co-axial cable adapter (1/2 inch to ¼ inch)
- Aluminium frame
- Micro-Epsilon OptoNCDT 2300 laser (laser, power cable, power adapter, USB cable)
- PR holder to mount PR onto aluminium frame
- Audio Precision Audio Analyzer and software
- Micro-Epsilon SensorTool software (available for free at Most Advanced Laser Displacement Sensor | Micro-Epsilon)

Setup

1. Attach the microphone onto the adapter inside the subwoofer.
2. Mount the PR onto the back panel of the subwoofer. A custom adapter can be designed and 3D-printed. Avoid air leakage.
3. Place the subwoofer such that the PR is 50mm from the laser since the laser has a measuring range of 40-60 mm. Due to the larger amplitudes of oscillation, it is necessary for the PR (at rest) to be in the middle of the laser's measuring range. For amplitude larger than the larger than 10 mm the subwoofer can placed such that the PR is at the close of far end of the laser's range, but this only allows for either positive or negative amplitudes to be measured, not both.
4. Adjust height of laser if necessary.
5. Make sure that both the subwoofer and aluminium frame are stable.
6. Connect subwoofer to audio output, microphone, and laser to power and PC.

Method

1. Open the AP template SpeakerPassiveMeasurements_xW_yOhm_laser available at NBAudio ("Y:\Measurement_templates\Speaker passive measurement\SpeakerPassiveMeasurment_xW_yOhm_Laser.approjx")
2. Ser the frequency range 1-1000Hz over 15s. Run the sequence for a relevant range of powers (more measurements yield more accurate results). The microphone can generally handle power up to 30W.
3. The template exports three files. Save all compliance measurement files together in a separate folder (not together with free air resonance frequency files).
4. Run the python script *Compliance_measurement.py* ("Y:\Results_others\Exjobb - Valter & Fabrice\Script_for_laser_measurments\Compliance_measurement.py") and observe the results. The script outputs the results as a .csv file in the parent directory.

Mechanical Quality Factor

Mechanical quality factor measurements are based on the IEC (International Electrotechnical Commission) 62459 standard.

Follow the guide for compliance measurements.

Components

Same as for compliance measurements.

Setup

Same as for compliance measurements.

Method

1. Follow steps 1-3 in method for compliance measurements. If compliance measurements have already been made skip this step.
2. Run the python script *Q_mp_measurement* ("Y:\Results_others\Exjobb - Valter & Fabrice\Script_for_laser_measurments\Q_mp_measurement.py") and observe the results. The script outputs the results as a .csv file in the parent directory.
3. Optional: The python script *Q_mp_measurement_singular* ("Y:\Results_others\Exjobb - Valter &

Fabrice\Script_for_laser_measurments\Q_mp_measurement_singular.py ") can be run to see graphs for an individual measurement.

Area

The area, S_{dp}, is the addition of the cone/plate area and a third of the suspension area. For the most general form, a circular PR, the area is calculated using the following equation.

$$S_{dp} = \frac{\pi \times D^2}{4}$$

Where D is the total PR diameter, which is the diameter of the plate and one third of the suspension at both ends (Dickason, V. *Loudspeaker Design Cookbook*, 2006, p.37).

V_{ap}

Can be calculated from mechanical compliance and area using the following equations:

$$C_{ap} = C_{mp} \times S_{dp}^2$$

$$V_{ap} = C_{ap} \times 1.42 \times 10^5$$

Where S_{dp} is the effective area of the PR.

Measuring Frequency Response

Frequency response measurements are based on the internal [redacted] guide "Guideline for acoustic measurements at T0", chapter 10. ("Y:\Measurement_templates\Instructions\Guideline for acoustic measurements at T0.docx").

Components

- Speaker box which incorporates the PR
- Cart with foam mattress
- ½ inch microphone
- Microphone stand
- VituixCAD software

Setup

Far field:

1. Place loudspeaker on the foam mattress and connect terminals.
2. Place the microphone 1,78 m from the speaker driver. Adjust the height of the microphone until it is level with the driver.

Near field driver:

1. Place the microphone 5 mm from the speaker driver. Adjust the height of the microphone until it is level with the centre of the driver.

Near field PR:

1. Place the microphone 5 mm from the PR. Adjust the height of the microphone until it is level with the centre of the PR.

Method

1. Open the AP template "SpeakerPassiveMeasurements_xW_yOhm" available at NBAudio ("Y:\Measurement_templates\Speaker passive measurement\SpeakerPassiveMeasurment_xW_yOhm.approjx")
2. Set frequency range to 1 Hz - 20 kHz at 1W of power.
3. Follow steps 1-2 for far field, near field driver and near field PR.
4. Run python script *convert_ap_to_vituix_data.py* ("Y:\Results_others\Exjobb - Valter & Fabrice\Script_for_laser_measurments\convert_ap_to_vituix_data.py") to convert AP files to new files compatible with VituixCAD.
5. Open Merger tool in VituixCAD. Import measurement files and adjust the near field dB scale to fit.
6. Export results and run python script *Scaled_plots_vituixCAD.py* ("Y:\Results_others\Exjobb - Valter & Fabrice\Script_for_laser_measurments\Scaled_plots_vituixCAD.py") to convert the exported results to a graph.

Further improvements

- Resonance frequency is not calculated using FFT.
- Python scripts need to be run separately and are not part of the AP template sequence which isn't very convenient.
- No GUI for the python scripts.

- Each AP sequence for different powers needs to be run separately and manually. Sometimes the software plays the sweep twice, making the measurement take twice as much time.

Appendix C Compliance comparisons

C.1 PR3A

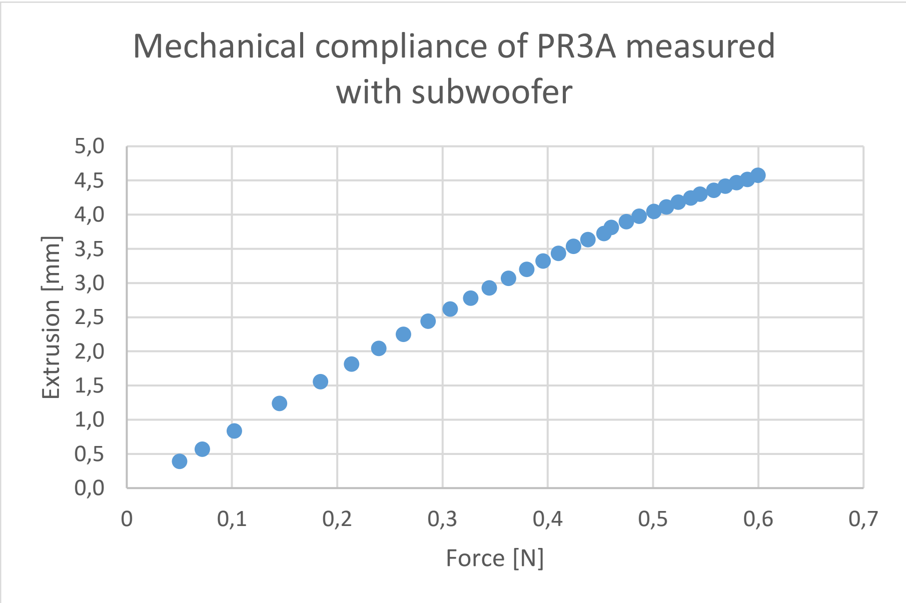

Figure C1: Mechanical compliance of PR3A measured with subwoofer

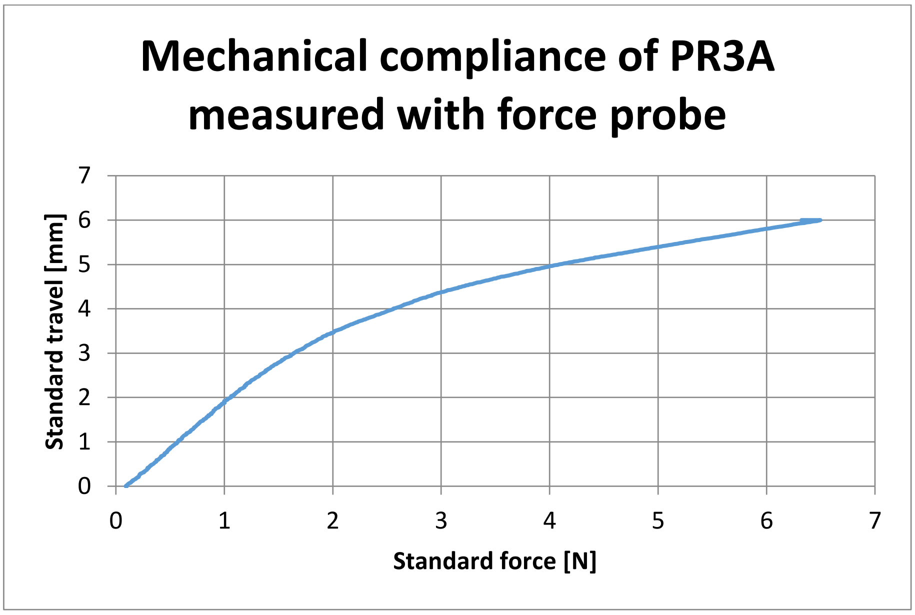

Figure C2: Mechanical compliance of PR3A measured with force probe

C.2 PR6A

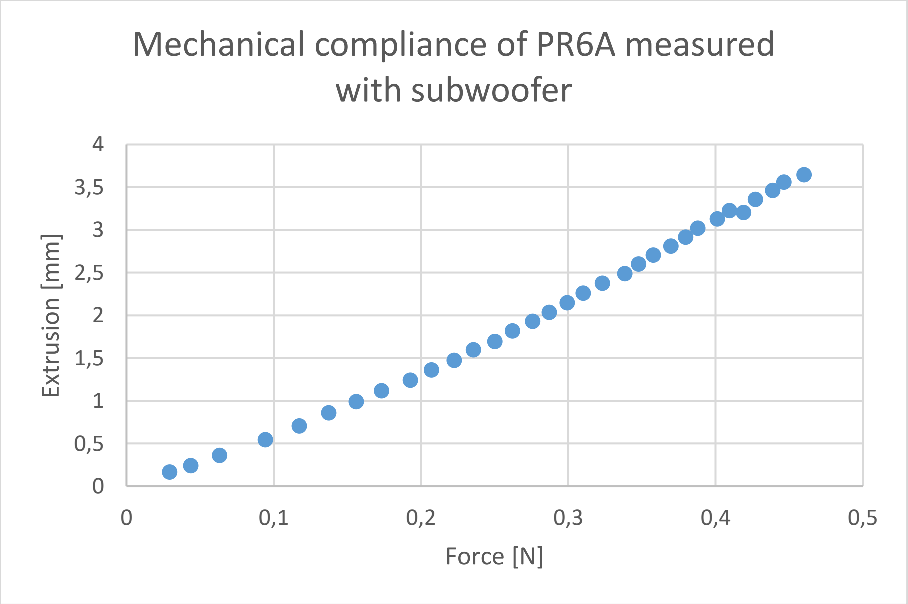

Figure C3: Mechanical compliance of PR6A measured with subwoofer

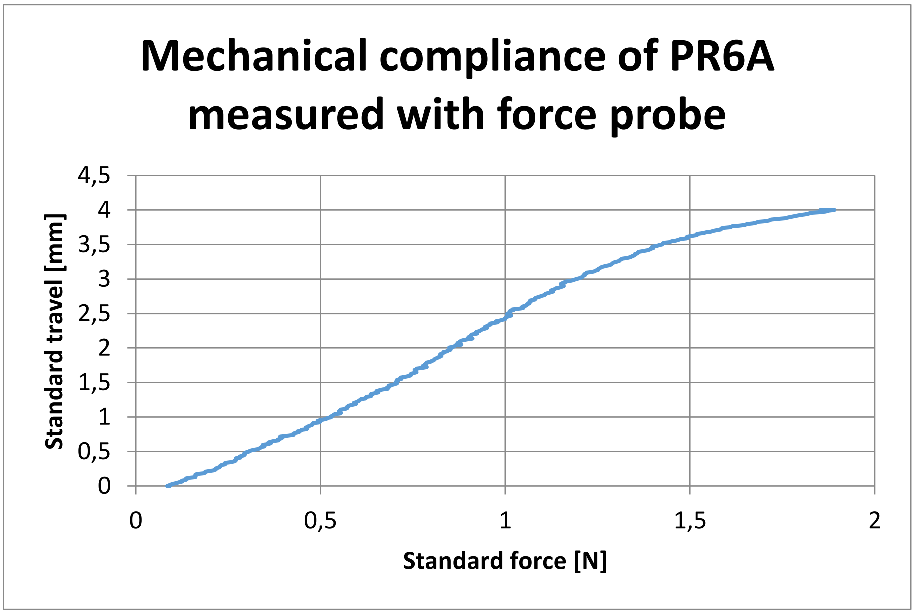

Figure C4: Mechanical compliance of PR6A measured with force probe

C.3 PR8A

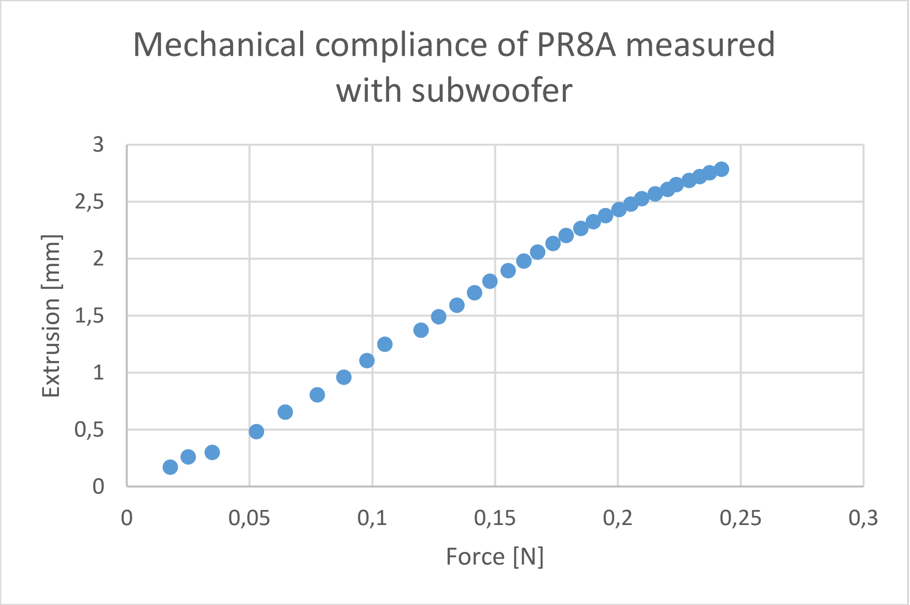

Figure C5: Mechanical compliance of PR8A measured with subwoofer

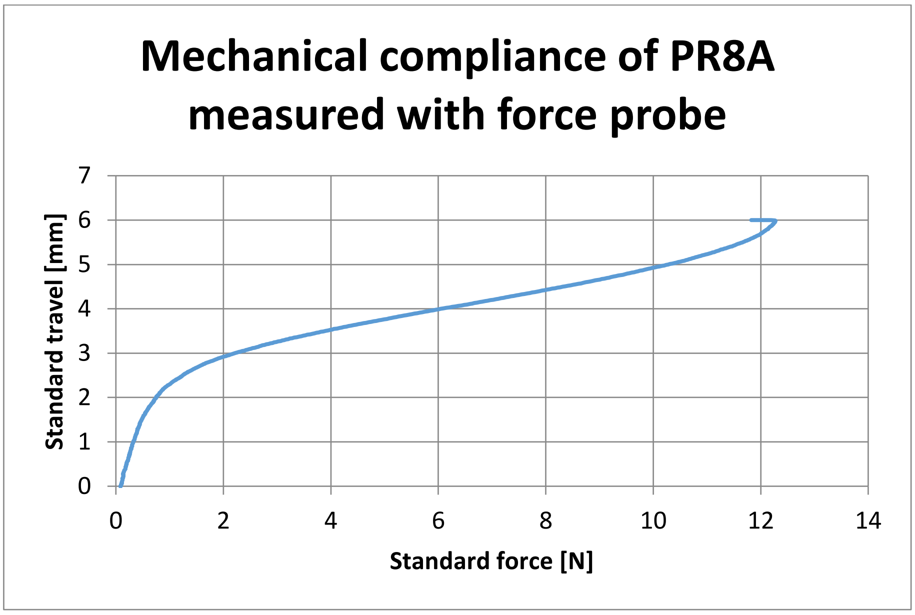

Figure C6: Mechanical compliance of PR8A measured with force probe

C.4 PR11

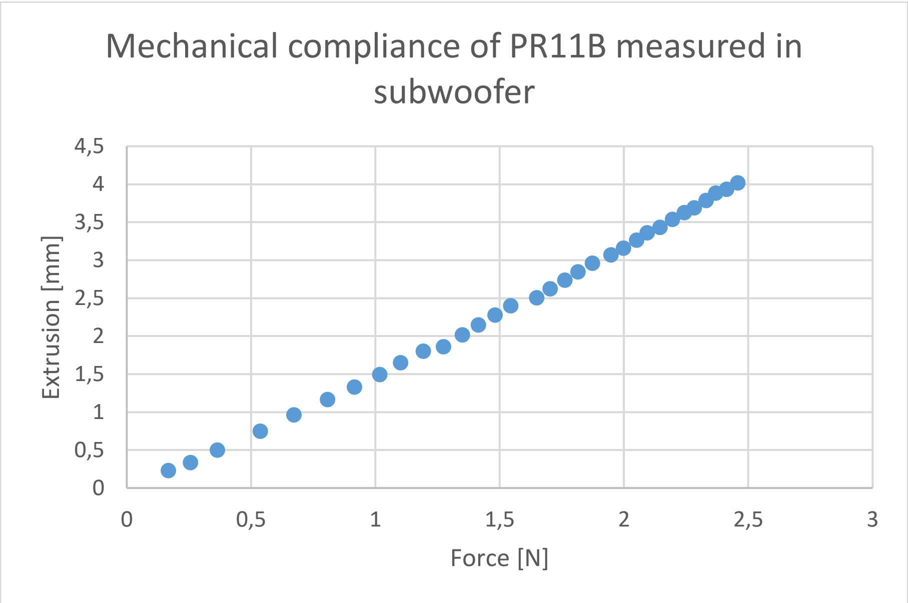

Figure C7: Mechanical compliance of PR11B measured with subwoofer

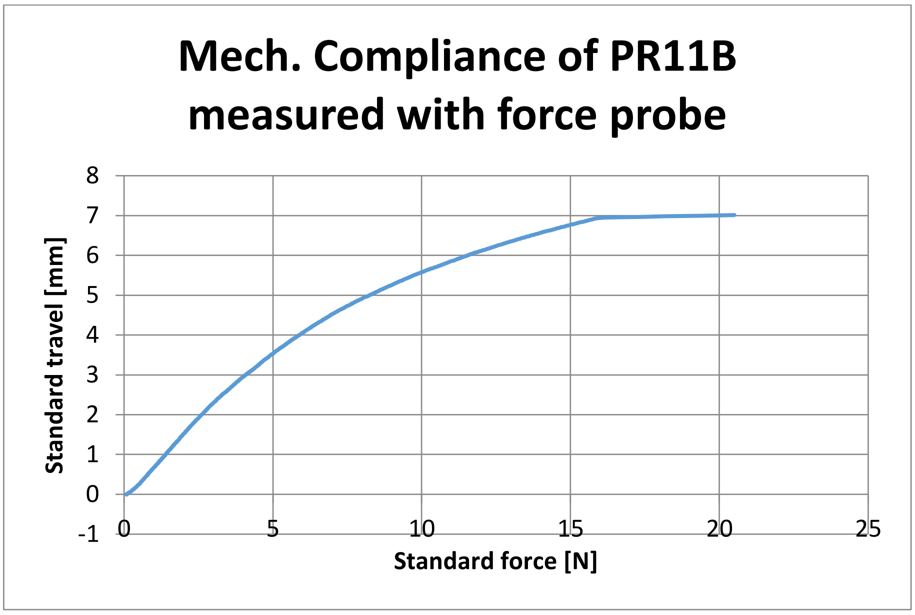

Figure C8: Mechanical compliance of PR11B measured with force probe

Appendix D Measured frequency responses

A selection of measured frequency responses is included in this appendix.

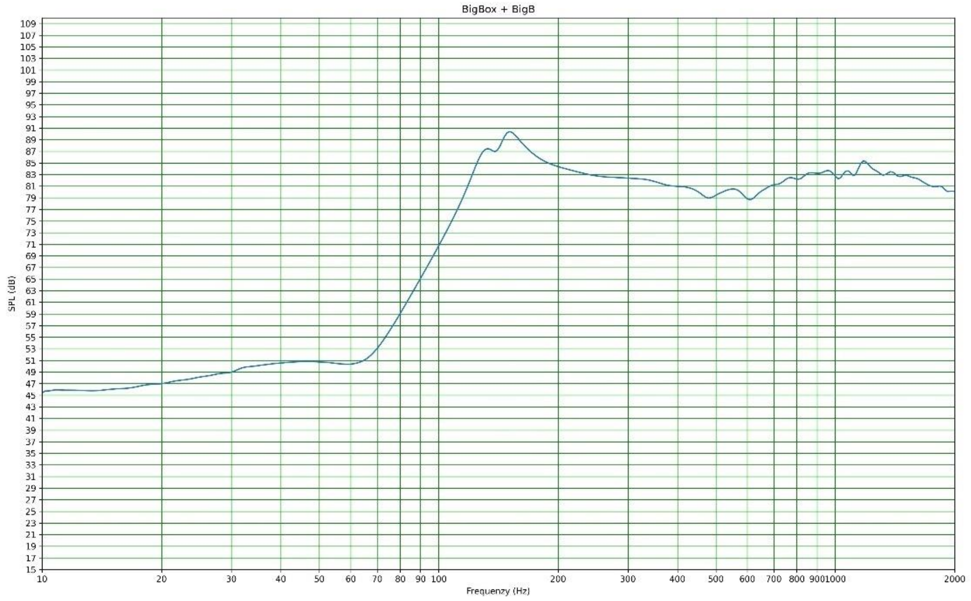

Figure D1: Measured frequency response of BigBox + BigB

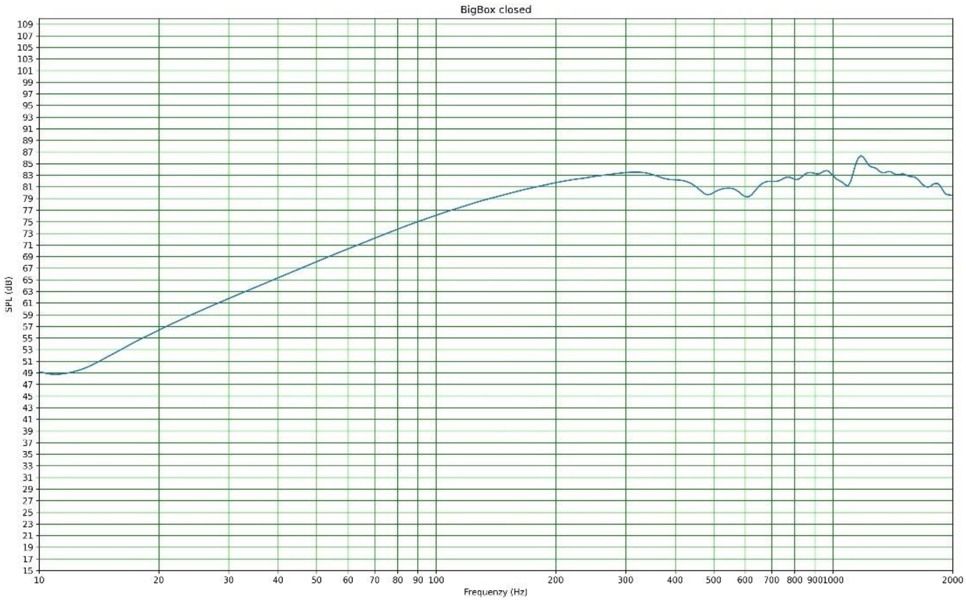

Figure D2: Measured frequency response of BigBox closed

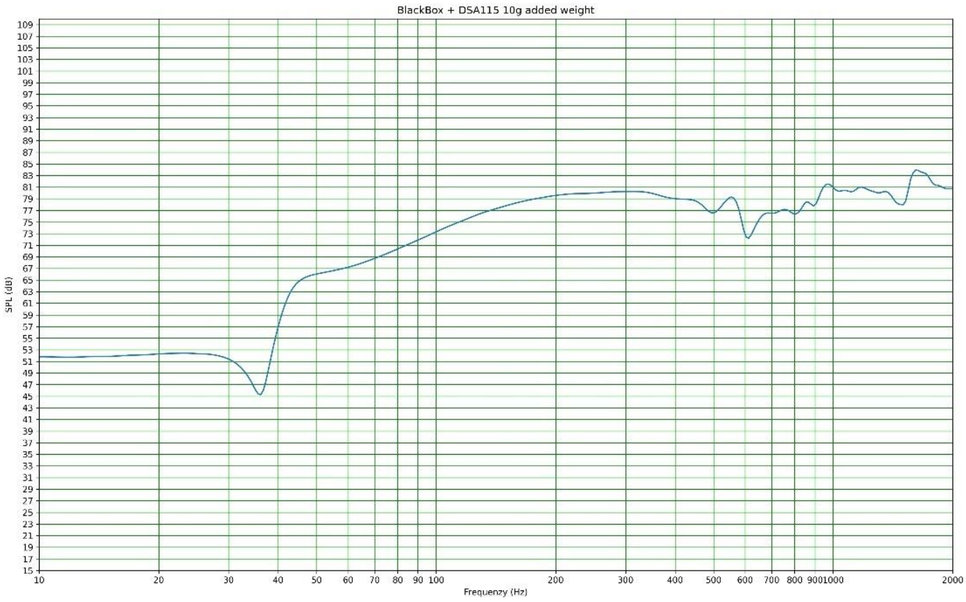

Figure D3: Measured frequency response of BlackBox + DSA115 10g added weight

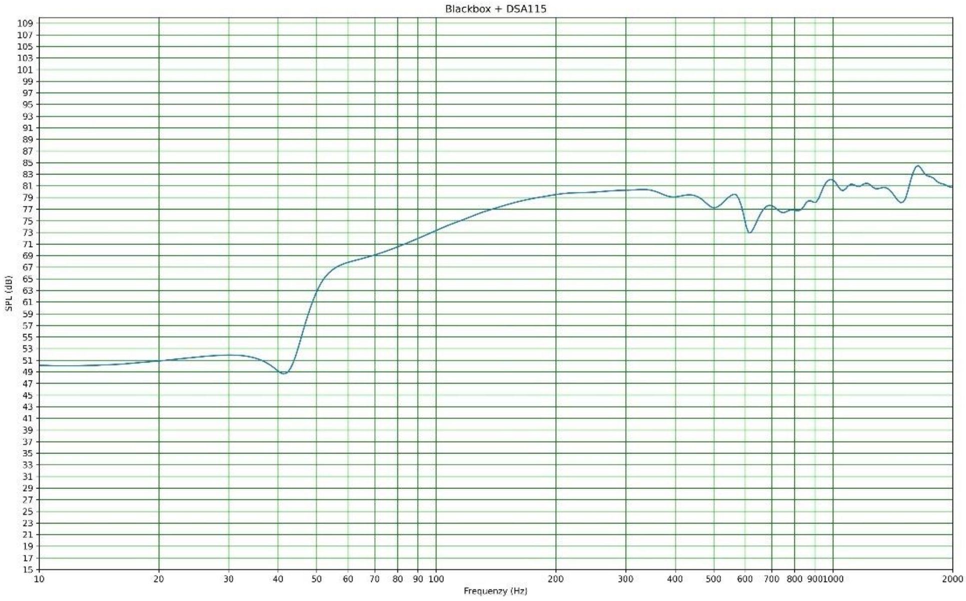

Figure D4: Measured frequency response of BlackBox + DSA115

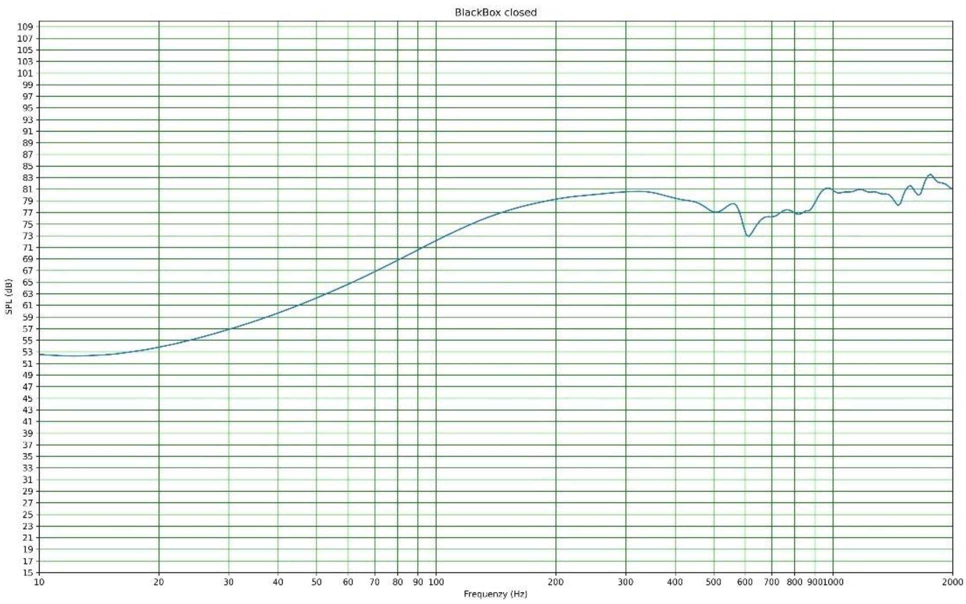

Figure D5: Measured frequency response of BlackBox closed

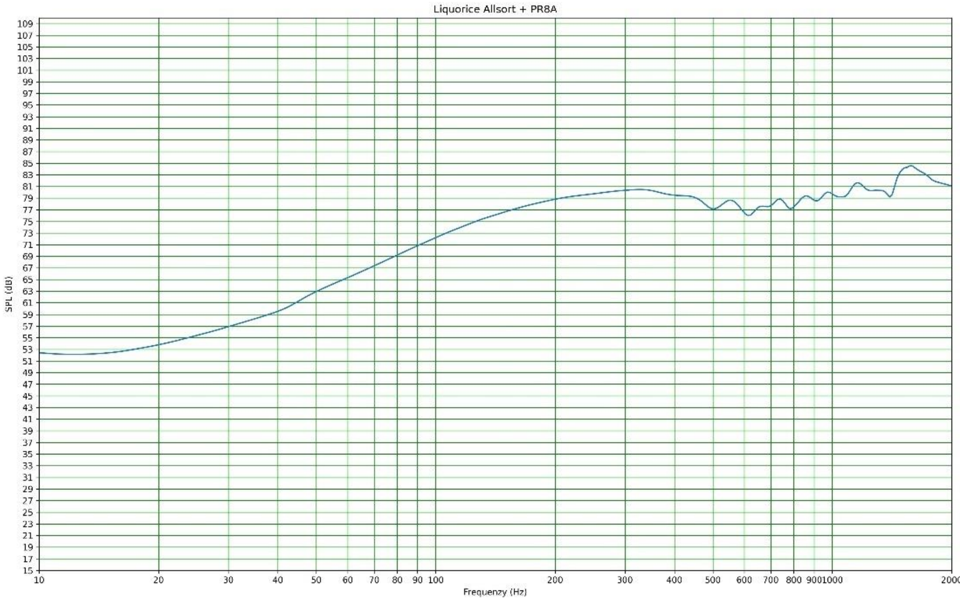

Figure D6: Measured frequency response of Liquorice Allsort + PR8A

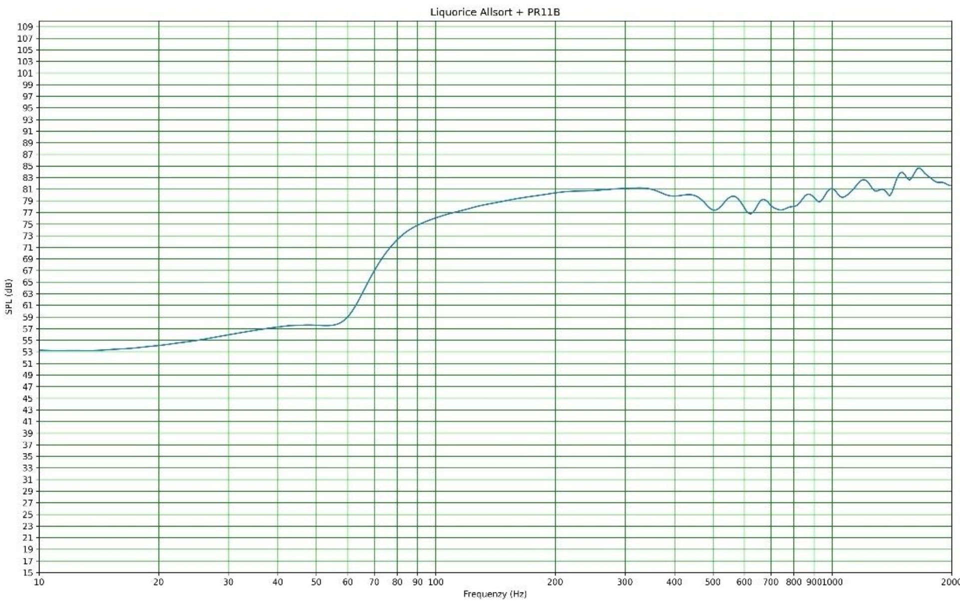

Figure D7: Measured frequency response of Liquorice Allsort + PR11B

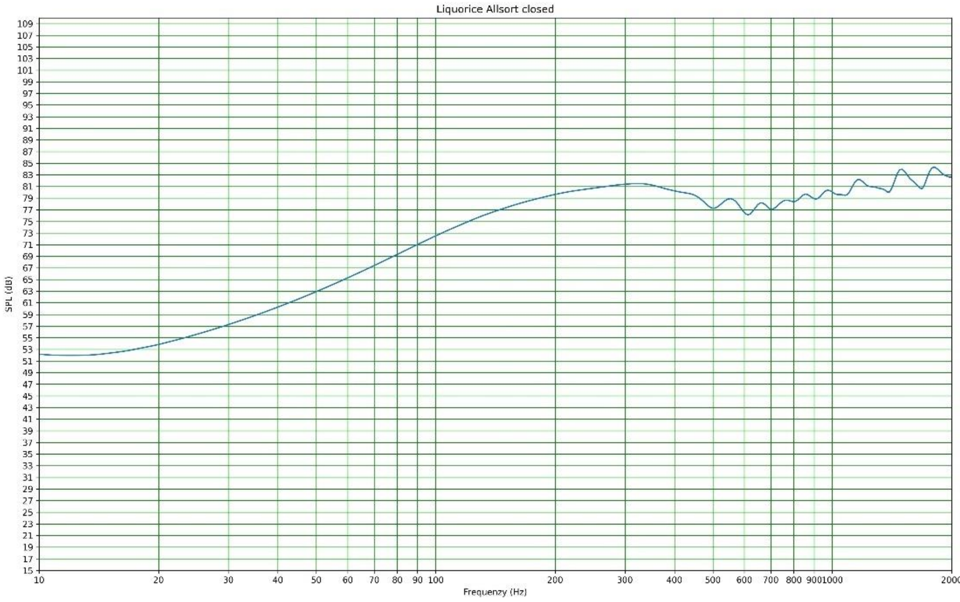

Figure D8: Measured frequency response of Liquorice Allsort closed