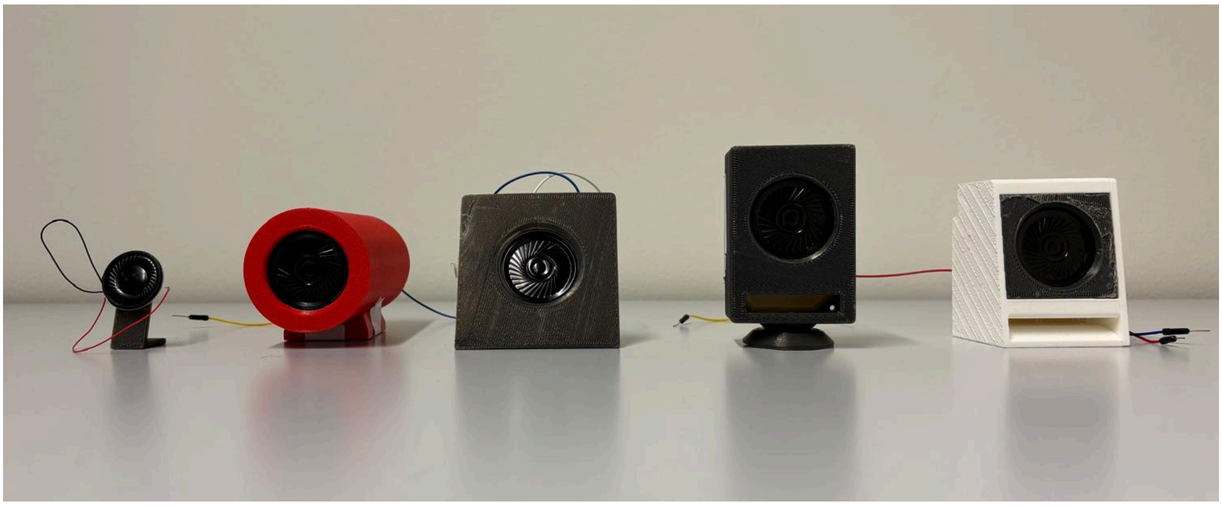
FINAL PROJECT REPORT

Acoustics Engineering



Rita Cots Forteza - U218913

Aina Gutiérrez Llaó - U213911

Pau Noguera Mulet - U213916

Xavier Riera Feliu de la Peña - U214387

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Acoustics Engineering

ÍNDEX

1. INTRODUCTION:

1.1. Context and background

Sound is generated by the vibration of the particles in a medium. When an object vibrates, its vibrations create pressure waves that propagate in all directions, creating sound waves that move nearby particles and carry the vibrations further. The properties of these vibrations determine the behaviour and characteristics of the sound wave: the frequency of the sound wave determines the pitch of the sound produced and the amplitude, its volume. During the transmission, the properties of the medium, such as its density and the speed of sound in the medium, influence the speed and quality of the sound. Other factors, such as the room in which the sound is generated or the speaker enclosure used, also affect the transmission of the sound. Finally, when said sound waves reach the receiver (a microphone, a human ear, etc.), the pressure variations of the sound wave are transformed into electrical signals that can be analyzed either digitally or by our brain.

1.2. Problem statement and objectives

The main objective of this report is to study how room acoustics and speaker enclosures affect the perceived sound. During the project, we used five different 3D printed speakers with different enclosures and characteristics. To analyse how the different enclosures work, we recorded the same sound using all five speakers and computed the transfer function of each of the recorded sounds. Furthermore, we repeated the recording in a different room to also understand how different acoustics and reverberation affect and modify the sound. Finally, we conducted recordings using both a low-fidelity device (a Nothing phone) and a high-fidelity sound Zoom recorder to evaluate how the choice of equipment influences the quality and characteristics of the captured sound. The aim of the report is therefore to compute the transfer function of each speaker used and the transfer function of the rooms where the audios were recorded. Once these have been calculated, they can be applied to the original sound in order to synthetize a sound that resembles and imitates the characteristics of the different speakers and rooms.

1.3. Hypothesis

As we have learned in the theory sessions, speaker enclosures and room acoustics significantly affect how a sound wave is propagated through a medium. Nonetheless, not all speaker enclosures have the same impact as others. The most common speaker shape used by manufacturers is the rectangular geometry because of its straight walls and sharp corners. For this reason, and based on what we have learned in the theory sessions, we believe that both speakers **4** and **5** would generate the best results, with the least distortion generated and the highest fidelity to the original sound.

Taking into account the rooms used for the recordings, we think that the soundproofed room will produce recordings with the least reverberation and distortion due to its controlled acoustic environment, designed to absorb sound reflections and minimize interference. Conversely, we expect the library room, which is less acoustically treated and has reflective surfaces such as walls, and tables, to result in recordings with more reverberation and sound coloration.

Additionally, we predict that the type of recording equipment will also influence the perceived quality of the captured sound, with the high-fidelity Zoom recorder providing more accurate and consistent recordings than the low-fidelity Nothing phone. This is because professional-grade equipment is designed to capture a wider dynamic range and reproduce frequencies with greater precision, whereas lower-fidelity devices typically compress audio and introduce noise.

2. METHODOLOGY:

2.1. Experimental setup

The first step of the project was to 3D print the five speakers. Each one of the speakers have different geometry and enclosure properties and, therefore, their transfer functions are different and affect the generated sound in a different way. Once we printed the speakers, we assembled the circuit using an MP3-DF Mini Player Module, a MicroSD card and a 4.5 V voltage supply. We also assembled each speaker enclosure with a speaker with 2W of power.

Figure 1. Material for the circuit

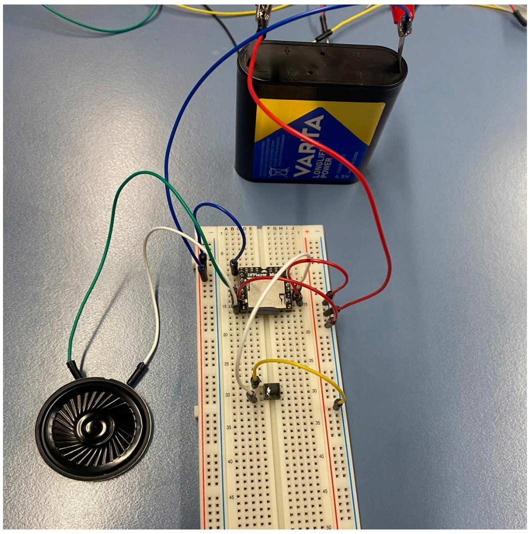


Figure 2. Assembly of the circuit

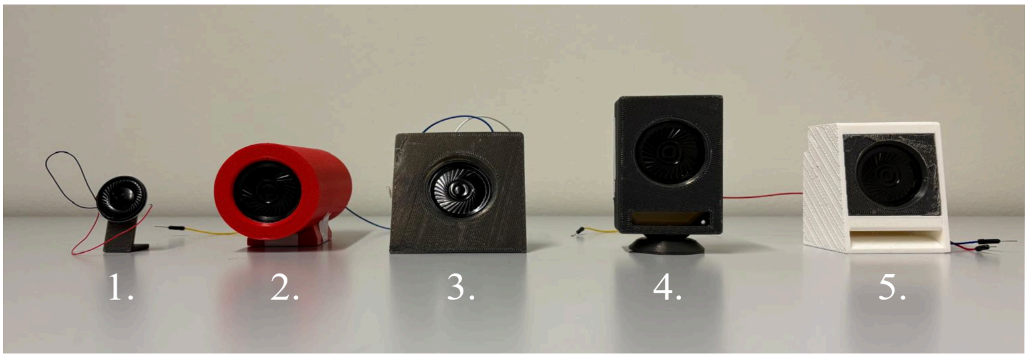


Figure 3. All of the speakers

After assembling all five speakers, we went to UPF 54.025's classroom and library to record the audio using the different speakers. Speaker **1** does not have an enclosure, while Speaker **3** is equipped with an open enclosure or infinite baffle support. These two configurations alter the generated sound differently compared to closed-enclosure designs. Specifically, the sound waves emitted from the back of these speakers interfere with the waves generated at the front, leading to resonance and diffraction effects.

In contrast, the remaining speakers (**2**, **4** and **5**) have closed enclosures, which amplify the output by reducing interference from the waves coming from the back.

The audio we used is the laser gun sound provided in Aula Global. During the recordings, we kept the initial conditions for each speaker the same. This included keeping the placement of the speaker and the sound recorder constant across all speaker enclosures and in both testing environments.

2.2 Environmental Conditions

As previously mentioned, the recordings were conducted in two distinct spaces with different acoustic characteristics: the soundproof room at UPF and one of the library's pods.

2.2.1 The soundproof room

At UPF, we have access to a soundproof room where we used four acoustic panels. These panels absorb sound energy, reducing reflections and reverberation to create a "dry" or "dead" acoustic environment that emphasises direct sound. By using them, we tried to replicate an anechoic chamber, allowing us to capture the raw sound produced by the speakers without interference from external factors or alterations caused by the room's transfer function.

In an anechoic chamber, distance perception depends entirely on sound level (volume). As the distance from the sound source doubles, the volume decreases by approximately 6 dB, following the inverse square law. However, given that our set up is not entirely anechoic (we would have to cover the room with acoustic panels instead of using just four panels), some reverberation was created, causing some distortion and resonance.

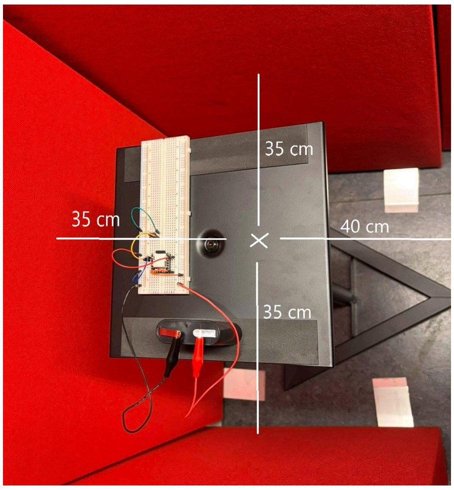


Figure 4. Measures of the room

Figure 5. Soundproof room

2.2.2 The library room

The second room we used for the recordings was one of the workrooms located on the second floor of the library. We chose this space because of its simple architecture.

The room is characterised by highly reflective materials, which reflect most sound waves instead of absorbing them. This creates a “bright” and “live” acoustic environment, where sound is sustained over a longer period of time.

The distant walls and lack of wall decorations contribute to the development of more complex and spacious reverberation patterns. In this environment, distance perception is influenced by the balance between direct sound and the surrounding reverberation.

Unfortunately, the air conditioning in the chamber was running during the recordings, resulting in background noise. This interference could impact the accuracy of the analysis and potentially alter the synthesis process by introducing unwanted artifacts when replicating the original sound.

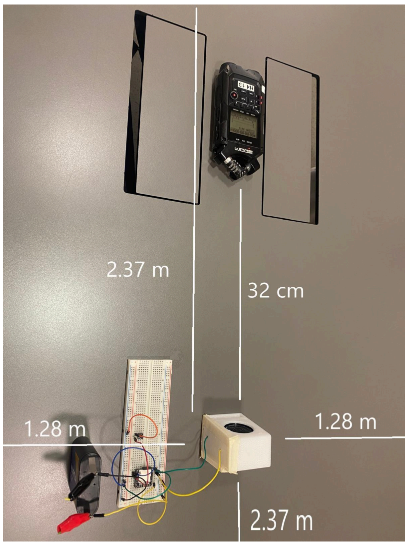


Figure 6. Measures library room

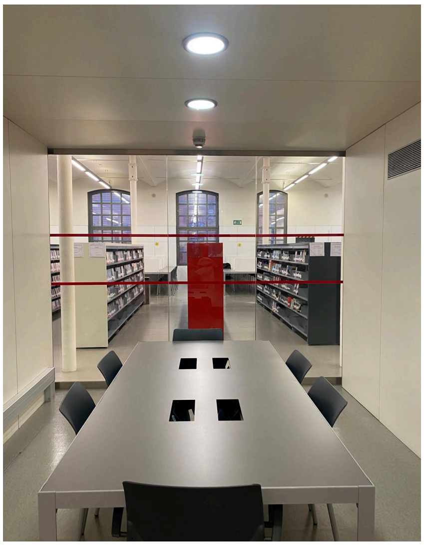


Figure 7. Library room

2.3 Procedure

To investigate the relationship between audio signals and various experimental setups, the procedure involved careful playback and measurement of audio samples under controlled conditions. The audio signal used was a laser sound.

The sound was recorded using a microphone/iphone placed at a fixed distance (40 cm) and angle (0º) from the speakers, ensuring consistent spatial relationships across different setups. The recordings were performed in the same room to minimise external interference that was not part of the experiment.

Its frequency response was analysed using the code developed throughout the seminars to determine how different setups affected the representation of various frequency bands. Additionally, while recording the sound, we took notes on our subjective impressions of the different speaker enclosures, paying special attention to clarity, tonal balance, and loudness.

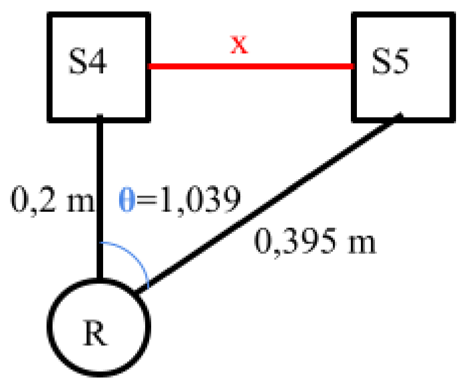
The independent variables in the study included the design of the speaker enclosures, the fidelity settings of the recording systems, and speaker configurations (e.g., polarity). The dependent variables were the resulting frequency responses. By isolating and controlling these variables, the procedure aimed to accurately capture the impact of the experimental conditions on audio quality. For each of the experiments we fixed some variables or others.

2.3.1 Experiment interference with two similar speakers

Additionally, we made an independent experiment to work with interference between speakers. The goal of this experiment was to investigate interference patterns created by two speakers in different configurations (normal polarity and switched polarity) and understand how these patterns affect sound quality and signal strength. To expand the investigation, we attempted to find the exact distance at which sound from the two speakers would cancel out completely (destructive interference).

Before conducting the practical experiment, we revisited the theoretical basis of sound wave interference. When two sound waves of the same frequency meet, they can interfere constructively (amplitude increases) or destructively (amplitude decreases or cancels out). Destructive interference occurs when the sound waves are π radians out of phase, causing their amplitudes to cancel each other. This phenomenon depends on the phase relationship and the distance between the speakers and the listening point.

To simplify the experiment and try to ensure consistent results, we downloaded a sinusoidal wave of 880 Hz. This frequency was chosen as it falls within the audible range and has a well-defined wavelength. We used the two speakers more similar to each other, speaker 4 and 5.



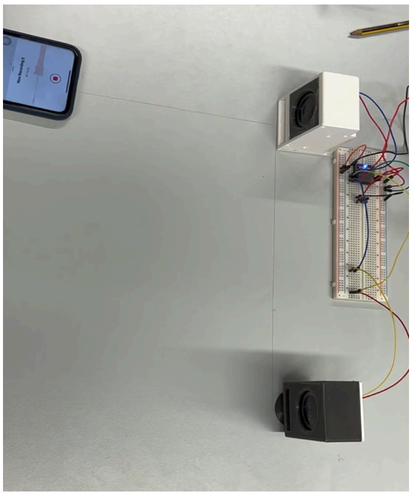


Figure 8. & 9. Diagram and assembly of the experiment

In order to determine the position at which the sound waves interfere destructively with each other, we computed the wavelength of the sound by using the formula:

$$\lambda = \frac{v}{f};$$

where v is the speed of sound in the air (343 m/s) and f is the frequency of the sound (880 Hz).

Thus, the wavelength is

$$\lambda = \frac{v}{f} = \frac{343}{880} = 0,389\ m.$$

As we previously said, to have destructive interference, the sound waves have to be out of phase by π radians; that is, the difference between paths (distance from the speaker to the recorder) has to be of half a wavelength: 0,195 m.

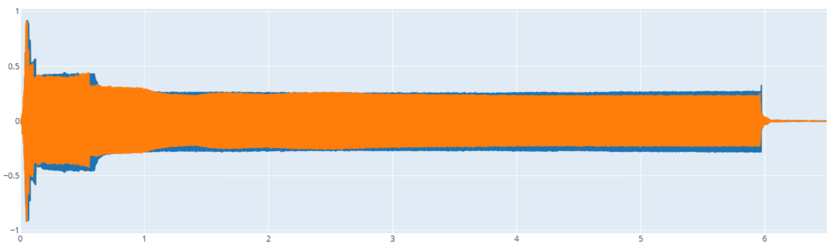
Now that we know the path difference, we placed the recorder 20 cm away from one speaker in a straight line and, knowing that the distance from the other speaker to the recorder has to be 39,5 cm, we computed the angle as

$$cos(\theta) = \frac{20}{39,5} \rightarrow \theta = 1,039\ rad$$

and computed the distance between speakers as

$$sin(1,039) = \frac{x}{39,5} \rightarrow x = 34,06\ cm.$$

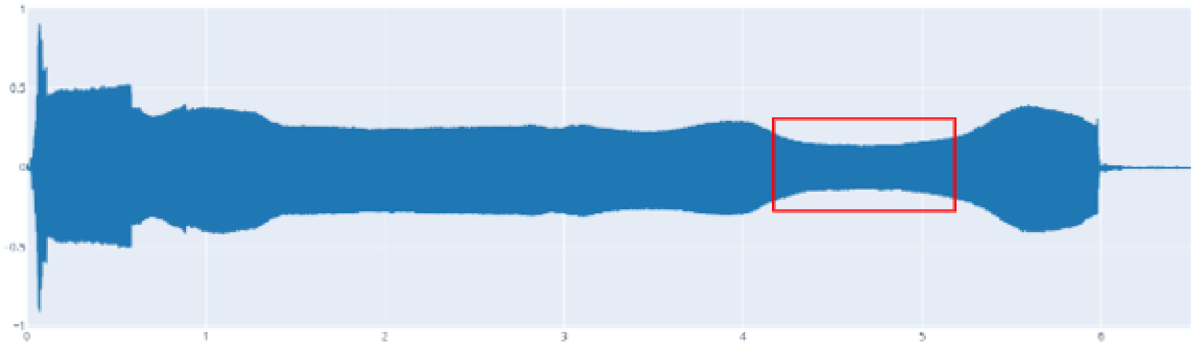
Firstly, we recorded the sound where destructive interference was expected to occur, and the following plot was obtained



Graph 1. Plot without moving the recorder

We need to keep in mind that, although achieving completely destructive interference is not possible due to the room's reverberations, it is still possible to generate destructive interference between the wavefronts emitted by the speakers. In this part of the experiment, the vertical distance between the recorder and the speakers was kept constant at 20 cm, while the recorder was moved horizontally to find the point of destructive interference.

Next, we moved the speaker from a random location to a zone where destructive interference was expected (the one we calculated before).



Graph 2. Plot when moving the recorder

As shown in the graph, without increasing the distance between the recorder and the speakers, the sound wave's amplitude decreases significantly when the recorder is positioned at the calculated point of destructive interference (red square). The amplitude increments before and after the destructive interference part, are due to the noise produced by moving the phone.

While we were unable to achieve completely destructive interference due to the room's reverberations and other limitations, the experiment provided results that suggest partial destructive interference at the calculated point. The reduction in amplitude observed in the recordings, along with the clear differences in sound intensity we noticed when listening at the calculated point compared to other angles, confirms that the setup successfully demonstrated some degree of wave cancellation, aligning with the theoretical expectations of destructive interference.

3. RESULTS

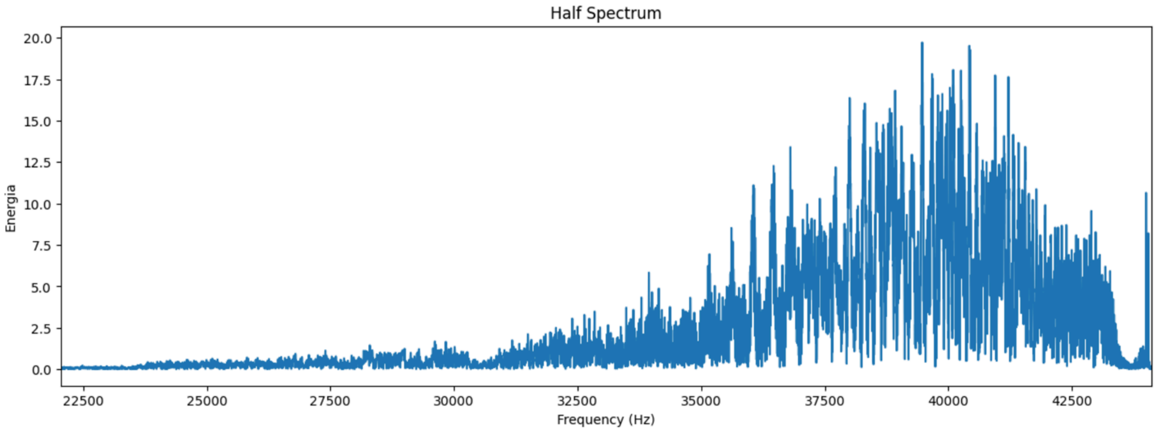
3.1 Data presentation

Audios of the experiments: Audios

3.1.1 Different rooms

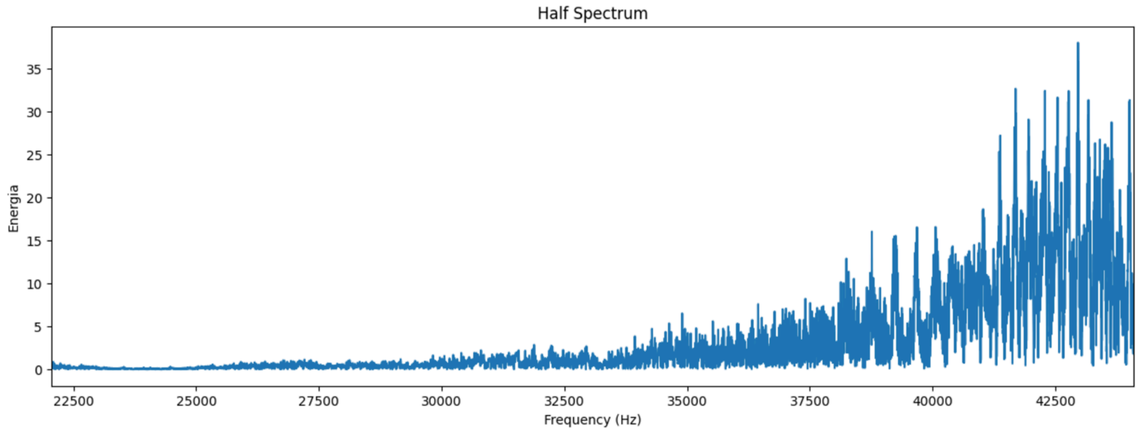
These recordings were made using a high-fidelity sound recorder to ensure optimal audio quality.

Spectrum of Speaker 1 in the Soundproof Room



Graph 1.

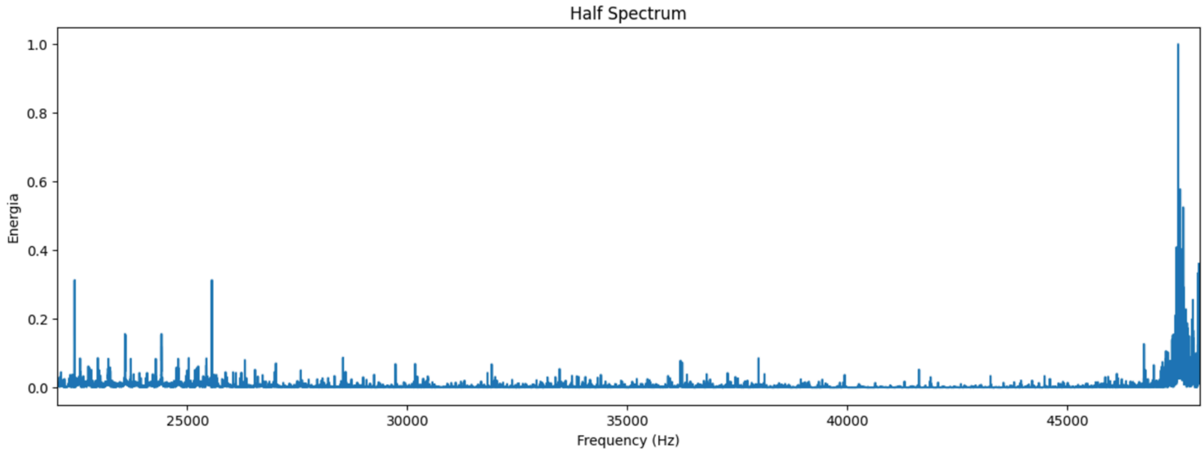
Spectrum of Speaker 1 in the Library Room



Graph 2.

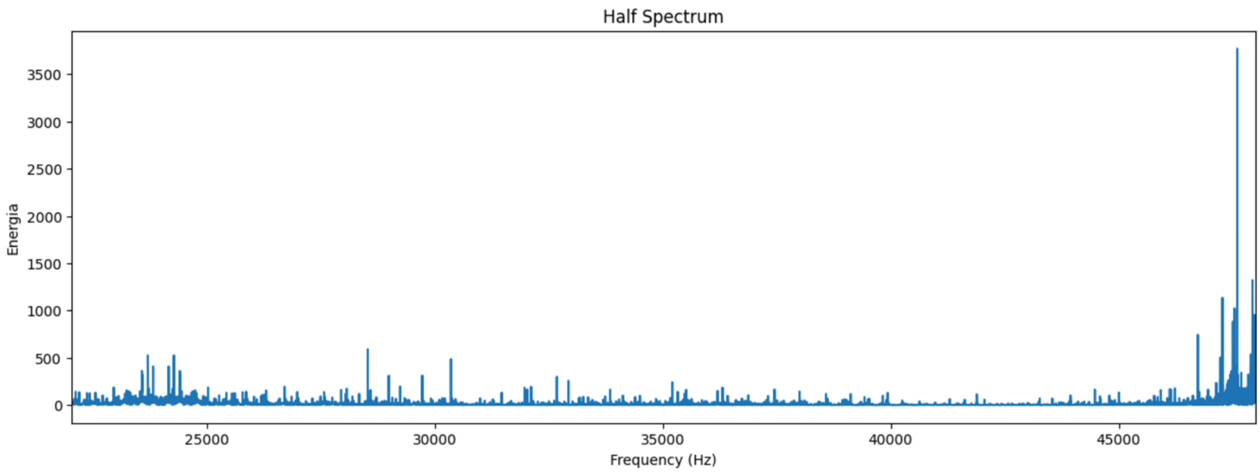
To better illustrate how the room affects the sound, we calculated the transfer function for both rooms taking the wet sound as the original sound file we downloaded.

Spectrum of the transfer function of the Soundproof Room



Graph 3.

Spectrum of the transfer function of the Library Room

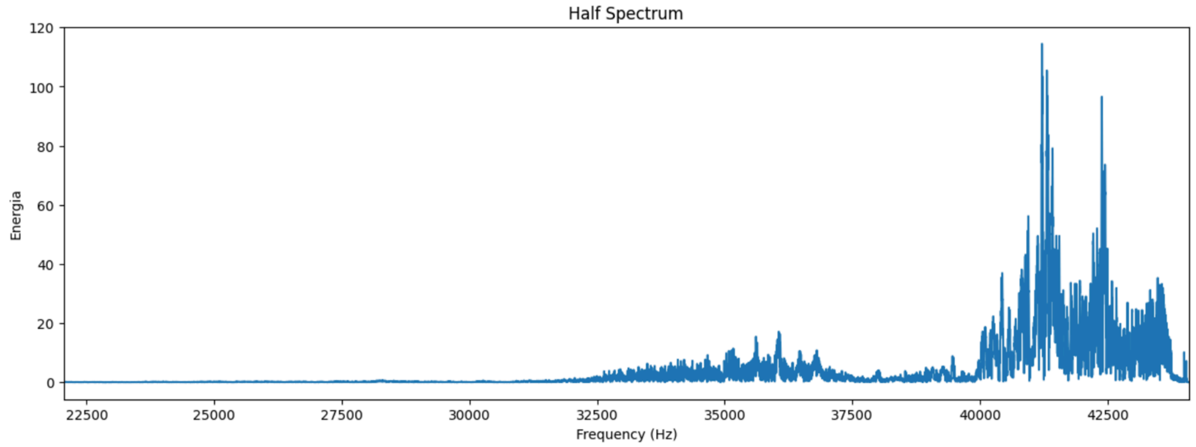


Graph 4 .

3.1.2 Different speaker enclosures

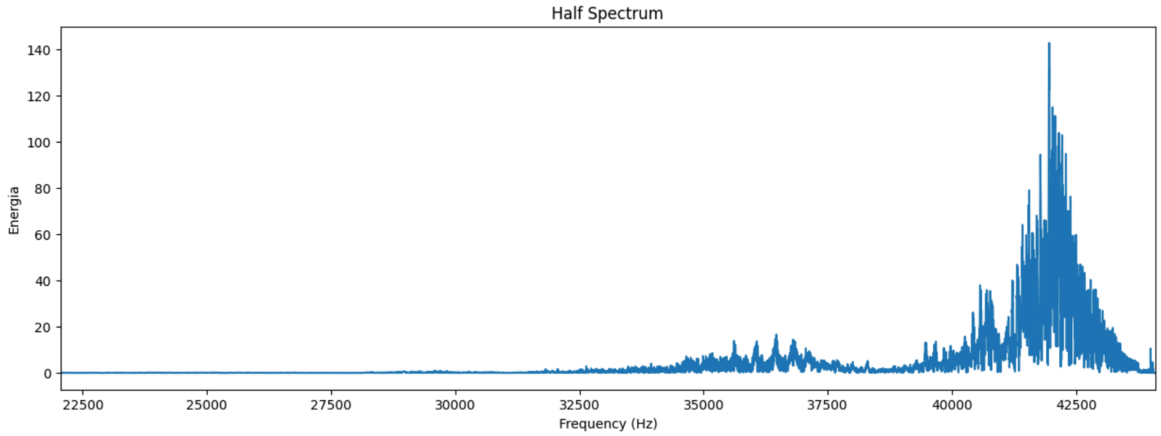
Also, these recordings were made using a high-fidelity sound recorder to ensure optimal audio quality.

Spectrum of Speaker 2 in the Soundproof Room



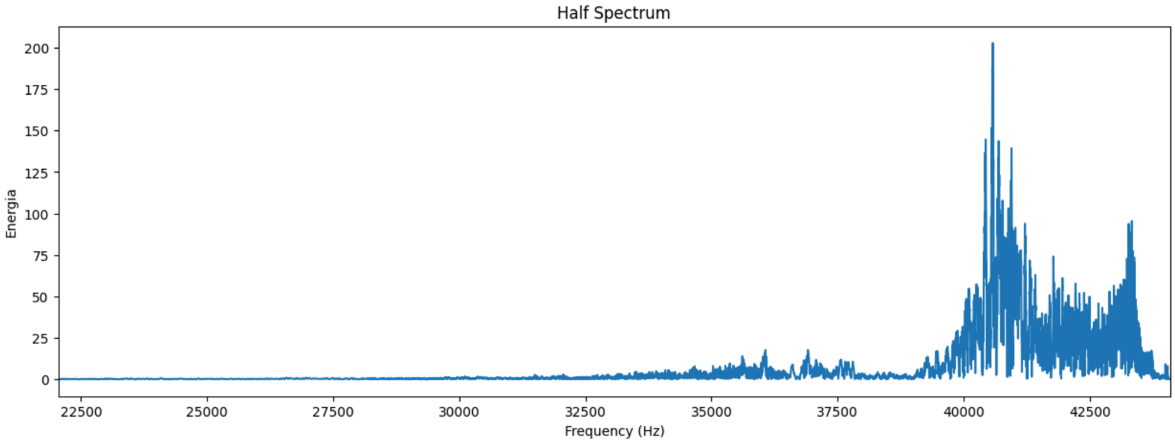
Graph 5 .

Spectrum of Speaker 3 in the Soundproof Room



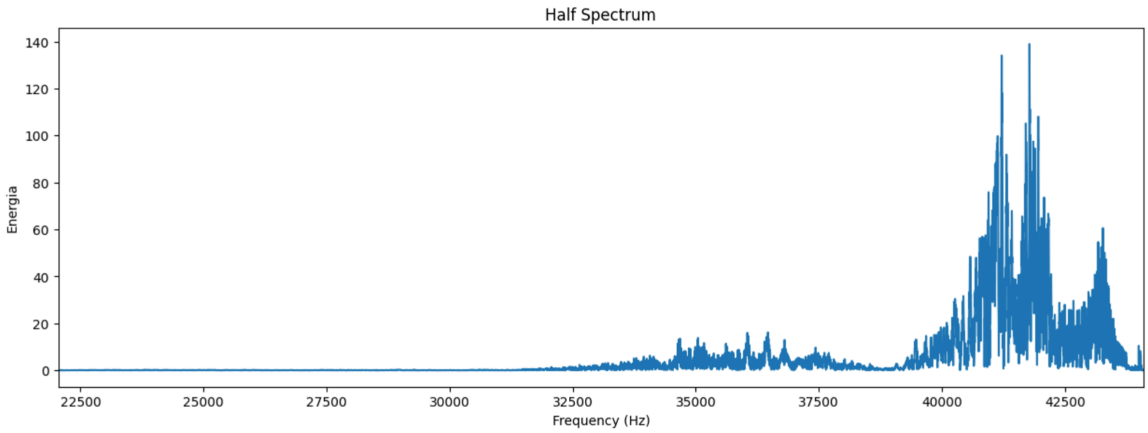
Graph 6.

Spectrum of Speaker 4 in the Soundproof Room



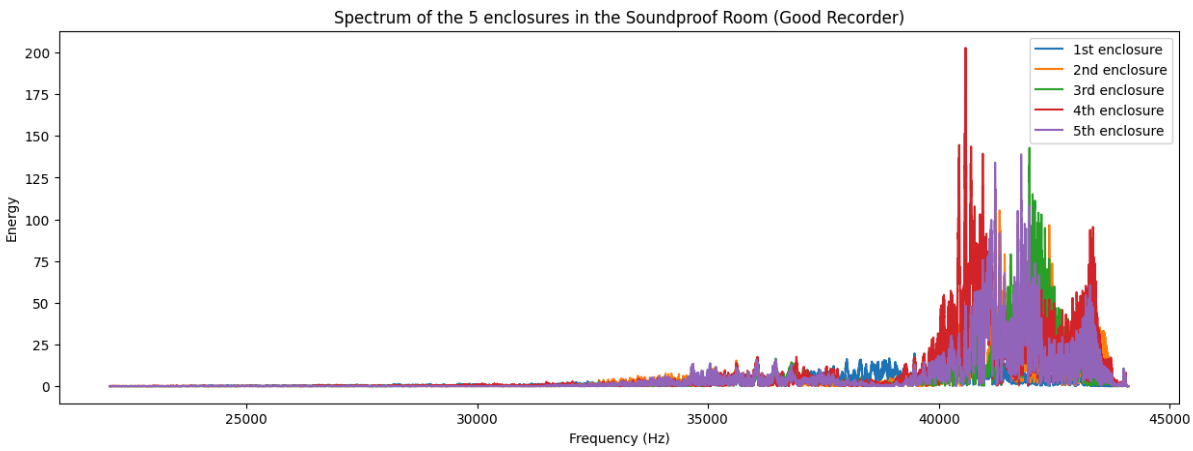
Graph 7 .

Spectrum of Speaker 5 in the Soundproof Room



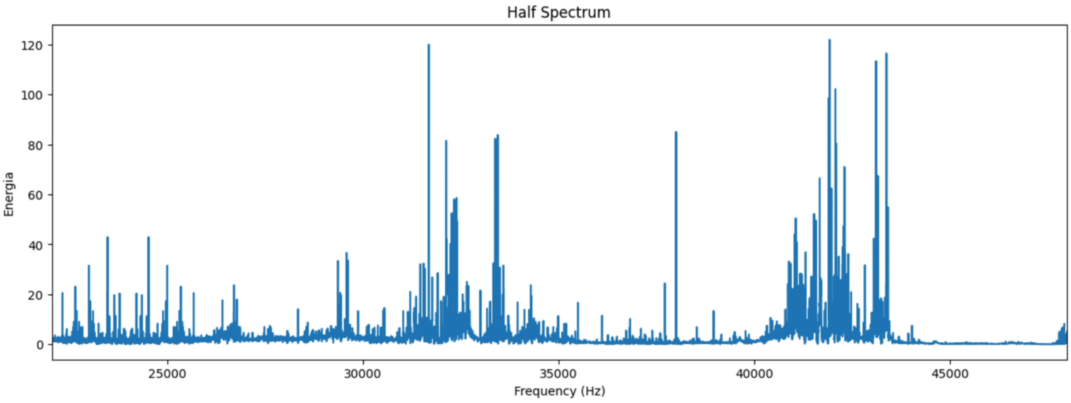
Graph 8 .

Spectrum of all 5 Speakers in the Soundproof Room:



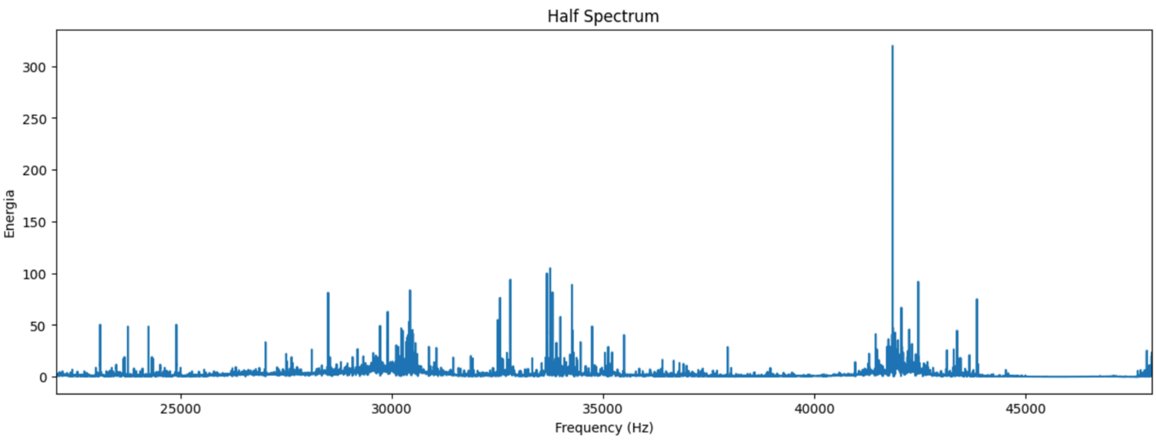
To better illustrate how speaker enclosures affect the sound, we calculated the transfer function for the four speakers, using the recorded sound from the first speaker enclosure in the soundproof room as the "wet" sound.

Spectrum of the transfer function of the second speaker enclosure



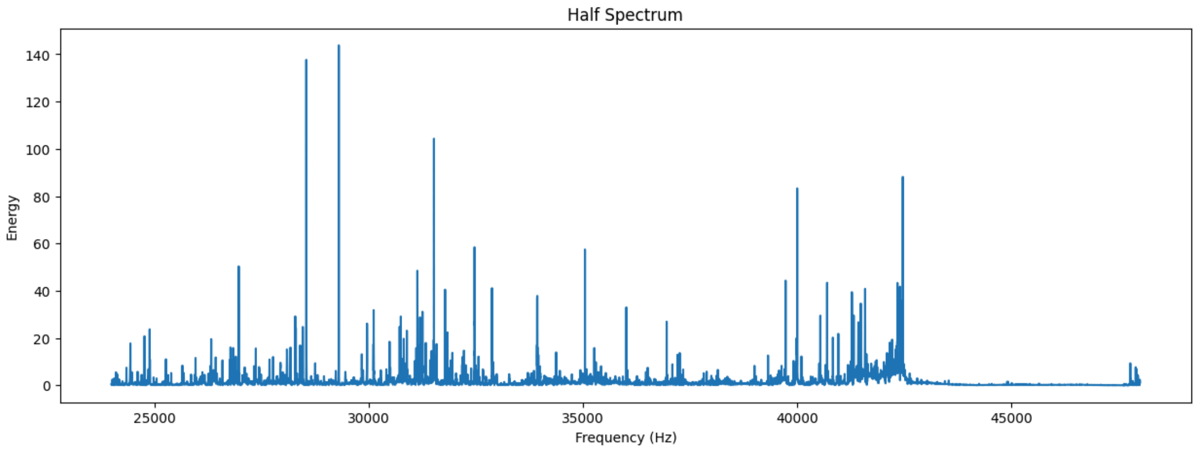
Graph 9 .

Spectrum of the transfer function of the third speaker enclosure



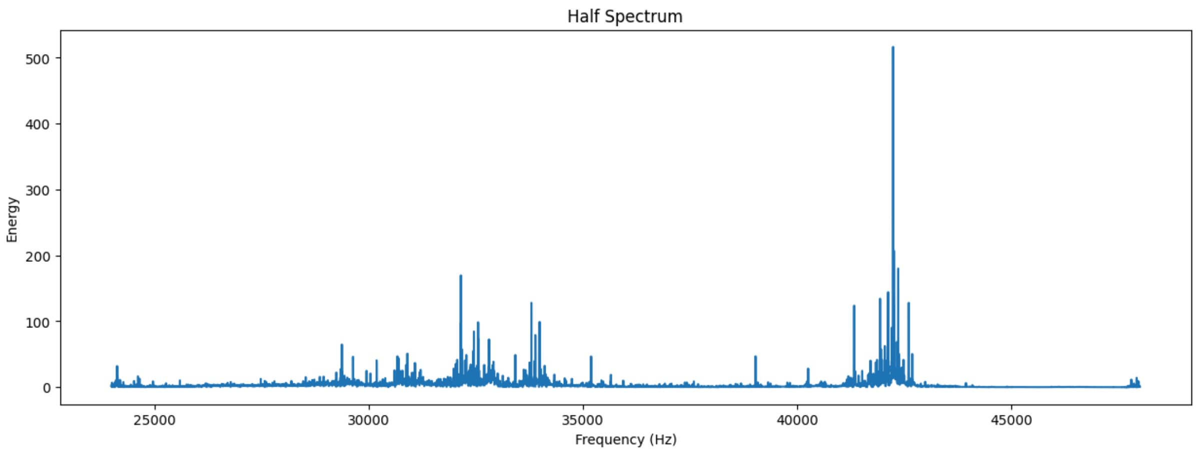
Graph 10 .

Spectrum of the transfer function of the fourth speaker enclosure



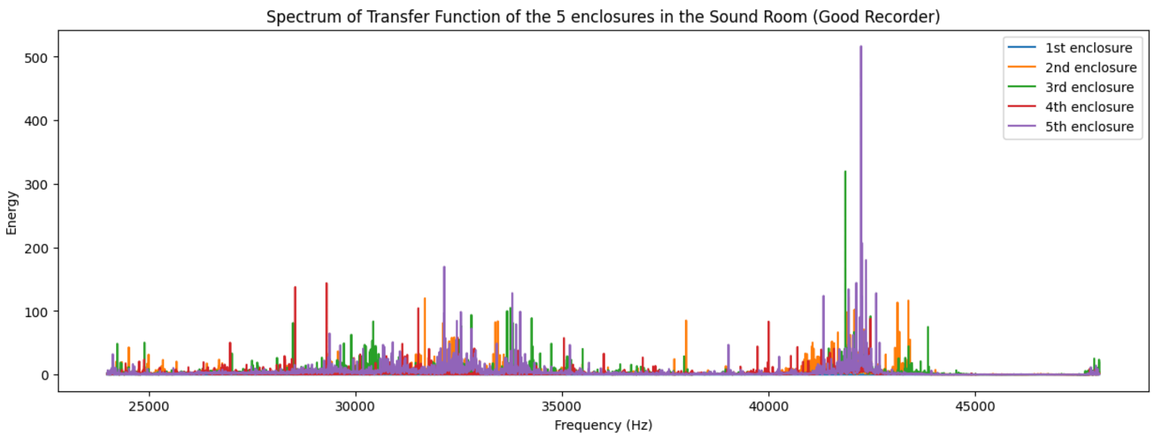
Graph 11 .

Spectrum of the transfer function of the fifth speaker enclosure



Graph 12 .

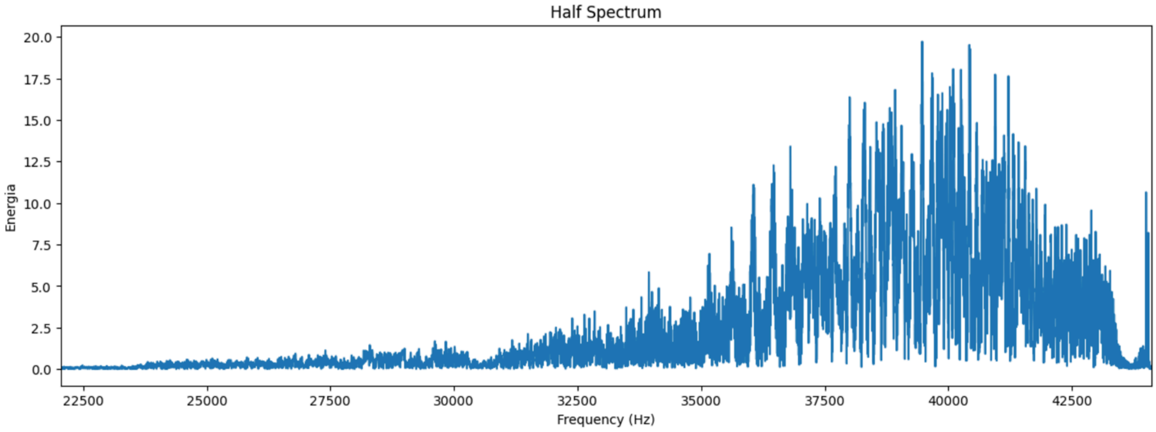
Spectrum of the transfer function of the all five speakers enclosure in the sound proof room:



3.1.3 Different quality sound

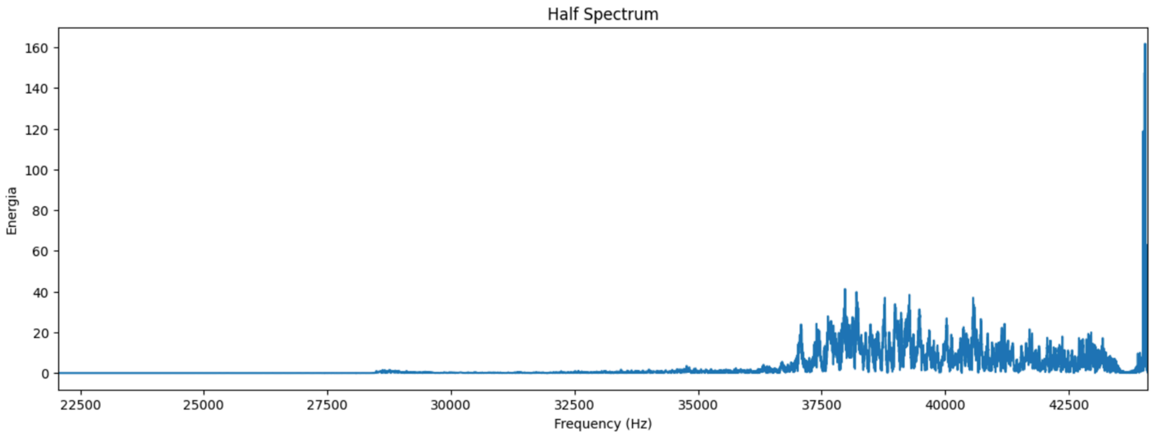
In this case, we made the recordings in the soundproof room using the first speaker, ensuring that no factors other than the quality of the sound would affect the results.

Spectrum of Speaker 1 in the Soundproof Room with the sound recorder



Graph 13 .

Spectrum of Speaker 1 in the Soundproof Room with the phone



Graph 14 .

Notebook : final project.ipynb

3.2 Data Analysis

3.2.1 Analysis of the rooms

As we can see in *Graph 1* in the soundproof room, the energy levels remain relatively low up to 30,000 Hz, with a gradual increase and notable peaks around 37,500 to 42,500 Hz. The highest energy concentration occurs around 40,000 Hz.

Conversely, in the library room, *Graph 2*, energy levels are similarly low at lower frequencies, but rise sharply above 35,000 Hz. The peaks in the library room are more pronounced, with energy exceeding 30 units in some cases, especially around 40,000 Hz.

For the transfer function spectrum, in *Graph 3* the soundproof room shows consistently low energy values, mostly below 1 unit, with a small peak near 45,000 Hz.

In contrast, *Graph 4* shows higher energy levels, with peaks above 3,000 in some regions. Strong resonance effects are evident across the frequency range in the library, particularly near 45,000 Hz, indicating a significant amplification of certain frequencies compared to the soundproof room.

3.2.2. Analysis of the speakers

As we can see from the previous graphs, the frequency response of the different speaker enclosures vary significantly. Regarding the audios recorded in the soundproof room with the high fidelity:

1. The first speaker (*Graph 1*), compared to the rest of the speakers, has a more uniform energy value across its range of frequencies (maximum energy value of approximately 20). Its transfer function (*Graph 3*) shows irregularities at high frequencies that indicate significant interference and diffraction effects, due to the lack of enclosure.

2. The second speaker (*Graph 5*) has energy peaks at frequencies 41 and 42,5 kHz and lower energy value for frequencies in the range of 32 and 40 kHz. The closed tube enclosure design amplifies certain resonances, while attenuating others. This can be seen at the transfer function as well (*Graph 9*), where it highlights specific high frequencies, amplifying them while attenuating lower ranges.

3. The third speaker (*Graph 6*) has a notable peak near frequency 42,25 kHz and reduced energy levels below 40 kHz. This suggests that the open enclosure design causes an enhancement of this frequency 42,25 kHz due to partial rear-to-front interference as it indicates the transfer function (*Graph 10*), with an elevated peak energy.

4. The fourth speaker (*Graph 7*) provides peaks at frequencies 40,5 kHz and 43 kHz. The transfer function (*Graph 11*) reflects the enclosure's ability to amplify certain frequencies, where its response remains far from flat, introducing noticeable richness to the sound.

5. The fifth speaker (*Graph 8*) shows two main peaks at frequencies 41 kHz and 42 kHz. But the transfer function (*Graph 12*) demonstrates the most concentrated energy around 42,5 kHz, with a sharp peak reaching 500 units, indicating strong resonance in this range. However, it also shows greater uniformity in lower frequencies compared to other designs. So, it suggests that the custom enclosure is designed to emphasize specific frequencies while minimizing distortion in others.

3.2.3 Analysis of the quality sound

Graph 13 shows relatively low overall energy levels, with a maximum peak of about 20. The energy is mainly concentrated in the frequency range from 35,000 Hz to 50,000 Hz. Below 35,000 Hz the energy remains minimal, indicating that most of the sound energy is in the higher frequencies. Within the range of 35,000 Hz to 50,000 Hz, the spectrum has distributed and fluctuating peaks. Beyond 50,000 Hz there is an abrupt drop in energy, marking a clear cut-off point.

In contrast, the spectrum recorded with the mobile phone (*Graph 14*) shows significantly higher energy levels, with a peak of over 160 units. Similar to the sound recorder, the energy is concentrated between 35,000 Hz and 50,000 Hz, with minimal energy recorded below 35,000 Hz. However, the telephone spectrum differs in that it has a dominant, sharp peak near 45,000 Hz that overshadows the rest of the frequency range. The variability in other parts of the spectrum appears less pronounced compared to the sound recorder. As with the sound recorder, there is a sharp cut-off above 50,000 Hz.

4. DISCUSSION

4.1 Interpretation of results

4.1.1 Different rooms

In the soundproofed room, *Graph 1* shows relatively low energy levels across the spectrum, with peaks only appearing at higher frequencies due to the principles of sound absorption in acoustically treated rooms. The use of four acoustic panels helps absorb sound and reduce reflections, allowing the direct output of the loudspeaker to come through more clearly, with minimal interference from the room. However, since the acoustic treatment doesn't cover the entire space, some residual reflections and reverberation remain, resulting in minor energy fluctuations and small peaks in the transfer function (*Graph 3*). This residual reverberation shows that although the soundproof room effectively minimises interference, it is not completely anechoic.

In the library room, *Graph 2* shows significantly higher energy levels and pronounced peaks, especially above 35,000 Hz. The highly reflective surfaces of the room, combined with the simple architecture and lack of sound-absorbing elements, contribute to prolonged reverberation and complex resonance patterns. This is evident in the transfer function (*Graph 4*), which shows energy peaks above 3,000 units, highlighting the strong amplification of certain frequencies due to constructive interference from reflected sound waves. The air conditioning noise in the library room adds an additional layer of interference, which is evident in the broad energy distribution across the spectrum.

These results demonstrate how room design and materials can significantly affect perceived and measured sound characteristics.

4.1.2 Speaker enclosures

The geometry and shape of each one of the speaker enclosures determine their acoustic behavior, as evidenced by the energy patterns and transfer functions previously described.

The open geometry of the first speaker results in a frequency spectrum with consistent values across its whole range of frequencies (*Graph 1*). However, its corresponding transfer function (*Graph 3*) shows a notable inconsistency at higher frequencies, which can be attributed to interference and diffraction effects. Due to the absence of an enclosure, the sound wave generated from the back of the speaker interferes with the sound wave generated at the front, causing interference and resonance that distorts and attenuates the perceived sound wave.

Regarding the second speaker, its closed cylindrical geometry highlights specific energy peaks at the frequencies 41 kHz and 42,5 kHz (*Graph 5*). Those peaks, which can also be seen by looking at its transfer function (*Graph 9*), reflect the enclosure's behaviour. The cylindrical shape of the speaker reduces interference and outputs a significantly mitigated output across all its frequencies, except for the 41 kHz and 42,5 kHz frequencies.

The third speaker, similarly to the first speaker, has an open enclosure that emphasizes the frequency corresponding to 42,5 kHz (*Graph 6*). By looking at the single peak corresponding to this frequency in its transfer function (*Graph 10*), we can see that the level of interference and distortion obtained using the third speaker is significantly less than the one obtained using the first speaker. However, the spectrum differs significantly from the spectrums of the closed speakers, denoting a lack of consistency and a high level of interference due to its geometry.

The box shaped geometry of the fourth speaker enclosure shows an improvement in the acoustic control of the generated sound. Its spectrum shows energy peaks at 40,5 kHz and 43 kHz (*Graph 7*), while its transfer function (*Graph 11*) shows peaks at various frequencies. Its transfer function shows the acoustic characteristics of the speaker, which amplify selected frequencies effectively. Nonetheless, interference is still perceptible. Those interferences are caused by the sharp edges and corners of the enclosure, which cause the sound waves to interfere destructively with themselves and reduce the total volume of the output sound wave.

Finally, the fifth speaker enclosure shows the most accurate performance of all the speakers. A peak at frequency 42,5 kHz with a high energy value in the spectrum (*Graph 8*) and the peak at the same frequency value in its transfer function (*Graph 12*) show how effectively the speaker is able to amplify certain frequencies. On top of that, the response at lower frequencies is smooth and uniform, which demonstrates that the speaker is also able to attenuate unwanted frequencies. That is to say, the fifth speaker stands out and shows a better performance by reducing interference and accentuating only the desired frequencies.

4.1.3 Quality of the recorder

The results show that the sound recorder captures a wider and more uniform frequency range, ensuring that all frequencies of the sound are recorded with consistent resolution and clarity. This is evident in *Graph 13*, which shows scattered and fluctuating peaks in the 35,000 Hz to 50,000 Hz range, reflecting its ability to capture finer details and variations in the energy of the sound over this range.

In contrast, the phone does not record frequencies as evenly. The phone's spectrum shows a dominant (*Graph 14*), sharp peak near 45,000 Hz, which overshadows other frequencies and suggests a less even capture of sound energy. This inhomogeneous recording means that certain frequencies are emphasised while others are under-represented, resulting in a less accurate reproduction of the original sound.

In addition, the overall energy levels captured by the phone are higher, but this does not necessarily translate into better sound quality, as the uneven distribution of frequencies compromises the fidelity of the recording.

High-fidelity sound equipment, such as the sound recorder, therefore provides a more faithful representation of the original sound by capturing a wider and more balanced range of frequencies. Conversely, low-fidelity devices, such as the phone, may lack the precision to record all frequencies equally, resulting in a less accurate and less natural sound reproduction.

5. FINAL CONCLUSION

This project has provided us valuable insights into how room acoustics, speaker enclosures, and recording equipment affect the quality and characteristics of perceived sound.

The results show that the environment where the recordings take place has a significant influence. The soundproof room allowed us to obtain recordings with minimal reverberation and distortion, showing its ability to isolate sound effectively. However, as it was not fully treated, some residual reflections remained. In contrast, the library room, with reflective surfaces and background noise, introduced more reverberation and interference, resulting in higher energy levels and altered sound clarity. These observations confirm the importance of the room's acoustic characteristics in shaping the quality of recorded sound.

The speaker enclosures also played a key role in the results. The fifth speaker demonstrated the best performance, as we anticipated at the beginning of this project, accentuating the desired frequencies and minimizing distortion. Its transfer function reflected an ability to amplify specific ranges effectively while keeping lower frequencies uniform. Open designs, like the first speaker, exhibited significant interference and inconsistent frequency responses, highlighting how the lack of an enclosure impacts sound clarity. Sealed and ported designs showed varying results, with some amplifying specific frequencies while attenuating others, depending on their geometry and construction. This was surprising, as we had expected similar performance from both the sealed and ported designs. These differences illustrate how enclosure design directly influences the behavior of the sound waves produced by the speakers.

The choice of recording equipment also impacted the results. The high-fidelity Zoom recorder captured a wider and more balanced range of frequencies, which translated into a more faithful representation of the sound. On the other hand, recordings made with the phone displayed uneven peaks and a less natural distribution of frequencies, compromising their accuracy. These findings reinforce the importance of using high-quality recording devices for capturing sound in experiments where fidelity is crucial.

This project has given us more knowledge for understanding how different factors affect sound reproduction. For professional recordings or environments where sound fidelity is critical, using controlled acoustic spaces and high-quality equipment is essential. Speaker design should prioritize geometries that minimize interference and enhance desired frequencies. Future studies could explore more advanced room treatments to reduce residual reflections, test new materials and geometries for speaker enclosures, and analyze performance with more varied audio signals or under different environmental conditions.