Universidade de Aveiro
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Hugo Luís Oliveira Loureiro da Silva Relva

Development of a Small-Scale Reverberant Chamber for Performing Sound Transmission Loss Tests

Desenvolvimento de uma Câmara Reverberante em Pequena Escala para Realização de Testes de Perda de Transmissão Sonora

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Relatório de Estágio apresentado à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizado sob a orientação científica de Doutor Rui António da Silva Moreira, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro e de Doutora Idalina Alcântara, Engenheira Acústica do Departamento TT-ES/PAB-E2 da Bosch Termotecnologia S.A.

Este relatório de estágio teve o apoio dos projetos UIDB/00481/2020 e UIDP/00481/2020.

o júri

presidente

Prof. Doutor Sérgio Manuel Oliveira Tavares
Professor Auxiliar da Universidade de Aveiro

Prof. Doutor José Fernando Dias Rodrigues
Professor Associado da Faculdade de Engenharia da Universidade do Porto

Prof. Doutor Rui António da Silva Moreira
Professor Auxiliar da Universidade de Aveiro

agradecimentos

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palavras-chave

Acústica; Câmara Reverberante; Perda por Transmissão Sonora; Compósito Plástico-Madeira; Som; Redução de Ruído

resumo

O presente trabalho tem o objetivo de desenvolver uma pequena câmara reverberante que possa ser utilizada para realizar medições de perda por transmissão sonora de amostras de materiais. Inicialmente, foram definidos os requisitos a cumprir e foram selecionadas dimensões e materiais a partir da literatura. De seguida foi criado um modelo CAD, de modo a definir o processo de montagem. Foi realizada uma simulação utilizando o software I-Simpa com o objetivo de avaliar a difusividade do campo sonoro dentro da câmara. A simulação mostrou bons resultados, havendo apenas uma variação de pressão sonora de aproximadamente 2 dB. No entanto, os testes experimentais de validação, revelaram que a câmara exibia um comportamento modal na gama de frequências entre 200 e 500 Hz, o que causou uma variação significativa no campo sonoro. Os testes de perda por transmissão realizados com amostras de WPC permitiram identificar que as placas com ocos ovais internos têm um melhor desempenho quanto ao bloqueio de som. Os testes realizados com geopolímeros acoplados ao WPC não produziram uma diferença significativa nos resultados. Testes de vibração realizados aos painéis revelaram que estes contribuíam para o comportamento modal do campo sonoro dentro da câmara.

keywords

Acoustics; Reverberant Chamber; Sound Transmission Loss; Wood-Plastic Composite; Sound; Noise Reduction

abstract

The present work has the purpose of developing a small reverberant chamber that is suitable for performing sound transmission loss measurements of material samples. Initially, requirements for the chamber were defined and dimension and materials were selected based on the literature. A CAD model was created in order to define the assembly process. A simulation study was done using the I-Simpa software in order to evaluate the sound field diffusivity inside the chamber. Simulation showed good results, with only a variation in sound pressure of approximately 2 dB. However, experimental validation tests revealed that the chamber exhibited a modal behaviour in the frequency range between 200 and 500 Hz, which caused a significant variation in the sound field. Sound transmission loss tests performed on WPC samples showcased that the boards with oval holes performed the best regarding sound blocking. STL tests performed on geopolymer samples did not produce a significant difference in the results. Panel vibration tests revealed that they contributed to the modal behaviour of the sound field inside the chamber.

Contents

1. Introduction

1.1 Context

This thesis was developed in an industrial context during a curricular internship as part of the acoustic team at Bosch Termotecnologia S.A. in Cacia. This team is a part of the company's residential heat pump branch, and it aims to reduce the noise emissions of these appliances.

1.2 Motivation

Despite their undeniable energy efficiency benefits, like many other household appliances, heat pumps also generate sound. The heat pump's sound emission can be linked to their components' operation, namely the compressor and the fan [1]. In most cases, the emitted noise may be an issue for end-users, who consider it undesirable.

Noise can affect physiological and psychological health of users by generating stress and lowering sleep quality. Recent exposure data from the European Environment Agency (EEA) shows that over 100 million European citizens are affected by high noise levels negatively impacting their health. Hence, direct consumers and the wider public have an interest in quieter heat pumps, which leads to acoustics becoming of a growing concern for the heat pump industry [2]. Furthermore, legislation is also becoming more demanding regarding the permitted noise emission levels of heat pumps. This presents one of the greatest challenges that Bosch faces when it comes to their heat pump design.

From another perspective, there is also an interest in utilizing renewable materials in the construction of their heat pumps. A previous project [3] found that an acoustic enclosure made from such a material, wood-polymer composite (WPC), showcased excellent sound blocking capabilities.

This sparked interest in Bosch's acoustic team to further explore the use of WPC and other renewable materials in their heat pump. And so, there was a need to perform sound transmission loss (STL) tests on those materials, to characterize their acoustic performance.

1.3 Objectives

The goal of this thesis is to develop a mini-reverberant chamber that can be used to perform sound transmission loss tests on various material samples, utilizing the hardware and software available in the acoustic lab at Bosch.

2. State of the Art

2.1 Reverberant Chambers

A reverberant chamber is a closed room where sound waves are completely and randomly reflected by the walls, producing a diffuse sound field, which means there is a uniform distribution of the sound pressure level (SPL) inside [4].

Achieving this is heavily dependent on the characteristics of the room. The acoustic response of a room is a superposition of its acoustic modes[5]. Room modes are created by resonance inside a room, and they are most prevalent at frequencies that have a wavelength equal to one of the room's dimensions [6]. This means that, when that mode is excited, there will be a large variation in sound pressure across the room.

A reverberant chamber performs best when several room modes are excited simultaneously. Indeed, a diffuse field is obtained when there is a significant overlap of room modes. This tends to happen at higher frequencies, as modal density increases with frequency. The frequency threshold at which a room's behaviour transitions from modal to diffuse is known as the Schroeder Frequency and it is calculated at follows:

$$f_{sch} = 2000\sqrt{\frac{T_{60}}{V}} \qquad 1$$

where T_{60} is the reverberation time (times it takes for a sound in the room to drop by 60 dB), and V is the volume of the room. This equation explains why reverberant chambers are typically very large, as increasing their volume means that the Schroeder frequency will be lower and, thus, diffuse field behaviour will start at much lower frequencies and modal behaviour is only present at very low frequencies.

2.1.1 Small-Scale Reverberant Chambers

Small-scale reverberant chambers have been used in several projects where there was no access to a full-sized reverberant chamber and building one was not feasible, as it requires a large space and can be very costly.

As mentioned above, reverberant chambers are usually very large to minimize modal behaviour. For smaller rooms, modal behaviour is prevalent up to higher frequencies, since the range below the Schroeder frequency is much larger. So, it is vital to optimize the modal response in this range. According to the Bonello Criteria [7], this is done by making sure that the room is designed in a way that the modal frequencies are distributed as uniformly as possible. Bonello stated that the number of modes per third-octave band should always increase. This can be achieved by choosing a good ratio between the room's dimensions.

Blaszak [8] conducted a study on the acoustic design of small rectangular rooms and proposed a ratio of 1:1.2:1.4. While developing a small reverberant chamber, Vivolo [9] compared the ratio suggested by Blaszak and 1:1.26:1.59, which is recommended by the American National Standard Institute (ANSI) [10] and found that 1:1.2:1.4 produced better results. Piollet *et al.* [5] also developed a similar small reverberant chamber with the ratios proposed by Blaszak [7] and were able to create a chamber suitable for frequencies starting from 400 Hz.

2.2 Sound Transmission Loss

Sound transmission loss (STL) is a property that refers to a material's ability to prevent the transmission of sound between two spaces. There are two main laboratory procedures typically used to determine it: the impedance tube method and the two-room method [11].

The impedance tube method (illustrated in Figure 1) is typically used for smaller material samples and components used in ducts. On one end of the tube, there is a sound source, and the tested sample is placed in the middle of the tube. Microphones are then placed on both sides of the sample and the STL value is obtained by comparing the sound pressure level on either side. This method, however, can only measure transmission loss of a normal incident sound field, whereas the two-room method allows for a diffuse sound field to be measured, which is a more accurate representation of the real applications of these materials.

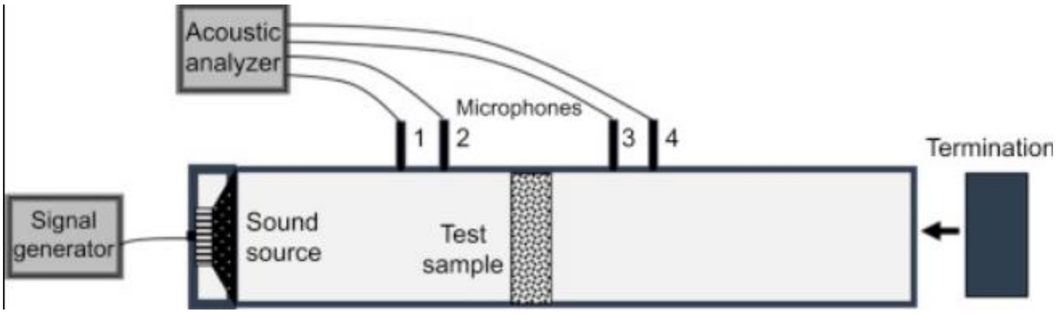

Figure 1 - Impedance Tube Method in STL Configuration

The two-room method consists of a setup where two rooms are separated by a test sample and a sound source is placed inside of one of the rooms. Then, measurements are made in both rooms to determine the STL of the sample. This method can be utilized in two different setups: two reverberant rooms, or one anechoic (or semi-anechoic) room combined with one reverberant room. With two reverberant rooms, STL is determined by measuring the sound pressure in both rooms and using the equation:

$$STL = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \quad 2$$

where L_1 is the average sound pressure level in the transmission room and L_2 is the average sound pressure level in the receiving room, S is the area of the tested object and A is the equivalent sound absorption [11].

With a reverberant room and an anechoic room, STL is determined by measuring the sound pressure inside the reverberant (source) room and scanning the sound intensity transmitted through the sample [12]. STL can then be calculated using the equation:

$$STL = L_{p_i} - L_{I_t} - 6.18 \quad 3$$

where L_{p_i} is the incident sound pressure, L_{I_t} is the sound intensity transmitted by the sample and 6.18 is a constant that accounts for air density and speed of sound [11].

This last one is the method that this work attempts to replicate on a smaller scale.

3. Chamber Design

This section presents the process of designing the small chamber. It goes over its requirements, and explains decisions made regarding its dimensioning and materials used.

3.1 Requirements

There were a few requirements for the chamber’s design. Since it needs to be easily movable in and out of the semi-anechoic chamber, this means that it can not be too heavy or too large to fit through the door. Another factor limiting its size is the fact that the larger it is, the more it will affect the sound field inside the semi-anechoic chamber, which should remain as close to a free field as possible [5]. However, as previously mentioned, if the chamber is too small, the Schroeder frequency will be higher and thus, measurements done with the chamber will be less accurate in the low frequencies. Additionally, it should be easy to assemble and disassemble to facilitate storage and transportation as well as setting up microphones and a sound source inside.

3.2 Dimensioning

Based on the requirements listed above, the internal chamber dimensions used by Vivolo [9] were chosen for this project. These dimensions not only meet the size constraints listed above, but they have also been optimized to provide the most uniform distribution of frequencies, due to their ratios of 1:1.2:1.4 [8]. The walls and ceiling were also angled, meaning that any two opposite faces are not parallel. This also helps to increase sound field diffusivity. Figure 2 presents a simplified layout of the chamber and its general dimensions.

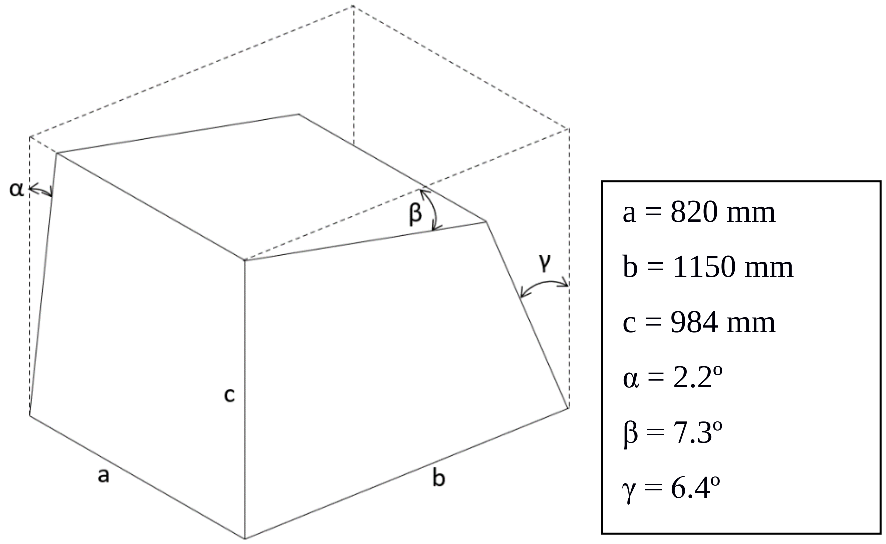

Figure 2 - Chamber Inner Dimensions

3.3 Choice of materials

Regarding the construction of the walls, a wood-based material was selected, since it would be simple to manufacture and allow for a rigid structure with low structural vibrations that would influence test results. At the same time, the chamber would still be light enough to be easily moved with a pallet jack.

The most important material property to guarantee is low acoustic absorption. This is key to achieve a diffuse field, as it means the walls will be very reflective. In the end, 30 mm thick Medium Density Fiberboard (MDF) was chosen based on its low absorption coefficient [13], adequate density, availability, and workability features.

Another important factor to consider was the assembly process. It was important that it guaranteed minimal gaps between the walls through which sound could leak. Furthermore, it was important that it also minimized wear on the MDF. To comply with this, aluminium Rexroth structural profile elements [14] were added to the chamber. There were several benefits to this approach. First of all, it allowed for all connection points between the walls to be outside of the chamber, where they were easily accessible. Secondly, it granted more structural rigidity. Thirdly, a frame could be built around the sample window, which would facilitate the installation of the material samples. Threaded inserts were also used, to protect the MDF from becoming worn every time the chamber was assembled and disassembled.

Figures 3 and 4 show the detailed CAD model that was designed to comply with the requirements listed above.

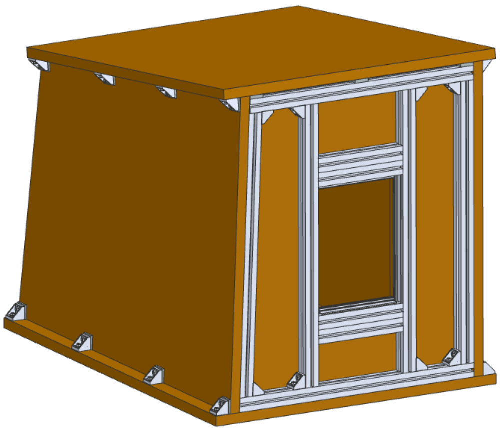

Figure 3 – CAD model of the chamber

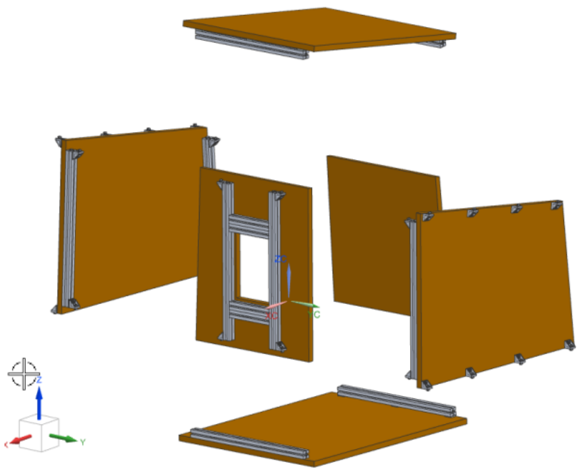

Figure 4 - Exploded view of the chamber showcasing the assembly process

Once the chamber was built (Figure 5), toggle clamps (Figure 6) were attached to the aluminium frame around the sample window. Small gaps between the walls were covered using Alubutyl and foam (Figure 7 and Figure 8).

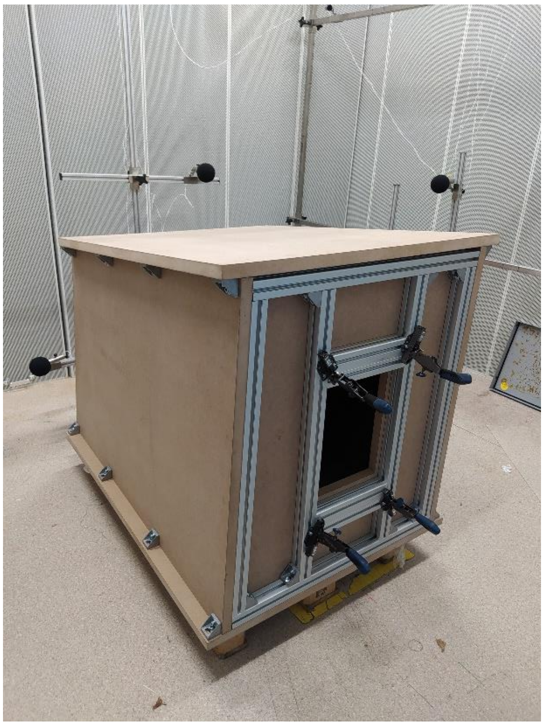

Figure 5 – The finished mini chamber.

Figure 6 - Toggle clamps used to hold the material sample.

Figure 7 - Air gap covered with Alubutyl.

Figure 8 – Foam used to cover air gap.

4. Simulation

As an initial validation and characterization of the chamber, and attempt to identify potential improvements, a sound field simulation was run, utilizing the I-Simpa software. This tool makes use of a sound particle tracing code, named SPPS (from French "Simulation de la Propagation de Particules Sonores") which is based on geometrical, energetical and probabilistic approaches. This method relies on tracking sound particles emitted from a source in a 3D domain. Each particle travels along a straight line until it collides with an object, at which point it may be absorbed, reflected, scattered, diffused, or transmitted, depending on the nature of the object. For this study, only phenomena of absorption and reflection were considered.

A room model of the interior of the chamber was modeled, and an omnidirectional sound source was placed inside. The resulting sound field was then analyzed.

4.1. Chamber modelling

The interior of the chamber was modelled in NX and exported in STL format. It was then converted to a PLY file and imported into I-Simpa.

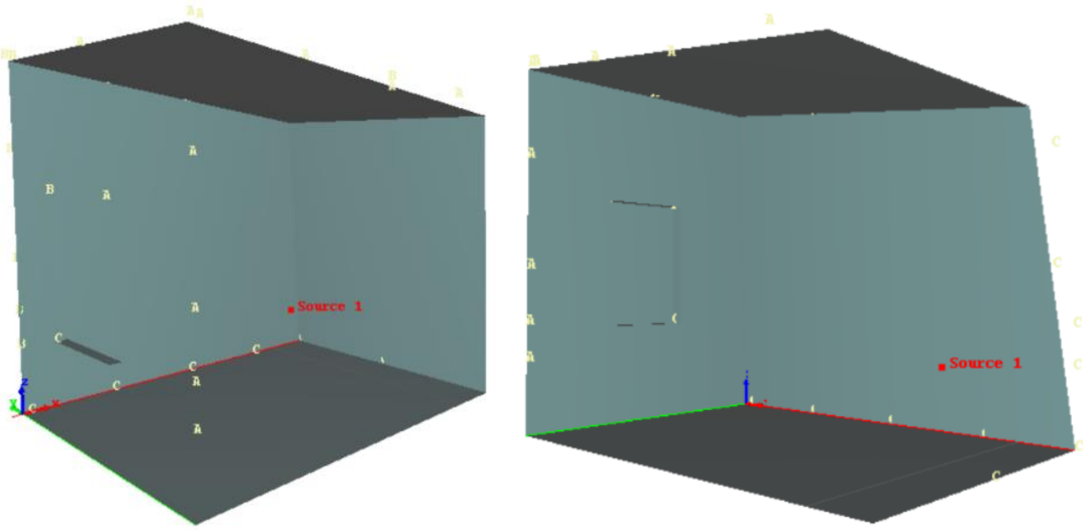

Figure 9 - Model of the interior volume of the chamber with sound source placed at the corner.

The walls were given a common mass density of MDF (800 kg/m^3) as well as its absorption coefficient, based on experimental data [13] and an omnidirectional sound source was placed in one of the back corners, as shown in Figure 9, and configured to emit pink noise at 80 dB.

4.2. Definition of measurement planes

Several measurement planes were then created with different orientations (Figure 10), including a plane in the sample window. Additionally, a measurement surface was created, which coincided with the walls of the chamber.

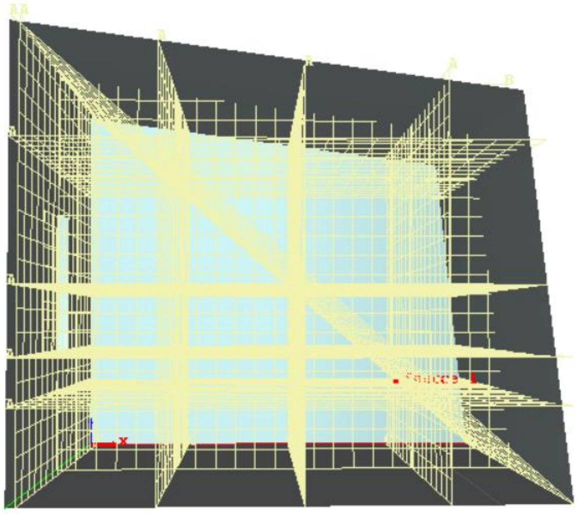

Figure 10 - Measurement planes defined for simulation.

4.3. Simulation configuration

The SPPS code was configured to run with 100000 sound particles. Two algorithms are available in the software: energetic and random [15].

The random algorithm attributes an energy value to a particle, which remains constant during its propagation. Following a probabilistic approach, the particle may be absorbed, disappearing from the domain, or be reflected, continuing its propagation. Thus, the number of sound particles will decrease over time.

In the energetic algorithm, the number of particles remains constant across the simulation. Instead, the physical phenomena of absorption and reflection cause a variation of particle energy. Since the number of particles does not decrease over time using this approach, computational time is higher. However, it is recommended by the developers, as it can produce better results. For this reason, this was the algorithm of choice for this simulation.

4.4. Results

The simulation showed good results regarding sound field diffusivity. Outside a 10 cm radius from the source, the largest variation of sound pressure inside the chamber was around 2 dB, as shown in Figure 11.

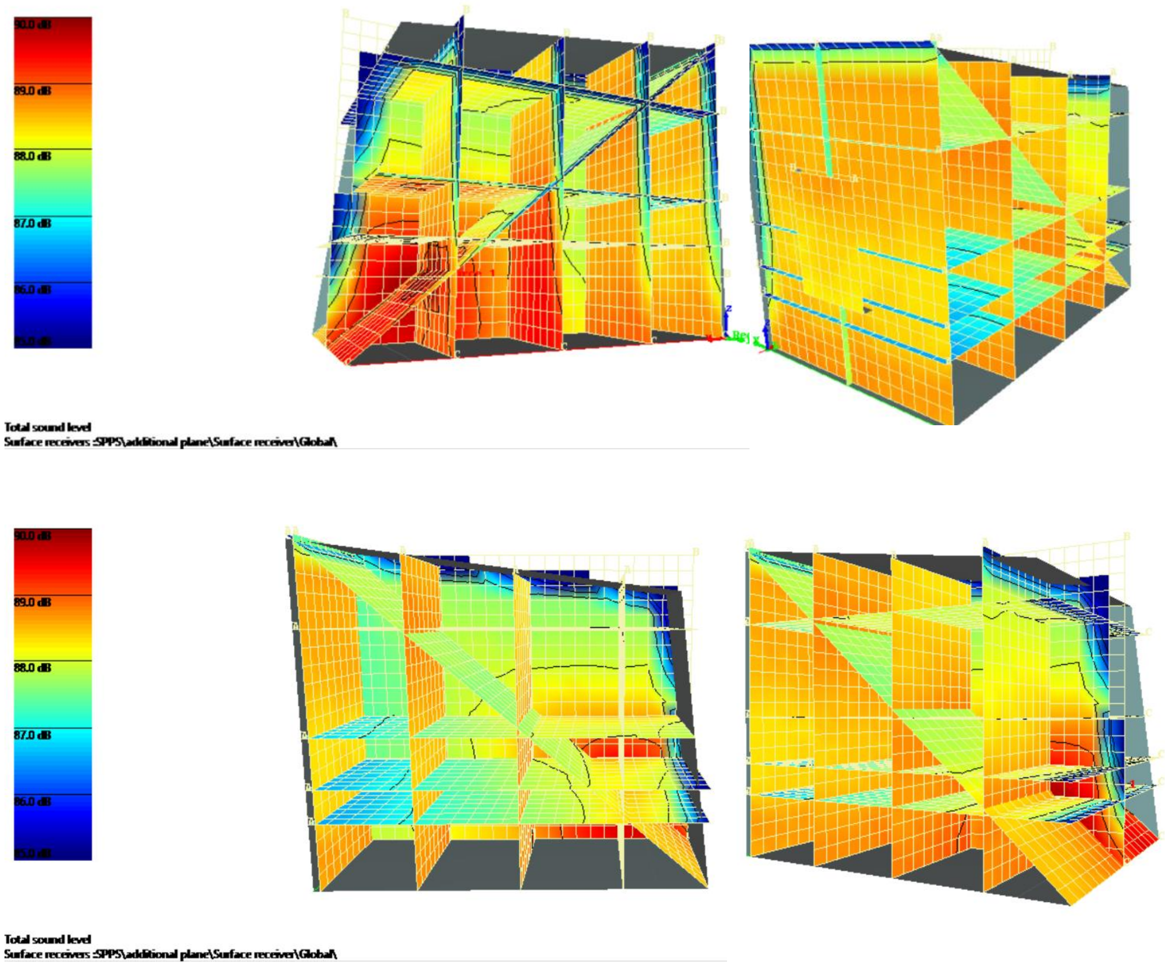

Figure 11 - Sound field simulation results

Moving the sound source to the center of the chamber was also tested but produced worse results, as shown in Figure 12.

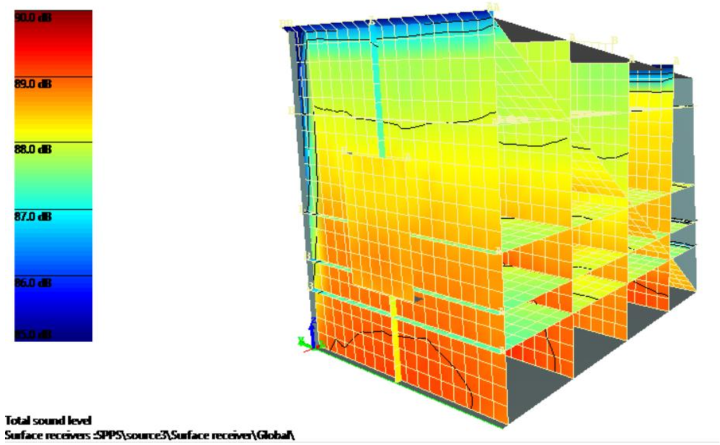

Figure 12 - Sound field simulation with sound source in the center of the chamber

4.5. Comparison to a full-scale reverberant chamber

A simulation of a full-scale reverberant room was run to compare its behaviour against the small reverberant chamber. The dimensions and properties were based on preliminary specifications of the reverberant chamber that was set to be built in a new lab in the Bosch plant. The sound source was placed in a similar position to the previous simulations and was set up to emit the same noise. Figure 13 shows the dimensions of the chamber in millimeters, as well as the simulation setup and results.

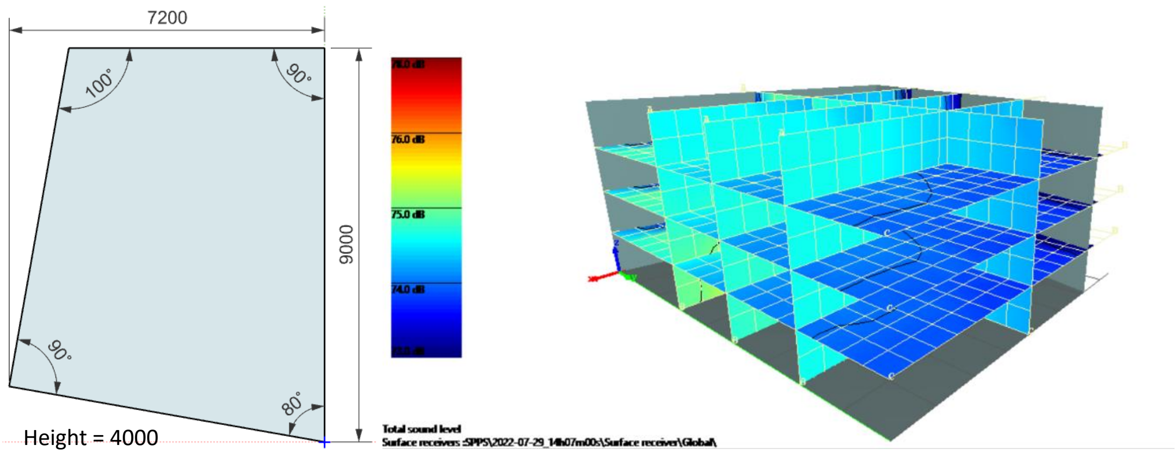

Figure 13 - Full-scale reverberant chamber simulation.

As expected, results of this simulation showed greater field diffusivity than the small-scale setup, with the largest sound pressure difference in the room being just above 1 dB, as shown in Figure 13. However, since the difference in performance between the two chambers was very small, the small setup can be considered valid.

4.6. Software Validation

To assess the accuracy of these results, the software was used to simulate a sound power test of a boiler that had previously been done in the acoustic lab at Bosch. The test setup was replicated in the software and the simulated results were compared with the experimental ones.

4.6.1. Test setup

The boiler was measured in a semi anechoic chamber, according to ISO 3744 [16] with additional diagonal microphones. This setup was then simulated in I-Simpa, with a few approximations: the boiler was represented as a single point in space and was an omnidirectional sound source.

A power spectrum was created based on the sound power results of the previous measurements and it was attributed to the source. The semi-anechoic chamber was modelled in the software and the virtual microphones were placed according to the standardized setup. To better visualize the results, 4 receiver planes were also created on the same planes as the microphones.

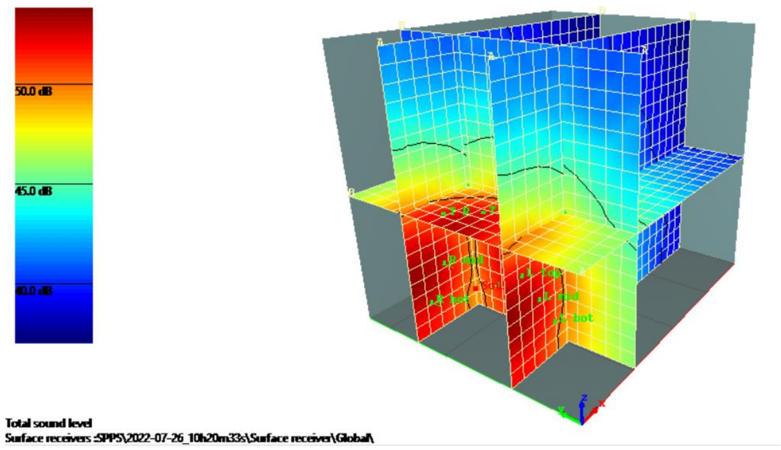

Figure 14 - Boiler test simulation

4.6.2. Results

Simulation results, showcased in Figure 14, were mostly like the real measured values. There were some deviations, which could be explained by the approximations made in the simulation. In fact, the largest deviations were observed in the top right and top middle microphone positions, which were in very close proximity of an exhaust duct on top of the boiler, as can be seen in Figure 15. This can explain why these positions had considerably lower (up to -8.9 dB) sound pressure values in the simulation.

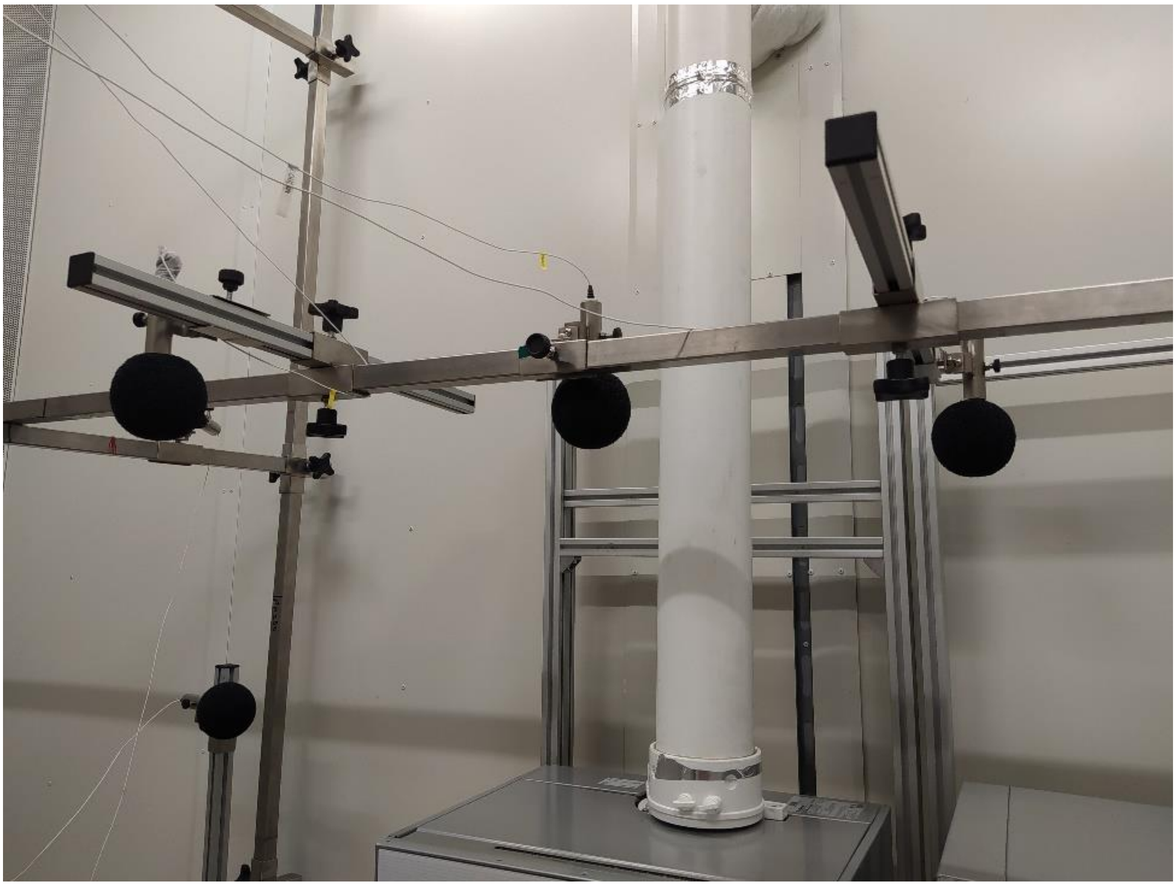

Figure 15 - Exhaust duct on top of the boiler

Table 1 contains the measured difference between the real and simulated sound pressure level values measured by every microphone.

Table 1 – Difference between simulated SPL values and real values

	Corner L	Corner R	F bot	F mid	F top	L bot	L mid	L top	R bot	R mid	R top	T left	T mid	T right
50	-3.7	-0.8	-1.1	0.0	-1.5	-3.7	-2.5	-2.3	-2.2	-1.6	-0.6	-1.4	0.1	0.1
63	1.2	1.7	-1.6	0.2	0.8	-2.1	-0.3	-0.1	-2.7	-1.5	0.3	0.9	-0.3	-1.4
80	2.2	3.1	-1.0	0.3	0.6	-1.5	0.2	0.1	-0.8	1.0	2.5	1.1	0.5	0.8
100	1.9	1.7	-3.1	-1.4	-0.6	-2.9	-1.9	-1.9	-2.6	-0.3	0.9	-0.3	-0.8	-0.4
125	1.0	1.8	-3.3	-1.4	-0.2	-4.5	-1.9	0.0	-3.5	0.2	1.4	0.2	1.2	0.9
160	2.5	3.3	-0.3	0.9	0.8	-5.3	-0.7	0.9	-5.3	0.9	3.4	1.6	-1.6	0.2
200	-4.4	-2.2	1.3	2.5	0.1	-2.2	-0.6	-3.1	-2.3	1.6	0.6	-1.9	-2.5	-1.8
250	-1.9	-0.1	1.8	-0.6	0.2	1.4	-1.0	-3.0	-3.9	-2.5	1.8	0.6	-0.1	-0.9
315	1.3	-2.3	2.4	1.1	0.4	0.5	-0.4	-2.0	-1.6	-1.4	0.3	-0.3	-3.5	-4.4
400	0.2	3.9	3.2	1.1	3.4	0.7	-3.6	-2.6	-3.3	-4.7	-2.5	4.6	1.3	2.8
500	0.8	-1.4	2.9	2.3	1.1	2.1	-1.9	-4.4	-2.2	0.6	-1.1	1.2	-1.4	-2.9
630	1.0	-0.9	3.5	1.6	2.0	-1.2	0.1	-4.3	-2.7	5.8	0.0	0.9	-3.7	-5.1
800	-2.6	-3.0	-0.4	1.9	1.4	-1.1	2.2	-0.5	-0.2	1.3	-1.5	-1.2	-4.1	-3.4
1000	-3.3	-4.1	-1.9	3.5	1.0	-0.9	0.9	-0.7	1.6	0.7	-1.6	-1.9	-4.1	-4.1
1250	-3.0	-2.2	2.9	5.2	1.2	1.8	0.6	4.7	4.6	-2.8	1.9	-3.6	-4.0	-6.6
1600	-2.0	-1.2	4.0	5.2	-0.1	1.1	0.9	2.2	4.6	0.5	1.2	-2.2	-7.2	-5.4
2000	-3.2	-1.3	0.6	2.5	0.9	1.0	2.1	-1.1	-0.8	0.9	-0.3	-2.8	-3.8	-4.5
2500	-1.4	1.1	1.5	1.8	-0.2	-0.2	1.0	0.6	0.2	0.4	-0.5	-3.0	-5.0	-3.9
3150	-0.5	-0.6	2.0	4.6	0.8	2.4	4.5	0.9	1.5	3.5	1.3	-1.3	-7.6	-6.2
4000	0.1	0.6	3.5	4.6	1.1	3.0	4.7	3.1	3.3	3.0	2.7	0.9	-8.9	-5.0
5000	-3.5	-2.4	-2.1	1.3	-0.6	-0.4	1.1	-0.1	-1.9	1.8	-0.1	-2.5	-2.8	-3.7
6300	-2.7	-2.4	-2.2	0.6	-1.5	-1.0	1.6	0.4	-1.7	1.2	-0.8	-3.8	-2.5	-2.9
8000	-4.1	-3.7	-2.9	0.5	-1.4	-2.4	-0.1	0.0	-0.7	1.4	-1.2	-2.9	-2.3	-1.9
10000	-3.7	-3.2	-2.9	1.0	-1.0	-1.8	-0.8	-0.3	-1.9	-0.3	-0.8	-1.2	-1.5	-2.6
12500	-3.6	-4.3	-2.6	0.8	-1.5	-2.2	-1.4	-1.1	-3.0	0.0	-2.7	-1.7	-2.0	-2.5
16000	-6.4	-7.8	-1.0	-0.3	2.8	-0.4	-5.4	-0.5	4.4	0.8	-8.4	0.7	-6.3	-0.9
20000	-4.8	-6.4	2.3	-0.5	3.2	-4.9	-3.8	2.5	-0.4	-0.1	-0.4	1.8	-0.3	-4.6
Global	-2.3	-0.4	-2.8	-1.6	-1.6	-3.8	-2.5	-2.7	-3.1	-1.0	-0.1	-1.7	-1.7	-1.4

5. Experimental Tests

This section will go over the tests performed in the acoustic lab using the chamber. The first test consisted of an initial validation test to verify if the chamber behaved as intended. Following that, sound transmission loss tests were conducted on WPC board samples. Additionally, a geopolymer insulation material was also tested by adding it to the best performing WPC board and comparing its STL with the one obtained previously.

5.1. Equipment Used

As mentioned previously, these tests were performed by placing the small chamber inside a semi-anechoic chamber. Noise was produced using a Norsonic Nor278 reference sound source (Figure 16), which had an A-weighted sound power output of 94 dB [17]. To measure the sound pressure inside the chamber, five PCB Piezotronics 378B02 microphones (Figure 17) [18] were used, connected to a Head Acoustics front end. The sound intensity emitted by the tested sample was measured with a Microflown PU probe (Figure 18) powered by a Microflown MFPA-2 preamplifier connected to a Scout V2 data acquisition system. Regarding software, sound pressure measurements were recorded with ArtemiS Suite 12.5 and sound intensity scans were processed with the Scan & Paint 2D module in Microflown Velo 5.

Figure 16 - Norsonic Nor278 Reference Sound Source

Figure 17 - PCB Piezotronics 378B02 Microphone

Figure 18 - Microflown PU Probe

5.2. Chamber Validation

A validation test was performed to assess the uniformity of the sound field inside the chamber. This was done by placing a reference sound source inside the chamber and measuring the sound pressure level at different points in the chamber, as illustrated in Figure 19.

Figure 19 - Validation test setup, mic stand positioned 25 cm away from front wall

The chamber was closed by covering the sample window with an MDF board of the same thickness as the walls. The microphone stand was placed at three different positions inside the chamber, 25, 50 and 75 cm away from the front wall. This last position required two microphones to be removed due to the space occupied by the source. In total, thirteen different microphone positions were recorded. The graph depicted in Figure 20, obtained in ArtemiS Suite 12.5, shows the A-weighted sound pressure values measured by the different microphones:

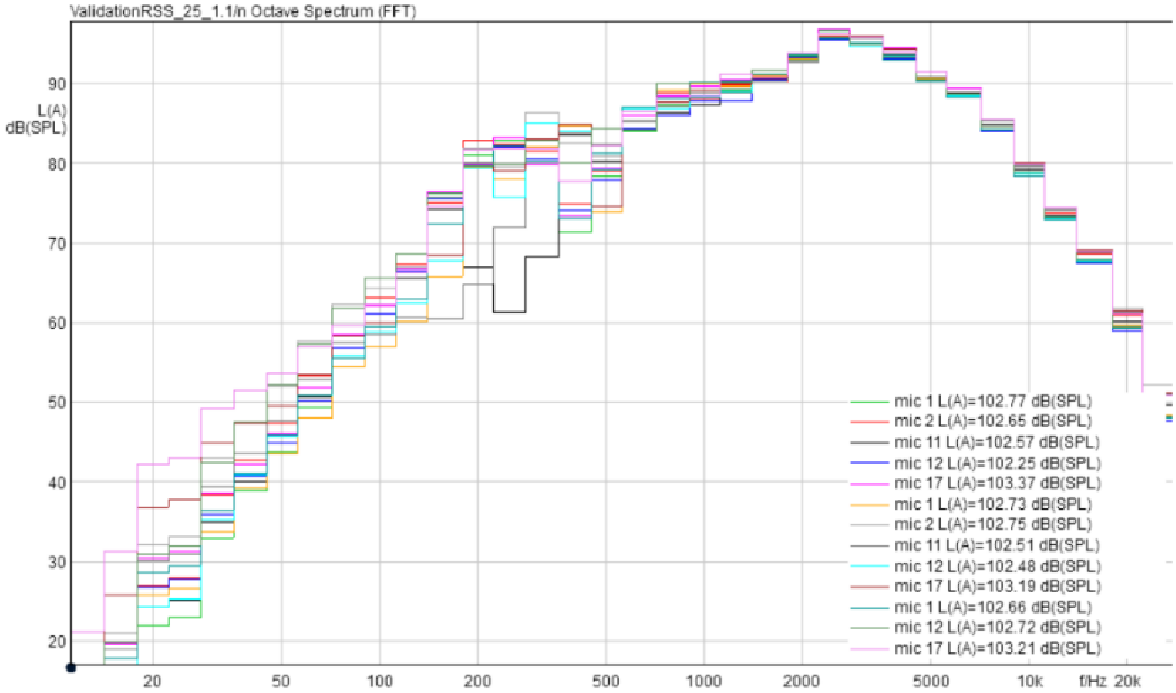

Figure 20 - SPL values measured at different microphone positions

These results highlighted a substantial variation in sound pressure throughout the chamber in the 200-500 Hz range. Upon closer analysis, the SPL values corresponding to microphone 11 were significantly lower than the others. This microphone was placed in the center of the stand, meaning that, in the affected frequency range, the SPL was higher closer to the walls and lower in the middle of the chamber.

To identify a possible cause for this phenomenon, other tests were performed, namely changing the position of the sound source, and using a different sound source - a Bluetooth speaker. Additionally, a measurement was done using only one hanging microphone (Figure 21) to eliminate the possibility of the behaviour being caused by the microphone stand.

Figure 21 - Single hanging microphone test

However, the chamber behaviour persisted throughout all different tests. Thus, the only conclusion that could be drawn was that this was in fact a fault of the chamber design. In fact, the frequency range at which it occurs coincides with the range at which a predominantly modal behaviour would be expected for a room of this size.

To mitigate the impact of this phenomenon in the STL tests, the setup was changed: instead of measuring the average sound pressure level inside the whole chamber, the average incident sound pressure on the sample window was used for STL calculation. Figure 22 shows the new setup and respective sound pressure graph.

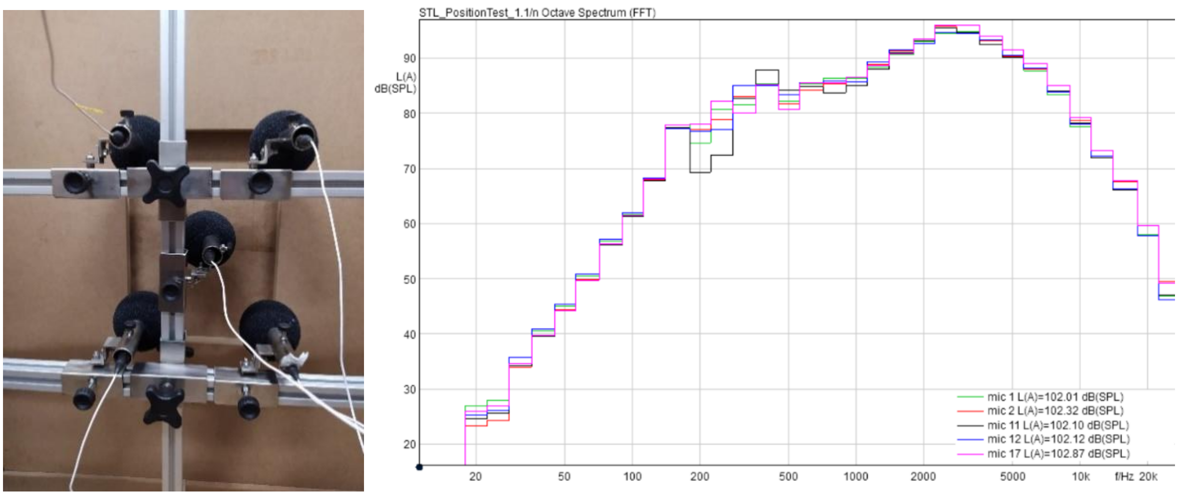

Figure 22 - Suggested mic setup for STL tests and SPL graph

As seen in the graph, the effect was still present, but was greatly reduced, and averaging the sound pressure level across these five microphones should provide an accurate enough value to perform the STL calculation.

5.3. Sound Transmission Loss Tests

5.3.1. Wood polymer composite panels

The STL tests were performed with two goals in mind. The first being to identify the best performing material sample, and the second being to assess whether the chamber was suitable for this sort of comparative test. The latter being the most fundamental, as it was the main motivation behind its development.

As previously mentioned above, the mini reverberant chamber was placed inside the semi-anechoic chamber in the acoustic lab. A reference sound source was placed inside it, along with the microphone setup from Figure 22 to measure the sound pressure level. Outside the small chamber, a PU probe was used to measure the sound intensity emitted by the material sample. This was done by performing a scan over the sample, while a camera tracked the position of the probe. This test setup is showcased in Figure 23.

Figure 23 - STL test setup with WPC sample

Initially, the STL tests were performed on three different types of Wood Polymer Composite (WPC) boards, shown in Figure 24, with dimensions of 395 x 280 x 24 mm. The WPC was chosen since this material exhibited great acoustic insulation performance in a previous project involving the development of an acoustic enclosure. Therefore, there was an interest in studying the impact of the boards' internal geometry.

Figure 24 - 3 WPC board types tested

For each material sample, two boards of the same type were placed side by side in the sample window. The rightmost sample on Figure 24 was also tested both with its grooves facing the inside and the outside of the chamber. Each measurement was repeated three times, and their results were averaged. Figures 25 and 26 show, respectively, the settings for processing the intensity measurements and the results of those measurements as a colormap.

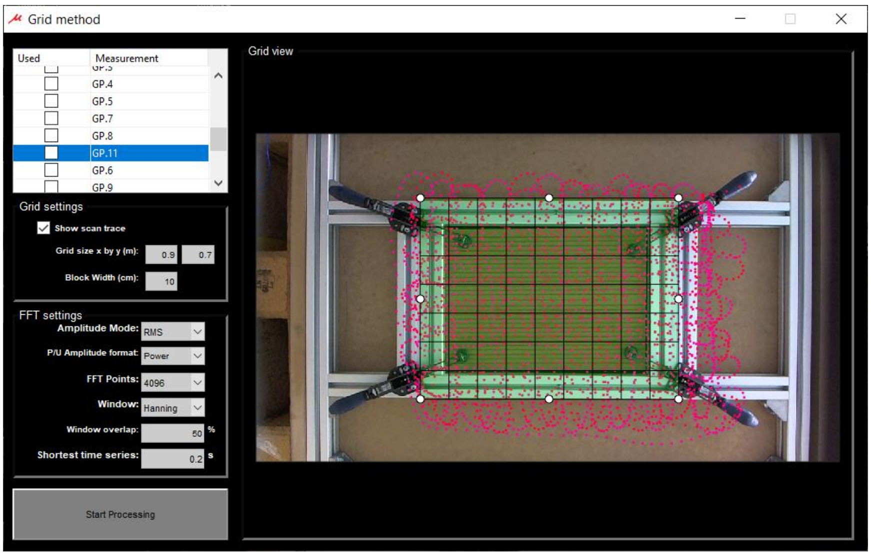

Figure 25 - Processing settings for the probe scans

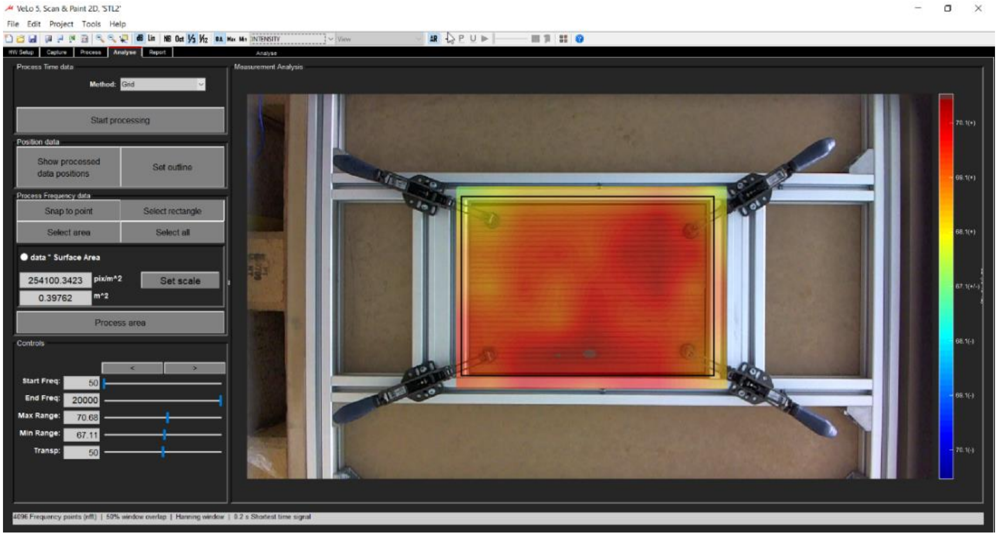

Figure 26 - Colormap of the sound intensity

The Sound Transmission Loss results were obtained by applying Equation (3) to the measured values of Sound Pressure and Sound Intensity across the third octave bands between 40 Hz to 12500 Hz, as this was the valid frequency range of the probe.

As expected, results show that the solid WPC boards have the highest STL value (Figure 27). However, it is important to highlight how similarly the boards with oval holes performed, while being significantly lighter.

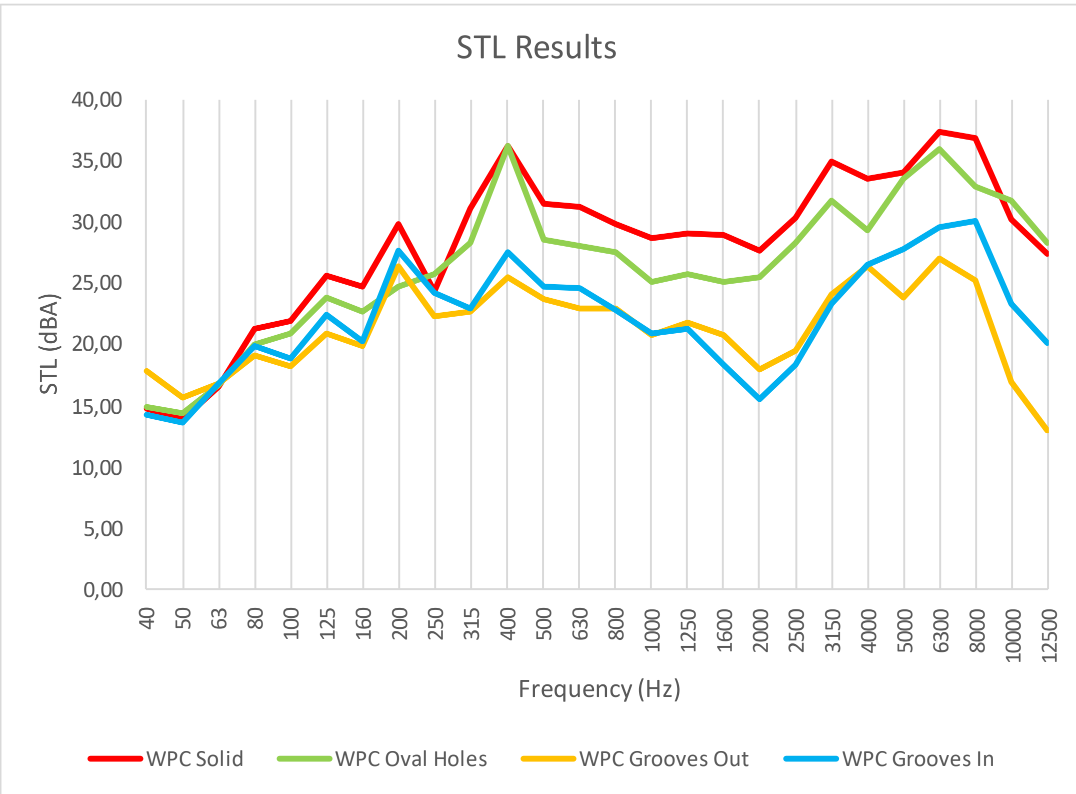

Figure 27 - STL results graph across the frequency spectrum

In fact, calculating the STL/mass ratio reveals that the solid samples are actually the worst choice for applications where minimizing weight is an important factor. In such scenarios, all other samples perform considerably better, as showcased in Figure 28.

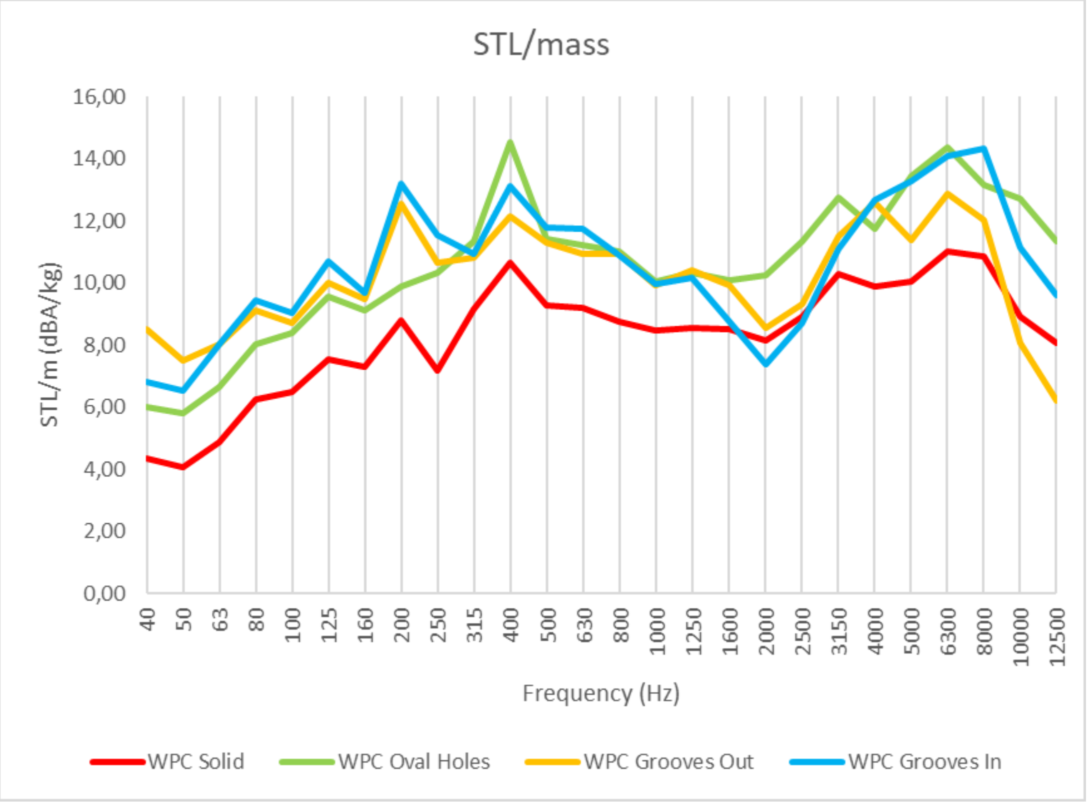

Figure 28 - STL/mass ratio results

Table 2 - STL test results

Sample	Mass (kg)	Average STL (dB)	Avg. STL/mass (dB/kg)
Solid	3.4	28.20	8.29
Oval Holes	2.5	26.44	10.57
Grooves Out	2.1	21.28	10.13
Grooves In	2.1	22.19	10.56

Table 2 clearly shows that, if weight is not a concern, the solid and oval holes samples perform the best. If weight is something that needs to be considered, the samples with oval holes and grooves become more appealing. Thus, the overall best performing sample is the one with oval holes, as it proves to be the most versatile, even coming close to the solid sample when disregarding weight.

For this reason, this sample was selected to be fitted with a geopolymer insulation and tested again to measure if an improvement could be made by adding this material.

5.3.2. Geopolymer and composite with geopolymer panels

While developing this thesis, there was an ongoing study being carried out by another master student, who was creating geopolymer materials to replace the expanded polypropylene (EPP) that was typically used in heat pumps. So, there was an interest to test how the material would perform acoustically and thus, the mini chamber was used for that purpose.

The initial sample had dimensions of 150 x 150 x 100 mm, so it was cut as follows: a 40 mm sample was cut for standalone testing (Figure 29) and the remaining material was divided to in a way that would allow for it to cover the WPC boards with roughly 8 mm of material (Figure 30).

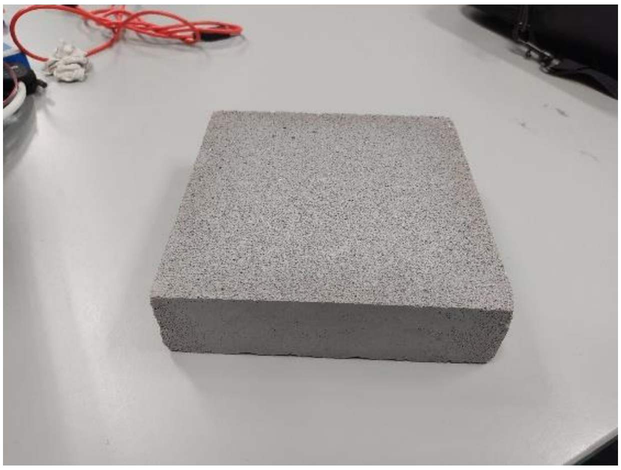

Figure 29 - 40 mm block for standalone testing

Figure 30 - WPC board fitted with 8 mm geopolymer

The 40 mm block was placed into the sample window of the chamber, using a CNC machined MDF board (Figure 31) to hold it in place.

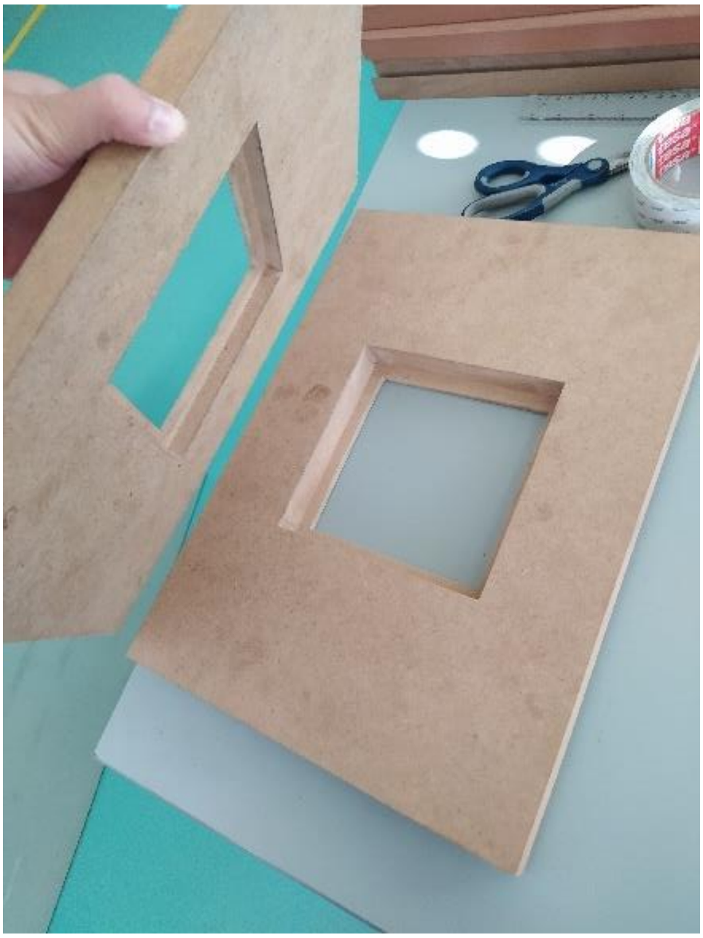

Figure 31 - Sample holder for smaller test samples

Measurements with this sample proved unreliable, since it was difficult to obtain valid results consistently. A lot of the measurements were exhibiting inconsistent results in the 200-500 Hz range. It is likely that the chamber's modal behaviour was the cause of this. Nevertheless, the results that were valid unveiled good STL performance, especially regarding the high frequencies. The graph of Figure 32 compares the geopolymer results with the solid WPC board.

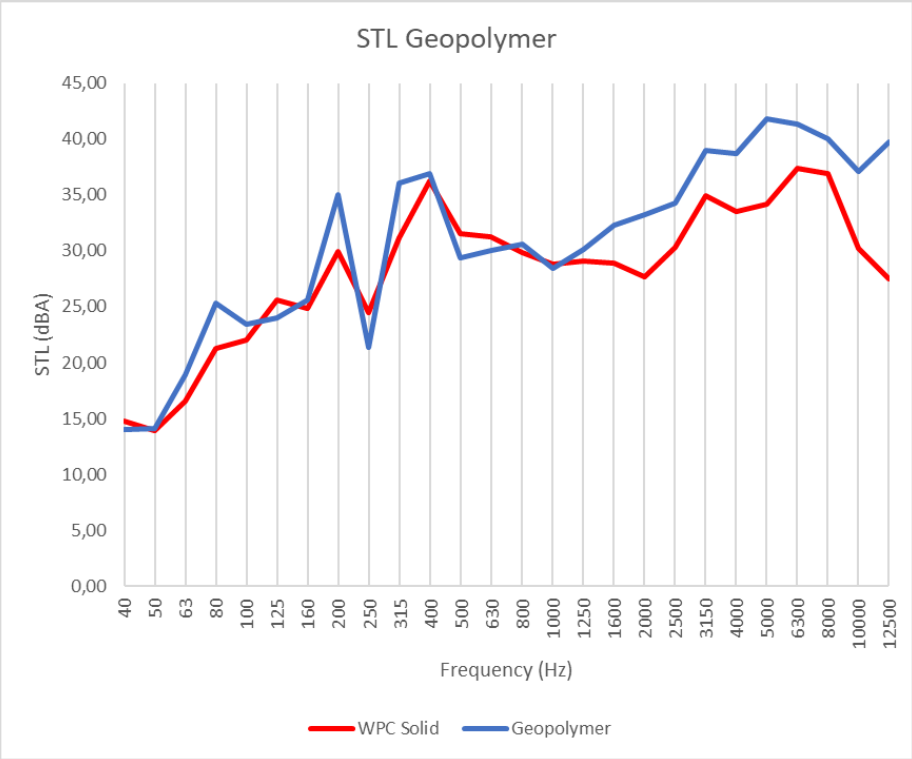

Figure 32 - Comparison between geopolymer and solid WPC

Surprisingly, fitting the WPC sample with the geopolymer material barely changed its STL result (Figure 33).

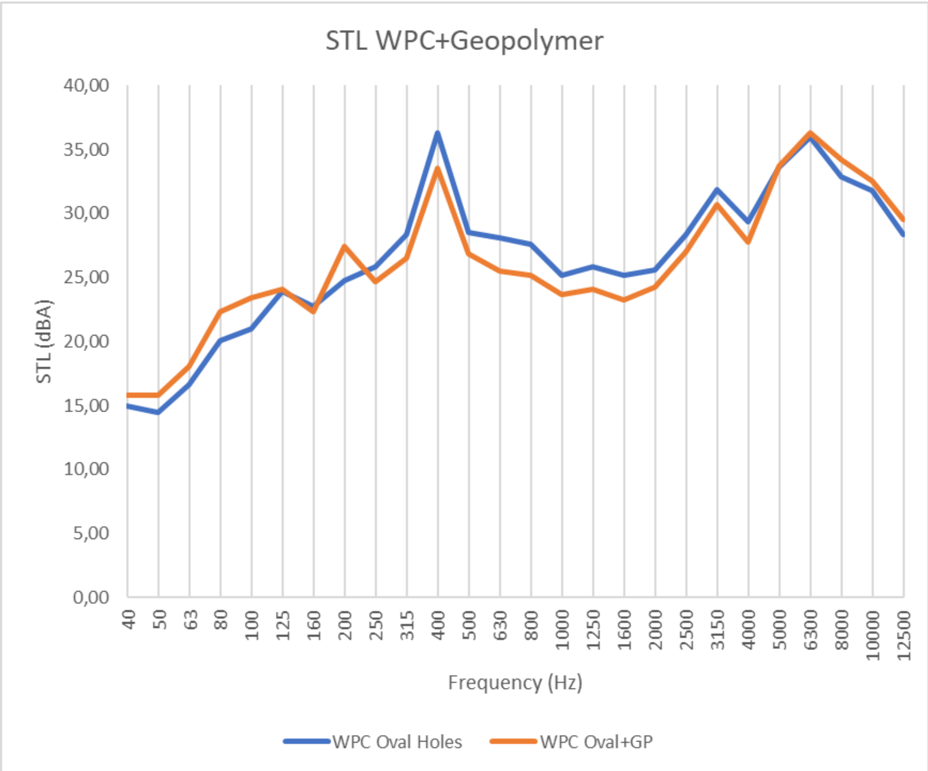

Figure 33 - STL graph of WPC sample with vs without Geopolymer

In fact, adding the geopolymer appeared to have made the WPC perform slightly worse. However, the difference was within the margin of error and, thus, could likely be attributed to other variables in the test conditions, such as scanning distance or speed.

Regardless, the expectation was that adding the geopolymer would improve STL performance, mainly in the high frequency range, as showcased in the previous test. It is possible that the geopolymer that was fitted onto the WPC was too thin to produce a significant difference. Unfortunately, the amount of geopolymer material available for testing was limited, so it was not possible to verify this hypothesis by repeating the test with a thicker sample.

5.4. Panel Vibration Analysis

With the goal of better understanding the cause behind the sound pressure variation inside the chamber, an experimental analysis was performed on the vibration modes of the panels that make up the chamber. This could help determine if the vibrations of the panels were responsible for causing, or at least, contributing to the sound pressure variation in the 200-500Hz range.

5.4.1. Test Setup and Procedure

This study was done in a similar way to a multiple point modal test. When performing a modal analysis test on a panel, the first step is to define a grid of points and choose whether to move the impact hammer or the accelerometer between measurements. Moving the hammer, known as the roving hammer method, has the advantage of not requiring the accelerometer to be unmounted and remounted in another position between measurements [19]. For that reason, and since the grids defined for the panels contained a large amount of measurement points (Figure 34), this method was chosen for this study.

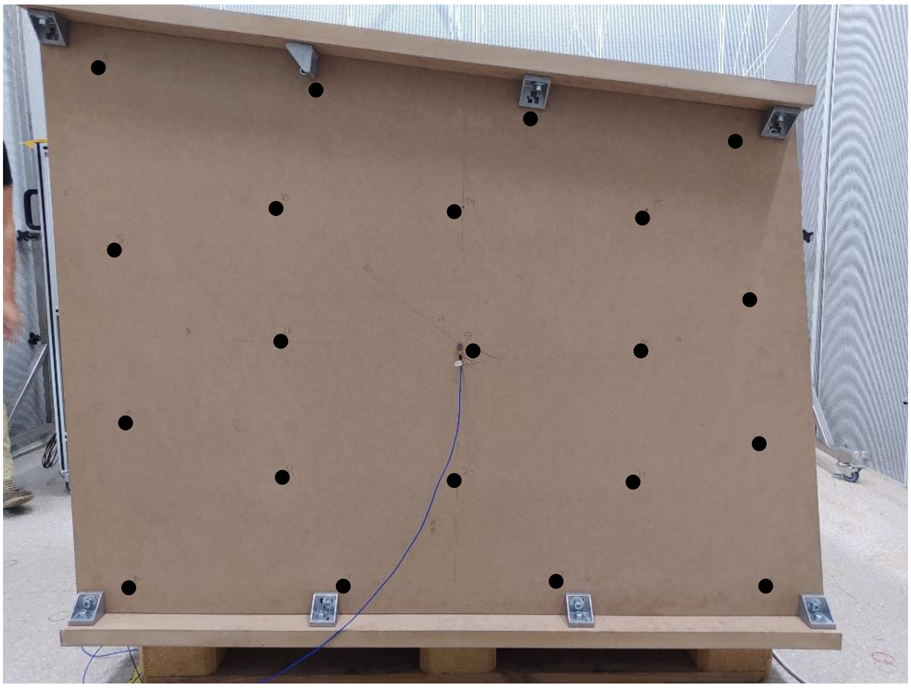

Figure 34 - Point grid on right panel with accelerometer mounted in the center

For each measurement point, five hammer impacts were performed and the readings from the accelerometer were processed in ArtemiS Suite 12.5 and exported into text files containing data regarding the panel's acceleration response in the frequency domain.

5.4.2. Results

A Matlab script was created to analyse this data and create the acceleration vs frequency graphs depicted in Figure 35. Even though the acceleration data obtained from the accelerometer was very noisy, it is still clearly possible to observe major acceleration peaks in the 200-500Hz frequency range in the larger panels (left, right and top). This shows that the panels of the chamber also contributed to the modal behaviour in the problematic frequency range.

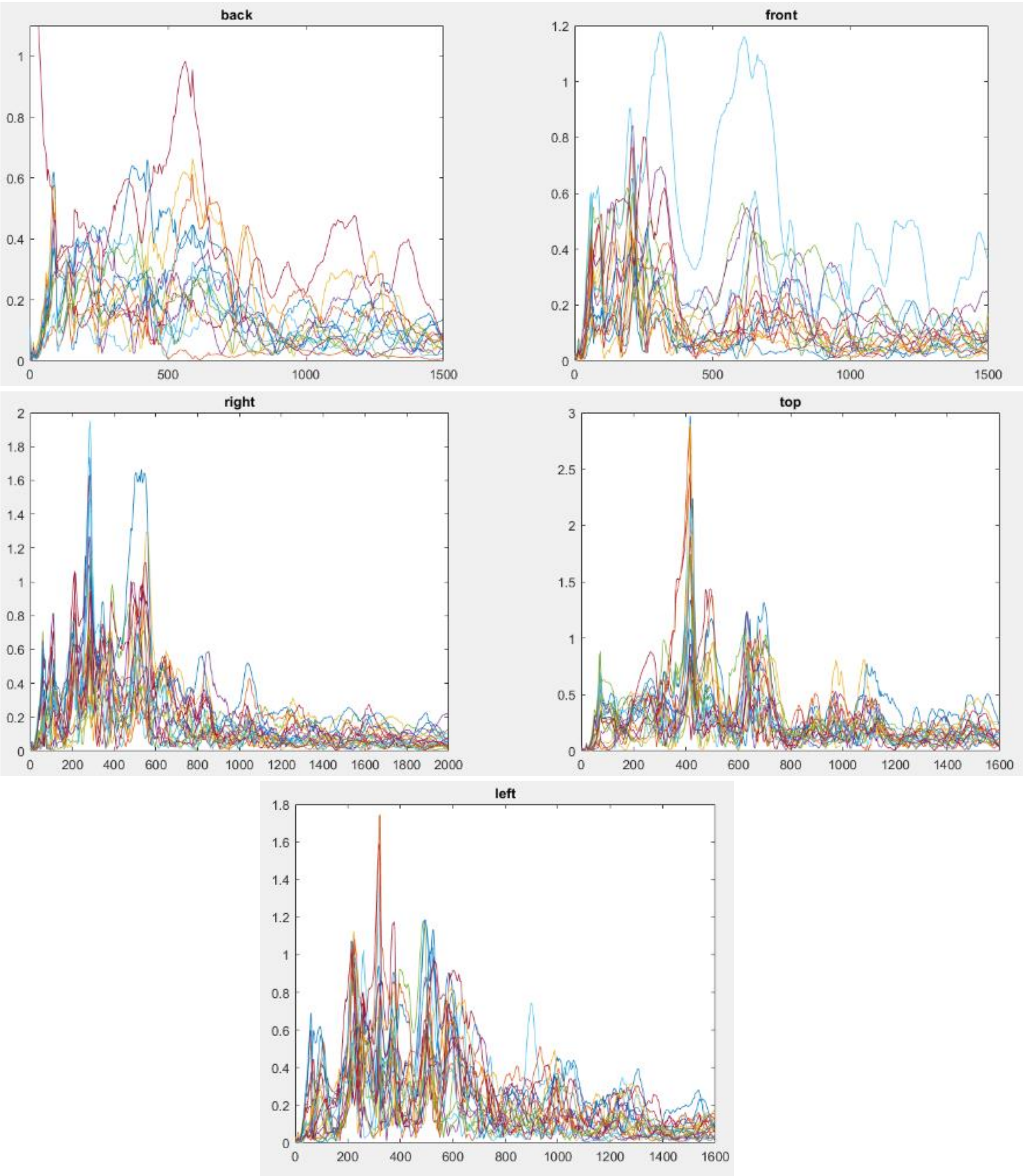

Figure 35 – Acceleration (m/s^2) vs frequency (Hz) plots for the chamber panels

However, the front and back panels were much less affected by this. This may be justified by presence of strut profiles in these two panels, which was done to simplify the assembly of the chamber. This indicates that the vibrations of the top, right and left panels could be greatly reduced by reinforcing these panels with more aluminium strut profiles, similarly to what was done to the front and back panels.

6. Conclusion

6.1. Summary

The primary goal of this master thesis was to develop a small-scale reverberant chamber that could be used to perform sound transmission loss tests inside a semi-anechoic chamber.

Designing a small reverberant chamber presents several challenges, primarily in guaranteeing sound field diffusivity inside it. Additionally, it was important that the chamber met the requirements of being easily movable in and out of the semi-anechoic chamber, as well as easily assembled and disassembled, which would, in turn, facilitate setting up the STL tests.

Internal dimensions of the chamber were chosen based on the literature and an initial CAD model was created. MDF was selected as the main material for the chamber. This choice was based on its low acoustic absorption and good workability and availability. Rexroth aluminum profiles were then added to the structure to greatly facilitate assembly.

To evaluate the chamber design, a sound field simulation was done with the I-Simpa software. Results showed good field diffusivity, with the largest variation sound pressure inside the chamber being only around 2 dB. Unfortunately, the good simulation results did not translate into reality, as the validation tests done on the chamber exhibited a large sound pressure variation in the 200-500 Hz frequency range. Thus, the STL test setup was slightly altered to minimize these effects.

The STL tests were performed on three different WPC samples and a geopolymer insulation material. These tests showcased that the chamber could indeed be used for such comparative tests, since it was possible to identify which WPC sample performed the best. That sample was then fitted with the geopolymer material, but that failed to produce any meaningful difference. However, the standalone test done on the geopolymer pointed towards the material being good at attenuating noise higher frequencies.

A vibration analysis was performed on the panels of the chamber, and it was found that they were contributing to the modal behaviour of the sound field inside the chamber in the problematic frequency range.

6.2. Suggestions for future work

There are a few ways in which the work presented here can be further built upon.

Most importantly, it would be ideal to study a way to improve the performance of the chamber, regarding its heavily modal behaviour in the 200-500 Hz frequency range. This could be done by installing diffusers, which is a common approach in normal-sized reverberant rooms. Adelgren *et al.* [20] studied the impact of installing boundary and hanging diffusers in small reverberant chambers. Wang *et al.* [21] utilized Boundary Element Method (BEM) and Statistical Energy Analysis (SEA) to simulate the installation of boundary diffusers and achieved good results regarding field diffusivity. It would be worthwhile to consider this approach, as it would likely improve the chamber's modal behaviour and the diffusers could be installed without the need to redesign the existing chamber.

As suggested by the results of the vibration tests, reinforcing the top, left and right panels with aluminium strut profiles could also help to minimize the modal behaviour of the sound field in the problematic frequency range. A proper modal analysis could also be performed to better understand the vibration of the chamber's panels. However, this would require repeating the impact hammer tests, since the current acceleration data is too noisy to accurately perform a modal analysis study.

Another suggestion would be to attempt to automate the measurement process, namely the scanning with the intensity probe. A manual scan will never be perfect and the distance between the probe and test object will suffer fluctuations and the scanning speed will also not be constant. Automating that process would allow greater control over those variables and reduce the necessity to repeat measurements.

A fourth suggestion would be to test more WPC samples with a hollow interior. It was clear that the sample with oval holes showed the best results, so it would be interesting to assess other interior hollow geometries.

Lastly, the final suggestion would be to further explore the geopolymer as a sound insulation material, namely testing different thicknesses. In fact, the same could be done with the WPC boards. This would be a good effort towards finding the optimal combination of these materials for sound blocking applications.

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Appendix A

Technical Drawings

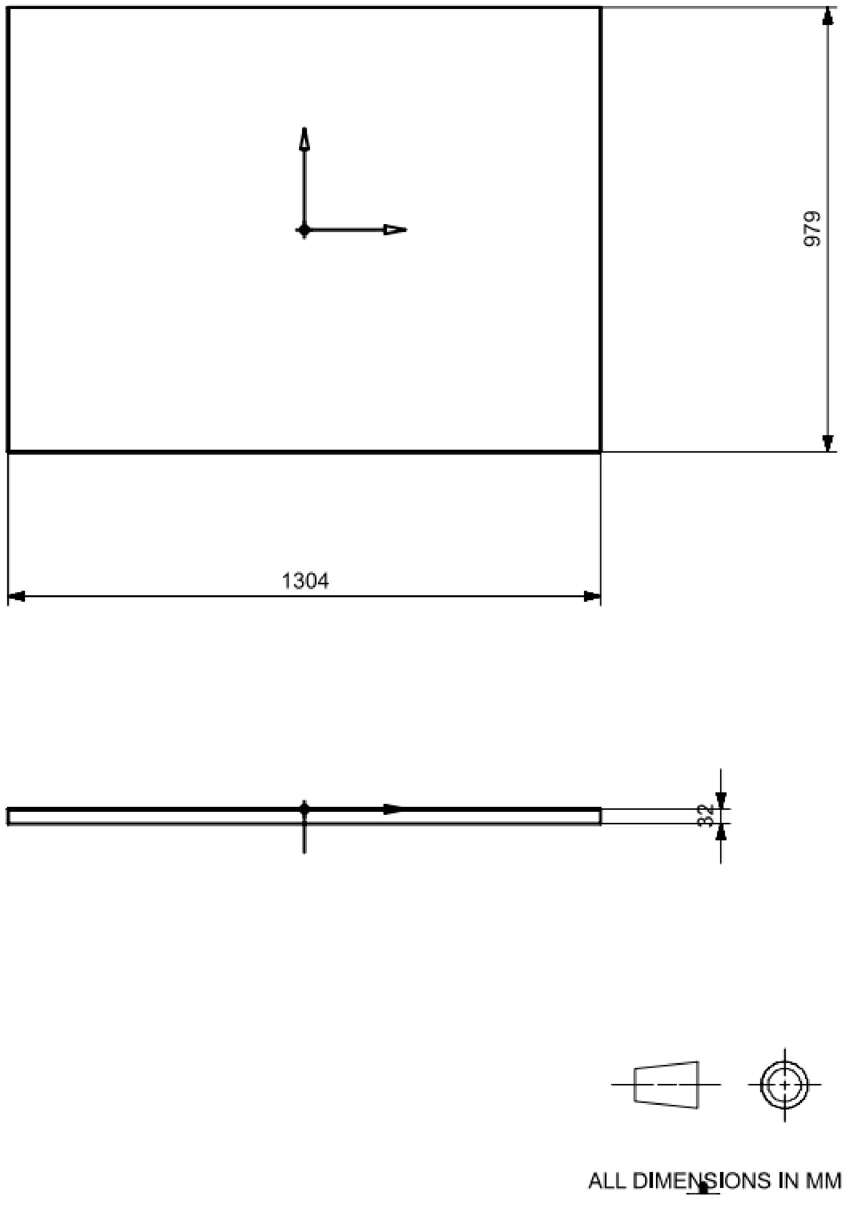

Figure 36 - Base

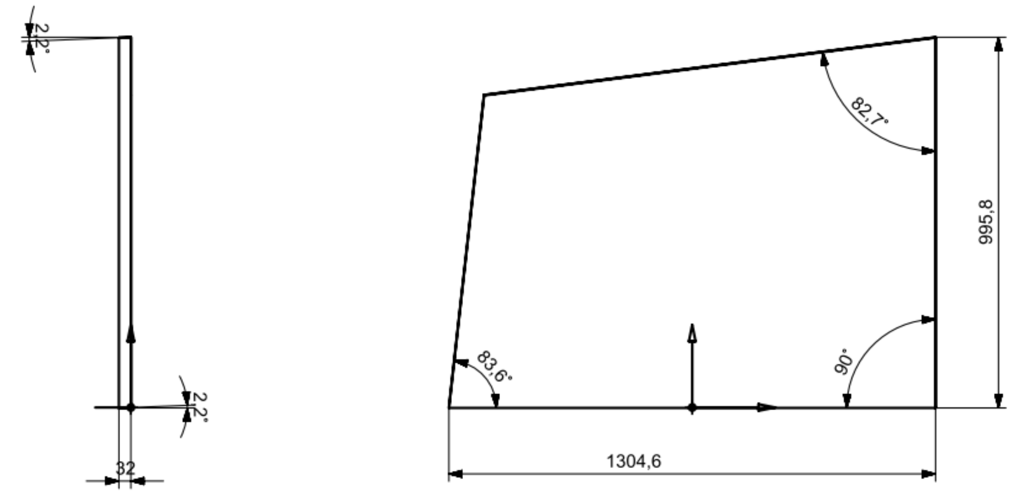

Figure 37 - Left Wall

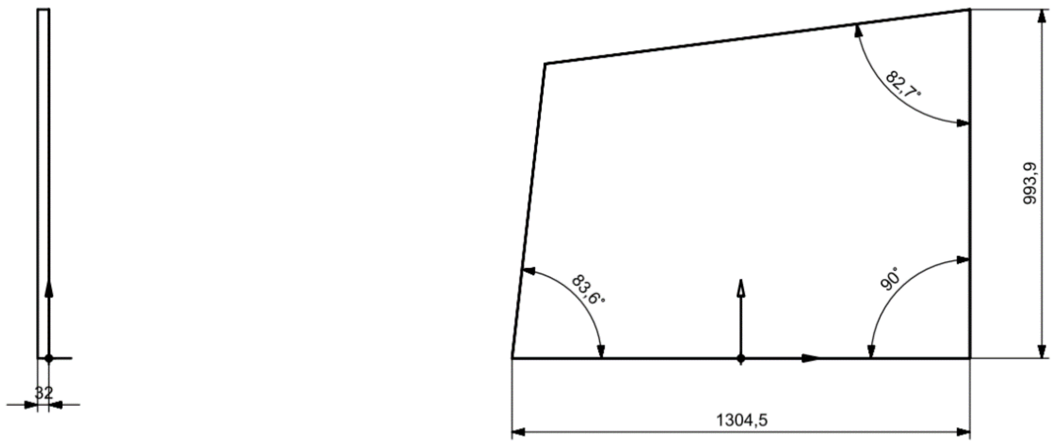

Figure 38 - Right Wall

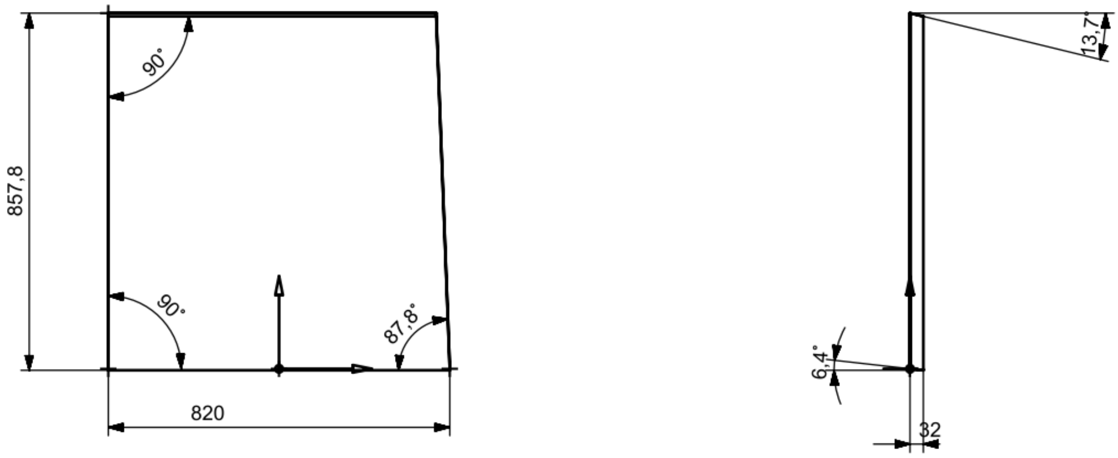

Figure 39 - Back Wall

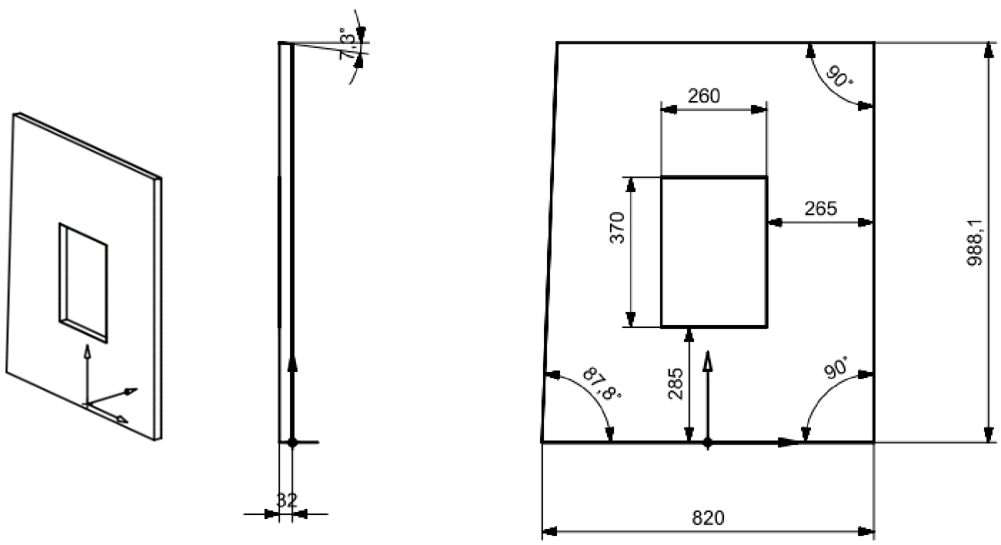

Figure 40 - Front Wall

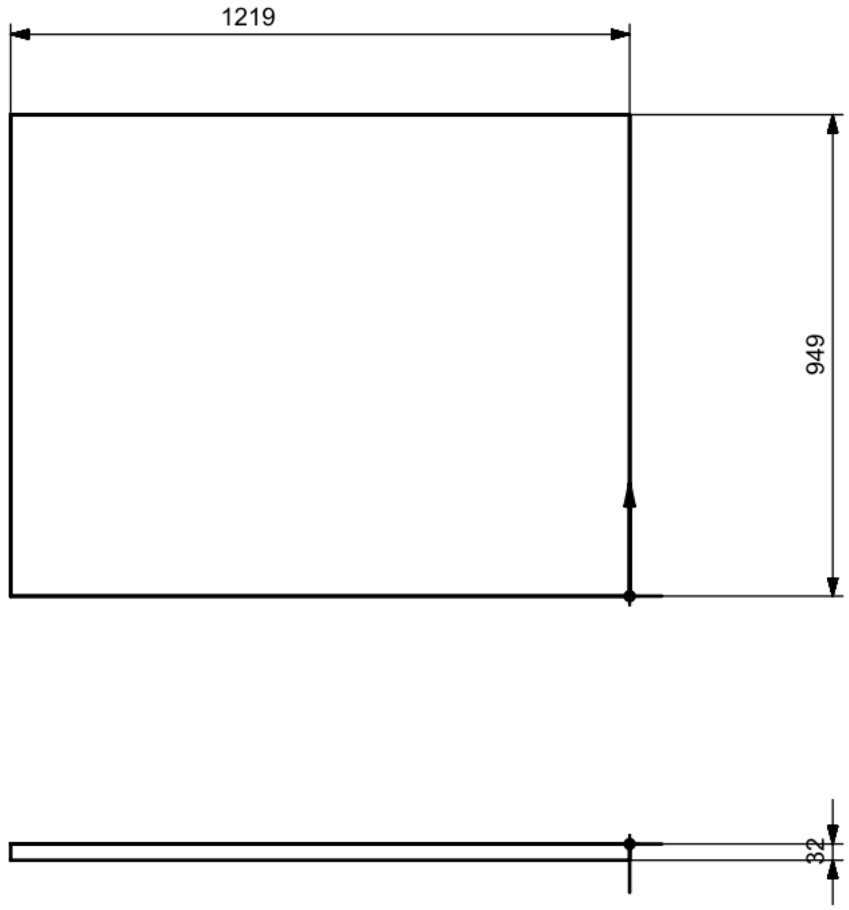

Figure 41 - Top

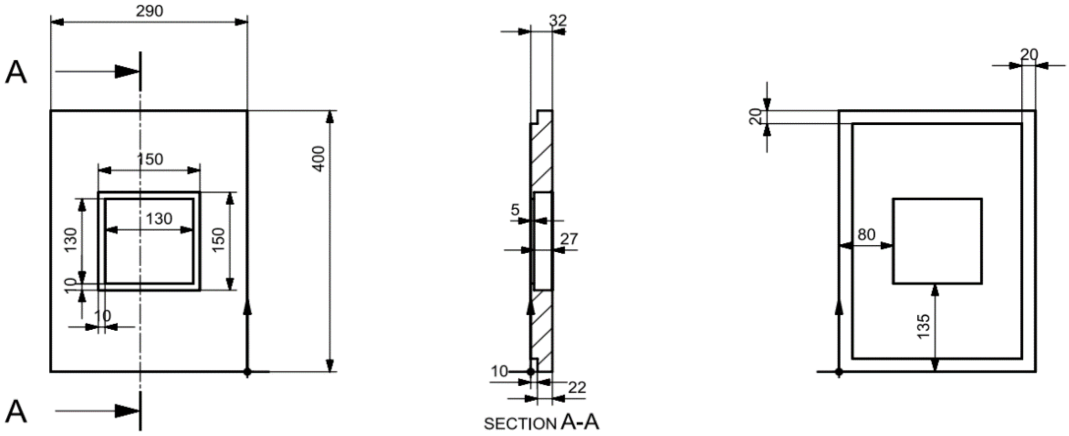

Figure 42 - Sample Holder 1

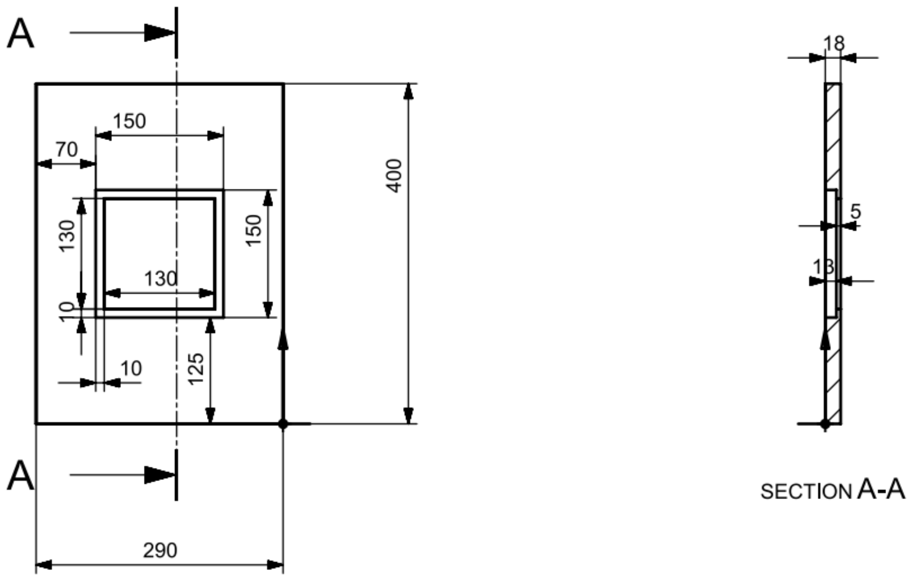

Figure 43 - Sample Holder 2

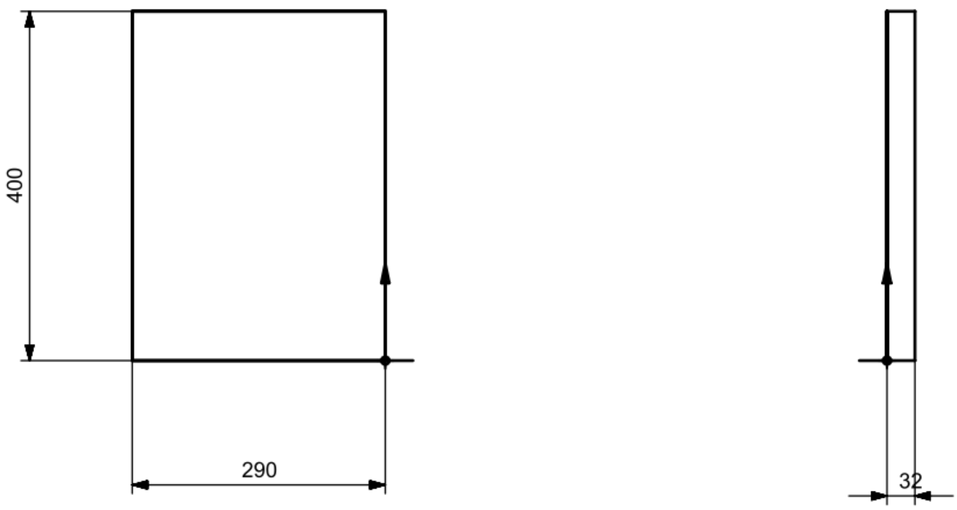

Figure 44 - Window Cover