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Article

Acoustic modeling and analysis for a multipurpose auditorium

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Abstract: The architectural acoustics of the theatrical space and the acoustics of the performance are key factors in achieving optimal acoustics in theater halls. This paper addresses innovative techniques for acoustic study dedicated to theater halls. More precisely, the study of the studio hall of the Colibri Craiova Children and Youth Theater is envisaged. This hall must align with recent trends, that of becoming and transforming, in a very short time, from a theater performance hall to an audition hall for classical music, then into a hall that hosts photographic art exhibitions. To define the model of the acoustic system in a virtual space, the existing auditorium was initially scanned in three dimensions using specific hardware and the *Geomagic* tool. Then the resulting model was loaded into *SolidWorks* for further modeling. Using Computer Aided Design techniques and the finite element method, various elements such as loudspeakers and chairs are embedded in the acoustic system model to obtain a realistic representation. Then, based on the obtained model of the acoustic system, several analyses and simulations were performed in the *Ansys Workbench* program. The key simulation results derived in this work are as follows: combined simulation tools and techniques allowed the auditorium's realistic modelling; acoustic pressures, sound pressure levels (SPL), and frequency band SPL measurements and detailed analyses were achieved, for various configurations and frequencies; the developed models and the performed analysis are useful for the optimization of the acoustic performance. These reported results, with areas of the hall subjected to extreme variations in sound pressure, i.e., with reflection and absorption problems, obtained through simulation, allow the practical implementation of acoustic optimization in other similar halls.

Keywords: acoustics; auralization; finite elements analysis; harmonic acoustics; performance hall; virtual methods

1. Introduction

This work was undertaken to highlight differences in approach, from both an acoustic and interpretative point of view, regarding multifunctional cultural spaces that must be adapted to current trends. The space selected for study exhibits the weakest acoustic characteristics and is the least likely to function as a theater, reading room, concert hall, exhibition space, or similar venue. It has a parallelepiped shape, flat walls, a concrete floor, and is practically a "box", which represents the worst configuration from an acoustic standpoint. Such spaces are extremely difficult to acoustically model and optimize, in accordance with established standards and, in particular, with the requirements of musicians. For this reason, the study represents a significant challenge, as most acoustic studies typically focus on dedicated performance halls. Consequently, a less conventional approach was adopted. In the first phase, classical acoustic parameters (such as reverberation time, clarity, etc.) were not prioritized; the analysis focused on the spectator, the knowledgeable audience, which is subjective and, perhaps for this reason, is more realistic and practical.

Two main factors compete in achieving optimal acoustics for a performance: the architectural acoustics of the theatrical space and the acoustics of the performance. By architectural acoustics we understand the quality that the stage-hall ensemble has of creating the best possible acoustics. This factor is determined by the construction of the hall itself, as is the case in this work, the study of the studio hall of the Colibri Craiova Children and Youth Theater (CCCYT), whose construction began in the late 1960s, and which has been modified over time. This hall behaves acoustically in a way that depends on the linear dimensions, the total volume, and the materials covering the surfaces. Sound waves travel spherically outward from the sound source, and when the waves encounter the boundaries of the space (ceiling, floor, and walls) or obstacles in the space (furniture, people, decorations, and accessories), part of the sound energy is absorbed, and the rest is reflected [1].

In this paper, we addressed an innovative technique for acoustic study, because this hall, a rectangular parallelepiped-shaped hall, which is unofficially defined as a shoebox, must align with recent trends, that of becoming and transforming, in a very short time, from a theater performance hall to an audition room for chamber or classical music, then into a hall that hosts photographic art exhibitions, painting or sculpture and then, into a conference hall or any kind of event. Thus, after performing these measurements and precisely establishing the details for each type of event, this transformation can take place in a short time following the simulations and graphs performed. The studies and research carried out and presented in this paper started from the idea of obtaining very good acoustic comfort, in a closed space, intended for carrying out public activities, performances, exhibitions, conferences, etc., in medium-sized working groups (25–50, 50–100 people). In the context of multifunctional performance spaces, *acoustic comfort* is defined as the set of acoustic conditions that ensure adequate speech or music intelligibility, balanced sound distribution, and listener or spectator satisfaction according to parameters such as reverberation time, clarity, and sound pressure level, as described in ISO 3382.

Starting from the geometry of the enclosed space, imposed by the construction of the studio hall of the CCCYT in Craiova, an acoustic optimization was sought that could be varied in time and space. The possibilities of removing the parallelism between the side walls, but also the ceiling of the room and its floor, and the formation of irregular surfaces on the walls were studied.

In the case of faulty acoustics, due to the placement of the decor, chairs, furniture, etc., the most annoying phenomenon can occur, namely, reverberation. If the sound vibration is reflected by a certain plane, overlapping the basic vibration that formed this sound, this phenomenon can occur, which can help the acoustics of the hall when the overlap is made with a delay greater than 0.1 s, when the sound is reinforced, and can harm when the superimposed sound has a greater delay, when the sound is prolonged. There are cases when this reverberation can help create a dramatic moment, but, still, through reinforced reverberation, the whispers of the actors or certain frequencies can be heard [1].

We can say that the architectural acoustics of the theater hall on a scientific basis was born at the beginning of the 20th century, thanks to the studies of the American professor Wallace Clement Sabin. Sabin's theoretical studies are based on Bernoulli's principle, which consists of studying the natural vibrations of the space formed by the hall, and Lambert principle, which consists of following a sound wave on its way through the hall and its reflection on the walls: T = KV/A, where V is the hall volume (m^3), T the reverberation time (s), A the total absorption of the hall and the stage (metric units) and K is a constant coefficient (K = 0.16). Analyzing Sabine's formula, we observe how the construction of the set and walls modifies factor A, that is, the total absorption of the hall and the stage; the rest of the parameters remain constant. Therefore, in a hall with an increased absorption coefficient, either through the materials used or through the positioning of the spatially arranged elements, the reverberation time T decreases, so the emitted sound decreases. Conversely, when the absorption coefficient of the hall decreases using highly reflective materials, the reverberation time increases, and the acoustics of the performance suffer, due to prolonged sounds that can reach the echo [2].

A particular interest has been shown recently in the acoustics of enclosed spaces and architectural acoustics, namely the way in which sounds propagate in enclosed spaces (rooms, halls, offices, etc.). As can be seen from the definition of reverberation, any enclosed space possesses this phenomenon due to the multiple sound reflections that occur after the sound source has been emitted. Depending on the destination of the enclosed space, the reverberation will have a certain duration, obtained by using appropriate acoustic materials and structures, in conjunction with the geometry of the enclosed space. The way in which these conditions are met will determine the level of acoustic comfort in the respective enclosed space.

Considering that the frequency analyses used in this paper are performed for frequencies of 400 Hz, 10.8 kHz and 20 kHz, the reasons for this selection are presented below.

Before the standardization of the A note at 440 Hz, various tuning forks oscillated in the range of 400–460 Hz. 400 Hz is sometimes used in audio engineering as a reference tone for calibrating signal levels and is sometimes preferred over the 1 kHz tone because it is less harsh to the human ear, while still being clear enough to detect distortion. The human ear perceives different qualities of the same note when produced by a piano, violin, or tuning fork, which is the simplest tone, the sound consisting of a vibration that is almost entirely the A note. Due to the acoustic and resonant properties of the eardrum, this pure tone reaches the ear mechanism in an unmodified form. The main components produced by the piano and violin are 440 Hz, but they contain multiple components, and the exact intensity of these harmonics defines the quality of the note. The 400 Hz frequency is often identified as the center of the area that causes a dull or dirty sound. Excessive energy buildup in this spectrum (especially from reverberations or the overlapping of multiple instruments) can make a mixed sound unclear or boxier. In proper balance, frequencies between 200 Hz and 400 Hz provide warmth and weight to instruments and vocals. Too much of a cut at 400 Hz can make the sound seem thin or lifeless. From about 300–400 Hz down, sound sources begin to radiate sound evenly in all directions, regardless of the shape of the enclosure. For acoustic treatment, this frequency is an important target for absorption and diffusion panels, as its wavelength interacts directly with the dimensions of the furniture, decor, and other elements of the multipurpose room.

The frequency of 10.8 kHz has a specific importance in acoustics, being located in the high range of human hearing (treble/brilliance). Frequencies around 10–12 kHz are responsible for the brilliance of a quality audio mix. At 10.8 kHz, the upper harmonics of many instruments are found, such as cymbals, hi-hats, or the attack of acoustic guitar strings. A balanced presence at this frequency provides realism and fine detail. Sound engineers monitor this area to avoid excessive sibilance (high-pitched "s" sounds) which can become tiring to the ear if amplified improperly. In digital sampling, in signal processing, to faithfully reproduce a frequency of 10.8 kHz without distortion (aliasing), a sampling rate of at least 21.6 kHz is required (according to the Nyquist theorem). The CD standard of 44.1 kHz and the media platform standard of 48 kHz comfortably cover this range, ensuring clean playback.

The frequency of 20 kHz is considered a fundamental target frequency because it marks the theoretical upper limit of the human hearing spectrum. This serves as a demarcation between audible and ultrasonic sounds and uses the 20 kHz threshold to define normal hearing in young adults. Recent research highlights that although children can perceive frequencies slightly above this threshold, sensitivity decreases rapidly with age, with the threshold often dropping to 15–17 kHz in adults. Increased attention is being paid to the physiological effects of these inaudible frequencies present in public spaces (from sensors or industrial devices), investigating symptoms such as dizziness or fatigue, even if the sound is not consciously perceived. In signal engineering (Nyquist Theorem) this frequency determines the standard sampling rates in digital processing. To faithfully reproduce the 20 kHz limit, a rate of at least 40 kHz is required, which underlies the industry standard of 44.1 kHz (CD) and 48 kHz in the media industry. Universities use 20 kHz as a basis for developing new technologies that translate high-pitched sounds (such as those emitted by bats or gas leaks) into the human audible spectrum, allowing precise localization of ultrasonic sources [3].

The present work is structured as follows. Section 2 presents the literature survey related to acoustic systems in performance halls. Section 3 is dedicated to the three-dimensional modeling of the acoustic system related to the Colibri Theater. To define the model of the acoustic system in a virtual space, the auditorium was scanned using specific hardware and the *Geomagic* tool. Then the resulting model was loaded into *SolidWorks*, where other specific elements are added (loudspeakers, chairs). In Section 4, by using the obtained model of the acoustic system, several analyses and simulations were performed in the *Ansys Workbench* program, for various configurations and frequencies. Finally, Section 5 concludes the paper.

2. Related works

Today, several theoretical and practical studies are known for designing theater halls with optimal acoustics. However, regarding the problem of performance acoustics in theater halls, there are few theoretical works reported on the large number of problems that can arise. Some acoustic research studies focus on the development and contribution that theater, in particular, has made over the centuries as a place of cultural propagation in all classes of society [4, 5], while others take these cultural heritage buildings as an opportunity to perform acoustic simulations and make improvements to them for contemporaneity and for the next few decades, to be adapted as an example of fire safety [6]. After the COVID-19 pandemic, many research studies have been conducted on the occupancy rate of performance halls, but at the same time, the reality is that there are also times when the halls are occupied in various configurations [7]. Studies conducted on the occupancy of a percentage of the performance hall, in which spectators were seated in disproportionately distributed groups, differ from the COVID-19 situation when the hall was occupied at a percentage similar to the studies conducted until then, the major difference being that during the pandemic the halls were occupied but the distribution of people was uniform, in order to respect the sanitary safety distance: 33% one occupied seat and two unoccupied seats, 25% one occupied seat and three unoccupied seats, etc. Starting from this premise, several investigations have been undertaken with reference to live virtual reality performances [8–10].

The scientific literature [11–16] presented several criteria that rooms intended for a certain purpose should meet, in this case: theater performance hall, chamber music hall, conference hall, painting, sculpture, or immersive exhibition hall. These criteria are based on measurable parameters of the hall, such as, for example, reverberation time, intelligibility, sound intensity, and noise [17–21]. However, in the real world, it has been demonstrated that, even when all the conditions for a hall are met, the spectator, listener, or event participant, being subjective, may still be satisfied or not with the sound message or the state he experiences [22–24]. Taking this reality into account, the study was carried out on a wide band frequency, but we chose to present some acoustic pressure simulations, examples performed at less commonly used frequencies, respectively, 400 Hz, 10.8 kHz, and 20 kHz. The analysis performed for these frequencies could reveal some specific problems, either for high frequencies (for example, stringed instruments can reach very high frequencies), or related to some harmonics that virtuosos use to give personality to their performances (around 10.8 kHz). Also, the frequency of 400 Hz was chosen for the study because the tuning of some musical instruments is done around this frequency (the piano is tuned at 440 Hz).

Some studies have addressed these issues based on objective results and human auditory perception [25, 26]. The quality of speech perception is influenced not only by the parameters related to the room acoustics, resulting from its design (construction, shape) and technical equipment, but also by the specifics of the performance. Depending on the staging, performances will differ in terms of stage decoration (trousers, side curtains, backdrops, sets, and textile horizons), acoustic panels (absorbent or reflective) [27], and choreography (placement of actors on stage or in the hall) [28]. Thus, it becomes important to identify the properties of the room acoustics that are relevant from a perceptual point of view, which affect the level of detail of the modeling. The perceptual effects of different surface modeling have not yet been fully investigated because the main disadvantage, at the current state of modeling software technology, is that different simulation tools require different input data [29, 30]. Thus, the material properties of surfaces or objects, such as absorption or reflection coefficients, have been shown, over time, to be aspects that contribute significantly to the margin of error in simulations and affect their comparative evaluation [31].

In other studies, various acoustic stage configurations were investigated based on the subjective assessment, this time, of the performers on stage, as well as on some of the most objective indices [32]. Thus, Barron studied the effects of stage configuration based on a survey conducted among musicians, mostly soloists, in various renowned concert halls [33]. A different approach was taken by those who evaluated the preferred stage acoustics for performances with solo performers or duos and chamber music groups [34,35]. The preferred positions of the musicians on stage were also investigated based on measurement data, and the results showed that positions in front of the stage were preferred [36]. Another category of studies and research that follows the acoustics of performance or concert halls has addressed the viewer's subjective perception of speech and music [37–40].

In studies on the acoustics of halls where orchestral concerts take place, emphasis has been placed on the volume of the stage, which is a crucial factor, since it includes the stage floor and the surrounding walls, which are closest to the direct sound. In addition, it affects the absorption or reflection of sound; it is the central element of the hall, which practically gives the shape of the entire hall. Studies on the effects of changes in the stage decor elements in a concert hall, on the audience in the auditorium, rather than on the performances on the stage, such as an orchestra, are insufficient. A landmark study on symphony orchestras examined the correlations between stage width, height, and depth and performer preference, after examining the effects of wide and narrow stage enclosures in successive virtual simulations, and found that the overall impression of performers showed a direct relationship to the height/width ratio of the stage. The research was extensive but focused only on performers on stage and did not address the effects on real-world audience acoustics [41].

Various investigations have focused on the ISO 3382-1 parameters [42], as these are used as design parameters on a larger scale. Other investigations on the effects of hemispherical reflection panels applied to rectangular and inverted fan-shaped hall surfaces confirmed the decreasing effects of diffusion panels on the important parameters: reverberation time (RT) and sound pressure level (SPL) [43]. Diffusive surfaces or panels are some of the most critical aspects in the acoustic design and renovation of concert halls, as the relationship between their placement and the effects on the sound field is subjective, with the design of the concert or performance hall being at the center [44–47]. In very large or very small rooms, the relationships between the different parameters may change and, consequently, the perceived differences may also be affected [48]. Therefore, the effects investigated in this research should be considered valid for the volume of the room in the case study and the associated RT intervals and could lead to a more detailed description of other attributes related to acoustic quality [49]. Previous studies of the use of reflective surfaces in favor of diffuse surfaces have shown approximately equal results in relation to the audience considered audiophile, experienced listener [50]. The effect of using diffusion or absorption panels on different types of symphonic music performances or concerts remains an actual topic, given the importance of the effects it produces for the audience and for the artists [51].

One of the most common ways of studying this is the use of multichannel devices for acoustic measurements, which has become very popular recently, especially among researchers interested in the development of auralization (i.e., the creation of audible acoustic scenery from computer-generated data) and can also be characterized by dynamic sound sources and receivers [52]. This solution of combining a virtual reality video with a 3D sound field is a way to allow a complete visualization and a useful auditory experience. This technique is the basis of technical application areas, including games, cinema, entertainment, and the automotive industry, with audio effects that make products more attractive and competitive in the global market [53]. The interest in auralization has brought improvements in algorithms for modeling diffusion, refraction, and absorption, binaural processing, and general reproduction techniques [54–56].

The approach proposed in the present work, unlike traditional methods that involve the use of specific equipment (e.g., laboratory microphones, omnidirectional loudspeakers, FFT measurement systems, etc.), is based on passive acoustic interventions, through treatments directed precisely at the most important acoustic parameters. Also, our approach does not require major investments in research infrastructure. Implicitly, it has a low research cost but, at the same time, is efficient and adaptable, offering high-level acoustic results in various architectural configurations, being at a high standard. This allows its use both in applied research and in practical interventions in already existing spaces. The proposed analysis and modeling method is versatile, being able to be applied effectively to any configuration of performance hall (theaters, philharmonics, etc.), conference hall, event hall, it can equally well be applied to classrooms in schools, high schools and universities, even in larger or smaller auditoriums and to unconventional reused spaces (industrial halls, heritage buildings, etc.) where acoustics are not at the highest levels or where noise should be attenuated or even eliminated. Moreover, this method can be used for any already built space (there are extremely many cases), which, after being studied, can be adapted and modified to obtain exactly the best results.

Compared to traditional measurement-based approaches, which rely on *in situ* FFT systems and omnidirectional sound sources, the proposed virtual modeling methodology allows for rapid evaluation of multiple configurations without physical reconfiguration of space. While measurement-based methods provide direct validation, the numerical approach offers flexibility, low cost, and efficient scenario testing during early-stage acoustic optimization or in multifunctional halls, historical theatres, churches, lecture halls, auditoriums, amphitheaters, etc. Advantages of the Virtual Method (Simulation): provide predictability, allow visualization of how passive materials (louvers, absorbers) will change the room before they are purchased or installed. Auralization: simulations allow listening to the virtual room, providing subjective evidence of the benefits of the acoustic treatment and identifying the exact points for panel installation using these sound intensity simulations, something impossible to achieve only through point FFT measurements. It depends on the accuracy of the absorption coefficients employed and the geometric modeling (e.g., using LiDAR or Geomatic techniques). Advantages of the Traditional Method (FFT): It is the only method that confirms whether passive intervention has reached the desired legal or technical parameters. Measurements can reveal acoustic bridges or structural vibrations that a virtual model, if not extremely complex, could miss. Qualitative analysis through simulation is superior because it prevents costly mistakes and allows experimentation with various materials (mineral wool, Helmholtz resonators, perforated panels, etc.), in various configurations (performance hall, chamber concert hall, exhibition hall, conference hall, etc.).

The novelty of the proposed approach, by comparison with other methods [4,8,13], lies in the integration of high-resolution 3D scanning, detailed CAD reconstruction, and harmonic acoustic analysis applied to a multifunctional auditorium with high constraints. Therefore, the approach does not involve a simplistic use of finite element acoustic simulations per se, but the integration of these scanning, reconstruction and harmonic analysis tools. Unlike previous studies which are focused on single-use concert or theater halls [6, 13, 16], the proposed workflow is adapted to rapid reconfiguration scenarios using passive acoustic interventions.

The proposed approach aims to adjust the acoustic parameters to achieve the optimal values recommended by international standards (e.g., ISO 3382 for concert halls or ISO 3382-3 for conference rooms). The goal is to reduce excessive reverberation time (over 1.2 s for speech rooms, respectively over 2.0 s for music rooms) and improve sound clarity (C80 > 0 dB for speech, > 5 dB for music) and especially, increase speech intelligibility (Speech Transmission Index, STI) in peripheral or geometrically disadvantaged areas.

The research in the field of performance acoustics using this approach will lead to superior results, allowing even spectators from the most awkward angles an optimal sound perception. Thus, the acoustics of the performances will emphasize and help the development of the dramatic, comic, or melodic action and the artistic act or spoken discourse become more intelligible, more expressive, and more acoustically balanced, regardless of the position occupied by the spectator or listener in the hall.

3. Three-dimensional model of the acoustic system

The acoustic system is defined as a space composed of all the physical components that delimit the environment in which the musical or artistic activity studied is carried out. Therefore, it is made up of the architecture of space, including the hall, the stage and everything that is normally an integral part of it, such as the armchairs, the stage, the ceiling, the floor, stage-technical equipment, etc. It must also include the thermo-hydrometric characteristics of the environment, i.e., the air temperature and its thermal gradient, the air velocity, the relative humidity.

To define the model of the acoustic system in a virtual space, the existing auditorium was initially scanned in three dimensions using an iPhone 12 Pro, as it offers very precise measurements with a LIDAR camera, through the "3D Scanner" application. The 3D scanning process was performed using the LiDAR sensor of an iPhone 12 Pro, offering a spatial resolution of the order of a few millimeters. Multiple scans were acquired from different viewpoints to minimize occlusions, and the resulting point clouds were aligned and merged in the Geomagic environment. Smoothing, geometric finishing, and noise reduction were applied before surface reconstruction. The LiDAR sensor on the iPhone 12 Pro is defined as a compact dToF (direct Time-of-Flight) system, based on an array of VCSEL (Vertical-Cavity Surface-Emitting Laser) laser emitters and SPAD (Single-Photon Avalanche Diode) receivers [57–59]. The sensor emits a network of 576 infrared dots (structured as 8 × 8 dots diffracted in 3 × 3 grids). The raw data is fused with the RGB camera to generate a 256 × 192-pixel depth map (49,152 points) at a frequency of up to 60 Hz. The range is limited to a maximum of 5 m for iPhone 12 Pro models, with optimal accuracy below 3 m. In controlled laboratory conditions (distances of 0.25–3 m), the sensor provides an accuracy of approximately ±1 cm for small objects. Studies have shown an RMSE (Root Mean Square Error) of 4.89 mm, comparable to professional laser scanners (TLS) that reach 3.44 mm in the same range. The generated point clouds are slightly noisier than those from professional equipment, requiring advanced filtering algorithms (e.g., Voxel Downsampling).

Calibration and accuracy optimization for the 3D Scanner App on an iPhone 12 Pro is not based on a single calibration button, but on a LiDAR sensor configuration methodology and data acquisition techniques to achieve an accuracy of approximately ±1 cm. Before scanning, the settings menu within the application was accessed to adjust the next hardware parameters. Confidence: set to HIGH because this forces the sensor to keep only the points with the highest degree of certainty, eliminating background noise, although it will reduce the range. Max Depth/Range: Limits the distance to 1.5–2.0 m. Resolution: a value between 5 mm and 10 mm was chosen for fine details. Values below 5 mm can generate artifacts on the iPhone 12 Pro due to the physical limitations of the 576-point matrix. The LiDAR sensor relies on the phone's positioning system (IMU) to "stick" the frames. The movement was slow and uniform, avoiding rescans and overlaps because the application can create wrong overlapping layers (ghosting). Although LiDAR works in the dark (being based on infrared), RGB textures require diffuse light, a problem that occurs in areas where the walls of the room are black, requiring multiple scans.

Figure 1 shows the auditorium of the CCCYT. The main result of the three-dimensional scanning was the so-called "point cloud" that was loaded into the *Geomagic* program, specific to reverse engineering techniques and methods, as shown in **Figures 1** and **2**. The initial "point cloud" was processed using specific reverse engineering techniques and methods. Thus, irregularities of a geometric nature, such as non-conforming surfaces, vertices and self-intersections, were eliminated. The "point cloud" was also transformed into elementary triangular surfaces. These were unified and transformed into larger continuous surfaces. Some of these successive operations are shown in **Figure 3**. The resulting model was then loaded into the *SolidWorks* program for further modeling (**Figure 4**).

Figure 1. The auditorium of the Colibri Craiova Children and Youth Theater.

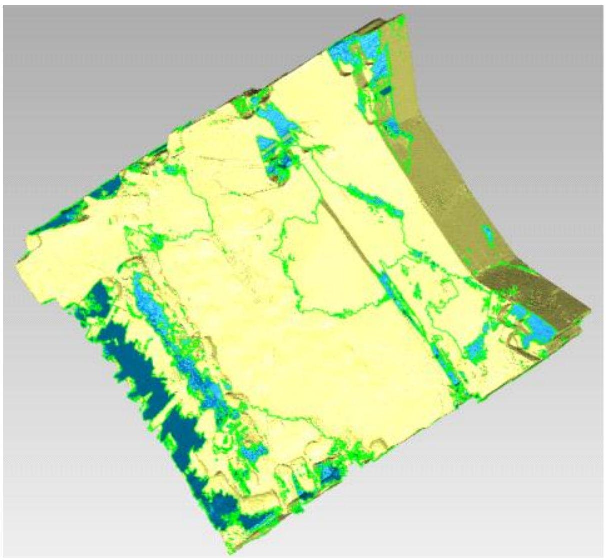


Figure 2. The initial point cloud of the auditorium generated from the 3D scan and processed in the Geomagic environment.

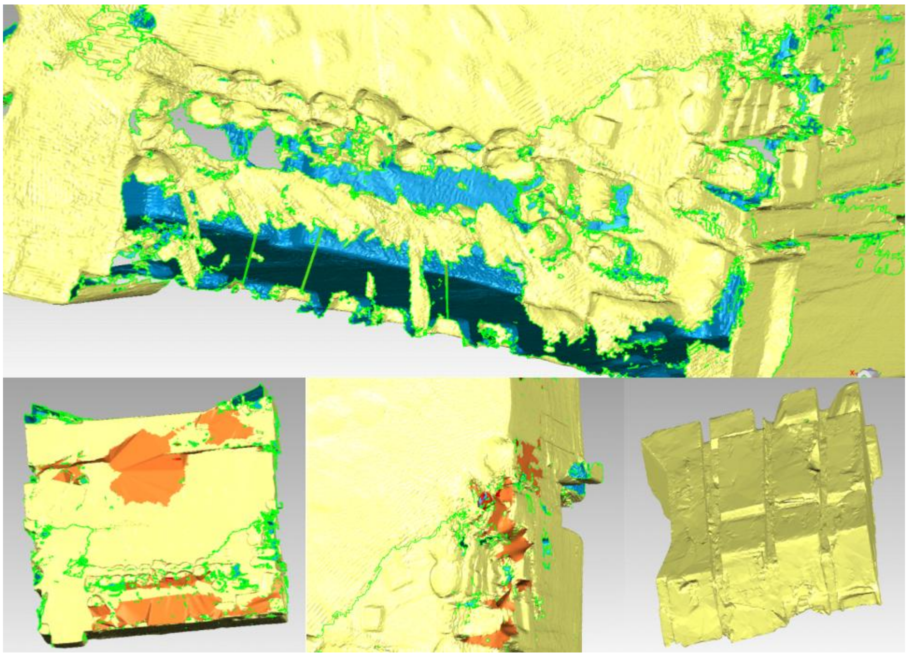
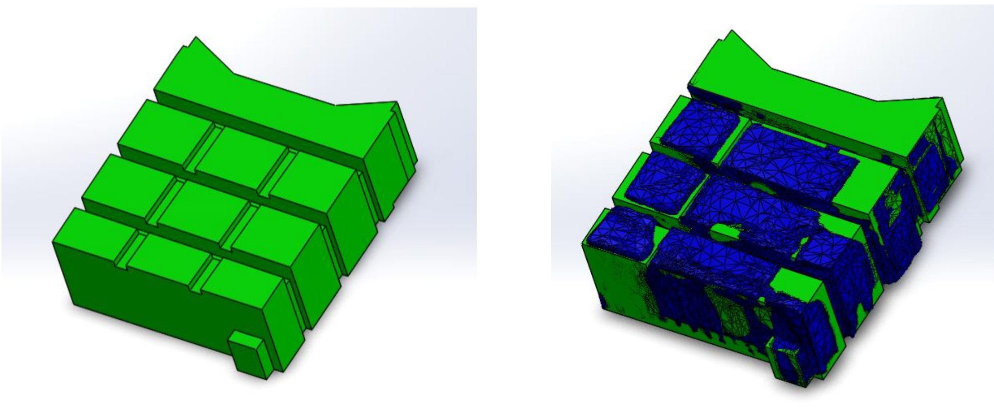


Figure 3. Removing the geometric irregularities using the *Geomagic* program (successive snapshots).

Figure 4. Model of the auditorium implemented in the *SolidWorks* environment.

Precision measurements were made on this model; reference planes were created, and some inherent corrections were made. Based on these, using CAD (Computer Aided Design) techniques, the air volume model of the auditorium was created. The model superimposed on the scanned model is presented in **Figure 5**. In this auditorium, the sound source is composed of two Yamaha DXR12 loudspeakers. One of these was also scanned in three dimensions (**Figure 6**). This loudspeaker model was loaded twice into the assembly module of the SolidWorks model. The loudspeaker models were positioned as in reality. Then, these were "subtracted" from the air volume using *Cavity* in *SolidWorks*, as shown in **Figure 7**. This final model was then exported to the *Ansys Workbench* software to perform the simulations we wanted, using the finite element method.



(a) **(b)**

Figure 5. Auditorium model: **(a)** final CAD-based acoustic model; **(b)** overlay of reconstructed model (green) and original scanned geometry (blue).

(a) **(b)**

Figure 6. Loudspeaker: **(a)** real; **(b)** implemented in *SolidWorks*.

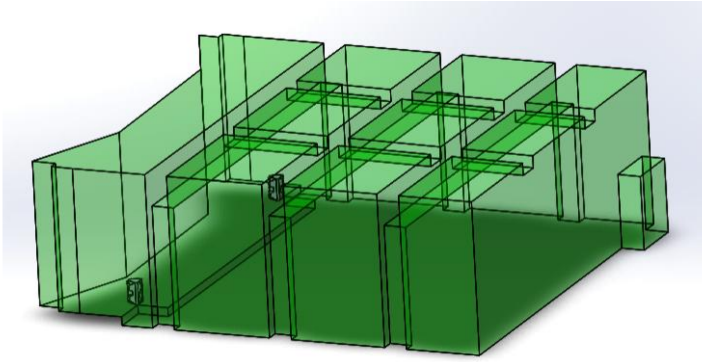


Figure 7. Final model exported to *Ansys Workbench*.

For the chairs that will equip the auditorium, the exact steps above were used, thus resulting in the virtual elements necessary for the simulations of activities on certain work groups and space occupancy. Modeling and operations performed on the element, the chair, in *Geomagic*, then in *SolidWorks* (**Figures 8** and **9**). Using the direct measurement method, as well as specific CAD techniques, the chair model was recomposed in the *SolidWorks* software.

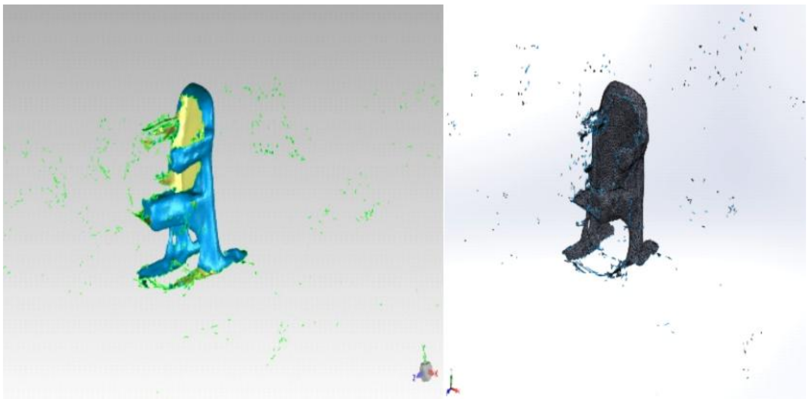
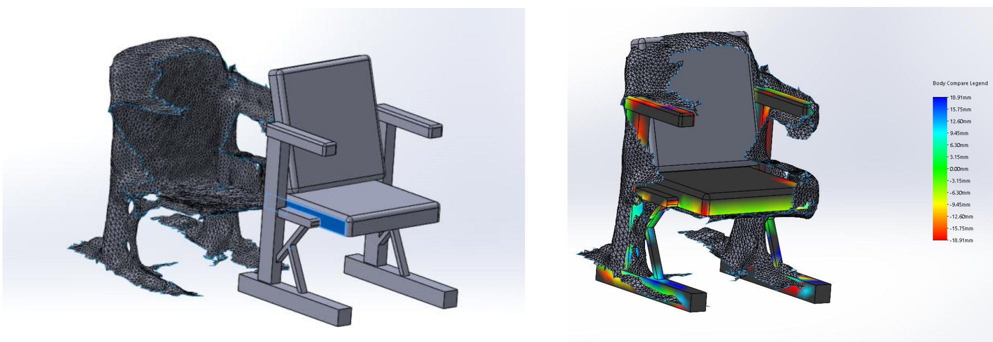


Figure 8. Chair model after scanning.



(a) **(b)**

Figure 9. Model of the chair in *SolidWorks*: **(a)** transition from scanned to final model; **(b)** Body comparisons.

This chair model was loaded into the auditorium model (**Figure 10**), taking into account the specific arrangement of the chairs, rows, and health and fire safety regulations, without exceeding these imposed limits. Since the hall is multifunctional, two scenarios were considered, with a minimum and maximum number of chairs. The operations for these scenarios, multiplication techniques were used for the two types of placements of the chair models, one of these placements being shown in **Figure 11**. In the next step, the goal was to obtain the model of the air volume through which the sound propagates in the auditorium. For this, specific CAD techniques were used, and the final model is presented in **Figure 12**.

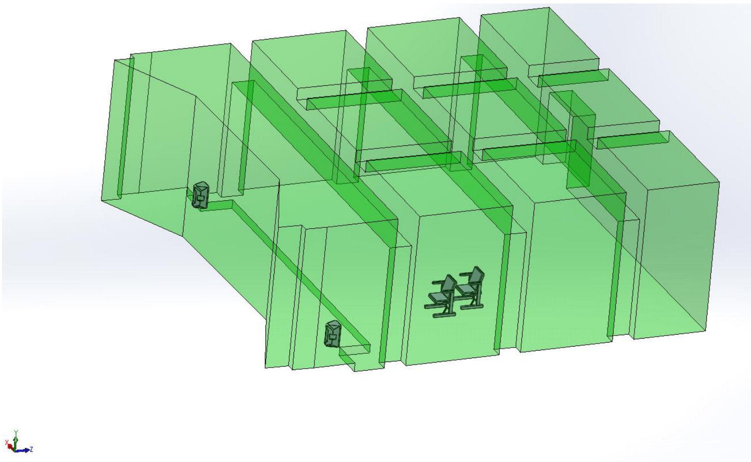


Figure 10. The chair model inserted into the auditorium model.

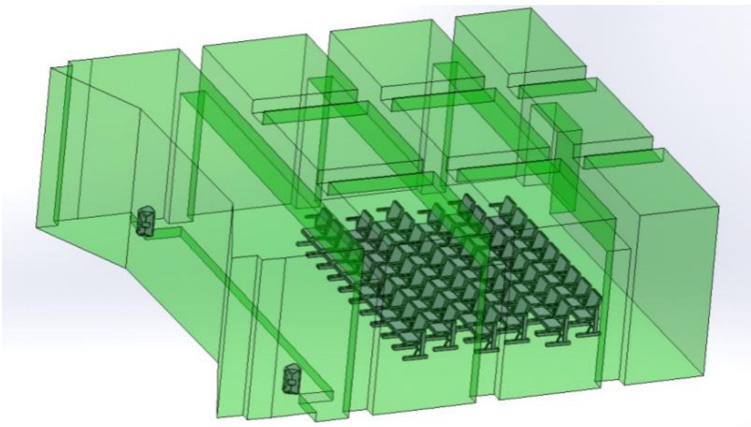


Figure 11. Multiplication according to scenarios—the maximum number of chairs.

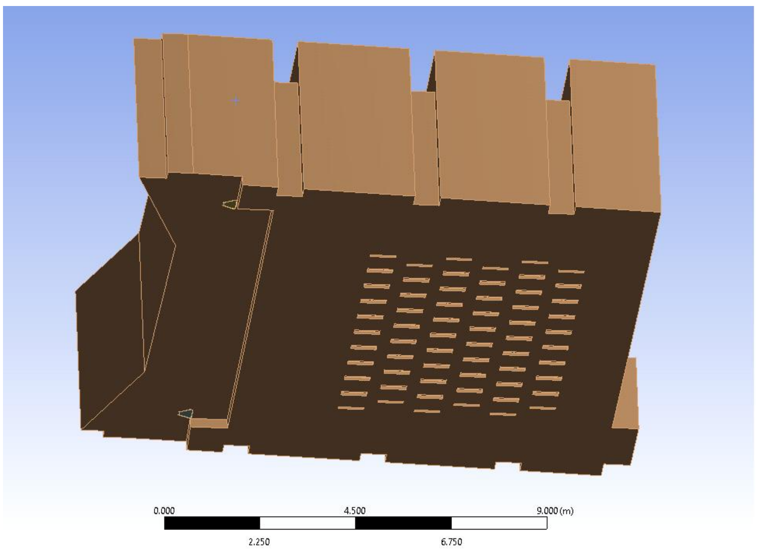


Figure 12. The air volume model of the auditorium in *Ansys Workbench*.

By using these models, three types of analyses and simulations were performed in the *Ansys Workbench* program (**Figure 13**):

- A modal analysis for the loudspeaker membranes and their enclosure;
- An analysis of the harmonic response type for the acoustic speakers;
- A Harmonic Acoustics type analysis for the air volume.

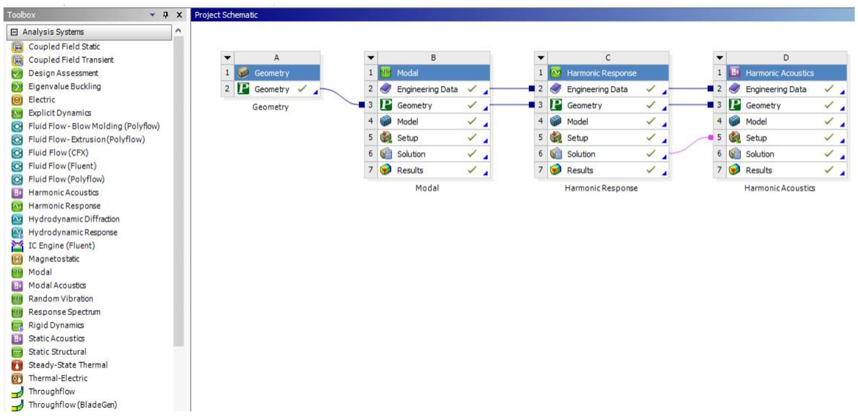


Figure 13. Simulations performed in *Ansys Workbench* and their nesting in the simulation of the air volume behavior of the auditorium.

Figure 14 shows the finite element structure of the analyzed model.

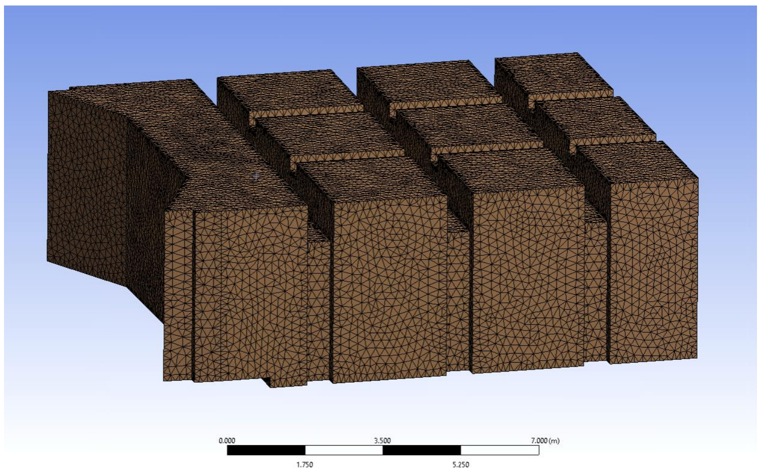


Figure 14. The finite element structure of the analyzed model.

4. Acoustics measurements and analysis

Next, several results regarding the acoustic measurements, as well as the analysis of these results, are presented. For the study with sound-absorbing material, in the software *Ansys 2022*, the side walls (except the side where the stage was located) were covered with absorbing material, the blue one, with an absorption coefficient of 0.5 (**Figure 15**). The measurements of the *Acoustic Pressure* are illustrated in **Figure 16**. The analysis of the dominant color, oriented towards the peak pressure gradient (maximum), signals acoustic energy concentrations. This refers to the analysis of high-frequency sound waves (20 kHz), which mark the high-frequency limit for human hearing and are used in precision acoustic experiments to detect reflections and examine sound dispersion. Sweep phase (operational sweep phase) of 0° indicates that the measurement was made without changing the phases, since the analysis focuses on the distribution of the sound wave at an instant. The values measured in the simulation indicate the following:

- Minimum sound pressure value: -3.6401×10^{-3} Pa;
- Maximum sound pressure value: 1.6590×10^{-3} Pa.

These values are expressed in Pascal (Pa). They represent the amplitude of the oscillations of the sound pressure in the air at different points in the auditorium.

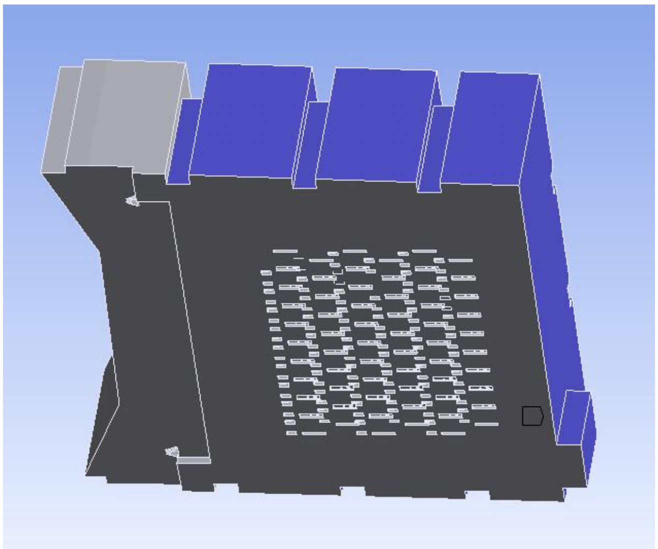


Figure 15. Sound-absorbing surfaces and their representation in *Ansys*.

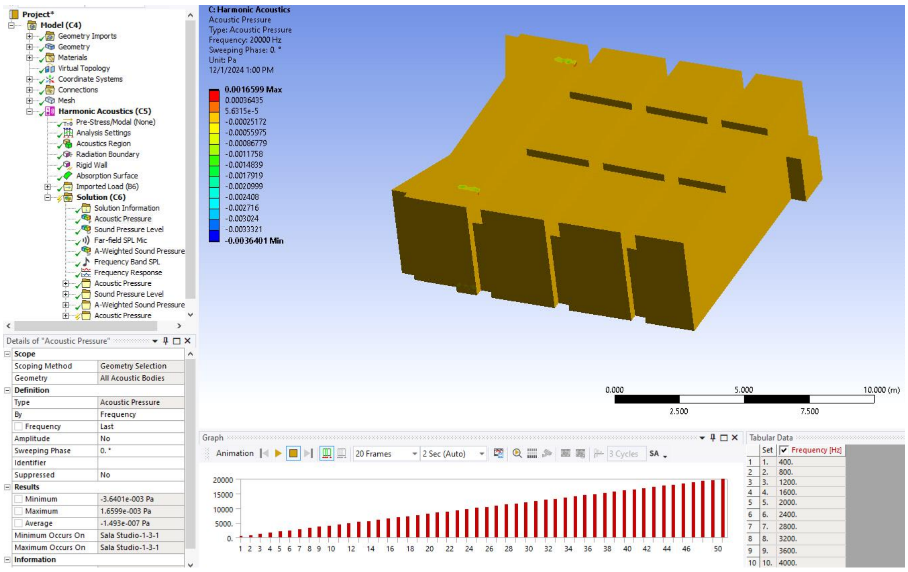


Figure 16. Acoustic pressures for the analyzed auditorium.

The difference between the maximum and minimum values is 5.2991×10^{-3} Pa, which is a relatively small variation in absolute terms, but has a significant impact on the perception of sound depending on the position of the listener or, depending on the configuration of the auditorium, the spectator. The difference between the minimum and maximum values shows that the sound is distributed relatively evenly, but there are local variations, especially on the ceiling, in front of the beams, in all corners of the hall, upper and lower, which are caused by reflections or interference, some constructive and others, on the contrary, destructive. These few negative values show us that the analysis also includes the oscillatory component of the sound wave (the acoustic pressure varies over time, passing through positive and negative values). These values are in the range of acoustic pressures encountered in closed spaces and can be compared with the hearing threshold of the human ear (~20 μPa or 2×10^{-5} Pa), and the pain threshold is located around 20 Pa. The values in the simulation are in the range of 10^{-3} Pa, which corresponds to a relatively low sound level. At 20 kHz, the wavelength is very short (~1.7 cm in air), which means that the sound is more directional and tends to be quickly absorbed by soft materials. At 20 kHz, these values indicate a clear sound, but poorly perceived by most listeners or viewers, as the sensitivity of the human ear decreases at high frequencies.

We should mention here that in acoustic physics, the idea of negative pressure is often a source of confusion, because in everyday life, we perceive pressure as something that presses down on us. To understand negative values in the context of oscillations, we need to make a clear distinction between absolute pressure and acoustic pressure. In an environment (such as the air in the auditorium that we extracted in the modeling), there is a static atmospheric pressure, which at the level of 110 m, at the altitude at which the auditorium is located, is approximately 101,325 Pa. Acoustic pressure is the variation (disturbance) from this equilibrium state. About the negative value in the acoustic pressure simulation, this does not mean that the total pressure is under vacuum, but that the pressure at that point is lower than normal atmospheric pressure.

As an additional remark, the ear, the human auditory apparatus, allows the perception of sounds produced by different sound sources and has the role of transforming sound into a sound sensation. The normal human ear perceives sounds with frequencies between 16 Hz and 20 kHz, this interval being the audibility range. Sounds with a frequency lower than 16 Hz define the range below the audibility limit and are called infrasound, and those with a frequency higher than 20 kHz define the range above the audibility limit and are called ultrasound. According to frequency, sounds can be ordered into three categories: low sounds (bass) (16–360 Hz), medium sounds (360–1400 Hz), and high sounds (1.4–20 kHz). For a sound to be perceived by the human ear, it is necessary that its acoustic intensity has a minimum value that depends on the frequency of the sound and the sensitivity of the ear. Very loud sounds produce a sensation of pressure on the eardrum and are perceived as pain. The phenomenon occurs when the sound pressure is 2×10 N/m^2 at a frequency of 1 kHz. The upper limit of audibility of sounds determines the threshold of pain sensation, which is defined by the value of acoustic pressure, for a given frequency that produces a sensation of pain to a normal listener.

The measurements of the *Sound Pressure Level* are illustrated in **Figure 17**. The simulation in **Figure 17** uses the "Harmonic Acoustics (CS)" method and analyzes the propagation of sound waves on a specific geometry, more precisely, the air volume of the hall. The main parameter monitored is the Sound Pressure Level (SPL)—the acoustic pressure level. The red areas show us regions with high acoustic pressure, which indicates areas where sound waves are concentrated, exclusively on the stage area, near the sound sources, and, again, the upper beam is the one that obstructs the sound waves. The blue areas indicate lower pressure levels, where the sound dissipates or where acoustic nodes can appear. The situation is observed on the wall farthest from the sound sources, which is flat and thus in the middle area is almost non-existent. This simulation shows clearly an uneven distribution of acoustic pressure, with areas of different intensity. The red sides indicate problems with sound reflection, which can lead to annoying echoes or distortions. The green and blue areas, located somewhat towards the middle of the hall, show regions with a more balanced sound pressure level. Areas with high pressure can be corrected by using absorbing materials positioned exactly in those areas of the hall, at the corners where the stage is located. The maximum sound pressure level of 42.25 dB is a relatively low value compared to the ambient noise levels: conversation: 60–65 dB, quiet room: 30–40 dB. However, 42.25 dB indicates a moderate acoustic level, which suggests that the sound waves are not very intense in the regions with maximum pressure.

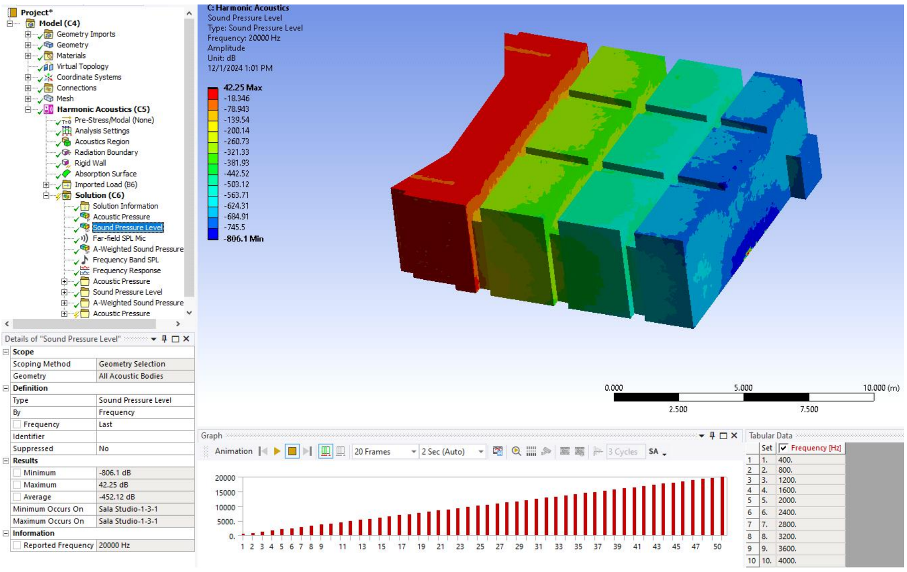


Figure 17. *Sound Pressure Level* (SPL) measurements.

It is observed that there are significant variations in SPL over the frequency range analyzed (**Figure 18**). This clearly indicates the existence of uncontrolled reflections and echoes. In the lower part of the spectrum, a tendency to decrease in the level is seen, which shows us greater absorption at low frequencies. The sound pressure level in the more distant areas indicates a more or less controlled dispersion of the sound. The minimum level is −1.3871 dB, which means that in some frequencies the signal is below the reference threshold, due to cancellation phenomena (destructive interference). The maximum level is 45.725 dB, indicating areas where the acoustic energy is concentrated, due to reflections or amplification in the corners.

The RMS level (effective sound pressure) is 2×10^{-5} Pa, which corresponds to a very low sound level (~26 dB SPL, which is close to the threshold of hearing under normal conditions). This uneven sound distribution also shows us that the loudspeaker system needs to be modified for a more uniform coverage of the hall. To improve sound quality and better clarity, the acoustic treatment must be optimized by using absorbing panels to reduce excessive reflections and diffusion panels, placed in the corners of the hall, especially in front of the beams, optionally.

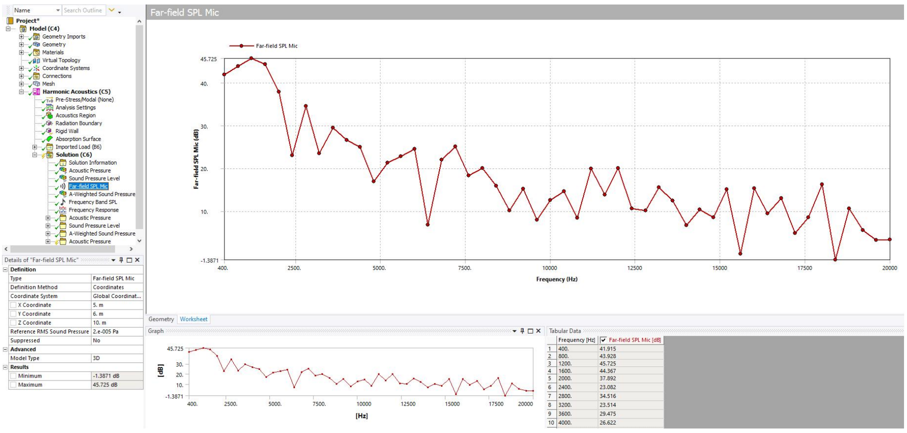


Figure 18. Far-field SPL analysis.

Next, the *A-weighted Sound Pressure Level* is presented and further analyzed. **Figure 19** represents the acoustic simulation that analyzes the distribution of *A-Weighted Sound Pressure Level* in the hall at 20 kHz. We observe a large variation in the sound pressure level depending on the position in the hall. The red areas indicate higher levels (~32.9 dBA), and the blue/green areas show us lower levels. At 20 kHz, the absorption is very high, and the reflections decrease rapidly, resulting in an uneven distribution of sound in the high frequencies. Since the SPL values drop sharply in certain areas, this indicates problems with sound diffusion or absorption and, worse, acoustic cancellation effects. Areas with high levels may indicate uncontrolled reflections and echoes. Areas with low levels may be affected by excessive absorption or incorrect speaker layout. At this frequency (20 kHz), most surfaces absorb sound, and the directionality of the speakers becomes a critical factor. Reflections are much weaker, so the uneven distribution means that some areas do not receive enough sound.

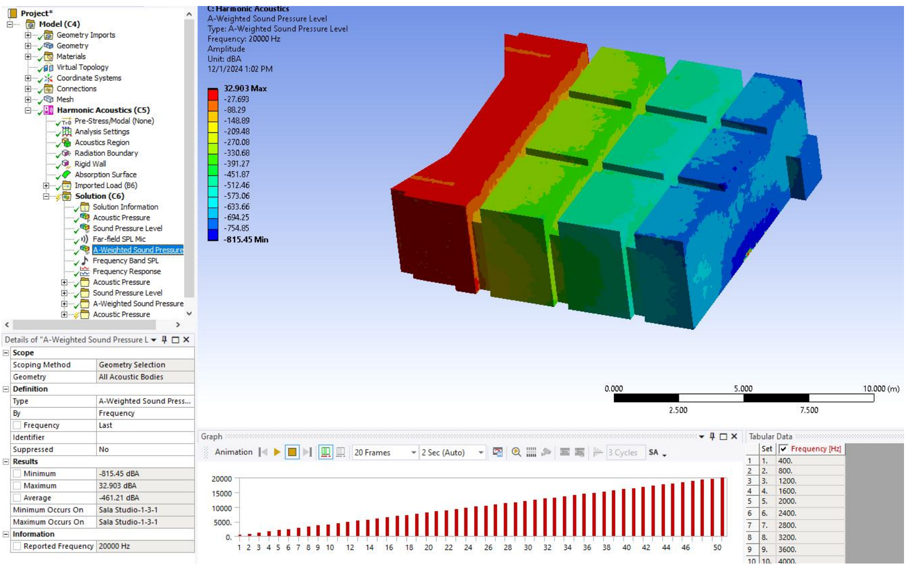


Figure 19. *A-weighted Sound Pressure Level* measurements results.

To optimize the sound coverage, we can take the following measures: adjusting the position and angle of the speakers for a more uniform distribution, and adding additional tweeters (high-frequency speakers) to improve the spread of high frequencies. To reduce large variations in SPL, different absorbing and diffusing materials must be tested and used. Since the room has too much absorption, it is necessary to introduce reflective elements to maintain an acoustic balance.

In order to have a broader view, a *Frequency Band SPL* analysis was performed (**Figure 20**). The sound pressure level (SPL) is represented by a color scale, where green indicates a moderate level of sound pressure, yellow indicates a higher pressure, and red indicates high sound pressure levels. We observe an uneven distribution of sound pressure, which clearly indicates sound reflections, echoes, interference, or local attenuation. The areas on the upper part of the analyzed surface show higher values, due to the reflection of sound waves from the edges of the structure, the ceiling beams.

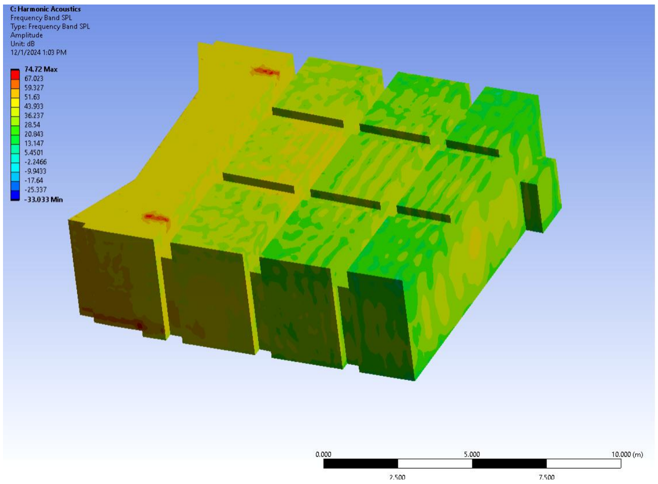


Figure 20. *Frequency Band SPL* analysis.

The simulation shows and suggests differences in the distribution of acoustic pressure; the areas with higher SPL will need to be doubled with sound-absorbing material for better acoustic absorption. A more special phenomenon appears again on the wall furthest from the sound sources. In the middle, the sound is much stronger due to the linearity of the sound sources.

To further analyze these results, the frequency response is depicted in **Figure 21**. The graph represents the acoustic response of the auditorium in a wide frequency range, from approximately 400 Hz to 20 kHz, which covers the entire human auditory spectrum.

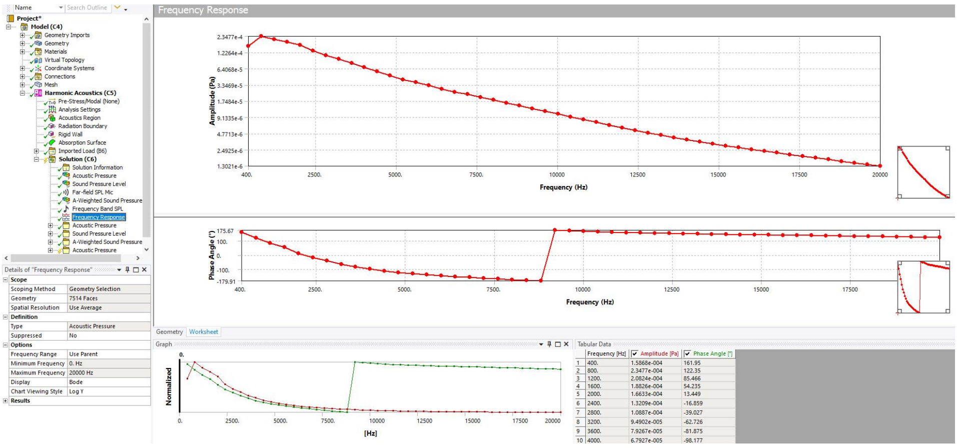


Figure 21. Frequency response (magnitude and phase).

Two main curves (with red dots) are displayed, indicating:

- Magnitude of the acoustic response (sound pressure in dB) as a function of frequency;
- Phase of the acoustic response, which shows how the sound waves are affected by the geometry of the auditorium.

A significant peak is observed around the frequency of 500 Hz, which indicates a resonance in that frequency range. After this peak, the acoustic response gradually decreases, which is a typical behavior of an optimized and acoustically treated hall. In the high frequency range (above 10 kHz), the attenuation is strong, which indicates that the absorbing materials installed in the hall prevent excessive absorption. The behavior at low frequencies, at the sound pressure level at 400 Hz, is in a stable area, without significant resonances. In a few points, it is observed that the level is high in this range, which indicates a problem of sound accumulation in the mid frequencies. The graph shows us that the auditorium has a reasonably balanced response, but there is a resonance peak in the low range (200 Hz). For this reason, acoustic diffusion panels or absorbing panels for low frequencies can be added.

The following detailed analyses were dedicated to *the acoustic pressure for various frequencies* (400 Hz, 10.8 kHz, and 20 kHz). A supplementary argumentation regarding the selection of these frequencies related to human perception is presented.

The 400 Hz frequency is considered the anchor of the low-mids spectrum. Because it is a relatively low frequency, its harmonics (multiples of 400 Hz: 800 Hz, 1200 Hz, 1600 Hz, etc.) cover the entire critical range of the human voice and melodic instruments, radically influencing the listener's experience. The harmonics of the 400 Hz frequency are what give substance to the sound. The higher harmonics (especially the first harmonic at 800 Hz and the second at 1200 Hz) must be balanced to give the listener a rich and honest sound. It is the area that makes a piano or guitar sound real, not like a toy. If there is excess energy in the 400 Hz fundamental and its first harmonics, the listener will have the unpleasant sensation of a boxy sound, as if the music were passing through thick cardboard. This stifles detail and quickly tires the brain as it tries to decipher the sound. Harmonics above 400 Hz are essential for locating the sound source, so a well-defined presence of the 800 Hz and 1200 Hz harmonics brings instruments to the front of the mix and makes the listener or viewer feel like the soloist is close to them. By controlled attenuation of these harmonics, sound engineers can push an instrument further back on stage, creating a special three-dimensional experience. The human voice has considerable energy in the 400–1200 Hz range, and the sharp consonants are higher, the weight of the vowels and the texture of the voice (the clarity of diction that makes us recognize who is speaking) depend on the integrity of the 400 Hz harmonics. If the passive acoustic treatment of the theater room selectively absorbs only the high frequencies and leaves the 400 Hz region and its lower harmonics uncontrolled, the listener will perceive the sound as dirty, muffled, or hollow. A buildup of energy at 400 Hz (due to the room's eigenmodes) will distort all higher harmonics, turning a high-fidelity auditory experience into a tiring and unclear one.

The frequency of 10.8 kHz is in the upper part of the treble spectrum, in an area that sound engineers often call Air or Brilliance. The harmonics in this spectrum do not define the musical note itself, but the texture and spatiality of the sound. At 10.8 kHz, the human ear no longer perceives only clear melodic tones, but rather ambient details that create a wide and open soundstage. If these harmonics are cut off (for example, by aggressive MP3 compression), the music sounds closed, two-dimensional, and lacking in realism. Instruments with metal tails (cymbals, hi-hats, acoustic guitar) or fine percussion have their imprint of realism in the 10–12 kHz area. The 10.8 kHz harmonics allow the listener to distinguish the exact moment when a finger touches a string or a stick hits a cymbal and, moreover, help separate instruments in the mix. In high-fidelity music (Hi-Res Audio), they provide the micro-detail that makes the experience immersive, and if the 10.8 kHz harmonics are too emphasized (through excessive processing or aggressive EQ), auditory fatigue occurs. Although the human voice has a much lower fundamental, the higher harmonics at 10.8 kHz capture the fine details of breathing and the consonants “s”, “f”, “t”. In “close-mic” recordings, these harmonics provide a sense of proximity and intimacy, making the listener feel that the performer is very close. In the context of passive acoustic modeling, controlling the 10.8 kHz harmonics is vital because porous materials (mineral wool, foam, etc.) absorb these frequencies very easily, and if inappropriate panels are placed in the room, these harmonics will be eliminated, resulting in a dead and unnatural sound. This is why acoustic diffuser panels are used to preserve these vital harmonics and maintain the liveliness of the sound.

The harmonics of the 20 kHz frequency lie at the border between bioacoustics and neurophysiology. Although 20 kHz is the upper limit of human hearing, its harmonics (40 kHz, 60 kHz, etc.) and their interaction with the audible spectrum affect the listener’s experience, which provides a sense of well-being, deep relaxation, and a perception of “extreme realism” that a recording limited to 20 kHz (such as the CD standard) cannot provide. This is the basis for the success of Hi-Res formats in 2026. Even though we do not hear the 20 kHz frequency or its ultrasonic harmonics, they interact inside audio equipment (amplifiers, speakers) and even inside the human ear. Two ultrasonic harmonics (for example, 40 kHz and 40.4 kHz) can interact to create a 400 Hz difference frequency, Beat Frequencies, which is perfectly audible. If the venue’s audio system doesn’t handle these high harmonics properly, dirty distortions can appear in the midrange, making the sound seem harsh or artificial. Very high harmonics (20 kHz+) are essential for defining the wavefront (the initial attack of a sound). 20 kHz harmonics provide the temporal resolution needed for a stable and precise soundstage, and without these high-frequency harmonics, instruments seem lost in space, allowing the listener or viewer to pinpoint exactly where each instrument is. In reality, the air itself acts as a filter for these harmonics over long distances, providing that natural sense of depth that the listener instinctively recognizes as real, true. Although we don’t hear 20 kHz harmonics as musical notes, they transform a simple auditory experience into a full sensory experience, providing realism, spatiality, and a physiological response of pleasure.

Figure 22 presents the results regarding the acoustic pressure at 400 Hz, **Figure 23** for 10.8 kHz, and finally **Figure 24** for 20 kHz.

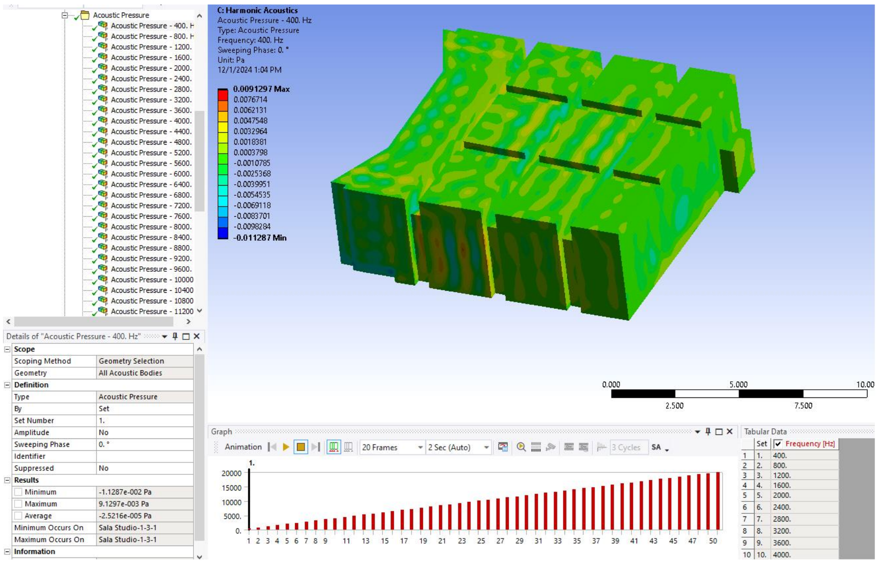


Figure 22. Acoustic pressure analyzed at 400 Hz.

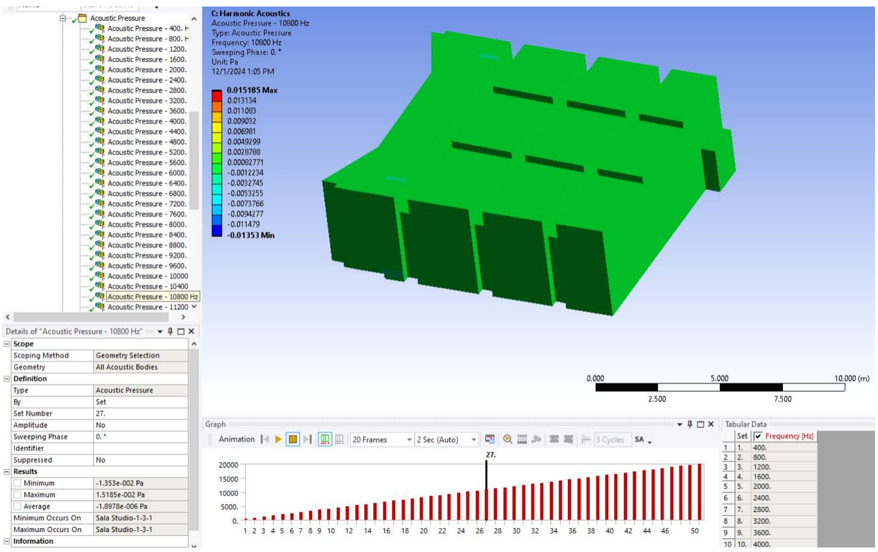


Figure 23. Acoustic pressure analyzed at 10.8 kHz.

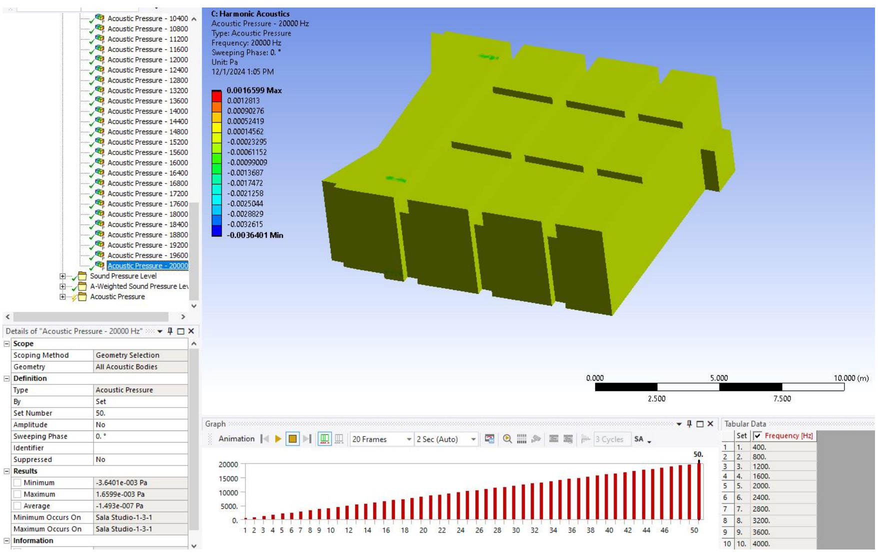


Figure 24. Acoustic pressure analyzed at 20 kHz.

This simulation shows in **Figure 22** the distribution of acoustic pressure in the studio room at 400 Hz, an important frequency in the human auditory spectrum, having an impact on the clarity of the voice but also of musical instruments. According to the data obtained, we have the maximum acoustic pressure: 0.0091297 Pa, the minimum acoustic pressure: −0.011282 Pa, and the average acoustic pressure: 3.246×10^{-5} Pa. The maximum and minimum values are relatively small, which indicates a simulation under low sound conditions and a very absorbent room. The presence of large variations between the maximum and minimum shows us that there are interferences and areas of acoustic cancellation in the room. The very low average pressure indicates significant acoustic losses. We can also observe the distribution of sound pressure from the fact that most of the room's surface is colored green, which indicates an average level of sound pressure. Yellow areas show higher concentrations of sound pressure, due to reflections or the accumulation of standing waves. Blue areas represent regions of negative pressure or cancellation of sound waves, which can lead to loss of sound clarity. In some areas of the hall, the sound may be too loud, and in others, too soft. Spectators in areas with sound cancellation may have difficulty perceiving the sound clearly. There are standing waves at 400 Hz, which lead to sound amplification in some places and loss in others. For this reason, we will also analyze other frequencies to verify if this effect is repeated.

According to the simulation, the hall has too many absorbing surfaces, which leads to energy losses at critical frequencies. To optimize the acoustic treatment, diffusion panels can be added to reduce the effects of standing waves, but the absorbing and reflecting materials must be balanced for a more uniform distribution. The simulation shows large variations in sound pressure at 400 Hz, which affects the clarity of the sound for the audience. The uneven distribution and standing waves suggest the need for acoustic adjustments, either by changing the materials in the hall or by optimizing the position of the speakers.

The simulation presented in **Figure 23** analyzes the sound pressure at the frequency of 10.8 kHz, a high frequency, particularly relevant for the clarity of sound details (e.g., shrill sounds, harmonics of instruments). The results are: Maximum sound pressure: 0.615135 Pa, Minimum sound pressure: −0.613533 Pa, and Average sound pressure: 1.6676×10^{-6} Pa. The maximum and minimum values are symmetrical, indicating a balanced distribution of sound waves, but at the same time, possible areas of strong interference. The average pressure is extremely low, which leads to high dispersion of the sound and reduces the perceived clarity in certain areas of the hall. The relatively large difference between the maximum and minimum values indicates the presence of standing waves in the hall. Most of the hall's surface is colored uniformly green, which indicates an average level of sound pressure, without sudden variations. The lack of intense red and blue colors indicates a balanced dispersion, but also a high absorption of high frequencies. The symmetry of the maximum and minimum values and the uniform distribution show that there are standing waves, which can lead to areas where the sound is perceived as weaker, but also a possible lack of clarity for high frequencies, where the clarity of the treble is essential for perceiving the details of the sound (e.g., cymbals, female voices, instrument harmonics).

According to the conclusions of this simulation, acoustic diffusers can be added to better disperse the sound and reduce the effect of standing waves, but over-absorption must be avoided, especially in areas where great details are important. The simulation at 10.8 kHz shows a relatively uniform distribution of sound pressure, but with the risk of a loss of clarity due to excessive dispersion and possible standing waves. The acoustic treatment can be adjusted to avoid excessive absorption.

The frequency analyzed in **Figure 24** is 20 kHz, which is at the upper limit of the audible spectrum for the human ear.

At this frequency, sound waves have short wavelengths, which means that interactions with surfaces are significant (reflections, diffraction, absorption). The maximum acoustic pressure values reach 0.001639 Pa, and the minimum ones are around −0.0003641 Pa. These values indicate variations in the distribution of sound waves inside the hall, suggesting areas of sound focus and possible points of acoustic cancellation. Certain areas of the hall are exposed to uneven sound pressures, which can affect the clarity of the sound perceived by the audience. The graph shows that the sound pressure varies with frequency, indicating resonance problems in the hall. There are significant variations in acoustic pressure, which cause non-uniformity in the distribution of sound.

Remark: Although the reverberation time is not directly calculated in harmonic analysis, the spatial non-uniformities observed in the sound pressure and SPL distributions are consistent with excessive reflective behavior and localized energy accumulation, which are characteristic of extended reverberation effects in enclosed spaces. Even if theoretically the reverberation time should be short, empirical simulation shows that the energy does not even have time to reverberate, being dissipated almost instantly in the air. At 400 Hz, the sound pressure map shows areas of constructive and destructive interference. At 10.8 kHz and especially at 20 kHz, it shows a drastic decrease in sound pressure, and air absorption becomes the dominant factor, not just the materials of the walls, ceiling, or floor.

5. Conclusion

The model of the acoustic system was obtained by using three-dimensional scanning combined with various tools such as *Geomagic* and *SolidWorks*. The CAD techniques and the finite element method were used to obtain models for various configurations of the performance hall of the Colibri Theater, taking into account realistic elements and including several objects such as loudspeakers and chairs. The analyses performed using these models were based on the *Ansys Workbench* environment. Acoustic pressures, sound pressure levels (SPL), and frequency band SPL measurements and analyses were achieved for various configurations and frequencies.

This study followed the acoustic effects at the frequencies of 400 Hz, 10.8 kHz and 20 kHz and from the study it emerged that the acoustic pressure was not uniformly distributed, in the studio hall of the CCCYT, which has consequences on the quality, from an auditory point of view, for spectators or participants, depending on the layout of the room for different events. The smooth and hard walls of the hall reflect a large percentage of the sound wave, and the reverberation time is long. The ceiling also plays an important role in the loss of energy of acoustic waves, both through reflection, absorption, and, especially, by accumulating energy in front of the beams perpendicular to the sound source. As the distance from the sound source increases, the sound field is formed mainly by reflected sounds and less by sounds coming directly from the source.

For low frequencies (400 Hz), we observe a relatively uniform distribution, but in some areas, there is an accumulation of pressure in some sections, which could turn into an excessive reverberation effect or even "buzzing" for the audience. Regarding high frequencies, i.e., 10.8 kHz and 20 kHz, the sound is quickly lost in some areas; the transposition affects the clarity of the sound and the acoustic details essential for a speech or a melody. There are areas subject to extreme variations in sound pressure, which indicates the presence of a reflection problem and an absorption problem.

In future research, some of the research limitations will be addressed. For example, the effect of audience occupancy on multi-purpose halls is considered one of the most complex variable factors in acoustic design, as the human body acts as a massive and nonlinear sound absorber. The human body and clothing absorb very effectively high frequencies above 2 kHz, which can make the sound appear dull in a full hall. Seated audiences (in the scenario for shows or concerts) have a lower absorption effect at low frequencies, which can lead to a tonal imbalance (whistling or booming sound) if the hall is not treated for bass. The audience is not only an absorber but also a source of noise (movement, breathing). To counteract variations caused by occupancy, the following will be used: chairs with equivalent absorption so that they have the same absorption coefficient when unoccupied as when occupied (through perforations in the lower part of the seat). The use of double-layer acoustic curtains or rotating panels to adjust the absorption according to the number of spectators. (Passive Variable Acoustics). Active Systems (Electroacoustics) will also be used, for example, the use of loudspeakers to inject virtual reflected energy.

The developed models and the performed analysis will be used in future research to obtain an optimization of the acoustic performance within the CCCYT and can be easily extended and applied to other theater halls. The parallelepiped-shaped halls, unfortunately, are often found in modernization reconstructions from the second half of the last century, since the construction costs were not high, being simple shapes (straight walls, flat floors, simple ceilings, etc.), and the execution period was short. In the last decade, many of these halls that had a single purpose began to be converted into multifunctional spaces. This specific case study can also be transposed into larger halls that will change their initial destination, sports halls where music concerts take place, industrial halls where theater performances will take place, etc., and the auditory experience must be of quality.

Author contributions: Conceptualization, CB, DS and MR; methodology, CB and DLP; software, CB and DLP; validation, CC, DS and MR; formal analysis, DLP; investigation, CB and CC; resources, CB and CC; data curation, MR; writing—original draft preparation, CB; writing—review and editing, DS and MR; visualization, CC and MR; supervision, DS; project administration, CB and DLP. All authors have read and agreed to the published version of the manuscript.

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