Acoutect Demonstrator for Social Gathering Places

A case study of acoustic treatment in a small restaurant

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ACOUTECT

CHAPTER 1

Problem definition

Noise has become the third most hazardous type of pollution caused by mankind, right after air and water pollution. Noise is prevalent in cities and places where human activities are carried out. In particular, restaurants and other places for social gathering are exposed to noise in a way that, in addition to the negative health effects, the activities being held at these places can be disrupted. Existing measurements show that clients and working staff in restaurants can be exposed to high sound pressure levels (SPL). To address these problems, noise treatment strategies are needed through room acoustics design and testing to keep the acoustic environment in such places comfortable and make the experience of the stay and communication more enjoyable. This work focuses on the analysis and treatment of a real restaurant by combining state-of-the-art techniques in acoustics, including room acoustic simulations, metamaterial design and manufacturing.

State-of-the-art

Current room acoustic solutions usually utilize hanging baffles, ceiling, and wall panels to treat the space for better speech intelligibility. Porous materials typically used in these solutions tend to suffer from poor performance at low frequencies. An often-used countermeasure to this issue is to increase the thickness of the material treatment. However, given the long acoustic wavelength at low frequencies, the thickness of an effective foam becomes unrealistic. For example, at 100 Hz the acoustic wavelength is 3.43 m; as a result, a foam of comparable thickness to the wavelength is far from being optimal. Arguably, fibre-based high-density foam can be used for better absorption. This, however, also comes with several downsides. Firstly, the adaption of these designs is demanding on the space, as items like hanging baffles take up a great part of the precious available space. This is especially problematic for small rooms. Secondly, for these designs, the functionality is almost always weighted over the aesthetics, which makes it challenging to design a visually pleasing space. Lastly, due to their high density, the panels and baffles are heavy, which can be challenging for the installation. In case of a fixture failure, damages and injuries are likely to occur. Thus, a lightweight compact acoustic treatment, which is at the same time visually appealing, is desirable.

Overview of the approach

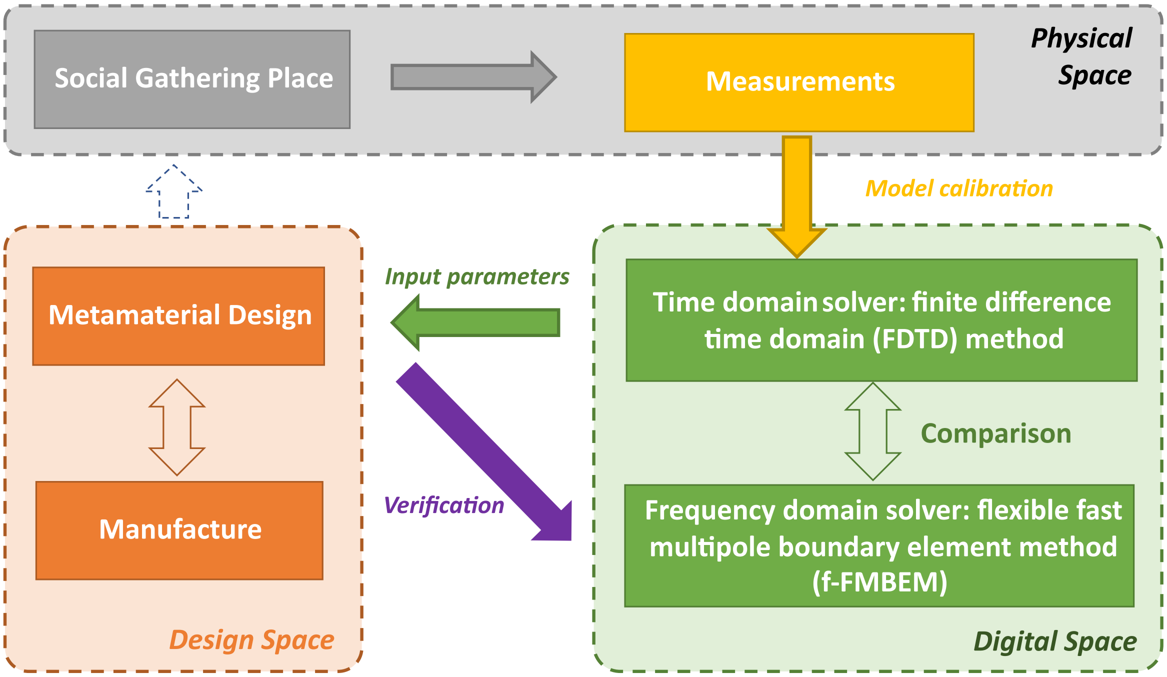

Figure 1: Methodology to solve the problem of noise in social gathering places.

In-situ measurements provide direct insight into the physical world. However, the measurements acquired can only reflect the existing room. By solely using measurements, it is difficult to predict the acoustic performance of a complete or partial acoustic treatment before the implementation in the physical space. Therefore, we generate a digital duplicate of the physical space based on in-situ measurements. This allows for numerical experiments of the new acoustic treatments and renovation ideas to be conducted in order to improve the acoustic quality of the space. In the digital space, two state-of-the-art numerical techniques are employed including both a novel frequency-domain method: the flexible fast multipole boundary element method (f-FMBEM) and a time-domain method: the finite-difference time-domain (FDTD). In-situ measurements have been conducted by our partner Level Acoustics & Vibration.

Firstly, the two numerical techniques are compared to each other on benchmark cases to verify the correctness of both implementations. Based on the information from the physical space, a digital model is generated and simulated using the two numerical solvers. A model correlation process is involved to calibrate the materials present in the space. Considering the inherent nature of the methodologies, the two solvers are analysed to identify their applicability to different aspects of room acoustics. Some acoustic parameters can be provided for the design space in Figure 1. To address the acoustic issue[s] found from the measurements and the digital twin, metamaterial-decorated hanging lamps are added to the room, which are designed to achieve a high acoustic absorption at low frequencies through a compact volume. Since acoustic metamaterials normally exhibit complex geometry, its manufacturing is not accomplishable by traditional production technologies. An innovative 3D-printing technology known as laser sintering (LS) is applied to realize the design as it offers flexibility in the production of complex shapes for metamaterial prototypes. The final metamaterial design is evaluated in the digital model. The two numerical techniques are used to simulate and analyse a wide range of scenarios, including new metamaterial design and deployment. Using a holistic engineering approach, this work presents a real showcase solution for noise reduction in spaces for social gathering.

CHAPTER 2

Details of the specific problem

The studied space as shown in Figure 2 is the front dining area of a restaurant named *Zarzo*, located in Eindhoven, the Netherlands. Consisting of approximately 24 m^2, it can accommodate a group of around 12-16 persons and is separated from the main part of the restaurant by windows. The space has been recently renovated and in-situ measurements have been carried out both before and after the renovation by our partner. Three metrics (the reverberation time, occurring sound level, and the speech transmission index) have been measured, which will be used in setting up the digital model.

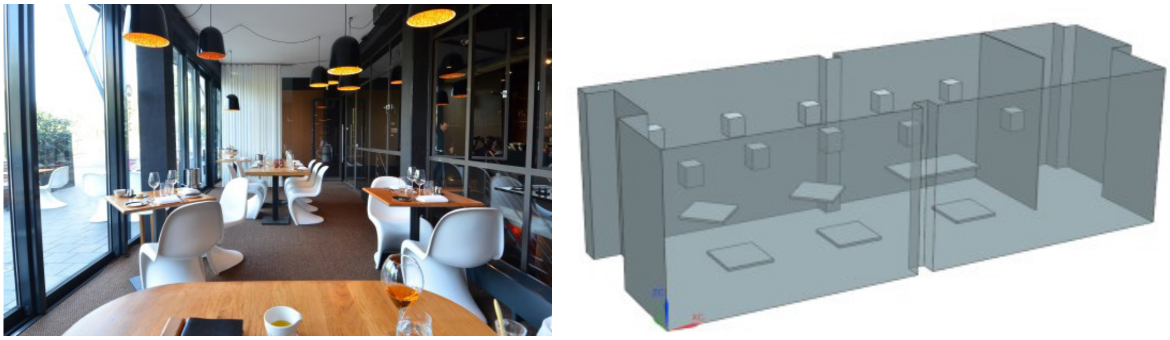

Figure 2: Picture of *Zarzo* restaurant (left) and its simplified 3D model (right).

Analysis of the problem

In the demonstrated case, the noise is typically occurring in the frequency range of 500 - 1000 Hz. The reverberation time, defined as the time it takes for the sound to decay by 60 dB, demonstrates excessively high values (attaining up to 1.32 s in the 400 Hz and 500 Hz octave bands) in that frequency range as shown in Figure 3. Speech intelligibility, which refers to how clear speech is to a listener, is related to the reverberation time. Poor speech intelligibility has been observed in the space due to the high reverberation time. Therefore, an acoustic solution is required to reduce the reverberation time in the frequency range of interest in order to improve the speech intelligibility in the space. This can be achieved by changing the sound-absorbing capabilities of the acoustic elements within the space until satisfactory room acoustic parameters (e.g., reverberation time, speech transmission index) are attained. We apply the holistic engineering approach from Figure 1 to solve this specific problem.

Numerical modelling and analysis

Although FDTD is a time-domain method whereas f-FMBEM is formulated in the frequency domain, these two numerical methods are comparable as both are wave-based. Before creating the digital twin of the studied space (i.e. to calibrate the model), several simple cases (e.g., rigid cubic and parallelepiped rooms) were simulated using the two solvers. The simulation results are compared to the known analytic solutions (when applicable) and between each other to verify the implementation of the two solvers.

The two numerical techniques are then applied to model the front dining area of the restaurant in both frequency and time domains. Some simplifications have been made to accommodate the numerical schemes (e.g., using rectangular shape as much as possible to avoid numerical inaccuracy in the FDTD solver), and to save the computational efforts (e.g., excluding details such as the chairs in the space as shown in Figure 2). One of the challenges for numerical modelling is to properly define the material properties in the

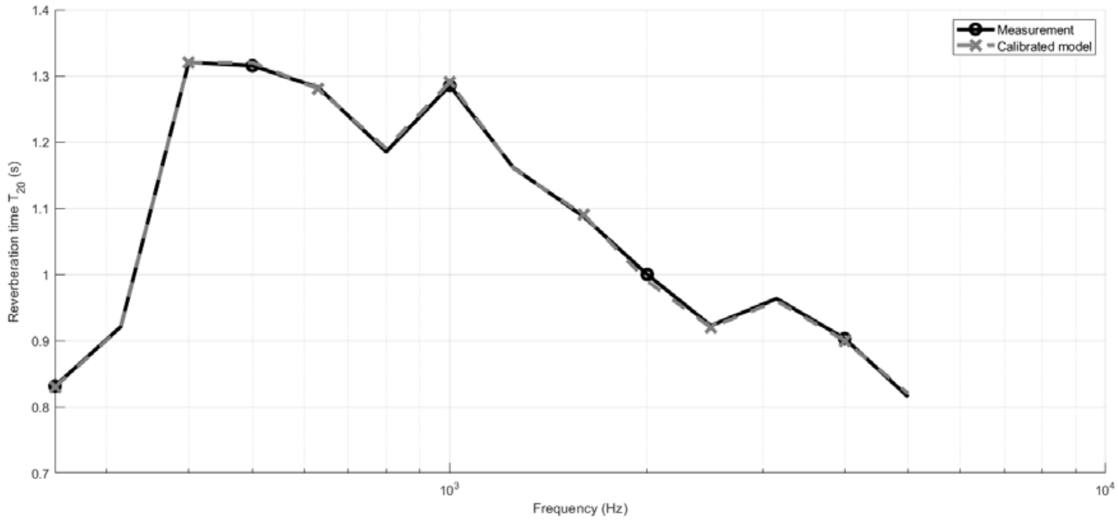

Figure 3: Reverberation time

room. The material properties typically require many more in-situ measurements which is impractical for the work. Instead, a model correlation process is involved to calibrate the material properties according to the measurements. More specifically, the surface impedance of each material is firstly estimated using publicly available databases for absorption coefficients. Based on Sabine's formula, an optimization process is created to adjust the material properties such that the reverberation times (T_{20}) from the simulations match with those from the measurements. Finally, the FDTD solver is used to simulate the entire room with all the computed properties to verify the calibrated results. The result of the calibration process is shown in Figure 3 in terms of the T_{20} obtained as a function of frequency.

While FDTD simulations provide the sound pressure with elapsed time, which is convenient to extract room acoustic parameters such as the reverberation time, f-FMBEM is applied to accurately predict the room modes and sound pressure level at different frequencies. Extracting such acoustic information from the space allows for the calculation of the target

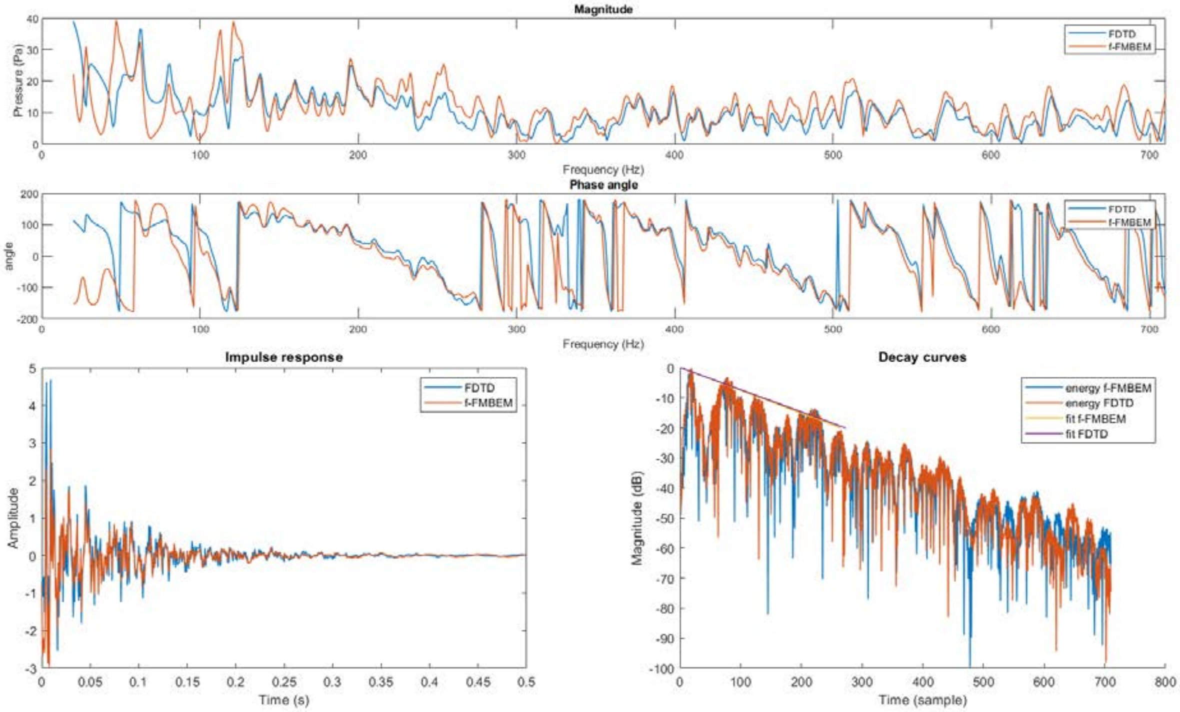

Figure 4: Comparison of FRF frequency response function (top), IR impulse response (bottom left) and T20 (bottom right)

frequencies and locations at which the metamaterial lamps should be placed. In particular, the number and location of absorptive surfaces in the calibrated model were adjusted until the reverberation time dropped as significantly as it did after the space was renovated. The surface impedance values of the absorptive surfaces are also estimated from a series of simulations. Based on the simulations from the digital model, parameters including target frequency range (from 500 Hz to 1 kHz), absorption coefficient, and dimensions of the metamaterial are obtained and provided as input for the metamaterial design such that it could be optimized to achieve the desired performance in reducing the reverberation time. Since an updated 3D model of the space containing the metamaterial solution for absorption can be simulated, the two numerical methods also play an important role in the validation and evaluation of the final metamaterial design to ensure that the manufactured product would lead to an improved acoustic quality of the space.

CHAPTER 3

Metamaterial design and manufacturing

As mentioned in the previous chapter, at relatively low frequencies the current solutions turn out to be less effective, thus, a new metamaterial design is applied in the room to provide effective absorption at low frequencies. As the metamaterial treatment takes up less space compared to the conventional acoustic treatments, it is incorporated in the enclosure design of a lamp. Six metamaterial plates are assembled as a cubic block which is used as an enclosure for the lamps in the restaurant. This integrated design gives an aesthetic appearance and is easy for installation and maintenance.

Acoustic surface solution

The proposed lamp enclosure is composed of six acoustic surfaces, with each composed of ducts of different dimensions attached to the plate of an area of 30 cm by 30 cm. Due to the duct resonances, the absorption can be maximized at each resonance frequency. As a result, if a sufficient number of ducts is used, a broadband high absorption can be achieved. A schematic illustration of the prototype is shown in Figure 5.

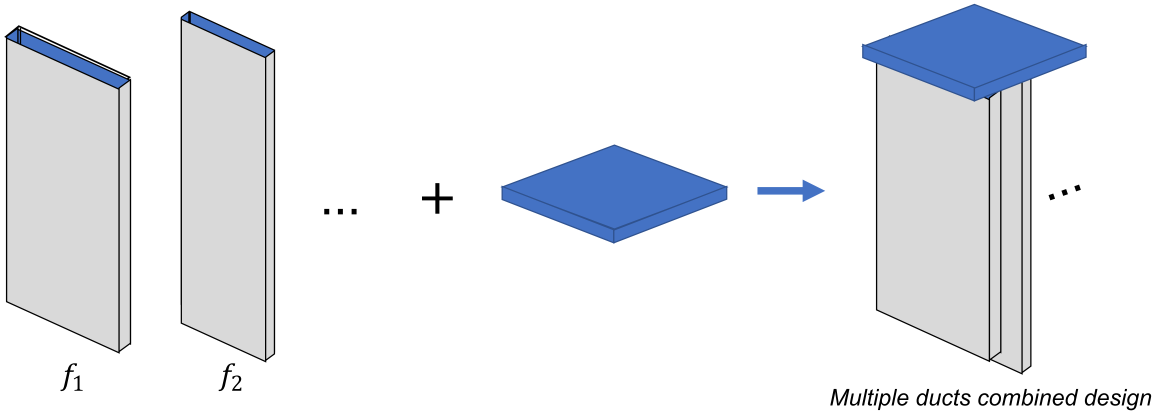

Figure 5: An illustration of the proposed structure

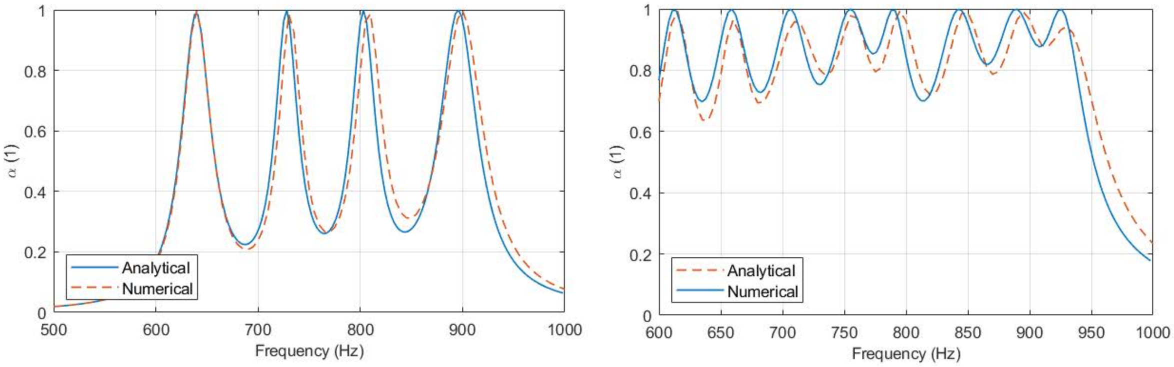

Figure 6: Two validation cases of the analytical model

In order to achieve the multiple ducts combined design, an analytical model to predict the acoustic absorption is firstly derived and validated by numerical simulations, as shown in Figure 6. Secondly, based on the analytical model, an optimization routine is devised, where the geometries of all ducts are optimized to maximize the absorption for a surface area of 30 cm by 30 cm and a total number of ducts of 15 from 500 Hz to 1000 Hz. Figure 7 shows the predicted absorption coefficient curve of the optimized structure from the analytical model, where a broadband high absorption is achieved. It poses another challenge when assembling all the six designed plates into one lamp enclosure. Due to the limited volume of the lamp, the ducts need to be re-arranged to avoid any space conflicts.

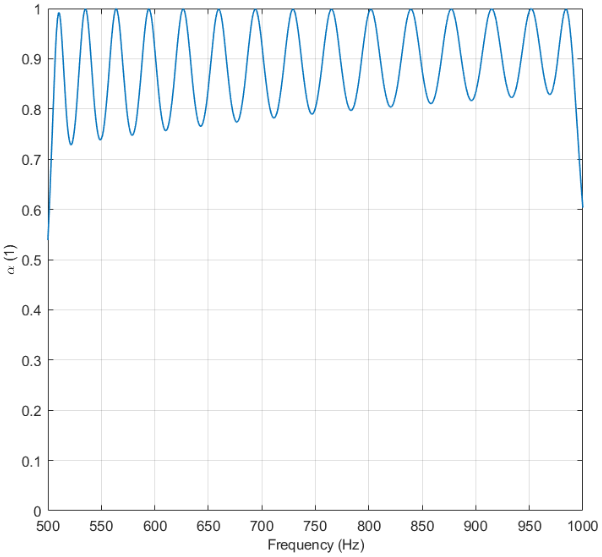

Figure 7: The absorption curve of the optimized structure based on 15 ducts

Manufacturing realization

In order to maintain a compact design for the lamp, the straight acoustic ducts are folded and well-positioned in a way to optimize the usage of the lamp volume. Apart from the acoustic functionality, the design also considers the optical clearance and aesthetics. An algorithm has been developed to adjust the geometrical parameters within the enclosed volume of the lamp. Figure 8 shows the final design of acoustic metamaterial lamp and the manufacturing criteria design.

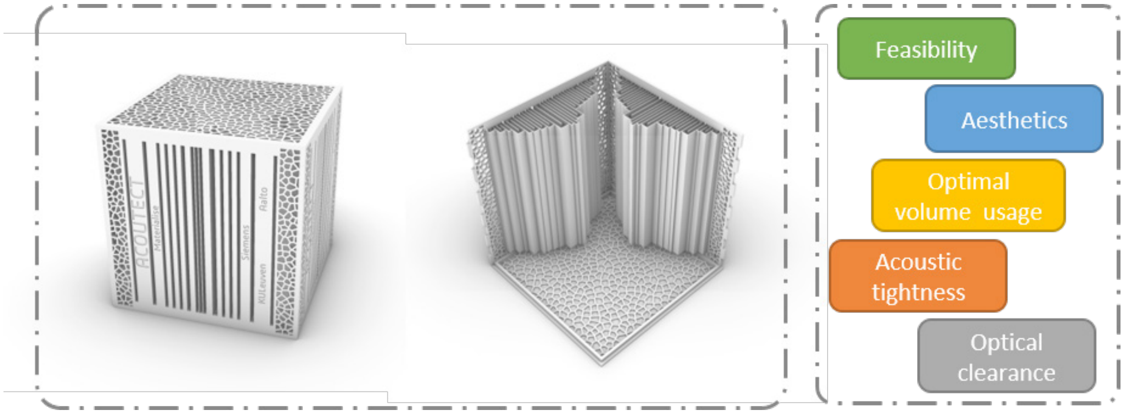

Figure 8: Acoustic metamaterial lamp and manufacturing criteria of design

The realization of the proposed acoustic metamaterials brings challenges in manufacturing due to their complex shapes and the small scale of the sample. Generally, conventional production technologies have limitations on fabricating them. Even with the modern 3D printing technologies, we observe large deviations in material dimensions and acoustic properties of the printed product. For example, in some pilot samples, the deviations between the original design and final product on the dominant absorption frequency can be as large as 10%. Fabrication of metamaterial with laser sintering allows a pre-printing assessment of the strategy which can sufficiently improve dimensional deviations and material properties. Research experiments with varying ranges of preheating temperatures and energy delivered to laser-scanned layers allow finding solutions for the potential scattering of mechanical properties and the dimensions within fabricated metamaterial. As such, the manufacturing process of 3D printed acoustic metamaterial is optimized to ensure the final realization of the product.

Numerical validation of the design

The new design of the metamaterial lamp is verified in the digital model for its acoustical performance. The f-FMBEM solver is used to simulate the room with and without the new treatment for the target frequency range. Three frequency snapshots at 800 Hz, 850 Hz and 900 Hz are presented in Figure 9. The acoustic source is positioned in the bottom left corner of the room. The top three plots are from the original room, while the bottom plots are from the room with the metamaterial lamps. As shown by the simulations, many of the high modes are mitigated by the new treatment.

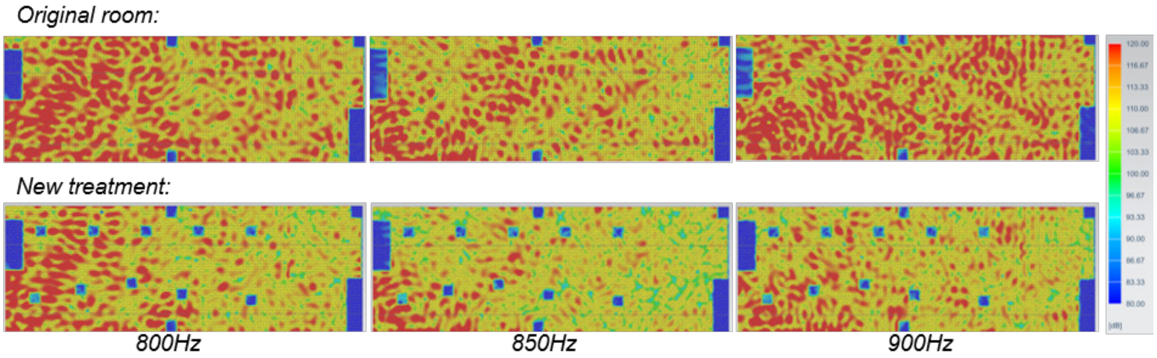

Figure 9: Top view of frequency response at 800 Hz, 850 Hz, and 900 Hz

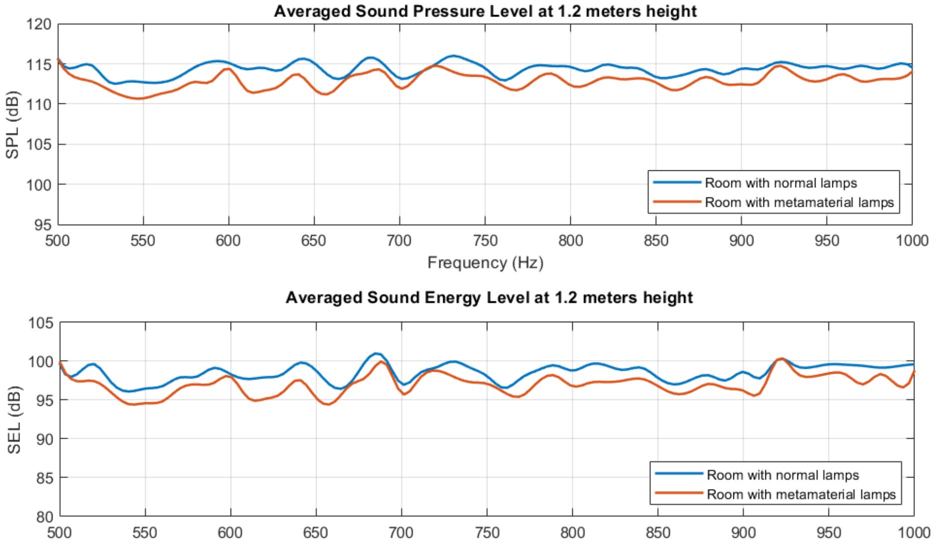

Figure 10: Comparison of averaged sound pressure level (top) and sound energy level (bottom)

Figure 10 shows the comparison of the averaged sound pressure level (SPL) and averaged sound energy level (SEL) over nearly ten thousand field points on a horizontal plane. The study selects the horizontal plane at 1.2 meters which represents the ear level when people sit. The top plot is a linear average of sound pressure level (in Pascal) and presented in decibel level. The bottom plot is a linear average of sound energy level with the reference sound energy of 10^{-12} joule. It can be found that the new metamaterial treatment reduces both the SPL and SEL over the target frequency band. A maximum of 3.5 dB reduction and an average of 1.5 dB reduction on both SPL and SEL can be obtained. The metamaterial design shows good performance considering its small volume compared to the room.

1/3 octave band	Original room	Room with new treatment
500	1.32 s	0.62 s
630	1.28 s	0.58 s
800	1.19 s	0.61 s
1000	1.29 s	0.76 s

Table 1: Reverberation time comparison

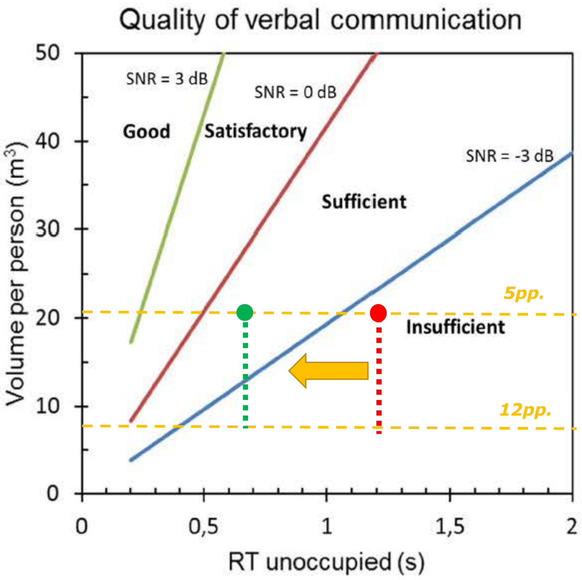

Figure 11: Quality of verbal communication
(adapted from J.H. Rindel, *The acoustics of places for social gatherings*, Euronoise, 2015).

Moreover, the reverberation time is computed based on the simulation results for each one-third octave band. As shown in Table 1, significant improvements can be observed when the metamaterial lamps are included in the room. For all the four target one-third octave bands, the new metamaterial lamps reduce the reverberation time by approximately 50%. The diagram of the verbal communication as shown in Figure 11 gives a general correlation between reverberation time, spatial volume, and quality of verbal communication. Considering two scenarios with 5 people and 12 people in the restaurant, the reduction of reverberation time (from red dashed line to green dashed line) improves the verbal communication from an insufficient level to a sufficient level in many cases.

The metamaterial lamp serves as a new acoustic treatment in social gathering places like restaurants and cafeterias, which provides several advantages comparing the conventional acoustic treatment. Firstly, the design is adaptive and can be customized for different spaces. The dimensions of the metamaterials are designed based on the characteristics of the room. The number of metamaterial lamps can be adjusted based on the acoustic requirement. The exterior design of the lamp can be adaptive to customer's taste. Secondly, the metamaterial lamp has a compact design and is easy for installation and replacement. Additionally, the metamaterial design provides aesthetic appearance which can be attractive to customers.

CONCLUSION

This work proposes a holistic engineering approach for acoustic treatment in social gathering places. We analyse the acoustics of a real restaurant. A digital model is created by using two state-of-the-art numerical methods. Based on in-situ measured data, a model correlation process is used to calibrate the material properties of the model. Acoustic parameters such as absorption coefficients are extracted from the model for the metamaterial design. The metamaterial plates are designed to form a lamp enclosure to provide acoustic absorption in the target frequency range. The laser sintering 3D printing technique is evaluated and used to manufacture and realize the proposed design. Numerical simulations demonstrate the improvement of sound absorption and speech intelligibility in the restaurant using the proposed treatment.

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