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EXPERIMENTAL RESEARCH OF SCATTERING COEFFICIENT OF TRIANGLE DIFFUSER MADE WITH CHARCOAL

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Abstract. The acoustic diffuser is the device that distributes the acoustic energy of intense reflections through their spatial and temporal dispersion. The device for reduction of unvented acoustic effects and improves indoor sound quality. Triangle diffusers are made of wood plates and covered with charcoal elements. The high sound reflection co-efficient of charcoal is in the production of diffusers. Charcoal is an ecologically friendly and natural material. The result of studies of the triangle diffusers made of charcoal showed high values of the sound scattering coefficient, with a maximum value (of 87) at the frequencies of 2000 with 80% of charcoal. Increasing the percent of charcoal increasing in sound scattering. The device installs in the audiences of concert halls, recording rooms, and museums.

Keywords: acoustic diffuser, reverberation chamber, reverberation time, sound diffusion, sound scattering coefficient wood charcoal.

Introduction

Due to urbanization, it is important aims to use renewable energy sources. RES significant for the energy sector to reach economic, environmental, social aims of sustainable development. Recycled wood materials are used for the production of fibreboard and chipboard (Daian & Ozarska, 2009). Wood waste species could be recycled and used for acoustic purposes (El-Hadad, 2018).

Nowadays the acoustic comfort important issues in environmental engineering. Constriction what allow to reduce sound propagation between rooms, adjust reverberation, improve speech intelligibility, remove echo, increase interest (Navarro & Escolano, 2015). Propagation of sound depends on the size of the room, the properties of the materials covering the walls, ceiling and floor as well as more various objects filling the room. For example, smooth oil-painted walls, glazed windows, parquet, and polished furniture are good sound reflectors. The energy of sound waves reflected from such surfaces is lost in small amounts. Conversely, the carpets, upholstered furniture, and heavy fabric draperies absorb well; their presence in the room drastically reduces the reverberation time (Beranek & Hidaka, 1998; Wahlberg & Larsen, 2017).

The quantity for describing rough surfaces is the scattering coefficient δ. The sound scattering coefficient is measured of the amount of sound scattered from a particular direction or distribution (Cox et al., 2006; De Beelde, 2022; Zhu, 2020). In room acoustics, the scattering coefficient of a scattering surface is defined as the ratio of the non-secularly reflected power to the total power reflected by the surface. The value of this coefficient (and its dependence on frequency) is of great importance to users of any modern room acoustics calculation tool. Several methods have been proposed to measure this value under well-defined sound field conditions (Embrechts, 2001). In 2004, ISO standardized the measurement method for the scatter random drop factor. In this method, the dissipation factor is measured in a reverberation chamber. The method based on an idea proposed by Vorländer and Mommertz. It uses the dispersion of the sound field as the test surface moves (Vorländer & Mommertz, 2000; Vorländer, 2006). AFMG Reflex software used to model and calculate scattering properties of the surface based on the Boundary Element Method (BEM) (Azad & Siebein, 2018; Devitasari et al., 2014). When applying the method, the dissipation factor is defined as one minus the ratio between the secularly reflected acoustic energy and the total reflected acoustic energy. When measured in an approximate diffuse sound field, the scattering coefficient is called the random incidence scattering coefficient (Vorländer & Mommertz, 2000). Values for this coefficient can vary from 0 to 1. The scattering coefficient, measured with the previously described method, is intended to characterize the degree of diffuse sound from a rough or uneven surface.

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The method for improve quality of room is the use of renewable absorbing materials or diffusers (Lee & Smith, 2004). Materials can not only absorb but also reflect and disperse sound. This section describes materials that have these properties. Reflection, that is, the reflection of sound a phenomenon is occurs when a sound wave falls on the interface between two elastic media and consists of the formation of waves propagating from the interface into the same medium from which the incident wave came. Devices are used for sound diffusion, allowing you to control the sound level in the room (Lock, 2016; Jiménez et al., 2017). There are different architectural forms of diffusers: curved, curvilinear, asymmetric honeycomb, curved surfaces, and Schroeder diffusers, which are computed according to the Quadratic Residual Diffuser (QRD) sequence. All diffusers are made of rigid material. Acoustic diffusers are installed in rooms to improve acoustics. Diffusers are placed inside the room at the upper corners in the room where the wall surface meets the ceiling surface, opposite the sound source. A diffuser is a device that scatters sound over a wide frequency range and is used to correct the acoustic characteristics of a room. Triangular diffusers shapes used for architectural acoustics purposes. Wedges and pyramids allow for the modification of sound reflections in concert halls and other performance spaces (Cox & D'Antonio, 2009, 2017).

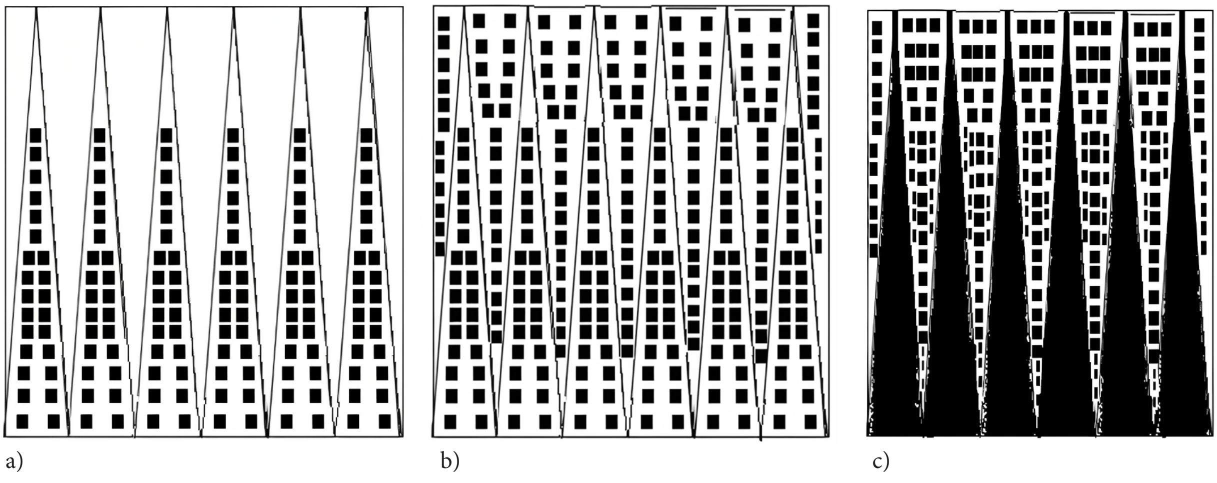
A large amount of wood waste accumulates on the planet what could be recycled and used for acoustic purposes. In connection with the decrease in the number of forests and the increase in the population, wood-based composites and low-quality wood materials necessary to study. Recycled wood materials: wood-plastic and wood-cement composite products, charcoal, industrial oil absorbents, insulation, speciality concrete, and wooden base materials derived from biorefinery processes with potential use in pharmaceutical, textile and food industries (Samsudin et al., 2016; Wang et al., 2017).

Charcoal is a natural, rigid, porous and homogeneous material by which most a sound wave can be reflected (Suh et al., 2013). The current literature has not explored the scattering properties of wood constructions covered by charcoal elements. The reflective materials ought to have a reflection coefficient of 1, which is high value useful for the creating diffuser. The studies showed that the charcoal samples had high sound reflection coefficients, the highest value of which was 1. Due to its reflective properties charcoal material can be used to covered of acoustic diffusers (Khrystoslavenko & Grubliauskas, 2022). Wood charcoal used in construction applications for example as an interior material (windows, doors, partition walls). Charcoal-based construction elements effectively isolate noise and improve sound insulation and the quality of internal reverberation (Lee, 2022).

Existing acoustic diffusers are wedge-shaped, rectangular planes that dissipate sound less efficiently than other forms. In the thesis, the designed and manufactured diffuser of wooden triangular perforated planes covered with charcoal cylinder elements. The article aims to evaluate of sound scattering properties of triangle diffusers modified with different sequences made of wood plates by increasing covered area of charcoal elements.

1. Methods and materials

A triangle acoustic diffuser was manufactured of wooden triangular plates with covered area (surface densities) by charcoal elements on 30, 60 and 80%. In the measured triangle wood diffuser, wood oak charcoal has a diameter of 25 mm. The mass of wood oak charcoal coverage was 60% of (0.57 kg) coverage area, 30% of (0.28 kg) coverage area, and 80% of (0.68 kg). The mass of each charcoal element was (0,003–0.007 kg) pieces. The charcoal elements inserted in the wooden acoustic diffuser. A triangle acoustic diffuser consists of a series of wells of the same width and different depths (Figure 1). The wells divided by thin fins. During one period, the depth of the wells determined by a mathematical sequence, such as a quadratic residue or a primitive root sequence.



a) b) c)

Figure 1. View of the covered area of triangle diffusers for the experiment:
a) 30% covered by charcoal elements; b) 60% covered by charcoal elements; c) 80% covered by charcoal elements

The triangular diffuser has a dimensions (width 1×1 m). The manufactured acoustic diffuser made of boards with quadrat charcoal elements has a wedge-like shape. Calculations of well depth, lower frequency limit, higher frequency limit of diffusors based on Eq. (1–3), are demonstrated in the Figure 2.

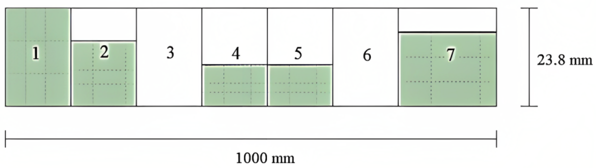


Figure 2. Triangle diffusers sequence depth scheme. Depth sequence: cm 1 = 0 cm; 2 = 5.9 cm; 3 = 23. 8 cm; 4 = 11.9 cm; 5 = 11.9; 6 = 23.8 cm; 7 = 5.9 cm

The calculation of quadratic residue diffuser. Schroeder diffuser consists of a series of cells of different depths. The construction of the diffuser is based on the mathematical sequence of quadratic residues from the theory of numbers, which is determined by the relation:

$$s^n = n^2 \, modulo\left(N\right), \tag{1}$$

where: s_n – the sequence of value s of the relative depth of the wells of the diffuser; n – nonnegative integer {0, 1, 2, 3 ...}, determining the number of the corresponding well; N – simple number {2, 3, 5, 7, 11, 13, 17...}. A prime number, this is different from 0 and 1, which is divided by the remainder only by 1 and by itself. For one period of an N = 7, quadratic residue diffuser has s_n = {0, 1, 4, 2, 2, 4, 1}. Quadratic residue sequences are symmetrical between $n \equiv 0$ and $n \equiv (N-1)/2$. (D'Antonio & Konnert, 1992; Schroeder, 1975, 1979).

Well depth d_n in the design of the diffuser depends on the value of its design frequency f_0:

$$d_n = s_n \times c \,/\, (f_0 \times 2 \times N), \tag{2}$$

where: d_n – well depth n, cm; f_0 – design frequency of the diffuser, cm; c – sound velocity in the air, m/s; N – prime number (the order of the diffuser) corresponding to the number of wells.

$$f_0 = \frac{S_{\max}}{N} \, \frac{c}{2d_{\max}}. \tag{3}$$

2. Method of Determination of sound scattering coefficient

The ISO 17497-1:2004 standard has been used for experiment, which defines the scattering coefficient s and the method of its determination in the reverberation chamber. Measurements of the scattering coefficient of the diffuser of quadratic residuals follow the ISO of a one-meter diffuser number 7 in the reverberation chamber. "Measurement of the random scattering coefficient in a reverberation chamber". The measurements system consists of a turntable on this table mounted with the test sample, a measuring microphone, an omnidirectional sound source, a measuring signal generator and a signal analyser (International Organization for Standardization [ISO] 17497-1:2004, 2004). The impulse response found during the scattering coefficient measurements of reverberation times measurements: for a rotating and stationary turntable with and without a sample. Schematic representation of the VILNIUS TECH reverberation chamber shown in Figure 3.

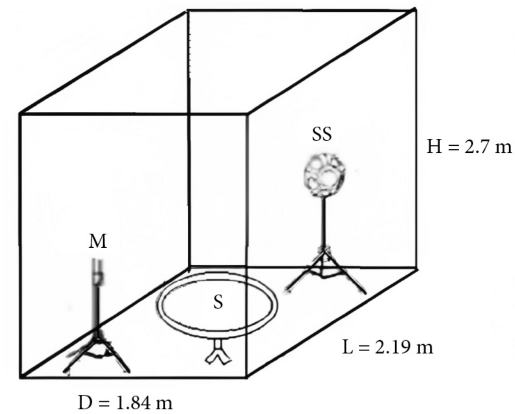


Figure 3. Physical model of a scaled-down reverberation chamber with a source and a microphone

The volume of the reverberation room is 11 m^3 the distance between the sound source (SS) and the microphone (M) is 1.5 m, and the distance from the sound source to the sample (S) is 1 m. Diffuser reverberation times value by integrating the impulse responses were received experimentally in the reverberation room. The received data of reverberation times of diffusers has let to calculate the absorption coefficient α_s and the specular absorption coefficient α_{spect}. Reflected sound measurements made of the three microphone locations relative to the sample and corner. The surface area should be as large as possible to ensure the required measurement accuracy. The reverberation sound absorption coefficient is calculated by the formula:

$$\alpha_S = 55.3\frac{V}{S}\left(\frac{1}{c_2 T_2} - \frac{1}{C_1 T_1}\right) - \frac{4V}{S}\left(m_2 - m_1\right), \tag{4}$$

where: V – reverberation chamber volume, m^3, (11 m^3); S – is the area of the test surface sample, m_2 (11 m^3); T_1 – reverberation time, determined in the absence of a test surface sample, but with a turntable, s; T_2 – is the reverberation time determined in the presence of a test surface sample, s; c_1 – speed of sound in air when measuring, T_1, m/s^2; c_2 – speed of sound in air when measuring T_2, m/s^2; m_1 – attenuation constant of sound energy in air, calculated in accordance with ISO 9613-1, at temperature and relative humidity when measured, (20.8 °C and 50 H m^{-1}); m_2 – damping constant of sound energy in air, calculated during measurements, m^{-1}. The reverberation times T_1 and T_2 are measured with the turntable stationary.

$$\tilde{N}=342.2\sqrt{\frac{273.15+t}{293.15}}, \quad (5)$$

where t – is the air temperature °C.

The same standard gives the sound pressure attenuation factor α, dB/m. The attenuation constant of sound energy in air, m, is calculated by the formula:

$$m=\frac{\alpha}{10\lg(e)}\approx\frac{\alpha}{4.343}. \quad (6)$$

Calculation of the reverberation coefficient of specular sound absorption. The reverberation coefficient of specular sound absorption calculated using the formula:

$$\alpha_{spect}=55.3\frac{V}{S}\left(\frac{1}{c_4T_4}-\frac{1}{C_3T_3}\right)-\frac{4V}{S}(m_4-m_3), \quad (7)$$

where: T_3 is the reverberation time determined with a rotating turntable without a test surface sample, s; T_4 is the reverberation time determined for a test surface sample on a rotating turntable, s; c_3 – speed of sound in air when measuring T_3, m/s; c_4 – speed of sound in air when measuring T_4, m/s; m_3 is the attenuation constant of sound energy in air during the measurement T_3, m^{-1}; m_4 is the attenuation constant of sound energy in air during the measurement T_4, m^{-1}.

Calculation of the reverberation scattering coefficient. The reverberation scattering coefficient calculated by using the formula:

$$s=1-\frac{1-\alpha_{spec}}{1-\alpha_s}=\frac{\alpha_{spec}-\alpha_s}{1-\alpha_s}. \quad (8)$$

3. Results and discussion

Figure 4 shows the result of the reverberation time of triangle diffusers comparing 30%, 60%, and 80% covered wood charcoal present in the frequency range of 315 to 5000 the measurement of reverberation time at 20° the rotating angle. The reverberation time measured by 1/3 octave bands plotted as a function of frequency.

According to the research, the reverberation time increase with the coverage area decrease. The diffuser with the higher charcoal coverage area 80% has a lover reverberation time. The results of the experimental study show the maximum reverberation time is (0.64) at a frequency of 800 Hz. The minimal reverberation time at a frequency of 315 Hz was (0.27). Figure 4 shows the results of studies on the scattering coefficient of an acoustic diffuser. The triangular planes filled with charcoal cylindrical elements reduce the reverberation time. The sound scattering coefficient of triangle diffusers is calculated according to Eqs (6–10).

Figure 5 shows the results of scattering coefficients of the acoustic diffuser with charcoal what is vary in the range from (0.33) to (0.87). The curve of sound scattething grows exponential increase within the frequency increase to a frequency of 3150 Hz. The peak of sound scattering was (0.87) at the frequencies of 2000 with 80% of perforation. The diffuser with the higher charcoal per cent has a higher scattering coefficient. The triangle diffuser without charcoal showed lower results of scattering coefficient compare to other diffusers in the same frequencies. The increasing scattering coefficient up to (0.87) with charcoal could be related to the increasing ratio of coverage area from 30 to 80%. In their study, Jeon et al. (2004) investigated how the sound scattering coefficient of wooden hemispheres and cube surfaces with varying sizes and densities increased in relation to the coverage area ratio.

The sound scattering coefficient increase to 1000 Hz from (0.33) to (0.85) depending on the coverage area, of the diffuser the 80% charcoal diffuser shows a peak of scattering at 500 Hz (0.63). The diffusers with 60%

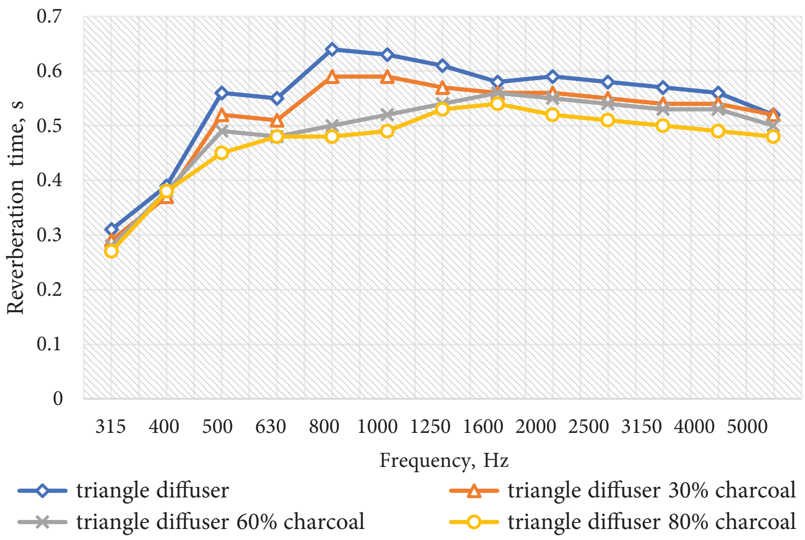


Figure 4. Reverberation time of triangle acoustic diffuser

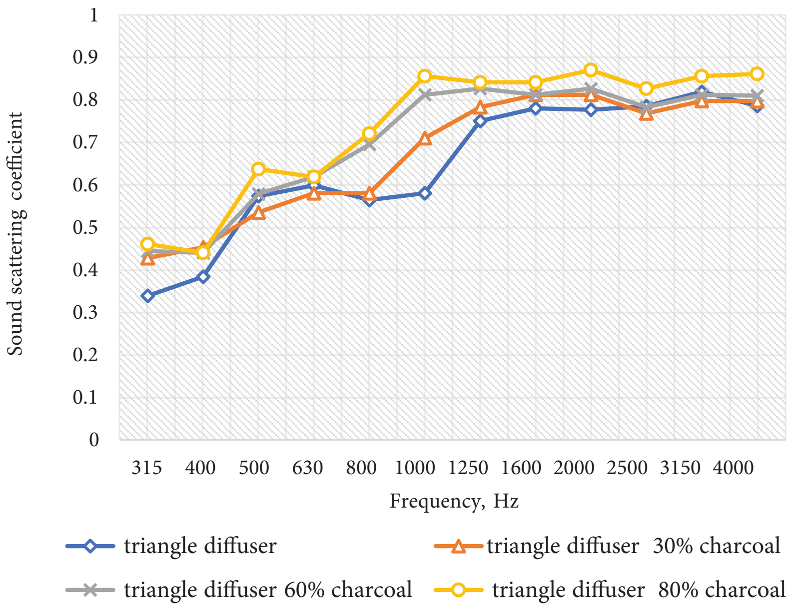


Figure 5. Sound scattering coefficient of triangle acoustic diffuser

and diffusers without covering show results at (0.57) at a frequency of 500 Hz. At the higher frequency of 1000 Hz scattering coefficient, maximum scattering was (0.85) for the diffuser with 80% coverage, minimum scattering (0.58) diffuser without charcoal, (0.71) for the diffuser with 30 % charcoal, and (0.81) of 60% charcoal. At the frequency, 2000 Hz scattering value of (0.82) of the diffuser 30 and 60% diffuser charcoal coverage with 80% show the same result of scattering (0.87) at the same frequency, the minimum scattering (0.76) shows the triangle diffuser without charcoal. The effectiveness of the diffuser depends on scattering frequency. At the frequency 2500 Hz sound scattering coefficient (0.78) for triangle diffuser and diffusers 30% and 60% covered. The most effective sound scattering at the frequency from 1000 to 4000 Hz triangle diffuser covered with 80% charcoal was (0.85 to 0.87).

Suh et al. studied charcoal's high sound reflection properties than other sound absorption materials this means that it has high reflective properties (Suh et al., 2013). Due to high reflection properties of charcoal elements and triangle shapes of diffuser the sound energy reflects better by add at different positions concerning the source, increasing the diffusion of the sound field in the room from the diffuser. The scattering coefficient grows when the diffuser density increase about 30% for 60% and 80% covered by charcoal elements.

Conclusions

The acoustic diffuser-made renewable energy source material has investigated. The triangle diffuser covered with wood charcoal elements. The investigated wood charcoal materials had high sound reflection coefficients, which are effective for diffuser production.

The acoustic properties of triangle diffusers covered with charcoal researched experimentally. The diffuser with the higher charcoal coverage area of 80% has a lover reverberation time. The charcoal diffuser has high efficiency, with a maximum scattering coefficient of 0.87, at the frequencies of 2000 with 80% of charcoal. The diffuser with the higher charcoal-covered area has a higher scattering coefficient. Research has shown the scattering coefficient increase with charcoal covered area. The effectiveness of the diffuser depends on scattering frequency. The sound scattering is most effective at the frequency from 1000 to 2000 Hz of a triangle diffuser covered with 80% charcoal elements.

The acoustic diffuser made renewable energy sources material has been investigating. The triangle diffuser was covered with wood charcoal elements. The investigated wood charcoal materials had high sound reflection coefficients, which are effective of sound diffuser production.

The acoustic properties of triangle diffusers were research experimentally. The diffuser with the higher charcoal surface densities of 80% has a lover reverberation time. The charcoal diffuser has high efficiency, with a maximum scattering coefficient of 0.87, at the frequencies of 2000 with 80% of charcoal. The diffuser with the higher charcoal-covered area has a higher scattering coefficient. Research has shown the scattering coefficient increase with charcoal covered area and densities of triangular diffusers. The effectiveness of the diffuser depends on scattering frequency. The sound scattering is most effective the frequency from 1000 to 2000 Hz of a triangle diffuser covered with 80% charcoal elements.

A triangular-shaped diffuser covered with charcoal elements allows the distribute of the reflected sound well at different positions concerning the source, increasing the diffusion of the sound field in the room.

The triangular-shaped sound diffuser with charcoal is an effective acoustic treatment.

References

Azad, H., & Siebein, G. (2018). On the prediction of sound diffusion coefficient. *The Journal of the Acoustical Society of America*, *143*(3), 1896. https://doi.org/10.1121/1.5036168

Beranek, L. L., & Hidaka, T. (1998). Sound absorption in concert halls by seats, occupied and unoccupied, and by the hall's interior surfaces. *The Journal of the Acoustical Society of America*, *104*(6), 3169–3177. https://doi.org/10.1121/1.423957

Cox, T. J., & D'antonio, P. (2009). *Acoustic absorbers and diffusers: Theory, design and application* (2nd ed.). CRC Press. https://doi.org/10.4324/9781482266412

Cox, T. J., & D'Antonio, P. (2017). Designing triangular diffusers for architectural acoustics. *The Journal of the Acoustical Society of America*, *141*(5), 3663. https://doi.org/10.1121/1.4987935

Cox, T. J., Dalenback, B.-I., D'Antonio, P., Embrechts, J.-J., Jeon, J. Y., Mommertz, E., & Vorländer, M. (2006). A tutorial on scattering and diffusion coefficients for room acoustic surfaces. *Acta Acustica United with Acustica*, *92*, 1–15. https://www.researchgate.net/publication/233688510

Daian, G., & Ozarska, B. (2009). Wood waste management practices and strategies to increase sustainability standards in the Australian wooden furniture manufacturing sector. *Journal of Cleaner Production*, *17*(17), 1594–1602. https://doi.org/10.1016/j.jclepro.2009.07.008

D'Antonio, P., & Konnert, J. (1990, September). The QRD diffractal: A new one-or two-dimensional fractal sound diffusor. Audio Engineering Society. In *89th AES Convention*. 2938. http://www.aes.org/e-lib/browse.cfm?elib=5755

D'Antonio, P., & Konnert, J. (1992). The QRD diffractal: A new one-or two-dimensional fractal sound diffusor. *Journal of the Audio Engineering Society*, *40*(3), 117–129. https://www.aes.org/e-lib/browse.cfm?elib=7057

De Beelde, B., Almarcha, A., Plets, D., & Joseph, W. (2022). V-band channel modeling, throughput measurements, and coverage prediction for indoor residential environments. *Electronics*, *11*(4), 659. https://doi.org/10.3390/electronics11040659

Devitasari, E. Y., Chorida, A., Muqowi, E., Haryanti, N., Harjana, H., & Yahya, I. (2014). Pengaruh Sisipan Resonator Celah Sempit pada Serapan dan Respon Spasial Quadratic Residue Diffuser. *Jurnal Fisika Dan Aplikasinya*, *10*(1), 31–36. https://doi.org/10.12962/j24604682.v10i1.821

El-Hadad, A., Brodie, G. I., & Ahmed, B. S. (2018). The effect of wood condition on sound wave propagation. *Open Journal of Acoustics*, *8*(3), 37–51. https://www.scirp.org/html/1-1610185_86746.htm

Embrechts, J.-J., Archambeau, D., & Stan, G.-B. (2001). Determination of the scattering coefficient of random rough diffusing surfaces for room acoustics applications. *Acta Acustica United with Acustica*, *87*(4), 482–494. https://www.researchgate.net/publication/233573762

International Organization for Standardization. (2004). *Acoustics – Sound-scattering properties of surfaces – Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room* (ISO 17497-1).

Jeon, J. Y., Lee, S. C., & Vorländer, M. (2004). Development of scattering surfaces for concert halls. *Applied Acoustics*, *65*(4), 341–355. https://doi.org/10.1016/j.apacoust.2003.11.001

Jiménez, N., Cox, T. J., Romero-García, V., & Groby, J.-P. (2017). Metadiffusers: Deep-subwavelength sound diffusers. *Scientific Reports*, *7*(1), 1–12. https://www.nature.com/articles/s41598-017-05710-5

Khrystoslavenko, O., & Grubliauskas, R. (2020, March). Theoretical predictions of sound scattering coefficient and sound diffusion coefficient from quadratic residue diffusers. In *22nd Conference "Environment Protection Engineering"* (pp. 80–87). Vilnius. https://doi.org/10.3846/aainz.2019.007

Lee, K., & Smith III, J. O. (2004). *Implementation of a highly diffusing 2-d digital waveguide mesh with a quadratic residue diffuser*. ICMC.

Lock, A., & Holloway, D. (2016). Boundary element modelling of a novel simple enhanced bandwidth schroeder diffuser offering comparable performance to a fractal design. *Acoustics Australia*, *44*(1), 137–147. https://doi.org/10.1007/s40857-016-0049-4

Navarro, J. M., & Escolano, J. (2015). Simulation of building indoor acoustics using an acoustic diffusion equation model. *Journal of Building Performance Simulation*, *8*(1), 3–14. https://doi.org/10.1080/19401493.2013.850534

Samsudin, E. M., Ismail, L. H., & Kadir, A. A. (2016). A review on physical factors influencing absorption performance of fibrous sound absorption material from natural fibers. *ARPN Journal of Engineering and Applied Sciences*, *11*(6), 3703–3711. https://www.researchgate.net/publication/301341460

Schröder, M. R. (1975). Diffuse sound reflection by maximum-length sequences. *The Journal of the Acoustical Society of America*, *57*(1), 149–150. https://doi.org/10.1121/1.380425

Schroeder, M. R. (1979). Binaural dissimilarity and optimum ceilings for concert halls: More lateral sound diffusion. *The Journal of the Acoustical Society of America*, *65*(4), 958–963. https://doi.org/10.1121/1.382601

Suh, J. G., Baik, K. m., Kim, Y. T., & Jung, S. S. (2013). Measurement and calculation of the sound absorption coefficient of pine wood charcoal. *Journal of the Korean Physical Society*, *63*, 1576–1582. https://doi.org/10.3938/jkps.63.1576

Wahlberg, M., & Larsen, O. N. (2017). Propagation of sound. In *Comparative bioacoustics: An overview* (pp. 61–120). Bentham Science Publisher. https://portal.findresearcher.sdu.dk/en/publications/propagation-of-sound

Wang, D., Peng, L. M., Fu, F., Song, B. Q., & Liu, M. H. (2017). Changes of microscopic structures and sound absorption properties of decayed wood. *Wood Research*, *62*(4), 529–538. http://www.woodresearch.sk/wr/201704/02.pdf

Zhu, X., Kang, J., & Ma, H. (2020). The impact of surface scattering on reverberation time in differently shaped spaces. *Applied Sciences*, *10*(14), 4880. https://doi.org/10.3390/app10144880