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# THEORETICAL PREDICTIONS OF SOUND SCATTERING COEFFICIENT AND SOUND DIFFUSION COEFFICIENT FROM QUADRATIC RESIDUE DIFFUSERS

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**Abstract.** Quadratic residue diffuser (QRD) is a device that distributes the acoustic energy of intense reflections by its spatial and temporal dispersion. The quadratic residue diffuser consists of a series of wells of different depths and the same width. Optimal diffusion is very important for perceiving musical sound and eliminating unwanted acoustic effects e.g. echoes. For the purpose to determine the optimal diffusion, Schroeder used mathematical number sequences allowing to diffuse the sound in a semicircular pattern from the devices. In this paper, the presented quadratic residue diffuser modeling method is presented. Result of theoretical modeling at a frequency of 500 Hz was obtained. The estimated width of the wells is 9.4 cm. The sound scattering and sound diffusion coefficient different number of the diffusor wells were researched. It was obtained that with an increasing number of wells of the diffuser leads to an increment in sound diffusion at the design frequency for diffuser the same width sequences.

**Keywords:** Quadratic residue diffuser (QRD), diffusion, sound scattering coefficient, frequency, sound diffusion coefficient, AFMG Reflex software

## Introduction

Sound striking a surface is transmitted, absorbed or reflected; the amount of energy going into the transmission, absorption or reflection depends on the surface's acoustic properties. The reflected sound can either be redirected by large flat surfaces (secularly reflected) or scattered by a diffusing surface. When a significant portion of the reflected sound is spatially and temporally dispersed, this is a diffusive reflection, and the surface involved is often termed as a diffuser. Diffusion coefficient (d), is a measure of the uniformity of the reflected sound. The purpose of this coefficient is to enable the design of diffusers and to also allow acousticians to compare the performance of surfaces for room design and performance specifications. Scattering coefficient (s), is a ratio of sound energy scattered in a non-specular manner to the total reflected sound energy. The purpose of this coefficient is to characterize surface scattering for use in geometrical room modelling programs. There is no direct relationship between the scattering coefficient and the diffusion coefficient. A high value of diffusion implies that scattering is also high, whereas a high value of scattering can be combined with any value of diffusion. (Vorländer & Mommertz, 2000; Cox & d'Antonio, 2016). Diffusion can also be described as multiple scattering, as the direction of scattering of sound rays is shown in Figure 1.

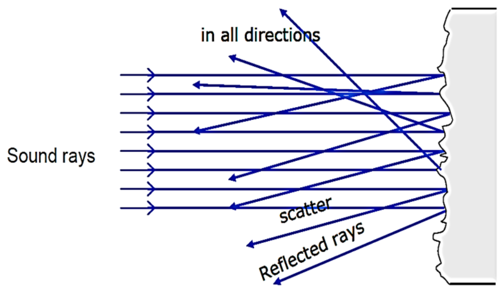


Figure 1. Sound waves scatter from rough surface

In the 1970s, Schroeder proposed methods for designing highly diffusing surfaces based on maximum-length sequences and quadratic residue sequences (Schroeder 1975, 1979). These so-called quadratic residue diffusers (QRD) have been widely applied to the design of recording studios and concert hall Quadratic Residue Diffuser) reflectors that induce diffusion. These reflectors can reduce echo problems as well (Lee & Smith, 2004). The primary requirements to achieve diffusion is that the profile depth of the relief is comparable with a quarter of the wavelength and the linear extension of the diffusion element (before it is eventually repeated) is comparable with the wavelength at the lowest frequency of interest to be diffused. Given this many different solutions can be imagined such as soft curved forms cast in plaster, broken stone surfaces, wooden sticks, irregular brick walls etc. Finally, it should be mentioned that strict periodic structures with sharp edges equally spaced along that surface can cause problems of harsh sound at frequencies above the design frequency range (Rossing, 2007).

There are several types of diffusers and the correct choice depends on the room characteristics and the use intended for the room. Some types of diffusers:

– *Geometrical diffusers*
Convex semi cylinder (Cox & D'Antonio, 2004).
Periodic geometrical structures (Ajlouni, 2018).

– *Composite of absorbing and reflecting materials* (Diffuser with bass trapping, 2019).

– *Mathematical diffusers*
QRD Diffusers (Quadratic residue diffuser).
One-dimensional.
Two-dimensional (Picaut, Hossam Eldien, & Billon, 2010).
Fractal diffusers (Lock & Holloway, 2015).

Curved diffusers (Yokota, Seimiya, Sakamoto, & Tachibana, 2000; Cox & d'Antonio, 2016; Rindel, 2004).

An acoustic diffuser is the surface profile designed to provide a diffuse reflection from an incident sound waves. While nearly every reflective surface will offer some degree of diffusion, an acoustic diffuser is designed to produce high levels of diffusion or specific diffusion characteristics, often for a design application or frequency range. Diffusion can be either temporal (time-related) or spatial, and is a useful tool in the acoustic treatment of spaces such as critical listening rooms and performance spaces, often to create a more even sound field or to avoid strong reflections. Where traditionally acoustic absorbers have been used to avoid undesirable acoustic effects, there is a growing trend towards the use of diffusers instead, and this has increased the need to accurately model their performance (Cox & D'Antonio, 2009; Lock & Holloway, 2015).

The sound diffuser materials what used for the manufacturing must be rigid enough to reflect acoustic energy, otherwise sound absorption occurs. Today, wood is the material that is most often used for the production of a diffuser,

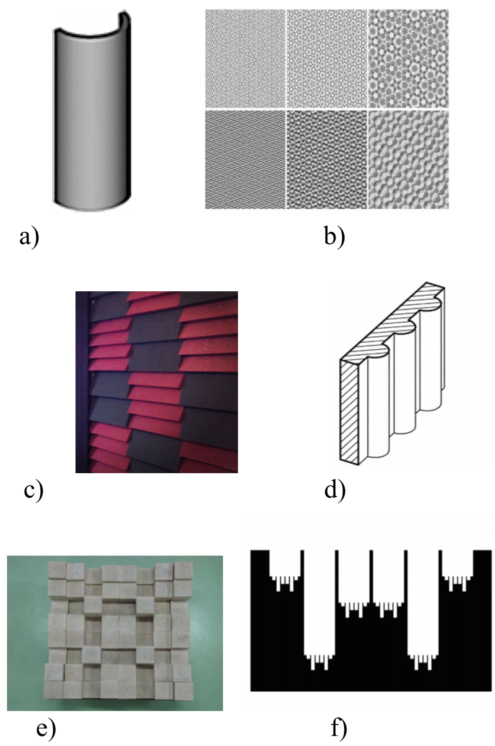


Figure 2. Types of diffusers: a) Convex semi cylinder; b) periodic geometrical structures; c) composite of absorbing and reflecting materials d) one dimensional; e) two-dimensional Schroder f) fractal diffusers

because it is sufficiently rigid to reflect the sound energy and environmental friendly. Analysis of the research results showed that the maximum value of the reflection coefficient of this material is 1, which is a very high indicator and allows using this material as a diffuser (Romadhona & Yahya, 2017; Jiménez, Cox, Romero-García, & Groby, 2017).

Cox et al. used numerical methods for the prediction of diffusion coefficient quadratic residue diffuser (QRD). Prediction can be obtained from numerical models reproducing transfer functions with the surface in free field commonly used boundary element method (BEM) for the production of the diffusion coefficient. (Cox et al., 2006; D'Antonio & Cox, 1998). AFMG Reflex software gives opportunity to model and calculate the reflection, diffusion, and scattering properties of the surface based on the Boundary Element Method (BEM) (Azad & Siebein, 2018).

Nowadays with the development of computational facilities, use of simulation software's for room acoustic modelling has been widely increased. It is important to use of the scattering and diffusion coefficient in room-acoustical computer simulations (Ziegler, 2018; Rindel, 2000; Postma & Katz, 2016; Jeong, Marbjerg, & Brunskog, 2016; Peters, 2015).

German software manufacturer AFMG Reflex, renowned for professional solutions simulating room acoustics, just released the first commercial software able to model the reflection, diffusion, and scattering of a sound wave by a defined geometrical structure. AFMG Reflex is available in two versions: the basic version aims at advanced home studio designs, home theater installations and other semi-professional applications (AFMG, 2019). AFMG Reflex software have been used for researches by the different authors Hough, C. et al. was done the researches sound scattering surfaces in the recently-opened Ukaria Concert Hall room using Reflex software (Hough, Nicol, & Sim, 2016). As well M. Flores 2012 used "AFMG Reflex" software for investigation of different prototypes, with simple geometrical figures like triangles, arcs or cubes, all based in acoustic theory. This prototype was studied compared and constructed (Flores, 2012).

Due to high diffusion performance was chosen QRD diffusers for research. It is important to investigate the acoustic properties of QRD. This paper aimed to investigate diffusion behavior QRD with a different number of sequences. An acoustic diffuser with different number of sequences is an object of researches.

Aim of research to find diffusor with optimal acoustic diffusion properties.

**Methodology**

Quadratic residue diffuser consists of a series of wells of the same width and different depths. The wells are divided by thin fins. During one period, the depth of the wells is determined by a mathematical sequence, such as a quadratic residue or a primitive root sequence. The incident wave will cause the pressure wave which travels to a solid bottom from which it is reflected. Returning to the input plane of the structure, these waves will undergo various phase shifts, corresponding to different path lengths they passed. If the phase differences are large enough, the structure will produce a significant scattering of the reflected wave, with scattering characteristics depending on the depth of the sequence of elements. In this case, many different depth sequences were used to construct the diffuser. Example of quadratic residue diffuser is shown in Figure 3.

The variation of the depth of the wells is only in one direction and the resultant diffusers being called 1D Schroeder diffusers. The diffusers studied here are designed based on quadratic residue sequence and are hence called quadratic residue diffusers (QRD), as shown in Figure 3.

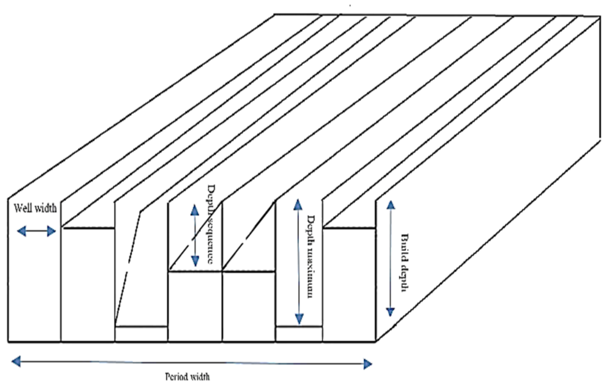


Figure 3. Quadratic residue diffuser of 7 wells

It was researched twelve types of diffusers, six types with design frequency 500 Hz and six types of diffusers an total length of 1 m different design frequency, letter N is the order of the diffuser corresponding to the number of wells. Diffusors have different total well width first type of diffusers what aimed to scatter energy at design frequency 500 Hz other constructions have a total length of 1 m. A design frequency of 500 Hz (frequency above which the diffuser is supposed to scatter sound with even energy in all directions) was chosen because it is corresponding middle diffuse frequency range which significantly affects the naturalness of sound reproduction and is useful in the frequency range of human voice. These constructions have different well width. All researches diffusers in modeling program have reflection coefficient of 1.

The calculation of quadratic residue diffuser. Schroeder diffuser consists of a series of cells of different depths and equal widths, made of rigid material. 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:

$$s_n = n^2 \text{ modulo (N)}, \tag{1}$$

where:

$s_n$ – the sequence of value s of the relative depth of the cells of the diffuser,

$n$ – nonnegative integer {0, 1, 2, 3 ...}, determining the number of the corresponding cell,

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.

An example of calculating the sequence of quadratic residues from number theory:

N = 5: 0 1 4 4 1 0
N = 7: 0 1 4 2 2 4 1 0
N = 11: 0 1 4 9 5 3 3 5 9 4 1 0
N = 13: 0 1 4 9 3 12 10 10 12 3 9 4 1 0

N = 17: 0 1 4 9 16 8 2 15 13 13 15 2 8 16 9 4 1 0.

Cell depth $d_n$ in the design of the diffuser depends on the value of its design frequency $f_o$:

$$d_n = s_n \times c / (f_o \times 2 \times N), \quad (2)$$

where:

$d_n$ – cell depth $n$;

$f_o$ – design frequency of the diffuser;

$c$ – sound velocity in the air;

$N$ – prime number (the order of the diffuser) corresponding to the number of wells.

A diffuser's theoretical working range is a main parameter that can be predetermined. This parameter can be the most important criteria to choose a given model, but it can also make way for another aspect of equal or higher importance in a given situation, such as periodicity (more on this later). These limits are roughly:

$$\lambda_{\max} = 2Nd_{\max} / n_{\max}, \quad (3)$$

where:

$\lambda_{\max}$ – higher frequency limit;

$d_{\max}$ – maximum well depth;

$n_{\max}$ – maximum number in the quadratic residue sequence;

$n_{\max}$ – maximum number in the quadratic residue sequence;

$$\lambda_{min} \approx 2\omega, \quad (4)$$

where:

$w$ – is well width;

$\lambda_{\min}$ – lower frequency limit.

Calculations of well depth, lower frequency limit, higher frequency limit of diffusors based on Eqs. (1–4), are demonstrated in the Table 1.

According to calculation for design frequency 500 Hz all diffusors have well width of diffusor 9.4 cm, theoretical working range low frequency 375 Hz, higher frequency 1824.8 Hz. The maximum value of depth sequence 29.8 have a diffusor N 17. The minimum values of depth sequence 1.5 cm have a construction of N 23. Another construction what has been chosen for researches is that having width of diffusers of 1 m, different prime number (N 7, N 11, N 13, N 17, N 19, N 23) and different design frequency, which are shown in the Table 2.

Diffusor N 7 have a well width, design frequency 330 Hz, a lower frequency limit 247.5 higher frequency limit 1204.4. The maximum value of depth sequence 32.4 have a diffusor N 17. The minimum values of depth sequence 0.7 have a construction of N 23. Diffusor N 11 have well width 7.7 cm design frequency 616 Hz, a lower

Table 1. Well depth calculation results for the QRD, design frequency 500 Hz

| Wells number | Order number | | | | | |
|---|---|---|---|---|---|---|
| | N 7 | N 11 | N 13 | N 17 | N 19 | N23 |
| | Depth sequence, cm | | | | | |
| 1 | 4.9 | 3.1 | 2.6 | 2 | 1.8 | 1.5 |
| 2 | 19.7 | 12.5 | 10.6 | 8.1 | 7.3 | 6 |
| 3 | 9.8 | 28.2 | 23.8 | 18.2 | 16.3 | 13.5 |
| 4 | 9.8 | 15.7 | 7.9 | **32.4** | 29 | 24 |
| 5 | 19.7 | 9.4 | 31.8 | 16.2 | 10.9 | 3 |
| 6 | 4.9 | 9.4 | 26.5 | 4.1 | 30.8 | 19.5 |
| 7 | 0 | 15.7 | 26.5 | 30.4 | 19.9 | 4.5 |
| 8 | | 28.2 | 31.8 | 26.3 | 12.7 | 27 |
| 9 | | 12.5 | 7.9 | 26.3 | 9.1 | 18 |
| 10 | | 3.1 | 23.8 | 30.4 | 9.1 | 12 |
| 11 | | 0 | 10.6 | 4.1 | 12.7 | 9 |
| 12 | | | 2.6 | 16.2 | 19.9 | 9 |
| 13 | | | 0 | **32.4** | 30.8 | 12 |
| 14 | | | | 18.2 | 10.9 | 18 |
| 15 | | | | 8.1 | 29 | 27 |
| 16 | | | | 2 | 16.3 | 4.5 |
| 17 | | | | 0 | 7.3 | 19.5 |
| 18 | | | | | 1.8 | 3 |
| 19 | | | | | 0 | 24 |
| 20 | | | | | | 13.5 |
| 21 | | | | | | 6 |
| 22 | | | | | | 1.5 |
| 23 | | | | | | 0 |
| Total wide, cm | 65.8 | 103.4 | 122.2 | 159.8 | 178.6 | 216.2 |

Table 2. Well depth calculation results for QRD, 1 m

| Wells number | Order number | | | | | |
|---|---|---|---|---|---|---|
| | N 7 | N11 | N 13 | N 17 | N 19 | N 23 |
| | Depth sequence, cm | | | | | |
| 1 | 7.4 | 3 | 2.2 | 1.3 | 1 | 0.7 |
| 2 | **29.7** | 11.9 | 8.6 | 5.1 | 4.1 | 2.7 |
| 3 | 14.9 | 26.8 | 19.4 | 11.4 | 9.2 | 6.1 |
| 4 | 14.9 | 14.9 | 6.5 | 20.3 | 16.3 | 10.9 |
| 5 | **29.8** | 8.9 | 25.8 | 10.1 | 6.1 | 1.4 |
| 6 | 7.4 | 8.9 | 21.5 | 2.5 | 17.3 | 8.8 |
| 7 | 0 | 14.9 | 21.5 | 19 | 11.2 | 2 |
| 8 | | 26.8 | 25.8 | 16.5 | 7.1 | 12.3 |
| 9 | | 11.9 | 6.5 | 16.5 | 5.1 | 8.2 |
| 10 | | 3 | 19.4 | 19 | 5.1 | 5.4 |

End of Table 2

| Wells number | Order number | | | | | |
|---|---|---|---|---|---|---|
| | N 7 | N11 | N 13 | N 17 | N 19 | N 23 |
| | Depth sequence, cm | | | | | |
| 11 | | 0 | 8.6 | 2.5 | 7.1 | 4.1 |
| 12 | | | 2.2 | 10.1 | 11.2 | 4.1 |
| 13 | | | 0 | 20.3 | 17.3 | 5.4 |
| 14 | | | | 11.4 | 6.1 | 8.2 |
| 15 | | | | 5.1 | 16.3 | 12.3 |
| 16 | | | | 1.3 | 9.2 | 2 |
| 17 | | | | 0 | 4.1 | 8.8 |
| 18 | | | | | 1 | 1.4 |
| 19 | | | | | 0 | 10.9 |
| 20 | | | | | | 6.1 |
| 21 | | | | | | 2.7 |
| 22 | | | | | | 0.7 |
| 23 | | | | | | 0 |
| Total wide, cm | 100 | 100 | 100 | 100 | 100 | 100 |

frequency diffusion limit 393.8, higher frequency limit 1916.1 Hz. Diffusor N 13 have well width 9.1 cm design frequency 525 Hz, a lower frequency diffusion limit 462 Hz, higher frequency limit 2248.2 Hz. Diffusor N 17 have a have well width 5.9 cm design frequency 800 Hz, a lower frequency diffusion limit 600 Hz, higher frequency limit 2919.7 Hz. Diffusor N 19 have a well width 5.3 cm, design frequency 890 Hz lower frequency diffusion limit 667.5 Hz, higher frequency limit 3248.2 Hz. Diffusor N 23 have a well width 4.3 cm, design frequency 1100 Hz lower frequency diffusion limit 825 Hz, higher frequency limit 4014.6 Hz.

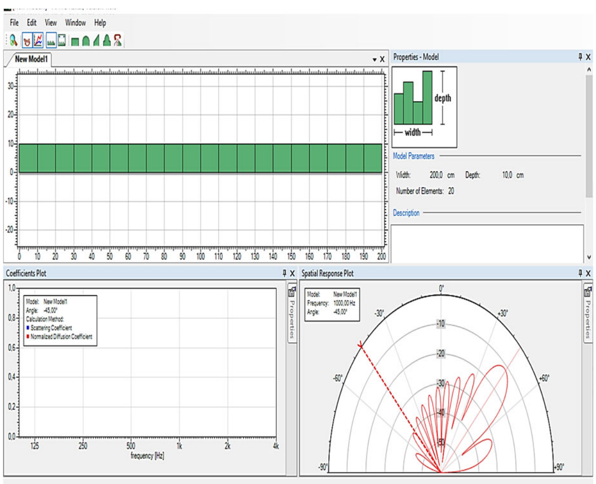

Figure 4. AFMG Reflex program for the room acoustic modelling

The acoustic software Reflex was used to model the diffusion of sound wave. Reflex window shown in Figure 4.

In the AFMG Reflex window the impute data is the initial number of diffuser elements and their properties such as a width a, depth b, and depth c, dimensions. AFMG Reflex will begin to calculate the diffusion, reflection, and scattering results for this model.

The numerical method calculates diffusion properties of the surface based on the Boundary Element Method (BEM). The reflective properties are displayed as a polar response graph for any angle of incidence and frequency of a sound wave. The scattering and diffusion coefficients are displayed as frequency response graphs). The calculation of the diffusion coefficients is according to Cox and D'Antonio and to the ISO 17497-2 standard (AFMG, 2019; Cox & D'Antoni, 2004; ISO 17497-2, 2012; Bansal, Feistel, Ahnert, & Bock, 2007).

## Results

The results of software simulation Reflex of the scattering coefficient and the normalized diffusion coefficient of diffusers in the frequency range of 100 to 4000 is present. Design frequency sound diffusion and scattering coefficients measured by 1/3 octave bands are plotted as a function of frequency.

According to the data analysis, the scattering coefficient increases significantly at high frequencies (Figure 5). The scattering increased in the frequency of 400 Hz for all diffusers. The scattering coefficient decreased in low frequency.

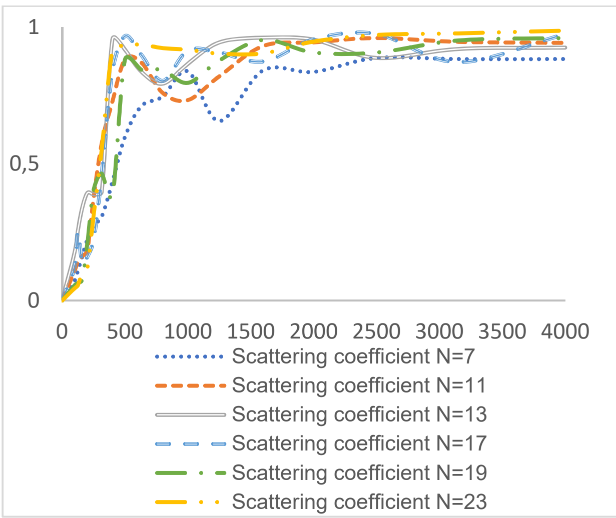


Figure 5. The scattering coefficient spectrum for the QRD with different number of sequences (design frequency 500 Hz)

Scattering coefficient only depends on energy movement away from a particular direction, and not on how this scattered energy is redistributed. Height values of scattering coefficients can be obtained by adding additional sequences. An increment in the number of sequences of the diffuser leads to an increasing value of sound scattering at the design frequency. The free field scattering coefficient is given by the sum of the reflection coefficients in square – there is no dependence on the order of the wells in the diffuser. The maximum value of scattering has a diffusor N 23 (0.99). One peak of decreasing of scattering has a diffuser N 7 at 1250 Hz (0.65). Diffuser N 7 have a lowest results of scattering coefficient there is a tendency for decreasing scattering coefficient with decreasing number of sequences. High scattering coefficient showed diffusers on the highest frequencies.

Figure 6 shows the normal diffusion coefficient in the frequency ranges of 100 Hz to 4000. Normalized diffusion coefficient was plotted for 6 samples of different sequences QRD. The normalized diffusion coefficient helps to predict the performance of surface geometry. Normalized diffusion coefficient shows diffusion filled QRD. There are significant peaks (minimum or maximum value of diffusion in some point in the graphics) occurring in the frequency spectrum. This is consistent with the operational characteristics of a QRD in which well resonances take place at various frequencies corresponding to the well depth sequence. The value of normalized diffusion increased at middle frequencies and showed good diffusion results. One peak of decreasing diffusion has a diffusor N 13 at 1000 Hz (0.133). Diffusor N 11 has the highest value of diffusion (0.61) at 800 Hz. The diffusive field is similar for all diffusers and not related to a number of sequences. At many frequencies, the QRD is diffusion considerably sound energy from the specular zone, but not evenly.

Results of software simulation of the scattering coefficient of constructions of width of 1 m in the frequency range of 100 to 4000 (Figure 7). Sound diffusion and scattering coefficients measured by 1/3 octave bands are plotted as a function of frequency.

The constructions of 1 m width have a peak of scattering in the design frequencies in comparison with constructions where design frequencies 500 Hz peak of scattering for all diffusers in the 500 Hz. The heigest scattering value have diffusor N 17 (0.98) Diffusor N 23 has the lowest value of scattering at low frequencies. Construction which has the highest well width has a better scattering value at low frequencies. With decreasing well width of diffusers scattering coefficient increasing at high frequency. Diffusor N 7 and N 11 have a higher value of scattering in the middle frequencies of 250 Hz (0.8).

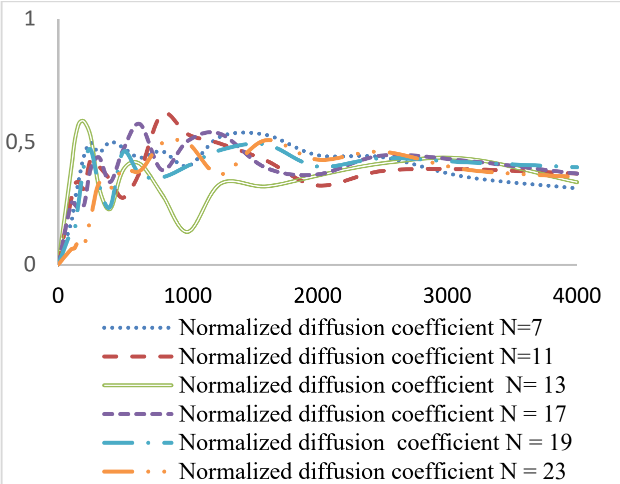


Figure 6. The normalized diffusion coefficient for the QRD with different number of sequences (design frequency 500 Hz)

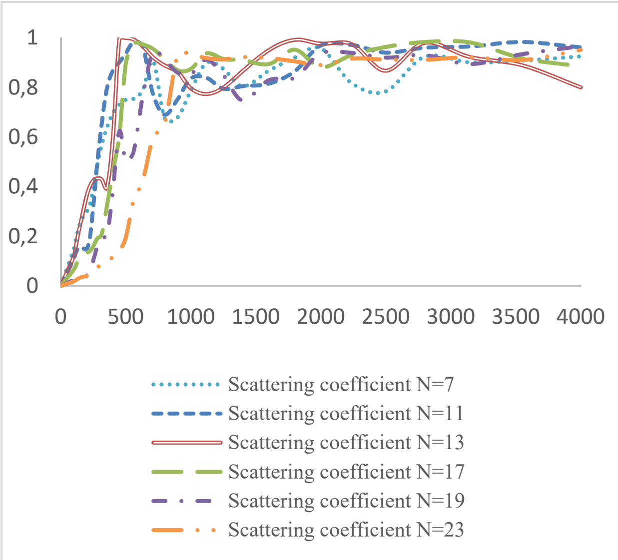


Figure 7. The scattering coefficient for the QRD with different number of sequence (width of 1 m)

Figure 8 shows the normalized diffusion coefficient of QRD of total well width of 1 m. The difference between all constructions is the frequencies' scattering range. All diffusers have better diffusion in different frequencies related to design frequency. Diffusors N 13 and N 11 have the highest value 0.6 in frequency of 200 Hz and 900 Hz. Diffusers of 1 m wide have fewer peaks than diffusers which have a design frequency of 500 Hz. Diffusor number 23 has the lowest value of the diffusion coefficient of 100 till 710 frequency competition with another diffuser. This lowest value of diffusion construction N 23 can be related to the lowest value of the well width.

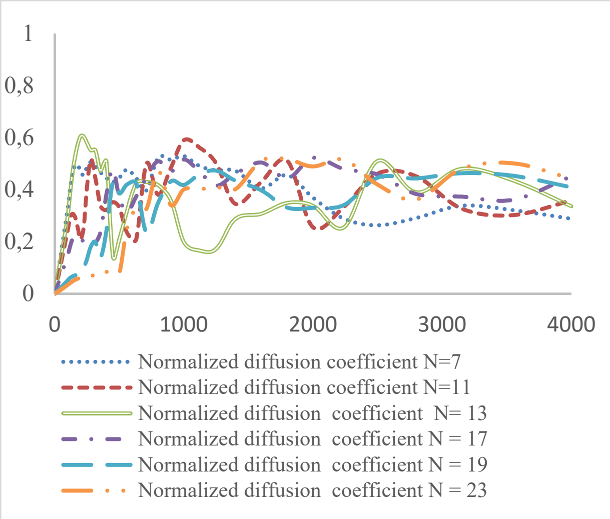


Figure 8. The normalized diffusion coefficient for the QRD with different number of sequence (width of 1 m)

## Conclusions

QRD has been researched using a Boundary Element Method (BEM) in modelling acoustic software AFMG Reflex. Quadratic residue diffusers showed the high-performance distribution of sound energy. A one-dimensional diffuser was calculated considering examples of diffusers with a quadratic residue. The sound energy is evenly dispersed. Diffusors which had different total well widths had a high scattering coefficient. The maximum scattering coefficient (0.99) has a diffuser with 23 number of sequences design frequency 500 Hz and diffuser N 17 (0.98) diffusor width 1 m. As the number of wells is increasing, the effectiveness of the diffusion increases either in the same design frequency. High diffusion can be realized with every depth sequence though. Choice sequence depends on the working range and design frequency. Choosing different depth sequences will change both ends of the working range. The best option for expanding the working range of a diffuser is to choose a higher N-number, but at the same time, the width of the wells should not be too small because it decreases scattering. When choosing a diffuser, it is important to determine the theoretical effective frequencies range.

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## GARSO SKLAIDOS IR GARSO DIFUZIJOS KOEFICIENTO TEORINIS PROGNOZAVIMAS NAUDOJANT KVADRATINĮ DIFUZORIŲ

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Santrauka

Kvadratinis difuzorius – įrenginys, kuris paskirsto intensyvių atspindžių akustinę energiją erdvinės ir laiko dispersijos būdu. Įrenginys susideda iš skirtingų gylių bet to paties pločio langelių. Optimalus paskirstymas yra labai svarbus norint suvokti garsą patalpose ir pašalinti nepageidaujamus akustinius efektus, tokius kaip aidėjimas. Šiame straipsnyje pateikiamas kvadratinių difuzorių modeliavimo metodas. Gautas teorinio modeliavimo rezultatas esant 500 Hz dažniui. Dizfuzoriaus langelių plotis yra 9,4 cm. Ištirti įvairių skaičiaus difuzinių langelių garso sklaidos ir difuzijos koeficientai. Buvo nustatyta, kad padidėjęs difuzoriaus elementų skaičius lemia garso difuzijos padidėjimą numatomame dažnyje, esant tos pačios sekos pločiui.

**Raktiniai žodžiai:** kvadratinis difuzorius, difuzija, garso sklaidos koeficientas, garso difuzijos koeficientas, AFMG Reflex.