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Technical Notes

The Effect of Geometrical and Material Modification of Sound Diffusers on Their Acoustic Parameters

Adam PILCH, Tadeusz KAMISIŃSKI

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: apilch@agh.edu.pl

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Sound diffusers, in particular those based on changes in the phase of the reflected wave (Schroeder diffusers), have recently gained greatly in popularity in acoustics as an effective means to eliminate defects and improve the acoustic performance of interiors. This paper draws attention to a possibility of shaping acoustic parameters of sound diffusers and fundamental errors made in applying diffusers. Also, an often neglected issue of sound absorption by diffusers has been tackled. The presented results of laboratory measurements indicate a great significance of the diffusers' rigidity and geometry on their absorption coefficient at low frequencies. The effect of arrangement of elements on the diffusion coefficient was analysed for two types of elements based on the prime number $N = 7$.

Keywords: Schroeder diffusers, scattering, diffusion, absorption.

1. Introduction

The chief task of acoustic engineers in developing guidelines on modification of interiors is to eliminate acoustic defects and to shape acoustic parameters depending on the purpose and volume of the space in question. The phenomenon of single or flutter echoes can be eliminated by reducing the energy reflected specularly. The use of absorbing elements at the rear wall of a concert hall allows for elimination of the echo heard by artists on the stage, but is disadvantageous in the case of large spaces, as it reduces the acoustic energy reaching the audience. This results in a decrease in the values of the reverberation time and sound strength G. In auditoria, an excessive reduction of these parameters leads to poorer speech intelligibility due to too small sound volume in the back of the room (Kamisiński, 2010). Eliminating defects while conserving the acoustic energy is possible when sound diffusion is applied. Reflection of acoustic waves in a direction other than specular is the easiest way to eliminate an echo caused by, for instance, reflection from the rear wall of the room. Directing the reflected wave in many directions, as is the case with a reflection from a cylindrical surface, allows for a better distribution of acoustic energy in the room. The sound diffuser based on a change in the phase of the reflected wave, which was introduced in the 1970s, causes not only spatial, but also temporal dispersion of the latter. The listener then receives many reflections of smaller energy, causing a subjective impression of an increased volume of the room.

2. Acoustic parameters of sound diffusers

Acoustic materials and systems used to modify interiors can be described by three independent acoustic parameters. The oldest and most widely used is the sound absorption coefficient α. It is determined based on measurements conducted in accordance with the PN-EN ISO 354:2005 standard. Sound diffusers are usually made of hard materials, so that their sound absorption is minimal. In the case of Schroeder diffusers it was observed that for some frequencies sound absorption is much greater than it is apparent from the material's properties. Theoretical analysis supported by experimental results showed that absorption was related to the flow of acoustic energy between the upper parts of the diffuser wells (Fujiwara *et al.*, 1992; Kuttruff, 1994; Mechel, 1995)

Sound scattering coefficient is defined by the ISO 17497-1 standard (2000) (based on Mommertz, Vorländer, 1995) as the ratio of the reflected energy in non-specular directions to the total energy reflected from the surface:

$$s = \frac{\alpha_{\text{spec}} - \alpha}{1 - \alpha}, \tag{1}$$

where s is the scattering coefficient, α is the absorption coefficient and α_{spec} is the specular absorption coefficient (the same as α when $s = 0$).

Figure 1 presents a definition of the sound scattering coefficient.

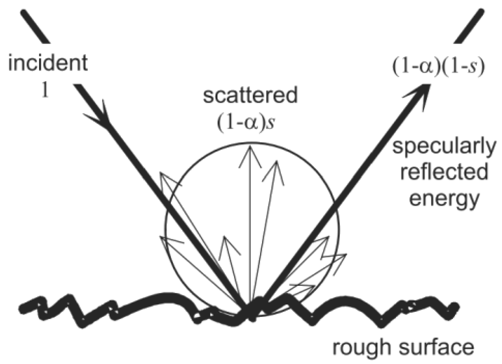

Fig. 1. Definition of the sound scattering coefficient (Cox, Dalenback, 2006).

Measurements of the scattering coefficient are carried out in the reverberant field and involve averaging of impulse responses at different angular positions of a circular sample. In this way one can quickly obtain the value for a random direction of incidence of the sound wave. The thus determined sound scattering coefficient is used by computer programs to predict the acoustic parameters of rooms.

The quality of sound wave reflections from a surface is determined by the diffusion coefficient defined in the draft ISO 17497-2 standard (2005), and was first introduced by (AES-4id, 2001):

$$d_\theta = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n} (10^{L_i/10})^2}{(n-1)\sum_{i=1}^{n} (10^{L_i/10})^2}, \tag{2}$$

where d_θ is the diffusion coefficient for the angle θ, L_i is the sound pressure level for i-th position of the receiver, and n is the number of receiver points.

The measurement, which is performed in the free field, determines the uniformity of the reflected wave characteristics. This parameter is used in the design of sound diffusers. A sample of a relatively small surface area is required for the measurements. This parameter is very sensitive to any deviations from non-uniformity of reflection in contrast to the scattering coefficient, which usually depends only on the depth of surface irregularities. The diffusion coefficient is of great importance in small rooms where precise distribution of reflected sound is vital.

The most commonly used diffusers based on the change in the phase of reflected sound waves are composed of wells whose depths constitute a random sequence. Most commonly used is the quadratic residue sequence s_n based on the prime number N:

$$d_n = \frac{s_n c}{2Nf_0}, \tag{3}$$

where f_0 is the lower frequency limit and c is the speed of sound.

A theoretical model allowing for determination of the sound diffusion coefficient assumes that only plane waves propagate down the well. Therefore, the upper frequency limit was adopted as that of a wave whose length equals a double well width. Above this frequency the structure also scatters sound, but with less efficiency. In view of these relationships there was a trend to build very deep and narrow wells which were intended to extend the diffuser's operating frequency range. Note that the system can only work for wavelengths smaller than the width of one period of the sequence. For the prime number 7, it is not possible to design an effective diffuser that would operate over more than 2 octaves. The prime number $N = 17$ allows for a frequency range of over 3 octaves. Diffusers based on large prime numbers, however, are much more difficult to build and yield a lower diffusion coefficient (Pilch *et al.*, 2011).

When designing diffusers for listening rooms or other small spaces, special attention should be paid to maintaining a minimum distance between the listener and the diffuser. To obtain the assumed sound diffusion, the listener must be at a distance equal to at least 3 wavelengths of the lowest diffused frequency. At shorter distances the effect produced by the wells is more local, and significant irregularities in the distribution of acoustic energy may occur.

Each wave whose half-length is smaller than the size of irregularities of the surface will be directed or reflected in different directions, i.e., scattered – according to the definition of the scattering coefficient. The scattering coefficient does not differentiate between the redirection of sound, as is the case where a flat panel is tilted at a certain angle, and differently directed reflections. It does not matter in the cases where the echo is cancelled. It is not important how the acoustic energy directed specularly is eliminated. What matters is that the sound of high energy concentrated in time should not return to the sender.

The main limitation of application of the sound scattering coefficient is that there are currently no reliable formulae allowing for its prediction, as is the case with the diffusion coefficient. Attempts to convert the value of the directional scattering coefficient only in some cases give results that agree with actual values. The lower frequency limit is usually half the value of the diffusion coefficient. The upper frequency limit is assumed to have the same value in the case of the diffusion coefficient. Above this frequency sound may be redirected instead of being diffused. But this is not reflected by the value of the scattering coefficient. For frequencies above 4 kHz, the scattering coefficient is often greater than 1. This is due to edge effects and air fluctuations caused by the movement of the turntable (Batko *et al.*, 2008). Even minor changes in the air temperature may change the time in which successive reflections reach the receiver, which significantly increases the scattering coefficient determined. In programs that simulate acoustic parameters of rooms, the scattering coefficient values must always be confined in the range from 0 to 1, as only such values have physical meaning.

3. Effect of material and construction on the sound absorption coefficient

When designing a sound diffusers, special attention should be paid to construction materials and precise workmanship. Scattering systems can be made of any hard material that does not absorb sound. In the case of low-frequency structures, it can even be built of properly arranged concrete blocks. The most commonly used construction material is wood and wood-based materials such as MDF. Especially in the case of QRD diffusers with wells separated by fins, it is very important that the surface is hard and free of pores. The benefit of coating the surface with paint is a reduction in the sound absorption coefficient as it can be seen in Fig. 2.

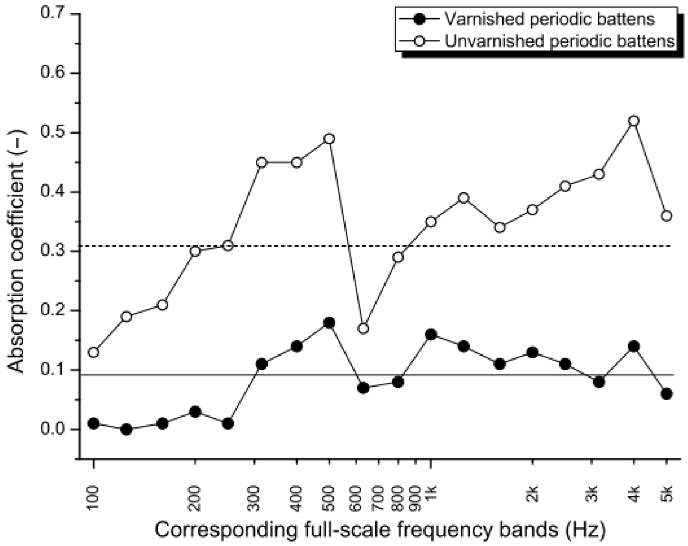

Fig. 2. The absorption coefficient of a wooden diffuser: varnished and unvarnished (Choi, Jeong, 2011).

Stiffness of scattering structures is also of great importance. These are usually spatial structures, so, in order to reduce weight and manufacturing costs, manufacturers tend to introduce elements of low weight and thus susceptible to excitation by acoustic waves. Fins between the wells and well bottoms have the greatest surface area in the diffuser, so the material from which they are made is of an utmost importance. Quadratic residue diffusers (QRD) with the same geometry (Fig. 3) but made of different materials were examined. Figure 4 compares absorption coefficients of the systems made of polyethylene (QRD 150 PE) and MDF panel (QRD 150 MDF). A reduction in absorption can be seen especially at low frequencies. Further reduction was possible by stiffening the structure by carefully gluing the elements in contact with each other. Places with the lowest stiffness were reinforced by adding 1 cm thick bars every 20 cm, placed in the deepest wells connecting two adjacent fins. Such improvements reduced the average absorption coefficient of an $N = 7$ QRD diffuser by about 20% (QRD 150

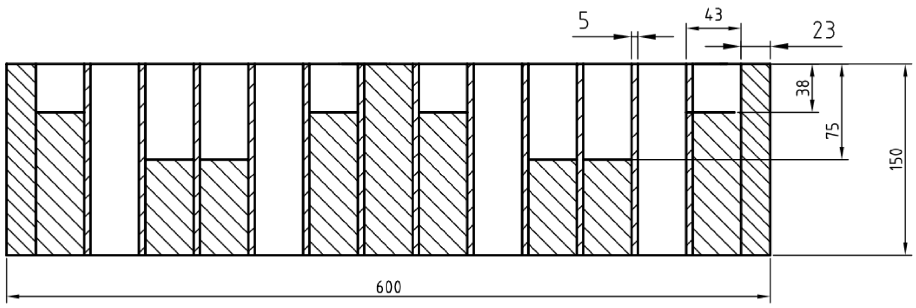

Fig. 3. QRD 150 diffuser's cross-section.

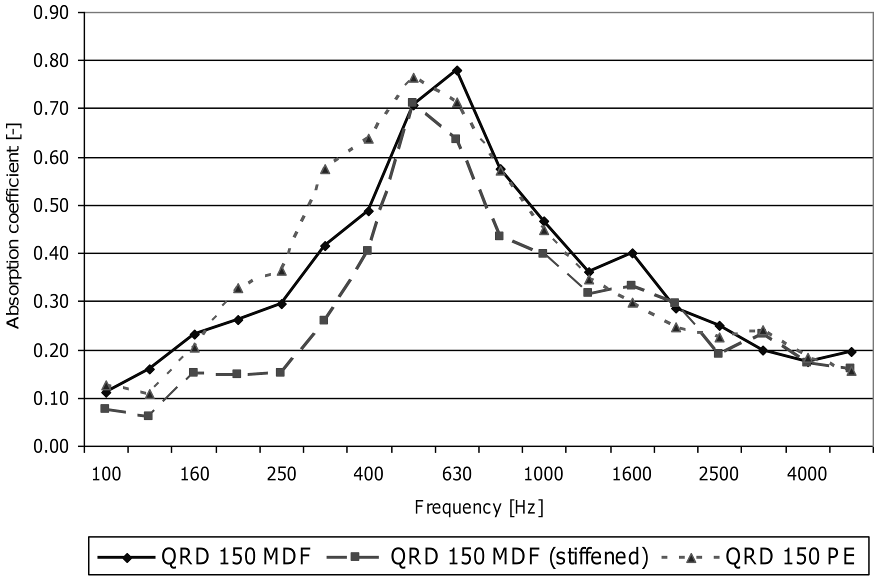

Fig. 4. The effect of stiffness and accuracy of workmanship of the diffuser on its sound absorption coefficient.

MDF in Fig. 4). For the frequency range of 500–630 Hz, in spite of a high stiffness of the material, the sound absorption coefficient was greater than 0.6. The system was designed as a diffuser, so absorption of sound was in this case unwanted. For the measurement of the scattering coefficient, the ISO 17947-1 standard allows only measurements at the absorption coefficient α below 0.5 throughout the frequency range. The scattering coefficient determined at α greater than 0.5 is very sensitive to changes in absorption and may assume values above 1.0.

The high absorption coefficient of diffusers operating on the principle of phase change of reflected sound was first observed by Fujiwara and Miyajima (1992). Initially it was maintained that the high absorption results from inaccurate workmanship of the diffuser. Kuttruff (1994) tried to explain it by the air flow between adjacent wells. The results obtained from the Kuttruff model, who assumed that the total sound pressure at the surface of the diffuser is fixed, were consistent with Fujiwara's measurements only for unrealistically narrow wells. In (Mechel, 1995) the effect of absorption in the near-field and reflection directivity in the far field were described. Sound pressure distribution of the reflected wave can also be computed by the inverse Fourier transform from their spatial spectra on the diffuser's plane, using a method developed in electrostatics (Tasinkevych, 2010).

As shown in (Wu *et al.*, 2000), it is possible to design such a sequence where, by proper selection of the well depths, the diffuser will have the highest possible absorption in a wide frequency range. Thus, it is possible to obtain a structure whose high diffusion will be combined with a small sound absorption. The easiest way to reduce absorption is to reduce the depth-to-width ratio for a single well. Changing the ratio from 3.5 (QRD 150 PE in Fig. 5) to 2.4 (QRD 130 PE) and then to 2.0 (QRD 110 PE) helped to reduce the absorption coefficient, especially for low and medium frequencies. The reduction in absorption was achieved at the expense of a lower diffusion at high frequencies. It is possible to improve the performance of the diffuser, while retaining its broad-band character, by using a stiffer material and by optimisation of the depths of the diffuser wells.

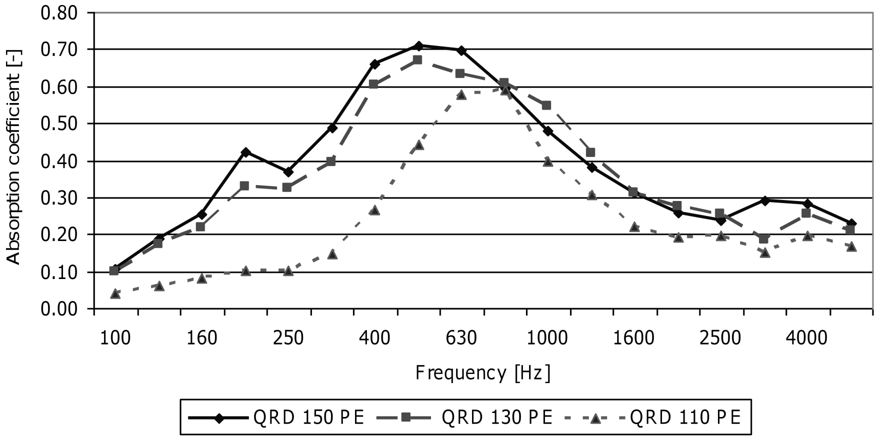

Fig. 5. The effect of QRD's depth on the absorption coefficient.

In the case of designing a cylindrical surface, the rigidity of the material also has a significant effect on the absorption coefficient α. Figure 6 shows absorption

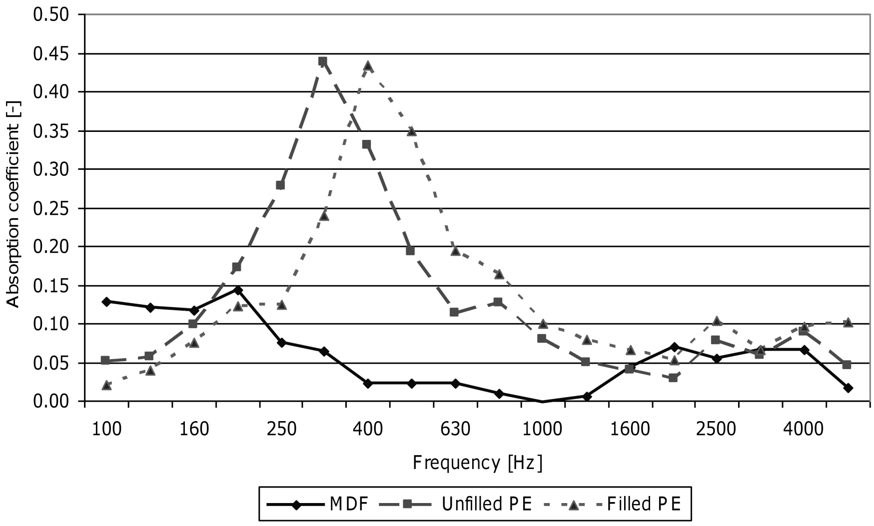

Fig. 6. The effect of the construction material on the absorption coefficient of a cylindrical diffusing element.

coefficients of a cylindrical surface made of an about 40 mm thick MDF panel and a curved 5 mm thick polyethylene panel. In the range of 200–500 Hz, the sound absorption coefficient increased (to 0.44 at 315 Hz in Fig. 6). As a result of filling the structure with polyurethane foam, the resonant frequency shifted towards higher frequencies but the values of the coefficient remained at similar levels. The use of cylindrical diffusers of polyethylene foam or other lightweight material can be justified only in cases where a higher absorption coefficient is allowed for low frequencies, and where mobility of the product is of a key importance.

4. The effect of a mutual arrangement of diffusers on the effectiveness of diffusion

Sound diffusing structures show the highest efficiency, especially when it comes to the diffusion coefficient, where a single element is used. Each repetition of the surface structure leads to deteriorated directional characteristics of the reflected sound. This is particularly evident in cylindrical surfaces (Fig. 7), where the system consisting of one segment of a cylinder gives a broadband diffusion, and the diffusion coefficient can even take the value $d = 0.6$. When using a structure consisting of two segments of a cylinder, the diffusion coefficient d decreased to a value $d = 0.4$ to reach a clear minimum at a frequency of 1600 Hz. Introduction of additional cylindrical surfaces leads to a further deterioration of the directional uniformity of reflection, but it is usually necessary in practical applications.

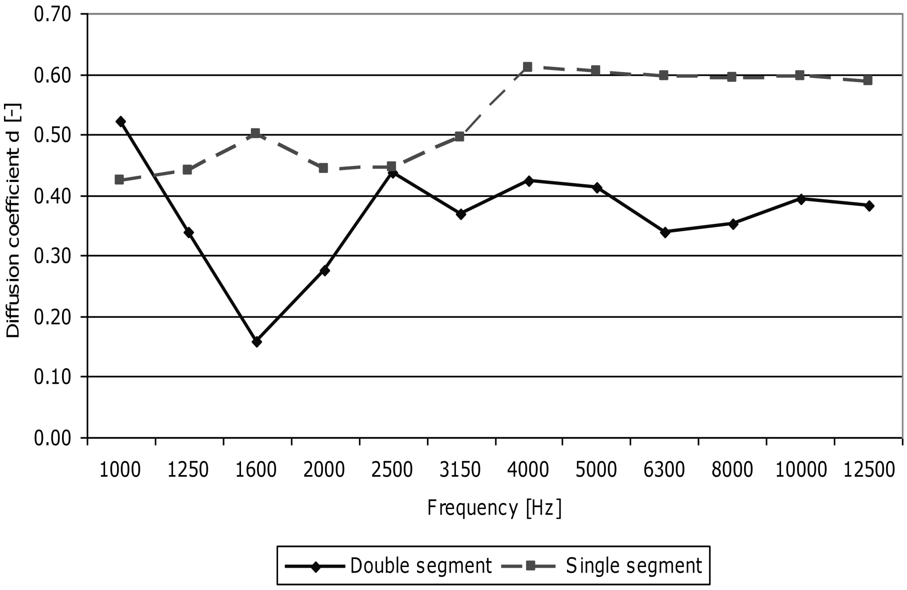

Fig. 7. Diffusion coefficient for one and two cylinder segments of the same total dimensions.

Similar phenomena occur in Schroeder diffusers. Application of a single sequence of pseudo-random numbers gives better results than duplicating this sequence. Introduction of a random sequence periodicity deteriorates the characteristics of reflection, which in extreme cases may have only a few dominant directions. To demonstrate the effect of arrangement of diffusers on the effectiveness of sound diffusion, measurements were conducted for 20 combinations of an arrangement of 4 elements with dimensions of 30 cm × 30 cm and a maximum well depth of 7.5 cm. Two types of diffusers based on the prime number $N = 7$ were used: $s_n = \{1, 4, 2, 2, 4, 1, 0\}$ and the inverse sequence $s_n = \{6, 3, 5, 5, 3, 6, 7\}$. Schematic representation of selected options is shown in Fig. 8. The results obtained are very similar for both structures in the same arrangement, which demonstrates reproducibility of the method within the series of conducted measurements.

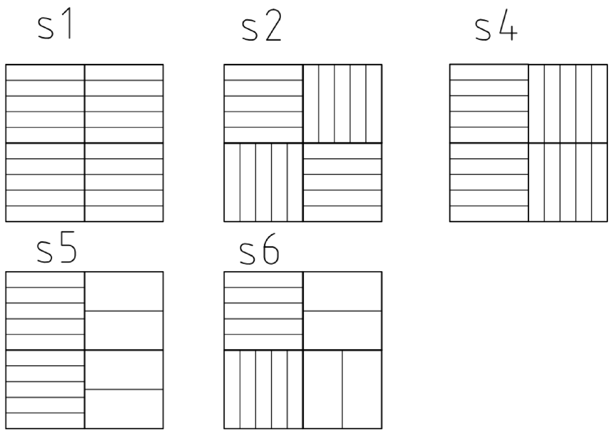

Fig. 8. Selected options of QRD arrangement for determining the diffusion coefficient.

The use of one type of diffuser (measurements s1, s2 and s4 in Fig. 9) gives lower values of the diffusion coefficient than both types (measurements s5 and s6) are used. This can be observed especially for the lower frequency limit, which in the latter case is shifted an octave down (from 4000 Hz to 2000 Hz). The high value of the lower frequency limit resulted in this case from a small prime number ($N = 7$) and narrow wells, and, therefore, the condition that the width of the system should be greater than the wavelength of the lowest frequency wave was not met. The use of both types of systems allowed to obtain a high diffusion at frequencies below the lower frequency limit ($d = 0.59$ for $f = 2000$ Hz, while $f_d = 2340$ Hz). As the two-dimensional diffusers are more expensive to manufacture than one-dimensional ones, it is very frequent in practical applications that one-dimensional structures are arranged to ensure diffusion in two planes (s2, s4, and s6 in Fig. 9). In arrangements composed of one type of diffuser, the very common checkerboard arrangement (s2) yielded significantly lower diffusion values than the one-dimensional diffuser s1 or a two-dimensional with a differ-

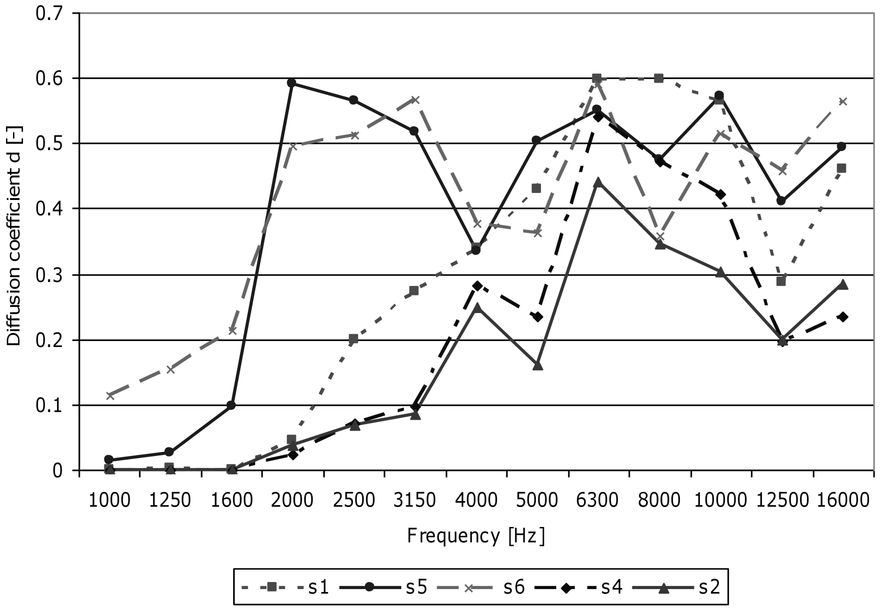

Fig. 9. Normalized diffusion coefficients for different arrangements of QRD samples.

ent arrangement (s4). Of all the arrangements, the highest values were obtained for the s5 (one-dimensional scattering) and for s6 (two-dimensional scattering). Especially the s6 arrangement is very advantageous in practical applications on side walls, where the bottom row diffuses in the horizontal plane. The top row, which is usually above the heads of the audience, diffuses sound in the vertical plane, and thus some part of the acoustic energy comes back towards the audience.

5. Summary

The article presents the basic issues and limitations associated with formation of acoustic parameters of sound diffusers. The presented results indicate that:

- The material, in particular, rigidity and precise workmanship of the outer layer, very strongly affects the absorption coefficient α of diffusers;
- A diffusers operating on the principle of changes of the phase of the reflected sound strongly absorb sound at low frequencies. A reduction in the well depth-to-width ratio, or appropriate selection of the sequence of well depths, allows for a reduction in sound absorption;
- Alternate arrangement of diffusers of the same type aimed at obtaining two planes of sound diffusing (the chequered arrangement) is unfavourable;
- If possible, at least two types of sound scattering regimes should be used to increase their effectiveness;

- QRD scattering regimes, when used in large buildings, should be positioned at small distances from the listeners (side walls, walls of the stage, stage shells, rear wall). The use of excessive numbers of diffusers can lead to an uncontrolled increase in sound absorption without the benefit of improved scattering of the acoustic field;
- In small rooms, a minimum distance limit $d > 3\lambda$ should be observed. If this distance is not feasible, a scattering structure operating on the principle of a change in the amplitude of the reflected sound (such as a BAD panel) or the use of sound absorbing material should be considered.

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