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ROOM ACOUSTICS DIFFUSERS: PYRAMIDS AND WEDGES

Trevor J. Cox

University of Salford, Acoustics Research Centre, Salford, UK
email: t.j.cox@salford.ac.uk

Simple surfaces such as pyramids and triangular prisms are used in performance spaces to create reflections that are less specular. They have also been suggested as a way of creating reflection free zones in studios. There is surprisingly little information about the reflection properties of these surfaces, however, and consequently limited design guidance. Simple geometric models applicable to high frequencies have previously established that depending on the angle between adjacent pyramids or triangular prisms, these surfaces can create dispersion or produce a reflection as strong as a flat surface. Without careful thought, these surfaces can fail to create any diffuse reflections. A new study has been carried out into triangular prisms using 2D Boundary Element Methods (BEMs) to begin developing better guidelines. A thousand different diffusers have been examined that have various depths and amounts of asymmetry. Both periodic and modulated arrays have been tested for normal, oblique and random incidence. For very shallow devices, the scattered polar responses show a broadening of the major reflected lobe, but the diffusion coefficient plateaus and never achieves a large value. These shallow devices seem to be good candidates for surfaces to mildly reduce specular reflections. Whether the prisms are asymmetric or symmetric makes little difference to performance in this case. For deeper devices, asymmetry is needed. When the prism width is twice its depth, then a pair of symmetric prisms creates a corner reflector that creates specular reflections. In this case a very asymmetric shape is best. An unsurprising result for normal incidence, perhaps, but the same is true for oblique and random incidence.

Keywords: architectural acoustics, diffusers, triangles, pyramids, BEM

1. Introduction

Geometric diffusers are commonly used in architecture. Angled surfaces such as triangular prisms and pyramids can display a wide variety of scattering behaviour, ranging from a good diffuser to a surface that generates specular reflections. The reflection from an array of prisms or pyramids is very much determined by the steepness of the side slopes and how neighbouring sections interact. For simplicity, the analysis below only considers a 2D case with triangles, but the findings should be easily extended to 3D surfaces, such as pyramids.

A simple ray tracing can help understand how a triangle reflects sound at high frequency, as Fig. 1 shows. For normal incidence, as the angle (χ) of the triangle varies, the reflection characteristic shifts between a notch where little sound is reflected in the normal direction, diffuse reflection and a specular reflection. Some of the general design rules that are applied to cylinders and Schroeder diffusers do not always apply to prisms, because each triangle creates strong reflections in two directions rather a general dispersion, and there can be strong interaction between neighbouring triangles.

The application of a geometric modelling technique to diffusers is problematic, however, because for some frequencies the surface roughness will be a similar size to the wavelength. At this point diffraction effects will become important, and these cannot be modelled by ray tracing. Furthermore, geometric models will fail to explain behaviour such as grating lobes that rely on modelling the wave properties of sound. For this reason, a study has been carried out using 2D Boundary Element Methods (BEMs) to better understand the reflections from triangular prisms. A thousand different diffusers have been examined that have various depths and amounts of asymmetry. Both periodic and modulated arrays have been tested for normal, oblique and random incidence. Normal and oblique incidence are examining the case where the location of the primary source that the diffuser has to disperse is known. Random incidence is examining a more general purpose diffuser.

2. Method

The BEM was a solution of the Helmholtz–Kirchhoff integral equation, with details given in reference [2]. These have been validated against measurement for a wide variety of diffuser shapes. The surface is assumed to have a surface admittance of zero. Above 440 Hz, a thin-panel solution based on an extrusion of just the front corrugated surface was used to speed calculations.

The base width w of each triangle was 60 cm. Nine different depths D were analysed, ranging from 2.5 cm to 40 cm. Moving the apex of the triangle by distance x allowed the angles of the sides to be varied from a completely symmetric shape (isosceles triangle) to something with asymmetry. Fifty different positions of the apex were created for each depth. 7 triangles were placed side by side as shown in Fig 2. In some predictions the triangles were arranged in a strict periodic arrangement (Fig. 2a), in others some of the triangles were flipped to form a modulated array (Fig. 2b). Modulation is examined because it has been shown to improve the dispersion of sound be reducing grating lobes. A number sequence known to have minimal sidelobes in the autocorrelation was used [2].

The reflection for nine frequencies within each one-third octave from 100 to 5000 Hz were calculated. These allowed the one-third octave polar responses to be estimated. From there, the normalised diffusion coefficient was calculated according to ISO 17497-2:2012 [4]. There were 91 receivers on a semi-circle 10 m from the middle of the array. Normal, oblique (45°) and random incidence were all examined. Random incidence was estimated by averaging the scattered intensity for 8 incident angles evenly spaced from -72° to +72° - as this is a 2D simulation Paris' formulation was not applied. For normal incidence the source was 20 m from the surface, for other cases it was 10 m from the triangles.

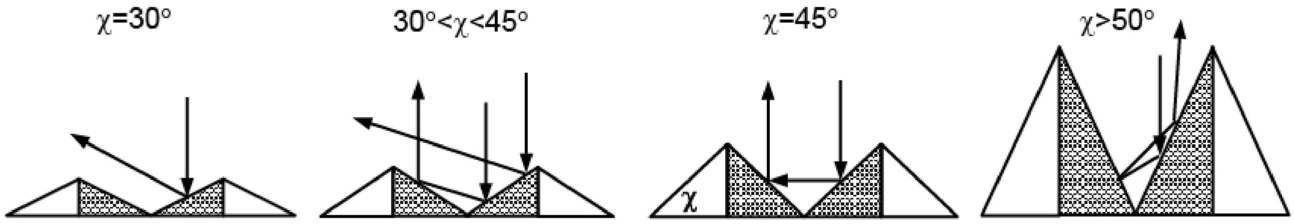

Figure 1. A ray tracing to show high frequency reflections from the centre of two triangles (After Cox and D'Antonio [1])

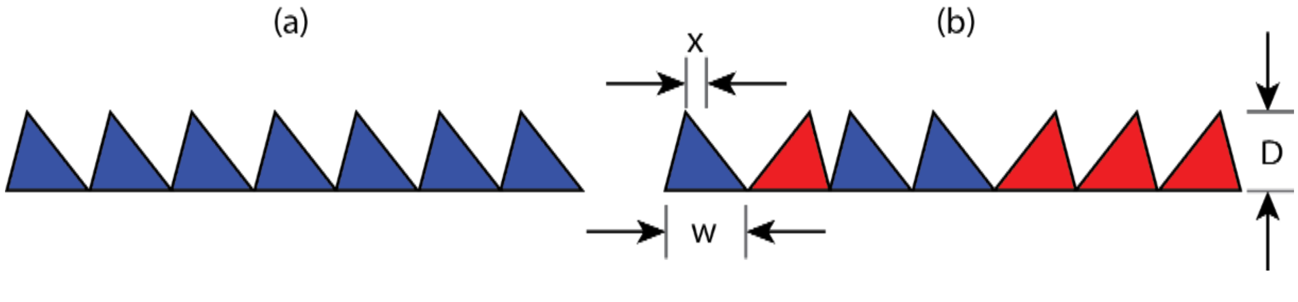

Figure 2, (a) a periodic arrangement of triangles and (b) a modulated array using the number sequence: 1, -1, 1, 1, -1, -1, -1.

3. Results

Figs. 3-6 give the results for normal incidence, Figs. 7-10 for oblique incidence and Figs. 11-12 for random incidence. As outlined above, predictions were carried out for nine different depths. It was found the results fell into three broad categories, so results are presented for one example for a shallow, intermediate and deep surface.

Figs. 3, 7 and 11 show the normalised diffusion coefficient averaged over the bandwidth within which the triangles created significant dispersion versus the position of the apex. So x=0 is a symmetric triangle. Each plot represents a different depth, starting with the shallowest on the left through to the deepest on the bottom right. For normal incidence the bandwidth is 630 to 5000 Hz, for oblique and random incidence the bandwidth is from 315 to 5000 Hz. The lower frequency limit changes because for oblique and random incidence the triangles produced dispersion an octave lower than for normal incidence.

Figs. 4, 8 and 12 show the normalised diffusion coefficient versus frequency. Each plot shows the response for the surface that had the highest normalised diffusion coefficient based on the plots in Figs. 3, 7 and 11. The best modulated and best periodic array are shown along with the angles of the triangles for the best designs. Again, each plot represents different depths: shallowest on the left and the deepest on the right.

Figs. 5-6 and 9-10 give polar responses for the normal and oblique incident cases for the surfaces with the highest normalised diffusion coefficient. As well as the scattering for the periodic and modulated arrays, the response for a plane surface is given as a reference. Two example one-third octaves are shown: 1000 and 4000 Hz.

3.1 Shallow surface

This is the case where the depth is less than about 10 cm, and for a symmetric triangle this means the angle of the sides is <18°. These surfaces broaden the main reflection lobe. For a flat surface the reflection is spread over the specular zone, but with a shallow array of triangles more receivers get significant reflected energy - see left most plots in Figs. 5-6 and 9-10. This is true for both normal and oblique incidence. The performance of modulated and periodic arrangements are similar – see Figs. 4, 8 and 12. For normal and random incidence the best shape is roughly symmetric with $x \approx 0$ *cm* – see Figs. 3 and 11. Unsurprisingly, for oblique incidence, some asymmetry can help improve performance – see Fig. 7. These surfaces offer some moderate dispersion without every achieving a high diffusion coefficient. Whether the diffusion is sufficient would depend on the application, and it is worth noting that the attenuation of the specular reflection is not that great for some frequencies. Take the case of normal incidence. At 1 kHz the diffusion coefficient is 0.4, but this represents only a 3-4 dB attenuation of the specular reflection at normal incidence and 1.5 dB at oblique incidence. At this frequency the depth of the surface is only about a fifth of a wavelength. At 4 kHz the diffusion coefficient is again 0.4, and for normal incidence the reflection is split into two lobes that are each ~3 dB less than the specular reflection from the flat surface. At this frequency the wavelength is slightly bigger than the surface depth, and other shapes such as curved surfaces and Schroeder diffusers are likely to create more dispersion if that is what is desired.

3.2 Intermediate surface

$D = 20$ *cm* is taken to illustrate this case, and these results are the middle plots in each figure. For normal incidence the best modulated and periodic arrays give similar performance – see Fig. 4. For this source conditions, the best modulated arrays are slightly asymmetric, whereas the best periodic arrays use isosceles triangles – see Fig. 3. For oblique and random incidence, there is some advantage to having an asymmetrical design – see Figs. 7 and 11.

For oblique incidence, it is notable that the arrays with the highest diffusion coefficients can redirect sound into other directions with little attenuation – see the polar responses in Figs. 9 and 10. For normal incidence, Fig. 5, little attenuation in the middle of the specular reflection is achieved at 1000

Hz. Taken together, these results indicate that the deeper surfaces that have stronger redirection abilities need to be used with caution. It might be that constructing arrays based on two or more different sized triangles might overcome the problem. This would allow many different angles between adjacent triangles, and so enable the reflected sound to be better spread around the polar response.

3.3 Deep surface

When *D = 30 cm* then a symmetrical triangle creates sides angled at 45°. Adjacent triangles then form *corner reflectors*, and for normal incidence all the sound is sent back to the receiver without dispersion. This is a useful feature in some situations, but this paper is focusing on creating dispersion. The best arrays for normal incidence are distinctly asymmetrical to ensure that there is not a 90° angle between the sides of adjacent triangles – see Fig. 3 (right plot). Asymmetry is also preferred for oblique and random incidence – see Figs. 7 and 11. Using modulation creates more dispersion than a periodic array – see Figs. 4, 8 and 12. For normal and random incidence the modulation provides a broadband improvement, but for oblique incidence the improvement is only at low frequency and a periodic arrangement is actually better at higher frequencies. As was the case for the intermediate surface, there is evidence of strong reflections into some angles in the polar responses – see Figs. 5-6 and 9-10. This again indicates the need to have more angles available by using two or more different triangles to allow better dispersion.

4. Conclusions

This study has examined the scattering from triangles using 2D BEMs. The reflection from a thousand different surfaces was predicted and evaluated in a number of different configurations. For shallow devices, the scattered polar responses demonstrate a broadening of the major reflected lobe, but the diffusion coefficient plateaus and never achieves a large value. These shallow devices might be good candidates for surfaces that mildly reduce specular reflections, but care in application is needed because the attenuation of the specular reflection is only moderate. For deeper devices, the strong redirection that adjacent triangles can create makes it difficult to create even dispersion of the reflections. In these cases, it might be advisable to use two or more triangles with different angles to reduce the risk of a strong redirected reflections.

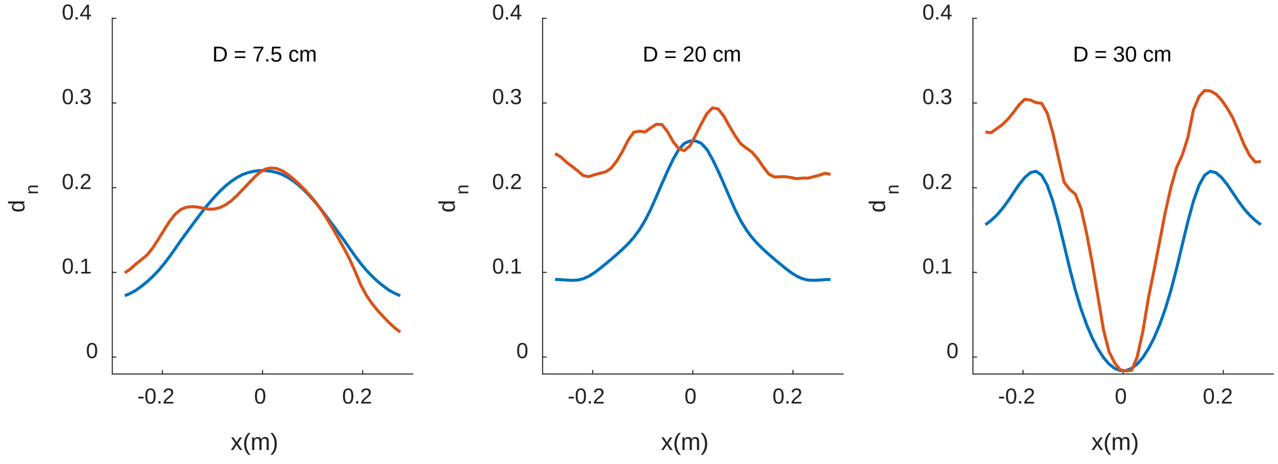

Figure 3. The normalised diffusion coefficient averaged over the bandwidth 630 Hz to 5000 Hz, as a function of apex position. ——— Modulated and ——— periodic arrays. Each plot represents a different maximum depth as indicated. Normal incidence.

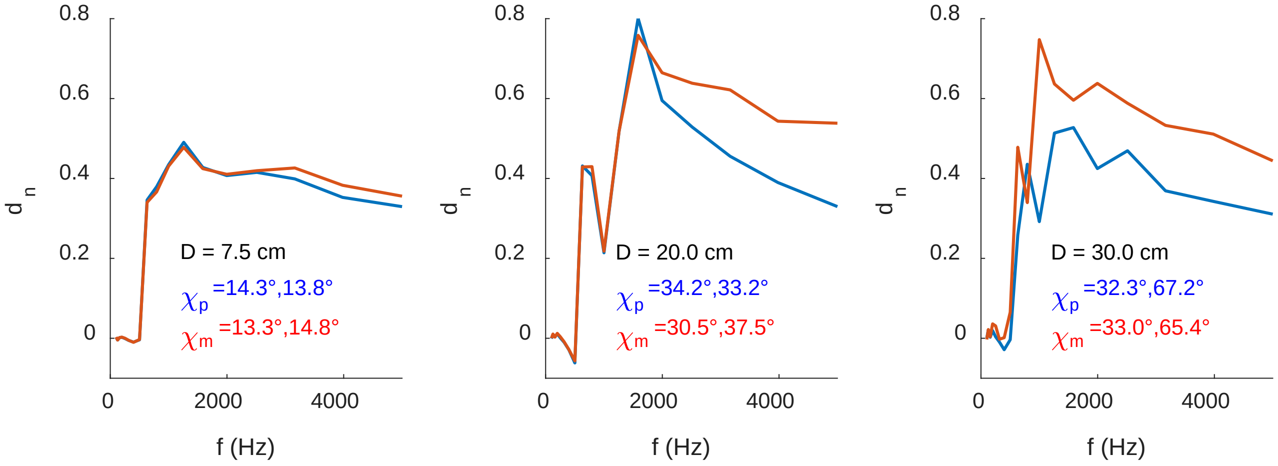

Figure 4. The normalised diffusion coefficient for the best triangle prisms found via exhaustive search. The angles of the triangles are indicated on the plots with subscript p meaning periodic and m modulated. Modulated and periodic arrays. Each plot represents a different maximum depth. Normal incidence.

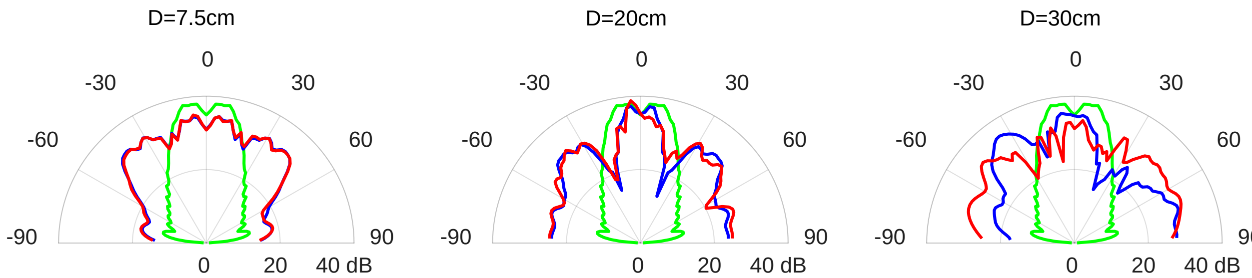

Figure 5. The scattered polar response for the best triangles found via exhaustive search. Modulated and periodic arrays. For comparison reference flat surface. Each plot represents a different maximum depth. Normal incidence, 1000 Hz.

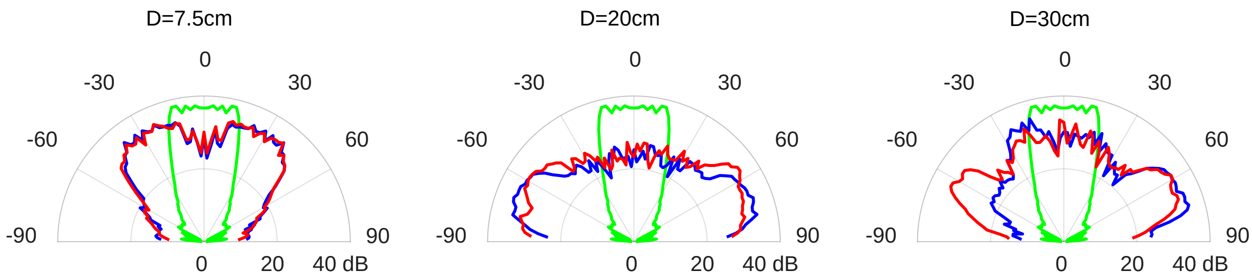

Figure 6. The scattered polar response for the best triangles found via exhaustive search. Modulated and periodic arrays. For comparison reference flat surface. Each plot represents a different maximum depth. Normal incidence, 4000 Hz.

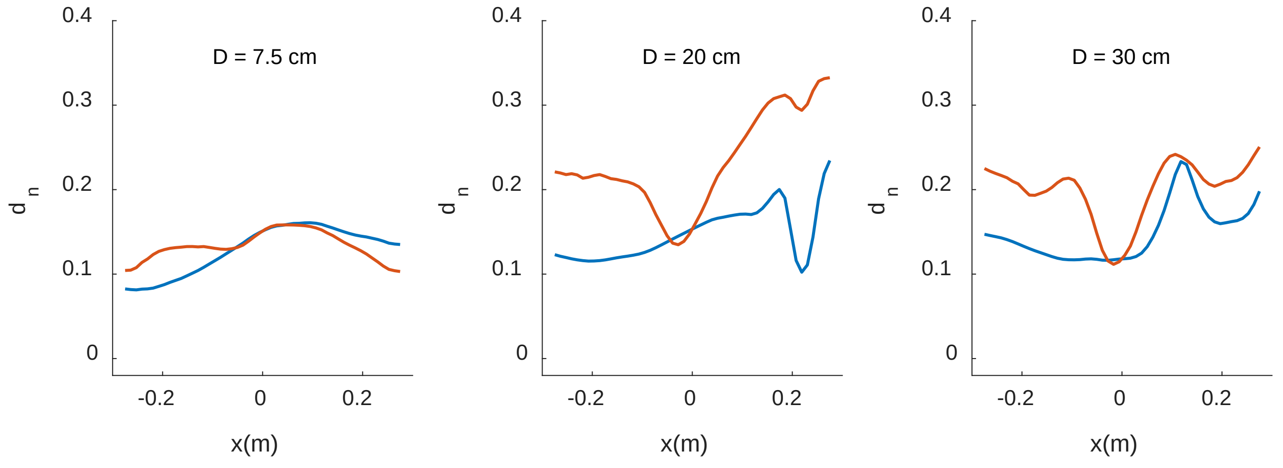

Figure 7. The normalised diffusion coefficient averaged over the bandwidth 315 Hz to 5000 Hz, as a function of apex position. ———— Modulated and ———— periodic arrays. Each plot represents a different maximum depth. Oblique incidence.

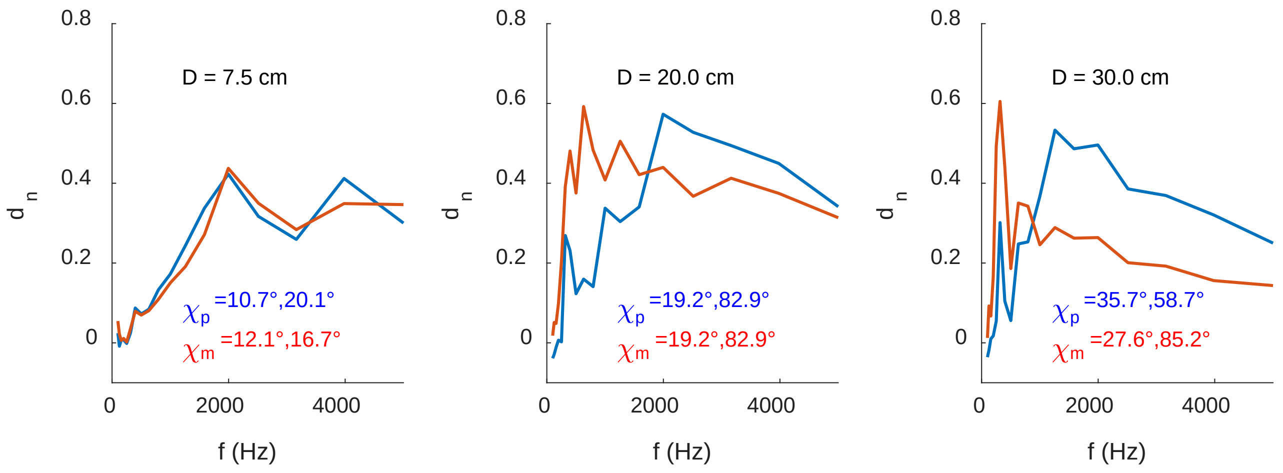

Figure 8. The normalised diffusion coefficient for the best triangles found via exhaustive search. The angles of the triangles are indicated on the plots with subscript p meaning periodic and m modulated. ———— Modulated and ———— periodic arrays. Each plot represents a different maximum depth. Oblique incidence.

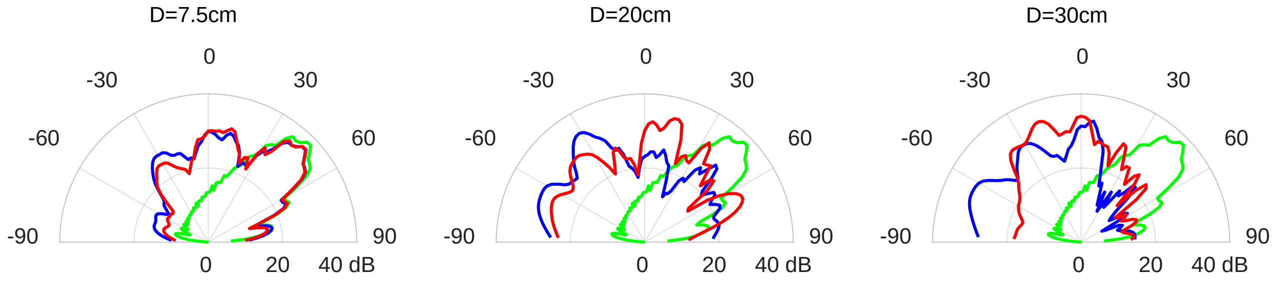

Figure 9. The scattered polar response for the best triangles found via exhaustive search. ———— Modulated and ———— periodic arrays. For comparison ———— reference flat surface. Each plot represents a different maximum depth. Oblique incidence, 1000 Hz.

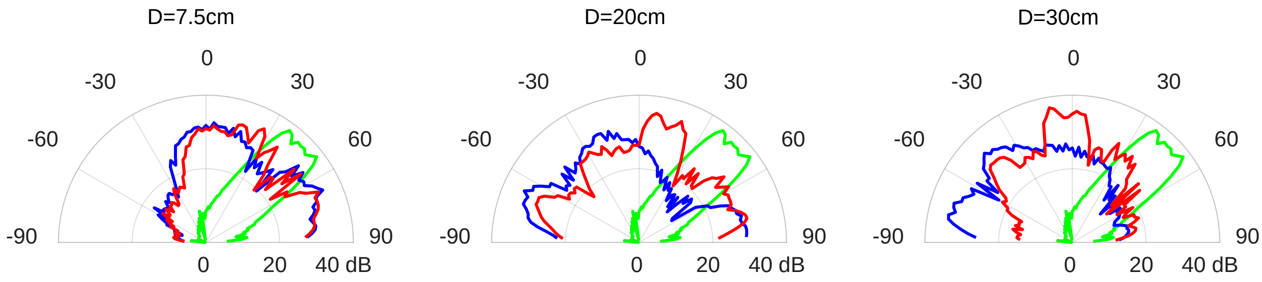

Figure 10. The scattered polar response for the best triangles found via exhaustive search. Modulated and periodic arrays. For comparison reference flat surface. Each plot represents a different maximum depth. Oblique incidence, 4000 Hz.

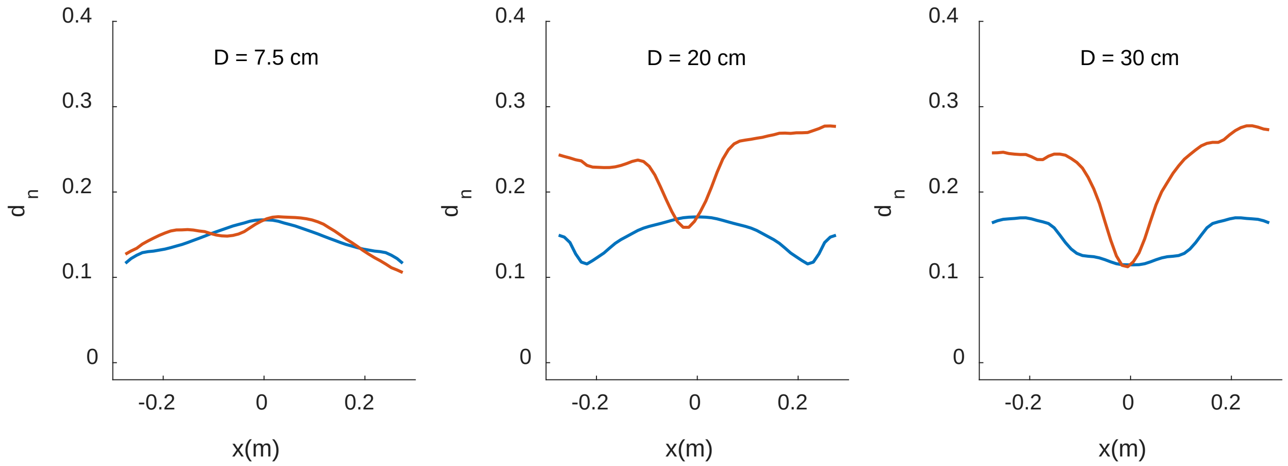

Figure 11. The normalised diffusion coefficient averaged over the bandwidth 315 Hz to 5000 Hz, as a function of apex position. Modulated and periodic arrays. Each plot represents a different maximum depth. Random incidence.

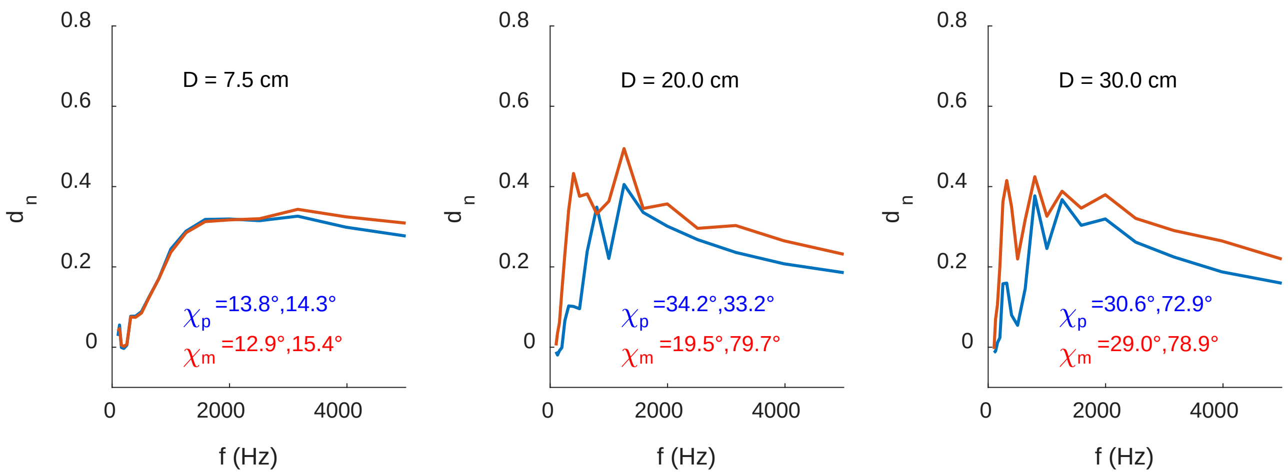

Figure 12. The normalised diffusion coefficient for the best triangles found via exhaustive search. The angles of the triangles are indicated on the plots with subscript p meaning periodic and m modulated. Modulated and periodic arrays. Each plot represents a different maximum depth. Random incidence.

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