PRACTICAL PERFORMANCE OF BINARY AMPLITUDE DIFFUSERS

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1 SUMMARY

Binary Amplitude Diffusers create dispersion by a pseudo-random arrangement of hard and soft patches. These are hybrid surfaces where partial absorption occurs and reflected sound is diffused. The original design work on these surfaces used approximate prediction models and so the performance of real surfaces has only been partially tested. The aim of this paper is to present the beginnings of work to gain better data for the absorption and diffusion performance of binary amplitude diffusers. Boundary Element Method (BEM) predictions and free field measurements of diffusion will show that BEM models can provide accurate predictions of the surface scattering. It will also be shown that the actual absorption of these surfaces does not follow the original design principles. The consequences of this to diffusion performance will be discussed for single plane diffusers.

2 INTRODUCTION

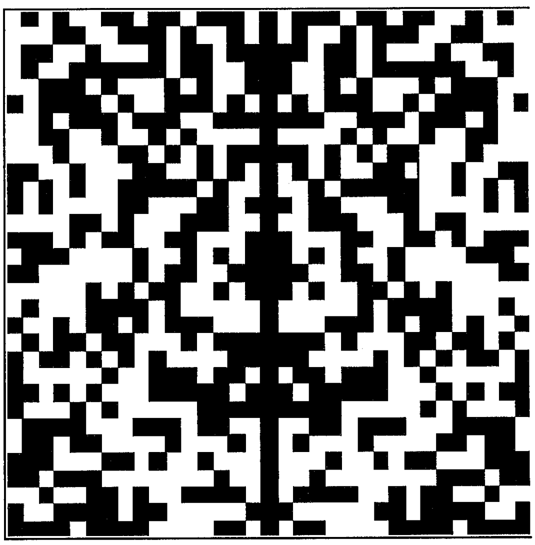

Figure 1. A mask used to form a diffusive, partially absorbing surface.

Diffusion is useful in treating a wide variety of spaces such as listening rooms, churches and auditoria; they can improve the acoustic[1]. Diffuser design has often concentrated on rigid surfaces, where the absorption is minimised. When the diffusers are being applied in large concert halls this is a normal design remit as absorption of surfaces in such spaces should be minimised. In many other applications, especially in small rooms, it is necessary to provide both diffusion and absorption. This can be achieved by a hybrid surface, i.e. a surface which partially absorbs while ensuring that reflected energy is diffused. Commercial examples of such surfaces are available and consist of a complex array of absorbent and reflective patches. These "diffsorptive" surfaces are formed by covering a bulk absorber with a perforated reflective mask. Such a mask is shown in Figure 1, where the light patches provide absorption through perforation and the dark areas reflection. The impedance changes across the surface provide the diffusion. It has been shown[2] that by curving these surfaces considerable improvement in the diffusing properties results, but this paper will concentrate on the performance of planar surfaces. The advantage of the planar surface is that diffusion can be created by a flat surface without visible corrugation; this is appealing to many architects, and cheap to manufacture. These new hybrid surfaces offer the designer an increased choice away from the extremes of completely absorbing or diffusing elements.

The concept of using absorption to break up reflected wavefronts is not particularly new, and examples can be found in studios dating back many decades. The surfaces discussed here are new in the sense that the size of the absorbing and reflecting patches used are considerably smaller than older designs and number theoretic considerations are applied to maximise dispersion. Angus, who has undertaken significant work in this area, devised this concept[3],[4]. His first paper used maximum length sequences to form surfaces with ≈50% open area, his second paper showed that the use of optical orthogonal sequences allows surface with different open areas to be formed. Optical orthogonal sequences are also better because they have good autocorrelation properties for a unidirectional sequence (0 and 1), whereas maximum length sequences require bidirectional sequences (-1 and 1). To a first approximation the soft surfaces can be modelled by a 0 and the hard surfaces by a 1 in the reflection factor, and consequently unidirectional sequences should give a better performance. Cox and D'Antonio[2] showed that optimisation was also a method to find appropriate binary sequences, but this only works when the number of terms in the sequence is small. They also showed that bending the surface so that the reflective parts of the diffuser were no longer in the same plane, greatly enhanced the diffusion performance. For flat surfaces, the specular reflection only has limited attenuation (6dB for a 50% open area) as a significant coherent wavefronts still remain.

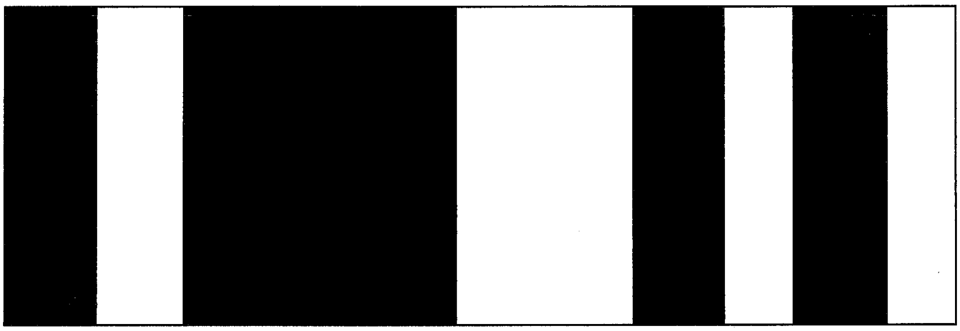

Figure 2. A one plane hybrid surface. The dark patches are reflective, and the white patches absorptive.

Previous work has relied on simplified prediction models. The reflection factor of the absorbent patches was assumed to be zero, which is not achieved in reality, especially at low frequencies. Furthermore, previous prediction studies have used simplified models which have assumed the Kirchhoff boundary conditions. Consequently, the aim of this paper is to use more rigorous testing regimes to assess the surfaces. Measurements and Boundary Element Method (BEM) predictions will be used to assess the performance of single plane (Figure 2) *diffsorbers*.

3 EXPERIMENT

A sample was constructed and measured using a maximum length sequence measurement technique. The process used followed the diffusion coefficient standard AES-4id-2001[5] and enabled the scattered polar response in 1/3 octave bands to be obtained. The sample tested was based on a fourth order N=15 maximum length sequence. Soft patches were formed from semi-rigid mineral wool and the hard parts from varnished MDF. The smallest patches where 12.7mm wide. The impedance of the mineral wool used in the prediction models was determined via impedance tube measurement. Figure 3 compares the measured scattering from the surface with two prediction models. The Boundary Element Model (BEM) is based on the single frequency Helmholtz-Kirchhoff integral equation. This technique explicitly models the mutual interactions on the diffuser surface[6], and is known to work well for rigid surfaces. It involves the solution of simultaneous equations and so its main disadvantage is that it is slow for large surfaces. The Kirchhoff model uses the Kirchhoff boundary conditions to approximate the surface pressures. This removes the need for simultaneous equations and the slow solution of these, and so has a greatly reduced calculation time when compared to the BEM model. The Kirchhoff boundary conditions assume that the pressures on the sides and rear of the panel are zero, and the pressures on the front is given by one plus the pressure reflection factor.

As might be expected the BEM model provides accurate predictions, and this enables further investigation to use BEM predictions only.

4 PREDICTION STUDY

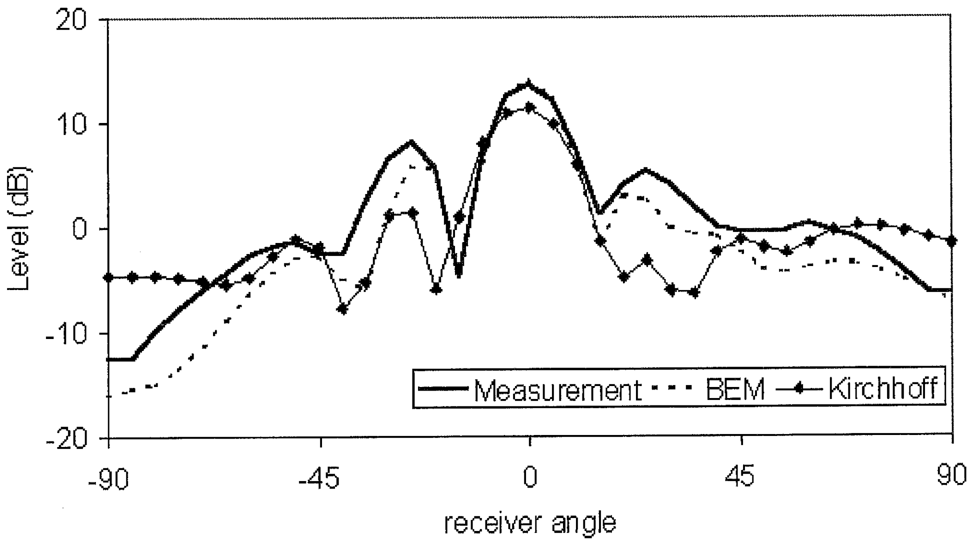

Figure 1 Scattering form a single plane fourth order mls surface

4.1 Surfaces Tested

The scattering from several different surfaces were formed to compare with the N=15 maximum length sequence (mls) sample. Each of the surfaces had the same proportion of absorbing elements as the mls sample to enable a fair comparison. One test sample was a periodic surface (101010101010101) which therefore represents a normal Helmholtz absorber with a regular arrangement of soft patches. Another sample was a surface with good aperiodic unidirectional autocorrelation properties. The original design of BAD diffusers[3] used mls sequences because of their good autocorrelation properties. This was to maximise the dispersion created by the surface and the concept is as follows. The far field scattering from a surface can be approximated by the Fourier Transform of the surface reflection factors on the front face only – a Fraunhoffer type prediction approach. Consequently, the best surface would be one where the Fourier Transform of the reflection factors is a constant. This is achieved by numerical sequences with perfect autocorrelation functions[7]. The maximum length sequence is the most popular sequence type and is used widely in engineering and science, and was the starting point for Schroeder's original work on diffusers. In the case of this single plane sample, however, better sequences exist. The perfect autocorrelation property of the maximum length sequence is only achieved for periodic autocorrelation. This would be approximately achieved if the sample were a large number of periods of the maximum length sequence. As only one sequence is present, the most appropriate autocorrelation function is aperiodic. Furthermore, the maximum length sequence perfect autocorrelation occurs when the binary sequence has opposite phase (+1 and –1), where as the reflection factor for the surface should be approximated by a binary sequence of 1 (reflection) and 0 (absorption). Consequently, it might be expected that better sequences might exist. For short binary number sequences, the best sequence can be found by an exhaustive search of all possible combinations in a length N=15 sequence. Every combination is examined until the one with the best autocorrelation function is found. This search is limited to sequences where there are eight reflective patches and 7 absorbent patches to allow a fair comparison with the mls sample. To do this search it is necessary to have a criterion for the best autocorrelation function, and in this case the merit factor is used[7]. If the autocorrelation function is given by $s_{xx}(\tau)$, then the merit factor M is given by:

$$M = \frac{s_{xx,0}^2}{\sum_{i=1}^{N} s_{xx,i}^2} \qquad (1)$$

The higher the merit factor, the lower the side lobe energy and so the better the autocorrelation properties of the sequence. The search yielded worse merit factors than that given in Reference 7, but the sequences given in reference 7 do not have the correct balance of 1s and 0s. Figure 4 compares three sequences and shows that the best autocorrelation sequence resulting from the search improves on the N=15 mls sequence (when this sequence is tested with an aperiodic autocorrelation and is assumed unidirectional).

For each surface, the polar distributions for the different surfaces were predicted using the BEM model and the polar responses compared. In addition, the absorption coefficient was calculated by summing the total energy scattered in all directions and comparing this to the expected total energy scattered from hard and soft surfaces of the same size. In all cases, normal incidence source only has been considered; the source and receivers are in the far field.

4.2 Results

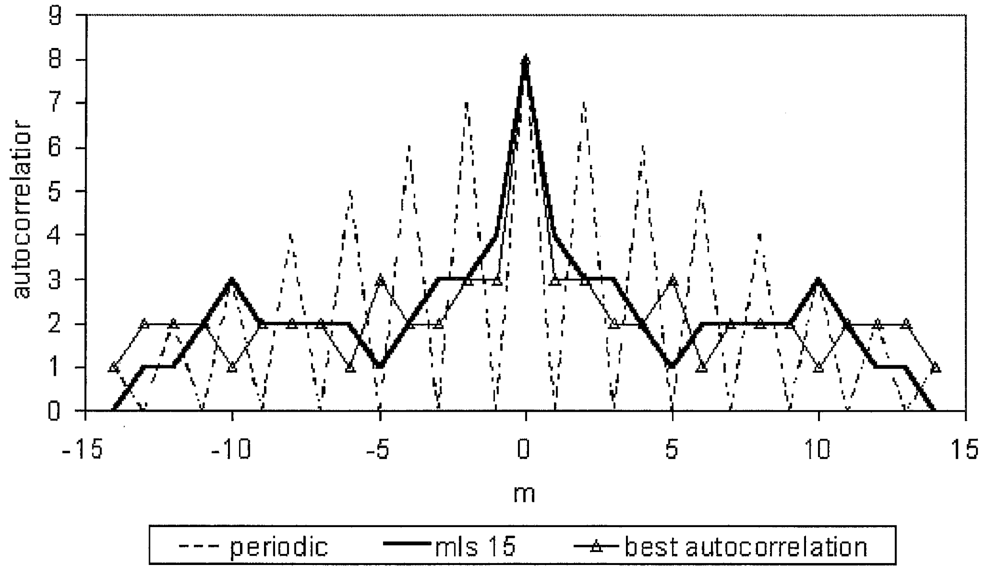

Figure 1 Autocorrelation function for 3 binary sequences

Figure 5 shows the scattered pressure level at 1.5 kHz. The attenuation caused to the specular reflection by the semi-hard surfaces can be seen. This equates to a rough absorption coefficient of 0.5 as might be expected. Analysis of the absorption coefficient does reveal excess absorption at these mid frequencies compared to a simple open area calculation. This is presumed to be due to surface scattering effects[8]. At this frequency, both the N=15 mls sequence and the best autocorrelation sequence give similar diffusion performance.

Figure 6 illustrates the scattering at a higher frequency of 6kHz. At this frequency a small improvement in the scattering performance is seen for the best autocorrelation sequence compared to the N=15 mls sequence. This lends a little support to the principle of designing using sequences with best autocorrelation properties. More surprising, however, is that the periodic surface is doing better than both the specialist sequences. This happens because the periodic surface has a small repeat length. Consequently, the surface generates grating lobes above 2.5kHz. Evidence for these grating lobes can be seen at ± 25 degrees. The other surfaces do not have periodicity and so they do not show grating lobes. These grating lobes provide additional obliquely propagating energy from the periodic surface, which contributes to a more even scattering response. Incidentally, this result is probably peculiar to the size and layout of surfaces chosen for this test. Preliminary results show that periodic surfaces with small repeat distance are worse than specialist pseudo-random sequences for more application-realistic samples. There are very few applications where a single isolated diffuser 33cm wide (as was tested here) would be used! In real applications large areas must be covered.

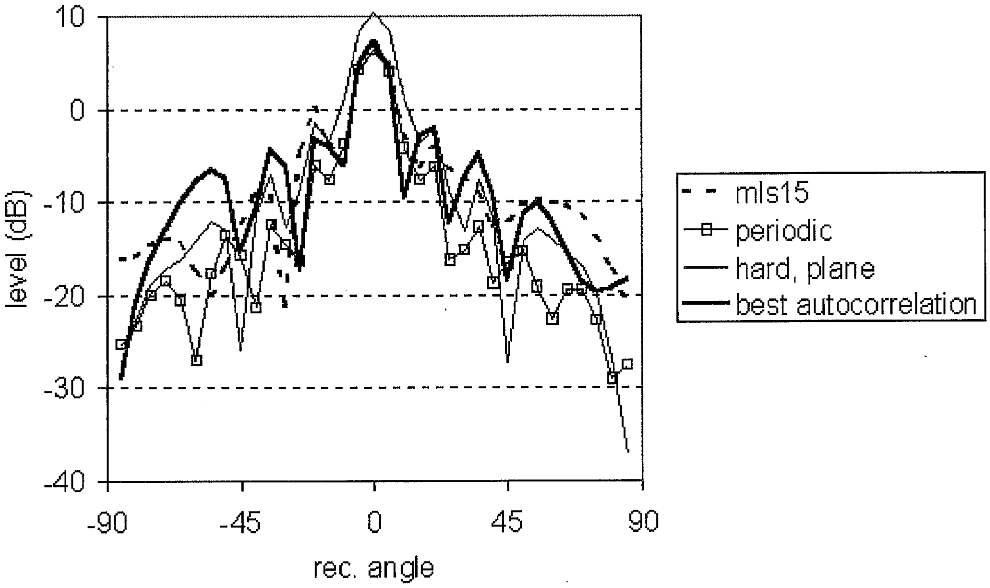

Figure 1 Scattering from four surfaces at 1.5 kHz.

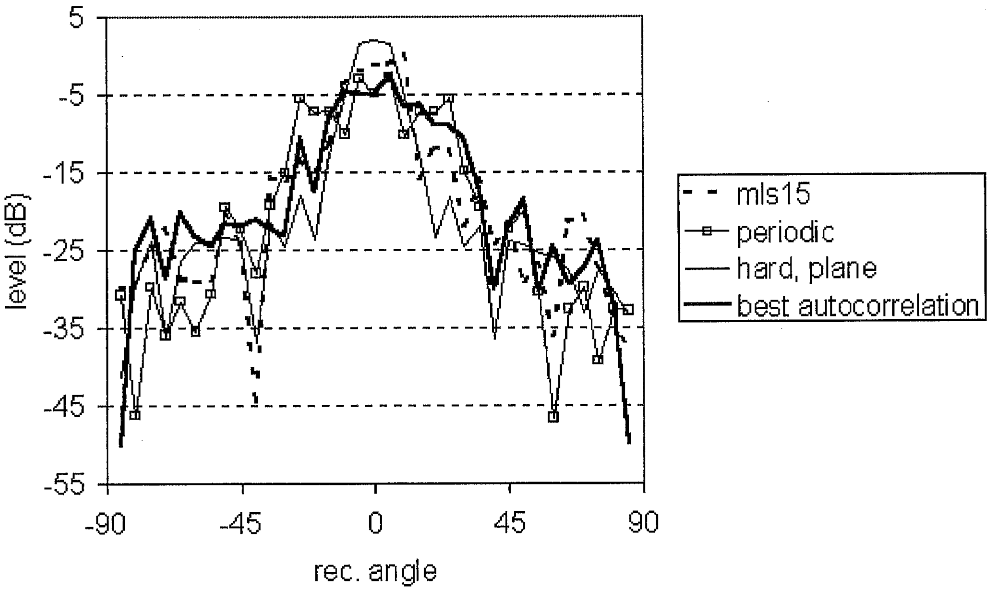

Figure 6 Scattering from four surfaces at 6 kHz.

4.3 Assumed Absorption

In the above predictions, the impedance of the soft areas was taken from standing wave tube measurements of a mineral wool sample. The original theory of these surfaces, however, as published in previous papers, assumed a reflection factor of 1. How does this assumption affect the performance of the diffusers? Predictions were calculated using the BEM model for an N=15 mls sample, but with the soft patches having an idealised reflection factor of 1. This is labelled "mls15 R=1". Figure 7 shows the diffusion coefficient[5] for the mls sequence, "mls15" which has application-realistic reflection factors, and "mls15, R=1" which has assumed perfect absorption. Also shown is the absorption coefficient for the mineral wool which was used in the BEM model. For most of the frequency range, the diffusion achieved by the actual mls15 surface is not as good as the one where R=1 is assumed. This is to be as expected, because the mls15 has a smaller reflection coefficient magnitude, which means it has less ability to perturb the wavefronts. It is only at high frequency, when the mineral wool achieves high absorption, that the diffusion from the two mls surfaces converge. This result implies that the diffusion performance of these hybrid surfaces need to be tested with application-realistic impedance coefficients, and an assumption of R=1 is best avoided.

5 DISCUSSIONS AND CONCLUSIONS

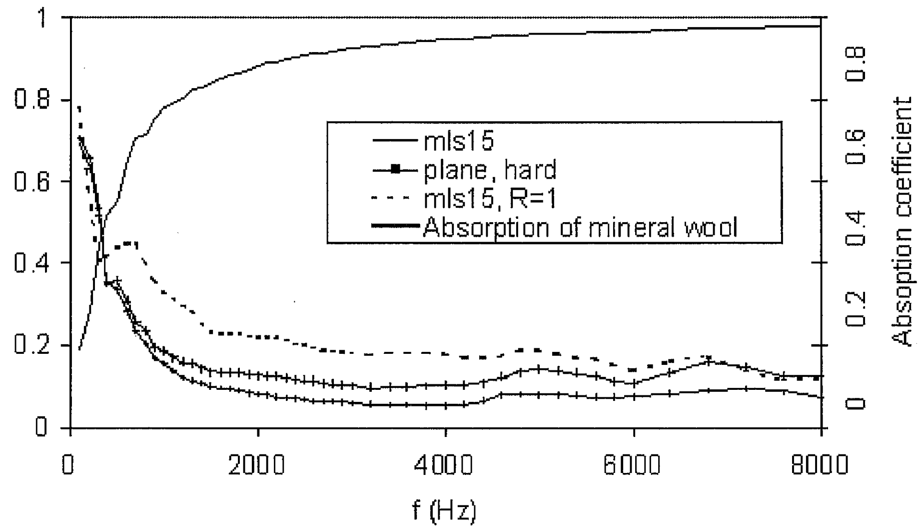

Figure 7 Absorption and diffusion spectra for some surfaces

This paper has presented some results concerning the performance of hybrid absorbing/diffusing surfaces. It has been shown that a Boundary Element Method (BEM) model can be used to obtain accurate predictions of surface scattering. The significance of this is that it allows BEM modelling to be used in testing the performance of more application-realistic surfaces. The surfaces tested here were chosen because of their simplicity to construct and measure in the laboratory. They are not the same as those used in real room, and so it is unwise to generalise from the above results to evaluate the performance of commercial samples. Evaluation of commercial samples requires hemispherical predictions from large arrays, and results and analysis are in their early stages. Problems arise because the Kirchhoff boundary conditions do not work well for the commercial configuration, and Boundary Element Models rapidly become too slow to enable processing of reasonable sized arrays. Improved techniques for BEM predictions are being developed which hopefully will facilitate the prediction of the scattering from large arrays of the surfaces.

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