IMPROVING THE BASS RESPONSE OF SCHROEDER DIFFUSERS

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1. INTRODUCTION

Room acoustic diffusers can be used to treat the acoustics of critical listening environments to improve speech intelligibility and to make music sound better[1]. The development of the modern sound diffuser can be traced back to the pioneering work of Schroeder, who developed the phase grating diffuser[2,3]. These consist of a series of wells of different depths separated by fins. The order of the well depth sequence is determined by a number theoretic sequence. If the quadratic residue sequence is used, then the diffuser produces grating lobes of similar energy at most integer multiples of the design frequency. Figure 1 shows a cross section through an N=7 quadratic residue diffuser.
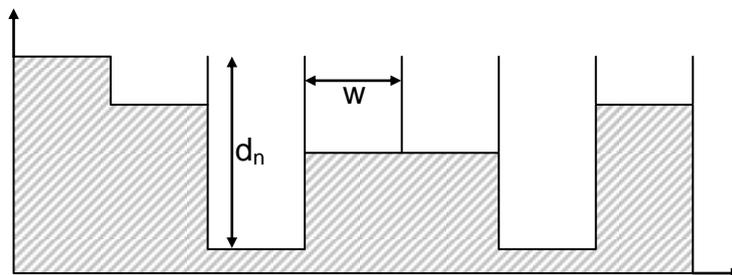
Figure 1. A Schroeder diffuser based on the N=7
quadratic residue sequence (0 1 4 2 2 4 1)

In any Schroeder diffuser, there is considerable amount of diffuser volume that is unused - the solid parts of the diffuser shown shaded above. This paper concerns better using this diffuser volume to improve the bass response. The depth of a practical diffuser is often limited by non-acoustic factors. Ultimately, the designer or architect will usually limit the depth available for acoustic treatment, although sometimes the maximum depth is restricted because of concerns about absorption. In any case, with the wavelength of audible sound extending to 17m, it is impossible to construct a practical diffuser that will cover the full audible bandwidth with low absorption, and is also usable in most rooms. Consequently, there is always interest in methods for extending the bandwidth of diffusing devices to a lower frequency without making the device deeper.

One regime to increase the bass response is to use perforated sheets within the wells to add mass to the impedance of the wells. This lowers the resonant frequency of the wells and thereby lowers the frequency at which the scattering is first optimal. Such an approach was tried for diffusion by Hunecke[4] using microperforation, and for absorption by Fujiwara et al[5] and Wu et al[6] using larger diameter perforations. Cox and D'Antonio[7] provide some evidence for the effectiveness of this approach. Another approach might be to use active surfaces[8], but the technology is still undeveloped, and is likely to be expensive to implement in comparison with passive diffusers.

This paper will examine a third technique, namely well folding. Jrvinen, Savioja and Melkas[9] and Mechel[10] and others have suggested such a modification. This enables much of the wasted space at the rear of the diffuser to be better used. Using a Boundary Element Model (BEM), it has been possible to examine the effects of well folding more exactly than previously. This provides evidence for the effectiveness of the technique at low frequencies. The effect of well folding on mid-high frequencies is also considered, especially the effects on critical frequencies.

2. TEST BED

BEMs have been shown to provide accurate predictions of the scattering from diffusing surfaces[7]. In this study a two dimensional BEM has been applied to a cross section through the diffuser, and the scattering evaluated. This BEM allows the surface shape to be modelled exactly. Six periods of each diffuser were modelled, giving a total width of 3.15m (a realistic size of a diffuser array in a small listening room). This enables the cumulative effects of multiple periods of the diffuser to be examined, without creating excessively large meshes that result in slow computation. Receivers were located in a semicircle above the diffuser at one degree intervals and modelling was performed for a normal and an oblique (45⁰) source. Both sources and receivers were located 100m from the diffuser to ensure that a proper far field evaluation was undertaken. The design parameters for the basic Schroeder diffuser are given in Table 1.

Table 1. Basic design data for the standard N=7 quadratic residue diffuser

Design frequency	f_0	490Hz
Unit depth	$\Delta d = \lambda_0 / 2N$	0.05m
Period width	W	0.525m
Well width	$w = W / N$	0.075m
First critical frequency	$f_C = N f_0$	3.4kHz
Well cut-off frequency	$f_m = c / 2w$	2.27kHz

Results are presented in terms of polar responses and also diffusion coefficients. Diffusion coefficients were evaluated using the method outlined in AES-4id-2001[11].

3.   WELL FOLDING

It is anticipated that well folding would have two key advantages: (i) improving the bass response, and (ii) dealing with critical frequencies. As previously discussed, well folding should improve the packing density, thereby reducing the physical depth of a specified diffuser. Alternatively, it could lower the design frequency for a diffuser of a specified maximum depth.

The second key advantage concerns critical frequencies, a phenomenon that occurs in diffusers based on integer number sequences. A critical frequency is when the diffuser appears to reflect sound like a flat surface and creates no dispersion[12,13]. For a quadratic residue diffuser this occurs at mN times the design frequency, when N is the prime number generator and m a positive integer. At these frequencies, re-radiated waves from the entrances of the wells all have the same phase, because the wells are all integer multiples of half a wavelength deep. Recent research[14] shows that critical frequencies may be a problem over a larger bandwidth than previously expected, even occurring for frequencies above the plane wave cut-off frequency of the wells. By appropriate bending of the wells, the effects of critical frequencies can be reduced. It might be anticipated that the behaviour of a folded well will be frequency dependant. At low frequencies, it might be expected to react much like a straight well of centreline length d_1+d_2 (Figure 2). At high frequencies, it might be expected that the plane waves reflect from the floor of the folded well, such that it behaves like a well with a shorter depth a. By bending the well at an appropriate place, such that a is not an integer multiple of half wavelengths, it should be possible to change the reflection factor of the well at the critical frequency, in such a way that the waves radiating from the well entrances are no longer all in phase at any frequency, and the diffuser no longer has critical frequencies.
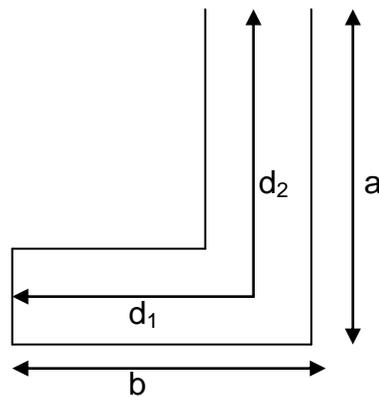
Figure 2. Geometry of a bent well

The folded well diffuser maintains exactly the same dimensions as the standard quadratic residue diffuser described above, except that its two longest wells have been folded to reduce its depth. The wells are folded in such a way so as to maintain centreline length and well width, and consequently, well volume. Figure 3a shows the new structure.
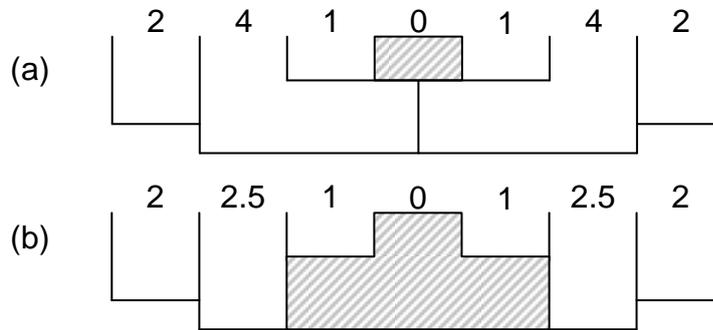
Figure 3. Diffuser geometries:
(a) with folded wells, and (b) with folded wells terminated at the bend.

The original diffuser was designed such that well width equals 1.5 times unit depth. This means when folded the diffuser is optimal in its use of space - a wider well width would result in a deeper diffuser, a narrower well width would result in the folded wells not physically fitting in all the space available behind the diffusing surface. An offset has also been applied to the well depth sequence, so that the bent well structure is conveniently contained within a single period. For comparison a third diffuser as shown in Figure 3b is introduced, this is identical to the folded diffuser except that the folded wells are terminated at the bend. The reason for doing this is to test whether the folded wells behave as though they are terminated at the bend at high frequency.

This diffuser in Figure 3a is now shallower by a factor of 2.5/4, and so the surface is 0.63 times as deep as the original diffuser. To further illustrate this, if restrictions limited the maximum depth of diffusing treatment to 0.125m, the diffuser with folded wells would have a design frequency of 490Hz, and a standard quadratic residue diffuser could only achieve a minimum design frequency of 780Hz in the same space.

4.   RESULTS

Figure 4 shows the scattering from the diffuser with folded wells compared to the standard Schroeder diffuser and a flat hard surface of the same external dimensions as the diffusers. This is the design frequency of 490Hz. Figure 4a shows this at normal incidence and Figure 4b at oblique incidence. At normal incidence the diffusers produce only a single lobe. This happens because this is at a frequency where the period width is narrower than the wavelength. The result for oblique incidence is more useful in comparing the performance of the folded well and standard diffuser, because the diffusers also produce one first order lobe, and the difference from the plane surface is more significant. At the design frequency, the diffuser with folded wells mimics the behaviour of the normal Schroeder diffuser, but in a shallower physical depth, providing evidence that well folding can work.

(a)
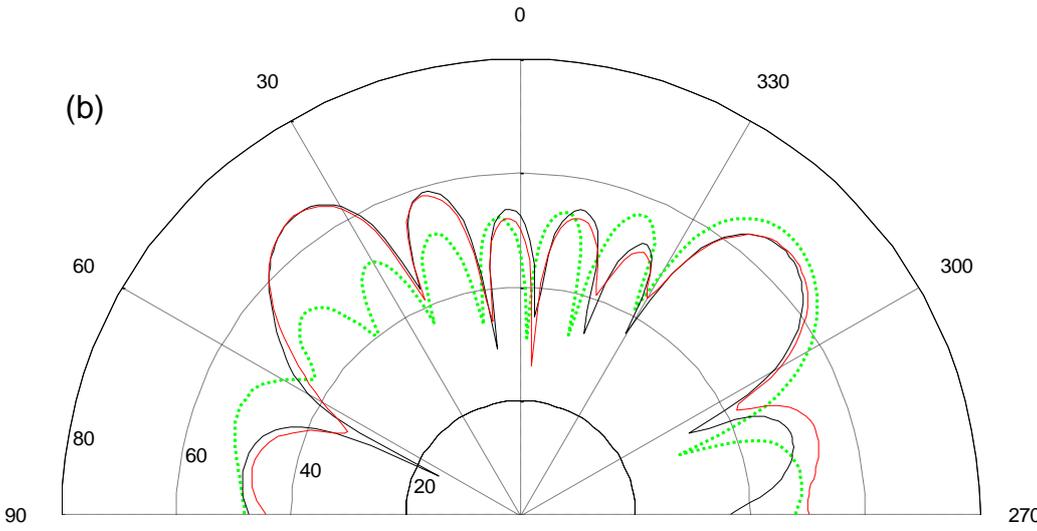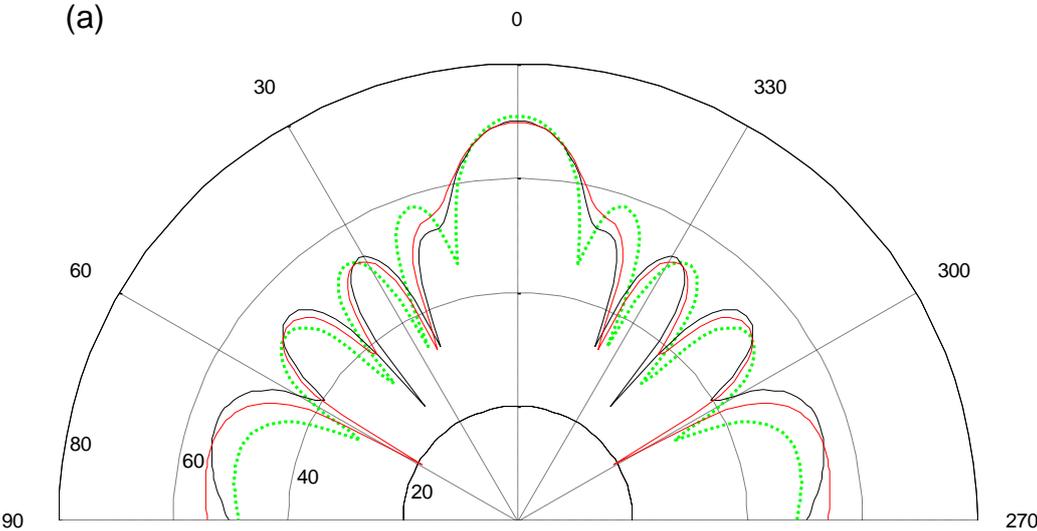
Figure 4. Scattered pressure level at 490Hz.
(a) normal incidence, and (b) oblique Incidence.
——————— Schroeder;
················· plane;
——————— bent;
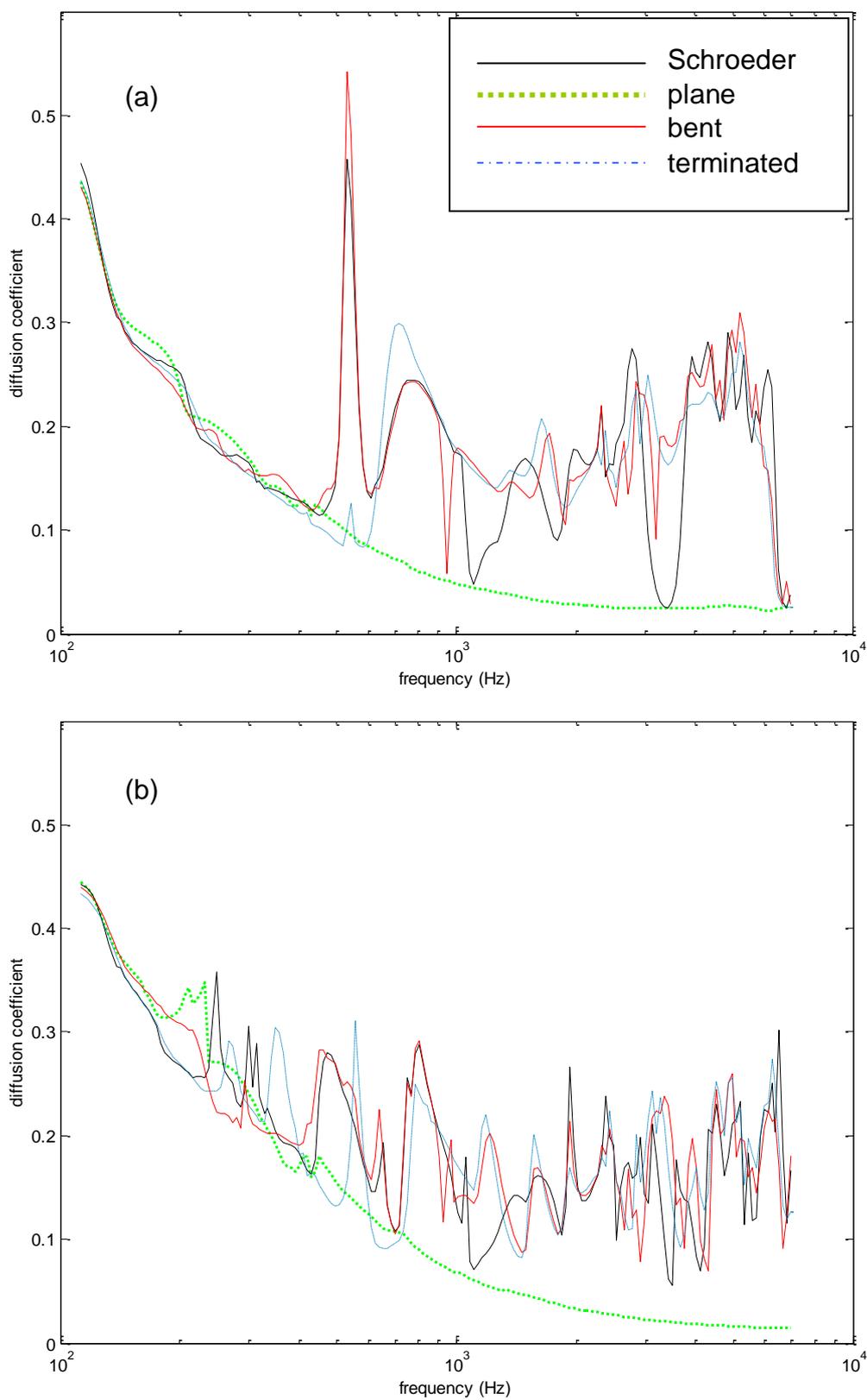
Figure 5. Diffusion coefficient vs. frequency :
(a) normal Incidence, and (b) oblique incidence.

Figure 5 shows the diffusion coefficient verses frequency for four surfaces. In addition to the surfaces described earlier, the diffusion coefficient is shown for a diffuser where the folded well is terminated at the bend as shown in Figure 3b. The diffusion coefficients are calculated at single frequencies rather than for 1/3 octave bands, and consequently the numbers are rather small and the graphs vary rapidly with frequency. Figure 5a shows the case for normal incidence, and Figure 5b for oblique incidence.

The diffusers start producing significant diffusion once first order grating lobes are produced, this happens at 650Hz for normal incidence and 380Hz for the oblique incidence case shown. Up until 1.25kHz, the diffuser with folded wells and the standard Schroeder diffuser produce very similar scattering results. It is presumed that at these frequencies, the sound waves easily propagate around the bend in the wells and so the folded well appears to be as deep as its centreline length. Above 1.25kHz, however, the diffuser with folded wells behaves differently as additional propagation modes within the folded well become significant. It might be expected that at very high frequencies, the dominant mode would be straight up and down the well, as though the bend does not exist. In middle frequencies, the modal behaviour will be more complex. Figures 5a and 5b also show the case where the diffuser is terminated at the bend and at high frequencies the folded well and terminated diffuser behave very similarly.

4.1 CRITICAL FREQUENCIES

Figure 6 shows the normal incidence response at the first critical frequency 3.4kHz. The standard Schroeder diffuser reflects sound in exactly the same way as the plane surface. This results in undesirable specular reflections. The diffuser with folded wells, on the other hand, is still diffusing effectively. Folding some of the wells has overcome the critical frequency problem. Also shown in Figure 6 is the response of the terminated Schroeder diffuser (Figure 3b), and this correlates very closely with the response of the folded well diffuser. This demonstrates that the primary mechanism occurring in the folded well at this frequency is plane wave reflection from the well floor. In this design, the folded well floor depth is not an integer multiple of the unit depth, and hence radiates out of phase with the other wells, interrupting the critical frequency effect and improving dispersion.
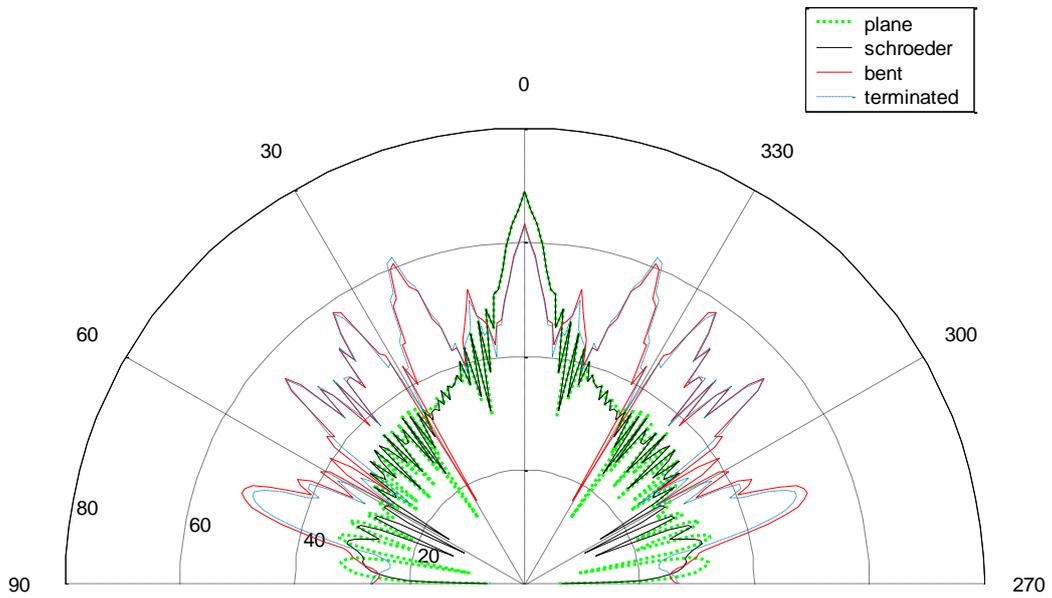
Figure 6. Scattered pressure level at 3.4kHz. Normal Incidence
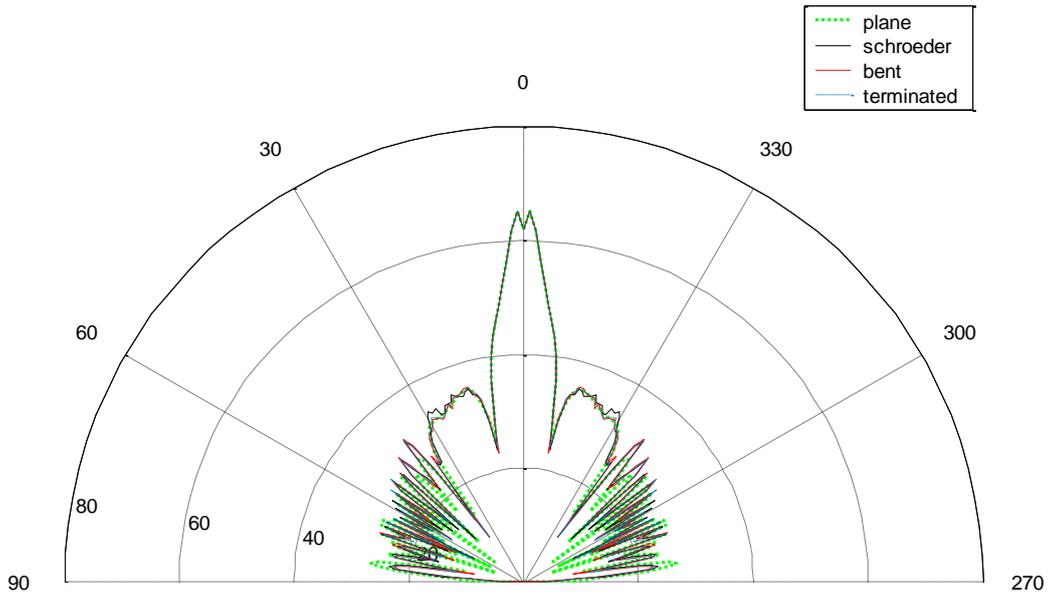
Figure 7. Scattered Radiation at 6.8kHz. Normal Incidence

Figure 7 shows the normal incidence response at the second critical frequency 6.8kHz. As might be expected, all the diffusers match the plane reflector response. This is because the floor of the folded well lies at 2.5 times unit depth, and will therefore introduce no phase change at double the critical frequency. This is further evidence that plane wave reflection from the bent well floor is the primary mechanism occurring in the bent well at this frequency. It is possible to construct the surface in such a way that the folded well will interfere differently at double the critical frequency and upwards and avoid all critical frequencies, although this will marginally lower the packing density.

5.   DISCUSSIONS AND CONCLUSIONS

An evaluation of using folded wells in Schroeder diffusers has been undertaken using a Boundary Element Method (BEM). The concept is to bend wells to utilise wasted space at the rear of the diffuser, and so produce more low frequency dispersion. The results demonstrate that the diffuser with folded wells enables diffusion to occur at a lower frequency from a given maximum depth. As the frequency increases, however, the apparent depth of the folded well changes as most of the sound wave no longer propagates around the bend. At mid-high frequency, the surface no longer behaves like a diffuser based on the original quadratic residue sequence, but rather like a diffuser based on a different number sequence. To maximise the performance of this type of diffuser, it would be best if the number sequence resulting from a diffuser with wells terminated at the bends, was also an optimal mathematical sequence for scattering. However, it is difficult to find a pair of sequences that allow good dispersion at both low and high frequencies because of geometric constraints. One solution to this would be to abandon the use of number theoretic sequences, and use an optimisation algorithm to search for appropriate bent well structures[15].

The change in the effective number sequence from low to high frequencies can be exploited to deal with critical frequencies. Critical frequencies are frequencies where the surface behaves as a flat plane reflector. The results have demonstrated that by bending the wells appropriately, critical frequencies can be suppressed.

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