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# REDUCING THE ATTENUATION OF SOUND PASSING OVER AUDITORIUM SEATING

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## 1. INTRODUCTION

The low-frequency attenuation of sound passing over seating at grazing incidence (the so-called 'seat-dip' effect) was first quantified in 1964 [1,2]. Since then, several experimental studies [3,4,5,6] have investigated the dependence of the attenuation on parameters such as the vertical angle of incidence of the direct sound. These have agreed on the effect of some measurement parameters on the attenuation, while others remain to be settled. A theoretical model of the seat-dip effect based on Green's theorem exists [7], but it is still not possible to predict the attenuation quantitatively for a given seat in a particular hall. This paper presents new data measured in a concert hall.

Seat-dip attenuation may be ameliorated by providing early energy at non-grazing incidence with ceiling reflectors [6], though this would tend to reduce the early lateral energy fraction. Alternatively, one might attempt to counter the destructive interference which causes attenuation by installing low-frequency absorbers in the seating floor [7]. In the present work, this second method has been examined in the concert hall.

## 2. CAUSES OF ATTENUATION

It was Sessler and West [2] who first proposed that seat-dip attenuation 'is most likely caused by a vertical resonance in the gaps between the rows'. Later, Ishida et al [5] concluded that the process is best thought of in the time domain as three successive groups of reflections. These can be difficult to separate in a real impulse response due to their number, and the fact that they are 'smeared' in time by diffraction. It is, however, possible to construct a very simple model using this idea.

The seat rows are represented by parallel barriers and a limited number of attenuated sound paths are constructed over them, assuming that diffraction occurs at the top of each barrier. Specular reflection at the tops of the barriers and at the floor between them is assumed. If no attempt is made to represent time

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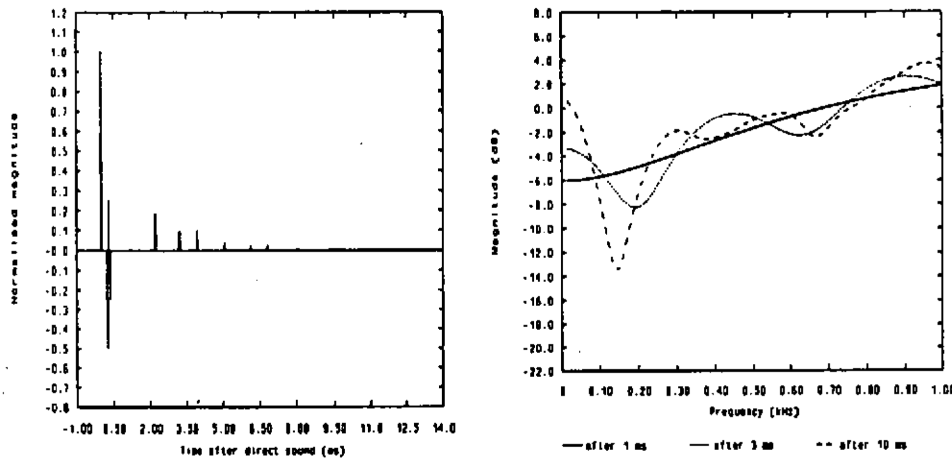


(a) (b)

**Figure 1:** Synthesised impulse response (a) and transfer function (b) of propagation across 'seat' barriers (3 rows, θ=87°, φ=90° - the angles refer to Figure 2).

smearing due to diffraction, the synthesised impulse response is a series of Dirac delta functions, as shown in Figure 1(a). The angles of incidence of the direct sound refer to Figure 2. The desired transfer function spectrum is then generated by a Fourier Transform. Transforming successively longer parts of this impulse response shows how the different groups of reflections contribute to the characteristic attenuation: Figure 1(b).

It seems likely that the most accurate model will result from a transient time-domain solution taking proper account of diffraction. An investigation using Green's theorem to do this for an arbitrarily-profiled surface is underway at Salford.

## 3. MEASUREMENTS IN A CONCERT HALL

The measurements were performed in a 2500-seat concert hall which has a stalls floor which is almost flat, and so might be expected to exhibit large attenuations. The basic set-up was as shown in Figure 2.

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The impulse response was obtained with a maximum-length sequence, giving high signal-to-noise ratios [8]. Then the transfer function of the early part of the impulse response was normalised to an anechoic calibration of the measuring system, so that the influence of the loudspeaker, microphone, etc., was removed. The spectra have also been corrected for excess attenuation due to distance. The value of (microphone height) $m$ = 1.14 metres, at which most of the measurements were made, represents a typical auditor ear height.

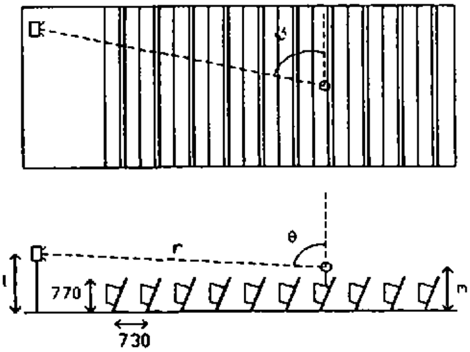


**Figure 2:** Arrangement for measuring sound transmission across seating.

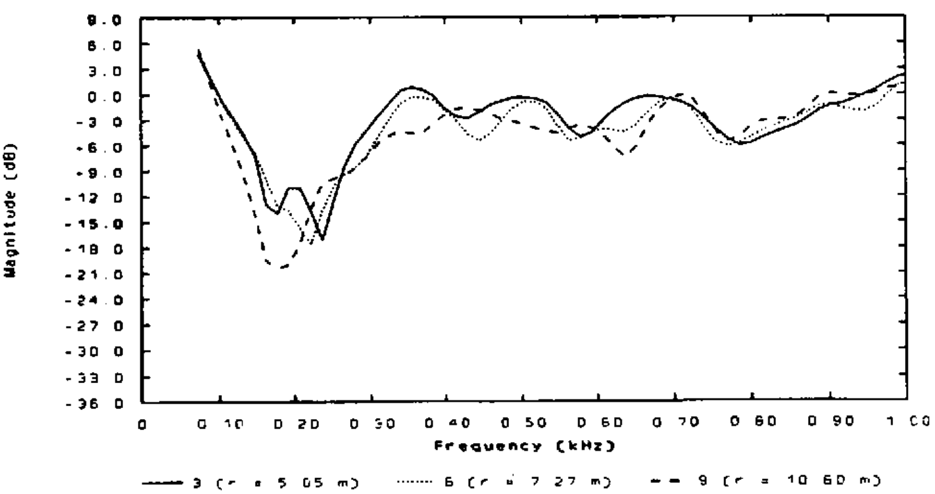


**Figure 3:** Transfer function (first 12.8 ms after direct sound) across stalls seats. Parameter: number of rows propagated over ($\theta$=87°, $\phi$=90°).

**3.1 Number of Seat Rows Propagated Over (*r*)**
Figure 3 demonstrates that a significant attenuation of 17 dB at 240 Hz has been established when sound has propagated over only three rows of stalls seats. The shape of the transfer function remains very similar six rows back. After nine rows, however, the maximum attenuation has increased by 3 dB and its frequency decreased slightly.

This result reflects the variation amongst the data in the literature for the effect of *r* on full-size measurements. Schultz and Watters [1] found little variation in attenuation with distance, as did Iida and Ando [4]. Sessler and West [2] found little change in the magnitude of the maximum attenuation, though it's frequency decreased steadily with distance, as here. However, Schroeder et al [3] measured significant increases in attenuation and decreases of dip frequency as *r* increases.

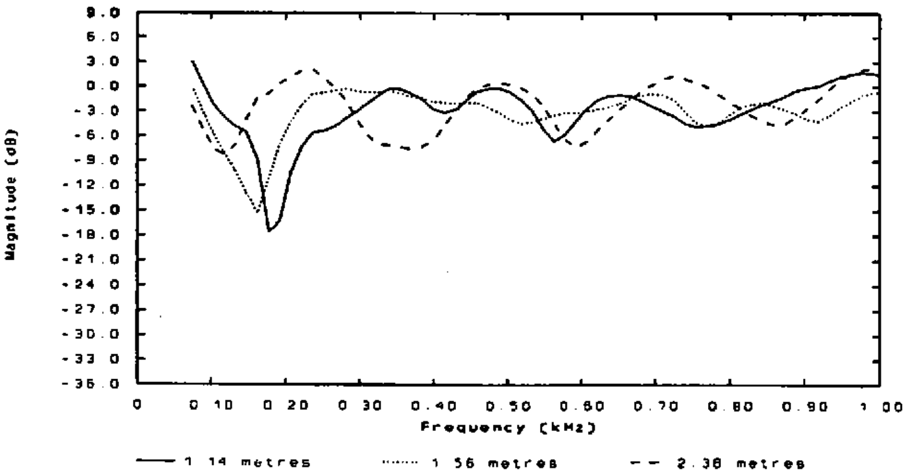


**Figure 4:** Transfer function (first 8.8 ms) across stalls. Parameter: microphone height, m (r=5.45 metres, l=1.77 metres, $\phi$=90°).

**3.2 Microphone Height (*m*)**
When the microphone height, *m*, is increased from 1.14 metres (ear height) through 1.56 metres to 2.38 metres, both the frequency of the dip and the maximum attenuation decrease, as shown in Figure 4. (For these measurements, loudspeaker height *l* was held constant,

so θ varies.) These results are in good agreement with those in the literature. When *m* = 2.38 metres, the transfer function is that of a comb filter. At this height, the impulse response is dominated by specular reflection from the tops of the seat backs, and the seat-dip effect may be adequately modelled by the locally-reacting surface of Cremer and Müller [9].

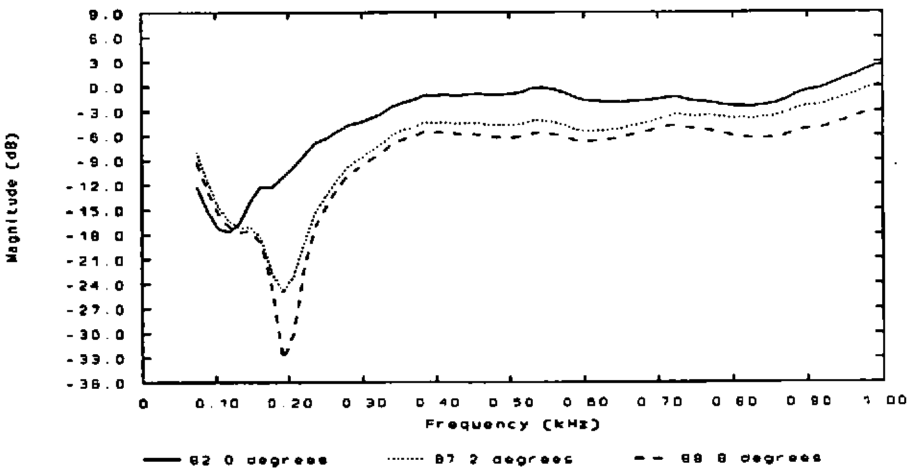


**Figure 5:** Transfer function (first 3.9 ms) across stalls. Parameter: θ (r=12.45 metres, m=1.14 metres, $\phi$=90°).

### 3.3 Vertical Angle of Incidence (θ)

At a fixed receiving position, as θ is increased, the frequency of maximum attenuation increases from 118 Hz to 192 Hz and the dip attenuation increases significantly - from 18 dB for θ = 82.0° to 33 dB for θ = 88.8°. This is demonstrated in Figure 5. These effects agree qualitatively with previous 1:10 scale model tests [1,5].

A slight increase in broadband attenuation is also seen for increasing θ in Figure 5. This is the only effect predicted by Ando et al's theoretical model [7], which exhibits a broadband increase in attenuation from 0 to 400 Hz and no change in the dip frequency, for θ increasing.

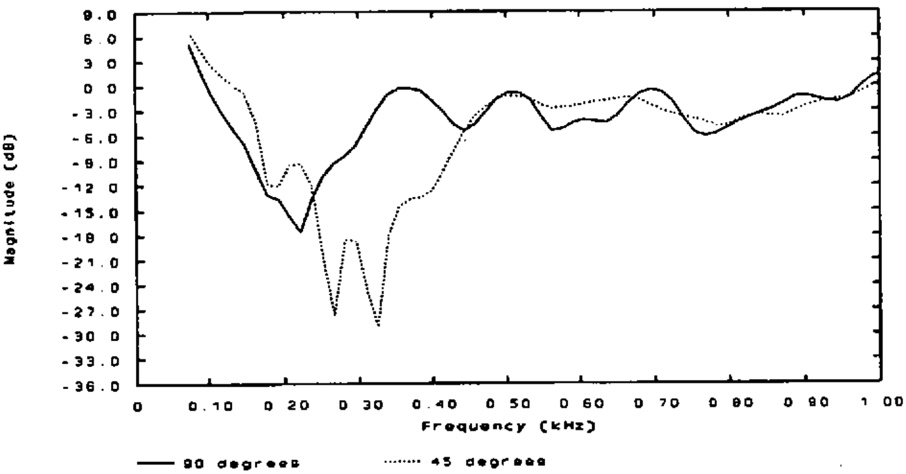


**Figure 6:** Transfer function (first 12.8 ms) across stalls. Parameter: $\phi$ (r=7.27 metres, m=1.14 metres, $\theta$=88°).

### 3.4 Horizontal Angle of Incidence ($\phi$)

Two values of $\phi$ were considered. Figure 6 shows that, when $\phi$ is changed from 90° to 45°, the frequency of the dip increases and the maximum attenuation is significantly increased from 18 to 29 dB. Both effects are described in previous 1:10 scale model measurements: Schultz and Watters [1] and Ishida et al [5] report both the dip frequency and the attenuation increases, while Sessler and West [2] found only the dip frequency increase. Ishida et al's results [5] also show the appearance of the double dip for $\phi < 45°$.

Though the agreement between these results and those in the literature is good as far as the effects of *m* and $\theta$, there is some disagreement over the effects of *r* and $\phi$. Given this contradicting data, a rigorous theoretical model of the impulse response would be useful to clarify the effects of measurement parameters.

## 4. MODIFICATION OF ATTENUATION WITH RESONANT ABSORBERS

Ando et al [7] used their computer model of transmission over seating to show that the attenuation might be reduced by installing slit resonators under the floor. In order to test the practicality of this idea in a real hall, the measurements described in part 3 above, were repeated, with Helmholtz absorbers placed on the floor between the seats. The random incidence absorption coefficient of the absorbers is given in Figure 7.

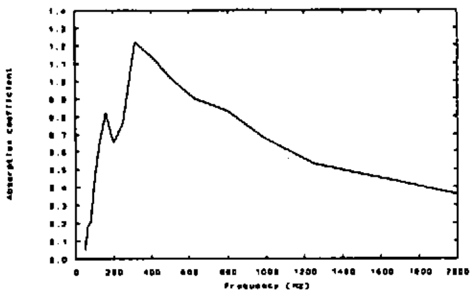

**Figure 7:** Random incidence absorption of modular resonant absorbers.

A sample result of the effectiveness of the absorbers in reducing attenuation, for the very early sound, appears in Figure 8. A row of five modular absorbers was placed on the floor between the seat rows in front of, and at, the microphone. The large attenuation of 27 dB without absorbers has been reduced to 15 dB, and the dip frequency has been shifted downwards.

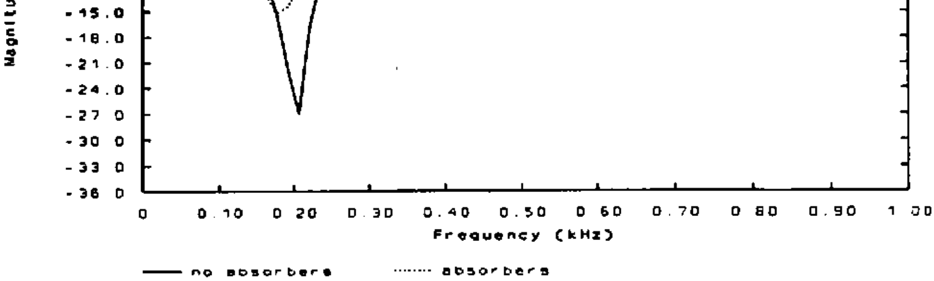


**Figure 8:** Transfer function (first 4.8 ms) across stalls, with and without Helmholtz absorbers between seat rows (r=5.05 metres (3 rows back), θ=87°, φ=90°).

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However, the effect of the absorbers on the dip depth varies substantially over time. In Figure 9, successively longer windows of the impulse response have been Fourier Transformed, with the start of the window held constant. The minimum of each FFT spectrum - i.e. the extent of the 'seat dip' - has been plotted against the time at which the window ends, referenced to the arrival of the direct sound. This gives a picture of how the maximum attenuation at the receiver evolves with time.

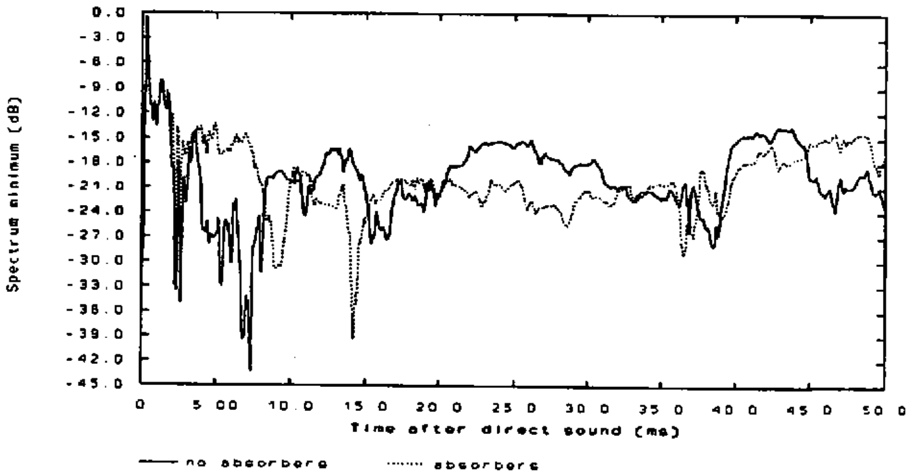


**Figure 9:** Minimum of seat dip spectrum versus duration of FFT window, with and without Helmholtz absorbers between seat rows (r=5.05 metres, θ=87°, φ=90°).

The first large attenuation occurs 2.4 ms after the direct sound. This is probably caused by a reflection from the floor in front of the seating block, as predicted by the simple model of Figure 1(a). No absorbers were placed here, so the attenuation is not affected. The next substantial attenuation occurs in the region 3.6 - 8.3 ms, when low-order diffracted reflections arrive from the floor between the seat rows, also as shown in Figure 1(a). These seem to have been substantially attenuated by the floor absorbers, as here the 'non-absorber' attenuation is an average of 12 dB below the 'absorber' case.

Between 8.3 and 12 ms, however, the attenuation for the absorber case is worse. It is tentatively proposed that this later attenuation is partially caused by sound reflecting many times between seat back, floor and seat squab. It is not unreasonable to suppose that the phase relationships between these complex paths may be adversely affected by the absorbers, so that destructive interference is increased for some points in time.

A reflection from the balcony should arrive at 12 ms, and the first one from the side wall at 23 ms. The non-absorber case shows a decrease in attenuation in these regions, probably due to the reflections arriving at a lesser vertical angle of incidence than did the direct sound. The attenuation for the absorber case is also worse here. In particular, using absorbers seems to have caused a dramatic increase in destructive interference for a short time, at 14.3 ms.

The performance of the absorbers is highly dependent on the measurement geometry, and varies from seat to seat in the hall. It does not seem to be closely related to any single parameter. The graph of spectrum minimum versus time looks quite different from Figure 9 for a receiver at the same angle of incidence but three rows further back, for example.

## 5. SUBJECTIVE IMPORTANCE OF ATTENUATION

Although much work remains to be done before the physical understanding of seat-dip attenuation is complete, the most urgent need is for an assessment of it's subjective importance. Whilst large attenuations appear in low-frequency early sound in the above measurements, it has been proposed [1] that these are compensated by low-frequency reverberant energy. That the frequencies subject to seat-dip attenuation are important for spaciousness, has been clearly demonstrated by Morimoto and Maekawa [10]. In their experiment, the inter-aural cross-correlation (IACC) and lower cut-off frequency of a stimulus were varied independently and subjects asked to equalise spaciousness. It was found that 'an increase of spaciousness caused by the components of 100 - 200 Hz is great, and is equivalent to an increase of spaciousness caused by the reduction of IACC from 0.8 to 0.5.'

The sensitivity of the ear to delay at low frequencies for a music stimulus is less clear, however. It is hoped to publish results soon of the difference limen for perception of the bass component in early reflections in a concert hall simulator. These should help decide whether seat-dip attenuation is really significant in concert halls, and whether floor absorbers are needed.

## 6. REFERENCES

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