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Considerations in characterising an almost anechoic room for interactive spatial audio reproduction

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ABSTRACT

Rooms for soundfield reproduction, such as for higher order Ambisonics, should be anechoic but also require many loudspeakers. Other practical considerations, such as a weight-bearing floor, mechanical services, and available room volume may limit the anechoic performance of such rooms. One way to characterise the performance of such rooms combined with their audio system is to measure the response from each loudspeaker to the listening area (or sweet spot). However, we consider the case of a room for interactive spatial audio reproduction, where a talking person's voice is reproduced in the virtual environment for that person to hear and interact with in real-time. We consider the practicality of various characterisation techniques, such as reverberation time, sound strength and deviation from the inverse-square law, for a small room containing 157 loudspeakers before and after sound absorptive treatment.

INTRODUCTION

Room acoustical criteria for listening rooms for audio system evaluation, audio production or critical listening have been considered by many, and various standards and recommendations exist [e.g., 1, 2]. However, such criteria are primarily intended for conventional monophonic, stereophonic and multichannel audio systems (such as 5.1 channel surround sound). The acoustical requirements for audio systems with many more channels are likely to differ, depending on the degree of control of the soundfield that is required at the listening area (or 'sweet spot'), and the extent to which the audio system can exclude or compensate for room effects. This paper considers how the room acoustics of a small room housing 157 discrete channel loudspeakers were refined and characterised by the authors. The system has been used for boundary surface control [3] and Ambisonics [4, 5] reproduction formats, but this paper is concerned with the room rather than audio coding methods.

A higher-order Ambisonics (HOA) reproduction system is ideally installed in an anechoic environment. In characterising rooms, it is common for people to consider reverberation time as the primary indicator of the room's acoustic influence. However, in a small room, the reverberation time itself is probably less important than the relative energy of the reflected (reverberated) sound in the room, which in simplistic terms is determined by the room constant rather than the reverberation time. A small room possessing a short reverberation time may still have substantial energy in its reverberation (relative to the source power) which would have an appreciable audible effect on the sound quality of the reproduction system.

Small rooms are also notorious for problems associated with room modal behaviour. Simple rectangular small rooms may also have acoustic irregularities from flutter echoes. Problems from discrete reflections can occur in any size room with uneven absorption distribution. Ameliorating these problems can involve reducing the reflected energy, and so this might be achieved by adding the sound absorption required to reduce the energy of the reverberation.

While an anechoic environment is the ideal for a HOA system, it is probably impossible to make a small room containing a large number of loudspeakers anechoic. One response to this issue might be to take the view that HOA systems should not be installed in small rooms, but instead should be installed in large anechoic rooms. However, for many situations this is an impractical ideal, and the issue addressed in this paper is how an 'almost anechoic' room housing many loudspeakers should be treated and characterised.

Instead of characterising a reproduction room, an entire system (incorporating the room, audio components, and computation) may be characterised. That is the approach taken, for example, by Favrot and Buchholz [6], who assess the fidelity of their loudspeaker-based room simulation by the deviation in room acoustical parameters (of large simulated rooms) introduced by the audio and acoustic components. Such an approach is useful when a system is being developed in conjunction with the room, but not if the room is being prepared for an arbitrary or unknown audio system. On the other hand, Sun *et al.* [7] characterise a highly absorptive room intended for loudspeaker-based reproduction of spatial sound fields based on the room acoustical performance – which is the approach taken here. Their approach was to assess the reproduction room against anechoic criteria. The room of concern in this paper is much smaller than that considered by Sun *et al.*, and so as our room cannot be as sound absorptive as theirs, we are not qualifying it as anechoic, but characterising it in relation to anechoic criteria.

DESCRIPTION OF THE ROOM

The surrounding loudspeaker room is a small rectangular room, 5.18 m x 3.38 m x 2.52 m (height). Hence its surface area is 78 m^2 and its volume is 44 m^3. It is a stand-alone construction within a pre-existing room, designed for moderate acoustic isolation. Pre-existing sound absorption within the room includes some fabric-faced fibre-glass panels on the walls and absorbers triangulating three of the four vertical edges of the room (Figure 1). The room walls, floor and ceiling probably also significantly absorb low frequency sound, as they are fairly lightweight.

The loudspeakers in the room are in cylindrical sealed enclosures, distributed evenly over the four walls and ceiling (Figures 1 and 2). The loudspeaker grid spacing is 0.5 m, and the face of the loudspeakers is 0.3 m from the room surface behind them. The loudspeaker driver is Fostex FE83E, with a nominal diameter of 0.1 m, and the cylindrical enclosures mean that the driver covers almost the entire loudspeaker face (thereby minimising acoustic reflections from the face).

Figure 1. Photograph of the room prior to acoustic treatment, showing a fibre-glass panel on the left wall, an edge absorber, and the cylindrical loudspeakers.

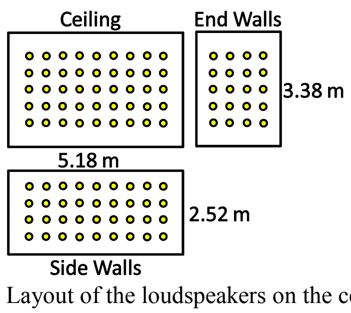

Figure 2. Layout of the loudspeakers on the ceiling and walls.

HOA reconstructs a soundfield at and around a sweet spot, and so our interest in the acoustic performance of the room is focused on the acoustics at the sweet spot that we defined for the HOA audio system (as well as the transfer function from each loudspeaker to the sweet spot, which is not the concern of this paper). The sweet spot that we chose is at $x = 2.59$ m, $y = 1.69$ m, and $z = 1.26$ m (i.e., seated height in the middle of the room plan).

Prior to modifying the room in the way described below, the room was used quite often for informal demonstrations of HOA reproduction (using recordings and auralizations). Although we argue in this paper that the room required the acoustic treatment that was subsequently applied, the demonstrations without room treatment were nevertheless almost universally well-received.

Modified room

Our acoustic treatment of the room was simple – we added a porous sound-absorbing material over almost the entire surface of the room (50 mm thick fibrous batts made from recycled polyethylene terephthalate, or PET). Over the four walls and ceiling, the pre-existing metal frame that supported the loudspeakers was used to support the batts. The 0.3 m space between the loudspeaker face and the room surface was filled with layers of this absorptive material – typically four layers were used within this space. A single 50 mm layer of the material was used to cover the floor. Indicative values for the normal incidence absorption coefficient of four layers distributed over this depth are given in Figure 3 (measured using the transfer function method using a Brüel & Kjær type 4206 0.1 m diameter impedance tube). The effective absorption coefficient of the surfaces involves several complicating considerations, such as the incidence angle of the sound (normal incidence coefficients are likely to be less than those for larger incidence angles), the reflective properties of the loudspeakers and other exposed elements in the room, the pre-existing absorption of the underlying room surfaces, and the variations in the lining configuration over the room surfaces.

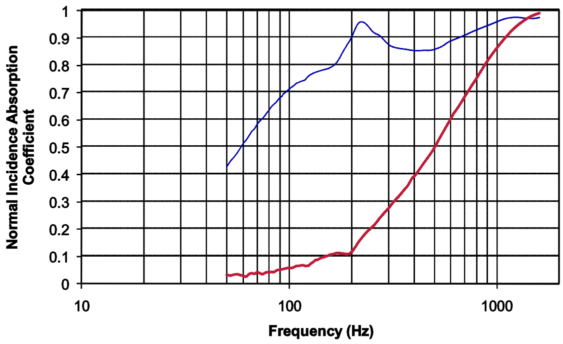

Figure 3. Normal incidence sound absorption coefficients of one 50 mm layer of the PET sound absorbing batt (no air gap, shown in red), and of the room lining as it was typically applied (four layers of 50 mm PET fibrous absorber distributed over a 300 mm depth, shown in blue).

Figure 4. Photograph of the room after acoustic treatment.

It is worth noting that as absorption is progressively introduced into a room, the acoustic effect of surfaces that have not yet been treated becomes audibly more prominent. Comb-filtering and other delay interference phenomena are obvious when there is just one reflection source, whereas the presence of other reflections serves to soften or obscure such phenomena. Although the floor had not been considered to be an acoustic problem prior to the installation of wall and ceiling absorption, after the walls and ceiling were treated, the reflection from the floor had a strong undesirable effect on the tone of the loudspeakers (the low loudspeakers had a short floor reflection delay at the sweet spot, and higher loudspeakers had longer floor reflection delays). This was largely solved with the installation of a single layer of batts over the entire floor.

CHARACTERISATION METHODS

Room acoustical performance can be assessed in many ways, and in this section we briefly review some options that could be applied to the small absorptive room under consideration.

Reverberation time

Reverberation time, as a function of frequency, is very often used to assess sound studios and listening rooms. However, measuring very short reverberation times can introduce some artefacts if techniques that work for more typical rooms are applied without due care. In small rooms, the source and receiver are likely to be in close proximity, which can lead to a relatively high direct sound level – meaning that measuring from -5 dB in the reverse integration curve may be inappropriate. The filters used for octave or 1/3-octave band analysis introduce time-smearing, which can influence measurements: time-reversing the signal prior to applying a minimum phase filter spreads the time-smear 'upstream' which can reduce this error in highly absorptive rooms. The loudspeaker itself also introduces some temporal distortion, thereby limiting the measurement of short reverberation times. Care is also needed with regard to the frequency-dependent truncation of noise prior to reverse-integration [8], and we followed the suggestion of Morgan [9]. Reverberation time may be estimated from various evaluation ranges, and we used visual inspection of the regression function in comparison with the reverse integrated level decay to select the best evaluation range for each band.

Another issue with reverberation time is the question of whether it is used to describe the acoustics of the whole room or the acoustics of particular locations within a room. In its more formal use, it should be used to describe the whole room, through spatial averaging. However, our interest in this paper is primarily with the sweet spot, and so our assessment of reverberation is focussed at and around this position.

Room gain

Another approach that can be taken to characterise such spaces is to measure the room gain, G_{RG}, as described by Brunskog *et al.* [10]. Room gain is concerned with the effect of a room on the sound of a person's speech at their own ears as they talk. It is measured from the mouth to ears of a head and torso simulator, and is the ratio of energy received at the ears in the room to that received in an anechoic room, expressed in decibels.

Room gain is of particular interest in this context because one envisaged application for the room is to have a subject hearing their own voice reflected in a simulated room as they speak, and G_{RG} is a way of directly quantifying how much sound from the voice is likely to arrive at the ears due to the room's acoustics (and thus suggests the minimum G_{RG} possible in any simulation). Unfortunately we were unable to measure room gain in this room due to the unavailability of a head and torso simulator that incorporated a mouth simulator.

Parameters related to room gain

There are various alternatives for quantifying the added sound energy from a room, relative to the sound from the source in an anechoic environment [11]. Strength factor (G) and stage support (ST), which are used in large rooms, could perhaps be adapted for small room use. In the latter case, the measurement is concerned with almost co-located source-receiver positions, and so the underlying concept is well suited to the measurement of room reflected sound at the sweet spot. The difficulty with calculating ST directly is that reflections from room surfaces arrive much earlier than assumed in the integration periods of ST. The 10 m reference distance in the calculation of G is probably inappropriate for evaluating small rooms, and perhaps a reference distance of 1 m would be better (i.e., a -20 dB offset), together with a measurement distance of 1 m (thereby creating a measure in some ways comparable to ST, except that the entire squared impulse response is integrated in the numerator).

Deviation from the inverse square law

Anechoic rooms are qualified by measuring sound pressure level along traverses that extend away from the acoustic centre of an omnidirectional sound source in the room [12]. Ideally sound pressure is inversely proportional to the distance from the acoustic centre (or equivalently, pressure squared is proportional to the inverse square of distance). The deviations from the inverse square law are related to factors such as the degree to which the loudspeaker is omnidirectional (including near-field effects), the presence of reflections and room modes, and the signal used for analysis (larger deviations are seen for pure tones than for 1/3-octave bands of noise) [13].

Although the surrounding loudspeaker room is not anechoic, even in its treated state, this approach has some potential for assessing the room conditions, because the ideal condition of the room is anechoic. However, we are only interested in the movement of a person's head in the horizontal plane around the sweet spot, so we have only measured horizontal traverses in the present study.

Loudspeaker characteristics

The main loudspeaker used to test the surrounding loudspeaker room was a small dodecahedral loudspeaker, with a diameter of about 0.1 m. Of course, the ideal loudspeaker is omnidirectional, has its impulse response energy within an instant, and has a flat frequency response (which would occur if the second condition were met). A dodecahedral loudspeaker is approximately omnidirectional, and in the high frequency range is better described as multidirectional. It does not have an instant impulse response, and the range in time delay from the various drivers can often be seen in the direct sound of a dodecahedral loudspeaker (the time response also may not be instantaneous because the drivers and enclosure may not be fully damped). The fine and coarse frequency responses will not be flat for several reasons, including the radiation impedance of the loudspeaker and interference between the drivers. The small dodecahedral loudspeaker that we used radiates omnidirectionally, within the constraints of ISO/DIS 26101, at and below the 3.15 kHz 1/3-octave band (as tested by the authors in a large anechoic room). It produces sufficient acoustic power at and above the 100 Hz 1/3-octave band using a swept simusoid to derive the room impulse response (its reponse at 100 Hz is -12 dB relative to the peak).

For traverse measurements, we also constructed a high frequency loudspeaker using a pipe, as described in ISO/DIS 26101 (1.5 m long, 6 mm internal diameter). This type of loudspeaker takes the sound from a driver into a long thin pipe, releasing it into the room at the other end of the pipe – thereby approximating a point source. We ensured that sound leakage was insignificant by using a double-walled damped stainless steel pipe over much of its length, and used a triple-walled box around the driver with damping in the interstices. The external surface of the box was faced with porous sound absorbing material so that the loudspeaker did not become a source of reflections. While this loudspeaker is omnidirectional over a wide frequency range, the pipe is resonant, which shapes both the frequency and time response of the loudspeaker. In a highly absorptive room, the time response of the loudspeaker is likely to be longer than that of the room that is being tested (this loudspeaker's mid-frequency reverberation time was about 0.07 s, with stepped reverse integration curves). The loudspeaker exhibited an average spectral peak spacing of 112 Hz (with both odd and even harmonics present).

RESULTS

Reverberation time

The reverberation time of the unlined room was measured with the dodecahedral loudspeaker at the sweet spot, and microphones at various distances and angles on the horizontal plane. The mid frequency reverberation time is about 0.2 s, and octave band values are shown in Figure 5. Figure 5 also shows the apparent reverberation time of the treated room, which is similar to the reverberation time measured using the same loudspeaker and analysis procedures in a large anechoic room. The similarity between these values suggests that the result for the treated room is not due to the room (but instead is due to the loudspeaker and other factors – differences between the treated room and anechoic room may be due to measurement error). The octave band filters (6th order Butterworth) were applied to the time-reversed impulse response, and so they had minimal effect on the reverse-integrated decay curve. Hence, reverberation time is evidently not a useful parameter to characterise the treated room, except perhaps to indicate that reverberation time is negligible.

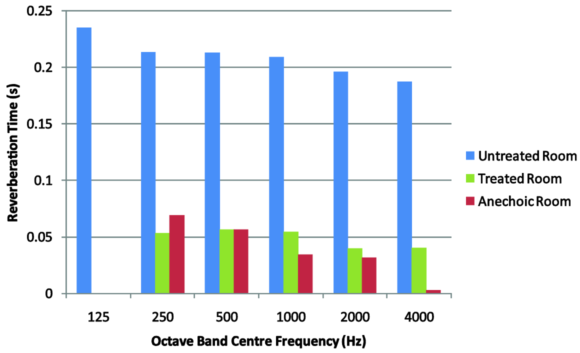

Figure 5. Measured reverberation time of the room prior to the installation of sound absorptive lining, after the installation of absorptive lining, and the apparent reverberation time of the measurement loudspeaker measured in a large anechoic room. In the latter two cases, reliable values could not be derived for the 125 Hz octave band.

Sound strength

Prior to room treatment, the room-reflected sound energy was considerable, and the modified strength factor values are given in Figure 6. These values are similar to (but a little higher than) the theoretical value of 3.3 dB which can be calculated from a room constant of 45 m^2 (which, in turn, is derived from the mid-frequency reverberation time of 0.2 s). Hence, although the reverberation time was very short by conventional listening room standards, the room-reflected sound was still playing a prominent role in the overall sound level, and this imposes a limitation on what can be realised by the audio rendering system.

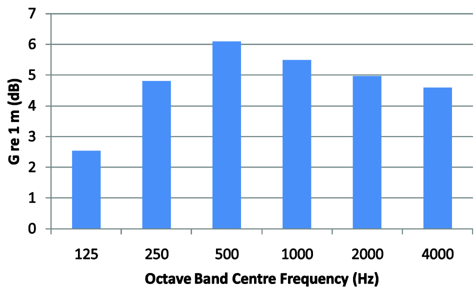

Figure 6. Measured *G*, referenced to 1 m instead of 10 m, measured at a distance of 1 m from the dodecahedral loudspeaker at the sweet spot in the untreated room.

Although we attempted to make similar measurements in the treated room, there was very little difference between the loudspeaker measured in a large anechoic room and in the treated room, and so we were not able to calculate values with any confidence. However, the *G* values (re 1 m, measured at 1 m) of the treated room would appear to be close to 0 dB.

Deviations from the inverse square law

Our most detailed measurements along traverses were made in the treated room, and these are presented here. For these, we recorded impulse responses along four horizontal traverses extending from the sweet spot (which was the position of the loudspeaker). Measurements were made at intervals of 50 mm along each traverse. Both loudspeakers were used, and the results in Figure 7 show values from the pipe loudspeaker for 1/3-octave bands at and above 4 kHz.

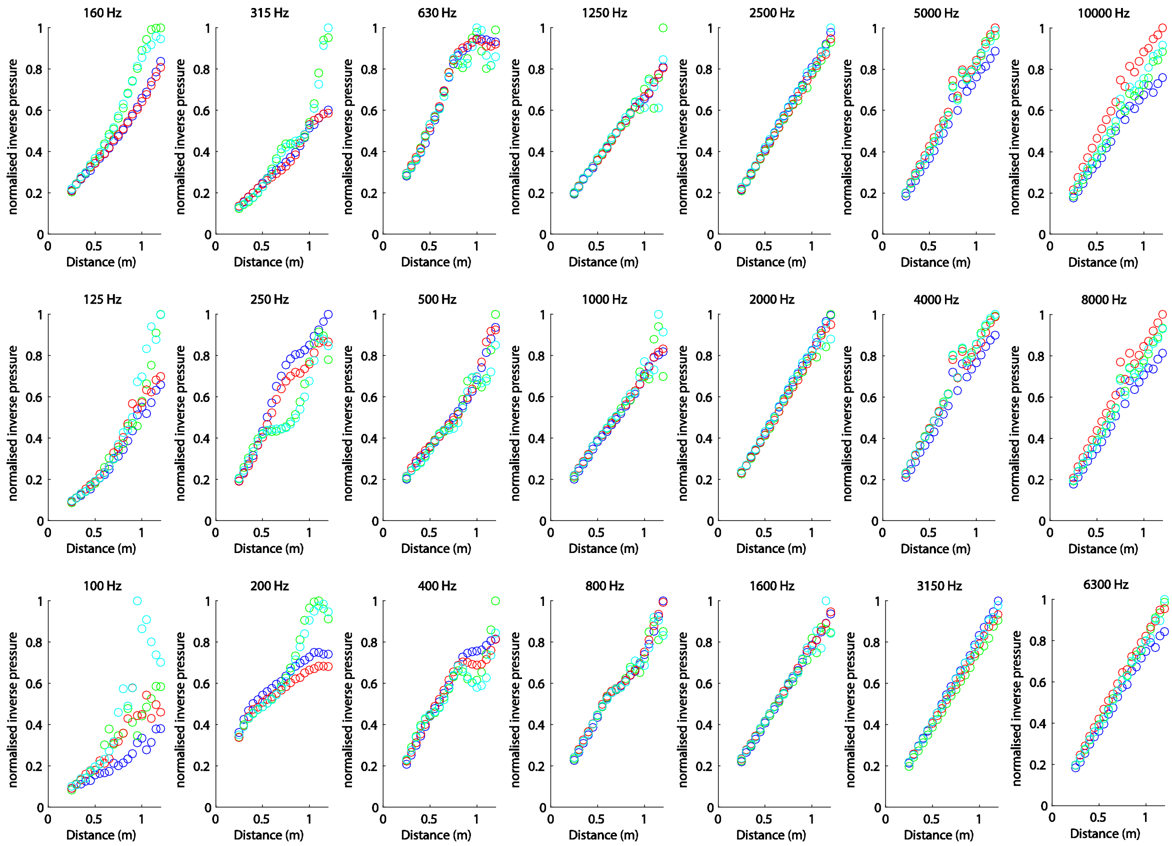

Figure 7. Inverse of pressure (the square root of integrated squared pressure) along the four horizontal traverses in 1/3-octave bands. Bands from 100 Hz – 3.15 kHz use the dodecahedral source, and bands from 4 kHz – 10 kHz use the pipe loudspeaker. The four traverses are indicated by four colours.

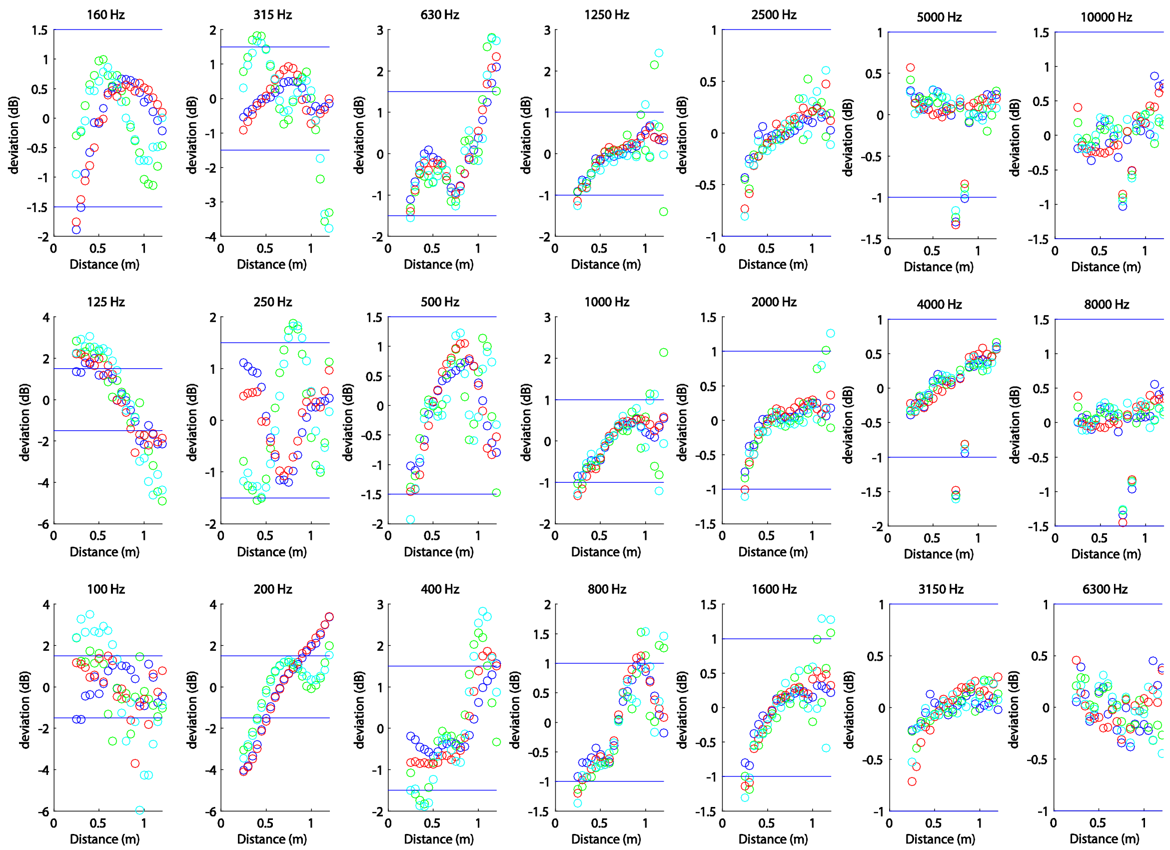

Figure 8. Deviations from the inverse-square law for 1/3-octave bands from 100 Hz-10 kHz (measured as described previously). The four traverses are indicated by four colours. The horizontal lines indicate the allowable limits for anechoic room qualification.

In Figure 7, the ideal values would form a straight line, which would intersect the origin if extrapolated. Something similar to this is seen, for instance, in the 2.5 kHz band. In the low frequency range, the room is clearly not anechoic. In the very high frequency range, there is some divergence between the data from each traverse, which is symptomatic of a loudspeaker that is not omnidirectional. Results for the pipe loudspeaker also see a disturbance at about 0.75 m, which we suspect is a measurement error (because the deviation occurs on all four traverses). Figure 8 shows the deviations from the inverse square law, together with the tolerance limits of ISO ISO/DIS 26101. Results indicate that a circle with a radius of 1 m around the sweet spot is approximately anechoic at and above the 1.6 kHz band, and deviations in some of the lower bands (from 315 Hz up) are not very far from anechoic within a somewhat smaller radius.

SUMMARY AND CONCLUSIONS

This paper presents a simple study of how the acoustics of a small room, containing many loudspeakers, could be characterised, independent of the audio system characterisation. Techniques that are used in conventional listening rooms, such as reverberation time measurement, do not produce useful data in a near-anechoic room. The untreated room considered here serves as a reminder that short reverberation times in small rooms do not mean that the room-reflected soundfield is negligible. After room treatment, we were able to assess the acoustics around the sweet spot using the traverse technique that is normally used for anechoic room qualification. Although the room was not conceived of as being anechoic, the results are not too-far removed from the inverse-square law deviation tolerance in the mid-high frequency range. However, it should be recalled that we only made measurements along horizontal traverses (due to our interest in the horizontal movement of a subject's head), and it is likely that deviations would be greater for vertical traverses (considering that the treated floor had just one layer of batts).

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