IMPROVING SOUND DIFFUSION IN A REVERBERATION CHAMBER

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Abstract

Accurate test data of the acoustic properties of materials are critical for effective engineering noise control and general acoustic design. Acoustic test facilities are custom built to enable the measurement of various acoustic parameters such as sound reduction, sound power and absorption. However these facilities have been plagued with poor inter-laboratory results due to the lack of sufficiently diffuse sound fields. This paper quantifies the acoustic utility of a reverberation chamber, specifically with regards to its diffusion levels and analyses the effect that diffuser panels have on variations in the uniformity of the sound field. The diffusion levels are analysed using the spatial uniformity of sound pressure levels, spatial uniformity of reverberation times and the degree of time series fluctuations in an impulse response. In addition the facility has been modelled with a ray-tracing program to assess the significance that the diffuser panel orientations have on the diffusion levels of the sound field. The results from these quantifiers indicate that the orientations of the diffuser panels do not have a significant effect on the diffusion levels of the sound field.

1. Introduction

In order for accurate measurements to be made in reverberation chambers, it is a requirement that the sound field be sufficiently diffuse [1-3]. A great deal of research and experimentation has been performed regarding the ways to generate a diffuse sound field in these facilities with varying degrees of success. This is mainly due to the lack of a standardised method to assess the diffusion levels in these facilities, with many experimental procedures being suggested but none being widely agreed upon by acousticians [1]. This paper deals with the testing and optimisation of the acoustical utility of Acran's transmission loss facility, specifically focussing on the diffusion levels in the receive room.

1.1. Facility description

Testing was performed in Acran's reverberation chamber located in Richlands, QLD. The chamber is part of a transmission loss suite consisting of a source and receive room. Testing was restricted to the receive room of this facility and will hereinto be referred to as the reverberation chamber. The reverberation chamber has a ceiling height of 4.275 m and a nominal volume of 170 m^3. The walls of the facility are constructed from 150 mm thick concrete tilt panels. The facility makes use of a total of 16 diffuser panels manufactured from MDF. Each panel measures 1.21 m by 0.8 m, with a thickness of 0.02 m.

Figure 1. Transmission Loss Suite (Left) and Receive Room (Right)

2. Measurement of Diffusion

Numerous techniques currently exist to quantify the diffusivity of a chamber. These include spatial uniformity (measuring the spatial variation of sound pressure levels), cross-correlation (measuring the degree of correlation between sound pressure measurements at different microphone positions), directional diffusion (using a directional microphone to measure sound levels in different directions to assess the levels of diffusion), acoustic wattmeters (measures vector energy flow to indicate diffusion levels), and reverberation time uniformity (measuring the spatial variation of reverberation times) [1]. The efficacy of these measurements has been debated and many experiments have been conducted but no consensus has been reached on which measurement should be used to accurately characterise the diffuseness of a sound field [1-4]. For example, Bradley [4] utilised three different diffusion qualifiers from different international standards while investigating the difference between hanging stationary panels and volumetric diffusers. The investigation found that measurements from these factors produced conflicting results, highlighting the lack of a standardised method to assess diffusion levels in these chambers.

It has been suggested that the development of a reference absorber is likely to be the best prospect for reducing inter-laboratory spread [5, 6]. Schultz [4] provides an excellent overview of the prevalent diffusion measurements, as well as the advantages and problems of each, but notes that none of these methods is very sensitive and the difference in test results is not large between the least diffuse condition and a room condition with almost perfect diffusion. While the concept of a diffuse field is well understood from a theoretical perspective, there are few practical methods of assessing diffusion levels [1].

2.1. Spatial uniformity of sound pressure levels

In a perfectly diffuse sound field, the sound pressure levels would be equal at different measurement points. Thus, one way of measuring the diffusion is to assess the spatial uniformity of the sound pressure field [3]. International standards [7] identify standard deviation limits for the sound pressure level to qualify measurements to be made in the sound field. It should be noted that the standard deviations prescribed by ISO 3741 were developed for a reference sound source, however the cut-off has been employed by Ramakrishnan and Grewal [3] using simple loudspeakers. This was found to provide a practical cut-off between the modal dominated region and a region where a high spatial uniformity can be obtained. Recently, a large grid of sound pressure levels has been used to assess sound fields at low frequencies to evaluate the dominance of room modes at these frequencies and suggest measurement procedures to reduce the spread of data at these frequencies [8, 9].

2.2. Spatial uniformity of reverberation times

The reverberation time is an important parameter for the calculation of acoustic parameters (such as absorption coefficients). In a perfectly diffuse field, the reverberation time measured at different points throughout the chamber would be equal. Therefore, the spatial uniformity of the reverberation time has been suggested as an easily measurable indication of diffusion, with smaller deviations being an indication of a higher-quality diffuse field [2, 4, 5]. Davy [10] calculated theoretical values for the expected spatial variance in a reverberation chamber. From his calculations, the expected theoretical spatial standard deviation can be predicted by

$$\sigma_s(T_{20}) = 0.882\sqrt{\frac{T_{20}}{B}} \ , \tag{1}$$

where T_{20} represents the reverberation time and B is the bandwidth of the frequency band. Barron [11] proposes that the ratio between the experimental spatial variation and the theoretical model can be used to assess the level of diffusion of a room. This is calculated by the Normalised Standard Deviation of Reverberation Time (NSDRT), which is defined as

$$\text{NSDRT} = \frac{\text{Measured Standard Deviation of RT}}{\text{Theoretical Standard Deviation of RT}} \, . \tag{2}$$

A NSDRT value close to unity indicates that the sound field is diffuse. This quantity is equivalent to the diffuse field factor f_d introduced in [2]. It has been noted that while a value of unity is expected in a suitably diffuse field, values that are less than predicted have been found [2].

2.3. Degree of time series fluctuations

Another method to assess the diffusion of a sound field is to analyse the time fluctuation in the reflected sound energy from an impulsive response. Hanyu [12] recently proposed a method to assess this by creating a decay-cancelled impulse response which effectively removes the decay slope of the impulse by normalising the impulse by the calculated Schroeder decay curve. The amount of diffusion present in the sound field is then evaluated by time fluctuations in the decay-cancelled impulse response. Lower time series fluctuations indicate a higher level of diffusion. This method allows the frequency characteristics of the sound field to be analysed and compared between different sound fields. The method calculates the decay-cancelled response by dividing the squared pressure fluctuations $p^2(t)$ by the Schroeder decay curve. This has the effect of removing the decay slope, leaving only the fluctuations of the curve. The decay-cancelled impulse response is calculated by

$$g^2(t) = \frac{p^2(t)}{E_s(t)} = \frac{p^2(t)}{\int_t^{\infty} p^2(\tau)d\tau} \tag{3}$$

This decay cancelled response is then normalised by the mean of the decay-cancelled response $\overline{g^2(t)}$ to give

$$h(t) = \frac{1}{\sqrt{\overline{g^2(t)}}} g(t) \tag{4}$$

From this response, the total area of the normalised impulse response is calculated as

$$R_{total} = \int_{t_1}^{t_2} h^2(t)dt \tag{5}$$

Additionally, the value $R(k)$ is calculated for cases when $h^2(t)$ exceeds a threshold value k. The probability that the relative magnitudes of sound energy compared to the average energy decay curve are above a threshold k is thus

$$z(k) = \frac{R(k)}{R_{total}} \tag{6}$$

A lower k threshold limit indicates a higher degree of the level of diffusion. Sakuma [13] analysed this method and found it to be one of the more robust estimators for room impulse response diffuseness.

These three measurement techniques were chosen as methods to assess the diffusion levels in the reverberation chamber.

3. Methodology

3.1 Sound pressure levels

The spatial uniformity of sound pressure levels was chosen as a method to assess the diffusion of the sound field. By creating a structured grid, a visualisation of the room modes at lower frequencies can be obtained to assess the diffusion levels of the chamber. A grid of measurement positions in the facility was set up and the average sound pressure level at each of these points measured. This was performed at heights of 1.26 m and 1.65 m above floor level to determine if there is any influence of vertical location on the results. From these measurements, contour plots show the uniformity of the sound field. The measurement grid was restricted to the typical measurement envelope used for sound measurements in this type of facility (i.e. at least 1m from any room boundary or diffuser).

3.2. Reverberation times

The spatial variation in reverberation times was also investigated. Measurements of the reverberation times on a three dimensional grid of points show the spatial variance of the reverberation times. The reverberation time was measured using the direct integrated impulse method by bursting balloons, as recommended in ISO 354 [14]. The reverberation times were recorded at 30 independent locations, with two source locations (at two corners of the room) being taken for each location, leading to a total of 60 measurements, with a grid spacing of 0.8 m. Measurements were taken at heights of 1.26 m and 1.65 m above floor level. This test was repeated for two other facility configurations to assess the effects of the diffuser panels. One configuration was tested with the eight bottom panels of the facility removed. The other was tested with the bottom eight bottom eight diffuser panels re-orientated at different angles in the vertical direction (i.e. panels that were originally orientated at +*x* degrees to the vertical axis were re-orientated to -*x* degrees). The tests were repeated using the interrupted noise method with a simple loudspeaker.

3.3. Simulations

In order to model the effect of differing diffuser orientations, simulations were run using the ray-tracing program, CATT-Acoustic. CATT (Computer Aided Theatre Technique) is a predictive modelling program that creates 3D geometric models to predict how a room will perform acoustically in octave bands between 125 Hz and 8 kHz, inclusive. CATT can predict echograms and room impulse responses, with its core algorithms based on various levels and combinations of actual and random diffuse ray split-up. The source and receiver positions were set up to mimic the in-situ testing performed. The simulated ray-traced reverberation time of the chamber aligned closely with the experimental values obtained (see Figure 2). The simulations were run with three diffuser arrangements: the currently implemented panel orientations, pseudo-random orientations which were created with a random number generator in Matlab and with the panels aligned vertically in the corners of the room (see Figure 3).

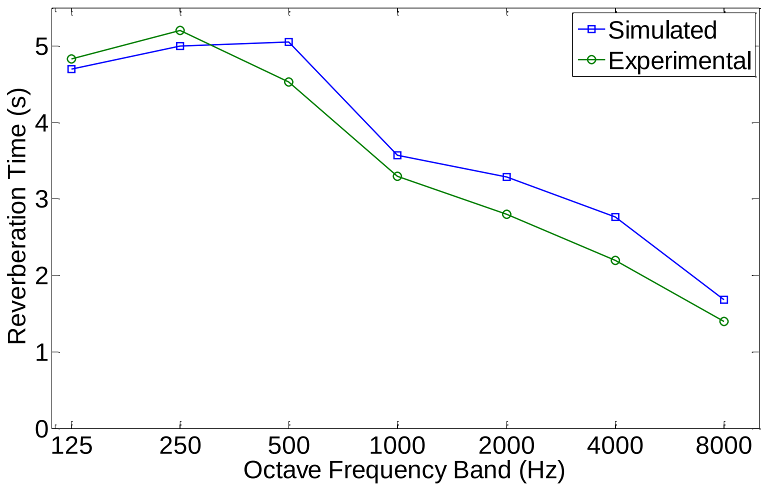

Figure 2. Reverberation time of chamber

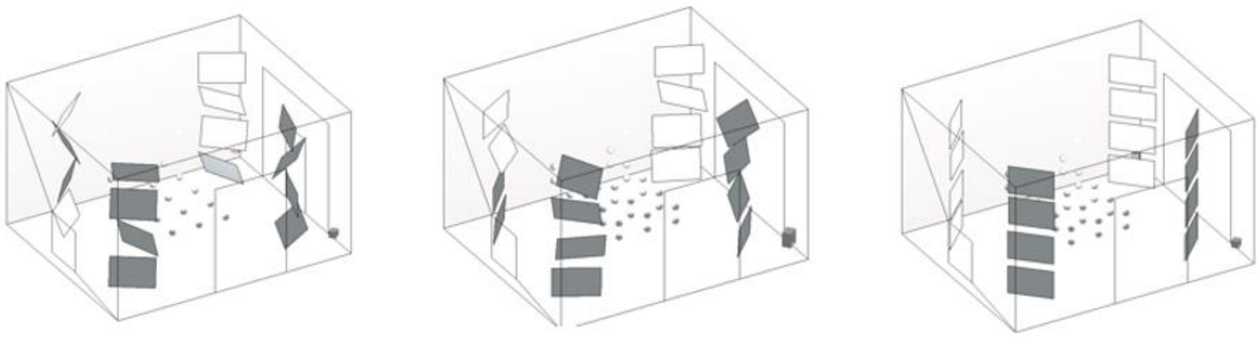

Figure 3. Orientation configurations: current design (left), randomly generated (centre), aligned (right)

4. Results

4.1. Spatial uniformity of sound pressure levels

In order to assess the dominance of singular room modes at low frequencies, the spatial distribution of sound pressure levels was investigated. The Sound Pressure Level (SPL) distributions of the third-octave bands 50 Hz to 100 Hz, inclusive, are presented in Figure 4. The existence of clearly distinguishable room modes that dominate the response are an indication that the room is not diffuse at these low frequency bands. In a diffuse field, the response should be random with only small variations in the sound field. The symmetry of plots also shows that the trends observed are from dominant room modes interacting. This is an indication of there being an insufficient number of room modes present to be able to produce a diffuse field.

It has been suggested that a cut-off between the modal dominated region and the diffuse region can be identified when the standard deviations of the response are lower than approximately 1.5 dB [3]. Table 1 presents a comparison of the standard deviations in the third-octave frequency range of 50 Hz-160 Hz. The results show the lower frequency measurements possess large deviations in the response, indicating that the sound field is quite variable at these low frequencies, producing a non-diffuse sound field. The lowest-frequency third-octave band in which a standard deviation of lower than 1.5 dB is attained is the 125 Hz band. This is also the lowest-frequency third-octave band in which the minimum 20-30 room modes is achieved, in line with the recommendation in [1]. The results indicate that there are relatively large variations in the SPLs in the third-octave bands below 125 Hz, indicating that there is low spatial uniformity in these bands and that a diffuse field is not attained below 125 Hz.

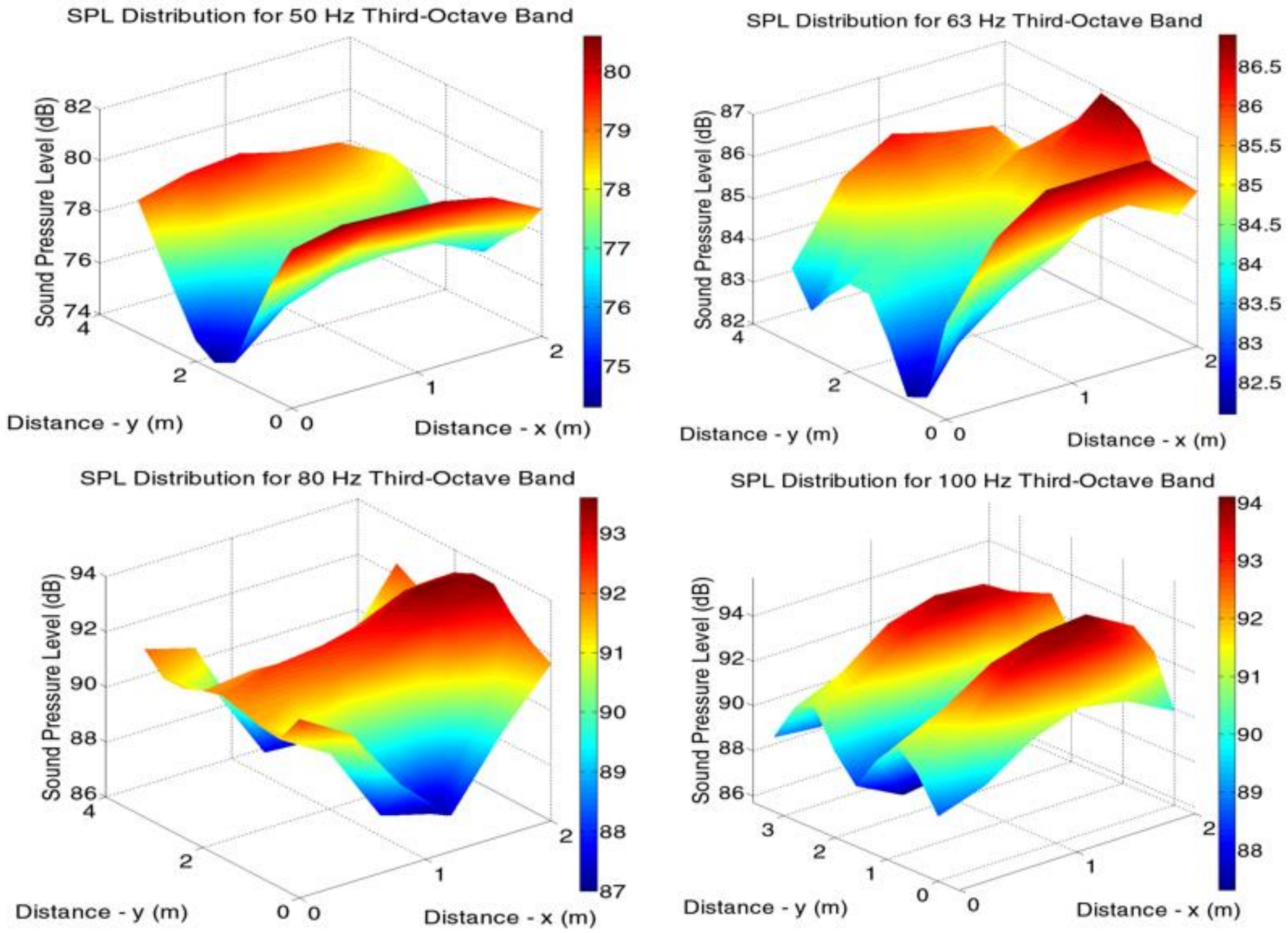

Figure 4. SPL Distributions: 50 Hz (top left), 63 Hz (top right), 80 Hz (bottom left), 100 Hz (bottom right)

Table 1. Spatial uniformity of sound pressure level (SPL)

1/3 Octave Frequency Band (Hz)	Average SPL (dB)	Range (dB)	Standard Deviation (dB)	Estimated number of modes
50	77.8	7.1	1.6	4
63	84.5	5.8	1.5	4
80	91.6	6.6	1.7	11
100	92.0	7.2	1.7	19
125	93.5	4.3	1.1	34
160	95.7	4.6	0.92	66

For higher frequency bands no discernible patterns occur, indicating that the sound field is highly uniform and can be deemed diffuse. An example of this can be seen in the results for the 200 Hz third-octave band in Figure 5. The SPL distribution at 200 Hz shows no discernible patterns and the variations in the sound field are small, with a standard deviation of 0.6 dB. Indeed, at all frequencies above and including 200 Hz, no observable patterns were found.

Simulations were run in CATT-Acoustic to analyse the effect that the orientation of the diffuser panels had on the variation of the sound pressure level distribution. All other aspects of the simulation (i.e. diffuser size & shape, speaker & receiver positions etc.) were kept constant in these configurations. The results are presented in Figure 6. The simulations indicate that the orientations of the diffuser panels have a minimal effect on the spatial variation of the sound pressure levels, with the differences between any of the configurations being of little practical significance. No configuration was shown to consistently reduce the standard deviation of the sound pressure levels in the chamber. It is concluded that altering the orientations of the diffuser panels in the present chamber will not lead to significant improvement in the diffusiveness of the room.

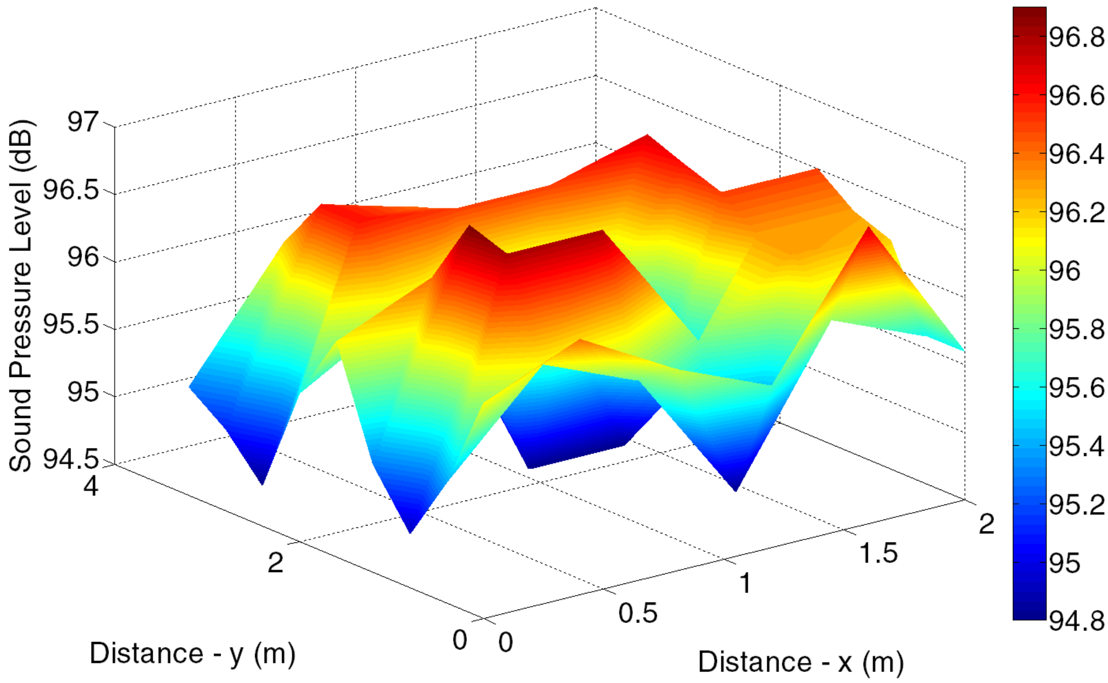

Figure 5. SPL distribution for 200 Hz third-octave band

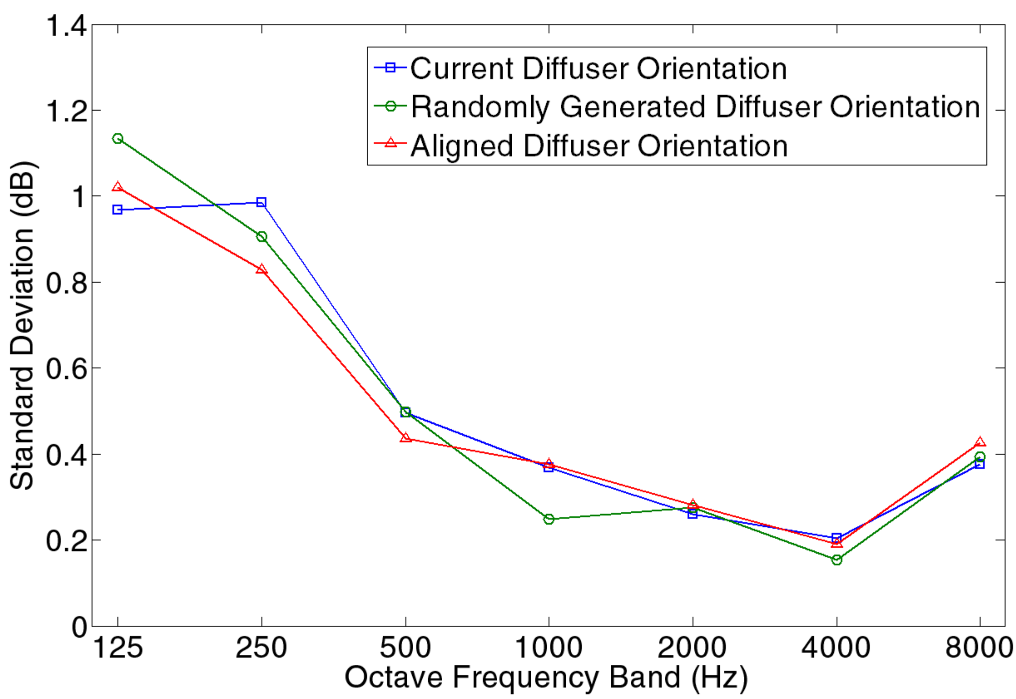

Figure 6. Standard deviation of sound pressure levels from CATT-Acoustic

4.2. Spatial uniformity of reverberation times

In order to quantify the deviations from the theoretical predictions, the Normalised Standard Deviation of the Reverberation Times (NSDRT) have been calculated using CATT-Acoustic for Octave Bands from 125 Hz to 8 kHz. The variations in reverberation times were simulated for several diffuser-orientation configurations. The configurations tested were: (1) with the diffusers in the current design configuration; (2) the diffuser panels orientated at randomly generated angles and (3) with all panels aligned to the room corners. The NSDRT values calculated for each octave band are presented in Figure 7.

From the geometric simulations, differences between any of the configurations considered were less than 25% in each octave band. Moreover, no configuration consistently reduced the spread of results. Experimental testing was also performed and the NSDRT values for these experiments are shown in Figure 8. At one-third Octave Band frequencies below 100 Hz, there are pronounced differences between the theoretical and experimental values (i.e. the NSDRT value is greater than unity), indicating the lack of an adequately diffuse sound field. This is particularly apparent for the 50 Hz frequency band, where the experimental value is almost three times the theoretical. This is likely attributable to the small number of room modes that propagate sound in preferred directions. A close agreement is obtained for the higher frequency range, indicating a higher quality diffuse field in the higher frequency range.

The NSDRT results from the integrated impulse method are compared with results from the interrupted noise tests in Figure 9. The results in Figure 9 show conflicting results between the interrupted test and the integrated impulse measurements. This is particularly pronounced in the one-third Octave Bands from 100 to160 Hz and at mid-frequencies from 500 to 1000 Hz. The low frequency responses for the interrupted noise method have much higher variations than do those for the integrated impulse method. Conversely, the mid-frequency results showed a lower spread for the interrupted noise method. A similar result was found by Lautenbach [2], where the interrupted method showed an apparently more diffuse field than the integrated impulse method. For example, the interrupted method produced a diffuse field factor (equivalent to the NSDRT) almost 3 times less than the integrated response at the highest frequency band. The cause of this discrepancy is unknown.

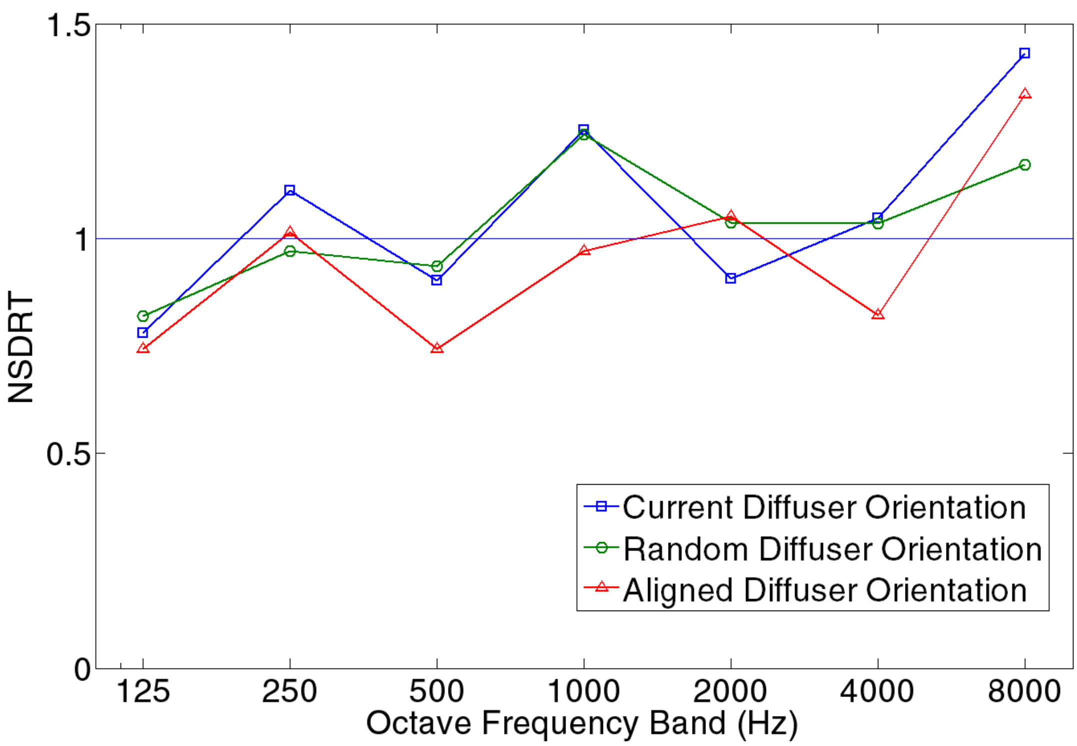

Figure 7. NSDRT from CATT-Acoustic

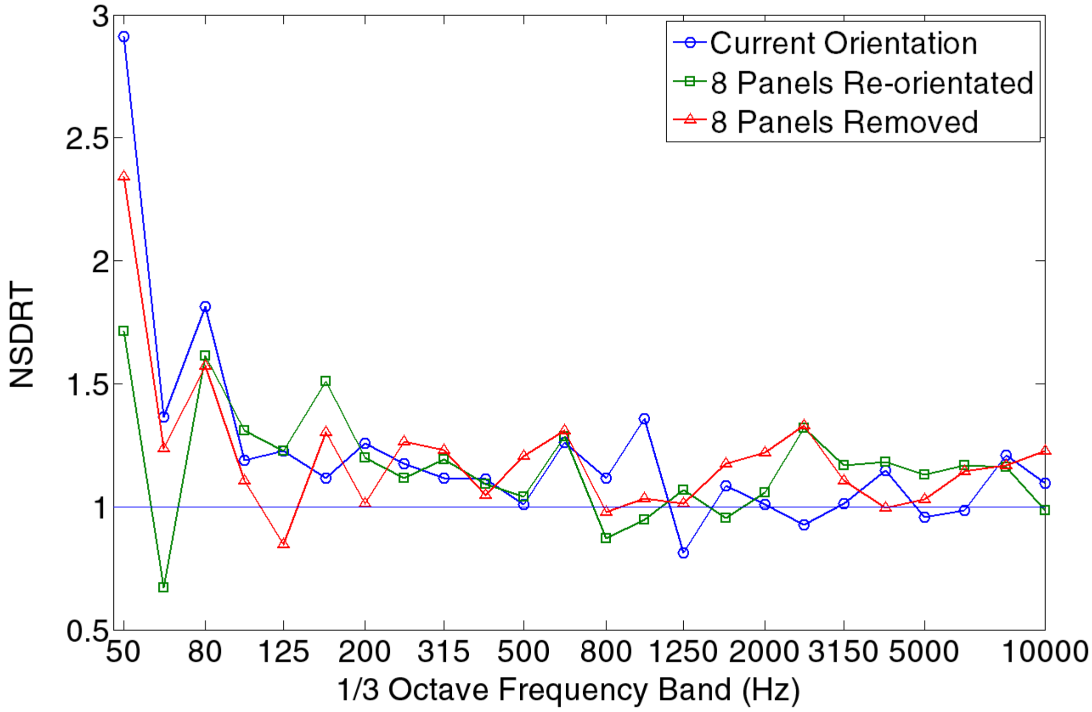

Figure 8. NSDRT for integrated impulse method

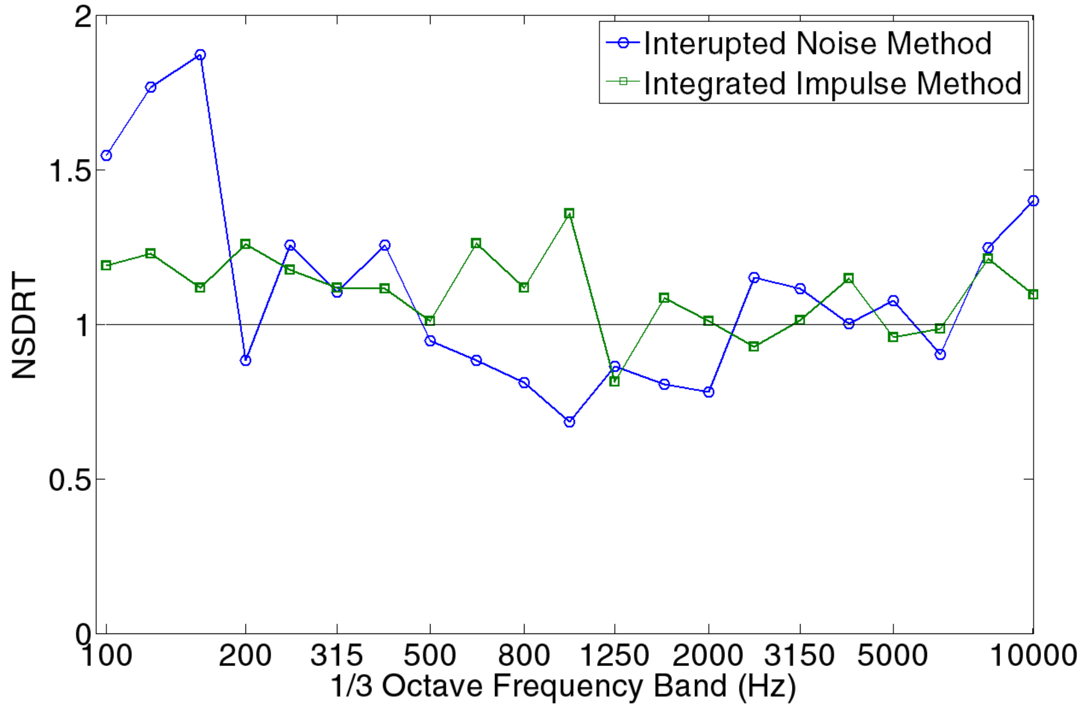

Figure 9. NSDRT: interrupted noise and integrated impulse methods

4.3. Degree of Time Series Fluctuations

From the impulse response measurements, the decay-cancelled impulse was calculated. As recommended in [12], the results have been averaged over the total number of measurements taken. The results averaged over 60 impulse measurements are presented in Figure 10.

The results in Figure 10 show that the degree of time series fluctuations is high at lower frequencies and begins to decrease after approximately the 250 Hz frequency band. No distinguishable differences were observed between the results from the three configurations tested in the facility. This indicates that the diffuser panel orientation does not have a significant practical effect upon the fluctuations of the decay curve and thus on the diffusion levels of the facility. It would also appear pertinent to assess the uniformity of the time series fluctuations in order to determine if the fluctuations are spatially uniform. In this analysis, the relative standard deviation of the time series fluctuations has been used to assess the spatial uniformity of the time series fluctuations.

The spread of results for the time series fluctuations decreases with frequency band, as is evident from Figure 11. This indicates that the degree of fluctuations is not spatially uniform at lower frequencies. From the experimental results, no orientations were shown to systematically reduce the spread of results. Thus, it is the conclusion from this quantifier that the orientations of the panels has an insignificant effect on the degree of time series fluctuations and thus on the levels of diffusion.

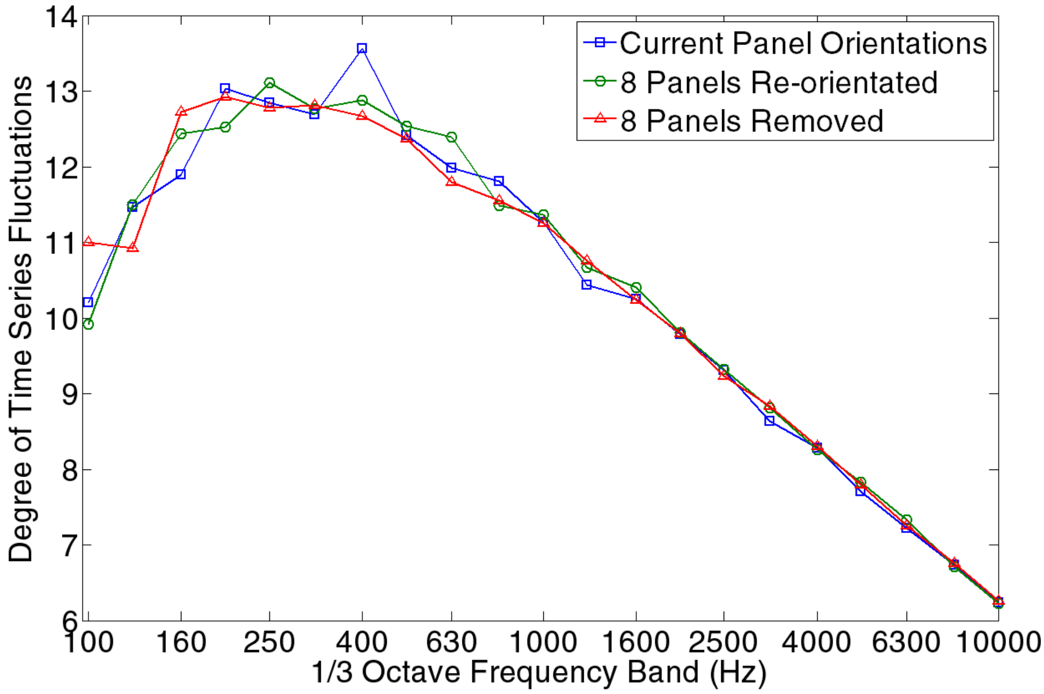

Figure 10. Degree of time series fluctuations

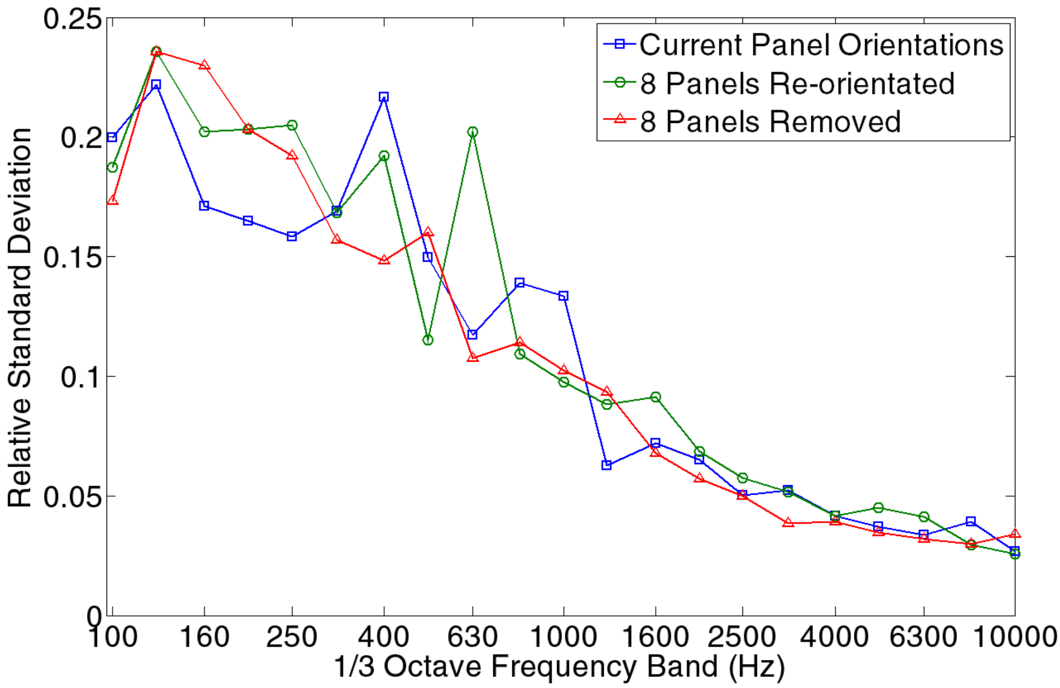

Figure 11. Relative standard deviation of time series fluctuations

5. Conclusions

It has often been stressed that diffuser panels should be randomly orientated to avoid the propagation of sound over preferred paths. However, the simulations and experimentation indicate that there is little difference between the orientations of these panels. These results indicate that there is no prospect of re-orientating the current diffuser panels to improve the level of diffusion. The introduction of a standardised measurement that accurately measures the level of diffusion in a sound field is important for future work in this field. Lack of adequately diffuse sound fields have plagued reverberation chambers for decades as there is currently no precise way to assess if the diffusion levels are sufficient. Although many methods currently exist, it has been shown that none are particularly sensitive to deviations from perfect diffusion and many do not allow for the identification of an ideal diffuser type [4].

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