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A case study on the new reverberation room built in University of Technology Sydney

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ABSTRACT

A new reverberation room has just been built at Centre for Audio, Acoustics and Vibration in University of Technology Sydney. This paper reports some key parameters of the room, which include the background noise and its spectrum, the number of modes in low frequency bands, the cut-off frequency, the standard deviation of the spatial variations of the reverberant field, the decay curves of the sound pressure level versus time, the reverberation times, and the absorption coefficients. The volume of the room is approximately 232 m^3 with a total surface area of approximately 247 m^2. The averaged overall background noise level inside the room is 23.1 dB and 18.1 dBA, the number of modes is greater than 30 in one-third-octave bands with centre frequencies of 160 Hz and above, the standard deviation of the sound pressure levels is less than 1.5 dB in one-third-octave bands with centre frequencies of 125 Hz and above, and the decay curves of sound-pressure level versus time is linear in all one-third-octave bands. The reverberation time of the room can be as long as 20 s in the low frequency range around 100 Hz, and the shortest reverberation time is about 3.1 s in the high frequency range around 5000 Hz. The equivalent sound absorption areas of the empty room in all one-third-octave bands are smaller than the threshold values specified in the standard, and the curve is smooth without any dips or peaks which differ by more than 15% from the mean values of two adjacent one-third-octave bands. The sound absorption coefficients in all frequency bands of the empty reverberation room are less than 0.02.

Keywords: Reverberation, decay curve

1. INTRODUCTION

A reverberation room is a room with low absorption (i.e. the total room absorption is small in comparison with the actual surface area) and large volume (i.e. the smallest dimension is large in comparison with the sound wavelength), designed to produce a nearly diffuse reverberant sound field (1). It can be used to measure sound absorption of materials and structures (2) and to determination sound power levels of noise sources using sound pressure precision methods (3). There is no strict dimension requirement for reverberation rooms, but it is recommended in the standards that the volume of the reverberation room shall be at least 150 m^3 (2). For new constructions, the volume is strongly recommended to be at least 200 m^3, but when the volume is greater than about 500 m^3, the sound absorption at high frequencies might be hard to be measured accurately due to air absorption (4).

The shape of the reverberation room shall fulfill certain requirements (2). For example, the length of the longest straight line which fits within the boundary of the room should be less than 1.9 times of the cube root of the volume of the room. To achieve a uniform distribution of natural frequencies, especially in the low frequency bands, no two dimensions of the room shall be in the ratio of small whole numbers. Stationary or suspended diffusers are often randomly installed (with random orientations) throughout the room to make the decaying sound field sufficiently diffuse. The size of the diffusers ranges from approximately 0.8 m^2 to 3 m^2 in area (for one side), and they can be plane or slightly curved sheets with low sound absorption and with a mass per unit area of about 5 kg/m^2. In

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rectangular rooms, the area (both sides) of diffusers usually needs to be 15-25% of the total surface area of the room to achieve satisfactory diffusion (2).

The equivalent sound absorption area of the empty room shall not exceed certain values (2). For a room with a volume of 200 m^3, this value is 6.5 m^2 for the one-third-octave bands from 100 Hz to 800 Hz. For the bands from 1000 Hz to 1600 Hz, it increases from 7.0 m^2 to 8.0 m^2 with a step of 0.5 m^2. At the bands of 2000 Hz and 2500 Hz, the values are 9.5 m^2 and 10.5 m^2 respectively. For the bands from 3150 Hz to 5000 Hz, it increases from 12.0 m^2 to 14.0 m^2 with a step of 1.0 m^2. If the volume of the room V differs from 200 m^3, these values shall be multiplied by $(V/200)^{2/3}$. The curve of the equivalent sound absorption area of the empty room versus the frequency shall be smooth without any dips or peaks which differ by more than 15% from the mean values of two adjacent one-third-octave bands.

The prediction accuracy using the diffuse-field formulae is related to the degree of sound-field diffuseness in the reverberation room (5). In some standards, there is a procedure to assist in ensuring that reverberation rooms create highly diffuse fields. For example, in Annex A of ISO 354-2006, a procedure is introduced to achieve acceptable diffusivity by using fixed diffusers. The idea is to check the change of the mean value of the sound absorption coefficients from 500 Hz to 5000 Hz with the number of diffusers until it approaches a maximum for a standard test specimen which has a sound absorption coefficient greater than 0.9 over the frequency range from 500 Hz to 4000 Hz (2). Even with this highly controlled environment in a reverberation room created and commissioned based on the standard, significant deviations in measured quantities have been found in many round-robin tests (6).

When measuring highly absorptive specimen of a certain size, the sound field in a reverberation room might not be diffuse. Furthermore, those panel diffusers introduce a number of uncertainties (7). Due to all these randomly placed panels, the acoustical behavior in the room is much more complicated, and it's not easy to determine the real acoustical effective volume and the total boundary surface of the reverberation room. Volume diffusors such as fixed reinforced concrete spherical diffusers have been used with an irregular shape and tilted walls to enhance the diffusivity in a reverberation room with the advantage of knowing the real volume and boundary area of the room (8).

Three reverberation rooms of different sizes (82 m^3, 125 m^3, and 150 m^3) and shapes prescribed by standards were studied by analyzing their capacity to approximate a diffuse sound field in terms of cut-off-frequency, number of modes, spatial uniformity of reverberant sound field, curvature of energy decay curves, accuracy of measured reverberation time and absorption coefficient (5). It is found that the measurement starting from the 160-Hz third-octave band using the 150 m^3 oblique-shaped reverberation room with the shortest vertical dimension gives a better reverberation time prediction accuracy and smaller sound pressure level spatial variation than the other reverberation rooms of different volumes and shapes.

A new reverberation room has just been built at Centre for Audio, Acoustics and Vibration in University of Technology Sydney (UTS). This paper reports some key parameters of the room, which include the background noise and its spectrum, the number of modes in low frequency bands, the cut-off frequency, the standard deviation of the spatial variations of the reverberant field, the decay curves of the sound pressure level versus time, the reverberation times, and the absorption coefficients.

2. THE REVERBERATION ROOM AT UTS

2.1 Dimensions

The reverberation room at UTS comprises an inner shell of concrete walls forming four walls and a roof, all mounted on a designed concrete floating slab floor which in turn is floated on correctly loaded anti-vibration mounts to reduce the inference from surround sound and vibration. The room has two double leaf triple seal access doors with the dimension of 1.30 m wide and 2.54 m wide, respectively. The structural opening for measuring the transmission loss with a receiving room is about 3.83 m wide and 2.99 m high with a clear opening 3.37 m wide and 2.99 m high. For the tests that only use the reverberation room, the opening is closed with a two double-leaf triple-seal thick door. Four randomly placed transparent perspex plane panels are suspended as diffusers from the roof of the room to tune the acoustics to meet the requirements of ISO 354. The size of the panel is 1.50 m × 1.20 m × 0.01 m. Figure 1 shows the geometry of the reverberation room, where *HT* means the height of wall from floor level and all units are in millimeter. Figure 2 shows 2 photographs inside the reverberation room.

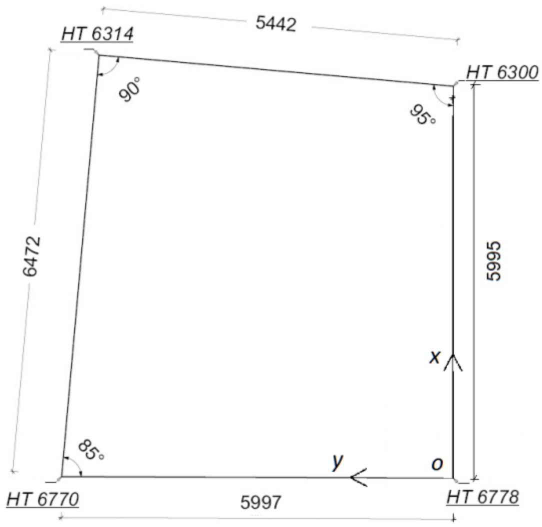

Figure 1 – Geometry of the reverberation room, where *HT* means the height of the wall from floor level with the default units being millimeter

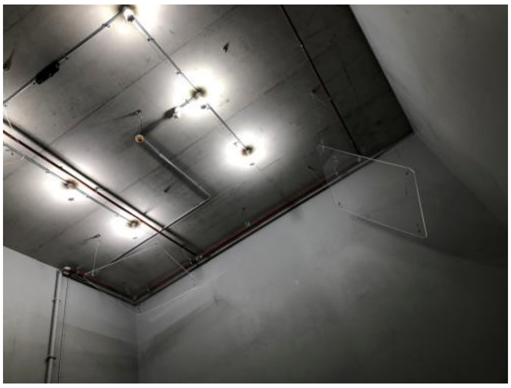

Figure 2 – Photographs of the reverberation room at UTS

Measurements were taken in 18 one-third-octave bands with the centre frequencies of 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz, and 5000 Hz according to ISO 354. The background sound pressure level was measured by using a Brüel & Kjær hand-held analyzer (Type 2250), and the other parameters were measured by Brüel & Kjær 4191 1/2" microphones with a Brüel & Kjær 4292-L high-power omnidirectional loudspeaker. The positions of the microphone and the sound source used in the measurements are listed in Table 1, and the origin of the coordinate is at the right bottom corner of the floor of the room as shown in Figure 1. The temperature and relative humidity in the room during the measurements are 22.8°C and 68%, respectively.

2.2 Background Noise

The background noise was measured at the 6 microphone positions shown in Table 1 following the requirements of ISO 354. The averaged measured values (arithmetic mean value of the values at the 6 microphone positions) in the 18 one-third-octave bands and the absolute criteria for background noise specified in ISO 3741 are shown in Figure 3. The averaged overall background noise level of the sound pressure level in the whole frequency band is 23.1 dB and 18.1 dBA.

Table 1 – The positions of the microphone and sound source in the measurements

Items	x (m)	y (m)	z (m)
Microphone 1	3.88	4.23	1.23
Microphone 2	5.14	2.66	1.23
Microphone 3	3.66	1.22	1.23
Microphone 4	1.08	3.62	1.23
Microphone 5	2.65	4.61	1.23
Microphone 6	2.27	1.01	1.23
Source 1	4.79	5.84	1.45
Source 2	5.50	0.66	1.45
Source 3	0.41	1.80	1.45

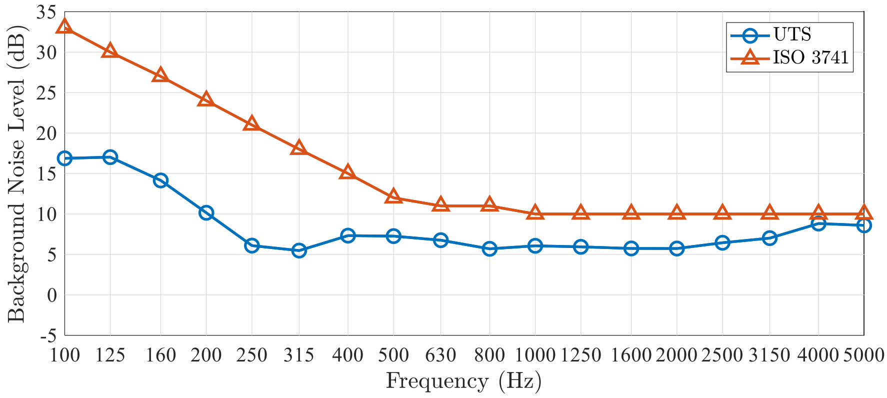

Figure 3 – The average background noise levels in the reverberation room at UTS measured with a Brüel & Kjær Type 2250 hand-held analyzer and the criteria for background noise specified in ISO 3741

2.3 Number of Modes in Low Frequency Bands

Figure 4 shows a typical frequency response measured at one corner of the room (0.80, 0.75, 1.23) m with a loudspeaker at the opposite corner of the room (5.80, 4.80, 1.45) m using the sweep sine waves, and the number of modes in the first 4 one-third-octave bands in the low frequency range are shown in Table 2. Because 20 is the minimum number of modes required for sufficient field diffuseness, it seems that the reverberation room at UTS meets the requirements for one-third-octave bands with centre frequencies of 160 Hz and above.

2.4 Spatial Variations of the Reverberant Field

The standard deviation of the sound pressure levels measured at six microphone positions for a sound source position in a one-third-octave band can be calculated with Eq. (1) following Chapter 8.4.1 of ISO 3741,

$$s_{\mathrm{M}} = \sqrt{\sum_{i=1}^{N_{\mathrm{M}}} \frac{(L_i - L_{\mathrm{M}})^2}{N_{\mathrm{M}} - 1}} \tag{1}$$

where L_i is time-averaged sound pressure level in the one-third-octave band measured at the ith microphone position, L_{M} is the arithmetic mean value of the time-averaged sound pressure levels in one-third-octave band measured at the six microphone positions, and N_{M} = 6 is the number of microphone positions. Table 3 lists the averaged standard deviation of the sound pressure levels for the 3 sound sources, which should not exceed 1.5 dB in any one-third-octave band. In this room, the averaged standard deviation of the sound pressure levels at 100 Hz exceeds 1.5 dB, so more diffuse panels might be needed in the room.

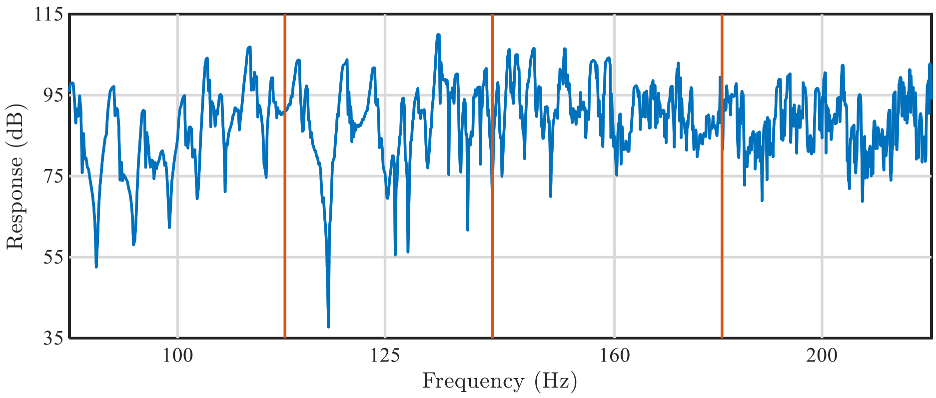

Figure 4 – A typical frequency response in the reverberation room at UTS, where the vertical lines are used to illustrate the first 4 one-third-octave bands with centre frequencies 100 Hz, 125 Hz, 160 Hz and 200 Hz.

Table 2 – Number of modes in the first 4 one-third-octave bands in the reverberation room at UTS

Frequency Band (Hz)	100	125	160	200
Number of Modes	17	17	33	54

Table 3 – The parameters of the reverberation room at UTS

Frequency (Hz)	Averaged standard deviation of the SPL (dB)	Mean RT (s) (interrupted noise method)	Sound absorption area (m^2)	Sound absorption coefficients
100	2.2	15.0	2.43	0.0099
125	1.2	19.3	1.86	0.0075
160	1.2	14.4	2.47	0.010
200	1.1	12.9	2.73	0.011
250	0.8	12.0	2.87	0.012
315	0.6	11.4	2.91	0.012
400	0.5	10.7	3.01	0.012
500	0.5	10.3	2.99	0.012
630	0.3	9.6	3.06	0.012
800	0.2	8.9	3.19	0.013
1000	0.3	8.9	2.99	0.012
1250	0.3	8.1	3.20	0.013
1600	0.2	7.3	3.44	0.014
2000	0.3	6.3	3.80	0.015
2500	0.2	5.6	4.03	0.016
3150	0.3	4.7	4.40	0.018
4000	0.3	3.9	4.75	0.019
5000	0.4	3.1	5.01	0.020

2.5 Decay Curves of the Sound Pressure Level versus Time

Degree of linearity of temporal-decay curves can be a good indicator of field diffuseness. The decay curves of sound-pressure level versus time should be linear to conform to the assumption of the diffuse-field theory. For each microphone/loudspeaker position, the decay curve is obtained by averaging 3 measurements as required by Chapter 7.2.2 of ISO 354. The decay curves recorded at different microphone/loudspeaker positions shall not be averaged. Figure 5 shows the decay curves of the sound pressure level versus time at all microphone positions in the one-third-octave bands of 100 Hz, 500 Hz, 1000 Hz and 5000 Hz with the sound source at position 1. The decay curves over 12.5 s are present. Following Chapter 7.4.1 of ISO 354, the evaluation of each decay curve for each frequency band shall start at 5 dB below the initial sound pressure level, the evaluation range shall be 20 dB and the bottom of the evaluation range shall be at least 10 dB above the overall background noise of the measuring system.

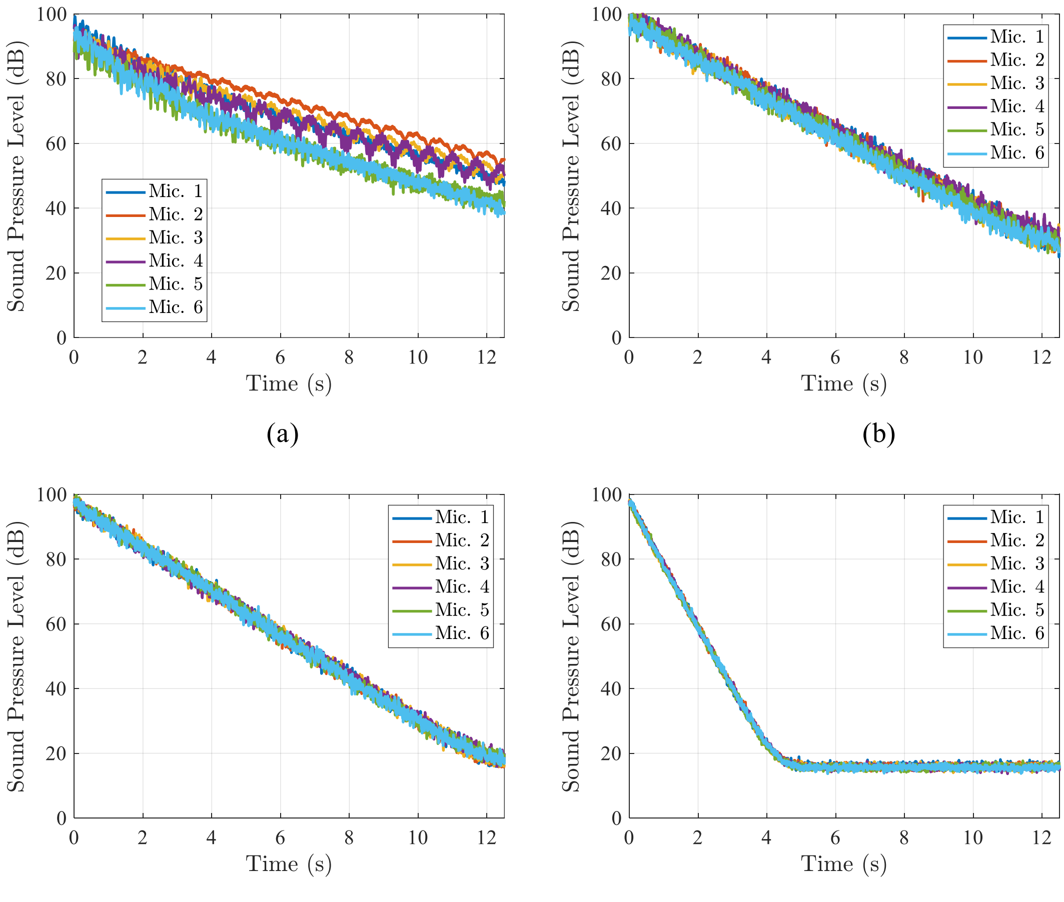

Figure 5 – Decay curves of the sound pressure level versus time for the 6 microphones with the sound source at position 1, (a) 100 Hz, (b) 500 Hz, (c) 1000 Hz, (d) 5000 Hz.

2.6 Reverberation Time

The interrupted noise method is chosen to measure the reverberation time as specified in Chapter 7.2 of ISO 354. The excitation time is set to 20 s in the experiments which is at least half of the estimate of the expected reverberation time in order to obtain steady-state conditions according to Chapter 7.2.1 of ISO 354. The number of spatially independent measured decay curves shall be at least 12. Six microphone positions and 3 sound source positions have been used, and their positions follow the guidelines specified in Chapters 7.1.2 and 7.1.3 of ISO 354. The mean reverberation time of the room in each frequency band is expressed by the arithmetic mean of the reverberation time measured in the frequency band as specified in Chapter 8.1.1 of ISO 354.

According to Chapter 3.2, the reverberation time (the time with a sound pressure level decrease by 60 dB) can be fulfilled by linear extrapolation of shorter evaluation ranges. The evaluation ranges for reverberation time (RT) calculation are 20 dB for lower frequency bands and 30 dB for higher frequency bands. Table 3 lists the mean RT values using the interrupted noise method as specified in ISO 354. The reverberation time can be as long as 20 s in the low frequency range around 125 Hz, and the shortest reverberation time is about 3.1 s in the high frequency range around 5000 Hz.

2.7 Sound Absorption Areas and Absorption Coefficients

As defined in Chapter 6.1.4 of ISO 354, the equivalent sound absorption area of the empty room shall not exceed certain values. For this room with a volume of 232.0 m^3, this value is 7.15 m^2 for the one-third-octave bands from 100 Hz to 800 Hz. For the bands from 1000 Hz to 1600 Hz, it increases from 7.7 m^2 to 8.8 m^2 with a step of 0.55 m^2. At the bands of 2000 Hz and 2500 Hz, the values are 10.5 m^2 and 11.6 m^2, respectively. For the bands from 3150 Hz to 5000 Hz, it increases from 13.2 m^2 to 15.4 m^2 with a step of 1.1 m^2.

The equivalent sound absorption areas listed in Table 3 are calculated with Eq. (5) in ISO 354 using the mean measured reverberation time of the room in each frequency band in Section 2.6. In the calculation, the volume $V = 232.0$ m^3, the sound speed $c = 344.7$ m/s, and the power attenuation coefficient $m_1 = \alpha/[10\times\log_{10}(e)]$, where α is the attenuation coefficient due to atmospheric absorption calculated according to ISO 9613-1 (9). Figure 6 shows the curve of the equivalent sound absorption area of this empty room versus frequency. The curve is smooth without any dips or peaks which differ by more than 15% from the mean values of two adjacent one-third-octave bands.

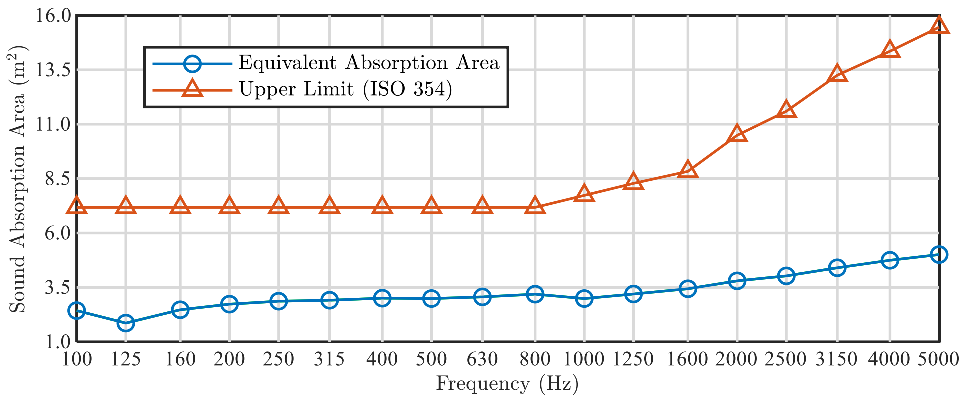

Figure 6 – The equivalent sound absorption area of this empty room versus the frequency

The sound absorption coefficient of the empty reverberation room in each frequency band is calculated by dividing the equivalent sound absorption area of the empty room with the total surface area (walls, ceiling, floor and two sides of each diffuse panels) in the room. In the calculation, the areas of the four walls are 42.34, 34.32, 38.74 and 40.62 m^2 respectively; the area of the ceiling is 41.22 m^2; the area of the floor is 35.43 m^2, and areas of the panel diffuses are $1.80 \times 8=14.40$ m^2, so the total surface area of the room is 247.2 m^2. The results are also listed in Table 3. The absorption coefficients in the low frequency range below 160 Hz is less than 0.01. In the frequency range from 200 Hz to 2000 Hz, it increases from 0.01 to 0.015. About 2000 Hz, the absorption coefficients are greater than 0.015, and the maximum value is approximately 0.02 at 5000 Hz. The absorption coefficients in all frequency band are less than 0.02.

Future work includes measuring the sound absorption coefficient with sound absorption materials, comparing the test results with that from other acoustics labs in the world (round robin tests), studying the effects of the diffuse panels and optimizing the location and number of the diffusers, exploring new materials and structures for better sound diffusion, and building up a fast measurement system.

3. CONCLUSIONS

A new reverberation room has just been built at Centre for Audio, Acoustics and Vibration in University of Technology Sydney. This paper reports some key parameters of the room, which include the background noise and its spectrum, the number of modes in low frequency bands, the cut-off frequency, the standard deviation of the spatial variations of the reverberant field, the decay curves of the sound pressure level versus time, the reverberation times, and the absorption coefficients. The volume of the room is approximately 232 m^3 with a total surface area of approximately 247 m^2. The averaged overall background noise level inside the room is 23.1 dB and 18.1 dBA, the number of modes is greater than 30 in one-third-octave bands with centre frequencies of 160 Hz and above, the standard deviation of the sound pressure levels is less than 1.5 dB in one-third-octave bands with centre frequencies of 125 Hz and above, and the decay curves of sound-pressure level versus time is linear in all one-third-octave bands. The reverberation time of the room can be as long as 20 s in the low frequency range around 100 Hz, and the shortest reverberation time is about 3.1 s in the high frequency range around 5000 Hz. The equivalent sound absorption areas of the empty room in all one-third-octave bands are smaller than the threshold values specified in the standard ISO 354, and the curve is smooth without any dips or peaks which differ by more than 15% from the mean values of two adjacent one-third-octave bands. The sound absorption coefficients in all frequency bands of the empty reverberation room are less than 0.02.

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REFERENCES

1. Morfey CL. Dictionary of Acoustics. London, UK: Academic Press; 2001. p.321.
2. ISO 354:2003. Acoustics – Measurement of sound absorption in a reverberation room. International Organization for Standardization; 2003.
3. ISO 3741:2010. Acoustics – Determination of sound power levels of noise sources using sound pressure precision methods for reverberation rooms. International Organization for Standardization; 2010.
4. Peterson JS, Bartholomae RC. Design and instrumentation of a large reverberation chamber. Proceedings of the 2003 National Conference on Noise Control Engineering (Noise-Con 2003); 23-25 June 2003; Cleveland, Ohio 2003.p.1-8.
5. Hasan MM, Hodgson M. Effectiveness of reverberation room design: Room size and shape and effect on measurement accuracy. Proceedings of the 22nd International Congress on Acoustics; 5-9 September 2016; Buenos Aires, Argentina 2016. p. 1-10.
6. Vercammen MLS. Improving the accuracy of sound absorption measurement according to ISO 354. Proceedings of the International Symposium on Room Acoustics; 29-31 August 2010; Melbourne, Australia 2010. p. 1-4.
7. Lautenbach MR, Vercammen MLS. Volume Diffusers in the Reverberation Room. Proceedings of the 20th International Congress on Acoustics (ICA 2010); 23-27 August 2010; Sydney, Australia 2010. p.1-7.
8. Xiang D, Wang Z, Chen J. Acoustic design of a reverberation chamber. Applied Acoustics 1991;32(2):83-91.
9. ISO 9613-1:1993 Acoustics – Attenuation of sound during propagation outdoors -- Part 1: Calculation of the absorption of sound by the atmosphere. International Organization for Standardization; 2003.