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Using an ambisonic microphone for measurement of the diffuse state in a reverberant room

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ABSTRACT

An ambisonic microphone was used to measure the degree to which a sound field varied with direction within a reverberant room. The apparent diffusivity of the room was varied by incrementally adding reflecting panels, according to AS ISO354 2008, producing seven different room states. In each reverberation time was measured using three loudspeaker positions and four measurement microphone positions, according to the interrupted noise method outlined in AS ISO354 2008. Recordings were made of sinusoidal sweeps for the three loudspeaker positions with a first order ambisonic microphone at three different positions in the room. The recorded sine sweeps were converted to impulse responses to measure the evenness of the sound field around the microphone in each room state. These results are compared with the traditional method of establishing a diffuse state in a reverberation room with a view to the development of a more direct method for establishing an isotropic state in reverberant rooms.

INTRODUCTION:

In the mid-1970's Furduev and T'ung[1] proposed a method for measuring diffusivity of sound fields through the rotation of a pressure-gradient microphone in the space to be measured. The basic premise was that the output of the microphone would be of the form $A + B\cos\theta$ when rotated in a free field and A(θ) or a unit circle when rotated in a diffuse field. The variation from these two ideal conditions is then measured by calculating the area difference between the measured plot and the ideal plot.

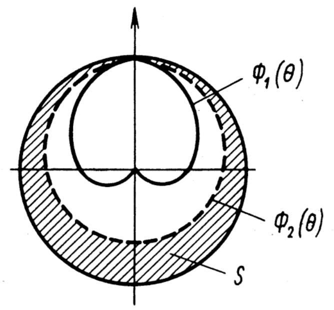

Figure 1: Variation in plot area between free, semi-diffuse and diffuse fields. [2]

In Figure 1 the area of the unit circle is denoted by S, the area of the normalised voltage output of the directional microphone in a free field is denoted $\phi_1(\theta)$ and the normalised voltage output in the measured space is denoted $\phi_2(\theta)$.

Their measure *df* is calculated from;

$$df = \frac{S_1 - S}{S_1} \qquad (1)$$

where: $S_1 = \pi - \phi_1$

$S = \pi - \phi_2$

π = area of the unit circle

For a free field S1 = S produces a *df* value of 0. For a perfectly diffuse field, outlined in (1) below, ϕ_2 = S produces a value of 1.

Previous work by the author has found some utility in the measure for assessing the time-varying diffusivity of sound fields. It is therefore interesting to explore the potential of the technique in the measurement of sound fields that are considered to be diffuse.

In assessing the degree of diffusivity in a space two criteria should be met.

1) "..all directions of arrival of sound energy are equally probable, and in any direction the time averaged sound energy flux is the same".[2] This is refered to as the isotropic state. The question of the duration for time averaging the arriving energy is unclear. For the series of measurements reported herein the entire impulse response or decay duration of the room will be calculated.

2) "..the time-averaged sound energy density at all points in the room is the same." [2] - then the field is considered homogeneous. This will be assessed through the difference in the measured reverberation time and consequent absorption coefficient for each measurement position in the room.

An ideal diffuse state will produce the same result regardless of measurement configuration. This is not possible to achieve in a reverberant room once an absorptive sample has been placed in the space. Schroeder has proposed that, in measuring diffusion in a reverberant room, it is not essential that the isotropic state be met for each point on the measurement wall but that a form of homogeneous state be achieved where the averaged angle of incidence over the measuring wall meets the criterion for an isotropic state at a single measurement point.[3] Lubman[4] and Schroeder [5] have proposed ststistical approaches to the measurement of what is essentially a stochastic process. Essentially the field is deemed to be adequately diffuse when the standard deviation or variance of the measured results is small. The Australian Standard AS 1045[6] Acoustics - Measurement of Sound Absorption in a Reverberation Room included a calculation for determination of repeatability standard deviation in its Appendix B. Section 8.2.3 of ISO 354 indicates that such a reproducibility test is still under investigation.

This work sets out to explore the measurement of the sound field within a reverberation room that is being tested for the establishment of a diffuse field in accordance with Appendix A of AS ISO 354, "Diffusivity of the sound field in the reverberant room"[7].

The approach taken is to place a sample of sound absorptive material in the room and measure its absorption coefficient using a number of source and receiver positions. Diffusing panels are added to the room in small increments. As panels are added, the measured absorption coefficient of the sample should increase to a stabilised point where no further addition of diffusing elements will alter the absorption coefficient. At that point the field is deemed to besufficiently diffuse for sound absorption coefficient measurements.

In a reverberant room, we combined the above approach with measurements made using an ambisonic microphone (Soundfield SPS422B) producing horizontal and vertical plots of the directional distribution of incident sound at the measurement points in the room. The level of diffusivity was calculated in accordance with Furduev's method and results were compared with values obtained from the standard method of preparing a room for sound absorption coefficient measurements.

THE ROOM UNDER TEST

Room dimensions

The room under test is located in the Faculty of Architecture, Design and Planning at the University of Sydney. It is a rectangular, painted concrete and rendered masonry room measuring 6.36m (l) x 5.12m(w) x 3.98m (h), producing a volume of 130m^2. AS ISO354 specifies a minimum volume of 150m^2. The standard also specifies dimensional ratio Imax < 1.9 $V^{1/3}$. For a rectangular room Imax equals the longest diagonal in the space. With a room volume of 130m^3 this would equate to a ratio 10.09 whereas the room under test is found to be 9.09 m. The test room does not meet the criteria set out in the standard for room volume but it does meet the dimensional ratio requirement. It is expected that the modal density of the room in the low frequency ranges will be less than would be expected in a standard room due to this lower volume. This would be expected to borne out in the results but for the lack of low frequency energy generated by the source loudspeaker.

Sample and placement

The standard specifies that the sample have an area of between 10 and 12 m^2 with a length to width ratio between 1:0.7 and 1:1. The specimen used was three pieces of Tontine Acoustisorb3 a 50 mm thick polyester batt. The samples were butted together and mounted in accordance with Type A outlined in appendix B of the Standard. The area covered by the sample was 3.12m x 2.16 m, a total area of 6.74 m^2 producing a length to width ratio of 1:0.69. The absorption coefficients of the sample published by the manufactureris listed in Table 1;

Table 1: Reported absorption coefficient of sample

Frequency(Hz)	125	250	500	1k	2k
Manufacturer	0.40	0.70	0.91	0.95	0.94

The specimen is smaller than outlined by the standard but when fitted into the smaller room met the criteria that it not be mounted parallel to the walls and be at least on metre from the walls

Temperature and humidity

In accordance with the standard the temperature and relative humidity were measured over the several days that it took to perform all the measurements. Temperature ranged from 23.6 to 24.1^{0}C with the relative humidity varying between 51.9 and 62.6%. Barometric pressure data for the measurement days were drawn from the Australian Bureau of Meteorology.

Noise and source level

The standard states that the source signal must be 10dB above the noise level at the end of the evaluation range. The standard recommends that the decay be measured from -5 to -25dB (T_{20}) but in this case the measurements were made from -5 to -35 (T_{30}). As can be seen in Figure 2, showing the measured pink noise output of the dodecahedral loudspeaker, its capacity to output low frequency signal diminishes significantly below 250 Hz. To maintain a difference greater than 45dB between signal and room noise results in all measurements below 125 Hz and above 16 kHz being discounted. (The actual difference at 125 Hz is 43 dB).

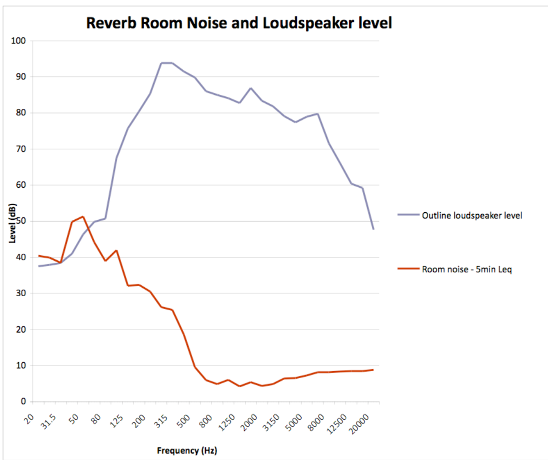

Figure 2: Signal level and background noise levels in the reverberant room.

Measurement set-up

Measurement in the reverberation room was carried out in two stages. The first utilised the Bruel and Kjaer Pulse system running the reverberation time measurement template in Labshop 12.6. The source, an Outline dodecahedral loudspeaker can be divided into four separate output sections. For this set of measurements the signal from the Pulse system was sent to all four zones via a Bruel and Kjaer 2716C amplifier. The source material was interrupted noise generated through the Pulse front-end. Three loudspeaker positions were selected in places that were calculated to be away from dominant nodes or antinodes of the lowest room resonances. Likewise four B&K 4189 microphones were placed to avoid obvious nodes or anti-nodes in the space. The interrupted noise source was run three times for each position with the Pulse system automatically averaging the results. Measurements were made for each of the loudspeaker–microphone configurations, a total of 36 measurements for each room state, output to twelve reverberation plots for each room condition.

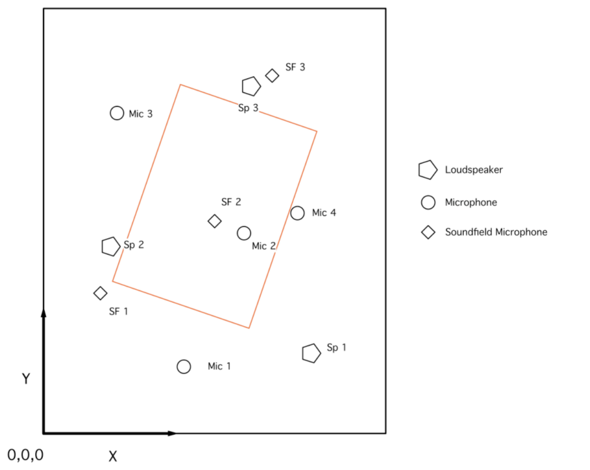

Figure 3: Measurement plan of the test room.

Table 2: Transducer positions in test room

	Sp1	Sp2	Sp3	M1	M2	M3	M4	SF1	SF2	SF3
x	100	400	310	210	300	110	380	85	256	342
y	280	120	520	100	300	480	330	210	318	536
z	155	190	240	110	280	300	140	250	200	65

Table 2 provides the length (y), width (x) and height (z) coordinates for each of the transducers in the room. All measurements are in cm. The position and orientation of the sample on the floor of the room is illustrated by the large skewed rectangle within the enclosure.

The second stage of the measurement procedure was to run three test sources from a ProTools digital audio workstation running four separate channels of audio through a Digidesign 003 audio interface. The four outputs were amplified with a Crown CP6600 amplifier connected to the four separate zones of the Outline loudspeaker. Correlated and decorrelated noise and swept sinusoids were output to the dodecahedral loudspeaker. The noise sources were intended for other work carried out by researchers in the Faculty and will not be considered in this paper. The 20 s swept-sine signal was replicated across the four channels, effectively producing the same signal from all components of the loudspeaker. A Soundfield SPS422B microphone was placed Soundfield SPS422B microphone was placed in three positions in the room. Like the B&K microphone positions two of the periphonic microphone placements were established in positions that aimed to avoid dominant resonant nodes or anti-nodes. The second position for the microphone (SF2) however was directly in the centre of the room. The microphone was aligned with the X-axis of the room. The outputs of the Soundfield B-Format processor were recorded, along with the Bruel and Kjaer microphone outputs, with the Bruel and Kjaer Pulse Time Data Recorder for later processing and analysis.

The four recorded sinusoidal sweeps were imported into Adode Audition and deconvolved from the original sweep signal using Farina's Aurora[8] package. The resulting four impulse responses were loaded into Matlab for analysis.

Room states

The process for establishing whether the sound field in the reverberant room is diffuse, outlined in AS ISO 354, is to progressively add reflective panels to the room with a sample present. It is recommended that the area of panels added, in each instance, be in the vicinity of 5 m^2. The field is deemed diffuse when the measured absorption coefficient reaches a maximum and remains unchanged if even more reflectors are added to the room.

The reflectors used were Perspex panels 1220mm x 915mm x 5mm, 1.1163m^2 per panel. The reverberation time was measured in the empty room, the room with the sample and with reflecting panels added five at a time. The panels were randomly suspended in the room. The maximum number of panels in the room was 25. A final measurement was made with 25 panels in the room, without the sample.

Reveration time results

There was significant variation in the measured results attributable to spatial variance in each of the room states. Of particular interest is the difference in average reverberation time for each of the room conditions. There is approximately a 1 second difference between the empty room reveration time and the *T* for the room with no sample but 25 reflective panels. Reference is made to this effect by Cox and D'Antonio[9], based on the work of Hargreaves.

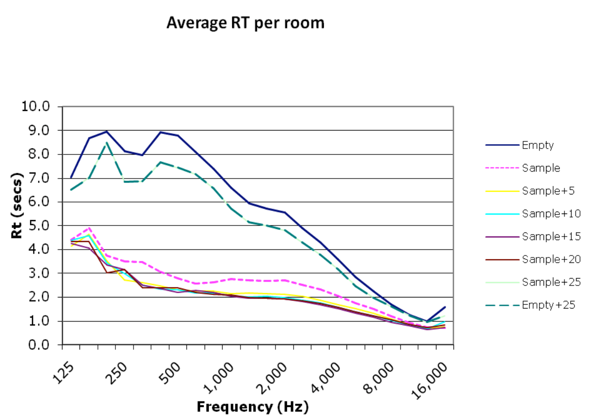

Figure 4: Spatially averaged reverberation time for each room state. The numbers in the legend (+5, +10, etc) indicate the numbers of diffusing panels in the room.

The results imply that the diffusing panels act as ‘agents’ of absorption. The assumption is that the more homogeneous sound field introduces greater phase cancellation within the enclosed space. This possible effect is separate to that of the panels effecting a greater presentation of the sound energy to the sample assumed by Sabine. [10] That effect is borne out in the results in Figure 3 where we see that the average reverberation time for each room state is less than that for the empty room with the sample.

Absorption coefficient results

The means of establishing that the sound field in the reverberant room is acceptably diffuse, according to AS ISO 354, is to continue adding diffusing panels to the space until the measured mean absorption coefficient reaches a maximum and doesn’t change with the addition of further diffusing elements. The mean absorption coefficient of the sample for each of the room states was calculated in accordance with section 8.1.2 of the standard. The mean absorption coefficient for the room states indicates that the diffuse state has been reached when 15 panels are placed in the room.

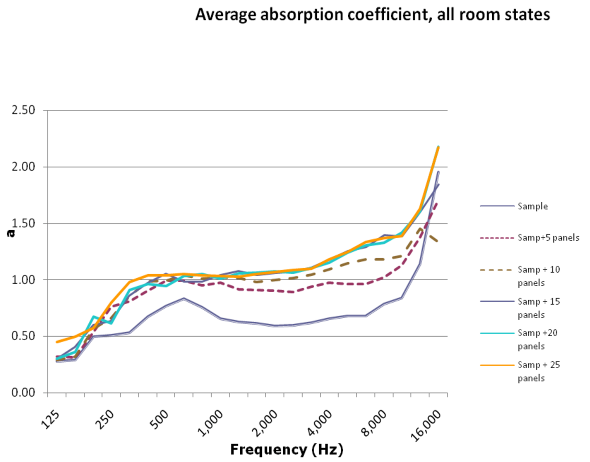

Figure 5: Mean absorption coefficients of sample with varying numbers of diffusing panels in the reverberation room.

There is however significant variation in the results as can be seen from the box-plots in Figure 6 and the Standard Deviation of the absorption coefficient in Figure 7.

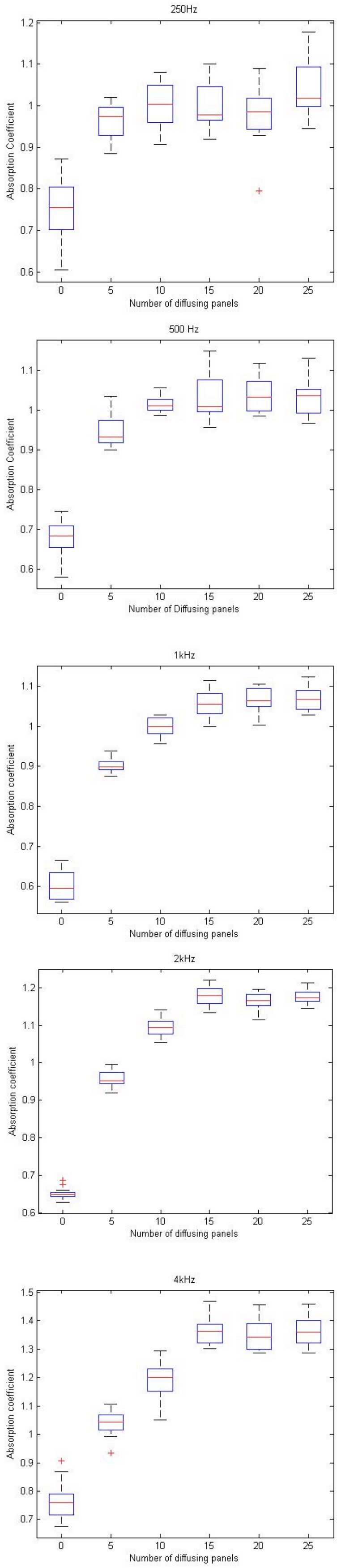

Figure 6: Plot of absorption coefficient variation over all measurement positions in octave bands for each room state.

The box plots in Figure 6 illustrate the distribution of measured results over the 12 measurement configurations plotted against the number of reflective panels placed in the room.

The line inside the box is the median with the upper and lower result quartiles enclosed within the box. The upper and lower extents of the results are marked by the T marks. Possible outliers are indicated by the + sign.

In the 1 kHz and 2 kHz octave bands there is a clear trend indicated with the absorption coefficient reaching a maximum value from 15 panels upward. The amount of variation in results at these frequency bands is low, as indicated by the standard deviation in Figure 7 below. The process of averaging to produce the octave band results, however, produces a smoothing of the results.

For the purpose of producing a reliable absorption coefficient measurement the placement of 15 panels within the room is adequate. The variation in the results beyond the point where, according to the standard, the room is deemed to be diffuse indicates that the sound field has not reached a homogenous state

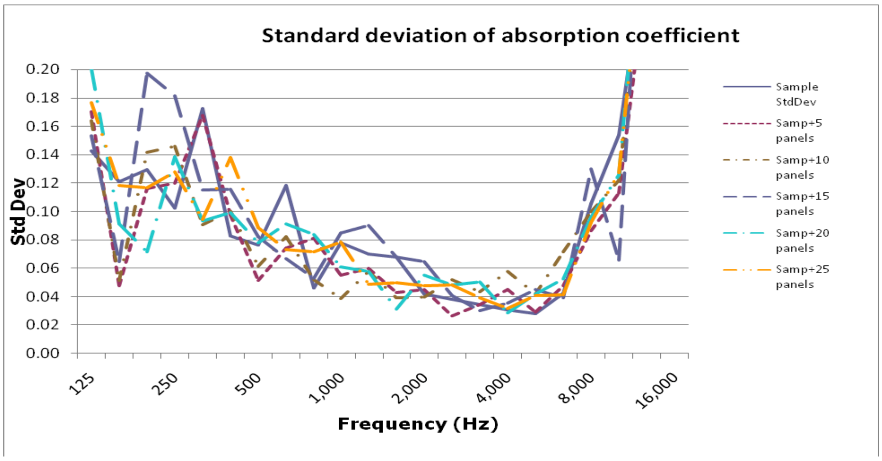

Figure 7: Standard deviation of the averaged absorption coefficients for each room state.

Soundfield microphone measurements

The room impulse responses measured by the B-format Soundfield microphone were processed in Matlab to produce the equivalent to a cardioid microphone pointing in 72 directions on the horizontal plane, the equivalent to 5^0 rotations on the circle. The output was filtered in 1/3 octaves and the amplitude at each orientation was normalised to the maximum amplitude. The normalised levels in the 72 directions, for each frequency band, were then used to calculate the area inside the plot of the virtual rotating microphone. This value was used to produce *S* for the diffusivity index originally proposed by Furduev and T'ung. The results in Figure 8 indicate that there is a fair degree of variation across the frequency bands for each of the room states but the overall trend shows that, according to this method, the sound field in the reverberation room is not diffuse but is approaching the state in each of the room conditions.

It is not possible to make a correlation between the *df* measure and the standard deviation of the absorption coefficient but in each case it is clear that none of the rooms have reached a fully diffuse state. The Soundfield directivity plots provide us with a visual indication of this where we see, in Figures 9 and 10, that the amplitude plot in both the horizontal and vertical planes show difference between the room with the sample and the empty room with 25 diffusing panels. This difference is not clear when the simple *df* value is examined which shows a high diffusivity index for each of the room states across the frequency range under test.

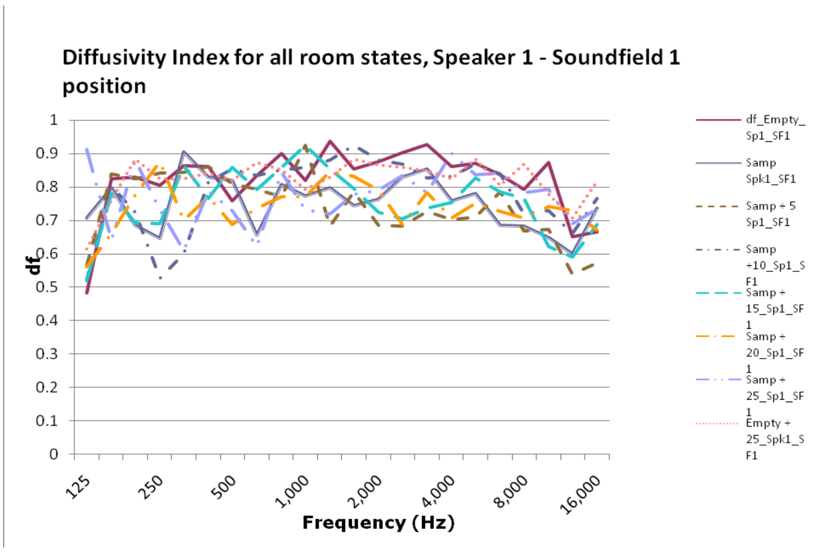

Figure 8: Diffusivity Index for loudspeaker 1 – Soundfield 1 configuration in all room conditions.

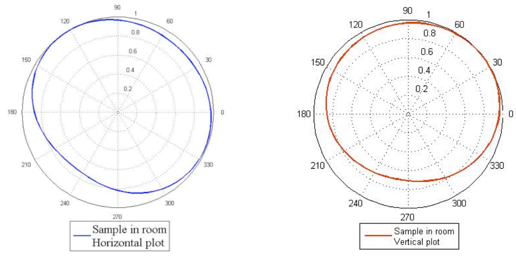

Figure 9: Horizontal and Vertical plots of amplitude from a virtual rotation of a cardioid microphone in the empty reverberant room with sample. (Horizontal plot on left, vertical on right)

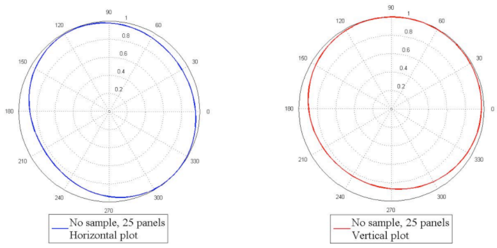

Figure 10: Horizontal and vertical plots of amplitude from a virtual rotation of a cardioid microphone in the reverberant room containing 25 diffusor panels, without sample. (Horizontal plot on left, vertical on right)

This is most marked in the vertical plots where there is greater amplitude in the lower hemisphere when there are diffusing panels in the room but no sample. The field, according to this measurement, is close to diffuse with less energy arriving at the microphone in the 230^0 to 270^0 direction. This effect is more obvious in the empty room with the sample on the floor which was in the 240^0 vertical direction relative to the microphone. This effect is less distinct in the horizontal domain, in part due to the height of the microphone relative to the sample on the floor. There is more energy arriving at the 240^0 direction when the diffusing panels are in the room.

CONCLUSION

The standard procedure for establishing a diffuse state in a reverberation room, outlined in AS ISO 354, and the measurement proposed by Furduev and T'ung have been carried out. Each method is assessed against the two criteria for a diffuse field proposed by Makrinenko. That is, that energy arives at the measurement point from all directions, over time at the same level and that this isotropic state can be measured in all parts of the enclosure.

The measurement regime outlined by the standard is a pragmatic approach intended to achieve reliable and consistent results in the measurement of the absorption coefficient of materials and objects. The isotropic nature of the field is implied by the normalisation of the measured absorption coefficient. There is an assumption that the soundfield is diffuse because the measured absorption coefficient is consistent regardless of source position. It could be argued that, where the sample covers a large section of the measurement surface, the field doesn't approach the isotropic state but achieves an equal distribution of angle of incidence over the sample. In that regard the method applied in the standard is not capable of clearly defining the field as diffuse. The Furduev method appears to be more able to indicate whether the sound field is close to isotropic but the degree of variation in the results, across the frequency range, suggests that the results are unreliable.

If the source produced a soundfield that was different for different placements in the space then the sound energy absorbed by the sample would differ dependent on the source position. We would expect the variation in results to diminish as the diffuse state is approached. This degree to which the field is homogeneous may be assessed through examination of the results for one source position and multiple receiver positions. If the field is homogeneous the measured reverberation time and consequent absorption coefficient would approach the same value regardless of receiver position.

In each of the cases above we have shown that the room reached a state where the field was adequately diffuse in that the variation in the measured absorption coefficient varied by a small quantity when there were 15 or more panels in the room. The overall variation in the measured values for absorption coefficients indicates that the sound field in the room is not completely diffuse.

The above conclusion is supported by the directional microphone method which indicates that the field in the room approaches an adequately diffuse state with *df* values of 0.8 to 0.9. The directional microphone method is useful in providing a visual analysis of the field which may assist in the placement of reflecting panels to more effectively achieve an isotropic and homogeneous sound field. This method however indicates that the field is relatively diffuse in each of the room states. It does not provide a useful variation in results that would allow assessment of the field for the purpose of carrying out absorption coefficient measurements in a reverberant room.

REFERENCES

1 Furduev, V. V., T'ung, C., *Measurement of diffuseness of the acoustic field in rooms by the directional microphone method.* Soviet Physics-Acoustics, 6,1, pp103-111, July-September 1960.

2 Makrinenko, L. I., *Acoustics of Auditoriums in Public Buildings*. (Woodbury, NY, Acoustical Society of America., 1994) Fig. 1.12

3 Schroeder. M. R., *Measurement of sound diffusion in reverberation chambers.* Journal of the Acoustical Society of America., pp1407-1414, Vol. 31,11 1959

4 Lubman D., *Fluctuations of sound with position in a reverberant room.* Journal of the Acoustical Society of America., pp1491-1502, Vol. 44,6 1968

5 Schroeder. M. R., *Effect of frequency and space averaging on the transmission responses of multimode media.* Journal of the Acoustical Society of America., pp277-283, Vol. 46,2 Pt1 1969

6 Standards Australia, *AS1045 Acoustics - Measurement of Sound Absorption in a Reverberation Room, Appendix B*, 1988

7 Standards Australia, *AS ISO 354, Appendix A, Diffusivity of the sound field in the reverberant room*, 2006

8 Farina, A. *Auralization software for the evaluation of a pyramid tracing code: results of subjective listening tests.* ICA95 (International Conference on Acoustics), Trondheim (Norway) 26-30 June 1995

9 D'Antonio, P., Cox T., *Acoustic Absorbers and Diffusers*, (Taylor and Francis) 2004

10 Sabine, W. C., *Collected Papers on Acoustics* (New York: Dover Publications, 1964)