Audio Engineering Society
Convention Paper 6922
Presented at the 121st Convention
2006 October 5–8 San Francisco, CA, USA

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Surface scattering uniformity measurements in reflection free environments

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ABSTRACT

Following previous investigation, carried out at the University of Parma in 1999 and 2000, LAE (Laboratory of Acoustics and Electroacoustics) started a new measurement campaign to compare with the original results on the same type of diffusor panels, to verify AES-4id-2001 measurement standard and to investigate the nature of scattering phenomena in more detail. Measurements are conducted on the floor of a large closed space to obtain a reflection free time window, long enough to study the first reflection from the panel; the use of sine sweep excitation signals instead of the recommended MLS ones permits to ameliorate the acquisition process. The present article discusses research background studies and the results from the first round of measurements.

1. BRIEF HISTORICAL REVIEW

In the last thirty years acoustical surface scattering has been studied in depth, in the nineties there was great spin to the topic, lead by Cox and D'Antonio [1] and by many researchers worldwide (i.e. Vorländer and Mommertz [2]), working to define the phenomenon with a well agreed single scattering coefficient.

Prof. Farina and his team at the University of Parma studied the matter in 1999-2000 with novel measurement techniques for the time [3, 4], discussing research results from others and giving different ideas for the definition of the coefficient itself.

In 2001 AES published an information document regarding 'the characterization and measurement of surface scattering uniformity' [5], while in 2004 ISO published the 17497 – 1 standard on 'the measurement of the random incidence scattering coefficient in reverberation room' [6].

The coefficient proposed by AES is now being evaluated for conversion into the second part of the ISO standard on sound scattering.

1.1. Past and present research background.

1.1.1. Past research.

The past research in Parma analyzed Dr. Cox contemporary proposal of a coefficient, the uniformity diffusion coefficient, which differs little from the one used nowadays and expressed in eq. 3

$$\delta_{UC} = \frac{\left(\sum_j I_j\right)^2 - \sum_j \left(I_j^2\right)}{(N-1)\sum_j \left(I_j^2\right)} \quad (1)$$

This is defined as the circular autocorrelation of the intensity values calculated from the array N microphones pressure values as:

$$I_j = \sum_n p_{j,n}^2 \quad (2)$$

where n is the sample number and j is the microphone number. The microphones were to be put on a semicircular array, centered at the panel center, as prescribed by the 2001 AES standard too; in Figure 1 a schematization of the arrangement is shown.

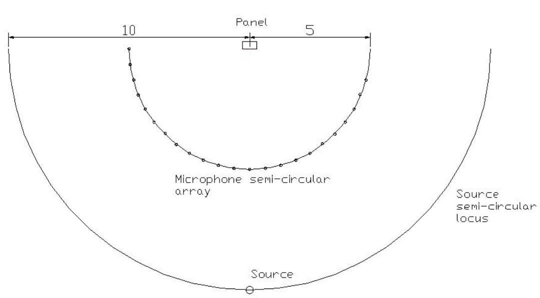

Figure 1.

The past measurements were taken using telecommunication mutuated wave field synthesis techniques [8] with a virtual linear microphone array: this was obtained by pulling a single Soundfield microphone along a straight line at 2 m height by equal steps, having the sound source flush mounted in the floor and the diffusor panel hung on top at about 4 m from the ground (Figure 2, 3). The experiments were taken in an industrial shed, large enough to create an anechoic time window to study the first sound reflection.

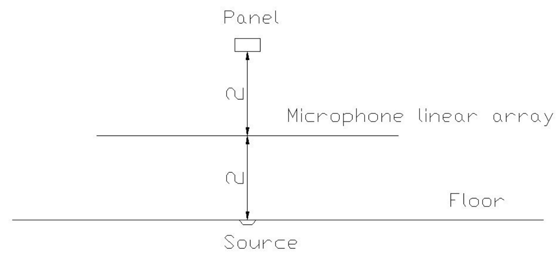

Figure 2.

Figure 3.

This measurement system was used to study normal sound incidence to panels. Its high spatial sampling rate, about 28 mm for 255 takes, permitted to draw useful wave field graphs, showing very distinct direct and reflected waves. Kirkeby inversion theorems [9] permitted to quickly deconvolve the measurement system response from data.

In Figure 4 are shown the graphs obtained from measuring a diffusor and the reference flat surface, both about the standard 600 x 600 mm in dimensions.

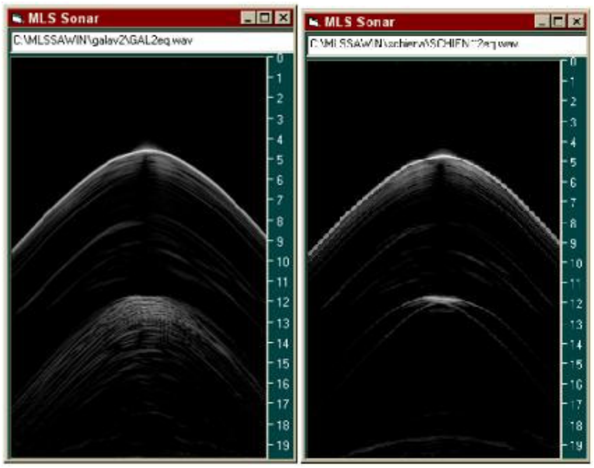

Figure 4 a, b.

The use of simple geometrical corrections led to polar graphs of reflection, each one obtained filtering the p_j pressure values in the main octave bands. Due to setup geometry, the domain span after conversion was defined only between –66° and +66°. In Figure 5 the elaborations from a poly-cylindrical panel are presented and in Figure 6 the ones from the reference flat panel.

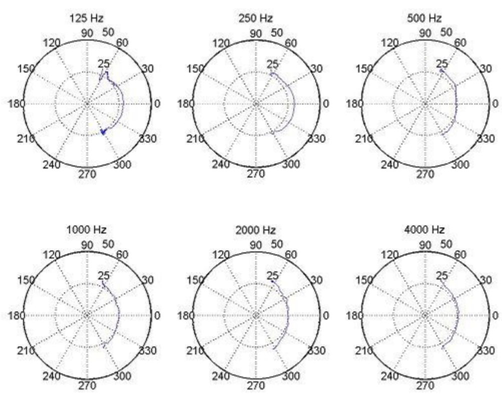

Figure 5.

Octave bands uniformity diffusion coefficients and scattering coefficients were then calculated and debated in comparison to energy related studies and this led to the proposal of an alternative definition of the energetic scattering coefficient [3].

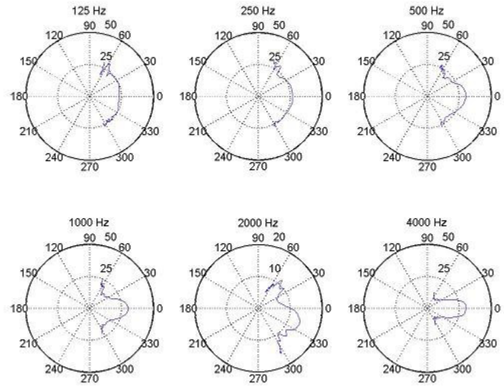

Figure 6.

1.1.2. Present day scattering coefficients.

The two present day coefficients have quite a different approach to describing diffuse reflection from surfaces.
AES parameter pragmatically says how uniformly is the sound reflection spread from the surface under exam in the emi-space in front of it; it is requested to measure pressure values from a emi-circular or emi-spherical microphone array in front of the panel (in an anechoic room or in special conditions as it will be discussed), giving a value of 1 for maximum spread and 0 for totally specular reflection.

$$d_\theta = \frac{\left(\sum_{i=1}^{N} 10^{L_i/10}\right)^2 - \sum_{i=1}^{N}\left(10^{L_i/10}\right)^2}{(N-1)\sum_{i=1}^{N}\left(10^{L_i/10}\right)^2} \quad (3)$$

In equation 3 it is shown the coefficient that is related to the angle of incidence θ, it is still a circular autocorrelation of the squared pressure values. The only difference with the latter coefficient (eq. 1) is a procedural one: today the L_i levels are calculated for every panel first in third octave bands, as the power in each band obtained by numerical integration assuming infinite roll-off filters at the band edges. In the interpretation of the past version the octave band values where calculated by filtering the temporal pressure values directly. A random incidence coefficient is obtained by averaging the results from different angles of incidence. The document recommends 18 but permits the use of 3 positions to quicken the process.

The coefficient defined by ISO 17497-1 follows Dr. Vorländer studies [2] and measures how much sonic energy is diverted from the specular path to all the other ones; this is done by measuring a random incidence absorption coefficient and a specular absorption coefficient in a reverberation room.

$$s = \frac{E_{diffusely\_reflected}}{E_{totally\_reflected}} = \frac{\alpha_{spec} - \alpha_s}{1 - \alpha_s} \quad (4)$$

This coefficient is very useful in computer aided geometrical models for room acoustics but it is valid only for shallow panel roughness, a small fraction of the test specimen width: it defines a physical property of the material itself. The first one, instead, is specific to characterize panel behavior, with no major depth restriction and permitting to plot polar graphs of spatial reflection distribution.

Another distinction is that *s* (eq. 4) actually refers to the property of an infinite surface, eliminating any edge effect; *d* (eq. 3) is measurable just for a small number of finite dimension panels, so it includes edge effects.

2. CHOOSING THE MEASUREMENT GROUND AND SETUP.

At the beginning of this research the choice was to remain consistent with past studies on diffusor panels and so to update the measurement system by using the 2001 AES information document as a reference, this system is specific to directly compare different types of diffusor panels and can be used, with proper modifications, to obtain a database, useful for a room acoustics modeling software as Ramsete (www.ramsete.com).

The document itself requires a large anechoic room as measurement field, but permits to use reflection-free environments as defined in Annex A [5]. By putting the measurement microphone array and the sound source on a flat reflective surface in a large enough empty space, a reflection free time window is obtained that is useful to analyze the single first reflection from the panels; this experiment was firstly done and reported by Dr. D'Antonio in the early nineties [7].

Studying 1999 results on single first reflection lengths, it was chosen to have a 10.5 msec anechoic time window, the measurement geometrical setup was the one recommended by the AES document: a 5 m radius for the microphones semicircle and a 10 m radius for the source positions, both centered at the panel position. These two parameters lead to require a large empty space around the measurement ground to have all the first reflections from the housing structure arriving late enough to create the needed reflection free (anechoic) time window.

Geometrical calculations [also in 7] led to defining a minimum volume of 37.2 x 21.1 x 9 m of height: this space was found in an industrial type of shed that is usually used to host shows and exhibitions (Figure 7) in Parma.

Figure 7.

During the preliminary visit to the location, its reverberation time was measured (Figure 8): this value is a key factor in deciding the MLS pseudorandom signal length, recommended to be used for the measurements by the AES document. The signal must be longer than the space reverberation time to avoid time aliasing corruption [10].

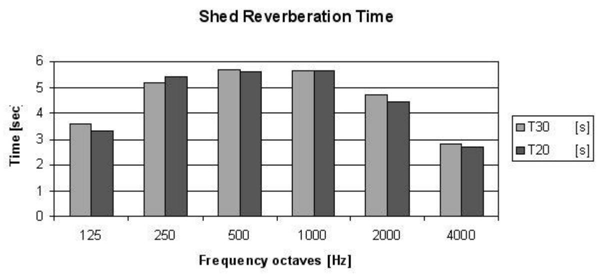

Figure 8.

Using the AD-DA converter sampling frequency of 48000 Hz, the RT values imposed an MLS order number *m* equal to at least 19, translated into almost 11 seconds of duration. This actually implicated a long measurement time for each panel and source position because MLS requires ensemble averaging to reject the noise floor: using a minimum of 4 averages plus 1 repetition at the beginning to put the overall system into a regime state, it means at least 55 seconds per measurement.
This led to consider using Farina's sine sweep impulse response measurement method [11] to quicken the measurement procedure and test its quality on this type of studies. In this case the same measurement needed just one take, for the duration of 15 seconds, saving about 60% of time in the overall man operated procedure.

A phonometric measurement gave a steady 45 dB(A) Leq value on a 2 minutes observation time, it is due to the presence of A1 highway just 200 m outside of the shed itself. This was another point to test the sine sweep capacity of rejecting background noise.

The measurement hardware was made by:

- 24 Bruel&Kjaer 4188 microphones with 2671 preamplifiers (phantom-powered);
- 3 8-channels Behringer AD-DA 8000 Converters;
- 1 RME Hammerfall DIGI9652 soundcard;
- 1 Turbosound TQ440 sound source.

The acquisition software was a pair of multichannel VST plug-ins (X-player, X-recorder), developed by the University of Parma, running on the Audio-Mulch platform. All post processing was executed using Matlab© specifically written functions.

In most measurements only three incidence angles were used, as suggested by the recommendation document for faster analyses (-55°, 0°, +55°). This means a minimum of 6 measures for each panel under test (3 with the panel present – h_1, 3 without the panel – h_2).
The number of microphones imposed an angular sampling of 7.5°, spanning from 90° to –82.5° (with 0° on the panel axis), a simple rotation of the panel and the source by 3.75° permits to acquire a second measurement that virtually sums to a 48 channel measurement (Figure 9), this allows to fulfill the request for a maximum angular resolution of 5°.

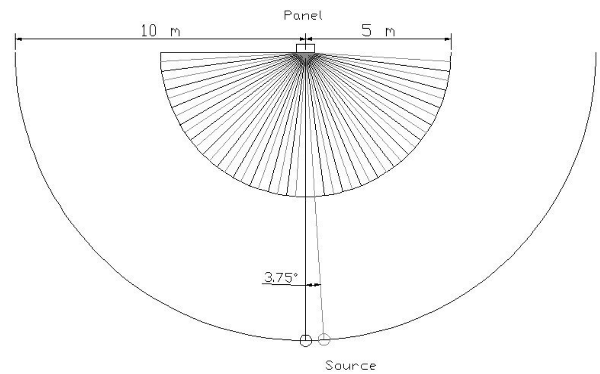

Figure 9.

In the first campaign one panel at a time was investigated, to be consistent with past research. However, the described experimental setup actually permits to study up to three panels mounted side-by-side for a total 1800 mm width, respecting theoretical constraints on far field positioning [5]. Upcoming campaigns will analyze a larger number of panels put side by side, to have valid low frequency behavior, less influence from edge effects and see polar plot lobe modifications, typical of enlarging the module number in modular panels.

3. DATA ELABORATION AND RESULTS

3.1. Signal processing

All the discussed impulse responses were taken using the sine sweep technique: a logarithmic sine sweep was generated using the Aurora Adobe Audition plug-ins (www.aurora-plugins.com). The signal ranged between 50 and 10000 Hz (respecting the document specifications on frequency bands), lasted 10 seconds and had a 5 seconds silence interval at the end. The

impulse responses were obtained convolving the recorded sine sweep response with the inverse sine sweep.
Every half day the system response (h_3) was calculated by putting the source at the panel position and pointing it to every microphone. For every source position two responses were taken: one with the panel in place (h_1) and one without the panel in place (h_2).

The technique permits to reject unwanted reflections by subtraction h_1-h_2 and still plot wave-field surface graphs similar to the ones analyzed in 1999-2000 (Figure 4). This time the reflected wave is horizontal because of the different microphone setup (Figure 10, 11), ideally following a semi-spherical reflected wave spreading. The less precise resolution, due to the small microphone number, requires graphic interpolation of the images. The interpolating function used in this case introduces spot-like spatial aliasing artifacts that should not be intended as a physical phenomenon.

At first inspection it is still clear the constant contribution given by the 'ideal' semi-cylinder (Figure 10) and the much more localized contribution of the flat reference surface (Figure 11), reflecting specularly towards the middle of the microphone array; both reflections are localized at a distance of about 10 m from the earliest part of the direct wave wavefront, as expected from theory.

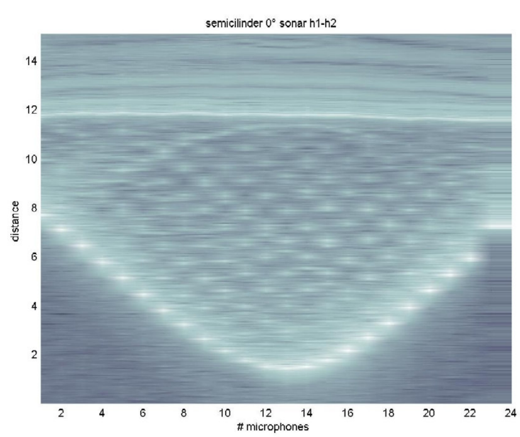

Figure 10.

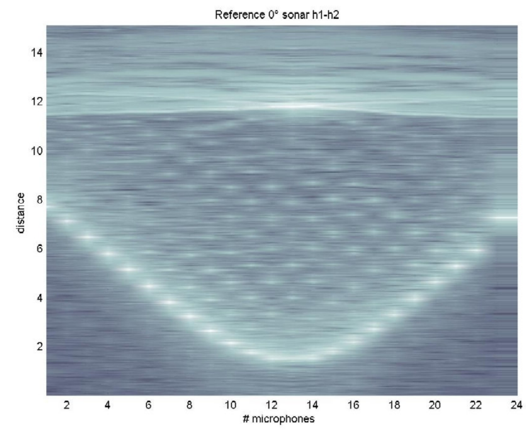

Figure 11.

The single first reflection impulse response h_4 was obtained by zero padding h_1-h_2 and h_3 to a length of 16384 samples, Fourier transformation, division in the frequency domain and subsequent anti-transformation:

$$h_4(t) = IFT[\ FT[h_1(t)-h_2(t)]\ /\ FT[h_3(t)]\ ] \quad (5)$$

Figure 12 shows the involved impulse responses - h_1, h_2, h_1-h_2, h_3 and h_4 – all windowed at the correct time (500 samples at 48000 Hz are about 10.4 sec) for the 12th microphone, recording the specular reflection from the 600 x 600 mm reference panel with 0° sound incidence on it. The time window start was decided by visual inspection and a smoothed rectangular window was applied to the data (short raised cosine were applied to both edges) to avoid truncation effects.

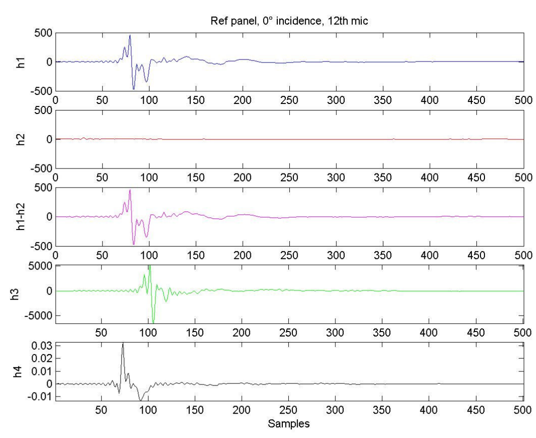

Figure 12.

After the division in the frequency domain, a frequency window was applied to the data, to cut out all of the high frequency discrepancies due to time windowing.

At this point the H_4 (FFT(h_4)) absolute values where squared and summed strictly within each third octave and octave frequency band limits for each microphone, obtaining the required L_i. Then these values were used to obtain the scattering coefficients and to plot the diffusion polar graphs in dB scale, both consistent with the new technical recommendation and with the ones in old studies.

3.2. Discussion of the first results.

3.2.1. Comparing old and new measurements.

Comparing Figure 13 and 14 with Figure 5 and 6, it is clear how the old study's conversion from linear to semi-circular coordinates created imprecise results in the polar plots at the domain edges (from about +55° upwards and –55° downwards), limiting the domain of valid data to less than a 110° span.

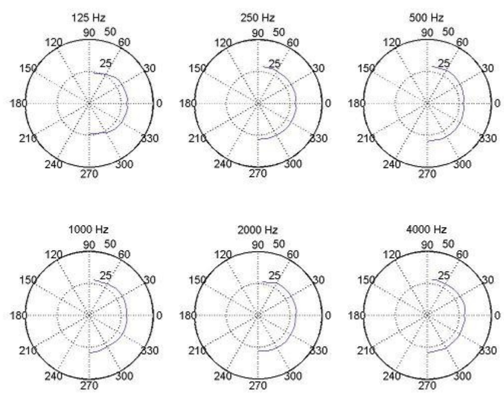

Figure 13.

The old study conversion was made on the hypothesis of an ideal reflection point and perfect ideal semi-spherical wave propagation instead of the one generated by a limited but well defined surface. So it worked well for the poly-cylindrical panel but suffered distortion with small square shaped ones (reference flat panel, QRD7®, gal2). This can be seen in Figure 6, where the reflection lobe is larger than expected and undefined compared to Figure 14.

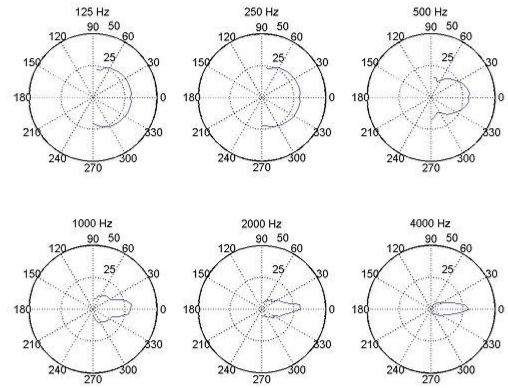

Figure 14.

Although not perfectly matching, the values within the 110° span limit are still consistent in both measurement techniques with theory and literature results.

Comparing the diffusion coefficient frequency octaves graphs from the two measurements (Figure 15, 16), there is still a good consistency between results. The differences are mainly due to the above mentioned mathematical distortion, and to lack of data in the lateral regions, both accounting negatively in the old measurement system: these are less effective for the semicircular panels because of their shapes, giving more constant reflected energy spreading on all angles of observation.

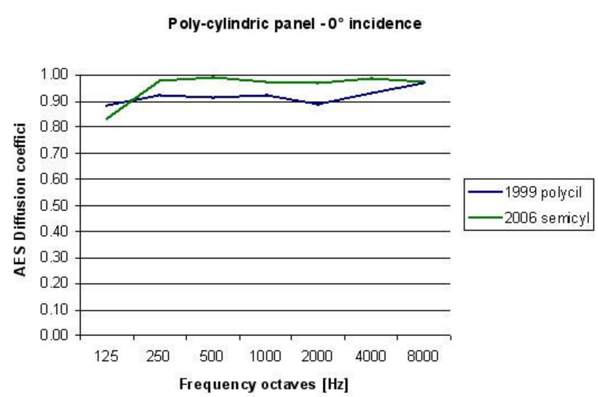

Figure 15.

The same differences are more visible in the reference flat panel measurements, since the lateral regions are important to lower the coefficient value in the overall array average.

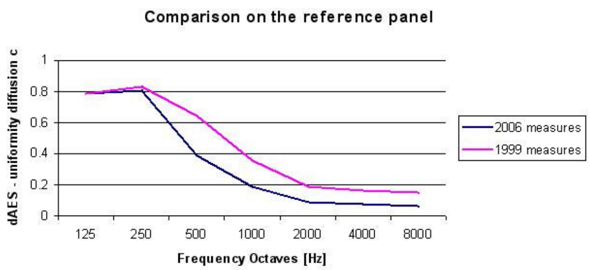

Figure 16.

3.2.2. Inclined incidence measurements.

The first novelty from the new measurement setup is the possibility to analyze the phenomenon for different angles of sound incidence on the panel.

The study of the reference panel gives further confirmation of the system reliability: polar plots (Figure 17) show the expected specular lobe steering, while wave field surface graphs (Figure 18) clearly show the different direct wave pattern, the specular reflection as a ‘condensing’ at the opposite side of the incidence one and the edge effect as an oblique downward line at the same side the sound is arriving. Simple geometrical considerations demonstrate the first arrival of the reflection from the panel corner at the lateral microphones.

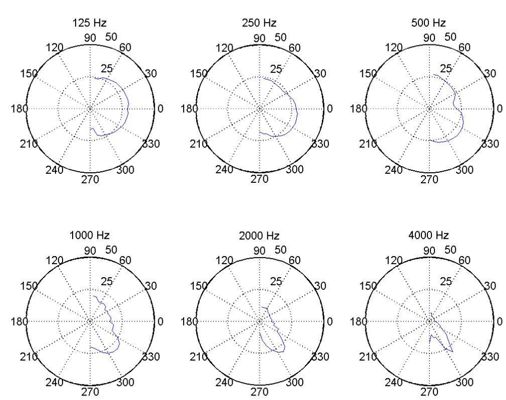

Figure 17.

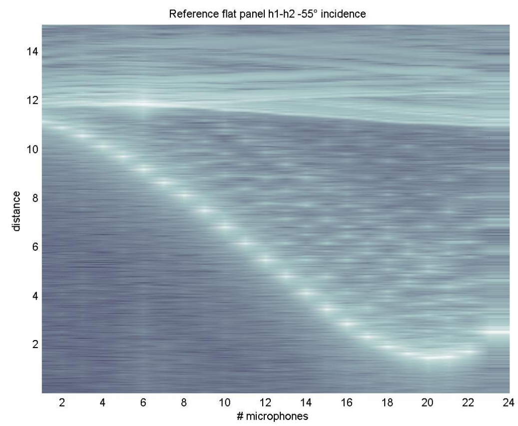

Figure 18.

3.2.3. Comparing 24 and 48 channel measurements.

Figure 19, 20, 21 permit to compare 24 and 48 channel measurements of a single RPG QRD7® panel.

All of wavefield surface graphs show that it is better to exclude the 90° microphone because its contribute is too different to be taken into account. Figure 19a, 19b show the better resolution obtained in the wave-field plot and the shape obtained with a 0° sound incidence from the source. The edge effect is still visible as a slight inclination of the reflected wave toward the source at the panel sides.

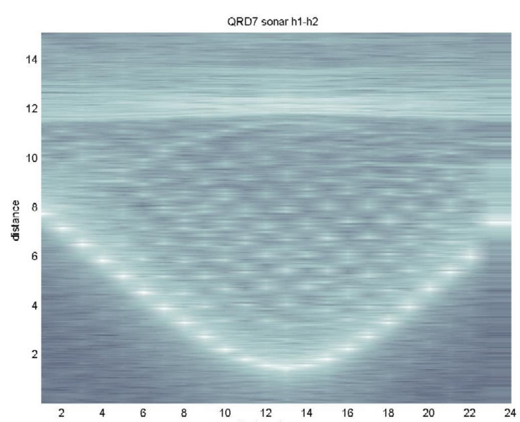

Figure 19a.

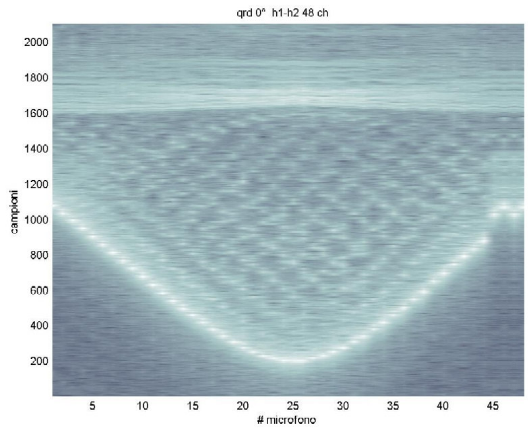

Figure 19b.

Polar plots of the QRD7® show a predictable better angular resolution in the shape of the reflection pattern (Figure 20a is a 24 channel measurement, Figure 20b a 48 channel one).

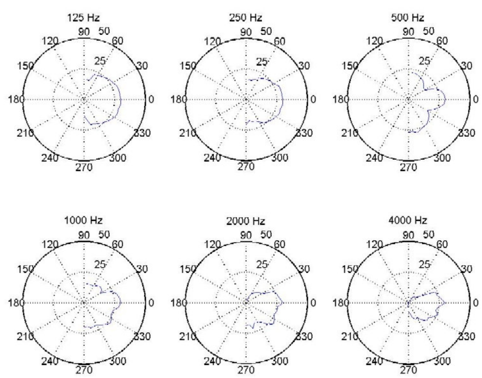

Figure 20a.

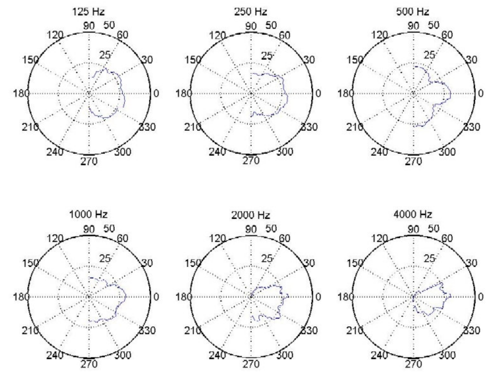

Figure 20b.

At first analysis angular diffusion coefficient graphs show small difference at doubling the microphone number for normal incidence (Figure 21), more measurements will allow a deeper insight into the matter.

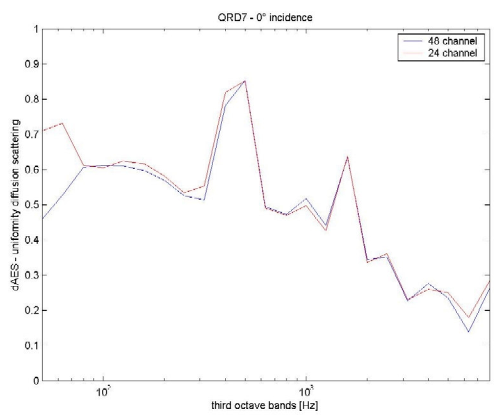

Figure 21.

3.2.4. Comparing random incidence results.

As prescribed by the AES 2001 document, the coefficients measured on 3 different sound incidence angles were averaged, obtaining single ‘random incidence’ coefficient values from fast measures.
Figure 22 shows the results from the 4 panels investigated up to now.

The reference panel shows a declining trend that attests for edge effects at low frequencies and almost perfect specular behavior at high frequencies.

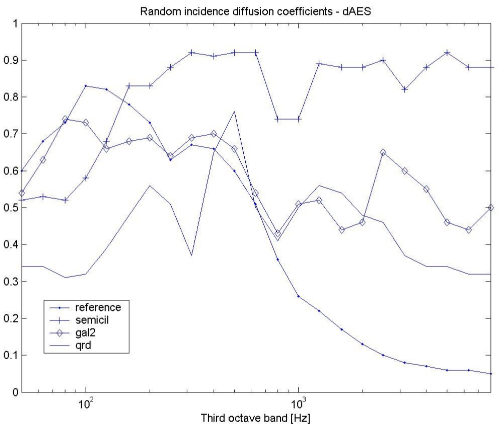

Figure 22.

The semi-cylinder graph has a quite steady high value as expected, since it gives uniform reflection at any incidence angle for frequencies above 160 Hz (as expected lower frequencies values should not be taken in account).

The two parallel-wells shaped diffusors are in between the limits stated by the above theoretically extreme situations: house developed gal2 panel (Figure 23) in average has higher uniformity diffusion value as found also in normal incidence past and present examinations.

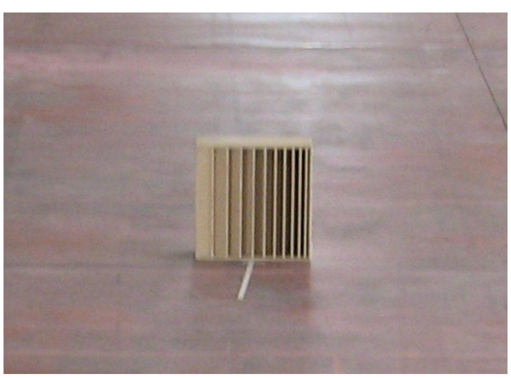

Figure 23.

4. CONCLUSIONS.

The first results show consistency with past measurements and literature, confirming the applied measurement system reliability in studying diffusion phenomena from 1-D diffusor panels at mid and high frequencies. LAE team has acquired the experience to optimize it continuing the study.

The first round of data acquisition and processing has also demonstrated the rapidity of the sine sweep impulse response measurement technique: about 267 24-channel sine sweep responses were collected in three full days (only 80 were used for this article). The method's capacity to reject background noise has permitted to obtain clear impulse responses despite the environment noise. Both these aspects are important for measurements such as the ones here described and lead to proposing using the sine sweep method to measure the uniformity diffusion coefficient, expecially in unorthodox but more common laboratory areas as the ones used for this study.

4.1. Future developments.

In the near future the laboratory aim is to continue research on the topic of sound scattering and measuring one dimensional diffusers.

A second round of measurements is planned for early 2006 autumn in which a larger number of the same panels will be investigated at the same time to have more consistent low frequency results; more experiments will be conducted on increasing the number of microphones and investigating SNR implications to sustain the measurement method strengths.

In the meantime the laboratory staff will process the remaining data already collected on different kinds of panels and from close-field analysis. The measurement procedure and processing algorithms will be optimized.

5. ACKNOWLEDGEMENTS

LAE [12] wishes to thank Ing. Alfieri and Fiere di Parma for permitting the use of the large space needed for the experiments.

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