Measurements of 3D sound characterisation in an UNESCO theatre in Italy

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Abstract: - The analysis of the sound field's 3D properties has been strongly improved in recent years, after spatial properties of sound propagation have been acknowledged to be important during the design or correction of theatres and auditoriums. Besides, a proper assessment of spatial accuracy is requested for 3D sound reproduction systems, initially designed for acoustical virtual reality and now also employed in the entertainment/cinema industry.
Often only monoaural or binaural measurements are performed by means of omni-directional microphones and dummy heads, although international standards like ISO 3382/1:2009 also define some "truly spatial" parameters such as JLF and JLFC. The two latter parameters are derived from measurements made with a pressure velocity (p/v) microphone, but this is still a 2-channel measurement. 3D Impulse Responses (4-channel B-format) have for many years been measured and employed for sound reproduction. Recently, higher-order 3D Impulse Responses have been measurable thanks to the availability of compact microphone arrays employing a much larger number of transducers.
In this paper, a procedure for measuring and analysing the complete spatial sound information is presented, which is aimed to create easy-to-understand images and videos showing the direction-of-arrival of the room reflections. The description of this technique is emphasised and applied in the Teatro all'Antica in Sabbioneta, Italy

Key words: - UNESCO sites; 3D microphone array, Listening room, Architectural acoustics
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1 Introduction

Many attempts were made to standardise the acoustic measurements in theatre and sacred spaces [3, 4] by taking into account several sound source positions, microphone positions and room conditions. On the other hand, only a few attempts were made to analyse and standardise the effect of test signals employed during the measurements and the types of sound source and microphones [5]. These details become crucial when measured Impulse Responses (IRs) are employed for performing 3D auralisation of the room, rather than for simply obtaining the numerical values of ISO 3382 parameters. Moreover, the full spatial sonic behaviour of a theatre, which includes information about energy, intensity and location of early reflections in the room, is required to determine and solve some acoustic problems that could not be resolved by only considering mono or 2-channel IRs.
A new measurement method was described in 2003 and 2005 [5, 6] which in-corporates all the previously known measurement techniques in a single, coherent approach. Three different microphone systems were mounted on a rotating beam (a binaural dummy head, a pair of cardioids in ORTF configuration, and a Soundfield microphone), as shown if Figure 1, and a set of Impulse Responses were measured at each angular position. The ORTF configuration represents a standard method (adopted by French Radio/Television) for recording dual-channel signals, employing two cardioid microphones spaced 170 mm and divergent from each other by 110 degrees. The Sound-field microphone, introduced by Gerzon, enabled the measurement of 4-channel Impulse Responses and, therefore, spatial

properties of the sound field. A Soundfield microphone captures a set of four signals known as "B-format" signals: one omnidirectional (sound pressure) and three with a polar pattern called "figure-of-eight", oriented along the three Cartesian axes X, Y, Z (these three channels capture a signal proportional to the Cartesian components of the particle velocity vector).
The combination of the three aforementioned different measurement methods pro-vided a general method from which all standard multi-channel playback formats (i.e., 2.0, 5.1, 7.1, 10.2, etc.) could be derived.

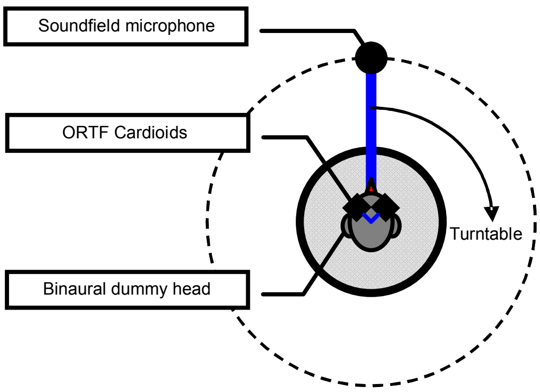

Figure 1 measurement method previously proposed in 2005

2 Enhanced methods

The main problems with the method presented in [5,6] were that it was very slow, the setup of the microphone system was tediously delicate and it was difficult to com-bine the information coming from the three microphone systems employed together.
Recently, a much more powerful, elegant and simple recording/measurement system was proposed [7], based on a spherical microphone array equipped with 32 capsules mounted on the surface of a small sphere (80mm diameter), containing the preamplifiers, A/D converters and an audio-over-ethernet chipset - the Eigenmike™. This probe makes it possible to measure 3D multichannel Impulse Responses, and provides a much finer spatial resolution than previously possible.

3 Microphones

So far, the ISO 3382/2009 standard [9] requires omnidirectional, monoaural micro-phones to be utilised in the measurement of monophonic acoustic parameters and only specifies the dimension of the microphones (preferably less than 13mm). Moreover, the ISO 3382/2009 standard describes the characteristics of binaural microphones (real heads or dummy heads), which could be used to measure binaural Impulse Responses and IACC. The standard also considers using figure-of-eight microphones to measure some lateral-energy parameters, such as LF and LFC, but does not provide technical specifications for these types of directive microphones.
However, it is evident that monoaural or even figure-of-eight microphones cannot pro-vide complete information about spatial sound distribution in the theatre. For this purpose, a multi-microphone system is necessary to capture the complete spatial information.

3.1 B-format microphones

Leaving aside binaural measurements, required only for binaural parameters, a B-format microphone (such as the Soundfield™) has been considered for many years to be the optimal transducer for performing 3D Impulse Response measurements in theatres and auditoriums. The W channel is good for the monoaural parameters (omnidirectional), the Y channel provides the figure-of-eight signal required for computing LF, and the other two directive channels (X and Z) can be used for recreating the entire 3D soundscape inside a playback environment using the well-known 1st-order Ambisonics technology.
However, a 1st order Ambisonics playback system is currently considered incapable of providing accurate spatial cues to the listeners, as this technology does not synthesise sound fields exhibiting significant polarisation and consequently the sound is perceived to be coming from almost anywhere. A possible solution is to employ high-order Ambisonics (HOA) systems, which require capturing a multichannel signal corresponding to the spherical harmonics expansion up to 3rd or 4th order. While it was found that HOA works very well with synthetic signals (where the high-order spherical harmonic signals are

computer-generated), the recording of HOA signals is problematic, even when employing microphone arrays composed of dozens of elements: when the directivity of the harmonic patterns is high, the S/N ratio is poor at low frequencies and the spatial accuracy of the pattern is disrupted at high frequencies, resulting in the reduction of the useful bandwidth to less than one octave band.
Another viable approach is to employ “advanced” decoding methods applied to the 1st order B-format signal, which perform a “spatial analysis” of the signal, and therefore “steer” the sound just in the very precise directions from where it arrives from, at every instant and at every frequency. Two of these methods are currently being employed, namely Sirr/Dirac by Pullki [12] and Harpex by Berge and Barrett [13]. The former is based on the Sound Intensity theory while the latter is based on plane wave decomposition.

3.2 Large-number microphone array

Recently, a 32-capsule microphone system was made available (EigenmikeTM) and the authors developed a novel processing method of the signals captured by this probe, making it possible to directly synthesise a number of “virtual microphones” with arbitrary directivity pattern and aiming, without passing through HOA, spherical harmonics and the like [14].

4 Spatial analysis of 3D Impulse Responses

The spatial analysis was developed for analysing B-Format Impulse Response measured by means of a B-format microphone and is presented here for the first time.

4.1 Analysis from B-Format signals

The method exploits the capabilities of the B-Format signal of detecting the direction-of-arrival of each impinging wavefront by computing the “instantaneous” sound intensity vector I and the instantaneous value of the energy ratio r_E and is based on the same vector decomposition scheme initially proposed in [16], also related to the later SIRR method [12]. The three components of the sound intensity vector can be simply obtained from the B-Format Impulse Response by means of the following equations:

$$I_x = w \cdot x; \quad I_y = w \cdot y; \quad I_z = w \cdot z; \quad (1)$$

Where w, x, y and z represent the four signals of the B-Format IR. Keeping in mind these signals are proportional to sound pressure and particle velocity, the total energy density can be computed by means of the following equation:

$$E_D = \frac{\sqrt{w^2 + x^2 + y^2 + z^2}}{c} \quad (2)$$

It is also useful to compute the modulus of the sound intensity vector:

$$|I| = \sqrt{I_x^2 + I_y^2 + I_z^2} \quad (3)$$

The ratio between the active intensity and energy density is computed with the following equation:

$$r_E = \frac{|I|}{E_D \cdot c} = \frac{\sqrt{(w \cdot x)^2 + (w \cdot y)^2 + (w \cdot z)^2}}{\sqrt{w^2 + x^2 + y^2 + z^2}} \quad (4)$$

Finally, the azimuth (horizontal) a and elevation (vertical) e angles are simply obtained from trigonometric equations, i.e.:

$$a = \arctan \frac{I_y}{I_x}; \qquad e = \arcsin \frac{I_z}{|I|} \quad (5)$$

All these quantities are averaged over 1ms time slices, creating a “time history” of the above-defined descriptors along the whole length of the measured Impulse Response.
The results can be visualised dynamically by means of a properly developed post-processing tool, plotting at every “frame” a circle, located at position (a,e), having a diameter proportional to the sound intensity modulus |I| and opacity proportional to r_E. The moving circle is plotted over a panoramic 360°x180° photographic image taken from the microphone position, while a synchronised marker moves over the Impulse Response graph so that it is easy to see the arrival direction of each reflection and how much the corresponding wavefront is “polarised”.

The meaning of r_E is related to the fact that the sound energy is significantly oriented along one direction (r_E approaching 1, travelling wave), or instead is diffuse (r_E approaching 0, standing wave).
The chart does not display the "Impulse Response of r_E", but rather the superposition of the "energetic" Impulse Response (that is ED in dB) and the "intensimetric" Impulse Response (that is, |I| in dB), having aligned both dB scales so that, for a perfectly plane, progressive wave (when r_E =1) the two values in dB are the same both for ED and |I|.
Hence, the dynamic display of the spatial-temporal distribution of sound along the duration of the Impulse Response does not only carry the information of the trajectory of the reflected sound, but also about the degree of diffusion. The sound is fully diffused when the level of ED is much larger than the level of |I| (and hence r_E approaches 0). When, instead, the two levels are almost equal (meaning that r_E =1), the sound is strongly "polarised", a propagative wave traveling in a precise direction.
This method allows for processing of a large amount of B-format IRs previously measured in the scientific community by means of Soundfield microphones or other tetrahedral probes, obtaining much more information than traditional acoustic parameters.

5 Post processing

After measuring in each position a 3D impulse response (B-format), it is possible to post-process the results in two ways:

- A graphical analysis can be performed, showing the spatial distribution of the incoming energy along the running time – this allows to "see" from where the room's reflections are coming
- An audible rendering can be presented to a group of listeners, inside a special room equipped with a suitable array of loudspeaker, surrounding completely the listening area around a sphere

The graphical analysis is performed thanks to two post-processing software tools:

- the first shows the "moving circle", which corresponds to the instantaneous direction of arrival of the sound intensity, based on the analysis of a B-format impulse response performed according with the algorithm previously described.
- the second creates an animated colour video rendering of the sound map, overplotted over the panoramic image. In this case no graphical algorithm is required, as a standard graphic library is employed for obtaining the colour map, based on the 32 "instantaneous" values of the sound pressure level captured by the 32 virtual microphones.

These tools create an animated video rendering of the instantaneous sound intensity vector, in one case, and of a colour map of sound distribution, in the second case, plotted over the panoramic image. Frames of such video renderings are shown in Figures 5 and following.
The audible rendering is obtained by reprocessing the original impulse response recording: a new set of virtual microphones is extracted, one feeding each loudspeaker of the playback array. Again, the processing is slightly different for B-format impulse response, and for 32-channels impulse responses, although a same methodological approach is employed.
The set of filters employed for deriving the "playback" virtual microphones is obtained by solving a linear equation system, imposing that the signals re-recorded placing the probe (the B-format microphone) at the centre of the playback system are maximally similar to the original signals recorded in the theatre. This approach, which is not Ambisonics-based, also corrects inherently for deviations from ideality of the loudspeakers employed, both in terms of magnitude/phase response, and in terms of placement/aiming/shielding.

6 Results

The experiment represents the post-processing of measurements conducted in the Teatro All'Antica in Sabbioneta (MN), Italy in 2015. In this case, the B-Format Impulse Responses were measured by means of a 3D cylindrical array made of 32 capsules and of a digitally equalised dodecahedron sound source fed by the ESS signal. Taking into consideration the exact position of the microphone and of the sound source, the original measurements were post-processed and combined with a recent panoramic image of the church from the same microphone position, as shown in figure 2.

Figure 2 Measurements in the Teatro all'Antica in Sabbioneta, Italy, with the 3D Cylindrical array

In this case, the 32-channel method allows for localising very early reflections, after which the value of r_E becomes small and the sound field becomes diffuse,

This example shows the possibility of obtaining spatial information about room acoustics from 3D arrays and B-format measurements collected during past years, provided that the exact positions of sound source and microphone were accurately documented.

7. Conclusions

This article has described two novel methods for measuring and analysing 3D Impulse Responses in theatres, providing a spatial resolution significantly better than what was obtainable with existing technology (sum-and-delay beamforming for massive microphone arrays, 1st order Ambisonics for B-format microphones); furthermore these new methods produce easy-to-understand graphical animations of the spatial-temporal information.

The first method is able to display very precise spatial information when a 32-channel spherical or cylindrical microphone array is used in the receiver position and is based on the synthesis of 32 highly-directive virtual microphones, which are obtained employing a huge matrix of FIR filters.

However, useful results are obtainable also using 4-channel B-Format Impulse Responses employing the second method presented here, based on "instantaneous sound intensity" analysis. This makes it possible to analyse the spatial acoustical properties of theatres measured in the past by means of B-format microphones, provided that the exact position of sound source and microphone was documented and a panoramic photo was taken from each microphone position.

The system allows the acoustician to easily understand not only the acoustic behaviour of a room at a specific measuring position, but also to find out the direction from where the cause of a specific reflection is arriving.

When the 32-channel microphone system is employed, it becomes possible to get a continuous colour map, showing the complete spatial distribution of the sound arriving at any given instant, by means of a number of highly directive virtual microphones, which operate a simultaneous spatial sampling of the whole sound field (a spatial filter bank); when a simpler B-format microphone probe is employed, the system currently can display just the instantaneous direction of the total energy flow, given by the sound intensity vector, accompanied by the information of the diffuseness of the sound field, given by the ratio r_E.

However, the research is now assessing the possibility to reprocess a B-format Impulse Response with the available high resolution analysis methods (SIRR, Harpex), as these can, in principle, provide results similar to those currently obtained with the Eigenmike™ probe, at a fraction of the cost.

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