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EXPERIMENTS ON ROOM PLANE WAVE DECOMPOSITION FOR VIRTUAL ACOUSTICS

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Abstract

Throughout history, emblematic theatres, concert and opera halls have disappeared and with them their acoustic behaviour. For some, it is now possible to recreate its behaviour thanks to technicians and scientific that measured their rooms before its loss, by means of impulse response measurements. When these measurements are made only at certain spots, they are not capable of providing angle-dependent information of reflections. In this paper, a recent procedure of measuring spatial sound characteristics by means of a circular array of microphones is presented, allowing for a complete description of impulse responses coming from a variety of directions. In order to have a general and more flexible description of the sound field not linked to specific microphone positions, decomposition of the sound field into plane waves is considered. Finally, a variety of rooms have been measured and analyzed in order to validate the method and to be used in virtual acoustics and 3D sound reproduction.

Keywords

Auralization, Spatial sound properties, Plane-Wave Decomposition, Cylindrical Harmonics, Circular Array.

1. Introduction

Room acoustics is an old scientific domain. Amphitheaters and legendary concert halls with amazing acoustic behavior have already been built years ago. The application of analysis methods in room acoustics is a new and interesting topic, and the experimental determination of impulse responses is a fundamental task in the acoustics of a room. Some spatial parameters (e.g. apparent source width or listener envelopment) involve directionality and are measured with slightly more complex microphone arrangements or dummy head microphones. An overview of classical measurement methods is given in [1]. However, these methods are optimized for human perception only and are not applicable for a physical description or reconstruction of the incident wave field, neither for the high definition extraction of directional acoustic properties and other methods have to be applied for these purposes [2], [3].

Knowledge about the complete pressure wave field can deliver more information than a single-point omnidirectional or stereo measurement optimized than human perception can [4], [5], [6].

By using arrays of microphones, re-bendings and other distortions in the propagation of sound can be obtained. So, the spatial characteristics of a particular room can be achieved. The basic theory of wave field decomposition and application of microphone arrays has already been explored to a wide extend [7]. Nevertheless, currently there is not an exhaustive study of room acoustics using synthesis techniques with speaker arrays, where arrays of microphones to decompose the sound field in plane waves are previously used. For this reason, it is interesting to have a method that enables the perceptual assessment of the complete hall including all temporal and spatial cues and can be applied to both calculated impulse responses for modeled halls and measured impulse responses for existing halls.

In this paper, a recent procedure of measuring spatial sound characteristics by means of circular arrays is presented, which has been shown [7], [8], [9] that provides added features to another type of array as the linear arrays. In order to have a general and more flexible description of the sound field not linked to specific microphone positions, decomposition of the sound field into plane waves is considered. For a circular array, the Kirchhoff-Helmholtz and Rayleigh integrals are used to later extrapolate the sound field using cylindrical harmonics. This tool can be regarded as making auralization system that renders audible a 3D model of an acoustic environment and reconstructions by means of today’s surround system, or others as Wave Field Synthesis, without limiting the future usage by sticking to the limited reproduction technology currently available.

The advantages over conventional measurement technologies have been investigated and evaluated. Furthermore, to enable practical research on this measurement method, a circular microphone array has been designed and built, and also different halls have been analysed in order to demonstrate the potentials of the proposed method. With these results, a complete acoustical description of the sound field inside the room is acquired, which allows designers to investigate benefits but also possible defects or unwanted reflections to be corrected just as auralizing these signals with a 3D model of the room.

2. Cylindrical Harmonics

To carry out the implementation of the performed method, it is necessary to take the cylindrical harmonics as starting point. For further explanation, refer to [9] and [10].

In this work, one method is examined to identify, separate, and reproduce the relevant reflections. This method decomposes the data into cylindrical harmonics and aims to transforming the array data set from the “data space” to a “model space” in such a way that interfering events in the data space appear as distinct points in the model space. By this way, it will be easy to identify different events and separate them from each other. Besides cylindrical harmonics are used to decompose a sound field recorded with a circular array [11]. Cylindrical harmonics are the 2D variant of spherical harmonics.

To decompose a sound field into cylindrical harmonics, there has to be found a $M^{(1)}(k_\varphi,\omega)$ and $M^{(2)}(k_\varphi,\omega)$ such that [11]:

$$P(k_\varphi,\omega,R)=M^{(1)}(k_\varphi,\omega)H^{(1)}_{k_\varphi}(kR)+M^{(2)}(k_\varphi,\omega)H^{(2)}_{k_\varphi}(kR),$$

$$j\rho cV_n(k_\varphi,\omega,R)=M^{(1)}(k_\varphi,\omega)H'^{(1)}_{k_\varphi}(kR)+M^{(2)}(k_\varphi,\omega)H'^{(2)}_{k_\varphi}(kR). \tag{1}$$

This set of equations can be solved for $M^{(1)}$ and $M^{(2)}$ if the sound field on the array, i.e. at $r=R$ is known. $M^{(1)}$ and $M^{(2)}$ are the expansion coefficients of the sound field in terms of cylindrical harmonics. The decomposition and reproduction of sound fields in terms of spherical or cylindrical harmonics is called ambisonics [12], [13]. Therefore $M^{(1)}$ and $M^{(2)}$ will be denoted as the incoming and outgoing ambisonic representations of the sound field. Once $M^{(1)}$ and $M^{(2)}$ are known, it is straightforward to calculate the sound field anywhere in space using:

$$P(k_\varphi,\omega,r)=M^{(1)}(k_\varphi,\omega)H^{(1)}_{k_\varphi}(kr)+M^{(2)}(k_\varphi,\omega)H^{(2)}_{k_\varphi}(kr),$$

$$j\rho cV_n(k_\varphi,\omega,r)=M^{(1)}(k_\varphi,\omega)H'^{(1)}_{k_\varphi}(kr)+M^{(2)}(k_\varphi,\omega)H'^{(2)}_{k_\varphi}(kr), \tag{2}$$

3. Measurements and results

3.1 System implementation

Measurements were performed in three halls of University Castilla-La Mancha located in Cuenca, Spain. The positions of the array were chosen according to recommendations of [14] and they are illustrated in the floorplan in Fig. 1, which has been shown that such arrays provide significant improvements in capturing the sound field of a room, [15], [16], [17].

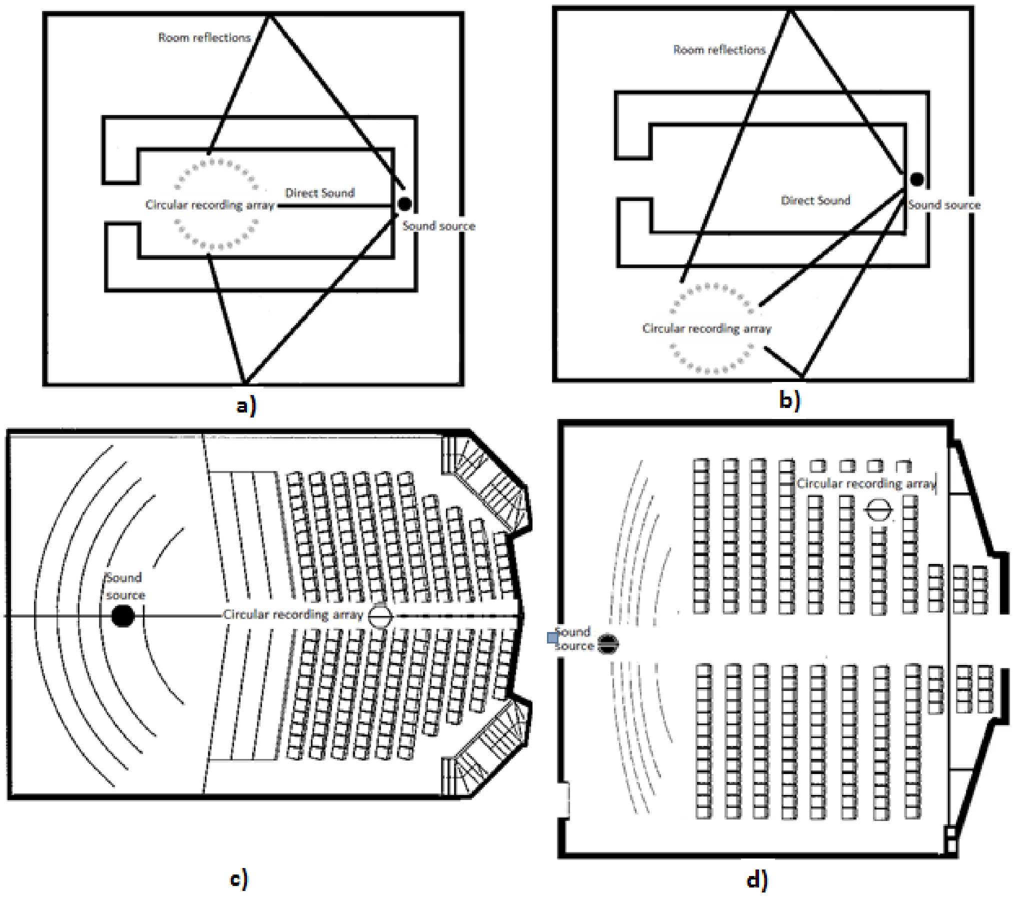
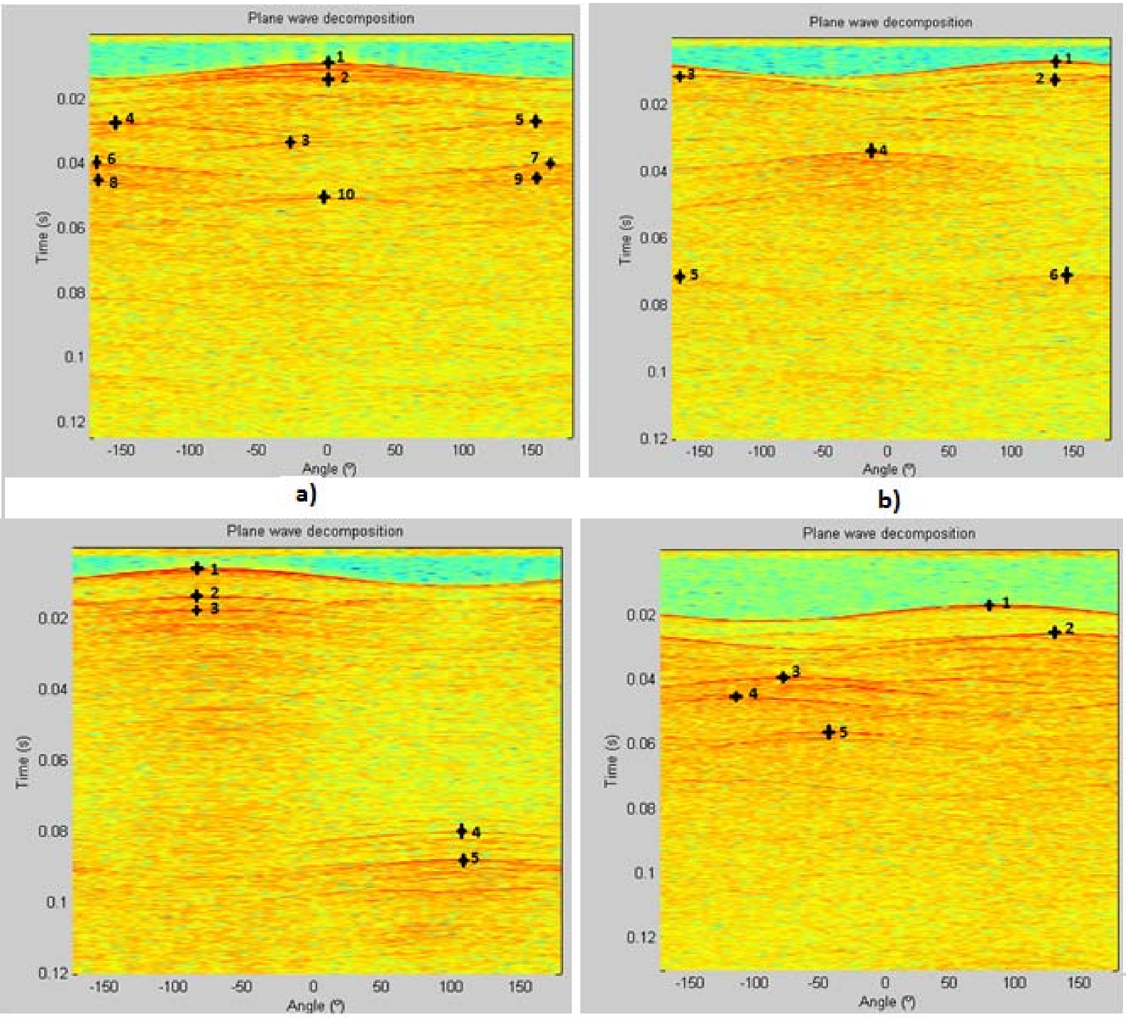


Figure 1 - Floorplan of the hall 1 (a, b), hall 2 (c) and hall 3 (d).

The rooms were not acoustical conditioned with reflections in walls and floor (the ceiling in all halls were slight conditioned). The Room Impulse Responses (RIR’s) were measured using 2 cardioid microphones attached to a rod on a turntable in 180º, evenly distributed over a circle of 2 m diameter placed within the listening A set of 36 x 2 RIR’s were obtained using Maximum Length Sequences (MLS) using software developed ad-hoc. From these RIR, and as direct sound as acoustics of the hall were recorded simultaneously by the array, plane waves decompositions of the room responses with the direct signal and all reflections were obtained.

3.2 Results

With changes in source and array positions, results were consistent with the location of source and receivers as well as the reflections by these positions.



a) b) c) d)

Figure 2 – Multitrace impulse reponses measured for a center (a) and lateral (b) array position respectively in the measurement hall 1, (c) for a center source and array position in the hall 2, (d) and for a center source and a lateral array position in the hall 3.

Figs. 2a-d shows the recorded wave field, where the zero-offset point is located at the array center. Displaying the impulse responses for all neighbouring receiver positions along the circular array reveals the spatial structure of the wave field. The first arrivals represent the hyperbolic direct wave front marked ‘‘1’’ in Figs. 2a-d. In the bounded of the analysed rooms, however, the direct wavefront is reflected by the side walls. In the offset-travel time display, this appears as a ‘‘folding’’ of the hyperbola.

The vertical axis in Figs. 2a-d, represents the time *t* which equals zero when the pulse leaves the source. Already without any further processing the dataset clearly shows the wave character of the sound field. In spite of the complex structure of the field due to interference and diffraction, many reflection and diffraction events can be easily discriminated since other than when displaying individual, isolated impulse responses now the spatial correlation between neighboring responses is revealed.

By taking the halls geometries into account, the origins of many reflected or diffracted wave fronts can be identified, as indicated in Figs. 2a-d. By applying a spatial Fourier transform to the dataset, the wave field is decomposed into plane wave components [16], [18]. More hyperbolic wavefronts can be distinguished in Figs. 2a-d as reflections with the walls, floor and other obstacles in the halls, which are marked with ‘‘2,’’ ‘‘3,’’ etc, having their apices at later delay times and, hence, having a flatter shape. In Fig. 2a these hyperbolaes represent spherical wavefronts first reflected by the floor “2”, right wall “3”, rigth-side table “4”, left-side table “5”, left wall “6”, front wall ”7”, the rear wall “10”, first front then rear wall “8” etc. In Fig. 2b these hyperbolaes represent spherical wavefronts first reflected by the floor “2”, right wall “3”, left-side table “4”, left-wall “5”. Note that, apart from travel time information, there is discrimination between wavefronts arriving from front or rear as long as cardioid microphones are used.

Reflections of these wavefronts at the side walls again appear as folded versions. It can be clearly observed that the density of these folded versions and the variety of their propagation directions increase with travel time. This phenomenon qualitatively supports the usual assumption that later reflections together form an isotropic distribution of plane waves. Fig. 2b shows the response for the same source position with a lateral array position, now with different distances to walls and the table (right and left) . The reflection density is the same than in the case above. Plane waves that representing the later reflections are seen to propagate in many directions, thus building up a reverberant field with a high degree of diffusivity. Note that the array cannot discriminate between different vertical angles of incidence. In the displays of Fig. 2, wavefronts having a vertical propagation component are seen as rotated to the horizontal plane over a cylinder with radius t. In order to analyze the vertical spatial properties of the wave field, vertical microphone arrays (or source arrays) should be applied. Fig. 2c shows the multitrace impulse responses measured for a center source and array position respectively in the hall 2, and Fig. 2d shows the multitrace impulse responses measured for a center source and a lateral array position in the hall 3. Source and array positions are specified in Fig. 1c and Fig. 1d respectively. It should be mentioned that, in the analysed method considered here, the reflections, effects of diffraction due to the finite boundary dimensions and boundary irregularities have been taken into account.

All results obtained by extrapolation match up with distances in the real measured halls with a lower difference in these measurements regarding the real distances.
Therefore, these results reveal that the method implemented in this work achieves a satisfactory distances values as additional information.

4. Conclusions and future work

In this paper, a decomposition of the data into cylindrical harmonics has been used for identification and separation of plane wave events in impulse response measurements with a circular array. Furthermore, this proposed method based on the measurement of impulse responses along a closely spaced array of microphone positions, has revealed the spatial coherence of neighboring responses, leading to a far better insight in the complex wave fields in enclosed spaces than the analysis of individual impulse responses. This approach has enabled perceptual evaluation of the sound field in a volume of the hall, instead of at one local position, without the use of headphones, i.e., with natural temporal and spatial cues. This may yield a major step forward in room acoustic consultancy practice. By applying processing techniques from one array measurement ample 3D information on the acoustics of a hall can be obtained. Also, the influence of interior design modifications, removal or renovation of chairs, addition of screens, etc. on the acoustic field can be evaluated physically and perceptually.

Consequently, this method provides the best available approach for storing the acoustical properties of rooms, such as concert halls, and theatres, and preserving them for the posterity. The resulting data can be used for audible reconstructions (auralization) by means of today's surround system, or others as Wave Field Synthesis, without limiting the future usage by sticking to the limited reproduction technology currently available.

It is expected that a better description of complex wave fields in practical situations may generate more insight in the way these wave fields are perceived. The use of optimal array processing methods for sound field analysis and reproduction by means of Wave Field Synthesis or other synthesis systems with Distributed Modes Loudspeakers (DML) is proposed for future work.

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References

[1] H. Kuttruff, “Room Acoustics”. Taylor & Francis, 4th edition, 2000.
[2] T. Peltonen, T. Lokki, B. Goutarbés, J. Merimaa, and M. Karjalainen. “A system for multi-channel and binaural room response measurements”. In AES 110th Convention, Amsterdam, The Netherlands, 2001. Preprint 5289.
[3] V. Pulkki. “Virtual sound source positioning using vector base amplitude panning”. J. Audio Eng. Soc., 45(6):456–466, 1997.
[4] D. Blackstock, “Fundamentals of physical acoustics”, Wiley-Interscience, New York, 2000.
[5] J. Picaut, L. Simon and J. D. Ploack, “A mathematical model of diffuse sound field based on diffusion equation”, Acust. Acta Acust. 83, 614-621, 1997.
[6] M. Abramowitz and I. Stegum, “Handbook of mathematical functions”. Dover Publications Inc, New York, 1965.
[7] D. Hulsebos, de Vries, “Auralization using wave field synthesis”. PhD thesis, Delft University of Technology, Delft, 2004.
[8] D. d. Vries, L. Hörchens, P. Grond, “Array Measurements for Auralization with Wave Field Synthesis”, Laboratory of Acoustical Imaging and Sound Control, Department of Image Science Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands, EURASIP Journal on Advances in Signal Processing Volume 2007, Article ID 13416,2007.
[9] D. d. Vries and J. Baan, “Auralization of sound fields by wave field synthesis”, 106th AES Convention, Munich, Germany, 1999, p. preprint 4927, 2009.
[10] Hulsebos et al., 2001, “Improved microphone array configurations for auralisation of sound fields by Wave Field Synthesis”, AES 110th convention, Amsterdam, The Netherlands
[11] Bamford, J. S., 1995,”An analysis of ambisonic sound systems of first and second order”, Ph. D. Thesis, University of Waterloo, Ontario, Canada.

[12] J. Bamford, .”An analysis of ambisonic sound systems of first and second order”, PhD Thesis, University of Waterloo, Ontario, Canada, 1995, p. PhD Thesis.

[13] J.Merimaa,T. Peltonen, T. Lokki, “Concert Hall Impulse Responses. Analysis Results”, Telecommunications Software and Multimedia Laboratory,Helsinki University of Technology, P.O.Box 5400, FI-02015TKK, Finland, 2005.

[14] L. Tronchin, A. Farina, “Room acoustics measurements and auralization”. 108th Convention 2000, February 19-22 Paris, France, 2000. [14] P. Grond, “Extraction of 3D information from 2D array measurements”, M. Sc. Thesis, 2005.

[15] V. D. d. Berkhout, A.J and J. Boone, M.M. Sonke, “Array technology for acoustic wave.eld analysis in enclosures”, J. Acoust. Soc.Am, vol. 102, no. 1, pp. 2757.2770, 1997.

[16] E. Start, “Direct sound enhancement by wave field synthesis”. PhD thesis,Delft University of Technology, Delft, 1997.

[17] A. Berkhout, .A holographic approach to acoustic control,.Acous.Soc.Am., vol. 36, no. 12, pp. 977.995, 1988.

[18] ISO 3382. “Acoustics- Measurement of the reverberation time of rooms with reference to other acoustical parameters”. International Standards Organization, 1997.

[19] J.-M. Jot, L. Cerveau, and O. Warusfel. “Analysis and synthesis of room reverberation based on a statistical time-frequency model”. In AES 103rd Convention, New York, NY, USA, 1997. Preprint 4629.

[20] V. Pulkki, J. Merimaa, and T. Lokki. “Reproduction of reverberation with Spatial Impulse Response Rendering”. In AES 116th Convention, Berlin, Germany, 2004b. Preprint 270.

[21] A.C.Gade “ Acoustical survey of eleven European concert halls. A basis for discussion of halls in Denmark”. Technical Report 44, The Acoustics Laboratory, Technical University of Denmark, 1989.[23] A. Farina. “Simultaneous measurement of impulse response and distortion with a swept-sine technique”. In AES 108th Convention, Paris, France, 2000. Preprint 5093.

[22] A. Farina, R. Avalon, “Recording concert hall acoustics for posterity”, AES 24th International Conference on Multichannel Audio, Industrial Engineering Dept., University of Parma, ITALY, 2005.

[23] A. Farina, L. Tronchin, “Measurements and reproduction of spatial sound characteristics of auditoria”, 1Industrial Engineering Department University of Parma, Department of Energetic, Nuclear and Environmental Control Engineering,University of Bologna, Acoust. Sci. & Tech. 26, 2, 2005.

[24] A. Kulowski, “Algorithmic representation of the ray tracing technique,” Appl. Acoust., vol. 18, no. 6, pp. 449–469, 1985.

[25] B. Rafaely, I. Balmages, L. Eger, “High-resolution plane-wave decomposition in an auditorium using a dual-radius scanning spherical microphone array”, Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Acoustical Society of America, Israel, 2007.