Savioja, Lauri; Xiang, Ning

Introduction to the Special Issue on Room Acoustic Modeling and Auralization

Published in:
Journal of the Acoustical Society of America

DOI:
10.1121/1.5099017

Published: 01/04/2019

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Savioja, L., & Xiang, N. (2019). Introduction to the Special Issue on Room Acoustic Modeling and Auralization. Journal of the Acoustical Society of America, 145(4), 2597-2600. https://doi.org/10.1121/1.5099017

Introduction to the Special Issue on Room Acoustic Modeling and Auralization

Lauri Savioja, and Ning Xiang

Citation: The Journal of the Acoustical Society of America **145**, 2597 (2019); doi: 10.1121/1.5099017
View online: https://doi.org/10.1121/1.5099017
View Table of Contents: https://asa.scitation.org/toc/jas/145/4
Published by the Acoustical Society of America

Introduction to the Special Issue on Room Acoustic Modeling and Auralization

Lauri Savioja[1,a)] and Ning Xiang[2,b)]
[1]*Department of Computer Science, Aalto University, Espoo, Finland*
[2]*Graduate Program in Architectural Acoustics, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*

(Received 25 March 2019; revised 1 April 2019; accepted 2 April 2019; published online 30 April 2019)

This Special Issue on Room Acoustic Modeling and Auralization contains nineteen research papers. A majority of the papers focus on various room acoustic simulation techniques, while the remaining ones concentrate on auralization of either simulation or measurement results. Using room acoustic simulation, the last paper in this issue presents a case study of the historic venue, Palais du Trocadero in Paris, France.

https://doi.org/10.1121/1.5099017

[JFL] Pages: 2597–2600

I. INTRODUCTION

Computational room acoustic modeling and auralization were envisioned almost 60 years ago when Schroeder *et al.* (1962) presented the principal ideas behind these concepts at the 1962 International Congress on Acoustics. Recently, Krokstad *et al.* (2015) also provided a historical review on room-acoustic computer simulation using ray tracing.

At its early stage, room acoustic computer simulation was developed without audible components (Schroeder, 1973; Krokstad *et al.*, 1983). In binaural room simulation (Blauert *et al.*, 1990), auralization was already a part of modeling, and the phrase itself implicitly reflects rendering binaurally for auditory perceptual evaluation through room acoustic modeling. In a more recent overview of reverberation techniques, Välimäki *et al.* (2012) convey that the focus of room acoustic modeling is obtaining room responses by computational simulation. Those responses can then be rendered for auditory perception. In room-acoustics, Kleiner *et al.* (1993) coined the term "auralization," which was motivated by "visualization" as used for visual rendering. Summers (2008) notes that auralization represents acoustic modeling as the agent that performs the rendering for the purpose of auditory perception and the sound events being rendered are created via simulation. Vorländer (2007) expands the term to include any process that renders audible data through simulation, synthesis, or even measurements. In modern parlance, both the process and the result of the process are termed as auralization (Summers, 2008).

There are several approaches on room acoustic modeling; on a very high level the techniques can be categorized according to the underlying equation. The most rigorous simulations aim at solving the acoustic wave equation, a second-order partial differential equation that describes the behaviour of sound in an ideal medium, or, the Helmholtz equation, its counterpart in the frequency domain. Solving these equations is difficult, and analytic solutions exist only in some rare cases. For this reason, practical solvers apply some discretization of the space and/or time. In general, these are called wave-based computational methods and this family of methods includes such methods as the finite-difference time-domain (FDTD), the finite-element (FEM), and the boundary-element methods (BEM). The first papers to discuss use of FDTD in room acoustics simulations date back to 1994 (Botteldooren, 1994), and there has been significant progress in the ensuing years. Special attention has been paid, for example, on how to model complex geometries (Bilbao, 2013).

Geometrical acoustics is another approach that is widely used in room acoustic modeling. The basic assumption in geometrical acoustics is that sound is supposed to act as rays, and all the phenomena caused by the wave-nature of the sound are neglected (Savioja and Svensson, 2015). In practice this means that geometrical acoustics models are computationally much more efficient but less accurate than the wave-based models. These techniques have been in practical room acoustic modeling use for over 50 years as Krokstad *et al.* (1968) published their seminal work on acoustic ray-tracing in 1968. Another key method in this family is the image-source method. While originally introduced in 1948 (Cremer, 1948), the widespread adoptance of the technique can be credited to Allen and Berkley (1979), and to Borish (1984) who extended the technique to arbitrary polyhedra. Later advancements include such techniques as beam-tracing that speeds-up the computation of image sources (Funkhouser *et al.*, 2004). There are also techniques that enable modeling of diffuse reflections such as the acoustic radiosity (Carroll and Miles, 1978; Miles, 1984) and the diffusion equation (Ollendorff, 1969; Valeau *et al.*, 2006). All these techniques have their advantages and disadvantages, and there are various hybrid models that aim at combining the best parts of each technique, such as combining ray-tracing and the image-source technique (Vorländer, 1989). The room acoustic rendering equation is a mathematical framework that covers all the geometrical acoustics modeling techniques (Siltanen *et al.*, 2007).

[a)]Electronic mail: Lauri.Savioja@aalto.fi
[b)]Electronic mail: xiangn@rpi.edu

II. CONTRIBUTIONS IN THIS SPECIAL ISSUE

This Special Issue contains nineteen research papers. The majority focus on various room acoustic modeling techniques while the remaining concentrate on auralization of either simulation or measurement results. The last paper in this issue presents a case study (Postma *et al.*, 2019) of the historic building Palais du Trocadero in Paris, France.

A. Room acoustic modeling

Reference solutions are essential when validating simulation results. Raudales *et al.* (2019) present analytical solutions to broadband sound fields in three cases that can be used as benchmarks when validating simulations.

1. Wave-based models

Bilbao and Hamilton (2019) present a general framework for time-domain simulations with arbitrary room geometries and pay special attention to the boundary conditions, as those are typically challenging in non-rectangular geometries. Source and receiver directivities are essential factors for accurate room acoustic auralization. In their paper, Hargreaves *et al.* (2019) present a framework for incorporating the directivities in auralization of BEM simulations. Takeuchi *et al.* (2019) discuss modeling of source directivity in FDTD simulations. The discontinuous Galerkin method has been used since 1970s for solving partial differential equations. Wang *et al.* (2019) discuss how this method can be used in the simulation of room acoustics.

2. Diffraction and scattering

Pulkki and Svensson (2019) aim at perceptually plausible simulation of scattering from an object. They utilize machine-learning to obtain parameters for a filter structure to represent the scattering. The applied artificial neural networks can be trained both with simulated and measured data. The quality of the output is close to that of the training data.

Rozynova and Xiang (2019) demonstrate that sound diffraction around a rectangular rigid plate can be predicted using the physical theory of diffraction with high computational efficiency. The physical theory of diffraction relies on both geometrical and physical principles yet emphasizes the physical one. One of the important features of this physical acoustics approach is the ability to calculate the sound field more accurately in shadow boundaries (Ufimtsev, 2006).

3. Geometrical acoustics

Geometrical acoustics techniques typically operate with sound energies, but the image source method is able to handle the sound pressure, and correspondingly the phase. Boucher *et al.* (2019) have studied use of plane and spherical wave reflection coefficients in the image source method and conclude that the use of the spherical wave reflection coefficients provide more accurate results. The results are numerically more accurate and listening tests show that the differences are audible in most cases involving small rooms.

B. Reverberation modeling

As regards late reverberation techniques, when the accurate reverberation tails of room impulse responses are of secondary importance, artificial reverberation tails can be appended for computational efficiency (Moorer, 1979). The technique combines early portions of room impulse responses modeled by pertinent simulation tools, including geometrical acoustics modeling incorporating detailed binaural receiving characteristics, with stochastic reverberation tails originated by Moorer (1979). Martin *et al.* (1993) extended Moorer's approach for binaural auralization. They mixed two largely decorrelated random noise signals to obtain desirable energy decays and interaural cross-correlation coefficients in the binaural room impulse response tails. The artificial reverberation implemented in this way represents a filter approach based on finite-length impulse responses for auralization; that is in contrast to Schroeder's (Schroeder, 1962) all-pass filter approach. In this Special Issue, Xiang *et al.* (2019) investigate the spatial enveloping reverberance with respect to interaural decorrelation coefficients between two channels of binaural room impulse response tails. The spectra of the interaural decorrelation coefficients of binaural room impulse responses need to be shaped to contain specific profiles that are crucial for creating natural and enveloping perceived reverberance. A simple mixing network for a reciprocal maximum-length sequence pair is used for ease of generating artificial reverberation.

1. Analytical and equation-based models

Diffusion equation-based modeling of reverberation processes in enclosed spaces has recently drawn attention in room-acoustic simulations. Originated by Ollendorff (1969) for room-acoustic applications, room simulations are carried out based on analytical equations, subject to rigorous boundary conditions (Jing and Xiang, 2008a). Solutions of the diffusion equation rely on a numerical finite element framework achieved, for example, using the finite element method (Valeau *et al.*, 2006) and the finite difference time domain scheme (Xiang *et al.*, 2013). However, mean-free-path lengths of the space under test dictate the required elementary meshing condition, independent of the wavelength when modeling single-volume spaces. The numerical solution, therefore, requires much less computational burden. Deeply rooted in Fick's law (Jing and Xiang, 2008b), the diffusion equation predicts sound energy fluxes more efficiently than existing numerical tools. The recent decade has also witnessed other equation-based approaches (Dujourdy *et al.*, 2017; Jing *et al.*, 2010). In this Special Issue, Sü-Gül *et al.* (2019) applies the technique in historically significant mosques. Diffusion equation modeling incorporates energy absorption into the boundary conditions (Jing and Xiang, 2008a; Valeau *et al.*, 2006); Navarro and Escolano (2019) further discuss a mixed boundary condition for the diffusion equation models. Note that diffusion equation modeling is also able to incorporate mixed absorption/scattering boundaries (Foy *et al.*, 2016). Embrechts (2019) discusses another approach using an analytical model, the approach is able to incorporate both specular and diffuse reflections. Badeau (2019) introduces a mathematical model that can be used to generalize several formerly presented models.

C. Auralization

Auralization embodies both the modeling process and the result of the process being rendered for auditory perceptual evaluations by human subjects (Kleiner *et al.*, 1993; Summers, 2008). This section introduces contributions on auralization based on both simulation and measurement results.

1. Auralization of simulation results

Brinkmann *et al.* (2019) describe round robin tests pertaining to room acoustical simulation and auralization in which perceptual evaluation of room acoustic simulations has been reported for the first time.

Saarelma and Savioja (2019) have studied perception of the dispersion error inherent in FDTD simulation results. Earlier studies on the same topic have focused solely on the direct sound without any reflections. In this paper, audibility of the error with a single reflection is investigated and the primary finding is that the dispersion error in a reflection is more audible than the corresponding error in the direct sound.

The wave-based methods are typically constrained to low frequencies due to the excessive computational load imposed by expanding the simulations to cover the full audible bandwidth. Southern *et al.* (2019) present a technique to extrapolate spatial impulse responses to cover higher frequencies as well. The technique is capable of handling both measured and simulated responses.

2. Auralization based on measurements

Ahrens and Andersson (2019) have compared auralizations based on spherical microphone array recordings to direct dummy-head recordings. One of their findings is that those two are partially indistinguishable from each other at spherical harmonics of eight order and higher.

Dick and Vigeant (2019) have investigated listener envelopment utilizing a spherical microphone array and third-order Ambisonics reproduction. Listener envelopment, also addressed by Xiang *et al.* (2019), is a desirable attribute of performance spaces that deserves attention in the field.

III. CONCLUDING REMARKS

Over the past five decades, room-acoustic modeling has been undergoing a number of decisive breakthroughs to arrive at the state-of-the art today. Computational resources have been drastically advanced so that complex simulation tasks, once impossible to achieve, can nowadays be accomplished. The contributions of this Special Issue cover a wide variety of research efforts in modeling and auralization with many of them providing new aspects and developments that will inevitably move the field forward. Early round robin tests and the one reported in this Special Issue still hint at profound challenges for room-acoustics scientists and engineers yet to come.

Ahrens, J., and Andersson, C. (**2019**). "Perceptual evaluation of headphone auralization of rooms captured with spherical microphone arrays with respect to spaciousness and timbre," J. Acoust. Soc. Am. **145**(4), 2783–2794.

Allen, J. B., and Berkley, D. A. (**1979**). "Image method for efficiently simulating small-room acoustics," J. Acoust. Soc. Am. **65**(4), 943–950.

Badeau, R. (**2019**). "Common mathematical framework for stochastic reverberation models," J. Acoust. Soc. Am. **145**(4), 2733–2745.

Bilbao, S. (**2013**). "Modeling of complex geometries and boundary conditions in finite difference/finite volume time domain room acoustics simulation," IEEE Trans. Audio Speech Lang. Process. **21**(7), 1524–1533.

Bilbao, S., and Hamilton, B. (**2019**). "Passive volumetric time domain simulation for room acoustics applications," J. Acoust. Soc. Am. **145**(4), 2613–2624.

Blauert, J., Lehnert, H., Pompetzki, W., and Xiang, N. (**1990**). "Binaural room simulation," Acustica **72**, 295–296.

Borish, J. (**1984**). "Extension of the image model to arbitrary polyhedra," J. Acoust. Soc. Am. **75**(6), 1827–1836.

Botteldooren, D. (**1994**). "Acoustical finite-difference time-domain simulation in a quasi-cartesian grid," J. Acoust. Soc. Am. **95**(5), 2313–2319.

Boucher, M., Rychtarikova, M., Zelem, L., Pluymers, B., and Desmet, W. (**2019**). "Reverberation time and audibility in phased geometrical acoustics using plane or spherical wave reflection coefficients," J. Acoust. Soc. Am. **145**(4), 2681–2690.

Brinkmann, F., Aspöck, L., Ackermann, D., Lepa, S., Vorländer, M., and Weinzierl, S. (**2019**). "A round robin on room acoustical simulation and auralization," J. Acoust. Soc. Am. **145**(4), 2746–2760.

Carroll, M. M., and Miles, R. N. (**1978**). "Steady-state sound in an enclosure with diffusely reflecting boundary," J. Acoust. Soc. Am. **64**(5), 1424–1428.

Cremer, L. (**1948**). *Die wissenschaftlichen Grundlagen der Raumakustik: Geometrische Raumakustik* (S. Hirzel Verlag, Stuttgart, Germany), pp. 15–29.

Dick, D., and Vigeant, M. (**2019**). "An investigation of listener envelopment utilizing a spherical microphone array and third-order ambisonics reproduction," J. Acoust. Soc. Am. **145**(4), 2795–2809.

Dujourdy, H., Pialot, B., Toulemonde, T., and Polack, J.-D. (**2017**). "An energetic wave equation for modelling diffuse sound fields—Application to corridors," Acta Acust. Acust. **103**(4), 480–491.

Embrechts, J.-J. (**2019**). "An analytical model for reverberation energy decays in rooms with specular and diffuse reflections," J. Acoust. Soc. Am. **145**(4), 2724–2732.

Foy, C., Picaut, J., and Valeau, V. (**2016**). "Including scattering within the room acoustics diffusion model: An analytical approach," J. Acoust. Soc. Am. **140**(4), 2659–2669.

Funkhouser, T., Tsingos, N., Carlbom, I., Elko, G., Sondhi, M., West, J. E., Pingali, G., Min, P., and Ngan, A. (**2004**). "A beam tracing method for interactive architectural acoustics," J. Acoust. Soc. Am. **115**(2), 739–756.

Hargreaves, J., Rendell, L., and Lam, Y. (**2019**). "A framework for auralization of boundary element method simulations including source and receiver directivity," J. Acoust. Soc. Am. **145**(4), 2625–2637.

Jing, Y., Larsen, E., and Xiang, N. (**2010**). "One-dimensional transport equation models for sound energy propagation in long spaces: Theory," J. Acoust. Soc. Am. **127**, 2312–2322.

Jing, Y., and Xiang, N. (**2008a**). "On boundary conditions for the diffusion equation in room acoustic prediction: Theory, simulations, and experiments," J. Acoust. Soc. Am. **123**, 145–153.

Jing, Y., and Xiang, N. (**2008b**). "Visualizations of sound energy across coupled rooms using a diffusion equation model," J. Acoust. Soc. Am. **124**(6), EL360–EL365.

Kleiner, M., Dalenbäck, B.-I., and Svensson, P. (**1993**). "Auralization—An Overview," J. Audio Eng. Soc. **41**(11), 861–875.

Krokstad, A., Strøm, S., and Sørsdal, S. (**1968**). "Calculating the acoustical room response by the use of a ray tracing technique," J. Sound Vib. **8**(1), 118–125.

Krokstad, A., Strøm, S., and Sørsdal, S. (**1983**). "Fifteen years' experience with computerized ray tracing," Appl. Acoust. **16**(4), 291–312.

Krokstad, A., Svensson, U. P., and Strøm, S. (**2015**). "The early history of ray tracing in acoustics," in *Acoustics, Information, and Communication—Memorial Volume in Honor of Manfred R. Schroeder*, edited by N. Xiang and G. M. Sessler (Springer, Cham), Chap. 2, pp. 15–30.

Martin, J., Maercke, D. V., and Vian, J.-P. (**1993**). "Binaural simulation of concert halls: A new approach for the binaural reverberation process," J. Acoust. Soc. Am. **94**(6), 3255–3264.
Miles, R. N. (**1984**). "Sound field in a rectangular enclosure with diffusely reflecting boundaries," J. Sound Vib. **92**(2), 203–226.
Moorer, J. A. (**1979**). "About this reverberation business," Comput. Music J. **3**(2), 13–28.
Navarro, J. M., and Escolano, J. (**2019**). "A mixed boundary condition for accounting energy absorption and transmission in a diffusion equation model," J. Acoust. Soc. Am. **145**(4), 2718–2723.
Ollendorff, F. (**1969**). "Statistical room-acoustics as a problem of diffusion a proposal," Acustica **21**, 236–1245.
Postma, B., Dubouilh, S., and Katz, B. F. G. (**2019**). "An archeoacoustic study of the history of the Palais du Trocadero (1878–1937)," J. Acoust. Soc. Am. **145**(4), 2810–2821.
Pulkki, V., and Svensson, U. P. (**2019**). "Machine-learning-based estimation and rendering of scattering in virtual reality," J. Acoust. Soc. Am. **145**(4), 2664–2676.
Raudales, D., Bliss, D., Michalis, K., Rouse, J., and Franzoni, L. (**2019**). "Benchmark analytical solutions for steady state high frequency broadband sound fields in three rectangular enclosures," J. Acoust. Soc. Am. **145**(4), 2601–2612.
Rozynova, A., and Xiang, N. (**2019**). "Sound diffraction prediction of a rectangular rigid plate using the physical theory of diffraction," J. Acoust. Soc. Am. **145**(4), 2677–2680.
Saarelma, J., and Savioja, L. (**2019**). "Audibility of dispersion error in room acoustic finite-difference time-domain simulation in the presence of a single early reflection," J. Acoust. Soc. Am. **145**(4), 2761–2769.
Savioja, L., and Svensson, U. P. (**2015**). "Overview of geometrical room acoustic modeling techniques," J. Acoust. Soc. Am. **138**(2), 708–730.
Schroeder, M. R. (**1962**). "Natural-sounding artificial reverberation," J. Audio Eng. Soc. **10**(3), 219–223.
Schroeder, M. R. (**1973**). "Computer models for concert hall acoustics," Am. J. Phys. **41**, 461–471.
Schroeder, M. R., Atal, B. S., and Bird, C. (**1962**). "Digital computers in room acoustics," in *Proceedings of the 4th International Congress on Acoustics*, Copenhagen, Denmark, pp. M21.1–M21.4.
Siltanen, S., Lokki, T., Kiminki, S., and Savioja, L. (**2007**). "The room acoustic rendering equation," J. Acoust. Soc. Am. **122**(3), 1624–1635.
Southern, A., Murphy, D., and Savioja, L. (**2019**). "Boundary absorption approximation in the spatial high-frequency extrapolation method for parametric room impulse response synthesis," J. Acoust. Soc. Am. **145**(4), 2770–2782.
Sü-Gül, Z., Odabas, E., Xiang, N., and Caliskan, M. (**2019**). "Diffusion equation modeling for sound energy flow analysis in multi domain structures," J. Acoust. Soc. Am. **145**(4), 2703–2717.
Summers, J. E. (**2008**). "What exactly is meant by the term 'auralization?'," J. Acoust. Soc. Am. **124**(2), 697–697.
Takeuchi, D., Yatabe, K., and Oikawa, Y. (**2019**). "Source directivity approximation for finite-difference time-domain simulation by estimating initial value," J. Acoust. Soc. Am. **145**(4), 2638–2649.
Ufimtsev, P. Y. (**2006**). "Improved theory of acoustic elementary edge waves," J. Acoust. Soc. Am. **120**(2), 631–635.
Valeau, V., Picaut, J., and Hodgson, M. (**2006**). "On the use of a diffusion equation for room-acoustic prediction," J. Acoust. Soc. Am. **119**, 1504–1513.
Välimäki, V., Parker, J., Savioja, L., Smith, J. O., and Abel, J. S. (**2012**). "Fifty years of artificial reverberation," IEEE Trans. Acoust. Speech Lang. Proc. **20**(5), 1421–1448.
Vorländer, M. (**1989**). "Simulation of the transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm," J. Acoust. Soc. Am. **86**(1), 172–178.
Vorländer, M. (**2007**). *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms, and Acoustic Virtual Reality* (Springer-Verlag, Berlin, Germany).
Wang, H., Sihar, I., Muñoz, R., and Hornikx, M. (**2019**). "Room acoustics modelling in the time-domain with the nodal discontinuous Galerkin method," J. Acoust. Soc. Am. **145**(4), 2650–2663.
Xiang, N., Escolano, J., Navarro, J. M., and Jing, Y. (**2013**). "Investigation on the effect of aperture sizes and receiver positions in coupled rooms," J. Acoust. Soc. Am. **133**(6), 3975–3985.
Xiang, N., Xie, B.-S., and Trivedi, U. (**2019**). "Artificial enveloping reverberation for binaural auralization using reciprocal maximum-length sequences," J. Acoust. Soc. Am. **145**(4), 2691–2702.