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Published in:
Journal of the Acoustical Society of America

DOI:
10.1121/1.5087997

Published: 01/01/2019

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

Please cite the original version:
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Citation: The Journal of the Acoustical Society of America 145, EL116 (2019); doi: 10.1121/1.5087997
View online: https://doi.org/10.1121/1.5087997
View Table of Contents: https://asa.scitation.org/toc/jas/145/1
Published by the Acoustical Society of America

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Spatial analysis of modal time evolution in room acoustics

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Abstract: Time-domain simulation methods allow the observation of the state of the simulation domain at each discrete time step. In this work, an approach to analyze the progress of the sound field in the simulation domain using time-windowing and spectrum analysis is presented. The method makes it possible to analyze the effect of geometric structures into the spatiotemporal distribution of energy in the domain at a frequency range of interest. Several examples are presented.

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Date Received: November 9, 2018  Date Accepted: January 1, 2019

1. Introduction

Simulation is a common approach to predict different properties of acoustic systems. For visualization purposes, geometric methods offer an intuitive and direct way to study the different propagation paths of sound energy. Knowledge of the propagation paths allows the user to visualize the direction of arrival, and the distribution of the energy within the room geometry. Visualization of geometric acoustic prediction may be very informative, but the downside of the approach is that it does not accurately represent certain physical phenomena such as diffraction and resonances in general geometries. Wave-based simulation methods are commonly used for acoustic problems where either a structural vibration affects the propagation or where wave phenomena are otherwise in a large role. Finite element and boundary element methods have been used to predict and visualize the structural vibration and acoustic radiation of loudspeaker sources. Time-domain methods have been proposed for visualization of sound propagation in air.

Some examples of combined visualization of measured and simulated results have been suggested. Siltanen et al. proposed an approach where the energy of measured impulse responses is plotted in CAD model surfaces in different time instances. Saarelma and Greco presented an approach to concurrently simulate the sound field of a room and visualize a measured directional response.

The downside of a visual investigation of the spatial propagation of pressure waves in time is that although the interference phenomenon is visible throughout the domain, the effect of the pressured distribution to frequency, and time-frequency responses, in a given location are not apparent. In this work, a method to investigate the time-frequency response in the spatial domain is proposed. The approach is to record a time history of a finite-difference time-domain simulation domain or partial domain, transfer the time history at each discrete point to a frequency domain, and visualize the frequency response at each spatial point. The results are illustrated with several example scenarios.

2. Methods

A scalar wave equation is used here as a model for propagation of sound in air, which in a three-dimensional Cartesian coordinate system is given by

$$\frac{\partial^2 p}{\partial t^2} = c^2 \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right),$$

(1)

where $p = p(x, y, z, t)$ is the acoustic pressure and $c$ is the speed of sound, taken here to be 344 m/s. Equation (1) can be discretized by substituting the partial derivatives with finite differences.
\[ \delta^2 p_{k,l,m}^n = \lambda^2 \left( \delta_x^2 + \delta_y^2 + \delta_z^2 \right) p_{k,l,m}^n, \]

where \( \lambda = c \Delta t / \Delta x \) denotes the Courant number, and \( \Delta x \) is the spatial step size and \( \Delta t \) is the sampling interval. The difference operators are defined,

\[ \delta^2 p_{k,l,m}^n = p_{k,l,m}^{n+1} - 2p_{k,l,m}^n + p_{k,l,m}^{n-1}, \]
\[ \delta_x^2 p_{k,l,m}^n = p_{k+1,l,m}^n - 2p_{k,l,m}^n + p_{k-1,l,m}^n, \]
\[ \delta_y^2 p_{k,l,m}^n = p_{k,l+1,m}^n - 2p_{k,l,m}^n + p_{k,l-1,m}^n, \]
\[ \delta_z^2 p_{k,l,m}^n = p_{k,l,m+1}^n - 2p_{k,l,m}^n + p_{k,l,m-1}^n, \]

with \( p_{k,l,m}^n = p(x, y, z, t) \), with \( x = k \Delta x \), \( y = l \Delta x \), \( z = m \Delta x \), and \( t = n \Delta t \). A uniform update including both the update for air and for first-order accurate boundary conditions is used in the solver implementation that is utilized in this work. The update for the pressure at a future time step reads

\[ p_{k,l,m}^{n+1} = \frac{1}{1 + \lambda \beta} \left[ (2 - K \lambda^2) p_{k,l,m}^n + (\lambda \beta - 1) p_{k,l,m}^{n-1} \right] + \lambda^2 \left( p_{k+1,l,m}^n + p_{k-1,l,m}^n + p_{k,l+1,m}^n + p_{k,l-1,m}^n + p_{k,l,m+1}^n + p_{k,l,m-1}^n + p_{k,l,m+1}^n \right), \]

where \( \beta = (6 - K / 2 \zeta) \) and \( \zeta \) is the specific acoustic impedance of the boundary node. Variable \( K \) represents the orientation type having different values for different positions (\( K = 6 \) for air, \( K = 5 \) for wall, \( K = 4 \) for wall-wall intersection, and \( K = 3 \) for corner).

The sound field is solved discretely in time-domain, which allows the access to pressure values at each spatial point at each discrete time step. This enables the recording of the pressure time history over large spatial regions with a negligible computational cost. If an impulse-like source signal is used, the pressure time-histories are band limited impulse responses at each discrete point. When the time-history of a spatial two-dimensional slice inside the domain is visualized as subsequent frames of an animation, what is observed is a propagating wavefront in the spatial domain.

With the intuition that the impulse responses of spatially distributed points illustrate the spatial propagation of the wavefronts, the analysis of the propagation behavior in the spatial domain may be further analyzed using fairly conventional methods. By taking a discrete Fourier transform (DFT) of each time-domain response at each spatial point, the dataset is turned into a collection of spectra that represents the frequency bins over the spatial region. The distribution of energy at a specific frequency bin, or over a combination of bins, can be analyzed by plotting the chosen frequency range of the steady state spectrum data over the region of interest. The combination of bins can be chosen arbitrarily, practical options being octave bands, third octave bands, or critical bandwidths. Time-frequency analysis may be carried out by windowing the captured impulse responses with chosen time increments and utilize DFT for each time window separately. The method of the time-frequency analysis in the spatial domain is illustrated in Fig. 1. The analysis may also be carried out using a sliding window in place of the expanding window presented in Fig. 1. A rectangular window is used throughout this work.

The memory consumption of the spatiotemporal dataset used for the analysis can be calculated from the dimensions of the spatial region and number of time steps used. As an example, in the case of the animations Mm. 1–12, the dataset is of the size \((700 \times 300 \times 1) \) (spatial points) \(\times\) 1135 (time steps) that results in approximately 0.95 GB in memory. A frame of animation is captured with five time step increments of the expanding window. Therefore, 1135/5 \(\times\) 700 \(\times\) 300 DFT evaluations are conducted in total. Naturally, the result of each DFT contains a range of frequencies, hence multiple animations for different frequency bins, or combinations of bins, can be generated simultaneously.

3. Results

In the following several examples of the proposed approach are presented. The first example is the visualization of the amplitude distribution inside a rectangular enclosure. A 1 s response in a rectangular room with the dimension 7 m \(\times\) 5 m \(\times\) 3 m is simulated. A normal incidence reflection coefficient \( R = 0.999 \) was used for each wall surface. A time history of a single “slice” of the domain in the \(x-y\) plane at the height of 1.5 m is captured. The source is located in the corner of the room at the coordinates 0.1, 0.1, and 0.1 m. The complete response is used in the DFT (number of bins = 2\(^{18}\)).
Fig. 1. (Color online) Illustration of the method of spatial time-frequency analysis. The impulse response of each spatial point is windowed and transferred to frequency domain in chosen time intervals. The energy of a chosen frequency range can be analyzed in the spatial domain, and time evolution may be investigated by analyzing subsequent frames.

Fig. 2. (Color online) Visualizations of different frequency bins in a region on the x-y plane of a rectangular room. The DFT is taken from 1 s impulse responses. Each bin corresponds to a different analytic room mode. From the top left to bottom right the number of mode planes and the corresponding frequencies are [1,0,0] 25 Hz, [0,1,0] 34 Hz, [1,1,0] 42 Hz, [2,0,0] 49 Hz, [0,2,0] 69 Hz, [2,2,0] 84.6 Hz, [3,0,0] 74 Hz, [0,3,0] 103 Hz, [3,3,0] 127 Hz.
Nine different frequency bins that correspond to the modes of the room are visualized in Fig. 2. It can be seen that the visualization matches the mode planes very well. The case where three mode planes are visualized illustrates an effect related to the current approach: as a wide bandwidth of frequencies is solved at once, a single bin may be affected by several different room modes. In Fig. 2, the bottom left capture contains energy from the axial mode \([3,0,0]\) at 74 Hz, and also from the tangential mode \([1,2,0]\) at 73 Hz.

In Fig. 3, the method is applied to a simulated field that contains the direct sound and a single boundary reflection. The top row contains the time-domain captures of the simulation data in five different time moments. A point source that emits a low-pass filtered impulse-like source signal is located 1.5 m above the reflective boundary. The reflective boundary is located at the bottom of the spatial region. A normal incidence reflection coefficient \(R = 0.999\) was used for the surface. It can be observed that before the wave reflects the boundary (columns 1 and 2) the energy distribution across the frequencies is the same. As an expanding analysis window is used, the energy of the passed wave trails behind the propagating wavefront. At the time windows where both the direct wave and the reflected wave have both passed a part of the capture region (columns 3, 4, and 5), a frequency dependent energy distribution emerges. This spatial distribution of energy in the visualization is referred to as \textit{interference patterns} hereafter. Animations of the time evolution of each frequency bin (50, 100, 400, and 1000 Hz) are presented in Mm. 1, 2, 3, and 4, respectively. The color range in the animations corresponds to Fig. 3. In this simple geometry, the interference pattern reflects the distance differences between the propagation paths of the direct and reflected wave in the different receiver locations. A similar interference pattern can be observed with a field generated using a simple image source model. A formulation for two point sources (one source and one image source, the surface reflection coefficient \(R = 1\)) can be written,

\[
P(r_1, r_2, t) = \frac{S}{4\pi} \left( \frac{1}{r_1} e^{i(\omega t - kr_1)} + \frac{1}{r_2} e^{i(\omega t - kr_2)} \right),
\]

\[
r_1 = ||p_{\text{rec}} - p_{\text{src}}||,
\]

\[
r_2 = ||p_{\text{rec}} + p_{\text{src}}||,
\]

(5)
where \( \mathbf{p}_{\text{rec}} \) is the current receiver position coordinate vector that corresponds to the image pixel, \( \mathbf{p}_{\text{src}} \) is the source position coordinate vector, \( \mathbf{p}_{\text{isrc}} \) is the image source position coordinate vector, \( \omega \) is the angular frequency, \( k \) is the wave number, and \( S \) is the used source function in the frequency domain. The point source formulation corresponds to simulation run with a soft source that is scaled with \( c^2 \left( \frac{\Delta t^2}{\Delta x^2} \right) \).\(^{10}\)

As a comparison to the reflection from a smooth surface, illustrations of reflections from scattering structures are presented in Fig. 4. The first structure that is included is a one-dimensional \textit{quadratic residual diffuser} (QRD) (Ref. 11, p. 291) with design parameters \( N = 17 \), well width = 3 cm, and well depth = 43 cm. The second structure is a group of vertical barriers with a height and a barrier-to-barrier distance of 1 m. Three different time moments from the beginning of the source on-set are visualized. The proposed approach is presented as captures of four different frequency bins: 50, 100, 400, and 1000 Hz with the time window length varied according to the time moments of the time-domain captures. Animations visualizing the time evolution of each frequency bin (50, 100, 400, and 1000 Hz) in each geometry condition are presented, respectively, in \textit{Mm. 1, 2, 3, and 4 (Smooth), Mm. 5, 6, 7, and 8 (QRD), and Mm. 9, 10, 11, and 12 (Barriers)}. The color range in the animations corresponds to Fig. 4.

\textit{Mm. 5.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a QRD diffuser surface, and a corresponding spatial frequency plot at the frequency bin corresponding to 50 Hz. This is a file of a type “mov” (879 KB).

\textit{Mm. 6.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a QRD diffuser surface, and a corresponding spatial frequency plot at the frequency bin corresponding to 100 Hz. This is a file of a type “mov” (836 KB).

\textit{Mm. 7.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a QRD diffuser surface, and a corresponding spatial frequency plot at the frequency bin corresponding to 400 Hz. This is a file of a type “mov” (851 KB).

\textit{Mm. 8.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a QRD diffuser surface, and a corresponding spatial frequency plot at the frequency bin corresponding to 1000 Hz. This is a file of a type “mov” (868 KB).

\textit{Mm. 9.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a surface with several 1 m high barriers, and a corresponding spatial frequency plot at the frequency bin corresponding to 50 Hz. This is a file of a type “mov” (341 KB).

\textit{Mm. 10.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a surface with several 1 m high barriers, and a corresponding spatial frequency plot at the frequency bin corresponding to 100 Hz. This is a file of a type “mov” (322 KB).

\textit{Mm. 11.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a surface with several 1 m high barriers, and a corresponding spatial frequency plot at the frequency bin corresponding to 400 Hz. This is a file of a type “mov” (334 KB).

\textit{Mm. 12.} Animation of point source emitting a low-pass filtered impulse-like source signal, 1.5 m above a surface with several 1 m high barriers, and a corresponding spatial frequency plot at the frequency bin corresponding to 1000 Hz. This is a file of a type “mov” (343 KB).

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Fig. 4. (Color online) Visualization of the sound fields time evolution with three different geometric structures. The first row illustrates the time-domain pressure field with each structure and time moment. The remaining rows illustrate the time evolution of each visualized frequency bin. The color range in the plots represents 10 to –30 dB.
Several observations can be made from the captures. In the time-domain visualization, the wavefront breaks both in time and spatial domain after interacting with the structures in comparison to the smooth surface. Individual reflected wavefronts can be identified in the case of the vertical barriers, but in the case of the diffuser, the wavefront is largely broken up, and individual diffracted or reflected waves are very hard to differentiate from each other. When comparing the interference patterns of the flat wall and the QRD diffuser, it can be seen that they are relatively similar up to the 400 Hz bin, which is the lower frequency limit of the diffuser design. At 1000 Hz, it can be seen that the distinct interference patterns that are present with the flat surface become more complex above the diffuser structure. When comparing both the reflections from the flat surface and QRD diffuser to the reflection from the structure with the barriers, it can be seen that there are differences in the interference patterns beginning from the 50 Hz frequency bin. In the case of the 50 Hz bin, the interference patterns of the barrier case are very similar, but it has more attenuation over the second and third barrier. For the higher frequency bins, the interference patterns are noticeably different, as the waves that are diffracted from the barriers affect the responses.

The accompanied animations explicitly illustrate how the frequency domain response is affected by different geometric structures. By viewing the time-domain propagation of the wavefront and the emerging interference pattern in sync, it is sufficiently easy to see which structures have a significant impact on a frequency range of interest.

4. Conclusions

An approach to visualize frequency domain energy distribution in any general spatial region of interest was presented. The method visualizes time-domain data captured in a spatial region in the frequency domain using time-windowing and DFT. The advantage of the proposed approach is that instead of interpreting the propagation of the time-domain wavefront, it is possible to directly assess the effect of each physical scatterer into the frequency range of interest in time-domain. The method may also be used for inspecting various different modes of the simulated enclosure after a single simulation, as the time-domain simulation result contains a wide bandwidth of frequencies. The method can be used in the analysis of scattering structures in performance spaces, such as diffuser surfaces and seating. Additionally it can be used in gaining intuition in how frequency domain behavior evolves inside enclosures, and possibly in pedagogical work to illustrate interference and other wave phenomena.

Acknowledgments

Sebastian Prepelita and Antti Kuusinen are thanked for commenting on the manuscript. This work has received funding from Academy of Finland, Project No. 265824.

References and links