Auralization of a Hybrid Sound Field using an Energy-Stress Tensor Based Model

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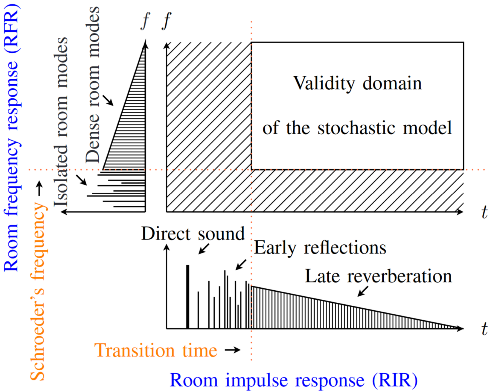
Introduction - Hybrid Acoustical Modeling

- Wave based
  - Accurately represent acoustic phenomena
  - Computational complexity $\to f^3$
  - No real-time audio tasks
- Geometric
  - Efficient for early reflections
  - Full band response
  - Requires non-physical modifications
- "Late reverberation"
  - Energy-based (diffusion)
  - Tunable reverberation schemes (FDN)
  - Problems with direct / early part; calibration
  - Efficient (typically fixed cost)

Introduction - Statistical Reverberation

- Can be represented as a stochastic process [1]
- Low frequencies dominated by isolated modes
- Early time dominated by isolated reflections
- Delimited by transition time and Schroeder's frequency



[1] Roland Badeau. "Common Mathematical Framework for Stochastic Reverberation Models". In: *The Journal of the Acoustical Society of America* 145.4 (Apr. 2019), pp. 2733–2745. DOI: 10.1121/1.5096153.

Energy-Stress Tensor (EST) Model

- Theoretical approach to statistical late reverberation
- Energy-stress tensor: conserved quantity relating energy density, sound intensity, and wave-stress tensor
- Valid in long spaces above 250 Hz octave band[2]
- Efficient: large cell sizes and low sample rates
- Not yet auralized

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[2] Aidan Meacham, Roland Badeau, and Jean-Dominique Polack. "Lower Bound on Frequency Validity of Energy-Stress Tensor Based Diffuse Sound Field Model". en. In: *Proceedings of the 23rd International Congress on Acoustics*. Aachen, Sept. 2019. DOI: 10.18154/RWTH-CONV-239324.

Energy-Stress Tensor (EST) Model

- Supports a wave equation (unlike diffusion equation method)
- Sound fields that build up in time depending on geometry
- Time series of energy density envelopes

Why auralize?

- Practical: confirm characteristics for real-time audio
- Pedagogical: check theory and numerical implementation

Theory

- System of coupled equations relating energy density E, sound intensity $\mathbf{J}$, and the wave-stress[3] symmetric tensor $\underline{\underline{E}}$
- Dimensional reduction[4] eliminates off-diagonal terms; resembles pressure / velocity fields s.t. $\underline{\underline{E}} \rightarrow p$, $\mathbf{J} \rightarrow \mathbf{v}$
- Use common numerical schemes with a few modifications to the boundary conditions[5]
- Decay rate of diffuse high frequency energy doesn't change rapidly in time or space

[3] Philip M. Morse and Herman Feshbach. *Methods of Theoretical Physics*. Mc Graw-Hill Book Company, 1953; Philip M. Morse and K. Uno Ingard. *Theoretical Acoustics*. Princeton University Press, 1968.

[4] Hugo Dujourdy et al. "An Energetic Wave Equation for Modelling Diffuse Sound Fields – Application to Corridors". en. In: *Acta Acustica united with Acustica* 103.3 (May 2017), pp. 480–491. DOI: 10.3813/AAA.919077.

[5] Aidan Meacham, Roland Badeau, and Jean-Dominique Polack. "Implementation of Sources in an Energy-Stress Tensor Based Diffuse Sound Field Model". en. In: *Proceedings of the International Symposium on Room Acoustics*. Amsterdam, Sept. 2019. DOI: 10.18154/RWTH-CONV-240108.

Hallway

Figure 1: View of source and microphone

Figure 2: View down length of hall

Hallway

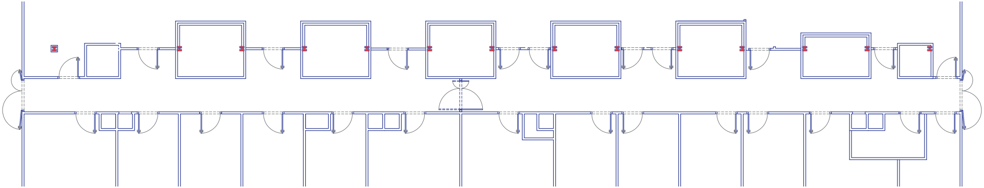


Figure 3: Floorplan for corridor under consideration

- 45 × 1.59 × 2.375 meters (LWH)
- Height measured to suspended metal grating
- Width increased to 2.39 meters in recesses
- Glass display cases or small pieces of furniture

Hybrid Model - EST

Finite volume time domain (FVTD) formulation of the EST model

- Frequency-dependent absorption and scattering coeffs.
- Brute force search matching measured acoustical indices $\pm 10\%$

Auralization

- Apply envelope in each frequency band to bandlimited noise
- Add resulting responses in the time domain

Hybrid Model - Low Freq. / Early Resp.

FVTD (pressure) through octave band centered at 500 Hz[6]

- Modal behavior and diffraction not modeled by EST method
- Assigned boundary conditions using example materials
- Oversampled and low-passed (dispersion)

Image source method (ISM) at final sample rate

- Freedom to choose maximum order of sources
  - Sufficiently represents early reflections
  - Unnecessary computation time for stochastic reflections

[6] S. Bilbao et al. “Finite Volume Time Domain Room Acoustics Simulation under General Impedance Boundary Conditions”. In: *IEEEACM Trans. Audio Speech Lang. Process.* 24.1 (Jan. 2016), pp. 161–173. DOI: 10.1109/TASLP.2015.2500018.

Calibration

Energy equalization

- Performed in frequency band with crossover (500 Hz)
- Reference distance of 1 m from source

Summation

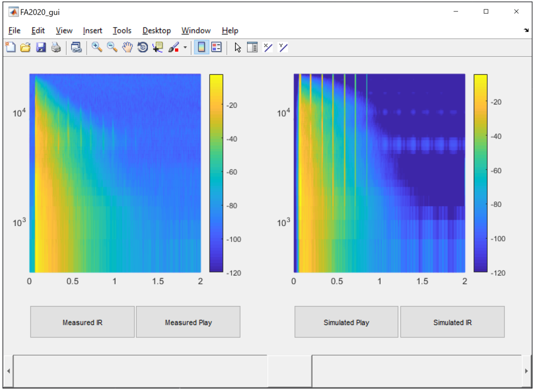
- Combine by superposition in the time domain
- Use wave simulation directly; high-pass others

Measurements

- Match levels at reference distance of 1 m
- Resulting gain applied regardless of sampling location

Evaluation by GUI

- Visual examination of spectrograms
- Direct auralization of impulse responses
- Convolution of IRs with source material
- Slider ranging from 1-42 m



Results - Demonstration

https://youtu.be/Pl2JDapt8Do

Results - The Good

- Overall decay times and absolute levels at any position
- Arrival times of most notable reflections
- Texture of late reverberation
- Overall impression of hallway
- With caching, quick to recomposite

Results - The Bad

- Decay times resulting from EST octave-band calibration
- Spatial decay not reproduced ideally in FVTD and ISM
- Accurate materials data for boundary conditions
- Viscothermal losses

Results - The Differences

- Near source, stochastic portion somewhat overrepresented
- Slight coloration shift toward higher frequencies
- Presence of a strong echo by far end of hallway courtesy of ISM not reflected in EST
- Using very low order ISM eliminates most salient features

Future Work

- Stationary vs moving sources (interpolate everywhere in advance / only recompute near receiver)
- Third-octave bands for EST calibration
- 3D model: differences in alcoves not covered by 1D model
- Directionality
- Anisotropy: consider non-homogeneous diffusion coefficients
- Predict EST boundary conditions from materials and geometry
- Temporal transition between high-frequency methods

Questions?

Find these slides and other resources at
http://aidanmeacham.com/fa2020/

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