Auralization of a Concert Hall through Computer Modeling Techniques

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INTRODUCTION

Research in architectural acoustics has become both a rigorous and complex task involving a variety of fields. Methods involving the assessment of the acoustic quality of a concert hall have increased in number as more variables are found to influence the path of sound from a source to the listener. The varied and numerous processes, however, ultimately aim toward the single goal of pleasing the aural perception of the listener.

Recent psychoacoustical experiments show the complexities of human aural perception, which are able to localize a sine-wave tone with considerable accuracy. In the forward direction, listeners are sensitive to differences as small as 1-2 degrees. The 1-degree difference in azimuth corresponds to an Interaural Time Difference of only 13 microseconds (Hartmann, 1999). Research in architectural acoustics has responded to the sensitivity of the listener by incorporating and expanding the parameters and methods of research. The researched geometry, materials, and conditions, which affect the qualities of an architectural enclosure, thus far have served as a basis for creating tools for designing, reconstructing and simulating the behavior of sound in a space.

This paper will study how the architectural elements of a concert hall affect the aural perception of the listener though computer modeling and its analysis. The elements of a specific concert hall such as the coffering of the ceiling and walls, balconies, and the orchestral shell will be modeled and compared with existing measured data to bring a better understanding of how a sound particular to a space is created. The paper also aims to provide an understanding of how reverberation time and an impulse response can be used to recreate the signature of an architectural space in an audio sample. The resulting analysis of the simulated music provides a sample portrayal of the significance of architectural acoustics research by generating a practical and comprehensible media for the public.

MODEL PREPARATION

The Boston Symphony Hall was chosen as the room to be modeled because of its available acoustic data and its popularity among the critics of the musical society. Rated as an "A+" hall, the architectural space of the concert hall has been a frequent subject of study (Beranek, 1996). Its classical "shoebox" geometry is studied in progressive stages from its simplest form to its existing form. With the following characteristics of the concert hall kept approximately constant when applicable, the various geometries of the architectural elements were modeled in CATT-Acoustic v7.1e. Five models of the room were constructed with increasing amounts of architectural detail added to the rooms. The characteristics of the rooms are summarized in Table 1.

The source, omni directional, was given sound pressure levels as follows. Since the maximum level of the anechoic music sample ranges up to the sound pressure level (SPL) of

	Volume	Architectural Characteristics
Boston Symphony	18,750 m³ (662000 ft³)	Main floor 1486 First tier 598 Second tier 541 Total 2625 seats
Model 1	20,560 m³	bare walls and ceiling, no orchestral shell, no tier levels
Model 2	19,000 m³	orchestral enclosure, bare walls and ceiling
Model 3	19,240 m³	orchestral enclosure, bare wall and ceiling, two tier levels
Model 4	19,170 m³	orchestral enclosure, coffered walls and ceiling
Model 5U and 5O	18,800 m³	orchestral enclosure, coffered walls and ceiling, two tier levels

Table 1. Summary of the characteristics of the five models and the Boston Symphony Hall

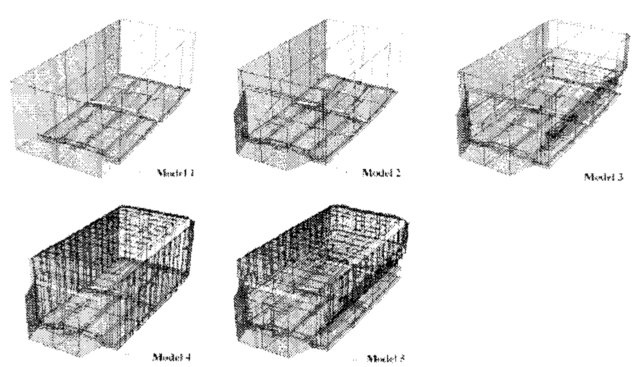

Fig. 1. This analysis was conducted with five models ranging from the simple, bare box to the approximation of the fine surface details and texture of the existing Boston Symphony Hall.

112 dB and chamber music in a small auditorium averages from 75 to 85 dB at the listener's ears, the SPL levels of the source were chosen accordingly (Benade, 1990). For the models, the SPL levels of 70,73,76,79,82,85 in the octave bands of 125, 250, 500, 1000, 2000, 4000 Hz respectively were used as the out put level of the source. A single receiver was located in the auditorium, where it would be considered the average seating condition for the auditorium. The coefficients of absorptions for wood, wood paneling, plaster on masonry, plaster on lath, audience, orchestra, and steel for the organ pipes and cast iron balcony fronts were input to reflect the conditions of the auditorium (Egan, 1988, Knudsen, 1978, Beranek, 1996).

ANALYSIS RESULTS

The acoustic modeling program uses Randomized Tail-corrected Cone-tracing that can generate echograms for auralization. (CATT-Acoustics) Since T-30 is considered to be the best estimate of the reverberation time it will be the main variable used in this comparison study. (CATT-Acoustics)

REVERBERANCE

The shoebox shape and volume contributed to the reverberation time, RT. The reverberation time for Model 1 is excessive as expected. The reverberation time calculated with T-30, which is derived from straight-line, least-square fits to

	Frequency					
	125	250	500	1000	2000	4000
Model						
Model 1 ($V=20{,}560\ m^3$)	3.93	4.48	4.90	4.91	4.52	3.30
Model 2 ($V=19{,}240\ m^3$)	3.86	4.33	4.72	4.49	4.09	3.09
Model 3 ($V=19{,}170\ m^3$)	3.18	3.37	3.37	3.11	2.98	2.38
Model 4 ($V=19{,}240\ m^3$)	4.01	4.39	4.38	4.27	3.78	2.87
Model 5U ($V=18{,}800\ m^3$)	2.32	2.44	2.32	2.41	2.37	1.99
Model 5O ($V=18{,}800\ m^3$)	1.84	1.98	1.84	1.77	1.64	1.37
Boston Symphony Hall						
Unoccupied	2.13	2.29	2.40	2.63	2.66	2.38
Occupied	1.95	1.85	1.85	1.85	1.65	1.30

Table 2. Summary of reverberation times calculated in the five models and average reverberation times actually measured in the Boston Symphony Hall (Beranek, 1996). 5U and 5O are values of Model 5 Unoccupied and Model 5 Occupied respectively.

Model. 1 2 3 4 5U BSHU 5O

EDT (sec.) 5.09 4.65 2.96 4.45 2.36 2.50
1.63
D-50 (%) 11.7 10.9 22.4 33.0 24.9 N/A
37.3
C-80 (dB) -5.9 -5.4 -1.9 -4.0 -1.7 -2.52 0.10
LEF (%) 35.3 30.1 38.6 33.0 34.2 23.5
14.9

Model	**1**	**2**	**3**	**4**	**5U**	**BSHO**	**5O**
EDT (sec.)	5.09	4.65	2.96	4.45	2.36	2.50	1.63
D-50 (%)	11.7	10.9	22.4	33.0	24.9	N/A	37.3
C-80 (dB)	-5.9	-5.4	-1.9	-4.0	-1.7	-2.52	0.10
LEF (%)	35.3	30.1	38.6	33.0	34.2	23.5	14.9

Table 3. Summary of acoustic measures made in each of the five models and the Boston Symphony Hall. All values relate to 1 kHz octave band. EDT, D-50, C-80, LEF values for the unoccupied Boston Symphony Hall (BSHU) are averaged values of two or more measurements (Beranek, 1996).

receiver decay curves at the interval of -5 to -35 dB, ranges from 2.36 to 5.09 seconds. The large volume coupled with large and flat parallel walls are the cause of the excessive reverberation. The echogram and the impulse response simulation depict the excessive late energy creating a significant amount of echoes. While there seems to be too much reverberance in the simple Model 1, the reverberation time gradually decreases in Models 2 through 5 as more elements and surfaces enter the hall. A slight decrease in RT for Model 2 can be attributed to the introduction of the orchestral shell, which varies the area and angle of the surface areas to change the room modes to eliminate a portion of the echoes and decrease the excessive RT. The addition of the balcony, represented by Model 3, further reduces the reverberation not only by increasing the surface area of absorption but also by delivering a stronger reflection to the main floor early. The improvement, or rather the decrease in RT, is approximately doubled from the first model.

The difference between Model 3, with balcony addition, and Model 4, with coffer addition, yields interesting results. The reverberation times for Model 3 throughout the frequency spectrum follow a consistent decrease from Model 2. Model 4 however produces increased reverberation time in the lower frequencies and decreased reverberation time in the higher frequencies. Model 4's surface area, which amounts to less than that of Model 3, and the large surfaces that are coffered yet parallel causes its RT in the lower frequencies to remain while the RT in the higher frequencies are decreased. The perceived reverberation of Model 5 Unoccupied and Model 5 Occupied, which reflect the conditions of the existing Boston Symphony Hall, are close to the measured data of the hall (Beranek, 1996).

The maps of the sound pressure levels throughout the audience show the distribution of early and late energy. The models show relatively similar peak SPL levels between 75 dB and 76 dB. Models 1,2, and 4, which do not have the audience

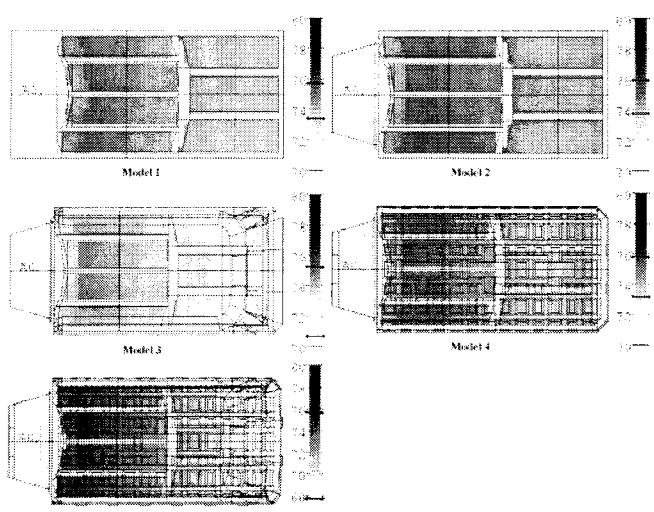

Figure 2. Audience mapping of sound pressure levels summing all octave band frequencies for each model.

tiers show a narrow range between 73 dB to just below 76 dB. Models 3 and 5 depict the effect the tiers have on the main audience floor with a larger range of 68 dB and 70 dB to just below 76 dB. The balcony covering the main floor area of the Boston Symphony Hall seems deep compared to the height of the opening. Barron (1996) advises a balcony height to balcony depth ratio of greater than 1. The quality of the rooms however cannot just rely on this mapping since excessive reverberation also may yield an even distribution of sound power levels throughout the room given enough time.

Barron (1996) suggests a range between 0.1 and 0.35 for objective envelopment (early lateral energy fraction, LEF), and a range between –2 and 2 for objective clarity (early to late sound index, C-80) for symphony concerts. For Model 1, the

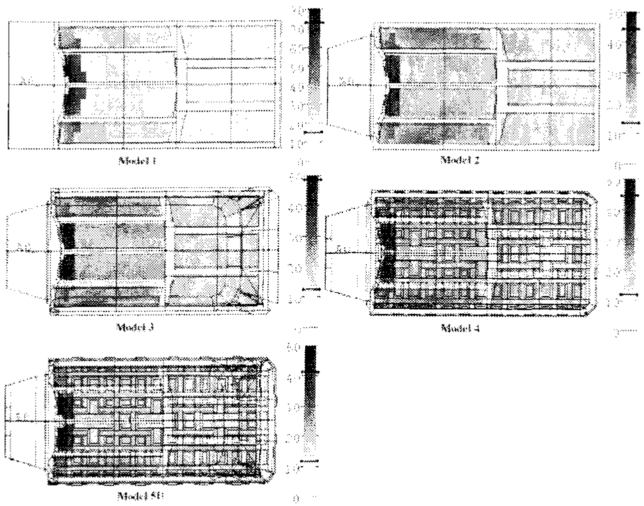

Figure 3. Audience mapping of lateral energy fraction for the five models.

response simulations generated for Model 2 and Model 5U are however clearly visible. The difference in amplitudes between left and right ears are much greater in Model 2 than in Model 5. The presence of a large second reflection after about 40

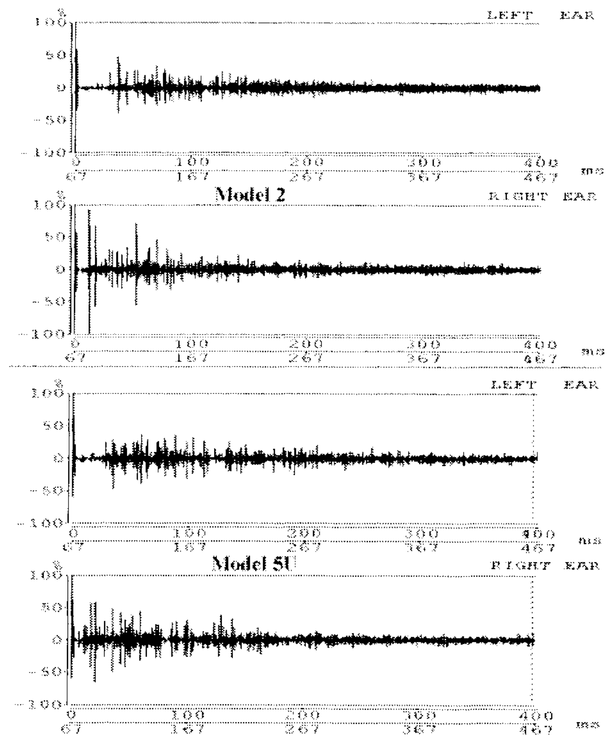

Figure 4. Binaural simulations based on T-30 calculations for Model 2 and Model 5U

LEF ranges from about 15% to 70%. The range of the LEF mapping gradually decreases to approximately 11% to 41% as indicated in Model 5U. As Table 3 depicts, the values for clarity of sound measured by D-50 and C-80 progresses into the ideal range for symphonic venues from Model 1 to Model 5.

AURALIZATION

Although the computer-generated results compare closely to the actual measured data, the quality of sound in a room is yet abstract to the majority of the public unknowledgeable in the field of acoustics. Therefore auralization becomes a necessary process to further evaluate subjectively and objectively the sound quality of an architectural space. From the impulse response calculations of the computer model, aural simulation files for the left and right ear were produced for each model through binaural post-processing.

Minute differences can be visualized incrementally from Model 1 to 5 in the plot files created. The differences in milliseconds after the arrival of the first reflected sound as indicated in the right ear of the Model 2 may result in the noticeable echoes for some listeners. The decay of sound for Model 5 is also a more gradual phenomenon than for Model 2.

From the binaural simulations, an anechoic digital sound sample from Mozart's "Le Nozze di Figaro," bars 1-18 was used to produce wave sound files reflecting the sound qualities of each room. Figure 5 shows the original monophonic recording of the sample and the convolved binaural output for Models 1, 3 and 5O.

The anechoic sample shows clear and visually divisible set of tempos and amplitudes throughout the frequencies, while Model 1 shows the degradation and dissipation of clarity. Model 3 illustrates another step toward an optimum sound quality. The final model (5o) represents the approximate ideal distribution of the frequency spectrum through time with visible as well as audible clarity and reverberation.

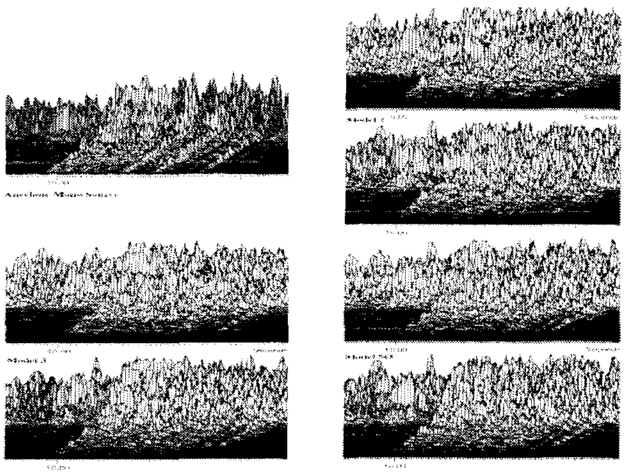

Figure 5. Spectral analysis graphs of music samples. The three-dimensional graph indicates amplitude versus frequency versus time in 1/32nd of a second increments. The higher frequencies are located closer to the time axis.

CONCLUSION

Although the computer model analysis depicts the approximate conditions of the auditorium, the actual result of the analysis closely resembles the behavior of sound in the concert hall. The effects of effects of sound diffusion are clearly seen in the impulse response and are heard in the auralizations as the model is developed from Model 1 to Model 5. The final model, 5, closely approximates the acoustics of the full size room in acoustic measures and in sound quality.

To achieve a concert hall with optimum reverberation time and sound quality, the process of addition of acoustical elements to a large hall of this size seems relevant and logical in computer modeling as reflected in the actual construction practice of modern architectural acoustics. The additive process of architectural acoustic elements to create rooms with ideal sound qualities is the case for many acoustical problems.

The analysis and accumulation of data from measurements and research and development of architectural acoustic designs would benefit from the generation of an audible medium. The ultimate approval of a concert hall lies in the form of audible sound and those who appreciate qualities of sound.

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