Project 1: Sound Field Simulator

The goal of this project is to process an audio signal with a filter whose impulse response resembles that of a large concert hall.

Concert Hall Acoustics

Sound Propagation

Definition: An environment in which the sound intensity varies as $1 / r^2$ (r is the distance from the source) is called a free field.

Example: A free field exists when a source of sound is very small (a point source) and is located outdoors away from reflecting objects. The presence of objects such as walls, will not produce uniformity in a free field.

Sound waves travel away from the source in all directions and hence we have spherical wave fronts. In a free field, the pressure is halved when the distance r doubles (except for high frequencies).

Free field conditions rarely occur indoors, except in reflection free anechoic rooms. Indoors, sound travels only short distances before encountering walls and other obstacles. These obstacles reflect and absorb sound in ways that largely determine the acoustic properties of the hall.

Direct Sound, Early Reflections, and Reverberation

Definition: Sound travels at c = 344 m/s (~1000 ft/s)

The direct sound (straight path from source to listener) reaches the listener in 20 to 200ms (depending on the distance ~7 – 70 m) after initiation.

Figure 1: Direct sound

A short time later, the same sound will reach the listener after reflecting from walls and ceiling. The first group of these reflections to arrive at the listener within 50ms of the direct sound are referred to as the *early reflections*.

Figure 2: Early reflections

After the early reflections, reflected sounds arrive thick and fast from all directions. These reflections become smaller and closer together, merging into what is called reverberant sound.

Figure 3: Reverberation

By carefully studying the direct, early, and reverberant sound, a simple but often accurate analysis of the acoustics of a hall can be obtained.

Figure 4: Lexicon Timeline

Demonstrations of Sound Field Processing

Direct Sound and Early Reflections

If the hall has the traditional "shoebox" shape, the first reflections will come from the nearest side wall (although those in the center may receive first reflections from the ceiling). "Shoebox" shape implies parallel side walls and a horizontal ceiling. If these early reflections do come from the lateral directions, they appear to broaden the source and thus increase the apparent source width (ASW). Studies have shown a high preference for concert halls with ceilings sufficiently high so that the lateral reflections reach the listener before the overhead reflections.

Lateral reflections are easy to achieve at listeners' positions in the center of the main floor of a "shoebox" hall. In a fan-shaped room the lateral reflections are directed to the rear seats.

Definition: If the total energy from lateral reflections is greater than the total energy from overhead reflections, the hall takes on a desirable "spatial impression " or SI.

Due to economic reasons many halls have turned to the fan shaped hall which allows more seats but has been shown to really reduce the SI. One current proposal is the reverse fan which computer models have shown to have SI similar to the box.

Figure: Fan / Reverse fan-shaped Halls

Reverberation

Definition: The reverberation time (RT) is defined as the time required for the sound pressure level (SPL) at 500Hz to decrease by one millionth (or 60dB) of its initial value.

Figure 5: SPL vs. Time

Reverberant sound is most pleasant if the listener hears it coming from all directions. This is sometimes referred to as "listener envelopment" (LEV). Before the 19th century music tended to be written for the performance in existing rooms. For example

- Organ music (Bach) was written for churches which, being large and lacking soft furnishings, had very long RTs.
- Chamber music (Mozart) was written for performances in well furnished private houses and emphasis could be placed on clarity (defined below).

Bach/Mozart Sound Clips

The rate at which that energy is absorbed depends on the area of all surfaces and objects in the room and their absorption coefficients.

Definition: RT is given by

$$RT = K\,V / A$$

where K = 0.161 s/m, V is the volume in cubic meters, A is the total absorption given by adding up the contributions from each surface exposed to the reverberant sound. The total absorption may be expressed as

$$A = \sum_i S_i a_i$$

where S_i is the area of the reflecting surface in m^2 and a_i is the absorption coefficient. Absorption coefficients are frequency dependent.

Example: Unpainted concrete has a = 0.31 at 500Hz.

Example: Audience in upholstered seats has a = 0.56.

In general, larger halls have longer RTs than smaller halls. The optimum RT is a compromise between clarity (short RTs), sound intensity (high reverberant levels), and liveliness (long RTs).

Figure: RT vs. Hall Volume.

Example: Symphony Hall in Boston (consider one of the best in the U.S.)

Built 1900
V = 18,740m^3
A = 1550m^2
Typical delay for direct sound = 15ms
Number of Seats = 2630
RT (125Hz) = 2.2s
RT (500Hz) = 1.8s
RT (2000Hz) = 1.7s

Note the “warmth” of Symphony Hall.

