Chapter (7)

Adjustable Acoustics

& Acoustic FDTD Simulations

By

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Acoustics

• The objective study of how sound behaves is called acoustics. Those who study and control sound behavior are called acousticians

Acoustic treatments are most often focused on two tasks:
Isolation, or “soundproofing,” which is aimed at keeping outside sound out, and inside sound in Surface treatment, which is aimed at controlling reverberation

• Isolation may be achieved by stopping the transmission of vibrations (sound) from one space to the next Isolation may be achieved by building boundaries with great mass, that will not vibrate Isolation may be achieved by mechanically decoupling interior walls from exterior walls
Acoustic FDTD Simulations

The FDTD method employs finite-differences to approximate Ampere’s and Faraday’s laws. Ampere’s and Faraday’s laws are first-order differential equations that couple the electric and magnetics fields. As we have seen, with a judicious discretization of space and time, the resulting equations can be solved for “future” fields in terms of known past fields.

Other physical phenomena are also described by coupled first-order differential equations where the temporal derivative of one field is related to the spatial derivative of another field. Both acoustics and elastic wave propagation are such phenomena. Here we will consider only acoustic propagation. Specifically we will consider small-signal acoustics which can be described in terms of the scalar pressure field \( P(x, y, z, t) \) and the vector velocity \( \mathbf{v}(x, y, z, t) \). The material parameters are the speed of sound \( c_a \) and the density \( \rho \) (both of which can vary as a function of position).

The governing acoustic equations in three dimensions are

\[
\frac{\partial P}{\partial t} = -\rho c_a^2 \nabla \cdot \mathbf{v}, \quad (7.1)
\]

\[
\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho} \nabla P, \quad (7.2)
\]
Taking the divergence of (7.2) and interchanging the order of temporal and spatial differentiation yields

\[ \frac{\partial}{\partial t} \nabla \cdot \mathbf{v} = -\frac{1}{\rho} \nabla^2 P. \]  

(7.7)

Taking the temporal derivative of (7.1) and using (7.7) yields

\[ \frac{\partial^2 P}{\partial t^2} = -\rho c_a^2 \frac{\partial}{\partial t} \nabla \cdot \mathbf{v} = c_a^2 \nabla^2 P. \]  

(7.8)
Rearranging this yields the wave equation

\[ \nabla^2 P - \frac{1}{c^2} \frac{\partial^2 P}{\partial t^2} = 0. \]

Thus the usual techniques and solutions one is familiar with from electromagnetics carry over to acoustics. For example, a harmonic plane wave given by

\[ P(x, y, z, t) = P_0 e^{-j\beta \cdot r} e^{j\omega t} \]

is a valid solution to the governing equations where \( P_0 \) is a constant and the wave vector \( \beta \) can be written

\[ \beta = \beta_x \hat{a}_x + \beta_y \hat{a}_y + \beta_z \hat{a}_z = \beta \hat{a}_\beta = (\omega/c_a) \hat{a}_\beta. \]

Substituting (7.10) into (7.4) and assuming \( \exp(j\omega t) \) temporal dependence yields

\[ v_x = \frac{\beta_x}{\rho \omega} P. \]

Following the same steps for the \( y \) and \( z \) components produces

\[ v_y = \frac{\beta_y}{\rho \omega} P, \]

\[ v_z = \frac{\beta_z}{\rho \omega} P. \]
Thus the harmonic velocity is given by

\[ v = v_x \hat{a}_x + v_y \hat{a}_y + v_z \hat{a}_z = \frac{1}{\rho \omega} (\beta_x \hat{a}_x + \beta_y \hat{a}_y + \beta_z \hat{a}_z)P = \frac{\beta}{\rho \omega} P \hat{a}_\beta. \quad (7.14) \]

Since the wave number, i.e., the magnitude of the wave vector, is given by \( \beta = \omega / c_a \), the ratio of the magnitude of pressure to the velocity is given by

\[ \left| \frac{P}{v} \right| = \rho c_a. \quad (7.15) \]

The term on the right-hand side is known as the characteristic impedance of the medium which is often written as \( Z \).
Draperies

draperies on the wall and carpets on the floor were often used to “deaden” studios

• It became more apparent that this radio studio treatment was quite unbalanced, absorbing middle- and high-frequency energy but providing little absorption at lower frequencies.

• As proprietary acoustical materials became available, hard floors became common and drapes all but disappeared from studio walls.
The effect of the fullness of the drape must be considered. The acoustical effect of an adjustable element using drapes can thus be varied from that of the drape itself when closed, to that of the material behind when the drapes are withdrawn into the slot provided,

as shown in Figure. The wall treatment behind the drape could be anything from hard plaster for minimum sound absorption to resonant structures having maximum absorption in the low-frequency region, more or less complementing the effect of the drape itself. Acoustically, there would be little point to retracting a drape to reveal material having similar acoustical properties.

The ambience of a room may be varied by pulling absorptive drapes in front of reflective areas.
Adjustable Panels: Absorption

- Portable absorbent panels offer a certain amount of flexibility in adjusting listening room or studio acoustics.
- The simplicity of such an arrangement is illustrated in Figure. In this example, a shallow wooden cabinet holds a perforated hardboard facing with acoustically transparent cloth covering, a glass-fiber layer, and an interior air cavity. This type of panel can be easily mounted on a wall or removed as needed.
For example, panels may be introduced to decrease reverberation for voice recording or removed to obtain a live effect for instrumental music recording

Removable panels can be used to adjust the reverberation characteristics of a room. For maximum variability, unused panels should be removed from the room entirely

**Hinged Panels**

- One of the least expensive and most effective methods of adjusting studio acoustics is the hinged panel. When closed, all surfaces are reflective (plaster, plasterboard, or plywood). When opened, the exposed surfaces are absorptive (glass fiber or carpet). These panels could be covered with acoustically transparent cloth to improve appearance. Spacing the glass fiber from the wall would improve absorption at low frequencies.
Room resonances

- Parallel surfaces can create standing waves, causing “room modes.” Modes are certain frequencies that are may be reinforced, causing “ringing.” Or certain frequencies may be cancelled, causing those frequencies to be lower in amplitude.

Calculating room modes

- Wavelength = Velocity ÷ Frequency
- Velocity = speed of sound = 1150 per second

\[
\frac{1130}{440 \text{ Hz}} = 2.56 \text{ Feet}
\]
**Room modes:** are the collection of resonances that exist in a room when the room is excited by an acoustic source such as a loudspeaker. Most rooms have their fundamental resonances in the 20 Hz to 200 Hz region, each frequency being related to one or more of the room's dimension's or a divisor thereof. These resonances affect the low-frequency low-mid-frequency response of a sound system in the room and are one of the biggest obstacles to accurate sound reproduction.

- **The mechanism of the room's resonances**
- The input of acoustic energy to the room at the modal frequencies and multiples thereof causes standing waves. The nodes and antinodes of these standing waves result in the loudness of the particular resonant frequency being different at different locations of the room. These standing waves can be considered a temporary storage of acoustic energy as they take a finite time to build up and a finite time to dissipate once the sound energy source has been removed.
Spherical waves and room acoustic

Room acoustics

- Sound in free air expands \textit{spherically}:

  \begin{align*}
  &\frac{\partial^2 p}{\partial r^2} + \frac{2}{r} \frac{\partial p}{\partial r} = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \\
  \text{solved by } \quad p(r, t) = \frac{P_0}{r} e^{j(\omega t - kr)}
  \end{align*}

(7.16)
Effect of rooms (1): Images

Ideal reflections are like multiple sources:

\begin{center}
\begin{tikzpicture}
\draw[help lines, color=gray!30] (-2,2) grid (2,-2);
\draw[ultra thick, dashed] (-1.5,0) -- (1.5,0);
\draw[ultra thick, dashed] (0,-1.5) -- (0,1.5);
\node at (0,0) [above right] {source};
\node at (1.5,0) [below right] {listener};
\node at (-1.5,0) [below left] {source};
\node at (0,1.5) [above left] {virtual (image) sources};
\node at (0,-1.5) [below right] {reflected path};
\end{tikzpicture}
\end{center}

‘Early echoes’ in room impulse response:

\begin{center}
\begin{tikzpicture}
\draw[help lines, color=gray!30] (-2,2) grid (2,-2);
\draw[ultra thick, dashed] (-1.5,0) -- (1.5,0);
\draw[ultra thick, dashed] (0,-1.5) -- (0,1.5);
\node at (0,0) [above right] {source};
\node at (1.5,0) [below right] {listener};
\node at (-1.5,0) [below left] {source};
\node at (0,1.5) [above left] {direct path};
\node at (0,-1.5) [below right] {early echoes};
\end{tikzpicture}
\end{center}

actual reflections may be \( h_r(t) \)

Effect of rooms (2): Modes

Regularly-spaced echoes behave like acoustic tubes

Real rooms have lots of modes!
\begin{itemize}
  \item dense, sustained echoes in impulse response
  \item complex pattern of peaks in frequency response
\end{itemize}
Rotating Elements

- Rotating Elements provide unique adjustability; because of size constraints, they are most often used in larger rooms.
- In this particular configuration, the flat side is absorbent and the cylindrical diffusing element is reflective.
- A disadvantage of this type of system is the space required for rotation.
- The edges of the rotating element fit tightly to minimize coupling between the studio and the space behind the elements.
- A good low frequency absorption decreasing at high frequencies, and high reflection absorbing little energy at low or high frequencies. However, such arrangements are expensive and mechanically complex.
• **The Triffusor**
  
  • Is a rotatable equilateral-triangular prism with absorptive, reflective, and diffusive sides.
  
  • A non rotating form of the Triffusor is available with two absorptive sides and one diffusive side, especially adapted for use in corners.
  
  • The nominal dimensions of the unit are: height 4 ft, faces 2 ft across. In a normal mounting, the edges would be butted and each unit supplied with bearings for rotation. In this way, an array of these units could provide
  
  • all absorptive, all diffusive, all reflective, or any desired combination of the three surfaces.

The Triffusor may be used in groups to provide variable acoustics in a space. Rotation of the individual units can bring diffusing, absorbing, or reflecting surfaces into play.
• **Variable Acoustics**
  The Triffusor was developed to make completely variable acoustics a reality.
  Triffusor modules can be arranged adjacent to one another in a linear array so that they form a surface of any desired acoustical character.
  These arrays combine the basic acoustical building blocks of absorption, diffusion, and reflection. With the Triffusor, small rooms take on a flexibility not possible before. You can easily adapt to the requirements of a particular situation and not be locked into a fixed acoustical environment.
  Even large rooms can be made more versatile by using movable Triffusor partitions or gobos to alter the localized acoustics. The Triffusor can also be flush mounted to form a variable acoustics wall.
ACOUSTIC RADIATORS

• **Spherical Waves**

• A radiation source whose nature is completely opposite to the infinite plane radiator is the point source, capable of emitting spherical waves. Consideration of this type of source is useful because superposition of such source permits finite sized radiators to be analyzed.

• The procedure is to consider the acoustical problem of waves from an oscillating spherical cavity of radius $a$.

• The velocity amplitude of the cavity oscillation is $v_0$. The situation is shown in Figure 1a. With the assumption that the cavity radius is small with respect to the acoustic wavelength ($a<<\lambda$) and that the radius, or the distance of the point of observation from the source, is large relative to the wavelength ($r>>\lambda$), the cavity shrinks to a point source, as shown in Figure 1b.
Figure 7.1 Spherical waves from (a) an oscillating cavity and (b) from an equivalent point source.
Both pressure and velocity distributions have to be of the form of a spherical wave:

\[ p(r) = p_o \frac{e^{i(kr - \omega t)}}{r} \]  \hspace{1cm} (7.17)

and

\[ v(r) = v_o \frac{e^{i(kr - \omega t)}}{r} \]  \hspace{1cm} (7.18)

The balance of momentum requires that

\[ \frac{\partial p}{\partial r} = -\rho \frac{\partial v}{\partial t}, \]  \hspace{1cm} (7.19)

where

\[ \frac{\partial p}{\partial r} = (i k - \frac{1}{r}) p_o \frac{e^{i(kr - \omega t)}}{r} \]  \hspace{1cm} (7.20)

and

\[ \frac{\partial v}{\partial t} = -i \omega v_o \frac{e^{i(kr - \omega t)}}{r}. \]  \hspace{1cm} (7.21)
By substituting Eqs. 7.4 and 7.5 into Eq. 7.3, the specific acoustic impedance of a spherical wave can be written as follows:

\[ Z_{sph} = \frac{p(r)}{v(r)} = \frac{p_o}{v_o} = \frac{i \omega \rho}{i k - \frac{1}{r}} . \]  

(7.22)

At large distance from the source, the specific acoustic impedance approaches that of a plane wave:

\[ \lim_{r \to \infty} Z_{sph} = \rho c , \]

(7.23)

while near to the source, it approaches the pure imaginary impedance of a vibrating mass

\[ \lim_{r \to 0} Z_{sph} = -i \omega \rho r . \]

(7.24)

The acoustic field radiated by a vibrating cavity of very small radius \((a << \lambda)\) can be calculated from the known velocity \(v_a\) of the radiator at its surface

\[ p(a) = p_o \frac{e^{i(k a - \omega t)}}{a} = -i \omega \rho a v_a e^{-i \omega t} , \]

(7.25)
therefore the complex amplitude of the pressure wave is

\[ p_o = -i \omega \rho a^2 v_a e^{-i k a} , \]  

(7.26)

or approximately

\[ p_o \approx -i \omega \rho a^2 v_a , \]  

(7.27)

since \( ka \ll 1 \). This result is usually expressed with the volume velocity of the source \( S_o \)

\[ S_o = 4 \pi a^2 v_a \]  

(7.28)

as

\[ p_o \approx \frac{\omega \rho S_o}{4 \pi i} . \]  

(7.29)
The $e^{i(kr - \omega t)}$ term in the pressure field describes an outward propagating spherical wave. Obviously, as the wave propagates outward, the radiated power per unit area, i.e., the intensity of the wave, must diminish. The second thing to note is that the decrease in the pressure goes as $1/r$, a simple inverse law. Thus, the ratio between the stresses at two successive locations is given by

$$\frac{p(r_2)}{p(r_1)} = \frac{r_1}{r_2} e^{i k (r_2 - r_1)}, \quad \text{where} \quad r_2 > r_1$$

(7.30)

or, dropping the phase factor,

$$\frac{p(r_2)}{p(r_1)} = \frac{r_1}{r_2}$$

(7.31)
NOISE POLLUTION

• Sound that is unwanted is called as noise. When there is lot of noise in the environment, it is termed as noise pollution.
• Sound becomes undesirable when it disturbs the normal activities such as working, sleeping, and during conversations.
• It is an underrated environmental problem because of the fact that we can’t see, smell, or taste it.
• World Health Organization stated that “Noise must be recognized as a major threat to human well-being”
Health Effects

• there are direct links between noise and health. Also, noise pollution adversely affects the lives of millions of people.
• Noise pollution can damage physiological and psychological health.
• High blood pressure, stress related illness, sleep disruption, hearing loss, and productivity loss are the problems related to noise pollution.
• It can also cause memory loss, severe depression, and panic attacks.
Sources of Noise Pollution

• Transportation systems are the main source of noise pollution.

• Construction of buildings, highways, and streets cause a lot of noise, due to the usage of air compressors, bulldozers, loaders, dump trucks, and pavement breakers.

• Industrial noise also adds to the already unfavorable state of noise pollution.

• Loud speakers, plumbing, boilers, generators, air conditioners, fans, and vacuum cleaners add to the existing noise pollution.
Solutions for Noise Pollution

• Planting bushes and trees in and around sound generating sources is an effective solution for noise pollution.

• Regular servicing and tuning of automobiles can effectively reduce the noise pollution.

• Buildings can be designed with suitable noise absorbing material for the walls, windows, and ceilings.

• Workers should be provided with equipments such as ear plugs and earmuffs for hearing protection.
Solutions for Noise Pollution

• Similar to automobiles, lubrication of the machinery and servicing should be done to minimize noise generation.
• Soundproof doors and windows can be installed to block unwanted noise from outside.
• Regulations should be imposed to restrict the usage of play loudspeakers in crowded areas and public places.
• Factories and industries should be located far from the residential areas.
• Community development management should be done with long-term planning, along with an aim to reduce noise pollution.
• Social awareness programs should be taken up to educate the public about the causes and effects of noise pollution.
Control of Interfering Noise

There are five basic approaches to reducing noise in an acoustically sensitive space:

Locating the room in a quiet place.

- Reducing the noise output of the offending source.
- Interposing an insulating barrier between the noise and the room.
- Reducing the noise energy within the room.
- Both airborne and structure borne noise must be considered

Locating an acoustically sensitive room away from outside interfering sounds

- Clearly, sites near airports, railroads, highways, or other noise sources are always problematic. It is useful to the doubling the distance from a noisy street or other sound source reduces the level of airborne noise approximately 6 dB
Whenever possible, floor plans should place noise sensitive rooms away from noise sources such as interior machinery rooms, or exterior noise sources such as roads.

If the room in question is a listening room or home studio which is part of a residence, due consideration must be given to serving the other needs of the occupants.

If the room is a professional recording or broadcast studio, it may be part of a multipurpose complex and the noises originating from business machines, air handling equipment, foot traffic within the same building, or even sounds from other studios, may dominate the situation.
Airborne Noise

• If an airway exists, then sound will easily travel though the air. It is therefore easy for sound to pass through an otherwise highly soundproof barrier.

• For example, a heavy metal plate with holes occupying 13% of the total area can transmit as much as 97% of the sound impinging on it. Furthermore, increasing the mass of the metal plate will have little or no effect. Solid wall because the air leak has a transmission loss of zero. Similarly, any flanking path will allow sound to travel around a barrier, severely compromising its transmission loss. For example, sound can easily travel from room to room through a common plenum or air-handling ducts.
Airborne Sound

Airborne sound includes conversation, outdoor noises, music and machine noises (machines usually also produce impact sound). It is the major source of intruding sound from rooms on the same floor and from the outdoors. It is controlled by:

1. Mass (weight),
2. Isolation
3. Absorption
4. Limpness of Construction.

These must be combined with airtight sealing and the elimination of flanking paths (routes by which the sound travels around a partition rather than being stopped by it).
**Direct Sound**
Since sound travels in all directions from the source, each listener will hear just the *segment* if the overall sound wave that is traveling in a direct line to his hear (in a space free from reflecting surfaces). As the distance from the source increases, the sound pressure at the listener's ear will decrease proportionately.

The shape of a space determines the sound path within the space. **Reverberation time must match room function**. Pure speech requires short reverberation time. Symphony blends notes with long reverberation time.

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**Reflection**
Diffraction: The Sound Squeezes Through

Sound waves are not always reflected or absorbed. When an obstacle is the same size as the wavelength or less, the sound can bend around obstacles or flow through small openings, and continue onward. This is called diffraction. This action is more likely for deeper sounds (of low frequency, and this with longer waveforms).
Reverberation

The perpetuation of reflected sound within a space after the source has ceased is called *reverberation*. The time interval between reflections is usually so short that distinct echoes are not heard. Instead, this series of reflections will blend with the direct sound to add "depth". Reverberation is a basic acoustic property of a room. It can enrich speech in all areas -- or it can slur speech and generate higher noise levels throughout a room, depending upon the room volume, timing, and absorption.

Studies based on the audibility of speech and music reveal that the most *desirable reverberation times*. These values are based on a sound frequency of **500 Hz** (approximate pitch of male speech).
Reverberation

- **Exponential decay of reflections:**
  \[ h_{\text{room}}(t) \sim e^{-t/T} \]

- **Frequency-dependent**
  - greater absorption at high frequencies
  \[ \Rightarrow \text{faster decay} \]

- **Size-dependent**
  - larger rooms \( \rightarrow \) longer delays \( \rightarrow \) slower decay

- **Sabine’s equation:**
  \[ RT_{60} = \frac{0.049V}{S\alpha} \]

- Time constant varies with size, absorption
Room Acoustics

Sound re-enforcement

Reflect

Absorb

Sound re-enforcement
Absorbing Materials
- Carpet
- Soft ceiling tile
- Rigid foam
- People

Reflecting Materials
- Masonry
- Wood – smooth panels
- Smooth concrete
- Glass

Reverberation time (in seconds) =

\[ \frac{0.05 \times \text{volume of room}}{\text{sabins}} \]

Sabin

The amount of sound absorbed is measured in sabins. One sabin is equal to the sound absorption of one square foot of perfectly absorptive surface. The sound absorption equivalent to an open window of one square foot. (theoretical, since no such surface exists).
Absorptive Surfaces:

Porous materials such as acoustical tile, carpets, draperies and furniture are primarily **absorptive**. They permit the penetration of sound waves and are capable of absorbing most of the sound energy. These materials may have absorption coefficients approaching **1.00 (one sabin per sq. ft.)**.
Impact Sound

Impact Isolation
If the surface receiving the impact, such as a floor, can be isolated from the structure, the impact sound will not be transmitted. Likewise, if the structure can be isolated from the ceiling below, the impact sound will be restricted from traveling into the room below.
Isolation of the ceiling of the receiving room can be accomplished with resilient mounting of the drywall panels or lath. This still allows some sound from above to enter the structure and travel to other rooms. **Resilient subflooring materials** such as insulation board and underlayment compounds are effective, as is heavy carpet over thick under pad. A combination of these methods is necessary to produce ideal attenuation of impact noise.
What is CAC?

A: CAC, or **Ceiling Attenuation Class**, is a **measure of the sound transmission loss as noise travels between rooms**. Essentially, it is the ability of a ceiling panel to block sound between rooms.

Q: *What spaces require CAC values?*
A: CAC values are essential in interior spaces that require physical separation from other areas such as conference and board rooms, private offices, bathrooms, and corridors.

Q: *Is CAC important in open plan offices?*
A: Actually, CAC is important to assure privacy for areas outside or adjoining an open plan such as private offices or conference rooms.
white noise

is a random signal with a constant power spectral density. White noise refers to a statistical model for signals and signal sources, rather than to any specific signal.

**White noise** is a type of noise that is produced by combining sounds of all different frequencies together. If you took all of the imaginable tones that a human can hear and combined them together, you would have white noise.

**Example of white noise:**

Like the tv when it has the fizzled out screen. It's muffled voices, or something you can't quite make out. Like a fan, if you turned on a fan and asked somebody what the noise was, you can get two answers, wind, and some people will guess fan and get it right. It's kind of like a noise that can be caused by multiple things but they sound so similar that it could be anything.