ARCHITECTURAL
ACOUSTICS
ILLUSTRATED

MICHAEL ERMANN

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MICHAEL ERMANN

Associate Professor
Virginia Tech School of Architecture + Design

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For Lauren, Zachary, and Miles

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Introduction

This book aims to translate the concepts of architectural acoustics into the graphic language of architecture, in the belief that not only architects and architecture students, but also engineers, physicists, musicians, builders, planners, real estate professionals, and interested laypeople will be served by the translation. What you are reading is a comprehensive book for those new or relatively new to acoustics, but those in practice as architectural acousticians will also find it valuable as a reference for its considerable library of data, its review of recent research, and its design checklists.

The study of architectural acoustics is a three-dimensional endeavor. Sound moves in Cartesian space, in real rooms, and through planes that typically don't precisely align with section and plan cuts. But architectural acoustics also maintains the three dimensions loudness, frequency, and time, which, for reader ownership of subject content, must be evaluated simultaneously. Thus, the study of architectural acoustics is itself an act of architecture—and architectural acoustics, as laid out in the pages that follow, sits under the broader umbrella of design. To that end, the illustrations and animations in this book should be viewed not as supplements to bolster the text, but rather as content on par with the text in importance. Indeed, in portions of the book, the text bolsters and supplements the content covered by illustrations and animations.

AV Content
Online

Intuition is a valid expression of design, as is empirical study, but neither is a substitute for a critical view and development through iteration. Empirical study, critical thought, and the iterative process all factor into architectural acoustics, as do the physical properties of energy flows. But in architectural acoustics intuition is less likely to play a role. This topic is rigorous and often quantitative, but in this book it is almost always filtered through the lens of spatial composition, haptic awareness, materiality, and perception. The reader finds the quantitative analysis necessary, but not sufficient: We built the three most admired concert halls in the world—the Vienna Musikvereinssaal, Boston's Symphony Hall, and the Concertgebouw in Amsterdam—in the late 1800s or early 1900s. What technology or science holds 120-year-old advancements as state-of-the-art? There must be something more than technology at work.

I intend to convey the importance of room shaping over motorized components, material selection over sound system design, noise-space-planning over engineered partitions, site selection over outdoor noise barriers—without omitting the important content of motorized components, sound system design, engineered walls, and outdoor noise barriers. The reader will gain the confidence to design rooms with sound in mind from the earliest stages of design, when decisions have the greatest impact on the quality of the acoustics. The reader will also better recognize where acoustic opportunities and pitfalls lie, address routine matters in architectural acoustics, and judge when outside professional consultation is required.

Contents

BASIC THEORY

SOUND LEVEL

Sound Level

A sound is made when an oscillating membrane disturbs the molecules in an elastic medium—and that disturbance is heard. While sounds may travel through solids or liquids, in the domain of architectural acoustics, we generally skew our discussion to the elastic medium of air (structure-borne sound notwithstanding). A nearby passing bus excites a window pane into vibration, which in turn excites the air molecules near the window, which in turn excite air molecules near the first group of air molecules, and so on, until the band of oscillating molecules reaches the ears of a listener; this creates a sound.

We say "The Wave" circles a full stadium, even if the participants don't themselves traverse the stadium's perimeter. Spectators merely stand up, then sit down. As each successive column of fans stands and sits, the wave propagates, though each particle (spectator) in the wave returns to its resting position (seated). Similarly, with propagating sound, each excited molecule returns to its steady state, but only after passing its energy to its neighboring molecules. Other parallel models exist to describe the propagation: the slinky, the water wave, the snapped towel, a crowded mosh pit with fans colliding.

> Three characteristics describe the physics of sound:
>
> Sound level (or energy, strength, amplitude, loudness)
>
> Frequency (or pitch, tone, wavelength)
>
> Propagation (or path, elapsed time)

A hard-plucked guitar string displaces the adjacent air molecules more than a gently plucked one; the collision with the hard-plucked string whips the molecules farther out of their steady state position, and each successive column of molecules whips harder into the next, and so on. We hear these waves of increased compression and rarefaction as louder. In the stadium wave analogy, a louder sound would be akin to the sort of wave where the spectators stand all the way up and raise their arms in the air; a quieter sound would be the sort of wave where spectators remain seated and only raise their arms. Loudness is thus defined by a wave's amplitude.

Not all vibrating membranes create a sound. If a vibrating element moves very little (less than the mean free path between molecules), it makes no sound because it fails to displace the adjacent molecules far enough that they collide into their neighbors. And if the vibrating element moves very slowly, the molecules simply move smoothly around the element, and again no sound is generated. The amplitude of the displacement may also fall below the threshold of human hearing, although our auditory system's sensitivity is remarkable. Very small sound pressures, relative to the ambient atmospheric pressures, are perceptible. Sounds generally blend together when we listen unconsciously, but with intentional listening, we can pick out a single instrument in a hundred-person orchestra, or listen to a story at a party even if the background noise far exceeds the speech signal.

Guitar string at rest — Air molecules at steady state — Graph describing air pressure (even across space at the level of atmospheric pressure)

Guitar string plucked gently — Area of molecule compression — Area of molecule rarefaction

Amplitude measured in Sound intensity (watts/m²) or Sound pressure (newtons/m²)

Peaks and troughs move away from source

With greater amplitude comes increased sound level, higher sound intensity, and higher sound pressure

Guitar string plucked firmly is louder

NOTE

For clarity, this model omits much of the true behavior of sound. Guitars, and most other musical instruments, do not produce sound at a single frequency (as drawn here), but rather at multiple frequencies simultaneously. A more complicated, but truer-to-life, illustration would incorporate several sine waves of varying size and a more complex molecule pattern.

Source Path Receiver

Sound Source

A guitar string plucked harder
- Oscillates farther from its resting position
- Displaces nearby air molecules
- Is heard as louder

Guitar

Path

Outdoors:
Six-decibel loss per doubling of distance in a free field
(Six-decibel gain per halving of distance)

Receiver

Oscillating air molecules vibrate the eardrum
- A three-decibel increase corresponds to twice the sound energy
- But a ten-decibel increase is required to subjectively *hear* the source as twice as loud

Ear

Unamplified source in a free field with a human receiver

Magnet vibrates diaphragm

Oscillating air molecules vibrate a diaphragm inside the microphone

Sound energy loss through spreading over distance

Equal

Equal

Indoors:
Sound-reflecting materials may add loudness
(Sound-absorbing materials add less)

Sound energy gains at receiver through building surface sound reflections

Loudspeaker

Mic
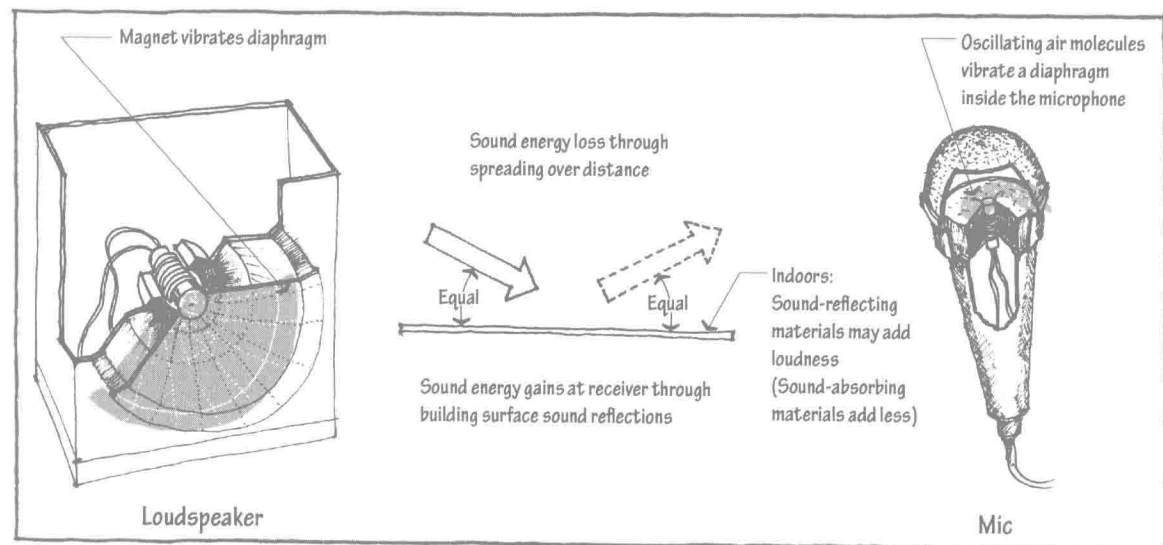
Amplified source indoors with a microphone receiver

Sound measurements:
Sound power (W), measured in watts
Sound power level (L_w), measured in decibels

Receiver measurements:
Sound intensity (I), measured in watts/m^2
Sound intensity level (L_I), measured in decibels

Sound pressure (P), measured in newtons/m^2
Sound pressure level $(L_p$ or $SPL)$, measured in decibels

Measuring Sound Level

Sound power (W) describes the strength at the *source*, and sound intensity (I) or sound pressure (P) describes the strength at the *receiver*, accounting for distance, room surface sound absorption, room geometry, and other environmental effects.

Sound power is measured at a source (piano, noisy air conditioner, human voice), to quantify how much sound energy that source radiates:

W = sound power, measured in watts

A microphone measures in one of two different methods at a receiver to quantify how much sound is arriving:

I = sound intensity, measured as the source power divided by the area over which the source energy has spread, expressed in the units watts/m²

or

P = sound pressure measured as the amplitude of the sound wave, in the units newtons/m²

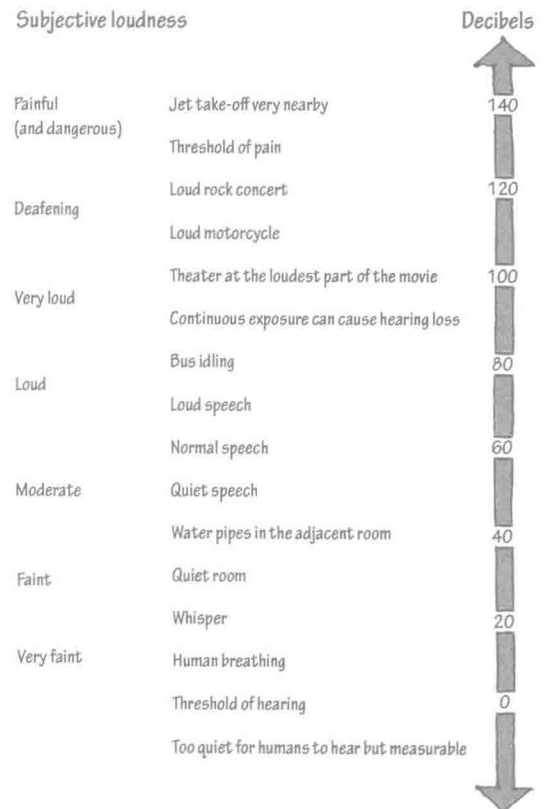While these three measures appropriately describe the physics of sound amplitude, they are nevertheless unappetizing in architectural acoustics applications, for three reasons. First, describing human response to sound in pressure or intensity overstates differences, because we don't hear 100 people clapping as subjectively 100 times louder than one person clapping. Second, the numbers expressed in newtons/m² or watts/m² are inconveniently small. A whisper measures at 0.000000001 watts/m², whereas a thunderclap measures at 0.1 watts/m². One is a hundred-million times the other, but both numbers seem small. (Sound pressures are not just small in their units of measure, but are also very small compared to the baseline of atmospheric pressure through which they move.) Finally, because it takes a hundred-million whispers to equal a thunderclap, the range of human hearing encompasses a vast range of values. If the sound intensity of human breathing is analogous to the geometric volume of a pea, then the sound intensity of a motorcycle would be analogous to the geometric volume of a house. For these three reasons, we use the decibel unit to both compress the yawning range of loudness values, and normalize the small-seeming numbers into values easier to consume. Zero decibels is normalized to the threshold of hearing, the quietest sound we can hear; 50 decibels is a quiet conversation; and 100 decibels can cause hearing loss over time.

Subjective loudness		Decibels
Painful (and dangerous)	Jet take-off very nearby	140
	Threshold of pain	
Deafening	Loud rock concert	120
	Loud motorcycle	
Very loud	Theater at the loudest part of the movie	100
	Continuous exposure can cause hearing loss	
Loud	Bus idling	80
	Loud speech	
	Normal speech	60
Moderate	Quiet speech	
	Water pipes in the adjacent room	40
Faint	Quiet room	
	Whisper	20
Very faint	Human breathing	
	Threshold of hearing	0
	Too quiet for humans to hear but measurable	

To translate source amplitude, watts, to decibels (dB), convert sound *power* (W) to sound *power level* (L_W). Start with sound power, W, normalize it (divide it by a reference value), then compress its range (with a logarithm function):

$$L_W = 10 \log \left[\frac{W}{10^{-12} \text{watts}} \right]$$

To derive sound intensity *level* (L_I) in decibels, from sound intensity (I):

$$L_I = 10 \log \left[\frac{I}{10^{-12} \text{watts/m}^2} \right]$$

What did we do to convert sound intensity (I) in w/m² to sound intensity *level* (L_I) in decibels (dB)? First we found the measured sound intensity (I) at the microphone and divided that measurement by the reference value 10^{-12} w/m², the quietest sound human beings can hear. If the resulting ratio is 200, then we recognize the measured sound intensity as 200 times the sound intensity of the human hearing threshold. Finally, we compress the range of possible values by taking the logarithm of the ratio, and we translate to more convenient numbers by multiplying by 10. Using a reference value equal to the threshold of hearing, we ensure that a sound intensity *level* of zero dB corresponds to the quietest hearable sound because log 1 = 0.

To derive sound pressure *level* (L_p) in decibels from sound pressure (P) in newtons/m²:

$$L_p = 20 \log \left[\frac{P}{2 \cdot 10^{-5} \text{newtons/m}^2} \right]$$

Sound intensity varies with the square of sound pressure, so the formulas are normalized such that sound intensity *level* (very nearly) equals sound pressure *level*. We typically measure with sound pressure level, and sound pressure level correlates best to the way we hear, but most of our calculations are performed using sound intensity level. In practice, values of the two metrics are fairly interchangeable. Because each is a unit-less ratio of the sound relative to a reference value, each can be expressed in decibels (dB).

The decibel unit provides some peculiar but consistent and easy-to-use rules of thumb. A sound, in a free field, drops by six decibels when measured at a distance twice as far away. Two identical sounds, when combined, produce a sound three decibels louder than either one alone. And for the human auditory system to perceive a sound as twice as loud, it will have to be amplified by 10 decibels (20 decibels is four times as loud, and so on). The reverse is also true. A point-source sound in a free field increases by six decibels when measured at half the distance; half the sound intensity translates to a three-decibel loss, and a 10-decibel loss sounds half as loud to the human ear.

Both speech and music rely on dynamic range, the vast span of sound levels between a whisper and a shout, between a pianissimo and a fortissimo passage. The dynamic range of symphonic music extends 70 decibels, so the loudest portions of the piece have 10 million times the energy of the quietest.

NOTE

Logarithms (base 10) compress the wide range of common sounds into a relatively narrow range of values because they are the exponents by which 10 is raised to produce a given number. For instance:

Log 1 = 10
Log 2 = 100
Log 3 = 1,000
Log 4 = 10,000

. . . . and so on, such that adding one and taking the Log equates to multiplying by 10 instead. Logarithms express numbers as orders of magnitude.

Originally, the unit of loudness did not include the 10 multiplier and was called the "bel" in honor of telephone inventor Alexander Graham Bell. After it was found that the just-noticeable difference (JND) for human loudness perception was approximately 1/10th of a bel, the 10 multiplier was added to the equation, and the unit was given the name "decibel."