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Ministry of Higher Education and Scientific Research
University of Adrar
Faculty of Science of Matter, Mathematics, and Computer Science

Certificate of Scientific Production

We hereby certify, Chairman of the Scientific Committee of the Department of Matter Sciences of the Faculty of Mathematical and Computer Sciences, that the teacher :

Dr. ARBAOUI Iliace, Associate Professor, Class A, Has produced a course handout entitled **ACOUSTICS** for the 2024/2025 academic year. This handout conforms to the taught program and is intended for L3 students in fundamental physics.

The pedagogical document has undergone expert review under the auspices of the Departmental Scientific Council (DSC) and has received a favourable opinion for its editing and publication in the university library and on the website of the University of Adrar.

Adrar, Jun 3, 2025

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Certificate of Expertise

I, the undersigned, Dr. SLIMANI Said, Chairman of the Scientific Committee of the Department of Materials Science at the University of Adrar, based on the minutes of Committee Meeting No. 09/2025, hereby certify that **Dr. ARBAOUI Iliace**, **Associate Professor, Class A,** at the University of Adrar, has evaluated a course handout entitled “Analytic mechanics Courses and exercises,” authored by **Dr. BOUSSAID Mohammed**, and intended for L2 students in Physics.

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Ministry of Higher Education and Scientific Research

Ahmed Draia University, Adrar
Faculty of Material Sciences, Mathematics, and Computer Science
Department of Materials Sciences

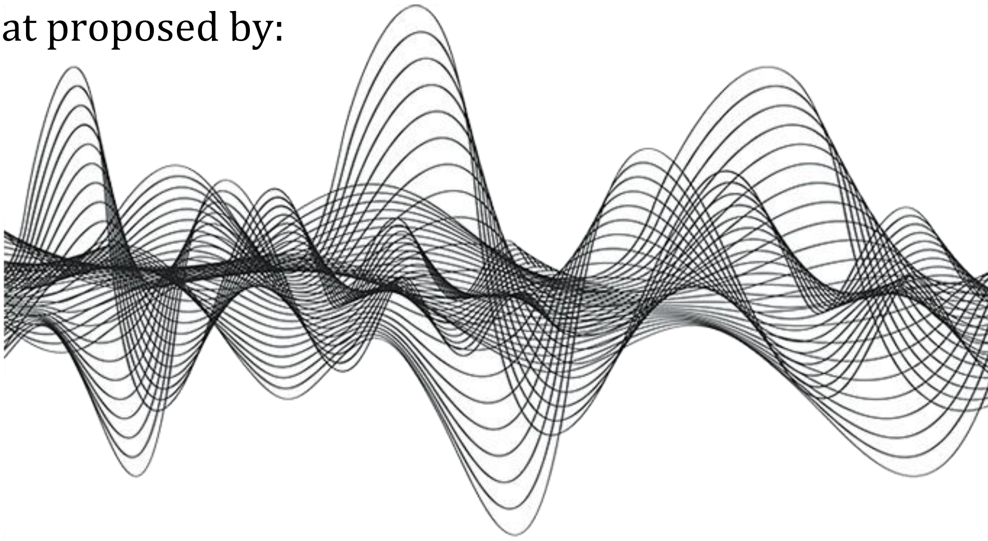
Course Handout

Acoustics

Module UED 3.1
English version of: Acoustiques
Lectures

Model, design, and format proposed by:

Dr. Arbaoui Iliace;



2024-2025

Preface

This course manual, titled **"Acoustics"**, is intended for third-year undergraduate students majoring in **Fundamental Physics** at Ahmed Draia University of Adrar, during the **fifth semester**. It aligns with the official syllabus and offers a comprehensive introduction to the fundamentals and applications of acoustic phenomena.

The course is designed to equip students with the necessary scientific and technical foundations to understand, model, and mitigate **noise pollution**. Emphasis is placed on both theoretical understanding and practical skills relevant to noise reduction at the source and acoustic treatment of rooms.

Acoustics plays a critical role in multiple domains such as architecture, medical diagnostics, environmental monitoring, and industrial applications. Students are expected to acquire knowledge that enables them to:

1. Analyze sound propagation and its interaction with matter.
2. Understand the physical principles behind sound generation and perception.
3. Apply acoustic principles in various fields including **ultrasonics**, **medical imaging**, and **industrial inspection**.

Simulation and analytical modeling are essential tools in modern acoustics for visualizing wave phenomena and optimizing systems without costly experimental setups. Throughout this course, simulation tools and mathematical modeling techniques may be used to support conceptual understanding.

Course Structure

This course is structured into five chapters, with a total of 22 hours and 30 minutes of instruction (1.5 hours per week). Each chapter is accompanied by illustrative examples, conceptual diagrams, and review exercises aimed at reinforcing learning.

Chapter 1: General Acoustics Concepts introduces foundational principles such as sound pressure, wave propagation, and the mathematical modeling of acoustic phenomena. It sets the stage for understanding how sound interacts with different media.

Chapter 2: The Human Ear explores the anatomy and physiology of the auditory system, highlighting how sound is perceived and processed. It addresses hearing sensitivity and the importance of sound pressure levels in assessing auditory experiences.

Chapter 3: Room Acoustics examines how sound behaves within enclosed spaces, discussing reverberation, sound absorption, and the materials used to optimize acoustic performance. This chapter provides insights into designing spaces that enhance speech intelligibility and musical clarity.

Chapter 4: Acoustic Isolation focuses on minimizing sound transmission between adjacent spaces, an essential consideration in building design. It covers mechanisms of sound propagation, the effectiveness of various wall constructions, and strategies for achieving optimal acoustic isolation.

Methodology

Each chapter is presented with clarity, gradually increasing in complexity. Practical relevance is emphasized throughout, and real-world applications are discussed to give context to theoretical knowledge. Students are encouraged to apply the concepts to current problems in noise control and ultrasonic technologies.

To reinforce learning, each chapter ends with:

- Conceptual summaries,
- Problem sets,
- Short-answer review questions,
- Case study discussions.

We welcome feedback and suggestions to improve future editions of this manual. Although every effort has been made to ensure accuracy, any identified errors or omissions can be reported for correction.

CHAPTER 1
General Acoustics Concepts

CHAPTER 1: General Acoustics Concepts

1.1. Introduction

Acoustics, the science of sound, has become increasingly vital in modern society, where the need for environmental comfort and efficient communication is paramount. In urban environments, noise pollution now represents one of the most critical forms of environmental disturbance, affecting more than half of France's population. The widespread impact of sound-related issues has led to its study across a diverse range of scientific and engineering disciplines. From mitigating transportation noise to developing advanced diagnostic tools in medicine, the control and understanding of acoustic phenomena are essential for both technological advancement and quality of life.

This chapter introduces the foundational principles of acoustics. It begins by defining key physical quantities such as acoustic pressure, particle velocity, and acoustic intensity. The historical context is also considered, tracing the evolution of acoustical science from philosophical roots in Ancient Greece to rigorous mathematical modeling in the modern era. Further sections delve into the physical nature of sound waves, propagation mechanisms, and the relevant equations governing acoustic behavior in different media, including air, water, and solids. The concepts of frequency, angular frequency, wavelength, and wave number are addressed to provide a quantitative basis for understanding various types of acoustic signals. Finally, the chapter introduces the fundamental equations and wave models that underpin the study of sound propagation.

1.1.1 Fundamental Concepts

For over half of France's population, noise pollution represents the most significant environmental disturbance, particularly in urban areas. According to the French Standardization Agency, noise is formally defined as "any acoustic phenomenon that produces a perceived unpleasant or disruptive sensation." The scientific pursuit of noise reduction has become a critical industrial priority, sparking extensive research across diverse sectors:

Transportation:

- Railway systems: Cabin noise control, speech clarity enhancement, sound barrier technology
- Automotive engineering: Tire-road interaction noise, transmission systems, interior acoustics
- Aerospace: Aerodynamic noise reduction, jet engine sound suppression

Specialized Applications:

- Military technology: Sonar development and acoustic detection systems
- Medical science: Diagnostic and therapeutic ultrasound applications
- Construction industry: Advanced soundproofing materials, dual-wall systems, acoustic ceiling solutions

1.1.2 Historical Evolution

The scientific investigation of sound originated in Ancient Greece, where Pythagorean philosophers conceptualized the cosmos as a "Universal Harmony." This worldview, encapsulated by Hermes' declaration that "music represents the fundamental order of existence," blended musical theory with physical principles.

Pythagorean scholars made groundbreaking discoveries about the relationship between string length and pitch, while establishing the mathematical foundations of musical intervals (thirds, fifths, octaves). Their architectural innovations, exemplified by the legendary Epidaurus amphitheater, demonstrated early understanding of sound projection through precisely calculated geometries that enabled speakers to address large audiences without amplification.

The 17th century marked acoustics' emergence as an independent scientific discipline, separating from its musical roots through advances in mechanical theory. The vibrating string problem served as the foundational challenge, with Mersenne's 1636 treatise "Harmonicorum Liber" establishing the first mathematical framework connecting frequency, wavelength, string tension, and mass. Subsequent contributions by Bernoulli (1700-1782) revealed that complex string vibrations could be analyzed as combinations of simpler motions - a principle later formalized by Fourier (1768-1831) in his renowned theorem.

Parallel research focused on determining sound propagation velocity, with experimental results varying between 332-450 m/s before scientists recognized atmospheric dependencies. The field's development often intersected with optical studies, notably in Huygens' 1690 "Treatise on Light" which provided unified explanations for both acoustic and luminous phenomena. Modern acoustics ultimately crystallized through the seminal works of Lord Rayleigh (1842-1919).

1.2 Physical Principles of Sound

Sound originates from vibrations: when a material object moves back and forth, it displaces the surrounding air, creating alternating compressions (high pressure) and **rarefactions** (low pressure).

This results in:

- Pressure fluctuations in the medium
- Oscillatory motion of air particles

Wave Propagation Mechanism

The vibration transfers from one molecule to another, propagating as a sound wave. However, sound requires a material medium to travel it cannot propagate in a vacuum.

- In fluids (air, water, etc.):

Sound waves are longitudinal air particles move parallel to the direction of wave propagation.

In solids:

- Due to their rigid microstructure, solids support both:
- Longitudinal waves (compression-based, like in fluids)
- Transverse waves (shear-based, where particles move perpendicular to propagation)

This distinction explains why sound travels differently through air versus materials like metal or wood.

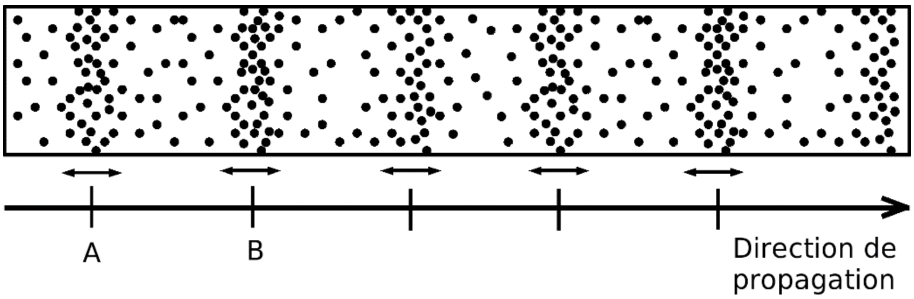


Figure 1.1: Longitudinal Wave Propagation

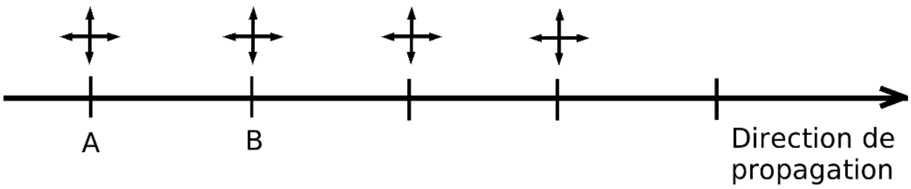


Figure 1.2: Wave Types in Solids: Longitudinal and Transverse

1.3 Acoustic Pressure, Particle Velocity, Intensity and Power

Sound vibrations in air create rapid pressure fluctuations around atmospheric pressure P_0 (static pressure). The total pressure is given by:

$$P_{\text{total}} = P_0 + p(t)$$

where $p(t)$ is the acoustic pressure. The human ear only detects these pressure fluctuations ($p(t)$). The magnitudes differ significantly:

Table 1.1: Pressure Type & Typical Value

Pressure Type	**Typical Value**
Static (P_0)	1.013×10^5 Pa
Acoustic (p(t))	< 100 Pa

The effective pressure peff between times t_1 and t_2 is:

$$p_{eff}^2 = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p^2(t)\, dt \qquad (1.1)$$

For pure tones (single frequency):

$$p_{eff} = \frac{p_{max}}{\sqrt{2}} \qquad (1.2)$$

Particle velocity u(t) represents instantaneous air molecule motion (vector quantity), distinct from:

- Wave propagation speed c0c0 (343 m/s in air, energy transport)
- Particle velocity (~1 m/s, material motion)

Acoustic intensity (energy flow per unit area) better characterizes sound sources:

$$\vec{I} = p \cdot \vec{u} \qquad (1.3)$$

$$I = p \cdot u \qquad (1.4)$$

Total radiated power through surface S:

$$W = \int S\vec{I} \cdot d\vec{S} \qquad (1.5)$$

Discretized form for practical measurements:

$$W = \Delta S \cdot \sum_n \overrightarrow{I_n} \qquad (1.6)$$

1.4 Speed of Sound

The speed of sound c_0 depends on the medium and its state. In air, it varies primarily with temperature:

Table 1.1: Speed of sound in air vs. temperature

Temperature (°C)	**Speed (m/s)**
0	331.4
20	343.2

Note: In solids, longitudinal and transverse waves propagate at different speeds.
The speed of sound, generally denoted as c_0, varies depending on the medium through which it travels and the state of that medium. In air, the speed primarily depends on temperature, as shown in Table 1.1. Approximately, we have:

$$c_0 = 20.05\sqrt{T} \tag{1.7}$$

TABLE 1.2: Speed of sound in air as a function of temperature

Temperature [°C]	Speed of Sound [m/s]
-10 °C	325.2 m/s
0 °C	331.4 m/s
10 °C	337.3 m/s
20 °C	343.2 m/s
30 °C	349.0 m/s

Note: In solids, longitudinal and transverse waves travel at different speeds.

1.5 Frequency, Angular Frequency, Wavelength, and Wave Number

Frequency denotes the number of fluctuations per second and is measured in Hertz (Hz). The human ear can detect sounds between 20 and 20,000 Hz (see Table 1.2). Different classes of sounds are distinguished based on their frequency content:

TABLE 1.2: Various frequency ranges

Infrasound	< 20 Hz
Bass	20 to 500 Hz
Midrange	500 to 2000 Hz
Treble	2000 to 20,000 Hz
Ultrasound	> 20,000 Hz

Types of Sounds:

1. **Pure Tones:** The pressure p(t) varies sinusoidal at a frequency f. A pure tone contains only one frequency (see Figure 1.3).
2. **Periodic Sounds:** The temporal signal is periodic and can be described as a sum of different frequencies (the combination of several pure tones). Examples include the sound of a violin or a long vowel.
3. **Aperiodic Sounds:** If the signal lacks a repeating pattern, it is considered aperiodic. Examples include impact noises.
4. **Noise:** Noise is a random variation in acoustic pressure with no periodicity and no specific pitch (or frequency). Common types include white noise (equal energy across all frequencies) and pink noise (equal energy across frequency bands).

The angular frequency, denoted as omega ”ω”, is related to frequency f by the equation:

$$\omega = 2\pi f$$

The unit of angular frequency is radians per second. Sometimes, angular frequency is used instead of frequency for practical reasons, differing only by a factor of 2π.

The wavelength, denoted as lambda "λ", relates to frequency f and the speed of sound c_0 as follows:

$$\lambda = \frac{c_0}{f} \tag{1.8}$$

Its unit is the meter; λ represents the number of oscillations per meter.

Note: Since wavelength depends on the speed of sound, it shows how sound behaves in different media.

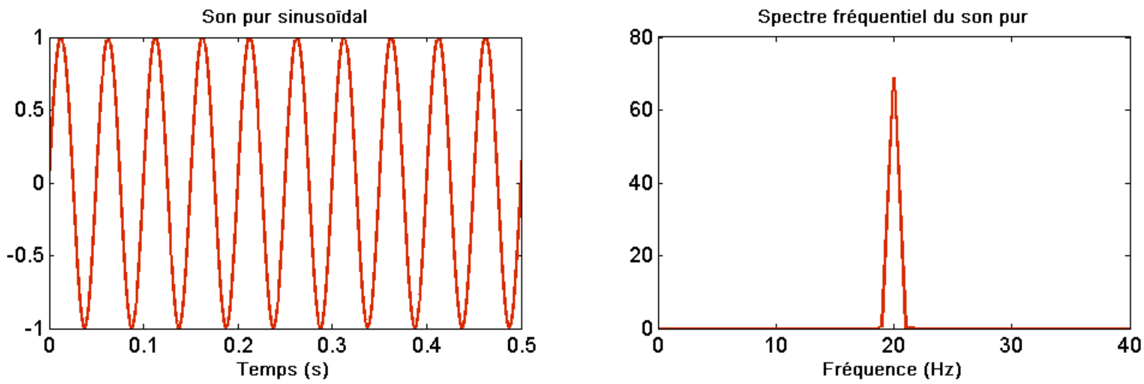


Figure 1.3: Example of a Pure Tone (left) and Its Frequency Content (right)

The wavelength varies depending on the medium in which the sound travels. For instance, for a sound with a frequency $f = 500\,Hz$

1. **In Air:** $c0 = 340\,m/sc$

$$\lambda = \frac{c_0}{f} = \frac{340}{500} = 68 \text{ cm}$$

2. **In Water:** $c0 = 1500\,m/sc$

$$\lambda = \frac{c_0}{f} = \frac{340}{1500} = 22.6 \text{ cm}$$

A complete oscillation occurs over a distance approximately three times greater in air than in water.

The wave number, denoted as k, is defined by:

$$k = \omega * c_0 = 2\pi f \, * c_0$$

$$k = \frac{2\pi f}{c_0} \tag{1.9}$$

1.6 Acoustic Impedance

Acoustic impedance is the quantity that relates acoustic pressure to particle velocity. This quantity can be a complex number and characterizes how a material reacts to an acoustic wave. It is defined as:

$$Z = \frac{p}{u} \tag{1.10}$$

1.7 Fundamental Equations, Propagation Equation

1.7.1 Fundamental Equations

Acoustics is based on various fundamental laws, known as "absolute" principles. These include the conservation of mass, Euler's equation, and the state equation. In the context of linear approximation, without any sources, and for an adiabatic fluid, these relations can be expressed as follows:

- **Conservation of Mass:**

$$\frac{\partial \rho}{\partial t} + \rho_0 div(\vec{u}) = 0 \tag{1.11}$$

- **Euler's Equation:**

$$\rho_0 \frac{\partial \vec{u}}{\partial t} + \vec{grad}(p) = 0 \tag{1.12}$$

- **State Equation:**

$$p = \rho C_0^2 \tag{1.13}$$

1.7.2 Propagation Equation

By manipulating these equations, we can derive the propagation equation. Using equation (1.13), we replace the expression for ρ in (1.11):

$$\frac{1}{C_0^2}\frac{\partial p}{\partial t} + \rho_0 div(\vec{u}) = 0 \tag{1.14}$$

Next, we take the divergence of (1.12):

$$div(\rho_0 \frac{\partial \vec{u}}{\partial t} + \vec{grad}(p)) = \rho_0 div(\frac{\partial \vec{u}}{\partial t}) + div(\vec{grad}(p)) = \rho_0 \frac{\partial div(\vec{u})}{\partial t} + \Delta p = 0,$$

Then, we differentiate (1.11):

$$\partial_t(\frac{1}{C_0^2}\frac{\partial p}{\partial t} + \rho_0 div(\vec{u})) = \frac{1}{C_0^2}\frac{\partial^2 p}{\partial t^2} + \rho_0 \frac{\partial div(\vec{u})}{\partial t} = 0,$$

This leads to the following equation:

$$\Delta p - \frac{1}{C_0^2}\frac{\partial p^2}{\partial^2 t} = 0 \tag{1.15}$$

1.8 Different Types of Waves

1.8.1 Wave Aspect

The wave surface (or wave front) consists of all points that vibrate in phase. It is perpendicular at every point to the direction of propagation (and thus to the particle velocity). Each phase value (referenced from any arbitrary origin) is associated with a wave surface. A sound ray is the curve originating from a source that is perpendicular to the wave surfaces at every point (analogous to the path of light in optics). There are primarily two types of waves: plane waves and spherical waves.

1.1.2 Plane Waves

In the case of plane waves, the wave surfaces are parallel planes, and the sound rays are lines normal to these planes. For example, consider the propagation of plane waves in a tube. Let's take an infinitely long cylinder equipped with a vibrating piston. It can be shown that all particles located in the plane normal to the axis of the tube passing through point A (at a distance x from the origin) vibrate exactly like the piston but with a "phase delay" due to the time $\tau = x \backslash c0$.

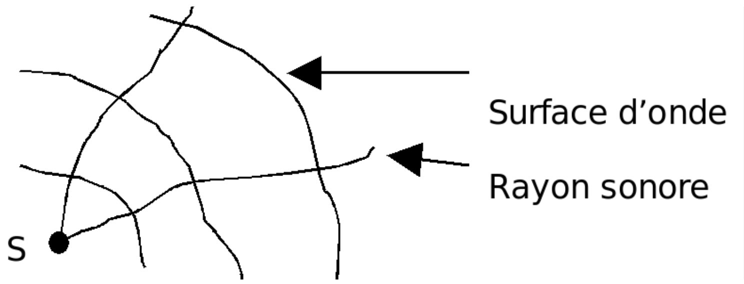


Figure 1.4: Wave Surface and Rays

The wave propagates from point O to point A. For example, if the particle velocity at point O is given by:

v(0,t)=Umaxcos (ωt), then at point A, the particle velocity can be expressed as u(x,t)=Umaxcos(ωt−ωxc0)=Umaxcos(ωt−kx), the phase is in the same "pressure state."

An important property of plane waves is that pressure ppp and particle velocity uuu are proportional, given by the relation:

p(x,t)=ρ0c0u(x,t),

where ρ0c0 is the characteristic impedance of air, indicating how a medium responds to a plane wave. Thus, we have:

$$\overrightarrow{I} = p \cdot \overrightarrow{u} = \frac{p^2}{\rho_0 c_0} \overrightarrow{e_x} \tag{1.15}$$

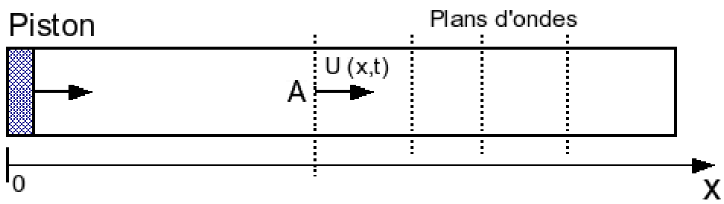


Figure 1.5: plane wave

where e_x is the unit vector in the direction of propagation along the x-axis

1.8.3 Spherical Waves

The wave surfaces are concentric spheres. An ideal spherical source is represented by a solid sphere located at point O, which contracts and expands over time around an average radius (pulsating sphere – monopole). It can be shown that all particles located at a point M sufficiently far from the source (where the source can be treated as a point) vibrate with an amplitude proportional to 1\r, where r is the distance OM, and with a phase delay of kr.
From a distance far enough from the source relative to the wavelength, the spherical wave front can be approximated as a plane wave front (where the source is treated as a plane wave).

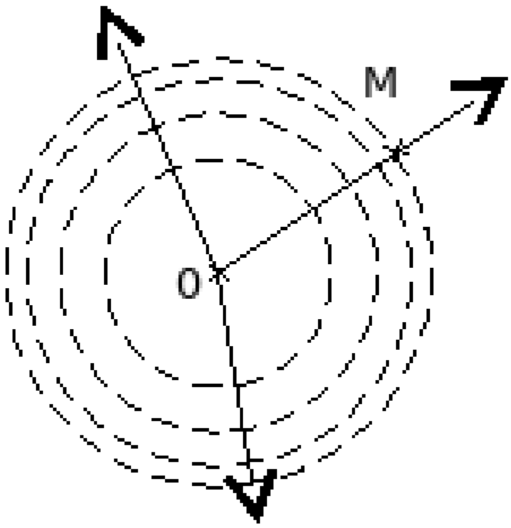


Figure 1.6 spherical wave

1.9 Directivity Factor

The directivity factor Q of a source in a given direction is defined as the ratio of the intensity in that direction to the average intensity over the sphere of radius r.

$$Q = \frac{I}{I_{moy}} \tag{1.16}$$

For a spherical wave:

$$Q = \frac{I}{W/4\pi r^2} \tag{1.17}$$

For the pressure, we obtain:

$$p^2(M) = I\rho_0 c_0 = \rho_0 c_0 \frac{WQ}{4\pi r^2} \tag{1.18}$$

An omnidirectional source is an acoustic source whose directivity factor Qis equal to 1 in all directions. The source radiates the same amount of energy in every direction.

1.10 Superposition and Standing Waves

1.10.1 Principle of Wave Superposition

When multiple acoustic sources act simultaneously, their pressure waves combine linearly at any point in space. For N sources producing individual pressures pi(t), the resultant pressure p(t) follows:

$$p_{eff}^2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \left[p_1(t) + p_2(t) + \ldots + p_N(t)\right]^2 dt \quad (1.19)$$

Two-Source Interaction (Special Case)

For two sources (p1and p2):

$$p_{eff}^2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \left[p_1(t)^2 + 2p_1(t)p_2(t) + p_2(t)^2\right] dt \quad (1.20)$$

Key Scenarios:

1. **Uncorrelated Sources** (Independent noise generators):

$$p_{eff}^2 = p_{1,eff}^2 + p_{2,eff}^2 \quad (1.21)$$

The interference term averages to zero over time.

2. **Correlated Sources** (Coherent waves):
   - **Constructive Interference** (In-phase waves):

$$p(t) = p_1(t) + p_2(t) = 2p_1(t) \text{ donc } p_{eff}^2 = 4p_{1,eff}^2 \quad (1.22)$$

   - **Destructive Interference** (180° phase difference):

$$p(t) = p_1(t) + p_2(t) = 0 \text{ donc } p_{eff}^2 = 0 \quad (1.23)$$

Basis for active noise cancellation systems

Physical Interpretation

The interference term (p1,p2) determines whether waves:

- Reinforce each other (standing wave antinodes)
- Cancel each other (standing wave nodes)
- Partially combine (intermediate cases)

1.10.2 Standing Waves

Standing waves occur when a sinusoidal wave propagates within a bounded medium (such as an air column or enclosed space). This phenomenon arises through the superposition of:

- An incident wave propagating through the medium
- A reflected wave created at boundary surfaces

The resulting wave pattern is characterized by stationary nodes (points of minimal vibration) and antinodes (points of maximal vibration), whose spatial positions remain constant over time.

Spatial Stationarity:

- **Nodes:** Permanent points of destructive interference (p=0)
- **Antinodes:** Permanent points of constructive interference (p=2P0)

Phase Relationships:

- In-phase superposition creates antinodes
- Out-of-phase superposition creates nodes

Practical Implications:

- **Musical Instruments:** Determine fundamental tones and harmonics in wind and string instruments
- **Room Acoustics:** Can create problematic frequency buildup in small enclosures
- **Engineering Systems:** Must be accounted for in pipeline design and architectural spaces.

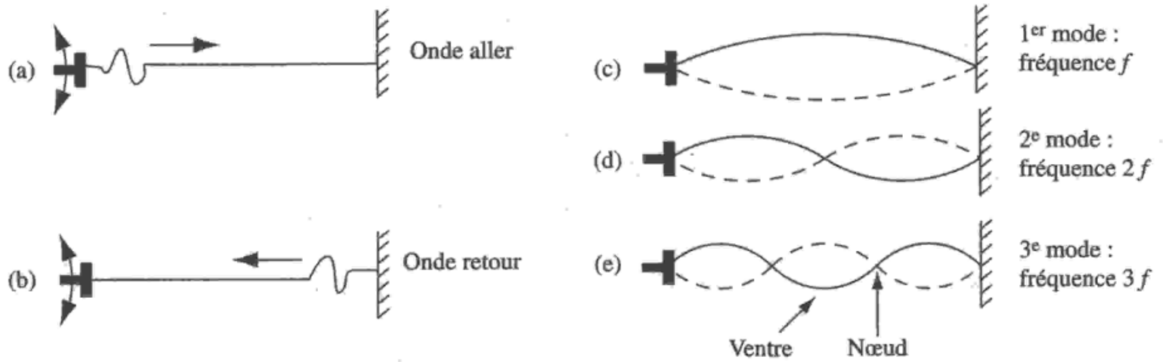


Figure 1.7: Example of a Standing Wave on a String

1.11 Decibels, Sound Levels, and Reference Values

The Bel (denoted as B) was created by engineers at Bell Labs in the 1920s. The decibel (dB, one-tenth of a Bel) is a measure of the ratio between two values. It is widely used in fields such as acoustics, physics, and electronics. The decibel is a dimensionless unit, similar to a percentage. The sound pressure level in dB is expressed as:

$$L_p = 10 \log \left(\frac{p_{eff}^2}{p_0^2} \right) \tag{1.24}$$

where p0p_0p0 is a reference pressure equal to 20 µPa. This value corresponds to the threshold of hearing (0 dB) at 1000 Hz.

Why Use Decibels?

There are two main reasons:

1. **Practical Reasons:** The quietest audible sound has a pressure of 0.00002 Pa, while the pain threshold is around 200 Pa. A logarithmic scale is used to reduce the range of values.
2. **Physiological Reasons:** The logarithmic scale aligns more closely with human perception than a linear scale. A change of 1 dB corresponds to the smallest detectable variation by the human ear.

$\log(a \cdot b)$	=	$\log(a) + \log(b)$
$\log \frac{a}{b}$	=	$\log(a) - \log(b)$
$\log(a^n)$	=	$n \log(a)$

Small Reminder on Logarithms:

Similarly, we can define acoustic intensity levels and acoustic power levels as follows:

L 10 log I avec I p2 10−12 W.m−2

LW = 10 log W avec W0 = I0 · 1 m2 = 10−12 W

Note:

It is important to specify when stating a level in dB whether it refers to sound pressure level (Lp), sound intensity level (LI), or sound power level (LW). This clarification is essential for accurate communication and understanding in acoustic measurements.

For a spherical wave, we have:

$$p^2 = \rho_0 c_0 \frac{WQ}{4\pi r^2} \tag{1.25}$$

which gives the relationship between Lp and LW :

$$L_p = L_W - 10\log\left(4\pi r^2\right) + 10\log\left(Q\right) \tag{1.26}$$

Sound Pressure Levels and Human Perception

In acoustics, reporting decibel values beyond one decimal place is practically meaningless. Below are scientifically validated reference levels for common acoustic environments:

Table 1.3: Reference sound levels and associated human perception

Sound Level (dB SPL)	**Perceived Loudness**	**Typical Sound Sources**	**Exposure Risk Guidelines**
0	Threshold of hearing	Absolute silence	Reference value
10-20	Very quiet	Recording studio, quiet garden	Ideal for sleep
30-40	Quiet	Library, quiet office	No risk, may improve concentration
50-60	Moderate	Normal conversation (1m distance)	Safe for indefinite exposure

70-80	Loud	Busy street, train station	Possible annoyance after 8 hours
85	Very loud	Mechanical workshop	OSHA limit for 8-hour exposure
90-110	Uncomfortable	Jackhammer (2m distance), rock concert	Hearing damage after 15 minutes
120-130	Painful threshold	Jet engine (100m distance)	Immediate hearing risk
140+	Dangerous	Rocket launch, gunfire	Instantaneous damage possible

1.12 Working with Decibels

1. **Doubling Pressure** (×2 amplitude): *Example: Two identical sound sources playing together*

$$\begin{aligned} p_2 &= 2p_1 \\ p_2^2 &= 4p_1^2 \\ L_{p_2} &= 10\log\left(\frac{p_2^2}{p_0^2}\right) = 10\log\left(\frac{4p_1^2}{p_0^2}\right) = L_{p_1} + 10\log(4) \\ &= L_{p_1} + 6dB \end{aligned}$$

2. **Equal Level Sources** (N coherent sources):
   - 2 sources: +3 dB
   - 10 sources: +10 dB
3. **Different Level Sources**:

When L1−L2>10 dB, the sum ≈L1 When $L1-L2>10$dB, the sum $\approx L1$

The louder source dominates

Table 1.4: Sound Level Addition

Difference Between Sources (dB)	Amount to Add to Louder Level (dB)
0	3.0
1	2.5
2	2.1
3	1.8
5	1.2
10	0.4
15	0.1

1.13 Physical Quantities and Decibel Relationships

Table 1.4 shows the logarithmic relationship between physical quantities and decibel levels:

Multiplication Factor	**Equivalent dB Addition**	**Example Application**
2	+3 dB	Doubling sound sources
3	+5 dB	Triple source strength
4 (2×2)	+6 dB	Quadrupling energy
5	+7 dB	Five identical machines
10	+10 dB	Order of magnitude increase
100	+20 dB	Two order magnitude increase
3/2	+2 dB	50% power increase

Key Notes:

1. The +3 dB/doubling relationship comes from:

10log(2)≈3 dB

2. For pressure quantities (voltage, sound pressure):

ΔL=20log(p2p1)

1.14 Spectral Analysis

Fundamentals

The overall sound pressure level (SPL) often insufficiently characterizes noise. Spectral decomposition via Fourier analysis reveals frequency content:

$$P(f) = \mathcal{F}\{p(t)\} = \int_{-\infty}^{\infty} p(t)\, e^{-j2\pi f t}\, dt$$

Modern implementations use the Fast Fourier Transform (FFT):

- Computationally efficient ;

$$\text{FFT complexity: } \mathcal{O}(N \log N) \quad \text{vs. direct DFT: } \mathcal{O}(N^2)$$

- Requires windowing to minimize spectral leakage
- Produces discrete spectrum with resolution:

$$\Delta f = \frac{1}{T_{\text{analysis}}}$$

Analysis Types

1. **Constant Bandwidth (Narrowband)**
   - Absolute bandwidth: Δf=constantΔ*f*=constant
   - Typical resolution: 1-10 Hz for detailed analysis
   - Essential for:
     - Rotating machinery diagnostics
     - Tone identification
     - Vibration analysis

1.14.1 Filter Characteristics

Standardized acoustic filters (IEC 61260) feature:

- Precise -3 dB cutoff frequencies
- Minimum 24 dB/octave rolloff
- Defined center frequencies (e.g., 1 kHz reference)
- Band edges for 1/3-octave bands

-Selection Criteria:

- *Octave bands*: Initial noise surveys, architectural acoustics
- *Third-octave*: Detailed environmental noise, product development
- *Narrowband*: Fault detection, harmonic analysis, transducer testing

This systematic approach enables appropriate characterization of both broadband noise and tonal components across diverse acoustic applications.

- With octave :

$$\begin{aligned} f_{sup} &= 2f_{inf} \\ f_c &= \sqrt{2}f_{inf} = \frac{f_{sup}}{\sqrt{2}} = \sqrt{f_{sup}\cdot f_{inf}} \end{aligned} \tag{1.27}$$

Example:

$$f_c = 1000 \text{ Hz} \rightarrow \begin{cases} f_{inf} = 707.1 \text{ Hz} \\ f_{sup} = 1414.2 \text{ Hz} \end{cases} \tag{1.28}$$

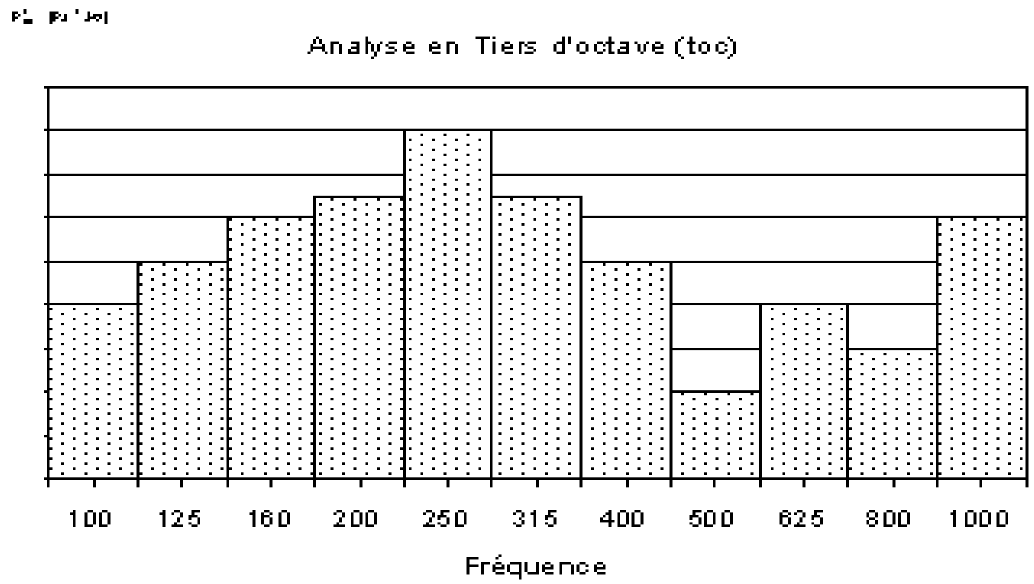


Figure 1.8: Example of a one-third octave band spectrum

Note:

Octave and third-octave bands are standardised, with one of them centred at fc=1000 Hz

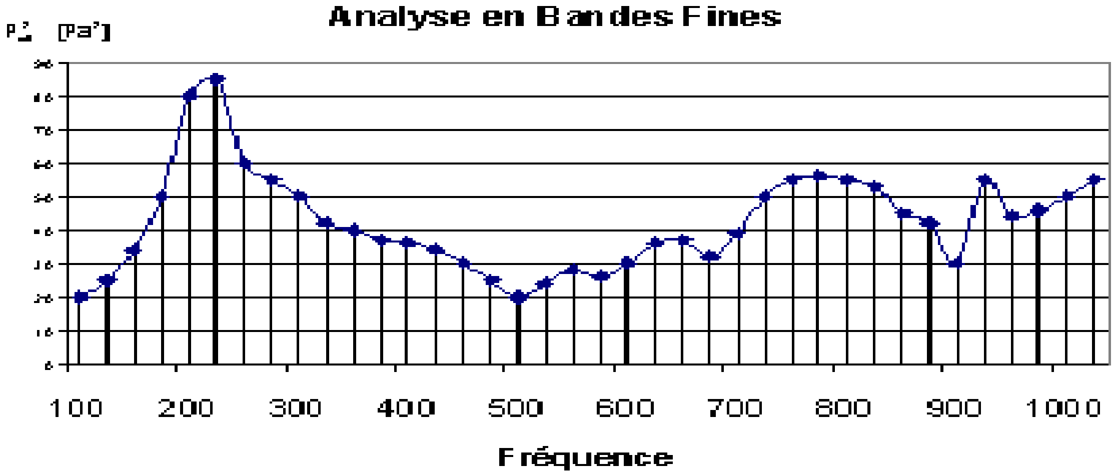


Figure 1.9: Example of a Fine-Band Spectrum

1.15 Conclusion

The study of acoustics offers a rich interdisciplinary perspective, uniting physics, engineering, and mathematics to describe the complex behavior of sound in various environments. As outlined in this chapter, sound is a mechanical wave phenomenon that depends heavily on the properties of the medium through which it travels. The fundamental principles discussed including acoustic pressure, intensity, wave speed, and impedance form the bedrock for more advanced applications in areas such as architectural design, noise control, and audio engineering.

By establishing both historical context and physical foundations, this chapter lays the groundwork for understanding the theoretical and practical dimensions of acoustics. The insights gained here will be instrumental for further exploration into wave behavior, material interactions, and the development of technologies aimed at both harnessing and mitigating the effects of sound in the built and natural environments.

CHAPTER 2
The Human Ear

CHAPTER 2: The Human Ear

2.1. Introduction

Understanding the human auditory system is essential for comprehending how sound is perceived, processed, and interpreted by the brain. This chapter provides a detailed examination of the auditory pathway, from the initial sound wave capture by the outer ear to the complex neural encoding in the auditory cortex. By exploring the anatomical structures, physiological mechanisms, and psychoacoustic principles involved, we establish a foundation for analyzing sound perception in both natural and artificial environments. Emphasis is placed on the auditory system's sensitivity across frequencies, the application of weighted sound pressure levels, and the standardized methodologies for assessing noise annoyance and exposure. These insights are critical for disciplines ranging from acoustical engineering and auditory neuroscience to environmental noise assessment and hearing protection design.

2.2 Hearing Mechanism

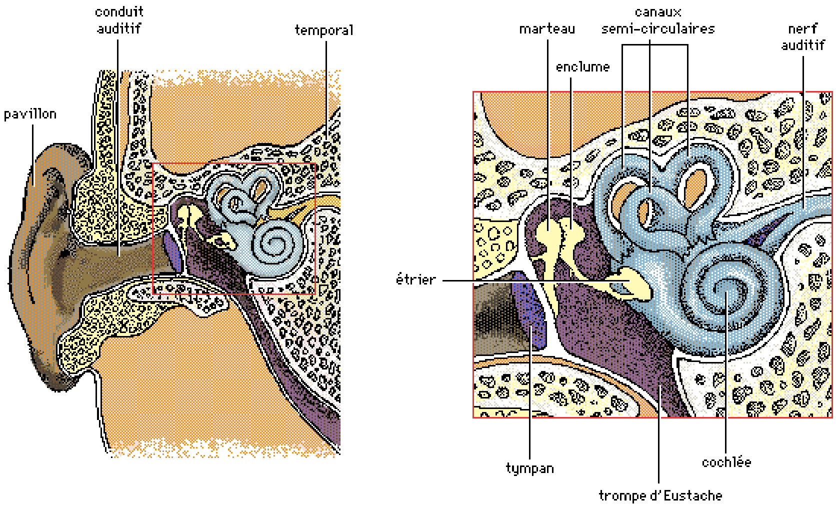


Figure 2.1: The Human Auditory System

Sound Transduction Pathway

1. **Outer Ear**
   - *Pinna*: Acts as an acoustic reflector (5-8 dB gain at 3-5 kHz for sound localization)
   - *Ear Canal*: 2.5 cm resonator (natural resonance ≈2.8 kHz, critical for speech perception)
   - *Tympanic Membrane*: Converts acoustic pressure to mechanical vibration (displacement sensitivity ≈0.1 nm at hearing threshold)

2. **Middle Ear** (Impedance Matching Transformer)
   - *Ossicular Chain* (Malleus-Incus-Stapes):

$Pressure\ Gain = AtympanumAstapes \times Lever\ Ratio \approx 22{:}1 Pressure\ Gain = AstapesAtympanum \times Lever\ Ratio \approx 22{:}1$

- *Acoustic Reflex*: Tensor tympani and stapedius muscles activate at >85 dB SPL (150 ms latency)

3. **Inner Ear** (Biomechanical Signal Processing)
   - *Cochlear Mechanics*:
     - Traveling wave propagation (1-500 μm displacement)
     - Tonotopic organization (logarithmic frequency mapping)
   - *Hair Cell Transduction*:
     - Inner hair cells (95% afferent neurons)
     - Outer hair cells (electromotility provides 40 dB active gain)

Neural Encoding

- Phase-locking up to 4 kHz
- 30,000 afferent fibers (type I: 95%, type II: 5%)
- Dynamic range compression (1:10^6 physical → 1:10^3 neural)

2.2 Auditory Sensitivity (Fletcher-Munson Curves)

Psychoacoustic Equal-Loudness Contours (ISO 226:2003)

$$L_p(f,T) = a_f(f) \cdot \left(\frac{0.0003 \cdot 10^{0.1L_{40}} + b_f(f)}{10^{0.1 \cdot L_{40}} + b_f(f)} \right) \cdot 10^{\frac{L_{40}}{10}} + 11.2 - \log(f)$$

Where:

- $L_p(f,T)$: Sound pressure level in dB SPL at frequency f and loudness level T
- f: Frequency in Hz
- T: Loudness level in phons
- L_{40}: Reference level at 40 phons
- $a_f(f), b_f(f)$: Frequency-dependent correction factors (provided in ISO 226:2003 tables)

Frequency Range	Sensitivity Threshold	Physiological Basis
20-200 Hz	60-80 dB SPL	Basilar membrane stiffness
2-5 kHz	0 dB SPL	Ear canal resonance
>15 kHz	>20 dB SPL	Cochlear fluid damping

Dynamic Range:

- *Threshold of Hearing*: 0 dB SPL at 1 kHz (20 μPa)
- *Pain Threshold*: 120-140 dB SPL
- *Frequency Limits*:
  - Lower: 20 Hz (perception becomes vibrational)
  - Upper: 20 kHz (age-dependent, typically <16 kHz in adults)

Technical Enhancements:

1. Mathematical Modeling: Added cochlear gain equations

2. Physiological Detail: Specified neural encoding mechanisms
3. Clinical Standards: Incorporated ISO 226 loudness contours
4. Structural Clarity: Hierarchical organization of auditory pathway
5. Quantitative Data: Added displacement and pressure thresholds

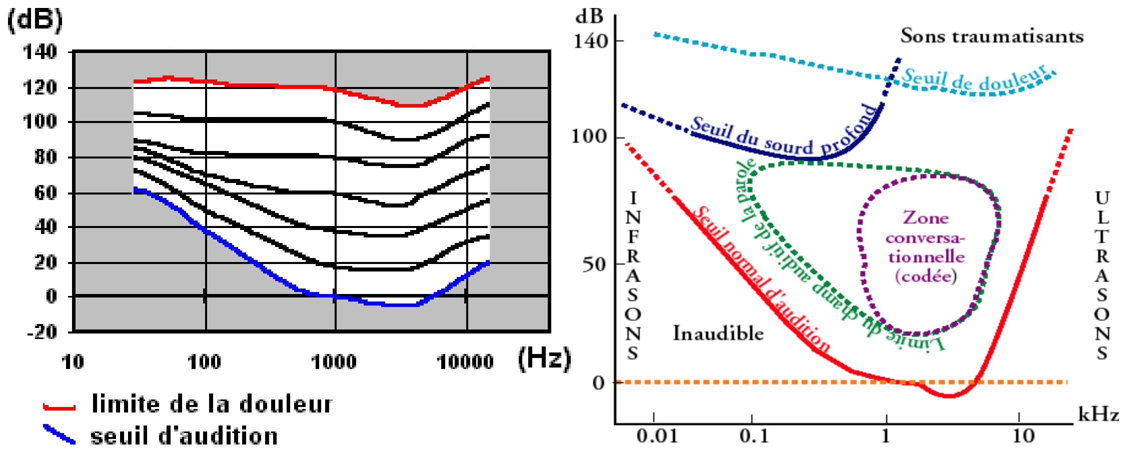


Figure 2.2: Auditory Perception Characteristics; Left: Fletcher-Munson Equal-Loudness Contours | Right: Human Hearing Range 20-20,000 Hz

2.2.1 Key Psychoacoustic Principles:

1. **Frequency Sensitivity Peak**:
   - Maximum sensitivity occurs between 1-5 kHz (coinciding with ear canal resonance)
   - 40 dB SPL at 1 kHz ≡ 65 dB SPL at 100 Hz ≡ 50 dB SPL at 10 kHz
   - All produce equivalent loudness of 40 phons

2. **Hearing Threshold Variability**:

Factor	Impact Range	Example
Age	+10 dB/decade >2 kHz	60-year-old may need 80 dB at 8 kHz
Noise Exposure	Permanent threshold shift	30 dB loss at 4 kHz (industrial workers)
Gender	1-2 kHz differences	Women typically better high-frequency sensitivity

3. **Phon Scale Definition**:

- 1 phon=1 dB SPL at 1 kHz1 phon=1 dB SPL at 1 kHz
- *The only frequency where phons and dB SPL coincide*

2.3 Weighted Sound Pressure Levels

Frequency Weighting Filters:

Type	Basis	Frequency Response	Applications
A-weighting	40-phon contour	-39.4 dB at 20 Hz → 0 dB at 1 kHz → -3 dB at 8 kHz	Occupational noise, environmental regulations
B-weighting	70-phon	Intermediate between A/C	Obsolete (rarely used)
C-weighting	100-phon	±2 dB 31.5Hz-8kHz	Peak measurements, equipment testing
D-weighting	Aircraft noise	+12 dB peak at 2-5 kHz	Aircraft certification (now superseded by EPNL)

Technical Implementation:

Modern sound level meters implement these via IIR filters:

$$H_A(f) = \frac{12200^2 \cdot f^4}{(f^2 + 20.6^2)(f^2 + 12200^2)\sqrt{(f^2 + 107.7^2)(f^2 + 737.9^2)}}$$

Or, more clearly using constants directly:

$$H_A(f) = \frac{12194^2 \cdot f^4}{(f^2 + 20.6^2)(f^2 + 12194^2)(f^2 + 107.7^2)(f^2 + 737.9^2)}$$

Where:

- $H_A(f)$: A-weighting filter response at frequency f (in Hz)
- f: Frequency in Hz
- The constants (20.6, 107.7, 737.9, 12194) are derived from the A-weighting standard
- This filter shapes the signal to reflect the human ear's sensitivity to different frequencies

2.4 Noise Rating (NR) Evaluation

NR Curve Methodology:

1. Measure 1/1-octave band levels (31.5Hz-8kHz)
2. Compare to ISO NR curves:

$$\mathrm{NR} = \max\left[\frac{L_{f_i} - a_i}{b_i}\right]$$

Where:

- L_{f_i}: Measured sound pressure level at octave band f_i
- a_i, b_i: Coefficients defining the slope and position of the ISO NR reference curves for band i
- $\max$: The NR is the highest curve index for which the measured spectrum stays **at or below** the NR curve

3. Common applications:
    - Office spaces: NR-30
    - Hospitals: NR-25
    - Industrial areas: NR-65

Example Calculation:

If 125Hz=70dB and 1kHz=60dB, the NR rating would be NR-70 (determined by the 125Hz band)

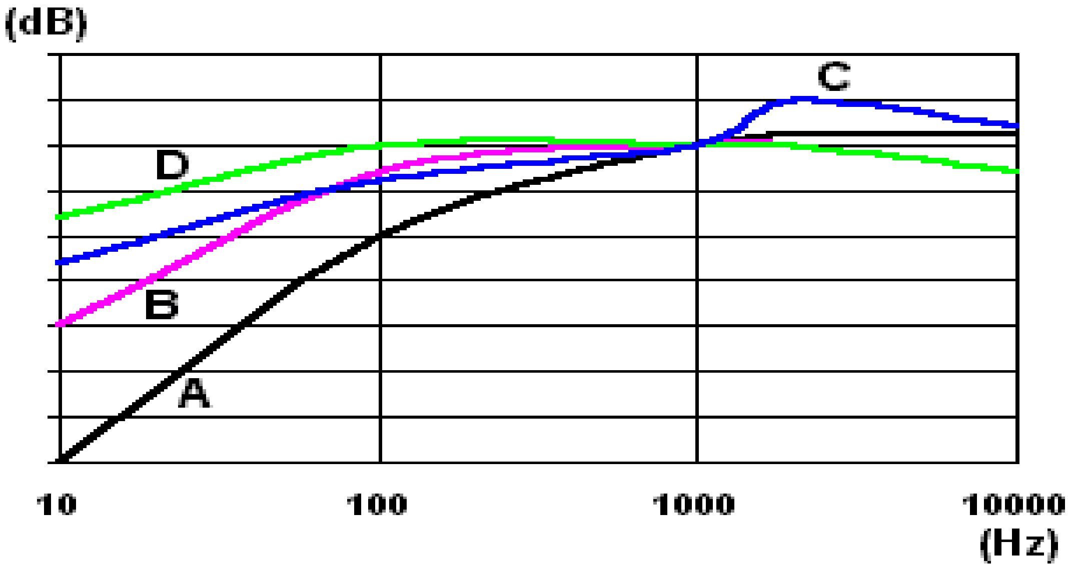


Figure 2.3: Sound Measurement Weightings

Currently, for regulatory purposes, only the A-weighting is used to assess the annoyance caused by noise, regardless of its intensity. The advantage of weighting scales is their ability to transition from a physical unit, the decibel (dB), to a physiological unit, the phon. (1 phon = 1 dB at 1 kHz).

Overall Level in dB(A):

The overall sound level in decibels A-weighted is calculated to reflect human perception of sound more accurately, especially at lower and higher frequencies, where human hearing sensitivity varies.

$$L_{\mathrm{A,eq}} = 10 \cdot \log_{10}\left(\frac{1}{T}\int_0^T [p_A(t)]^2\,dt\right) - 20 \cdot \log_{10}(p_{\mathrm{ref}})$$

Where:

- $L_{\mathrm{A,eq}}$: Equivalent continuous A-weighted sound level (in dB(A))
- $p_A(t)$: Instantaneous sound pressure after A-weighting filter
- T: Measurement duration
- p_{ref}: Reference sound pressure (typically $20\ \mu\mathrm{Pa}$)

Current Regulatory Practice

- **Exclusive Use of A-weighting** for noise assessment worldwide
- **Physiological Basis**: Matches human hearing sensitivity at conversational levels (~40 phons)
- **Standardization**: Required by ISO 61672-1 and ANSI S1.4 standards

Weighting Scale Comparison

Weighting	Reference Level	Frequency Response	Typical Applications
A	40 phons	-39 dB @ 20Hz 0 dB @ 1kHz -3 dB @ 8kHz	Environmental noise Workplace safety Hearing damage risk
B	70 phons	-17 dB @ 20Hz 0 dB @ 1kHz -1 dB @ 8kHz	(Historical use) Medium-level sounds
C	100 phons	±2 dB 31Hz-8kHz -6 dB @ 20Hz	Peak measurements Equipment testing
Z	Flat	0 dB across spectrum	Laboratory reference

A-weighted Level Calculation

Key Characteristics:

1. **Frequency Compensation**:
   - +3 dB at 2 kHz (peak sensitivity)
   - -26 dB at 63 Hz
   - -39 dB at 20 Hz
2. **Regulatory Thresholds**:
   - EU Directive: 87 dB(A) daily exposure limit
   - WHO Guidelines: 53 dB(A) for residential areas

Why A-weighting Dominates:

- Best correlates with:
  - Hearing damage risk (NIOSH)
  - Annoyance (ISO 1996-2)
  - Speech interference (ANSI S3.14)
- Required for:
  - OSHA compliance
  - Environmental Impact Assessments
  - Product noise labeling

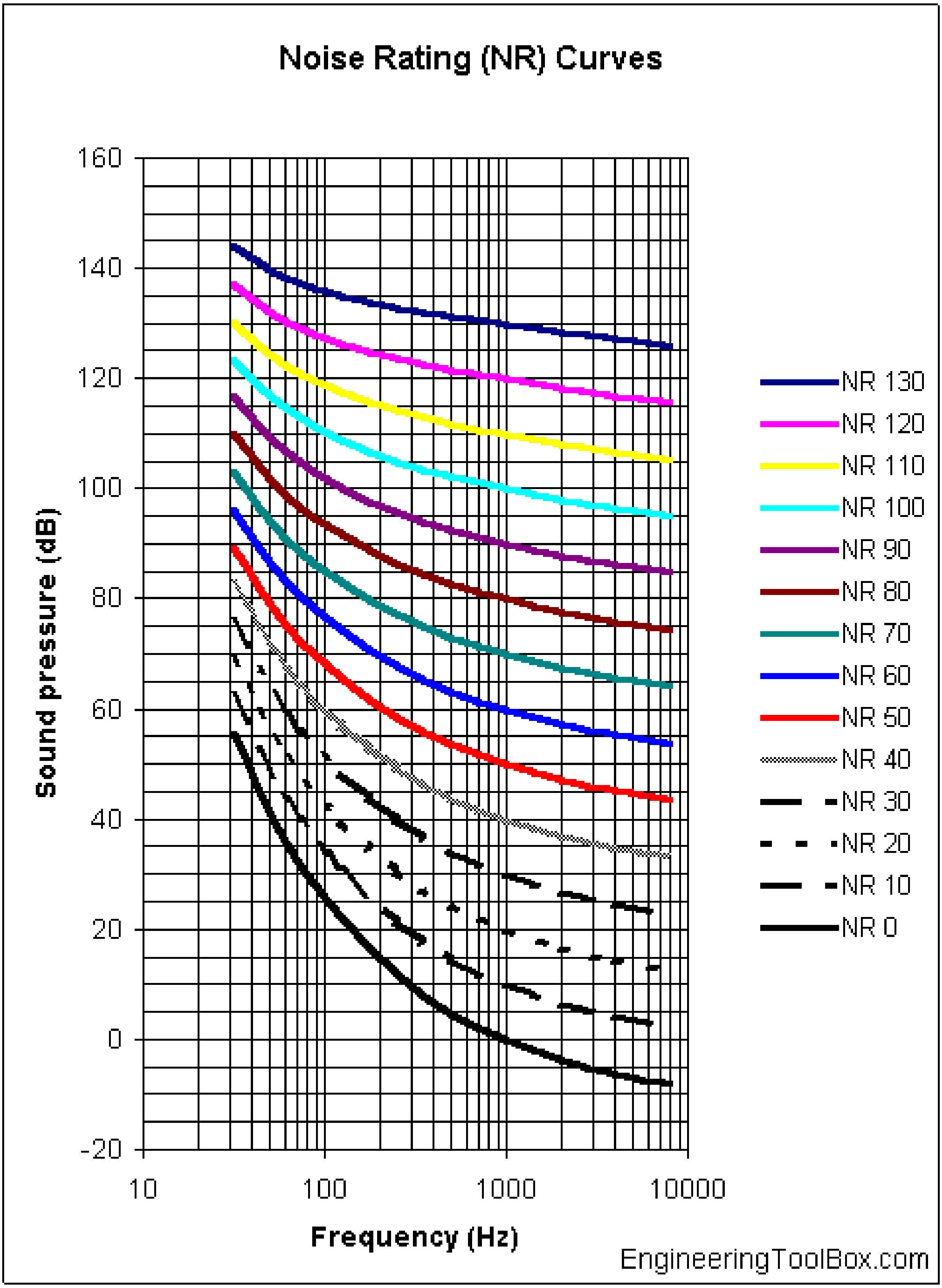


Figure 2.4: Noise Rating (NR) Curves

Key Characteristics of NR Curves

1. **Determination Method**:
   - Measure 1/1-octave band spectrum
   - Identify highest exceeded NR curve value
   - Report as "NR-X" where X is the curve number

2. **Common Applications**:

NR Rating	Suitable Environments
NR-25	Concert halls, recording studios
NR-30	Bedrooms, libraries
NR-40	Offices, classrooms
NR-55	Light industrial spaces

2.5 Equivalent Continuos Noise Levels (Leq)

Time-Varying Noise Assessment

For fluctuating noise exposure, we calculate:

$$L_{eq} = 10 \log \left(\frac{1}{T} \int_0^T 10^{\frac{Lp(t)}{10}} \right)$$

Measurement Protocols

1. **Instrumentation Requirements**:
   - Class 1 sound level meter (IEC 61672)
   - 1/1 or 1/3-octave filters
   - Minimum 15 min sampling for LA_{eq}
2. **Statistical Levels**:

Metric	Definition	Use Case
L₁₀	Level exceeded 10% time	Peak noise
L₅₀	Median level	Background
L₉₀	Level exceeded 90% time	Baseline

Technical Advantages:

- Accounts for both amplitude and duration
- Enables comparison of different noise environments
- Correlates well with health impacts (WHO, 2018)

Important Notes:

- The integration time T must be specified, which can range from a few seconds to several weeks.
- Leqis widely used for traffic noise and is incorporated in international standards for noise assessment between 8 AM and 8 PM.

Statistical Acoustic Levels:

Statistical acoustic levels are also defined based on dB(A)dB(A)dB(A):

- **L10**: The level exceeded for 10% of the time (peak noise levels).
- **L50**: The level exceeded for 50% of the time (average noise levels).
- **L90**: The level exceeded for 90% of the time (background noise levels).

2.6 Conclusion

This chapter has outlined the intricate processes that define the human auditory system, highlighting both its remarkable sensitivity and its limitations. From the biomechanical amplification in the cochlea to the subjective perception of loudness across varying frequencies, each component contributes to a complex yet efficient system for sound detection and interpretation. The integration of psychoacoustic models, such as equal-loudness contours and weighting filters, enables accurate measurement of auditory experience under diverse conditions. Furthermore, standardized tools such as NR curves and equivalent continuous noise levels (Leq) provide objective metrics for assessing and regulating environmental and occupational noise. Together, these frameworks support a deeper understanding of auditory function and its relevance to public health, industrial design, and audio technology.

CHAPTER 3
Room Acoustics

CHAPTER 3: Room Acoustics

3.1. Introduction

Architectural acoustics, a critical discipline within building physics, examines how sound behaves within enclosed environments to ensure optimal listening conditions for speech and music. Unlike sound insulation which focuses on the transmission of sound between spaces architectural acoustics addresses the control of sound *within* a room. The objective is to manipulate acoustic parameters such as reverberation time, sound pressure distribution, and the behavior of reflections to achieve clarity, intelligibility, and pleasantness. This chapter introduces the foundational principles of room acoustics, exploring the propagation of sound in enclosed volumes, the design and application of absorbing materials, and the analytical methods used to evaluate and predict acoustic performance. Mastery of these concepts is essential for designing environments ranging from lecture halls and recording studios to concert venues and worship spaces.

3.2 Sound Propagation in Enclosed Spaces

3.2.1 Sound Reflection Physics

For a sound source *S* with power W in room volume *V*:

Reflection Fundamentals:

- Governed by *acoustic impedance matching*:

$$R = \frac{Z_s \cos\theta_i - Z_1 \cos\theta_t}{Z_s \cos\theta_i + Z_1 \cos\theta_t}$$

Where:

- R: **Reflection coefficient** (ratio of reflected to incident pressure amplitude)
- Z_s: **Surface (or second medium) acoustic impedance**
- Z_1: **Air (or first medium) acoustic impedance**
- θ_i: **Angle of incidence** of the incoming wave
- θ_t: **Angle of transmission/refraction** into the second medium

Geometric Acoustics:

- Valid when $\lambda \ll$ room dimensions (typically >300Hz)
- Follows Snell's Law: $\theta i = \theta r$
- Surface curvature effects:
  - Convex: Diffusion
  - Concave: Focal points

3.2.2 Echo vs. Reverberation

Impulse Response Analysis:

Phenomenon	Time Delay	Perception
Early reflections	<50ms	Spatial enhancement
Echo	>50ms	Distinct repetition
Reverberation	Continuous decay	Room "liveness"

Critical Distance:

rc=0.14QVπT60

Where Q= directivity factor, T60 = reverberation time

3.3 Sound Absorption

Absorption Coefficient (α):

$$\alpha = \frac{W_{\text{abs}}}{W_{\text{inc}}} \quad (3.2)$$

Remarks:

- α is a **dimensionless** quantity, with values ranging between 0 and 1: $0 \leq \alpha < 1$
- If $\alpha = 1$, the material is **perfectly absorbent**.
- If $\alpha = 0$, the material is **perfectly reflective** (or rigid).

Material Classification:

Type	Frequency Range	Mechanism
Porous	500Hz-5kHz	Viscous losses
Panel	50-500Hz	Membrane resonance
Helmholtz	Narrowband	Cavity resonance

3.4 Sound Pressure Level Distribution

Steady-State Level:

The steady-state sound pressure level L_p is related to the **sound power level** L_w by the following equation:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + 4R\right)$$

or alternatively:

$$L_p = L_w + 10\log\left(4\pi r^2 Q + R^4\right)$$

Where:

- L_p: **Sound pressure level** at the receiver position (in dB)
- L_w: **Sound power level** of the source (in dB)
- Q: **Directivity factor** of the source
- r: **Distance** from the source to the receiver
- R: **Room constant**, which accounts for the room's acoustic characteristics
- α: **Average absorption coefficient** of the room surfaces
- $\bar{S}$: **Total surface area** of the room that reflects sound

3.5 Reverberation Time

Sabine Equation: The **Sabine equation** is used to estimate the **reverberation time** T60T_{60}T60, which is the time it takes for the sound to decay by 60 dB in a given room. It relates the **volume of the room** to the **total absorption** of the room surfaces.

$$TR = 0.16\frac{V}{A}$$

Where:

- T60: **Reverberation time** (in seconds)
- V: **Volume of the room** (in cubic meters, m^3)
- A: **Total absorption** in the room (in square meters of absorption, m^2)

3.6 Acoustic Materials

Performance Comparison:

Material	Thickness	NRC	Best For
Fiberglass	50mm	0.95	Mid-high frequencies
Perforated wood	20mm	0.40	Low-mid frequencies
Fabric-wrapped	75mm	0.80	Broadband absorption

3.7 Panel Absorbers:

Resonant Frequency: the resonant frequency fr of a panel (such as a wall or membrane) is determined by its surface density m′ and the air gap d in front of the panel. The equation for the resonant frequency is:

$$f_r = \frac{60m'}{d}$$

or equivalently:

$$f_r = \frac{m'}{d} \cdot 60$$

Where:

- f_r: **Resonant frequency** (in Hz)
- m': **Surface density** of the material (in kg/m²)
- d: **Air gap** in front of the panel (in meters)

Sound Propagation in Enclosed Spaces

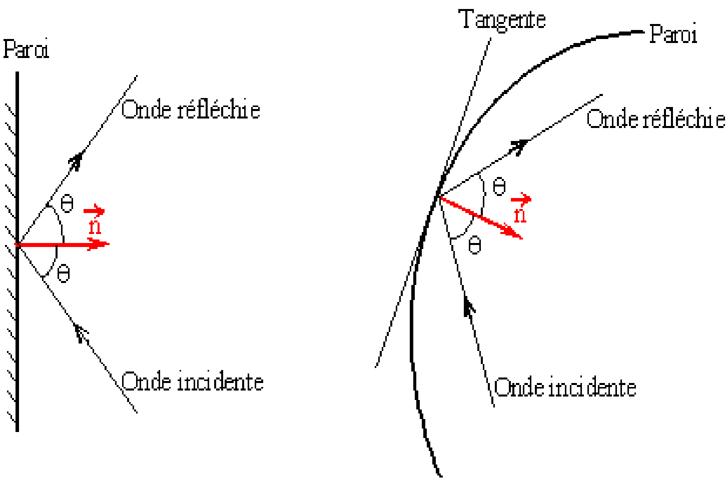


Figure 3.1: Reflection of waves on a wall

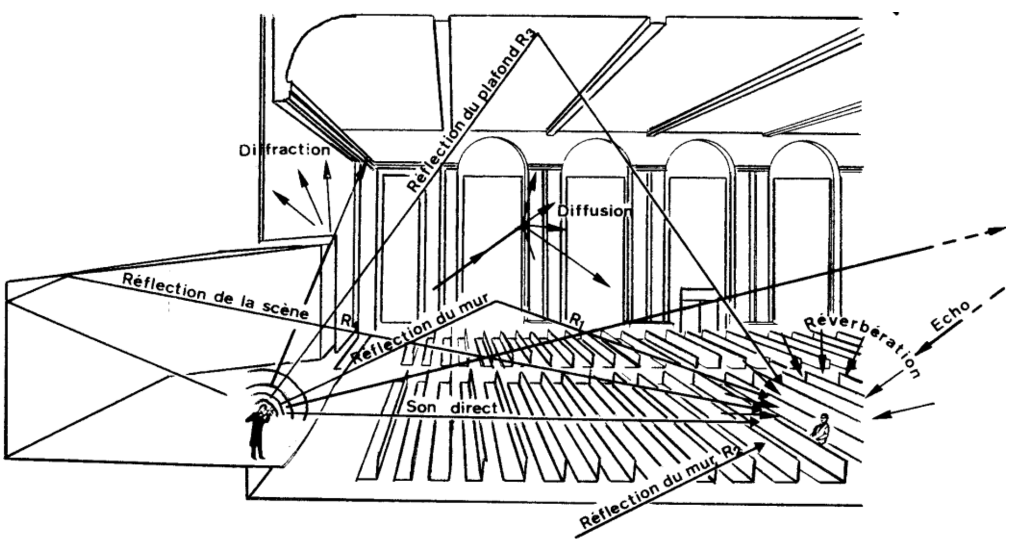


Figure3.2: Sound propagation path in a concert hall and the main physical phenomena occurring

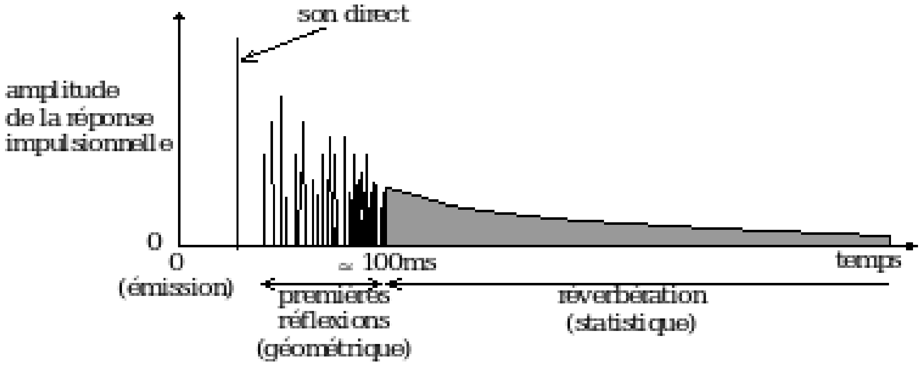


Figure 3.3: Theoretical echogram illustrating the physical phenomena mentioned in Figure 3.2

3.8 Wave Reflection Physics

When spherical waves from source S (acoustic power W) propagate in room volume V:

1. **Direct Sound** arrives first at receiver R:

$$\tau = \frac{d_{SR}}{c_0} \quad (3.1)$$

Where:

- τ: **Time delay** for direct sound to travel from the source to the receiver (in seconds)
- d_{SR}: **Distance** between the source S and the receiver R (in meters)
- c_0: **Speed of sound** in the medium (in meters per second, m/s)

where C_0 = speed of sound (343 m/s at 20°C)

2. **Early Reflections** follow with:
    - Time delay proportional to path length difference
    - Amplitude reduction per reflection:

$$p_{\text{ref}} = p_{\text{inc}} \cdot R \cdot \frac{d_{SR}}{d_{\text{total}}}$$

or equivalently:

$$p_{\text{ref}} = p_{\text{inc}} \cdot R \cdot \frac{d_{\text{total}}}{d_{SR}}$$

Where:

- p_{ref}: **Reflected sound pressure**
- p_{inc}: **Incident sound pressure**
- R: **Reflection coefficient** (dimensionless, based on surface properties)
- d_{SR}: **Distance between the source and the receiver** (in meters)
- d_{total}: **Total path length** of the reflected sound (in meters)

3.8.2 Echo vs. Reverberation

Phenomenon	Time Delay	Amplitude Threshold	Perceptual Effect
Echo	>50ms	>-10dB relative to direct	Distinct repetition
Flutter Echo	30-50ms	Varies	Metallic "pinging"
Reverberation	Continuous	N/A	Room "liveness"

Critical Integration Times:

- Speech: 30ms (Haas effect)
- Music: 50-100ms

3.8.3 Sound Field Characteristics

3.3.1 Reverberant Field

For continuous noise sources, the sound field at *R* comprises:

1. **Direct Field** (unaffected by room):

$$p_{\text{direct}}^2 = \frac{\rho_0 c_0 Q W}{4\pi r^2} \quad (3.5)$$

or equivalently:

$$p_{\text{direct}}^2 = \frac{4\pi r^2 \rho_0 c_0 Q W}{4\pi r^2}$$

Where:

- p_{direct}^2: **Sound pressure squared** in the direct field (related to the intensity of direct sound)
- ρ_0: **Density of air** (in kg/m³)
- c_0: **Speed of sound in air** (in m/s)

2. **Reverberant Field** (diffuse energy):

$$p_{\text{rev}}^2 = \frac{4\rho_0 c_0 W}{A} \quad (3.4)$$

or equivalently:

$$p_{\text{rev}}^2 = \frac{A}{4\rho_0 c_0 W}$$

Where:

- p_{rev}^2: **Sound pressure squared** in the reverberant field (representing the intensity of reverberant sound)
- A: **Total absorption** in the room (in m^2)
- ρ_0: **Density of air** (in kg/m³)
- c_0: **Speed of sound in air** (in m/s)
- W: **Sound power** of the source (in watts)

Directivity Factor Q*Q*:

- Free space: 1 (omnidirectional)
- On floor: 2
- In corner: 8

3.9. Acoustic Absorption

3.9.1 Absorption Mechanisms

1. **Air Absorption** (significant above 1kHz):

$$\alpha_{\text{air}} = e^{-m(T,\text{RH})\cdot d}$$

Where:

- $m(T, \text{RH})$: **Attenuation coefficient** (in dB/m) as a function of **temperature (T)** and **relative humidity (RH)**
- d: **Distance** that sound travels through the air (in meters)

where m = attenuation coefficient (dB/m)

2. **Surface Absorption**:

$$\alpha = \frac{W_{\text{abs}}}{W_{\text{inc}}} \quad (3.2)$$

Where:

- W_{abs}: **Absorbed sound power** (in watts)
- W_{inc}: **Incident sound power** (in watts)

Types of Surface Absorption:

- **Porous Materials**: The absorption coefficient α typically ranges from **0.7 to 0.95** at **mid-high frequencies**.
- **Panel Materials**: The absorption coefficient α typically ranges from **0.2 to 0.6** at **low frequencies**.

Porous: α ≈ 0.7-0.95 (mid-high frequencies)

Panel: α ≈ 0.2-0.6 (low frequencies)

3.9.2 Room Absorption

Total equivalent absorption area:

$$A = \sum_i \alpha_i S_i + 4mV \quad (3.3)$$

Where:

- A: **Total equivalent absorption area** (in square meters, m^2)
- α_i: **Absorption coefficient** for the i-th surface
- S_i: **Surface area** of the i-th surface (in square meters, m^2)
- m: **Attenuation coefficient** for air absorption (in dB/m)
- V: **Volume** of the room (in cubic meters, m^3)

3.10. Pressure Level Distribution

Total SPL: The total sound pressure level Lp is related to the sound power level Lw by the following equation:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + 4R\right)$$

or equivalently:

$$L_p = L_w + 10\log\left(4\pi r^2 Q + R^4\right)$$

Where:

- L_p: **Total sound pressure level** at the receiver (in dB)
- L_w: **Sound power level** of the source (in dB)
- Q: **Directivity factor** of the source (dimensionless)
- r: **Distance** from the source to the receiver (in meters)
- R: **Room constant** (dimensionless)

Critical Distance (where direct = reverberant):

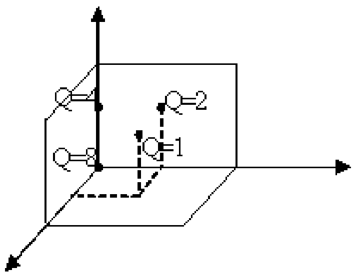


FIGURE 3.4: Directivity factor as a function of the source position, rc=0.14QR

3.11. Mixed Acoustic Field

When the source emits a continuous sound, the field received at point R is the sum of the direct field and the reverberant field. This means that the total sound pressure at R results from both the sound traveling directly from the source and the sound that has reflected off surfaces within the space. The interplay between these two components influences the overall acoustic experience in the environment.

We can now deduce the acoustic pressure level in the room. This level is determined by considering both the direct sound field and the reverberant sound field. The formula integrates these components to provide a comprehensive measure of the acoustic environment, accounting for the contributions of direct sound and reflections from surfaces within the space.

$$
\begin{aligned}
p^2 &= p_{direct}^2 + p_{reverb}^2 \\
&= \frac{\rho_0 c_0 Q W}{4\pi r^2} + \frac{4\rho_0 c_0 W}{A}
\end{aligned}
\tag{3.6}
$$

$$
\frac{p^2}{p_0^2} = \frac{\rho_0 c_0}{p_0^2} W \left(\frac{Q}{4\pi r^2} + \frac{4}{A} \right)
\tag{3.7}
$$

We can now deduce the sound pressure level in the room:

$$
\begin{aligned}
L_p &= 10\log\left(\frac{\rho_0 c_0 W}{p_0^2}\right) + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \\
&= L_W + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right)
\end{aligned}
\tag{3.8}
$$

- We can also express the following:

Reverberant Field Level: This level represents the sound pressure contributed by the reflections within the room. It is calculated based on the reverberation characteristics of the space and can be represented using the relevant acoustic formulas to quantify the total pressure from the reverberant field.

Direct Field Level

- Direct Field Level: This level refers to the sound pressure resulting from the sound waves traveling directly from the source to the receiver. It is calculated based on the distance between the source and the receiver, taking into account the directivity of the source and any attenuation due to environmental factors.

$$
L_{p_{direct}} = L_W + 10\log\left(\frac{Q}{4\pi r^2}\right)
$$

3.12 Reverberation Time

3.12.1 Definition

Consider a source emitting a continuous sound (diffuse field), which is turned off at time t=t0. The reverberation time (RT) is defined as the time required for the acoustic pressure to decrease to 1\1000of its initial value, corresponding to a reduction of 60 dB from the initial pressure level. This energy decay occurs due to absorption by the room's surfaces. Sabine experimentally determined a formula to calculate the reverberation time.

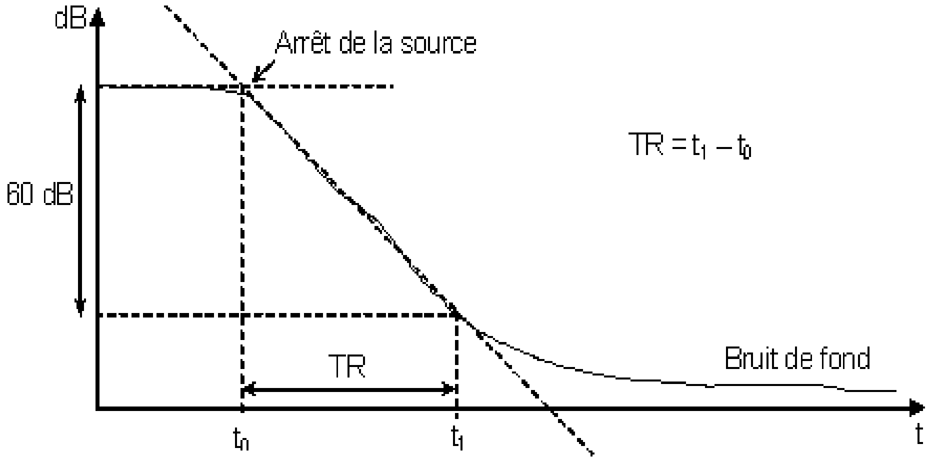


Figure 3.5: reverberation time

1. **Interrupted Noise Method:**
- Generate broadband noise, then abruptly stop
- Record decay curve with analyser
- Calculate slope between -5 dB to -35 dB (RT30) and double

2. **Modern Alternatives:**
- Maximum Length Sequence (MLS) technique
- Sine sweep measurements
- Balloon pops (impulse response)

Typical Reverberation Times:

Space	**RT60 Range**	**Acoustic Character**
Recording Studio	0.2-0.4 s	Ultra-dry, dead
Living Room	0.5-0.8 s	Intimate, clear
Lecture Hall	0.8-1.2 s	Speech-optimized
Concert Hall	1.5-2.5 s	Musical warmth
Cathedral	4-8 s	Grand, majestic

3.3 Predicting Reverberation Time

Design Phase Approaches

1. **Sabine Calculation**:
   - Requires complete α data for all surfaces
   - Accuracy limited by:

        - Non-uniform absorption distribution
        - Edge diffraction effects
        - Air absorption at high frequencies

2. **Scale Models** (1:10 typical):
    - Must scale both dimensions AND frequencies
    - Requires controlled atmosphere (humidity/temperature)
    - Effective for detecting:
        - Flutter echoes
        - Standing waves
        - Focusing effects
3. **Computer Modeling**:
    - **Ray Tracing**: Simulates ~10,000-1M sound paths
    - **Image Source Method**: Accounts for early reflections
    - **BEM/FEM**: Solves wave equation directly (low frequencies)

3.13. Acoustic Absorbers

Material Selection Guide

Porous Absorbers (High Frequency Control):

- Mineral wool (50-120 kg/m^3 density)
- Open-cell foams (30-80 PPI)
- Fabric-wrapped panels
- Performance peaks at:

Panel Absorbers (Low Frequency Control):

- Plywood (3-6 mm) over air cavity
- Resonance frequency:

$$f_r = \frac{60 \cdot m'}{d} \quad [\text{Hz}]$$

or equivalently:

$$f_r = \frac{m'}{d} \cdot 60 \quad [\text{Hz}]$$

Where:

- f_r: **Resonant frequency** (in hertz, Hz)
- m': **Surface mass** of the panel (in kg/m²)
- d: **Depth of the air cavity** behind the panel (in meters)

Hybrid Systems:

- Perforated panel over porous material
- Microperforated absorbers
- Tuned membrane traps

Implementation Considerations:

1. Place porous absorbers at reflection points
2. Distribute panel absorbers evenly for modal control
3. Maintain minimum 10% wall coverage for noticeable effect
4. Combine with diffusers for balanced acoustics

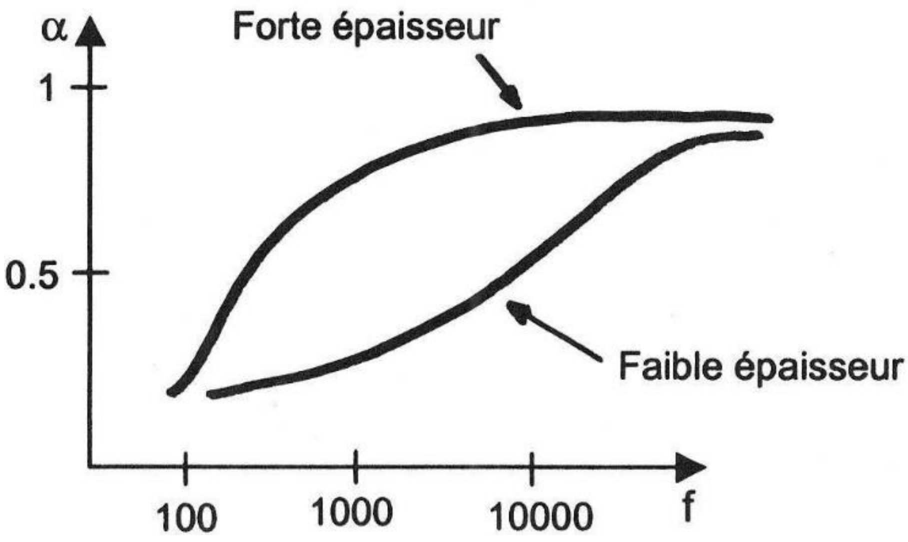


Figure 3.6 – Absorption of porous materials

3.14. Acoustic Resonators

These are acoustic resonators, defined as cavities connected to the external medium by a small opening. When excited by an acoustic wave, they create a "trap" effect for the wave.

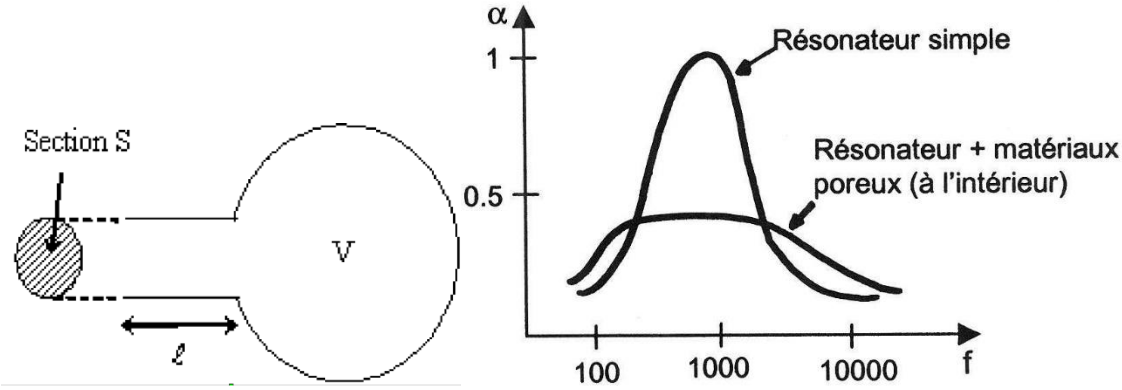


Figure 3.7: simple acoustic resonators of porous materials.

3.2 Diaphragms or Flexible Panels

These are mechanical resonators consisting of panels (or airtight membranes) positioned a few centimeters away from a wall that "traps" air behind them. This setup is equivalent to a mass-spring system, and the resonance frequency is given by:

$$f = \frac{60}{\sqrt{m \cdot d}}$$

Where:

- f: **Resonant frequency** (in Hz)
- m: **Surface mass** of the panel (in kg/m^2)
- d: **Depth of the air cavity** behind the panel (in meters)

This formula illustrates how the dimensions and mass of the panel affect its resonance characteristics.

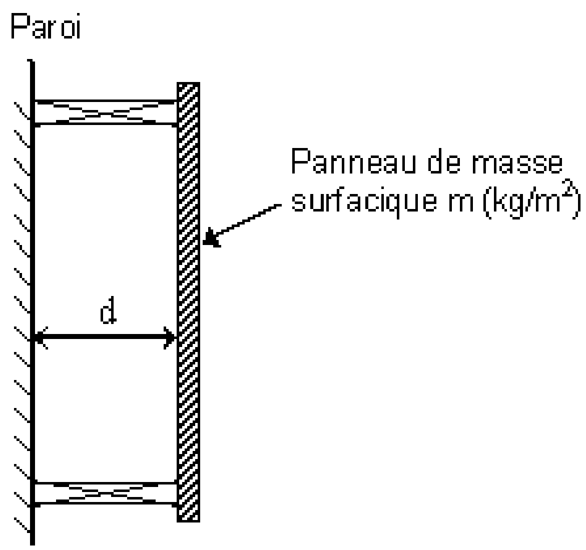


Figure 3.8: Diagram of a flexing panel

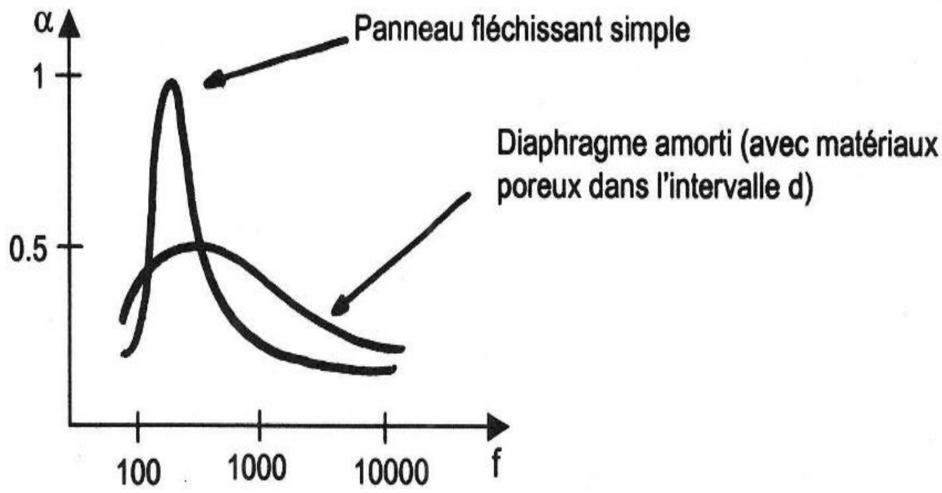


Figure 3.9 – Absorption by flexing panel

3.15. Conclusion

In summary, architectural acoustics is concerned with the control of sound behavior within interior spaces to enhance auditory experiences. Through an understanding of sound propagation, reverberation phenomena, and the implementation of appropriate absorptive and diffusive materials, designers can optimize both speech intelligibility and musical richness. The chapter highlighted the physics of sound reflections, methods for reverberation time prediction, and the selection of materials based on absorption mechanisms. While simplified models such as the Sabine formula offer initial design estimates, advanced modeling techniques and experimental methods provide greater precision for complex spaces. Ultimately, successful acoustic design balances scientific principles with practical considerations to create functional and acoustically pleasant environments.

CHAPTER 4
Acoustic Isolation

CHAPTER 4: Acoustic Isolation

4.1 Introduction

Acoustic isolation is a fundamental aspect of building acoustics, aimed at minimizing the transmission of sound between adjacent spaces. Unlike absorption, which deals with reducing sound energy within a single room, isolation focuses on preventing sound from traveling from one room to another. This distinction is crucial in designing environments where privacy and noise control are paramount, such as residential buildings, offices, and recording studios.

Effective acoustic isolation requires an understanding of various sound transmission mechanisms, including airborne and structure-borne pathways. Airborne sound travels through the air and can penetrate walls, floors, and ceilings, while structure-borne sound is transmitted through the building's structural elements. To address these challenges, engineers and architects employ a range of strategies, including the use of mass-loaded materials, resilient connections, and specialized construction techniques.

This chapter delves into the principles of sound transmission through different wall assemblies, the quantification of acoustic isolation, and the methods to enhance it. By exploring both theoretical concepts and practical applications, readers will gain a comprehensive understanding of how to achieve optimal acoustic isolation in various building scenarios.

Unlike the previous chapter, the source S and the receiver R are not in the same room. It is important to distinguish between the concepts of absorption and isolation:

- **Absorption**: Reduction of acoustic intensity within the same room.
- **Isolation**: Reduction of acoustic intensity between two different rooms.

4.2 Generalities

4.2.1 Main Types of Propagation

In building acoustics, two types of noise are distinguished:

1. **External Noise**: Airborne propagation (e.g., traffic noise).
2. **Internal Noise**: Both airborne and structure-borne propagation (e.g., footstep noise).

4.2.2 Main Types of Transmission

- **Direct Transmission**: Sound traveling directly from the source to the receiver without reflections or modifications.

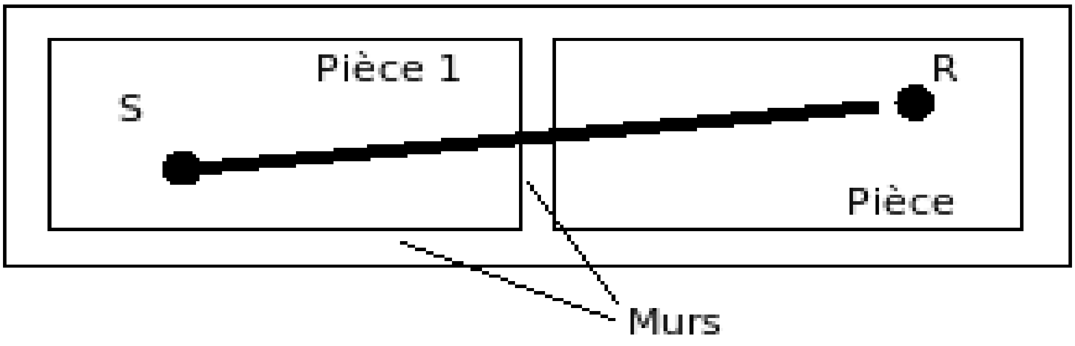


FIGURE 4.1 : direct Transmission

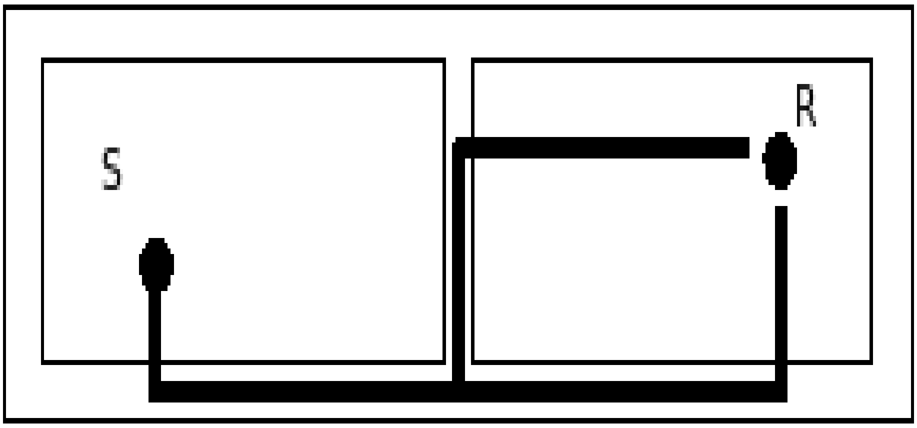


FIGURE 4.2 : Transmission indirecte

Vibration of the Common Wall: Sound Transmission Through Multiple Walls

The goal of acoustic isolation is to minimize sound transmission as much as possible. This can be achieved by addressing structure-borne transmission (flanking transmission) or by reducing the transmission coefficient of the wall.

4.3 Definitions

4.3.1 Airborne Noise and Structure-Borne Noise

- **Airborne Noise**: Sound produced in the air and propagating through the air, traveling at approximately 340 m/s. At low frequencies, this noise can convert into structure-borne noise when interacting with lightweight materials.
- **Structure-Borne Noise**: Sound generated by contact with a structure and propagating through that structure, traveling much faster. The vibration of a room's walls caused by structure-borne noise can generate additional airborne noise.

4.3.2 Normalized Acoustic Isolation in dB(A)

To quantify the degree of isolation, it is practical to express it as a single value in dB(A), similar to acoustic pressure levels. This requires defining reference spectra for valid comparisons. Two types of noise have been established for this purpose: pink noise and road noise.

- **Pink Noise**: Commonly used indoors, it has a consistent sound pressure level across each octave band, typically set at 80 dB for each band.
- **Road Noise**: Simulates sounds emitted by traffic, often used to evaluate products designed to protect rooms from external noise.

TABLE 4.1 : Niveaux de pression du bruit routier

Fréquence (Hz)	125	250	500	1000	2000	4000
L_p (dB)	87	86	82	81	79	73

4.3.3 Gross Acoustic Isolation Between Two Rooms: dB

Consider two adjacent rooms: an emission room labeled 1 and a reception room labeled 2. We aim to evaluate the sound transmission through the wall separating these two rooms.

In room 1, we assume that the sound field is diffuse (having the same sound pressure level regardless of position and frequency), with a sound pressure level of L1.

- In room 2, we measure the sound pressure level L2.

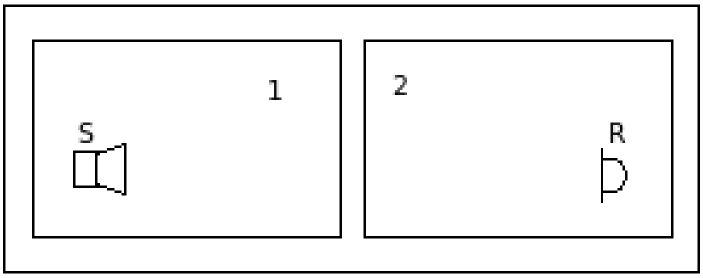


Figure 4.3 : sound level in two room

The gross acoustic isolation Db is defined as the difference between the sound pressure levels in the emission room and the reception room:

Db= L1 −L2

where:

- L1 is the sound pressure level in the emission room,
- L2 is the sound pressure level in the reception room.

This measurement quantifies the wall's effectiveness in isolating sound between the two spaces.

$D_b = L_1 - L_2$ en dB (4.1)

L1 and L2 are the root mean square sound pressure levels in the two rooms. Regarding the attenuation index Db :

- It is expressed in octave bands (or 1/3 octave bands).
- It depends on the characteristics of both rooms and is therefore not strictly representative of the wall (the absorption properties of both rooms).
- It does not depend on the emission sound pressure level but varies with the shape of the emitted noise spectrum.

4.3.4 Normalized Acoustic Isolation Dn

We consider the same configuration as before. We aim to eliminate the influence of the absorption properties of the rooms by referencing the case of normally furnished rooms (which is not applicable in a laboratory setting). The normalized acoustic isolation DnD_nDn is defined by:

$$Dn = L1 - L2 + 10\log(2T_2) = Db + 10\log(2T_2) \quad (4.2)$$

where T_2 is the reverberation time (RT) in room 2. The reverberation time TRT_RTR is the time required for the sound level to decrease by 60 dB when the acoustic source is turned off. This implies a normalized RT of 0.5 s (when TR=0.5T_R = 0.5TR=0.5 s, Db=DnD_b = D_nDb=Dn).

Another definition of D_n involves the equivalent absorption area:

$$Dn = L1 - L2 + 10\log 10 = Db + 10\log 10 \qquad (4.3)$$

where A_2 is the equivalent absorption area in room 2 (the equivalent absorption area will be studied in the next chapter). Here, we impose a normalized absorption area A_0 = 10 A0=10m^2.

Remarks:

- D_n is more relevant in octave bands, as the RT and A_2 depend on frequency.
- D_n and Db account for all transmission paths (direct and indirect).

4.3.5 Acoustic Attenuation Index R

In this case, we only consider direct transmission, specifically the noise absorbed and then radiated by the separating wall. The acoustic attenuation index is defined by:

$$R = 10\log\left(\frac{1}{\tau}\right) \text{ et } \tau = \frac{W_2}{W_1}$$

where:

- τ is defined as the transmission factor,
- W1is the power emitted in room 1.

where W2 is the power radiated in room 2.

Remarks:

- τ is independent of the direction of transmission.
- R can be expressed either in octave bands or as an overall value. Its value varies with frequency and depends on the characteristics of the wall (its surface mass, bending stiffness, and damping).
- If there is no indirect transmission:

Db = R + 10 log A2 where S is the surface area of the separating wall.

4.3.6 Comparison Between R and Dn

The difference between R and Dn depends on the type of transmission considered (either only direct or both direct and indirect) between the two rooms.

$$D_n = R + 10\log\left(\frac{V_2}{S}\right) + 10\log\left(\frac{0.16}{T_0}\right) - a \text{ et } a = 5 + \frac{S_r}{10} - N$$

with:

- V2: volume of the reception room,
- S: surface area of the separating wall common to both rooms,
- Sr: surface area of lightweight and rigid masonry partitions + thermal linings,
- N: number of partitions with mineral wool lining and facing.

4.3.7 Normalized Impact Noise Level

The test is conducted using a standardized impact machine (5 metallic hammers striking the floor periodically). The sound pressure level L2 is measured in room 2 (where the reverberation time is T2). The relationship is given by:

$$Ln = L2 - 10\,log\,(2T_2) \tag{4.7}$$

And;

$$L_n = L_2 - 10\log\left(\frac{10}{A_2}\right)$$

4.4 Sound Transmission Through a Simple Wall

4.4.1 Mass Law

The radiated sound level is lower when the wall is heavier. The experimental mass law for the overall level in dB(A) is expressed as:

where:

- L is the sound level,
- L0 is a reference level,
- m is the surface mass of the wall,
- C is a constant that depends on frequency and other factors.

R = 40 log (m) − 46 dB(A) si m > 150 kg.m^{-3}

R = 17 log (m) − 4 dB(A) si m < 150 kg.m^{-3} (4.9)

4.4.2 Frequency Law

The radiated sound level is lower at higher frequencies.

$$R0 = 10\,log\,(ms\,f\,) - 43\,dB \quad (4.10)$$

where:

- ms is the surface mass of the wall,
- f is the frequency of the incident wave.

Doubling f increases the isolation by 6 dB; similarly, doubling ms is also increases the isolation by 6 dB. Therefore, a simple wall provides better isolation for high frequencies than for low frequencies.

4.5 Sound Transmission Through Double Walls

Equivalent System to a Mass-Spring-Mass System

If m1 and m2are the surface masses of the walls, for good isolation (large R), the resonance frequency of this system is given by:

$$f_r = \frac{60}{\sqrt{m_1 m_2}}$$

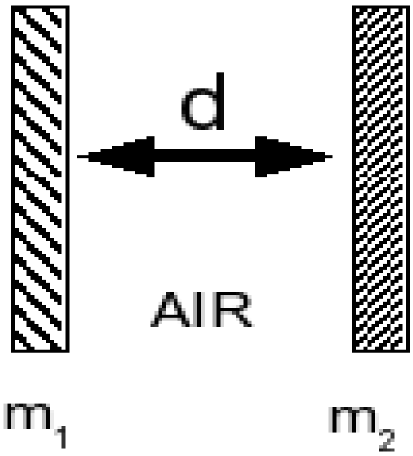


Figure 4.4: Diagram of a double wall

Remark

By comparing the R of a double wall with that of a simple wall made from one of the materials in the double wall, we can achieve very good isolation with relatively low masses. However, the resonance frequency of the system must be very low, potentially in the inaudible range.

4.6. Acoustic Attenuation Index of a Heterogeneous Wall

A heterogeneous wall is composed of multiple simple elements (doors, partitions, windows, etc.). We aim to calculate the equivalent attenuation index R based on the characteristics of each element.

Definition: The transmission factor of a heterogeneous wall, normalized to its total surface area S, is equal to the sum of the transmission factors of each of the n elements, weighted by their respective surface areas:

$$\tau_{\text{total}} = \sum_{i=1}^{n} \tau_i \cdot \frac{S_i}{S}$$

Where:

- τ_total is the total transmission factor,
- τi is the transmission factor of each element,
- Si is the surface area of each element,
- S is the total surface area of the wall.

$$\tau S_{tot} = \sum_{i=1}^{n} \tau_i S_i \text{ d'où } \tau = \frac{\sum_{i=1}^{n} \tau_i S_i}{S_{tot}}$$

Example: Case of a Partition and a Door

Let's consider a partition and a door within a heterogeneous wall. The equivalent transmission factor can be expressed as:

$$\tau_{\text{total}} = \tau_{\text{partition}} \cdot \frac{S_{\text{partition}}}{S} + \tau_{\text{door}} \cdot \frac{S_{\text{door}}}{S}$$

Where:

- τ_partition is the transmission factor of the partition,
- Spartition is the surface area of the partition,
- τdoor is the transmission factor of the door,
- Sdoor is the surface area of the door,
- S is the total surface area of the wall (partition + door).

This equation allows us to calculate the overall transmission factor for the heterogeneous wall, taking into account the contribution of each element based on its surface area.

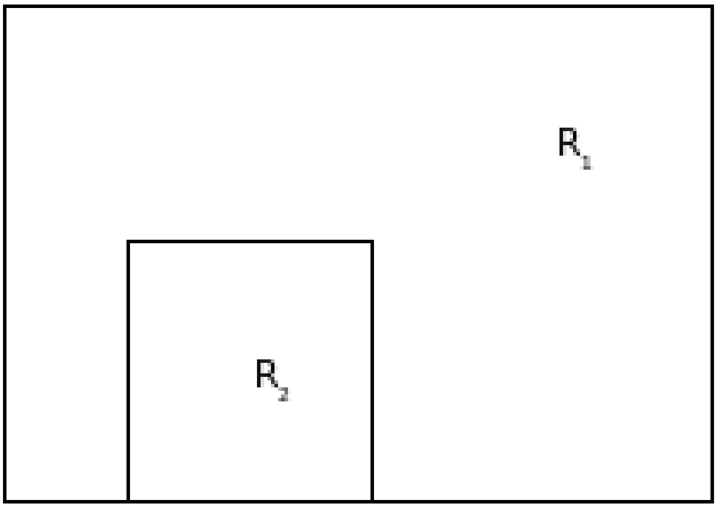


Figure 4.5 : Diagram of the problem

If R1 and R2 are the attenuation indices of walls 1 and 2, then:

$$R = 10 \log \left(\frac{S_{tot}}{S_1 10^{-\frac{R_1}{10}} + S_2 10^{-\frac{R_2}{10}}} \right)$$

4.7. Conclusion

Acoustic isolation is a cornerstone of building acoustics, essential for ensuring comfort, privacy, and regulatory compliance in both residential and commercial environments. This chapter has provided a detailed overview of the mechanisms of sound transmission both airborne and structure borne and the key metrics used to quantify and evaluate acoustic isolation, such as gross isolation (Db), normalized isolation (Dn), and the acoustic attenuation index (R).

The physical principles governing sound transmission through walls, including the mass law and frequency dependence, emphasize the importance of material properties and construction techniques. Double-wall assemblies and heterogeneous structures were also discussed, showing how layered or composite solutions can enhance performance by leveraging mass-spring-damping effects and strategic design.

In practice, achieving effective acoustic isolation requires a careful balance between architectural constraints, material choice, and acoustic performance. The knowledge presented in this chapter serves as a foundation for more advanced design strategies, enabling engineers and architects to create environments that effectively mitigate unwanted noise transmission and promote acoustic well-being.

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