1 # CHAPTER 8

SOUND TRANSMISSION

2 ## Preamble

- Sound fades away over distance
- Sound fades away over time
- Sound waves encounter obstacles

3 ## ATTENUATION OF SOUND INTENSITY OVER DISTANCE

- When sound is propagated in a free, unbounded medium (a medium with no obstacles to affect wave propagation), intensity decreases in a lawful way
- This is called the inverse square law
- Imagine sound produced by a point source in a free, unbounded medium
  - ♦ A longitudinal wave is propagated through the medium

4 ## Spherical Waves

- Compressions form a “spherical shell,” which is called a wave front
  - ♦ Wave front moves outward from source to A, B, C, etc.
  - ♦ How does wave front at C differ from wave fronts at B and A? Beyond C?
    - ☑ Spherical wave front becomes progressively larger from A, to B, to C, etc.

5 ## Plane Waves

- At some distance from source the spherical wave front becomes a plane wave front: Why?
  - ☑ Radius of sphere is large enough that curvature is negligible

6 ## Plane Waves

- Sine waves are spherical, or plane progressive, waves in a free, unbounded medium
  - ♦ Imagine a soap bubble becoming progressively larger; surface of bubble represents a wave front

7 ## THE INVERSE SQUARE LAW

- From A to B to C, energy is dissipated over a larger & larger surface area
- Power is energy / s
  - ♦ Therefore, same amount of power is dissipated over larger and larger surface areas.

8 ## THE INVERSE SQUARE LAW

- Intensity is energy / s / m^2
- If power remains constant, but surface area increases, what happens to intensity?
  - ☑ It must decrease
- Analogous to a constant force being exerted on a larger & larger area
  - ♦ Pressure (F / A) decreases

9 ## Intensity

- Place eye at point source and look outward at areas bounded by four lines of propagation
  - ♦ Intensity at 2X is 1 / 4 that at X

- At 4X it is 1 / 4 that at 2X
- and so on

- Intensity decreases lawfully -- the <u>inverse square law</u>. Why?
  - Intensity varies <u>inversely</u> with the <u>square</u> of the distance

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Intensity

- Area of sphere
  - $A = 4\pi r^2$
- Thus,
  - At 1m, $A = 12.6\ m^2$ $(4\pi 1^2)$
  - At 2m, $A = 50.3\ m^2$ $(4\pi 2^2)$
  - At 4m, $A = 201.1\ m^2 (4\pi 4^2)$

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Intensity

- Moreover,
  - At 2m, $50.3 = 12.6^2$
  - At 4m, $201.1 = 50.3^2$
- Finally, if A increases, energy / s / m^2 must decrease
  - Between 1m and 2m, A increases by 4:1
  - ∴ I must decrease--1:4

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THE INVERSE SQUARE LAW

- $I \propto 1 / D^2$, where
  - $D = d_i / d_r$
    - >> d_i is distance of interest, &
    - >> d_r is reference distance
- Therefore:
  - $I \propto 1 / (d_i / d_r)^2$
- Thus, intensity is <u>inversely</u> proportional to the <u>square</u> of the ratio of two distances, d_i and d_r

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The Inverse Square Law and Decibels

- How could we express the decrease in decibels?
- dB $= 10 \log_{10} 1 / (d_i / d_r)^2$
  - $= - 10 \log_{10} (d_i / d_r)^2$ Why?
    - ☑ Log Law 4
  - $= - 20 \log_{10} (d_i / d_r)$ Why?
    - ☑ Log Law 3

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The Inverse Square Law and Decibels

- Compare intensity at 2X with X: How many dB?
  - ☑ dB $= - 20 \log_{10} (2 / 1) = - 6$ dB
- Compare intensity at 4X with 2X: How many dB?
  - ☑ dB $= - 20 \log_{10} (4 / 2) = - 6$ dB

- Compare intensity at 4X with X: How many dB?
  - ☑ dB = - 20 $\log_{10}$ (4 / 1) = - 12 dB

15 ❑ **Sample Problems**

1. SPL = 90 dB at distance of 100 m from source. By how much is SPL <u>decreased</u> at 200 m?
   - ☑ dB = - 20 $\log_{10}$ (200 / 100) = - 6 dB
2. What is <u>SPL</u> at 200 m?
   - ☑ dB = 90 - 20 $\log_{10}$ (200 / 100) = 84

16 ❑ **Sample Problems**

3. SPL = 100 dB at 100 m from source. By how much is SPL decreased at 200 m?
   - ☑ dB = - 20 $\log_{10}$ (200 / 100) = - 6 dB
4. SPL = 80 dB at 100 m. What is <u>SPL</u> at 750 m?
   - ☑ SPL = 80 - 20 $\log_{10}$ (750 / 100)
   - ☑ = 62.5 dB SPL

17 ❑ **Sample Problems**

5. SPL of gunshot is 110 dB at 0.5 miles. Should shot be heard at 8,192 miles if threshold for hearing is 20 dB SPL?
   - ☑ dB = 110 - 20 $\log_{10}$ (8,192 / 0.5)
   - ☑ = 110 - 84.2
   - ☑ = 25.8 dB SPL
   - ☑ Yes! (In a free, unbounded medium)

18 ❑ **THE INVERSE SQUARE LAW**

- Inverse square law only holds strictly in free, unbounded medium with no obstacles
- If sound wave encounters obstacle, it will be:
  - ♦ reflected,
  - ♦ refracted,
  - ♦ diffracted, or
  - ♦ absorbed
- Will inverse square law then hold strictly?
  - ☑ No

19 ❑ **THE INVERSE SQUARE LAW**

- In what ways will it differ for reflection and absorption?
  - ☑ If reflection, energy retained in medium and there is less attenuation than law would predict
  - ☑ If absorption, attenuation will be greater than law would predict

20 ❑ **REFLECTION**

- Animation F8-3

- Angle of reflected path to the perpendicular equals angle of the incident path to the perpendicular

21 Reflection of Sound Waves

- Animation F8-4
- Spherical wave fronts generated by point source at s move from right to left -- encounter plane obstacle
- Obstacle offers large acoustic impedance
- A ray is a line perpendicular to the wave front

22 Reflection of Sound Waves

- With no obstacle, wave fronts would continue on toward s'
- Because of obstacle, sound wave is reflected back toward source with no change in speed of propagation
- Angles of the reflected rays to the perpendicular equal angles of incident rays to the perpendicular

23 Reflection of Sound Waves

- Energy is retained in medium and inverse square law does not hold
- Is the decrease in intensity < or > the law would predict?
  - ☑ Less than: energy is retained in medium

24 Reflection From Plane Surfaces

- Angles of reflected rays equal angles of incident rays to perpendicular
  - ♦ 45º in panel A
  - ♦ 30º in panel B
- Under what circumstance will a ray be reflected back on itself toward source?
  - ☑ 0º in panel C

25 Reflection From Convex Surfaces

- Animation F8-6
- Panel A: Obstacle surface is convex toward source of sound
  - ♦ Two incident rays are shown, i_1, i_2
- Reflected rays diverge; sound energy is scattered
- Intensity of reflected wave?
  - ☑ Less than I of incident wave at equal distance
- Example?
  - ☑ Exterior surface of domed roof

26 Reflection From Concave Surfaces

- Panel B: Obstacle surface is concave toward source of sound
  - ♦ Four incident rays are shown
- Reflected waves converge; sound energy is “collected” or concentrated
- Rays converge at focal point; energy density (intensity) is maximal
- Intensity of reflected wave?
  - ☑ Greatest at focal point
- Example?
  - ☑ Whispering galleries: interior surface of domed ceiling

27 Sound Wave Reflection (Summary)

- Regardless of whether the obstacle surface is plane, convex, or concave
- The angles of reflected rays to the perpendicular equal the angles of incident rays to the perpendicular

28 ## Echoes, Reverberation, and Reverberation Time

- Reflected waves often are called echoes or reverberating waves
  - ♦ Contrast reverberant rooms with anechoic rooms
    - >> Reverberant: rooms with hard surfaces to maximize reflections
    - >> Anechoic: rooms with absorbing surfaces to minimize reflections

29 ## Echoes, Reverberation, and Reverberation Time

- Reverberation Time
  - ♦ Time required for sound energy to decay by 60 dB (T_{60})
  - ♦ Volcanic explosion in Krakatoa in East Indies (1883) -- from barometric records speed of sound estimated at 320 m/s

30 ## Standing Waves

- Occur when two progressive waves, incident and reflected, of same frequency & amplitude, travel in opposite directions in or along medium
- Consider standing waves for transverse waves separate from those for longitudinal waves
- Will conclude by relating standing waves to resonant frequencies of strings and tubes

31 ## Transverse Wave Motion and Standing Waves

- Animation F8-7
- Panel A: String stretched with some fixed tension; dots painted at equal intervals
- Panel B: Source of sound causes one sound wave (dashed) to travel from left to right
- A second source causes a second wave (solid) to travel from right to left

32 ## Transverse Wave Motion and Standing Waves

- Points b, d, f, h, & j move alternately up and down: called displacement <u>antinodes</u> -- points of maximum vibration
- Points a, c, e, g, i, & k remain stationary: called displacement <u>nodes</u> -- points of no vibration

33 ## Transverse Wave Motion and Standing Waves

- <u>Loops</u> are formed between adjacent nodes
- Panel C: one cycle of each transverse wave:
  - ♦ Two <u>loops</u> are formed
- Distance between two nodes, or between two antinodes, <u>corresponds to one-half wavelength</u>

34 ## Transverse Wave Motion and Standing Waves

- Each wave is moving -- one from left to right, the other from right to left -- but the resultant wave is stationary
  - ♦ A standing wave

35 ## Longitudinal Wave Motion and Standing Waves

- Panel A: Air-filled tube open at one end and closed at the other end
  - ♦ Incident waves travel from L-R; will be reflected by closed end

- ♦ Reflected waves travel from R-L
- ♦ Two waves will interact along length of tube

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Longitudinal Wave Motion and Standing Waves

- Panel B: Incident & reflected waves are <u>in phase</u>: What happens?
  - ☑ Reinforcement, or constructive interference
- Panel C: Incident & reflected waves are <u>out of phase</u>: What happens?
  - ☑ Cancellation, or destructive interference

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Longitudinal Wave Motion and Standing Waves

- The two waves are moving <u>in</u> and <u>out</u> of phase over time
  - ♦ Each wave is traveling, but
  - ♦ Resultant wave is <u>stationary</u>
- At certain locations, dependent on L and f, they are always <u>in phase</u> -- at others, they are always <u>out of phase</u>

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Longitudinal Wave Motion and Standing Waves

- Interaction of incident and reflected waves
  - ♦ Dotted Line: Incident R-L
  - ♦ Dashed Line: Reflected L-R
  - ♦ Blue line: Resultant
- Resultant is point-by-point summation of i and r

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Longitudinal Wave Motion and Standing Waves

- Suppose f = 125 Hz; T = ?
  - ☑ T = 8 ms
- Each panel = 1 ms interval, or 1 / 8 of a period

40

Longitudinal Wave Motion and Standing Waves

- Solid vertical lines positioned on <u>antinodes</u>
  - ♦ A: partially in phase -- partial reinforcement
  - ♦ B: in phase -- maximal reinforcement
  - ♦ C: same as A
  - ♦ D: 180^o out of phase -- cancellation
  - ♦ E: same as C, but opposite
  - ♦ F: same as B, but opposite

41

Longitudinal Wave Motion and Standing Waves

- Dashed vertical lines positioned on <u>nodes</u>
- What happens at nodal point over time from A to F?
  - ☑ nothing
  - ☑ resultant wave remains on time axis

42

Standing Waves and Resonant Frequencies

- Tube open at one end; closed at other
- Panel A: Displacement pattern of air mass from 0^o (equilibrium), to 90^o (x_{max}), to 180^o, to 270^o, & to 0^o: <u>one cycle</u>
  - ♦ Two dashed lines trace maximum displacement (x_{max} envelope) patterns at 90^o & 270^o along length of tube

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Standing Waves and Resonant Frequencies

- Panel B: Displacement envelope from panel A

- Displacement <u>node</u>: Closed end
- Displacement <u>antinode</u>: Open end

- Panel C: Comparison of displacement and pressure nodes & antinodes
  - Pressure <u>node</u>: Open end
  - Pressure <u>antinode</u>: Closed end

44 **Standing Waves and Resonant Frequencies**

- Panel B: Displacement envelope
  - One node, one antinode, & 1/2 of one loop
  - Thus, standing wave created with λ = 1/4 length (L) of tube
    - >> λ = s / f
    - >> f = s / λ

45 **Standing Waves and Resonant Frequencies**

- For open-closed tube
  - >> F_1 = 1s / 4L (F_1 is first, or lowest, of series of resonances)
  - >> other resonances will be <u>odd</u> integer multiples of F_1

46 **Standing Waves and Resonant Frequencies**

- Panel A: Lowest resonant frequency-- F_1 = 1s / 4L
- Panel B: F_2
  - 2 nodes, 2 antinodes, and 1 1/2 loops
    - >> 1 loop = 1/4λ
    - >> 1 1/2 loops = 3/4λ
  - F_2 = 3s / 4L

47 **Standing Waves and Resonant Frequencies**

- Panel C: F_3
  - 3 nodes, 3 antinodes, and 2 1/2 loops
    - >> 1 loop = 1/4λ
    - >> 2 1/2 loops = 5/4λ
  - F_3 = ?
    - ☑ F_3 = 5s / 4L

48 **Sample Computations**

- L = .17 m; s = 340 m / s
- F_1 = ?
  - ☑ F_1 = 340 / (4 $\times$ .17) = 500 Hz
- F_2 = ?
  - ☑ F_2 = (3 $\times$ 340) / (4 $\times$ .17) = 1500 Hz
- F_3 = ?
  - ☑ F_3 = (5 $\times$ 340) / (4 $\times$ .17) = 2500 Hz
- Higher resonances are <u>odd</u> integer multiples of F_1
  - F_2 = 3 F_1
  - F_3 = 5 F_1

49 **Standing Waves and**

Resonant Frequencies

- What happens to F_1, F_2, and F_3 if L is shortened?
  - ☑ $F_n \propto 1/L$
  - ☑ They increase
- Equation 8.9
  - ♦ $F_n = [(2n) - 1]s / 4L$, where
  - ♦ $n = n^{th}$ resonance

50
Standing Waves and Resonant Frequencies

- Why not odd <u>and</u> even integer multiples of F_1?
  - ♦ Displacement node <u>must</u> be at closed end
  - ♦ Displacement antinode <u>must</u> be at open end
- Proof
  - ♦ If F_1 corresponds to 1/4 λ and 1/2 loop
  - ♦ $2F_1$ corresponds to 1/2 λ and 1 loop
  - ♦ To fit 1 loop into tube requires either
    - >> 2 antinodes and 1 node, or
    - >> 1 antinode and 2 nodes
  - ♦ neither is possible

51
Standing Waves and Resonant Frequencies

- Panel A: Tube open at both ends
  - ♦ Displacement antinodes at open ends
  - ♦ Displacement node in middle
- Panel B: Tube closed at both ends
  - ♦ Displacement nodes at both ends
  - ♦ Displacement antinode in middle

52
Standing Waves and Resonant Frequencies

- Panels A <u>and</u> B
  - ♦ 1 loop; 1/2 λ
  - ♦ $F_1 = 1s / 2L$
  - ♦ $F_n = ns / 2L$
  - ♦ Higher resonances are <u>odd and even</u> integer multiples of F_1

53
Sample Computations

- $L = .17$ m; $s = 340$ m / s
- $F_1 = ?$
  - ☑ $F_1 = 1s / 2L = 1000$ Hz
- $F_2 = ?$
  - ☑ $F_2 = 2s / 2L = 2000$ Hz
- $F_3 = ?$
  - ☑ $F_3 = 3s / 2L = 3000$ Hz
- Higher resonances are <u>odd and even</u> integer multiples of F_1

54 ## Vibration of Strings

- **Equation 2.10 from Chapter 2**
  - **$f = 1/2L(\sqrt{t/m})$**
- **That solves for <u>lowest</u> of a series of frequencies, f_0**
- **String also vibrates at harmonics of f_0**
- **Harmonics are <u>odd and even</u> integer multiples of f_0**
- **String is fixed at both ends**
  - **Analogous to tube closed at both ends**
  - **Displacement node at each end**
  - **Displacement antinode midway**

55 ## Vibration of Strings

- **Panel A: Stretched string attached to two pegs**
- **Panel B: Displacement pattern over time**
  - **1 loop; 1/2 λ**
  - **$f_0 = 1s/2L$, where**
    - **>> s = speed of sound (s = $\sqrt{t/m}$)**
    - **>> L = length**

56 ## Vibration of Strings

- **Panels C, D, & E**
  - **2 loops; 3 loops; & 4 loops**
  - **1λ; 1 1/2 λ; 2λ**
- **$f_n = ns/2L$, where n (coefficients) are integers**
- **Higher harmonics are <u>odd</u> and <u>even</u> integer multiples (harmonics) of f_0**

57 ## Sample Computations

- **s = 420 m/s; L = .93 m**
- **What is f_0?**
  - ☑ **$f_0 = s/2L = 420 / (2 \times .93) = 225$ Hz**
- **What are fs of next three harmonics?**
  - ☑ **$2 f_0 = 450$ Hz**
  - ☑ **$3 f_0 = 675$ Hz**
  - ☑ **$4 f_0 = 900$ Hz**
- **Harmonics are <u>odd</u> and <u>even</u> integer multiples of f_0**

58 ## REFRACTION

- **Recall: When a wave encounters an obstacle offering large impedance, the wave is reflected with <u>no change in speed of propagation</u>**
- **Now consider the case in which a wave moves to another medium, or encounters a change in the medium**
- **Speed of propagation changes and rays are bent**

59 ## REFRACTION

- **Light waves travel from air (M_1) to water (M_2)**
- **$s_{M_1} > s_{M_2}$**

- Image of stick is bent because of change in speed (s) of propagation: Snell's Law
- Refraction of sound waves: Bending of wave fronts due to change in speed of propagation

60 ## Sound Traveling With and Against Wind

- Animation F8-15
- Panel A: Sound travels L to R: No wind
  - Wave fronts are not bent
- Panel B: Wind speed shown as a vector quantity
  - What is shown?
    - ☑ Wind speed increases with increasing height above ground

61 ## Sound Traveling With and Against Wind

- Panel C: Sound travels <u>against</u> wind
  - What happens to wave fronts?
    - ☑ Refracted: bent upward
- Panel D: Sound travels <u>with</u> wind
  - What happens?
    - ☑ Wave fronts refracted downward, reflected upward, etc.
- Sound travels farther <u>with</u> wind

62 ## Sound Traveling in Early Morning vs. Midday

- Animation F8-16
- Panel A: Early morning
  - Warmer air is higher
  - Warmer air has less density
  - Less density -- increased speed $s = \sqrt{E/\rho}$
  - Wave fronts refracted downward, reflected upward, etc.

63 ## Sound Traveling in Early Morning vs. Midday

- Panel B: Midday
  - Warmer air is lower
  - What happens differently?
    - ☑ Wave fronts refracted upward into atmosphere

64 ## Reflected by Water?

- $Z_{water} > Z_{air}$
- 0.1% of incident energy penetrates water surface
- 99.9% reflected by water
- dB attenuation of wave from air to water?
  - $dB = 10 \log_{10} (I_x / I_r) = 10 \log_{10} (10^{-3} / 10^0) = -30$ dB

65 ## Attenuation in Air?

- 99.9% reflected by water
- How much is sound wave in air attenuated?
  - ☑ $dB = 10 \log_{10} .999$

    $= 10 \log_{10} (9.99 \times 10^{-1})$

= - 0.0043

66 ## DIFFRACTION

- What happens when water wave encounters a diving raft?
  - The wave bends around obstacle and reforms
  - This is called diffraction

67 ## Diffraction

- Panel A: plane progressive wave moving L-R
- Wave encounters barrier
  - Some energy reflected back
  - Wave fronts scatter, or bend, around obstacle
  - Wave fronts then reform and continue as plane wave fronts

68 ## Diffraction

- Panel B: Wave fronts encounter opening in wall
  - Some energy reflected back
  - Portions of wave fronts pass through and then reform as plane waves

69 ## ABSORPTION

- Opposition to sound transmission will exist at any boundary where impedances differ
- If impedance is infinite, intensity of reflected wave will equal intensity of incident wave
  - $I_r = I_i$

70 ## Absorption

- If impedance is not infinite, some sound energy will be absorbed by new medium
- Intensity of reflected wave will be less than intensity of incident wave
  - $I_r < I_i$

71 ## Absorption Coefficient

- Magnitude of absorption given by absorption coefficient, α
- α is the proportion of energy in incident wave absorbed by material
- $\alpha = I_a / I_i$, where
  - I_a = energy absorbed and
  - I_i = energy of incident wave
- Air to water
  - 0.1% absorbed
  - 99.9% reflected

72 ## Absorption

- Suppose SPL_i = 80 dB
  - ♦ $I_i = 10^{-4}$ watt / m^2
- Attenuate 30 dB
  - ♦ $I_a = 10^{-7}$ watt / m^2
  - ♦ $I_a / I_i = 10^{-7} / 10^{-4} = 10^{-3}$
  - ♦ $\alpha = .001$

73 Absorption

- If SPL_i = 80 dB, and .1% is absorbed, what is SPL of sound wave retained in medium?
  - ☑ dB = 10 log 0.999
  - ☑ = - 0.004
  - ☑ dB SPL = 80 - 0.004
  - ☑ = 79.996

74 Absorption

- Does "α" vary with intensity of incident wave; I_i ?
  - ☑ No
  - ☑ If α = .001, .1% of energy is absorbed regardless of intensity of incident wave

75 Sound-Treated Rooms

- <u>Anechoic rooms</u> have high absorption coefficient
  - ♦ Fiberglass wedges are absorbing material
- Sound isolated rooms
  - ♦ Designed to reduce sound transmission through walls
  - ♦ Reasonably high absorption coefficient

76 Absorption and Reflection

- Absorption is inversely proportional to reflection
- Thus, as absorption coefficient increases, reflection & reverberation time decrease

77 Absorption and Reflection

- Absorption coefficient, α, varies with frequency and with nature of materials

	Frequency in kHz					
	.125	.25	.5	1	2	4
Vinyl tile on concrete	.02	.03	.03	.03	.03	.02
Painted concrete block	.1	.1	.1	.1	.1	.1
Window glass	.3	.2	.2	.1	.1	.05
Plaster on lath	.2	.2	.1	.1	.05	.1
Unpainted concrete block	.4	.4	.3	.3	.4	.3
Thick carpet on concrete	.02	.06	.15	.4	.6	.6
Thick carpet on felt pad	.1	.3	.4	.5	.6	.7

Occupied upholstered seating .4 .6 .8 .9 .9 .9

78 ## Total Absorption

- <u>Total</u> absorption in a room depends on
  - Absorption coefficients of materials in room and
  - Room volume
- Quantified by <u>absorption units</u>
  - Sabine (fps)
  - Metric sabine (MKS)
- Total absorption for opening of 1 m^2 (MKS)
- Large, bare room with open window 1 m^2
  - α of window = 1.0 (100% absorption)

79 ## Absorption and Reflection

- Assume six surfaces of room absorb equally
- Theoretical reverberation time, T_{60}:
  - $T_{60} \propto$ V (volume of room)
  - $T_{60} \propto$ 1/A (area of opening)
  - T_{60} = k (V/A)
  - >>k = .049 (fps)
  - >>k = .161 (MKS)
- If V increases by some factor, x,
  - T_{60} <u>increases</u> by x
  - Sound energy <u>retained</u> in room for longer time
- If A increases by some factor, x,
  - T_{60} <u>decreases</u> by x
  - Sound energy <u>escapes</u> room more quickly

80 ## Total Absorption (A´)

- $A' = S_1 \alpha_1 + S_2 \alpha_2 + \ldots + S_n \alpha_n$
  - S = surface area
  - α = absorption coefficient of surface (S_n)
- Thus, A´, for multiple absorbing surfaces equals sum of the total absorption ($S_n \alpha_n$) of the individual surfaces

81 ## Sample Computation (f = 500 Hz)

	Dimensions (m)	S	α	A
Side wall	3×20	60	.10	6.0
Side wall	3×20	60	.10	6.0
End wall	3×12	36	.10	3.6
End wall	3×12	36	.40	14.4
Floor	12×20	240	.40	96.0
Ceiling	12×20	240	.10	24.0
				A´ = 150.0

82 ## Sample Computation

(f = 500 Hz)

- **A´ = 150**
- **V = $(3 \times 12 \times 20) = 720\ m^3$**
- **T_{60} = k (V / A´)**
  - **= .161 (720 / 150)**
  - **= .77 s**
  - **= 770 ms**

83 ## Optimal T_{60}

- **Speech in conference room**
  - **400 - 800 ms**
- **Chamber music**
  - **900 - 1400 ms**
- **Organ music**
  - **1500 - 2400 ms**
- **T_{60} varies with V and f**

84 ## Absorption and Diffraction

- **Air medium itself absorbs sound energy above 1000 Hz**
- **Example of fog horn vs. whistle for ships at sea**
  - **Foggy conditions**
  - **Air contains water droplets with small size re: λ of foghorn sound**
  - **Sound energy diffracted**
  - **Whistle with high f**
    - **>> short λ**
    - **>> absorption**

85 ## OTHER PHENOMENA IN SOUND TRANSMISSION

- **1. Beats**
- **2. Doppler Effect**
- **3. Sonic Booms**

86 ## 1. Beats

- **Two people walking at different rates:**
  - **One at 60 steps / min**
  - **One at 64 steps / min**
- **Moving in and out of step (in and out of phase)**
- **They will be “in step” 4 times / min (64 - 60) and “out of step” 4 times / min**

87 ## Beats

- **Same principle applies to sine waves of different frequency in same medium**

- Because frequencies differ, they will move in and out of phase

88 ## Beats (Example)

- f_1 = 496 Hz
- f_2 = 500 Hz
- In phase 4 times per s and reinforce each other
  - intensity increases
- Out of phase 4 times per s and interfere with each other
  - intensity decreases

89 ## Example

- Result
  - Periodic increases & decreases in amplitude; called beats
  - Beat frequency: The rate at which changes in amplitude occur
- Beat frequency = $f_2 - f_1$
  - 500 - 496 = 4 Hz
- Pitch corresponds to: $(f_2 + f_1) / 2$
  - (500 + 496) / 2 = 498 Hz

90 ## Another Example

- Panel A: f_1 = 50 Hz
- Panel B: f_2 = 55 Hz
- Panel C: resultant wave
  - At t = 0 and 200 ms,
    - >> in phase
    - >> constructive interference
    - >> intensity increases

91 ## Another Example

- At t = 100 ms,
  - >> 180^o out of phase
  - >> destructive interference
  - >> cancellation
  - >> intensity is momentarily zero

92 ## Example

- Why 200 ms interval between intensity maxima?
- What is beat frequency?
  - ☑ 5 Hz
- What is beat period?
  - ☑ T = 1/ f = 1/ 5 = 200 ms
- To what frequency does pitch correspond?
  - ☑ 52.5 Hz

93 ## 2. The Doppler Effect

- Strike tuning fork of 250 Hz
  - Air particles displaced at rate of 250 Hz
  - Disturbance propagated at rate of 340 m/s (speed of sound)
- That is true when source and receiver are stationary

94 ## The Doppler Effect

- If source moves toward observer, pitch rises
- If source moves away from observer, pitch falls
- Called the Doppler effect

95 ## The Doppler Effect

- A is location of moving source
- C is location of stationary receiver (340 m from A)
- s is speed of sound (vector): 340 m/s
- s_s is speed of moving source (vector): 85 m/s

96 ## The Doppler Effect

- Distance AC (340 m) = speed of sound (s = 340 m/s)
- Distance AB (85 m) = speed of moving source (s_s = 85 m/s)

97 ## The Doppler Effect

- A remains stationary
  - Compressions (& rarefactions) distributed over AC after 1 s
- A moves toward C
  - After 1 s, A moves to B
  - Same number of compressions crowded into distance BC
- What happens to λ ?
  - ☑ λ decreases
- What happens to f?
  - ☑ f increases ($f \propto 1/\lambda$)

98 ## Another Example

- Frequency = 400 Hz
- Speed of sound = 340 m/s
- Speed of source = 85 m/s
  - Altered f = 533 Hz
  - As source moves away, f drops from 400 Hz to 320 Hz

99 ## The Equations

- Toward observer
  - $f' = f\,(s/s - s_s)$
  - $= 400\,(340/340 - 85) = 533$ Hz
- Away from observer
  - $f' = f\,(s/s + s_s)$
  - $= 400\,(340/340 + 85) = 320$ Hz

100 ## 3. Sonic Booms

- Occur when airplane exceeds speed of sound
- Ratio of speed of airplane to speed of sound is called a Mach number
  - If airplane speed is 340 m/s, it has achieved Mach 1
  - At 680 m/s, Mach 2, etc.

101 ## Sonic Booms

- Below Mach 1, airplane is "chasing its own sound wave"
- As plane accelerates, sound waves in front impede flight
  - More thrust is required
- At Mach 1, the airplane "breaks the sound barrier"
- Beyond Mach 1, airplane is now in front of its own sound wave

102 ## Sonic Booms

- Compressions pile upon one another rather than being separated by rarefactions
- A very large compression is created with considerable energy
- Called a sonic boom
- Energy sufficient to break windows