ARCHITECTURAL ACOUSTICS

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First Pan-American/Iberian Meeting on Acoustics

Cancun, Mexico

2 – 6 December 2002

Acoustics

- Acoustics is the science of sound, including its production, transmission and effects - Allan D. Pierce, Acoustics An Introduction to Its Physical Principles and Applications, McGraw-Hill Book Company, New York, 1981 (ASA reprint 1989).

Architectural Acoustics

- Sound in an Enclosure.
(We all know what it is, but it's difficult to define.)

Density: $\rho_o(P_o,T)$

Pressure: $P_o \approx 100$ kPa

$p(t)$ = instantaneous

p = effective = $\sqrt{\langle p^2(t) \rangle}$

Frequency/ Wavelength:

Speed of Sound: $c = \lambda f$

$$c = 331.4 \sqrt{\frac{T}{273}}$$

$$c = \gamma \frac{P_o}{\rho_o}$$

Log Notation

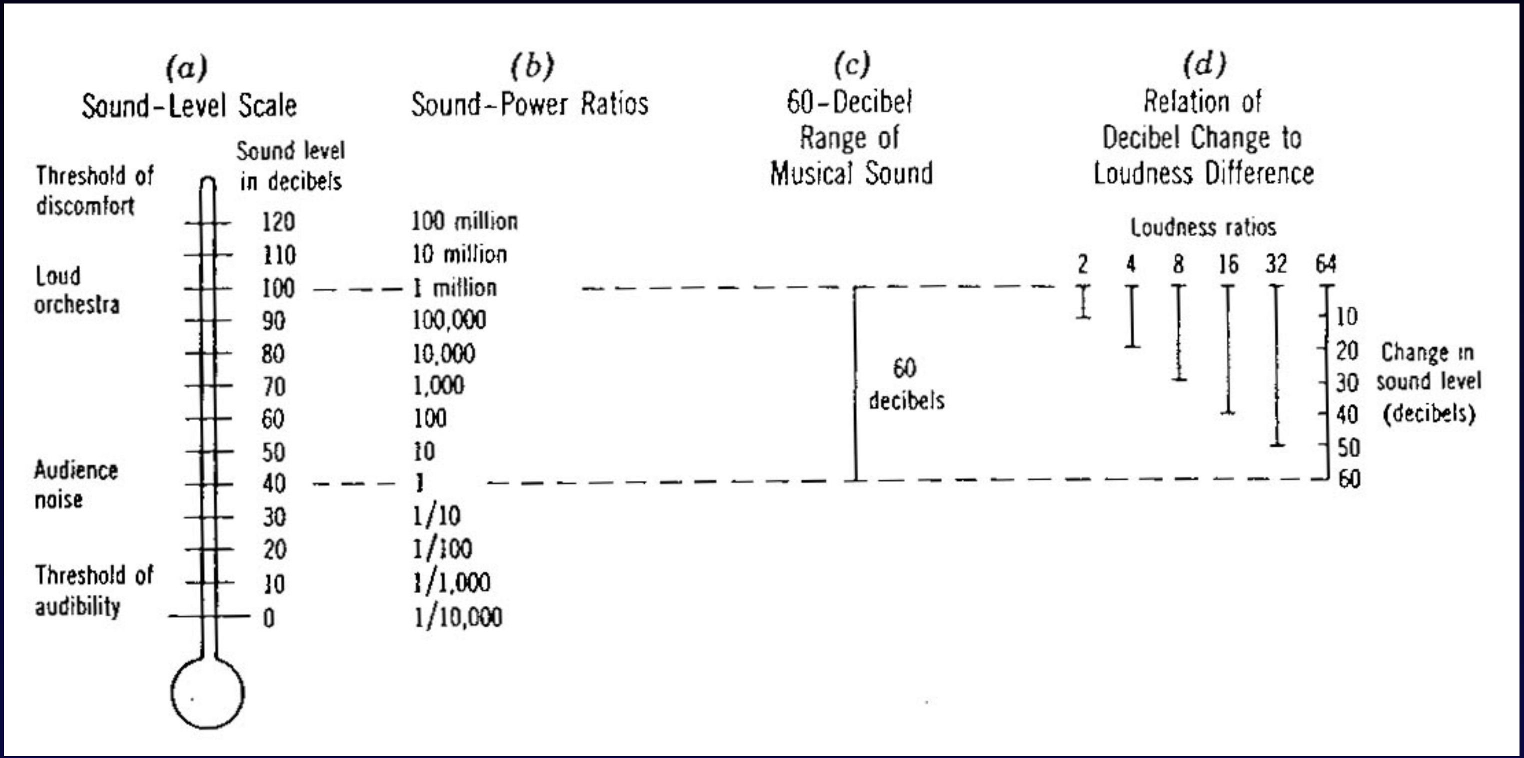


Figure 1

SPL (sound pressure level)

$L_p = SPL = 20 \log \; p/\,p_{ref}$

$p_{ref} = 0.00002 \text{ Pa}$

$\text{Pa} = [\text{N/m}^2] = [\text{Kg}\cdot\text{m/s}^2\cdot\text{m}^2] = [\text{kg/s}^2\text{- m}]$

SWL (sound power level)

$$SWL = 10 \log W / W_{ref}$$

$$W_{ref} = 1 \times 10^{-12}\ W = 1\ pW$$

$$W = [kg - m^2 / s^3]$$

I (intensity)

$$L_I = IL = 10 \log\ I / I_{ref}$$

$$I_{ref} = 10^{-12}\ \mathrm{W/m^2} = 1\text{x}10^{-12}\ \mathrm{kg/s^3}$$

Waves

PLANE:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

COMPLEX FORM OF THE HARMONIC SOLUTION

$$\mathbf{P} = \mathbf{A}e^{j(wt-kx)} + \mathbf{B}e^{j(wt+kx)}$$

Waves

CYLINDRICAL: $\nabla^2 p + k^2 p = 0 \quad (k=T/c)$

$$\nabla^2 = \frac{1}{w}\frac{\partial}{\partial w}\left(w \frac{\partial}{\partial w} \right) + \frac{1}{w^2}\frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2}$$

One solution:

$$\mathbf{p} = A \left[J_0\left(\frac{2\pi\nu w}{c}\right) + iN_0\left(\frac{2\pi\nu w}{c}\right) \right] e^{-2\pi i\nu t}$$

$$W \rightarrow \infty \quad A\sqrt{\frac{2}{\pi k w}}\, e^{ik(w-ct) - i(\pi/4)} \qquad k = \frac{2\pi\nu}{c} = \frac{2\pi}{\lambda}$$

$$W \rightarrow 0 \quad i\,\frac{2A}{\pi} \ln(w) e^{-2\pi i\nu t}$$

Waves

SPHERICAL:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial p}{\partial r}\right) = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

if $a \ll \lambda$ then $p/r \gg \partial p/\partial r$ @ $r = a$

$$P \cong \frac{\rho}{4\pi}\frac{dS}{dt} \quad \text{at } r = a$$

$$p \cong \frac{\rho}{4\pi r} S'\left(t - \frac{r}{c}\right) \quad \text{where } S'(z) = (d/dz)S(z)$$

S = Total Flow

Human Factors

RANGE
OF
AUDIBILITY:

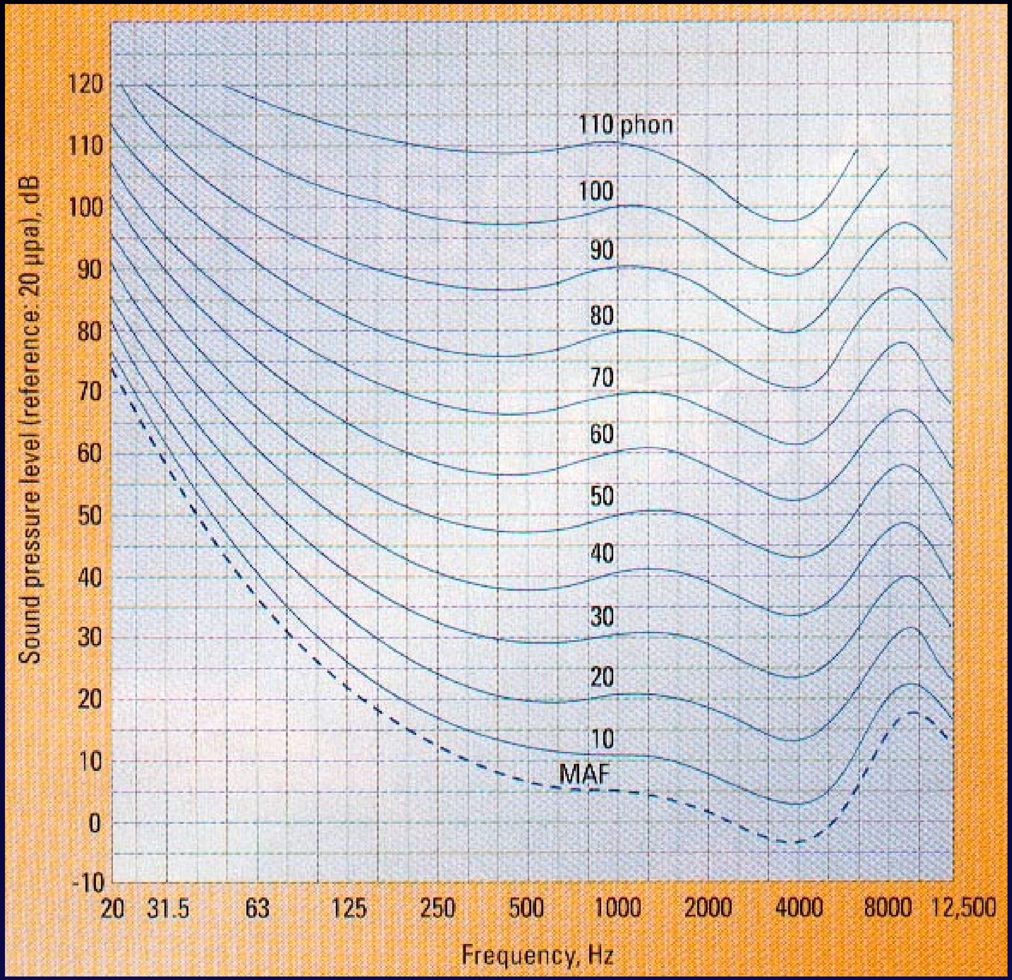


Figure 2

Human Factors

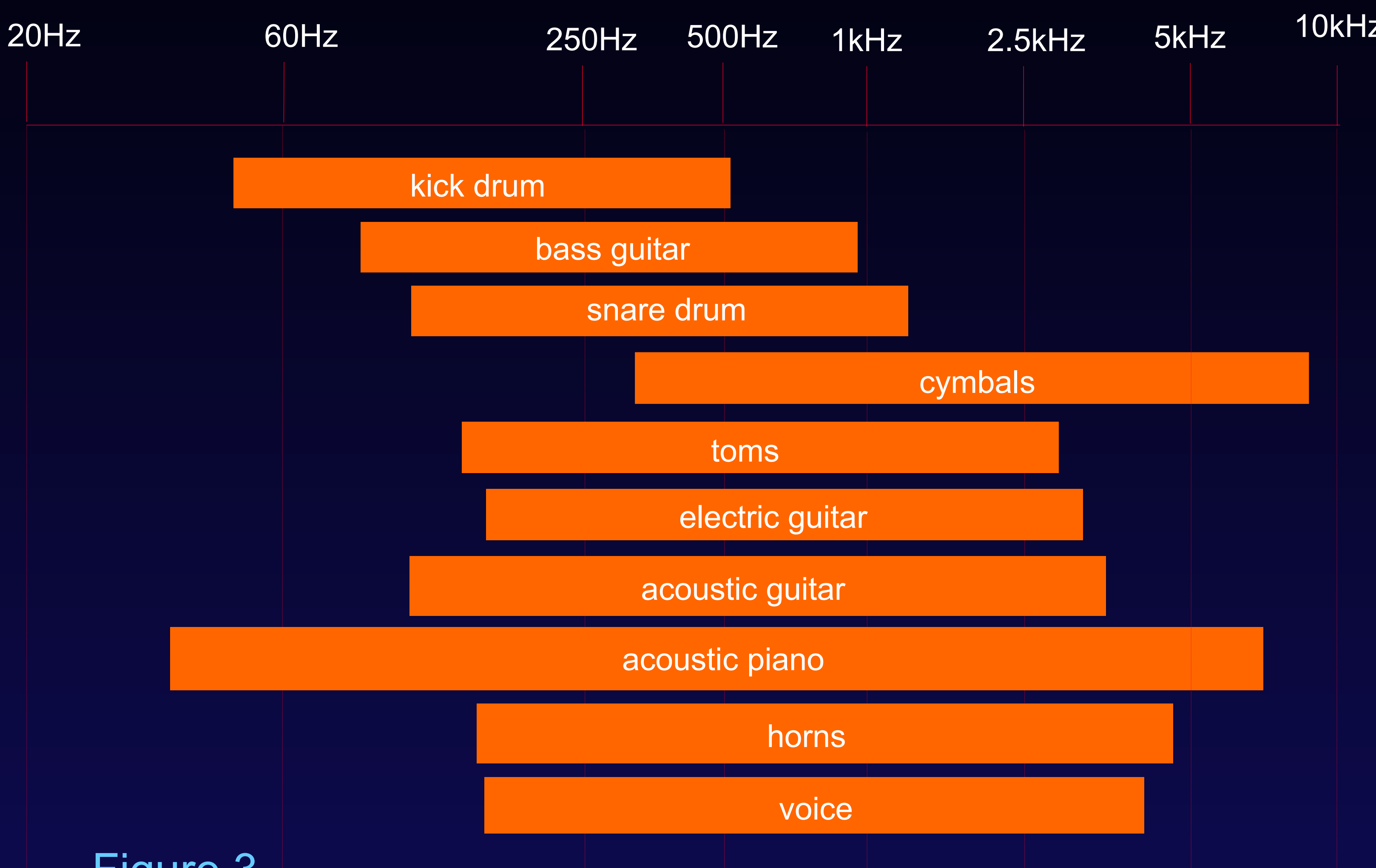


Figure 3

Human Factors

Range

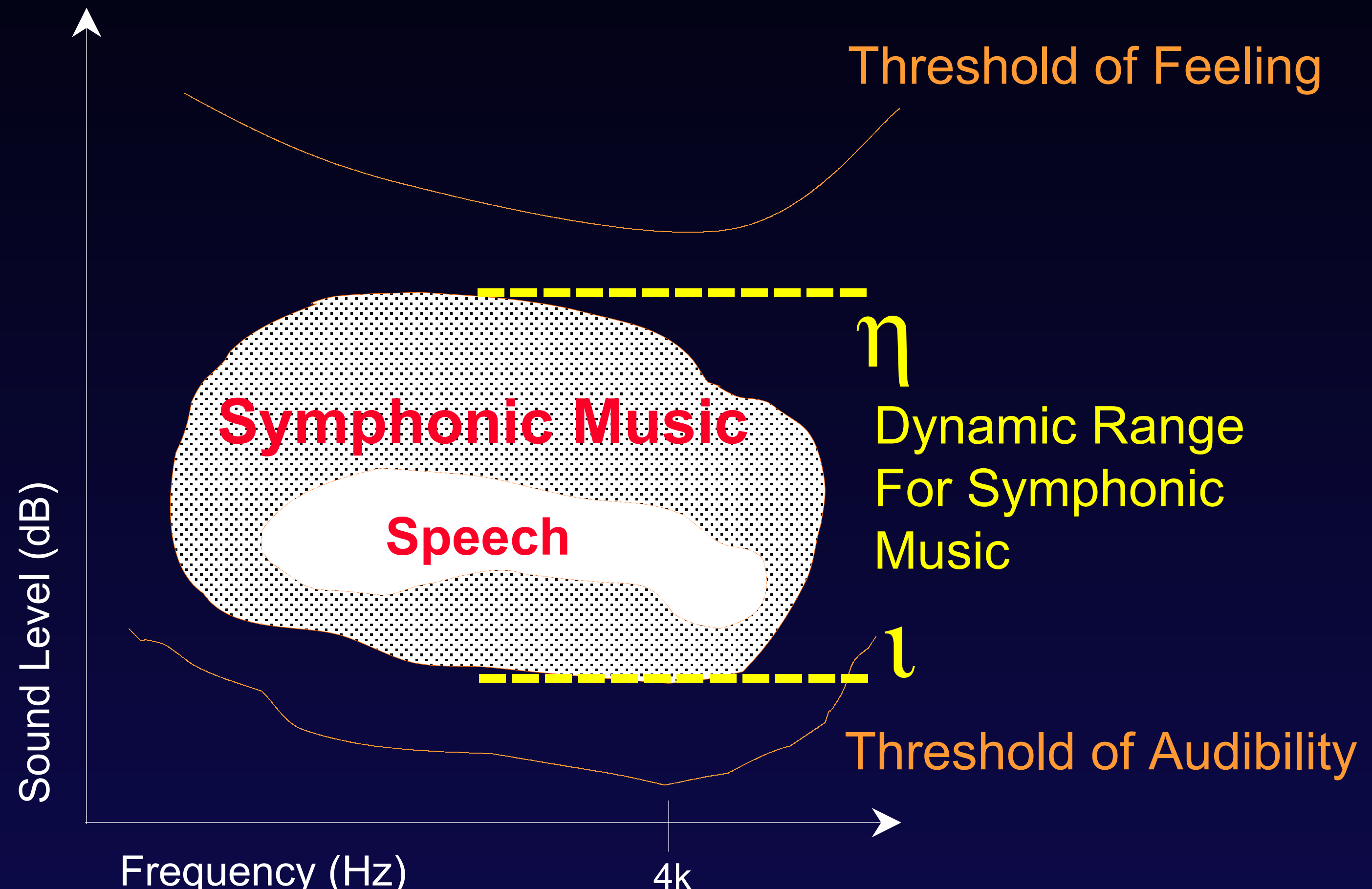


Figure 4

Human Factors

Band	CTR. FREQ. (Hz)	Bandwidth (Hz)	Band	CTR. FREQ. (Hz)	Bandwidth (Hz)
1	50	100	13	1850	280
2	150	100	14	2150	320
3	250	100	15	2500	380
4	350	100	16	2900	450
5	450	110	17	3400	550
6	570	120	18	4000	700
7	700	140	19	4800	900
8	840	150	20	5800	1100
9	1000	160	21	7000	1300
10	1170	190	22	8500	1800
11	1370	210	23	10500	2500
12	1600	240	24	13500	3500

Figure 5 Critical Bands

Common Sounds

	140 dB	
Jet Plane (100 feet)	130	
Amplified Rock and Roll (6 feet) **Threshold of Pain**	120	117 dB Chainsaw (3 feet) 115 dB Pneumatic Riveter (3 feet)
	110	107 dB Power Mower (3 feet)
Diesel Truck (30 feet)	100	
Food Blender (3 feet) Motorcycle (30 feet)	90	94 dB Subway (inside)
Automobile (25 feet) Loud Singing (3 feet)	80	
Inside Car	70	
Normal Conversation	60	
Quiet Street	50	
Quiet Home	40	
Quiet Whisper (3 feet)	30	
Rustling Leaves	20	
Human Breathing	10	
Threshold of Hearing	0	

Figure 6

Measurement

THIRD OCTAVE BAND NO.	CENTER FREQUENCY (Hz.)	FREQUENCY RANGE (Hz)	CORRESPONDING OCTAVE BAND
14 15 16	25 -- 31.5 -- 40	22 to 28 28 to 36 35 to 45	Sub-Octave 22 to 45
17 18 19	50 -- 63 -- 80	45 to 56 56 to 71 71 to 89	1 45 to 89
20 21 22	100 -- 125 -- 160	89 to 112 112 to 141 141 to 178	2 89 to 178
23 24 25	200 -- 250 -- 315	178 to 224 224 to 282 282 to 355	3 178 to 355
26 27 28	400 -- 500 -- 630	355 to 447 447 to 563 562 to 708	4 354 to 709
29 30 31	800 -- 1000 -- 1250	708 to 892 891 to 1123 1122 to 1413	5 707 to 1414
32 33 34	1600 -- 2000 -- 2500	1412 to 1779 1778 to 2240 2238 to 2819	6 1411 to 2822
35 36 37	3150 -- 4000 -- 5000	2817 to 3549 3547 to 4469 4465 to 5625	7 2815 to 5630
38 39 40	6300 -- 8000 -- 10000	5621 to 7082 7077 to 8916 8909 to 11225	8 5617 to 11234

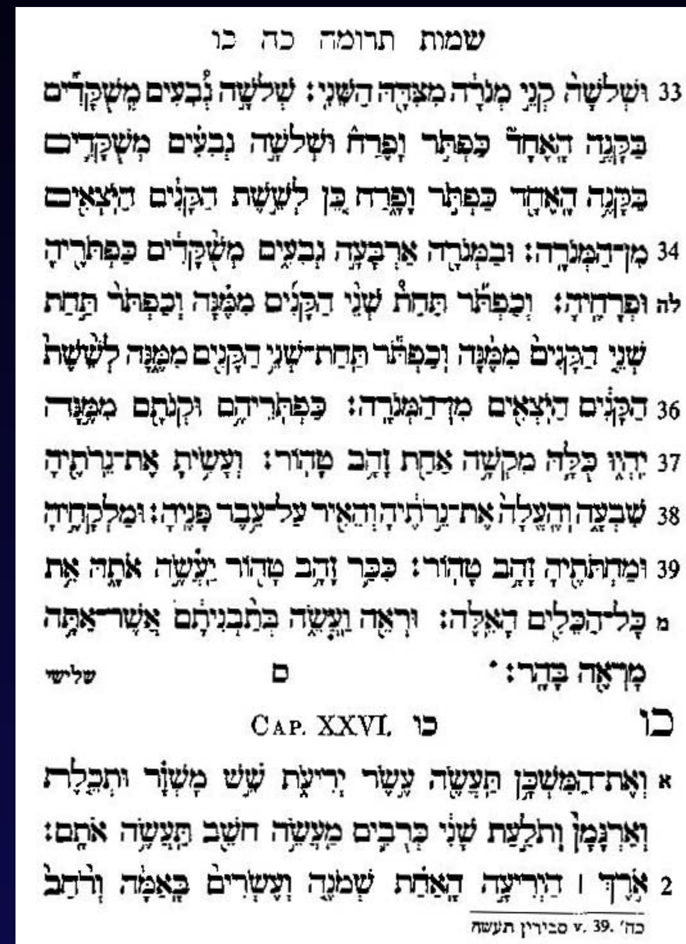
Figure 7

History


שמות תרומה כו

ארבע באמה היריעה האחת מדה אחת לכל־היריעת׃
3 חמש היריעת תהיין חברת אשה אל־אחתה וחמש יריעת
4 חברת אשה אל־אחתה׃ ועשית ללאת תכלת על שפת
היריעה האחת מקצה בחברת וכן תעשה בשפת היריעה
ה הקיצונה במחברת השנית׃ חמשים ללאת תעשה
ביריעה האחת וחמשים ללאת תעשה בקצה היריעה
אשר במחברת השנית מקבילת הללאת אשה אל־
6 אחתה׃ ועשית חמשים קרסי זהב וחברת את־היריעת
7 אשה אל־אחתה בקרסים והיה המשכן אחד׃ ועשית
יריעת עזים לאהל על־המשכן עשתי־עשרה יריעת
8 תעשה אתם׃ ארך היריעה האחת שלשים באמה
ורחב ארבע באמה היריעה האחת מדה אחת לעשתי
9 עשרה יריעת׃ וחברת את־חמש היריעת לבד ואת־
שש היריעת לבד וכפלת את־היריעה הששית אל־מול
י פני האהל׃ ועשית חמשים ללאת על שפת היריעה
האחת הקיצנה בחברת וחמשים ללאת על שפת

קמץ בז״ק v. 9.


שמות תרומה כה כו

33 ושלשה קני מנרה מצדה השני׃ שלשה גבעים משקדים
בקנה האחד כפתר ופרח ושלשה גבעים משקדים
בקנה האחד כפתר ופרח כן לששת הקנים היצאים
34 מן־המנרה׃ ובמנרה ארבעה גבעים משקדים כפתריה
לה ופרחיה׃ וכפתר תחת שני הקנים ממנה וכפתר תחת
שני הקנים ממנה וכפתר תחת־שני הקנים ממנה לששת
36 הקנים היצאים מן־המנרה׃ כפתריהם וקנתם ממנה
37 יהיו כלה מקשה אחת זהב טהור׃ ועשית את־נרתיה
38 שבעה והעלה את־נרתיה והאיר על־עבר פניה׃ ומלקחיה
39 ומחתתיה זהב טהור׃ ככר זהב טהור יעשה אתה את
מ כל־הכלים האלה׃ וראה ועשה בתבניתם אשר־אתה
מראה בהר׃ ס שלישי

כו CAP. XXVI. כו

א ואת־המשכן תעשה עשר יריעת שש משזר ותכלת
וארגמן ותלעת שני כרבים מעשה חשב תעשה אתם׃
2 ארך היריעה האחת שמנה ועשרים באמה ורחב

כה v. 39. סבירין תעשה

Exodus XXVI

History

COLLECTED PAPERS
ON ACOUSTICS

BY

WALLACE CLEMENT SABINE

LATE HOLLIS PROFESSOR OF MATHEMATICS AND NATURAL PHILOSOPHY
IN HARVARD UNIVERSITY

CAMBRIDGE
HARVARD UNIVERSITY PRESS
1927

History

ARCHITECTURAL
ACOUSTICS

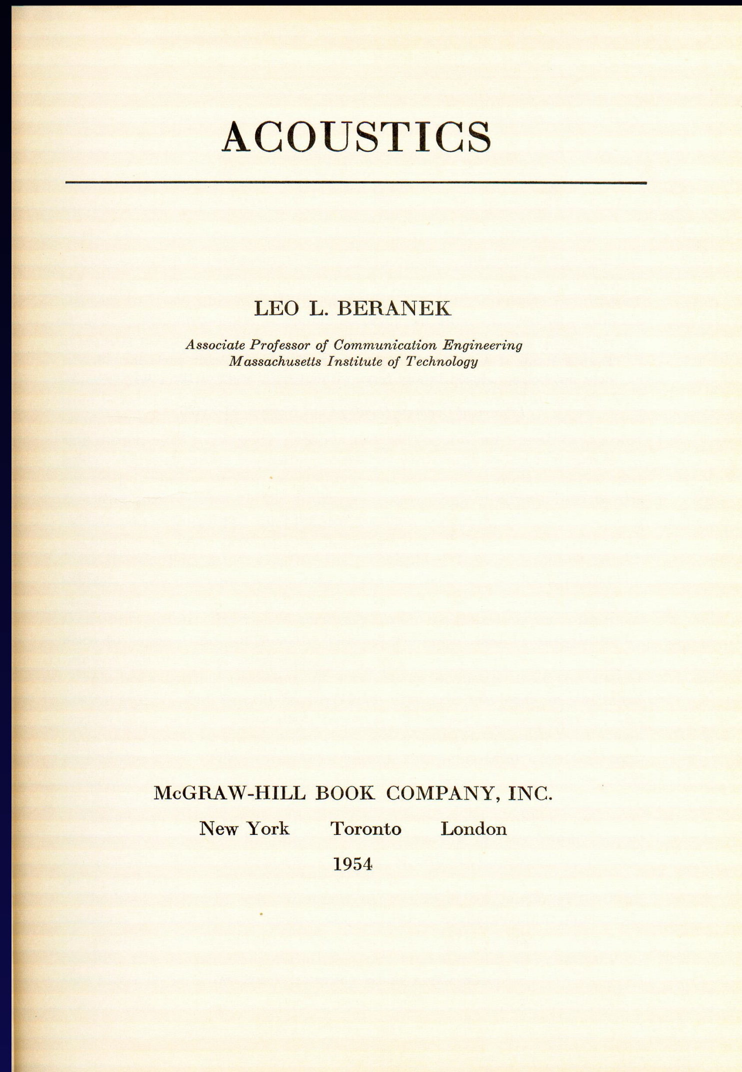
BY

VERN O. KNUDSEN, PH.D.

Professor of Physics and Dean of the Graduate Division
University of California at Los Angeles

NEW YORK
JOHN WILEY & SONS, INC.
LONDON: CHAPMAN & HALL, LIMITED

History



ACOUSTICS

LEO L. BERANEK

Associate Professor of Communication Engineering
Massachusetts Institute of Technology

McGRAW-HILL BOOK COMPANY, INC.

New York Toronto London

1954

History

Reflection

$x > 4\ \lambda$

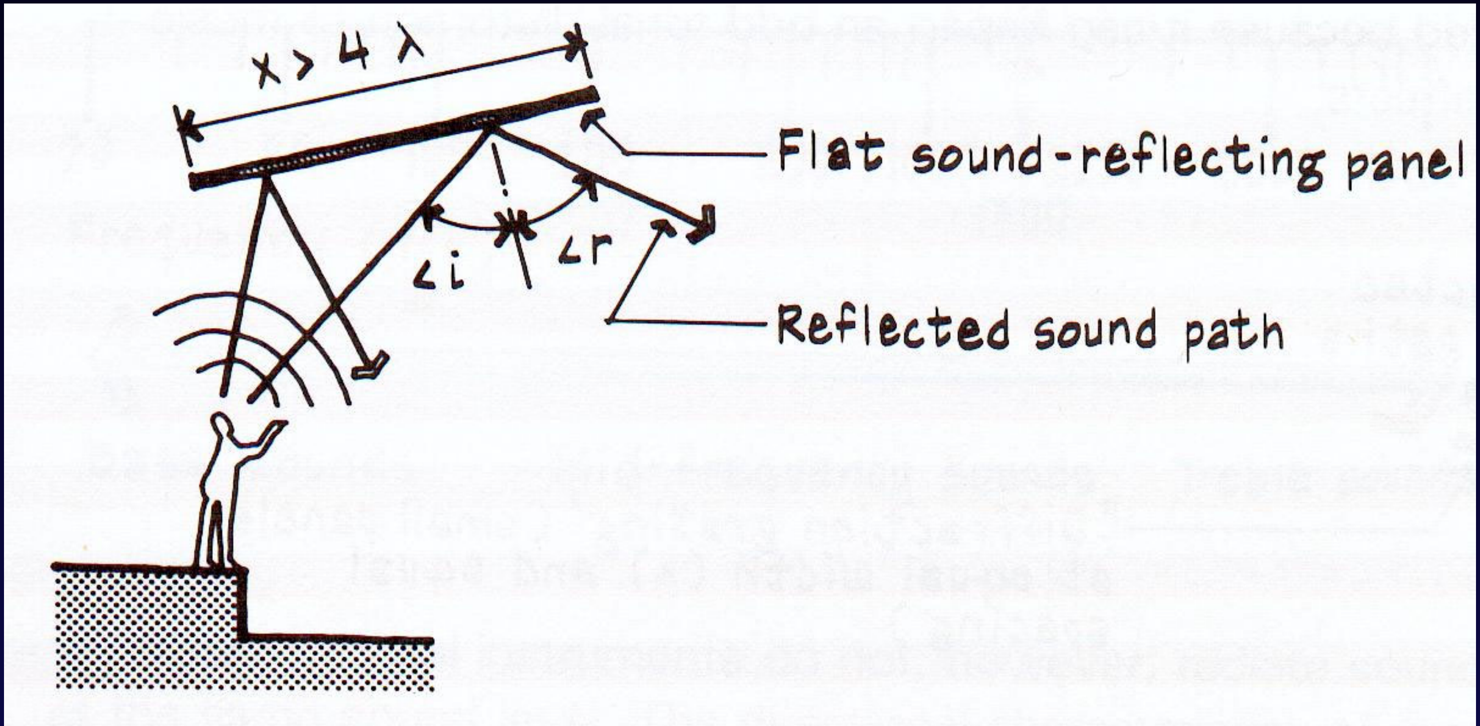


Figure 8

Diffusion

$x \approx \lambda$

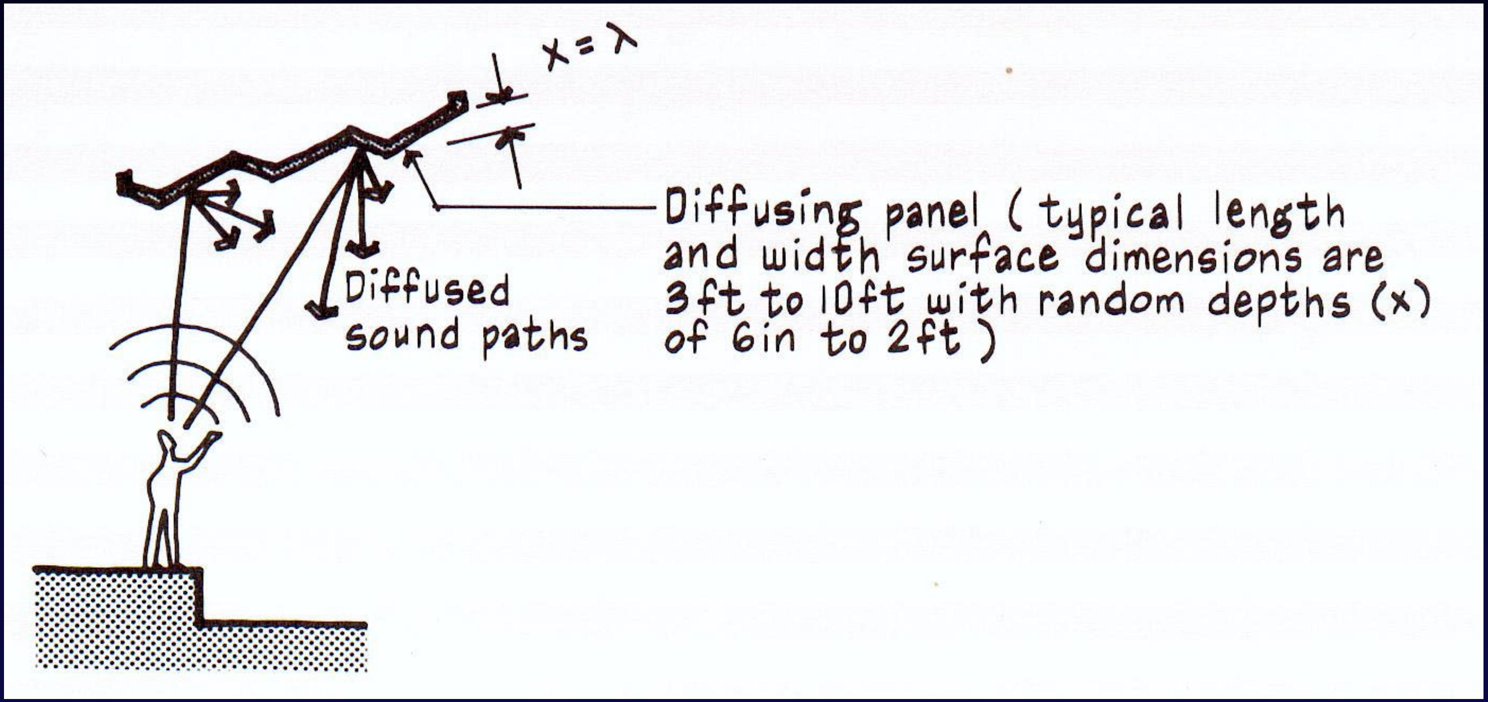


Figure 9

Diffraction

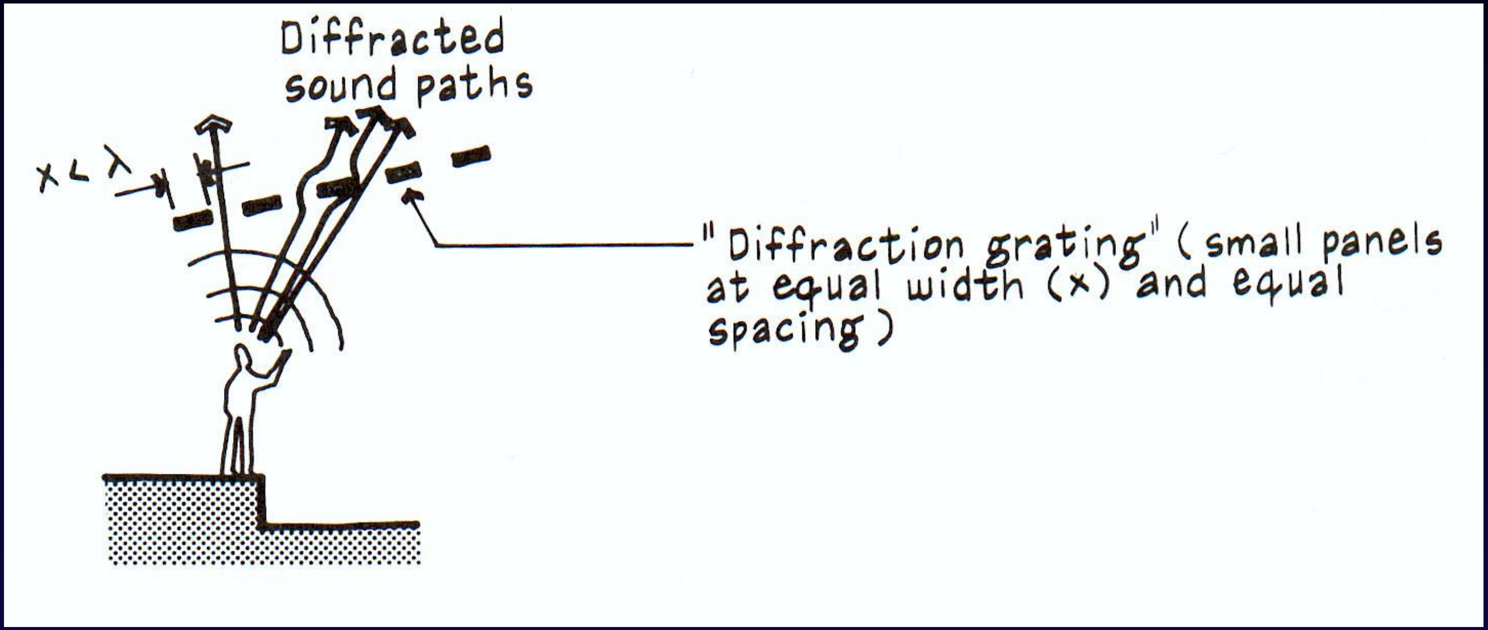


Figure 10

Concave Reflector

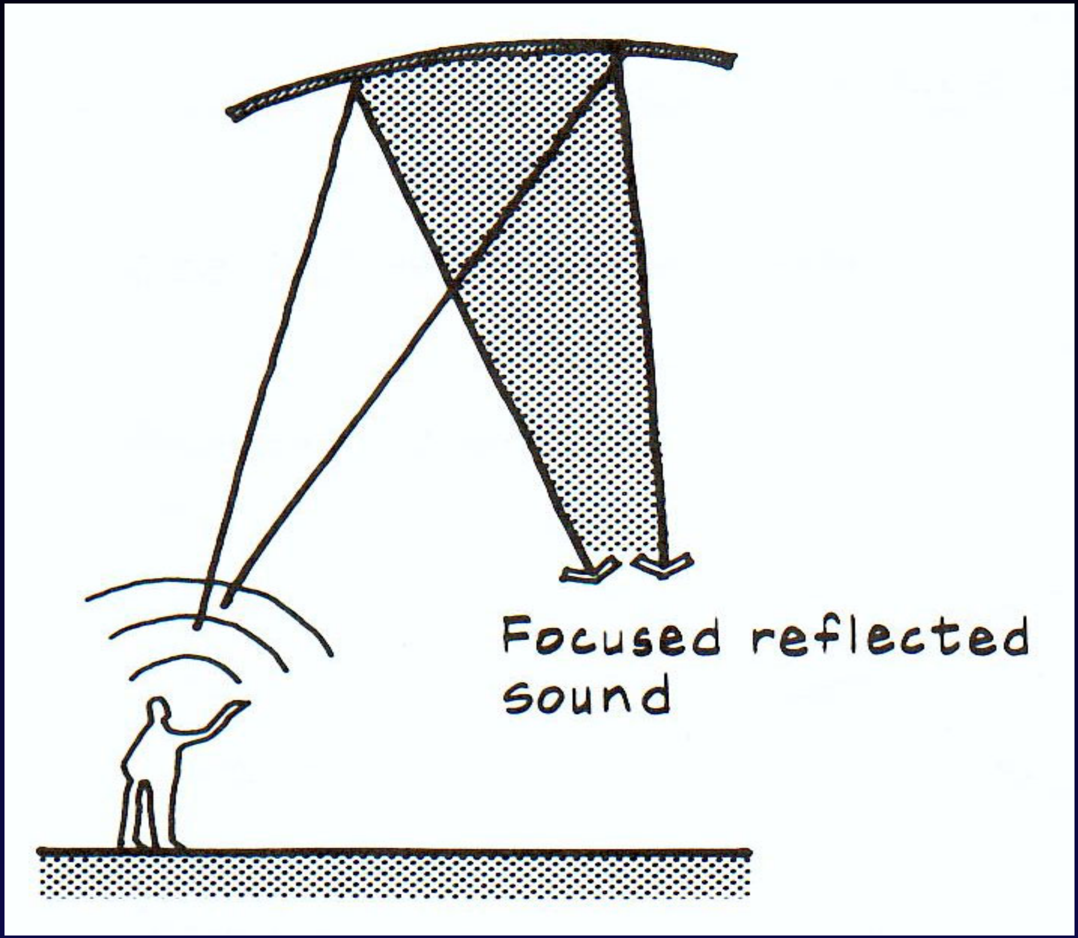


Figure 11

Flat Reflector

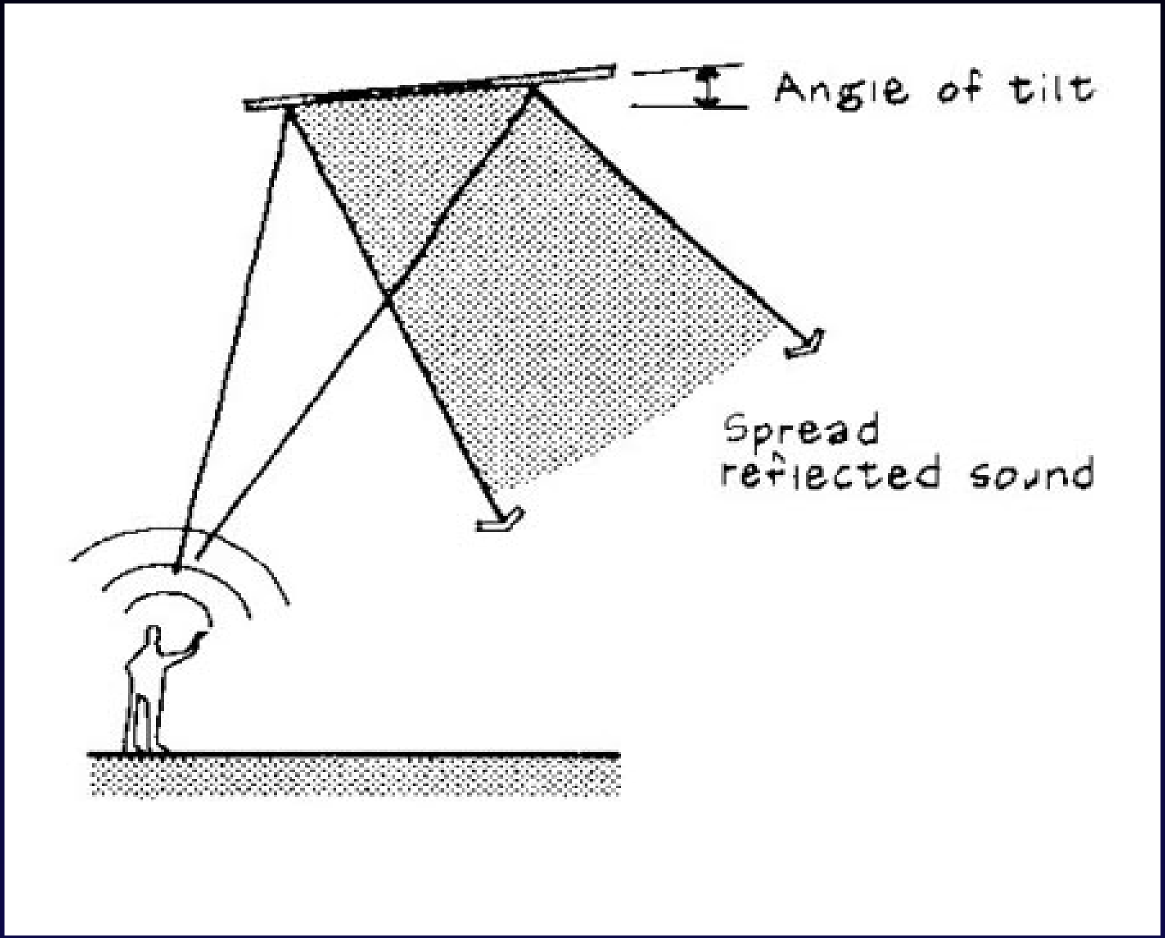


Figure 12

Convex Reflector

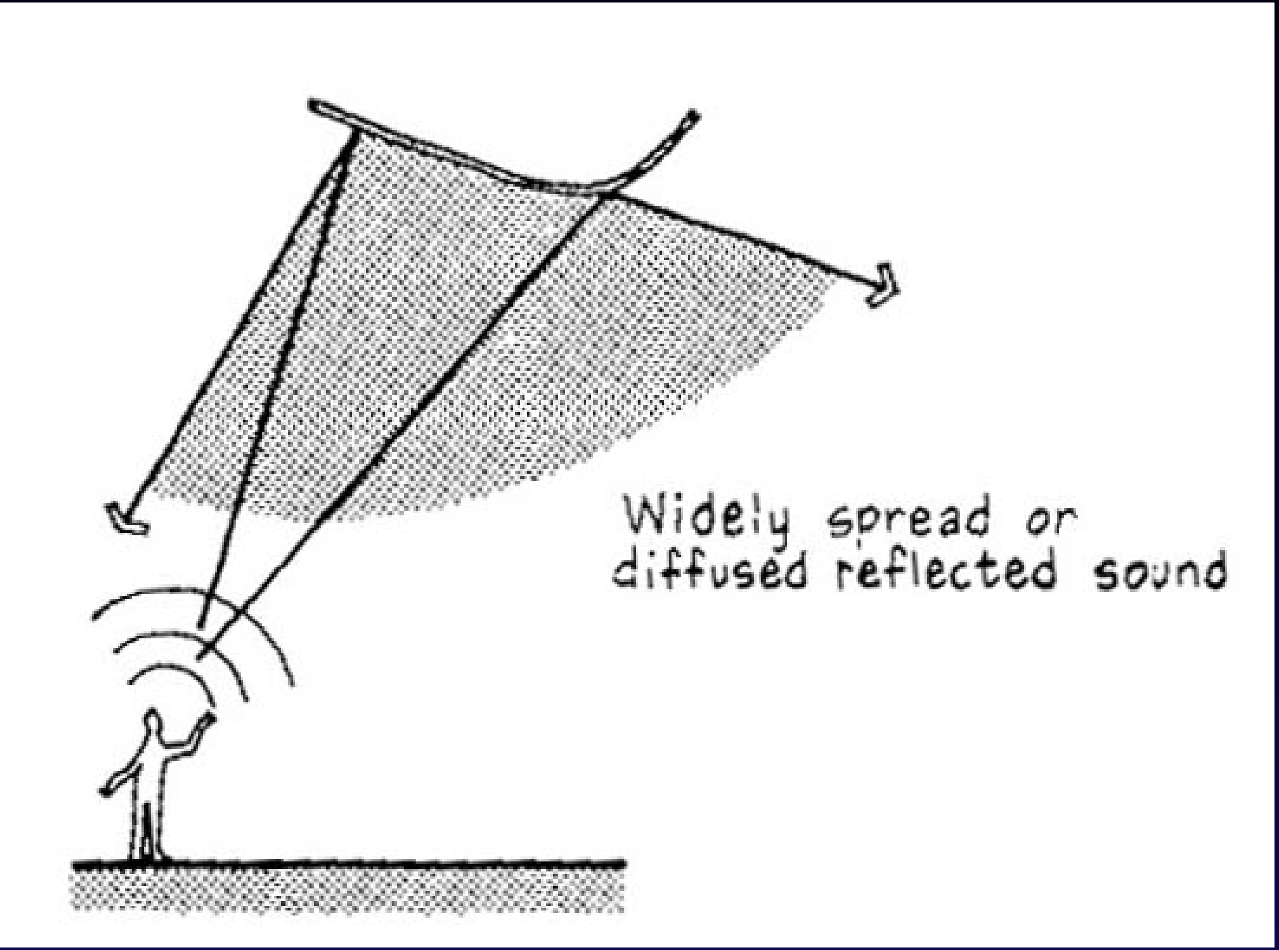


Figure 13

Room Modes

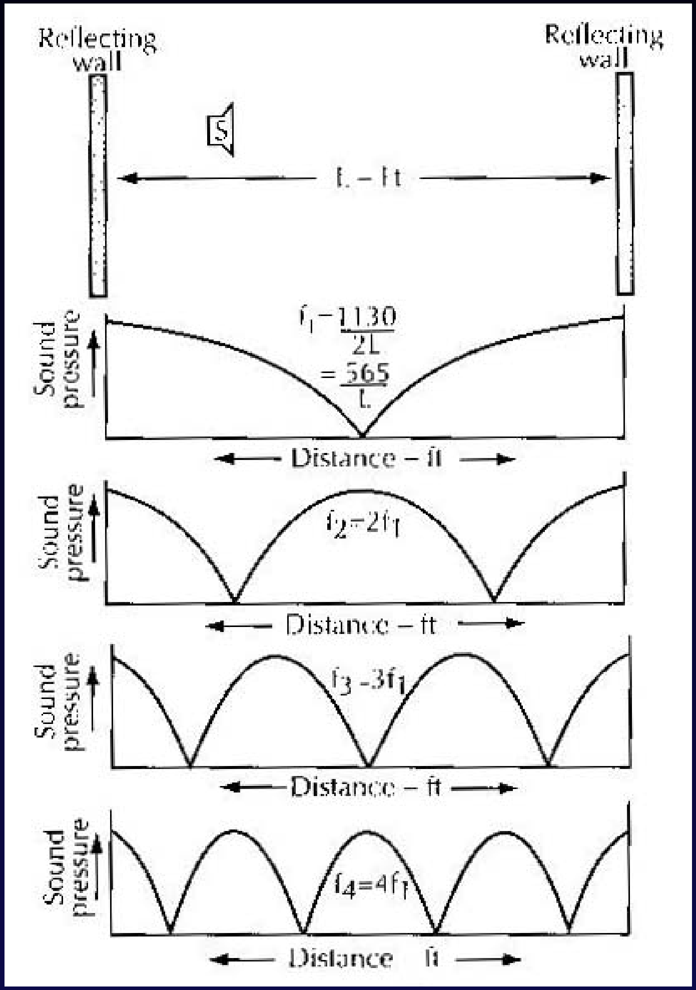


Figure 14

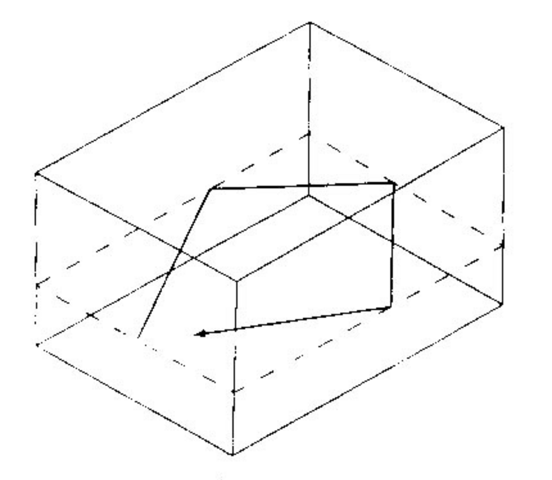


Figure 15

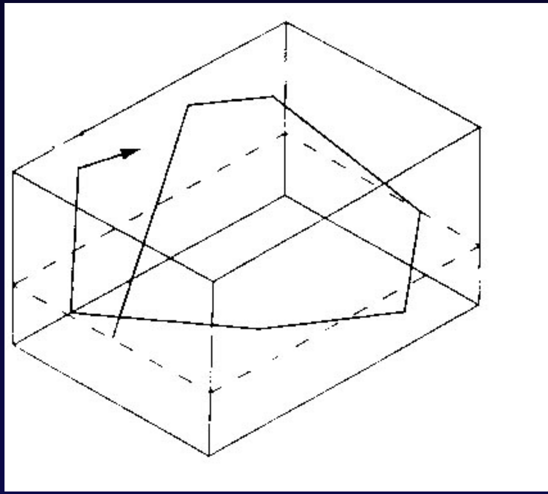


Figure 16

Reverberant Decay

large room

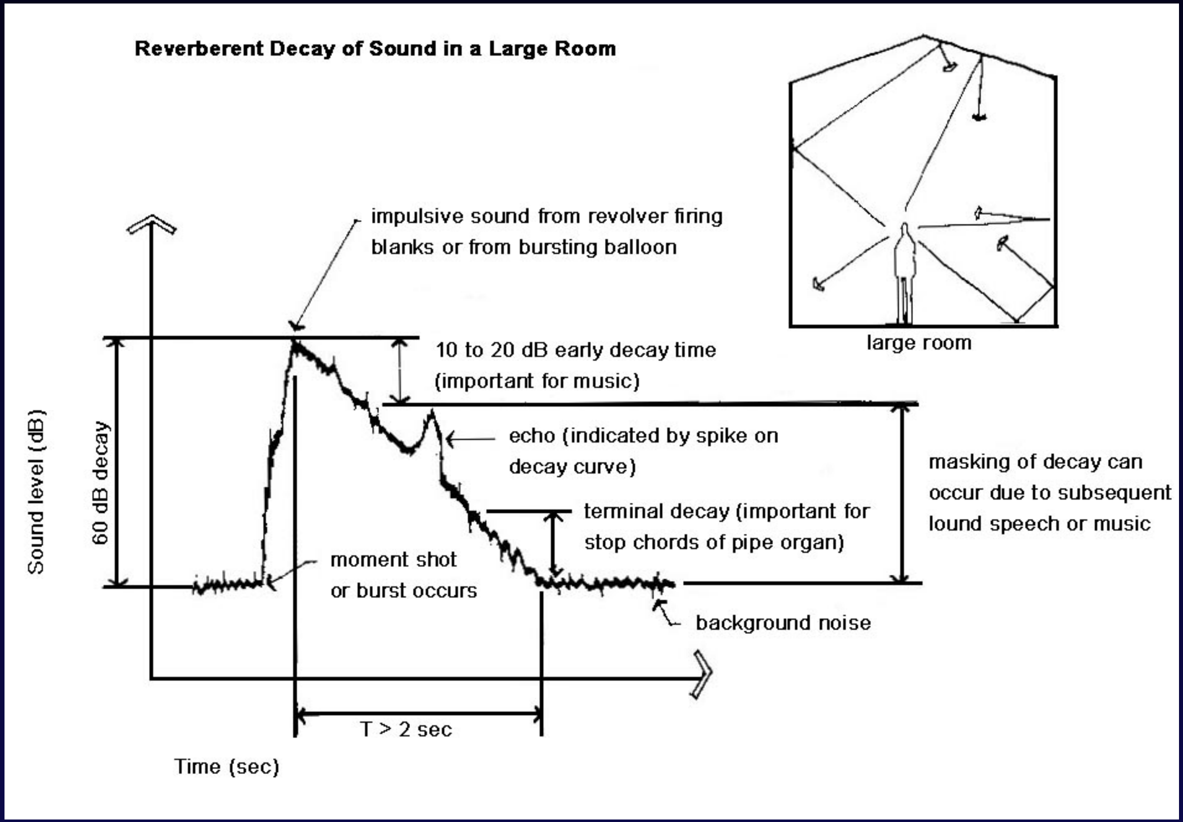


Figure 17

Reverberant Decay

small room

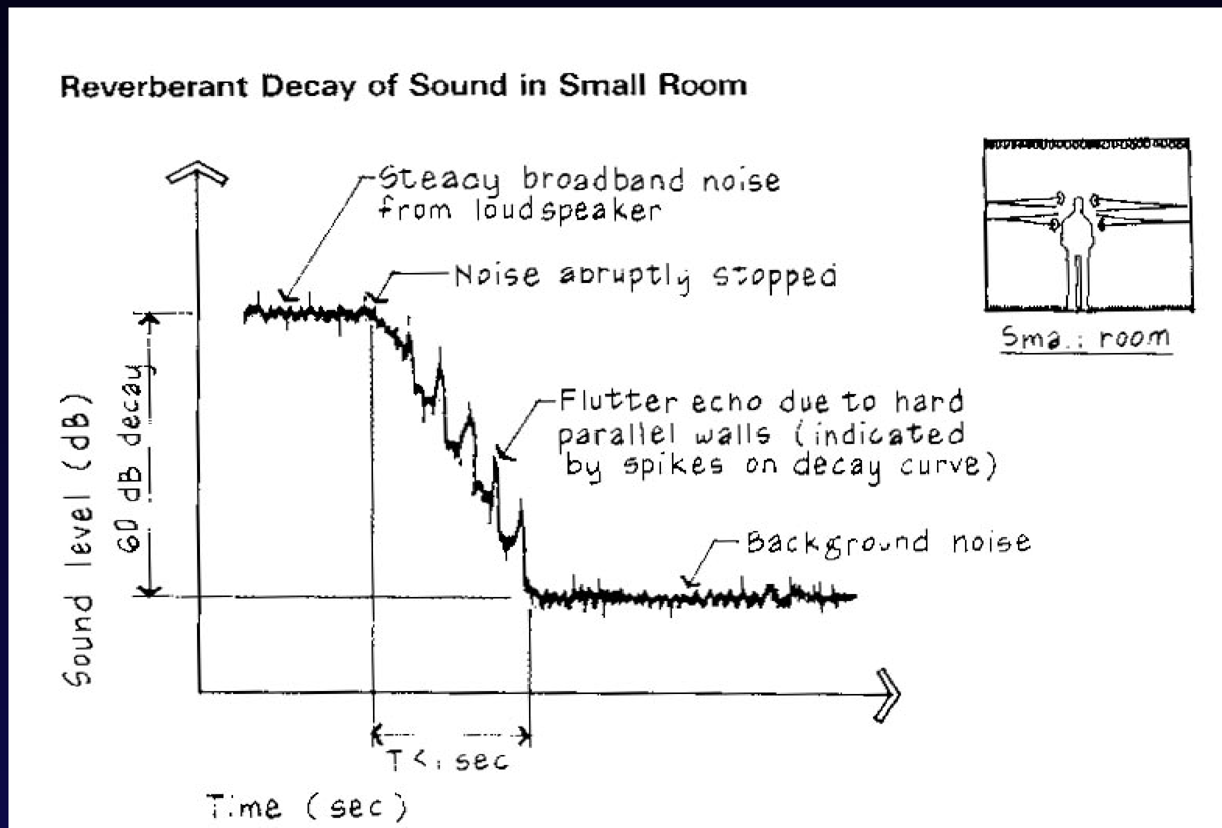


Figure 18

Materials

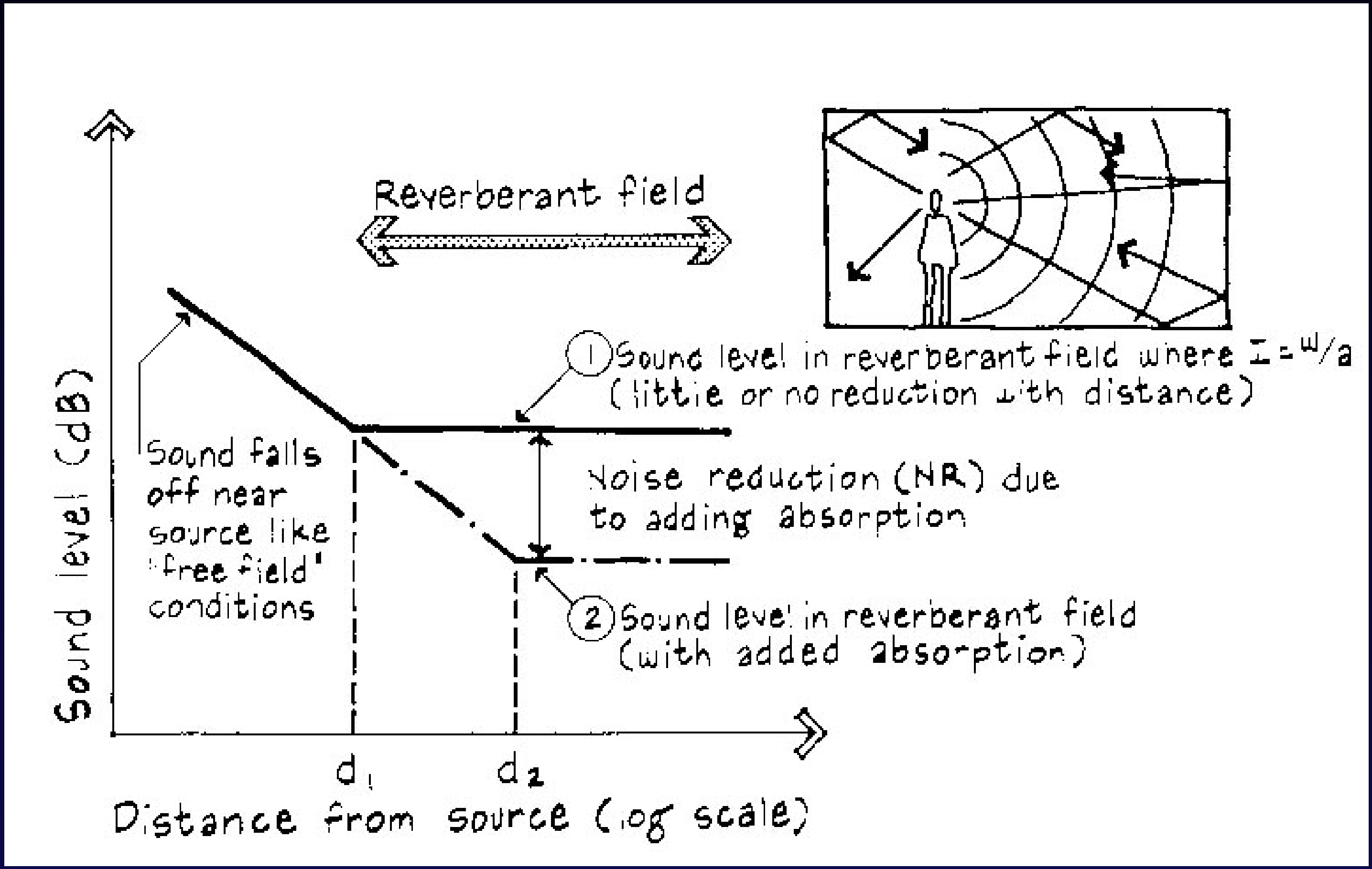


Figure 19

Small Rooms

- Modes
- Shape
- Reflection management

Large Rooms

TIME METRICS

Reverberation Time *(RT60)*

Bass Ratio *(BR)*

Large Rooms

ENERGY METRICS

Strength (G)

Sound Pressure Distribution (ΔL)

Center Time (t_s)

Energy Definition Measure (C_{50})

Register Balance Measure (B_R)

Speech Time Index (STI)

Articulation Loss (AL_{cons})

Subjective Intelligibility Tests

Clarity (C_{80})

Sound Coloration (K_t and K_h)

Large Rooms

Spacial Impression Measure for Music (*R*)

Lateral Efficiency *(LE for Music, LF and LFC)*

Interaural Cross Correlation Coefficient (*IACC*)

Interaural Time-Delay Gap (*ITDG*, *t1*)

Reverberance Measure *(H)*

Diffusion

Stage Support (*ST1*)

Texture

Early Decay Time (*EDT*)

Intimacy

Spaciousness

References

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Acoustics An Introduction to Its Physical Principles and Applications, Allan D. Pierce, McGraw-Hill Book Company, New York, 1981 (available from the ASA)

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Collected Papers on Acoustics, Wallace Clement Sabine, Harvard University Press, Cambridge, Massachusetts, 1922 (available from the ASA)

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List of Figures

- Waves equations (slides 9-10): Morse and Ingard
- Figure 2: *"Transition to Digital - Elements of Psychoacoustics,"* Michael Robin, Broadcast Engineering magazine, March 2002, p 34
- Figure 3: *"Panning for Gold,"* Randy Neiman, Electronic Musician magazine, March 2002, p 48
- Figure 4: derived from Egan, p 9
- Figure 5: *"Transition to Digital - Elements of Psychoacoustics,"* Michael Robin, Broadcast Engineering magazine, March 2002, p 32
- Figure 6: Egan, p 13
- Figure 8: Egan, p 89

List of Figures

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