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

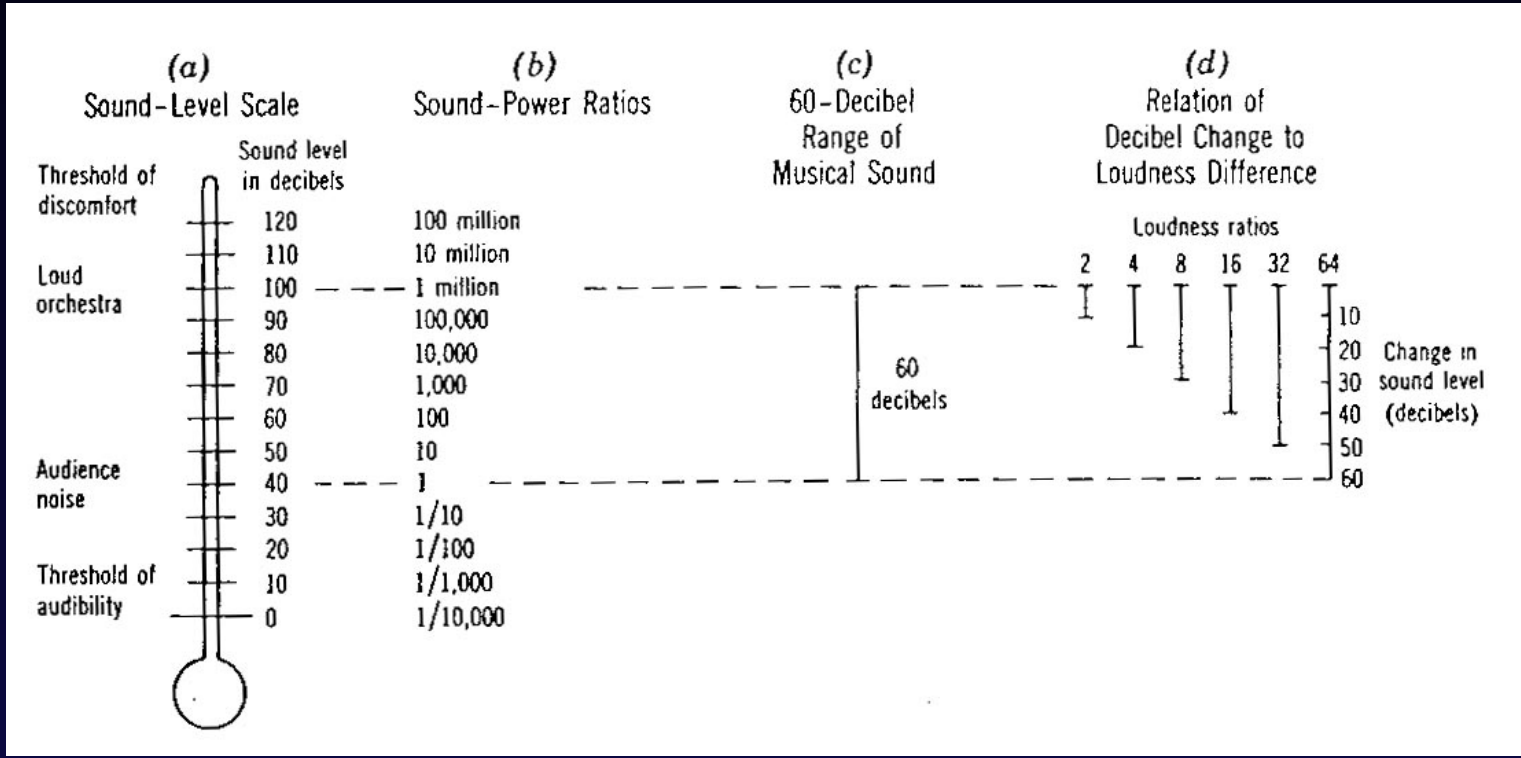


Figure 1

SPL (sound pressure level)

L_p= SPL = 20 log p/ p_{ref}

p_{ref} = 0.00002 Pa

Pa = [N/m²] = [Kg·m/s²·m²] = [kg/s²- m]

SWL (sound power level)

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

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

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

I (intensity)

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

$I_{ref} = 10^{-12}\ W/m^2 = 1x10^{-12}\ kg/s^3$

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:

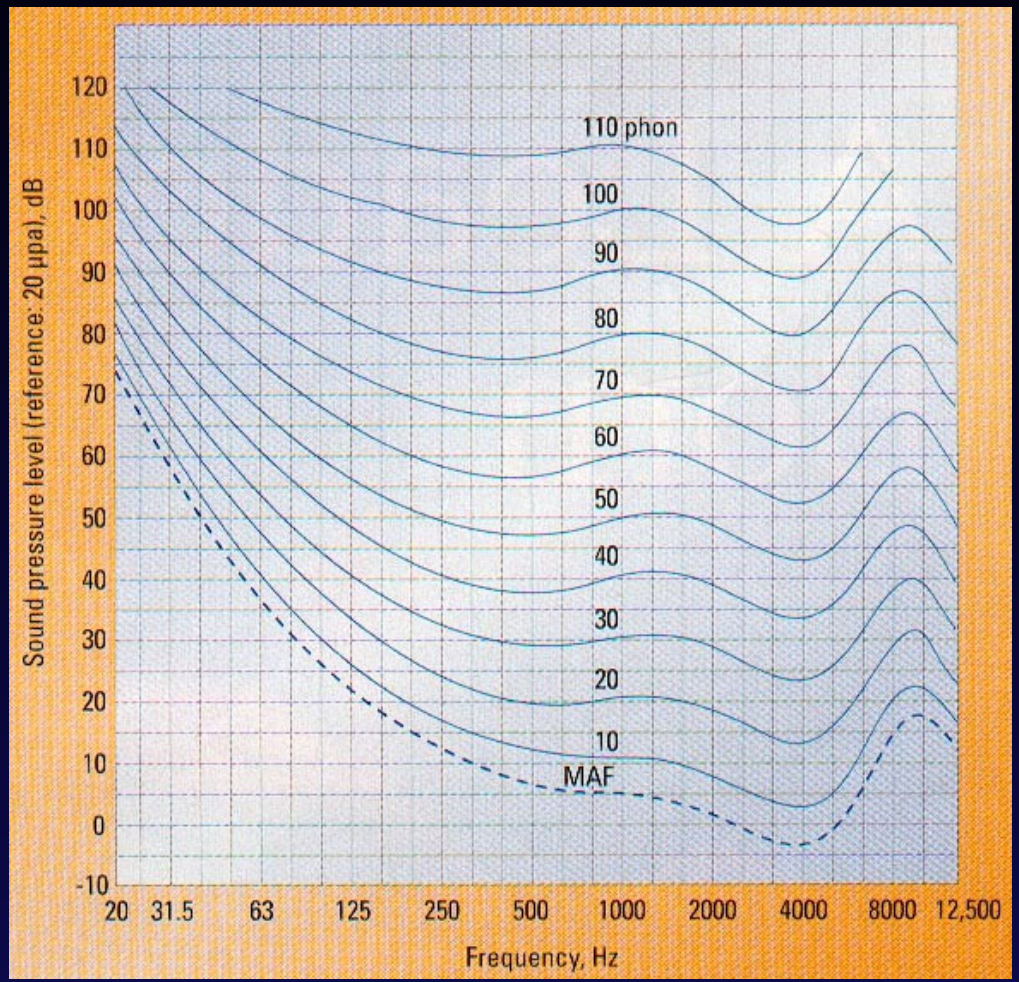


Figure 2

Human Factors

Figure 3

Human Factors

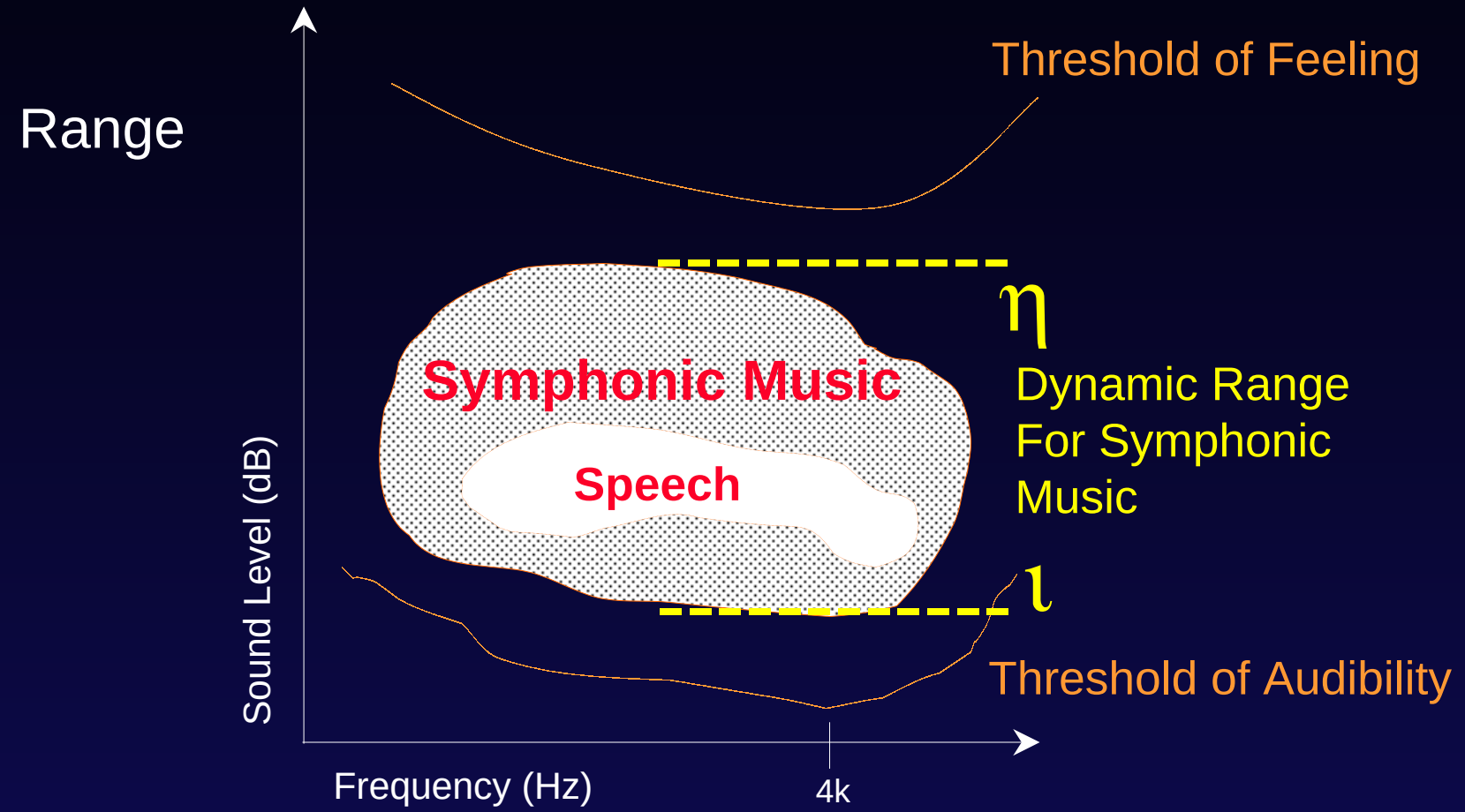


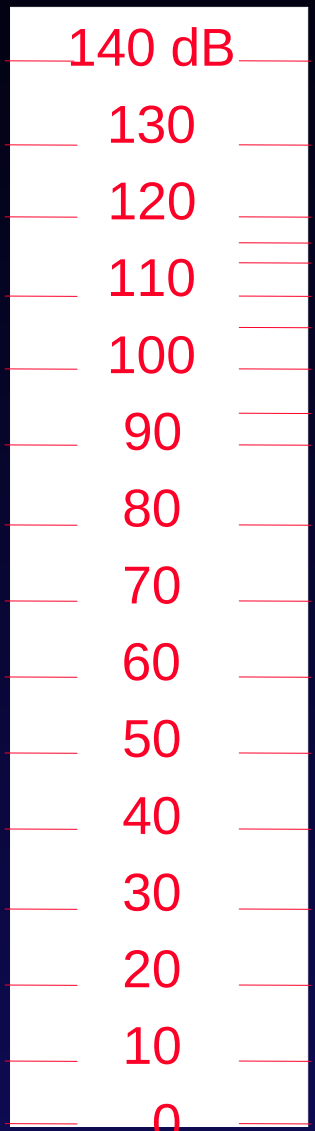
Figure 4

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



Jet Plane (100 feet)

Amplified Rock and Roll (6 feet)

Threshold of Pain

Diesel Truck (30 feet)

Food Blender (3 feet)

Motorcycle (30 feet)

Automobile (25 feet)

Loud Singing (3 feet)

Inside Car

Normal Conversation

Quiet Street

Quiet Home

Quiet Whisper (3 feet)

Rustling Leaves

Human Breathing

Threshold of Hearing

117 dB Chainsaw (3 feet)

115 dB Pneumatic Riveter (3 feet)

107 dB Power Mower (3 feet)

94 dB Subway (inside)

Figure 6

Measurement

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

Figure 7

History

שמות תרומה כו

אַרְבַּע בָּאַמָּה הַיְרִיעָה הָאֶחָת מִדָּה אַחַת לְכָל־הַיְרִיעֹת:
3 חֲמֵשׁ הַיְרִיעֹת תִּהְיֶיןָ חֻבָּרֹת אִשָּׁה אֶל־אֲחֹתָהּ וְחָמֵשׁ יְרִיעֹת
4 חֻבָּרֹת אִשָּׁה אֶל־אֲחֹתָהּ: וְעָשִׂיתָ לֻלְאֹת תְּכֵלֶת עַל שְׂפַת
הַיְרִיעָה הָאֶחָת מִקָּצָה בְּחֹבָרֶת וְכֵן תַּעֲשֶׂה בִּשְׂפַת הַיְרִיעָה
ה הַקִּיצוֹנָה בַּמַּחְבֶּרֶת הַשֵּׁנִית: חֲמִשִּׁים לֻלְאֹת תַּעֲשֶׂה
בַּיְרִיעָה הָאֶחָת וַחֲמִשִּׁים לֻלְאֹת תַּעֲשֶׂה בִּקְצֵה הַיְרִיעָה־
אֲשֶׁר בַּמַּחְבֶּרֶת הַשֵּׁנִית מַקְבִּילֹת הַלֻּלְאֹת אִשָּׁה אֶל־
6 אֲחֹתָהּ: וְעָשִׂיתָ חֲמִשִּׁים קַרְסֵי זָהָב וְחִבַּרְתָּ אֶת־הַיְרִעֹת
7 אִשָּׁה אֶל־אֲחֹתָהּ בַּקְּרָסִים וְהָיָה הַמִּשְׁכָּן אֶחָד: וְעָשִׂיתָ
יְרִיעֹת עִזִּים לְאֹהֶל עַל־הַמִּשְׁכָּן עַשְׁתֵּי־עֶשְׂרֵה יְרִיעֹת
8 תַּעֲשֶׂה אֹתָם: אׇרֶךְ ׀ הַיְרִיעָה הָאַחַת שְׁלֹשִׁים בָּאַמָּה
וְרֹחַב אַרְבַּע בָּאַמָּה הַיְרִיעָה הָאֶחָת מִדָּה אַחַת לְעַשְׁתֵּי
9 עֶשְׂרֵה יְרִיעֹת: וְחִבַּרְתָּ אֶת־חֲמֵשׁ הַיְרִיעֹת לְבָד וְאֶת־
שֵׁשׁ הַיְרִיעֹת לְבָד וְכָפַלְתָּ אֶת־הַיְרִיעָה הַשִּׁשִּׁית אֶל־מוּל
י פְּנֵי הָאֹהֶל: וְעָשִׂיתָ חֲמִשִּׁים לֻלְאֹת עַל שְׂפַת הַיְרִיעָה
הָאַחַת הַקִּיצוֹנָה בַּחֹבָרֶת וַחֲמִשִּׁים לֻלְאֹת עַל שְׂפַת

v. 9. קמין בו"ק

שמות תרומה כה כו

33 וְשִׁלִּשָׁה קְנֵי מְנֹרָה מִצִּדָּהּ הַשֵּׁנִי: שְׁלֹשָׁה גְבִעִים מְשֻׁקָּדִים
בַּקָּנֶה הָאֶחָד כַּפְתֹּר וָפָרַח וּשְׁלֹשָׁה גְבִעִים מְשֻׁקָּדִים
בַּקָּנֶה הָאֶחָד כַּפְתֹּר וָפָרַח כֵּן לְשִׁשֶּׁת הַקָּנִים הַיֹּצְאִים
34 מִן־הַמְּנֹרָה: וּבַמְּנֹרָה אַרְבָּעָה גְבִעִים מְשֻׁקָּדִים כַּפְתֹּרֵיהֶ
לה וּפְרָחֶיהָ: וְכַפְתֹּר תַּחַת שְׁנֵי הַקָּנִים מִמֶּנָּה וְכַפְתֹּר תַּחַת
שְׁנֵי הַקָּנִים מִמֶּנָּה וְכַפְתֹּר תַּחַת־שְׁנֵי הַקָּנִים מִמֶּנָּה לְשִׁשֶּׁת
36 הַקָּנִים הַיֹּצְאִים מִן־הַמְּנֹרָה: כַּפְתֹּרֵיהֶם וְקָנֹתָם מִמֶּנָּה
37 יִהְיוּ כֻלָּהּ מִקְשָׁה אַחַת זָהָב טָהוֹר: וְעָשִׂיתָ אֶת־נֵרֹתֶיהָ
38 שִׁבְעָה וְהֶעֱלָה אֶת־נֵרֹתֶיהָ וְהֵאִיר עַל־עֵבֶר פָּנֶיהָ: וּמַלְקָחֶיהָ
39 וּמַחְתֹּתֶיהָ זָהָב טָהוֹר: כִּכַּר זָהָב טָהוֹר יַעֲשֶׂה אֹתָהּ אֶת
מ כָּל־הַכֵּלִים הָאֵלֶּה: וּרְאֵה וַעֲשֵׂה בְּתַבְנִיתָם אֲשֶׁר־אַתָּה
מָרְאֶה בָּהָר: ס שלישׁ

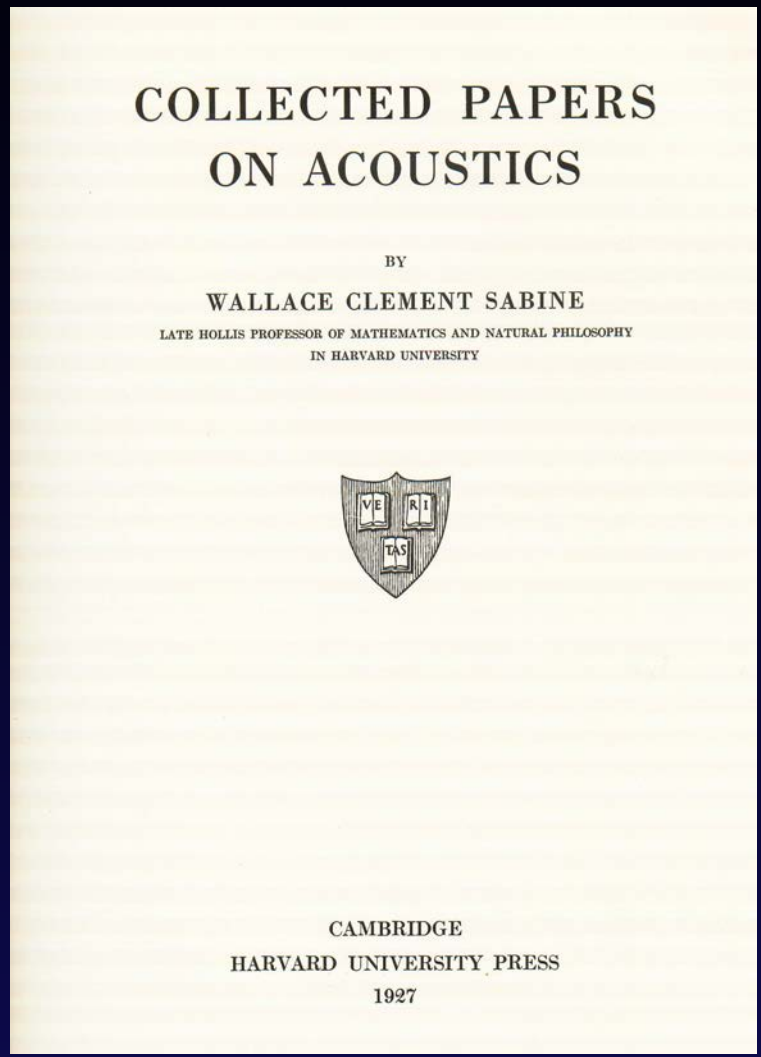
כו CAP. XXVI.

א וְאֶת־הַמִּשְׁכָּן תַּעֲשֶׂה עֶשֶׂר יְרִיעֹת שֵׁשׁ מָשְׁזָר וּתְכֵלֶת
וְאַרְגָּמָן וְתוֹלַעַת שָׁנִי כְּרֻבִים מַעֲשֵׂה חֹשֵׁב תַּעֲשֶׂה אֹתָם:
2 אׇרֶךְ ׀ הַיְרִיעָה הָאַחַת שְׁמֹנֶה וְעֶשְׂרִים בָּאַמָּה וְרֹחַב

כה' v. 39. סבורין תעשה

Exodus XXVI

History



COLLECTED PAPERS
ON ACOUSTICS

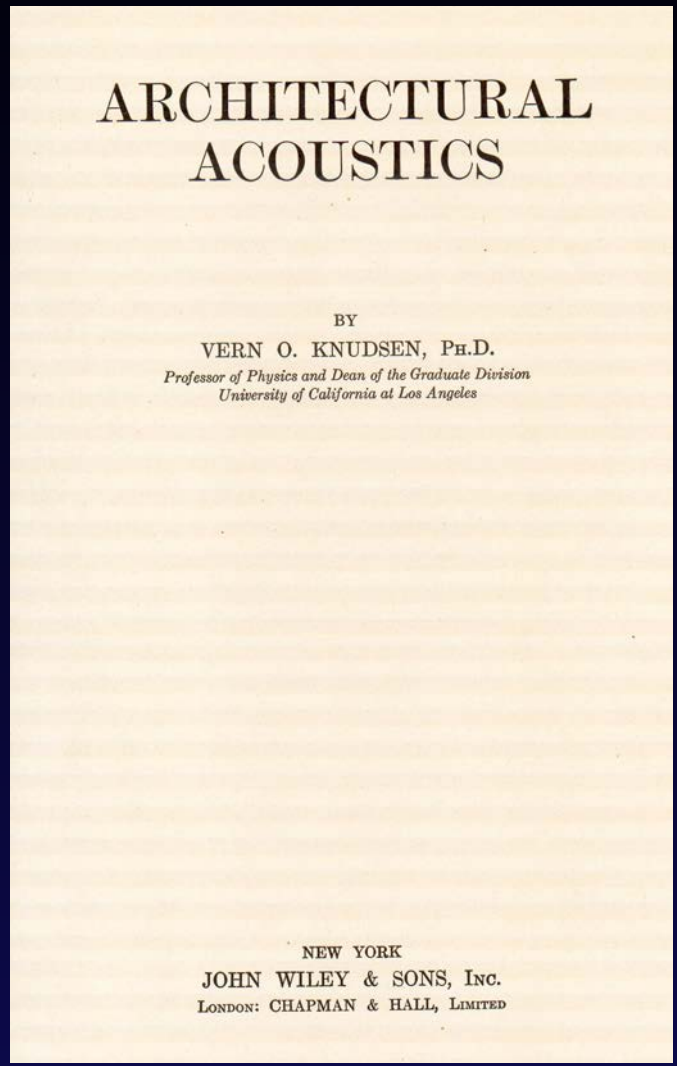
BY

WALLACE CLEMENT SABINE

LATE HOLLIS PROFESSOR OF MATHEMATICS AND NATURAL PHILOSOPHY
IN HARVARD UNIVERSITY

CAMBRIDGE
HARVARD UNIVERSITY PRESS
1927

History



ARCHITECTURAL
ACOUSTICS

BY

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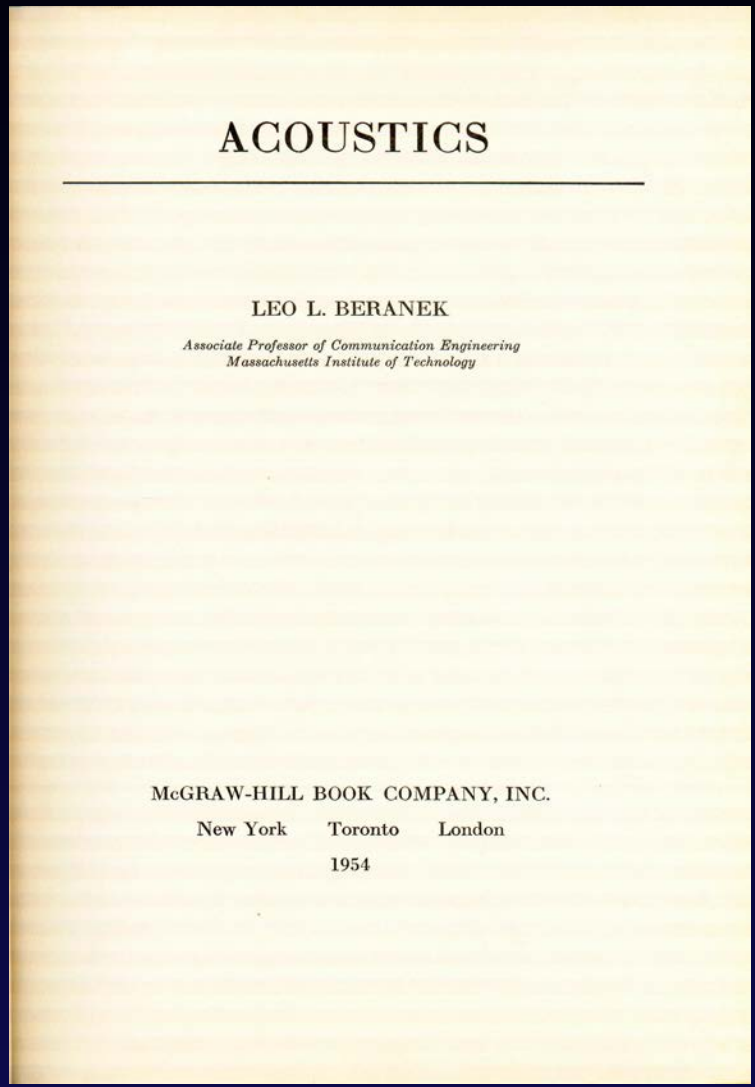
NEW YORK
JOHN WILEY & SONS, INC.
LONDON: CHAPMAN & HALL, LIMITED

History



ACOUSTICS

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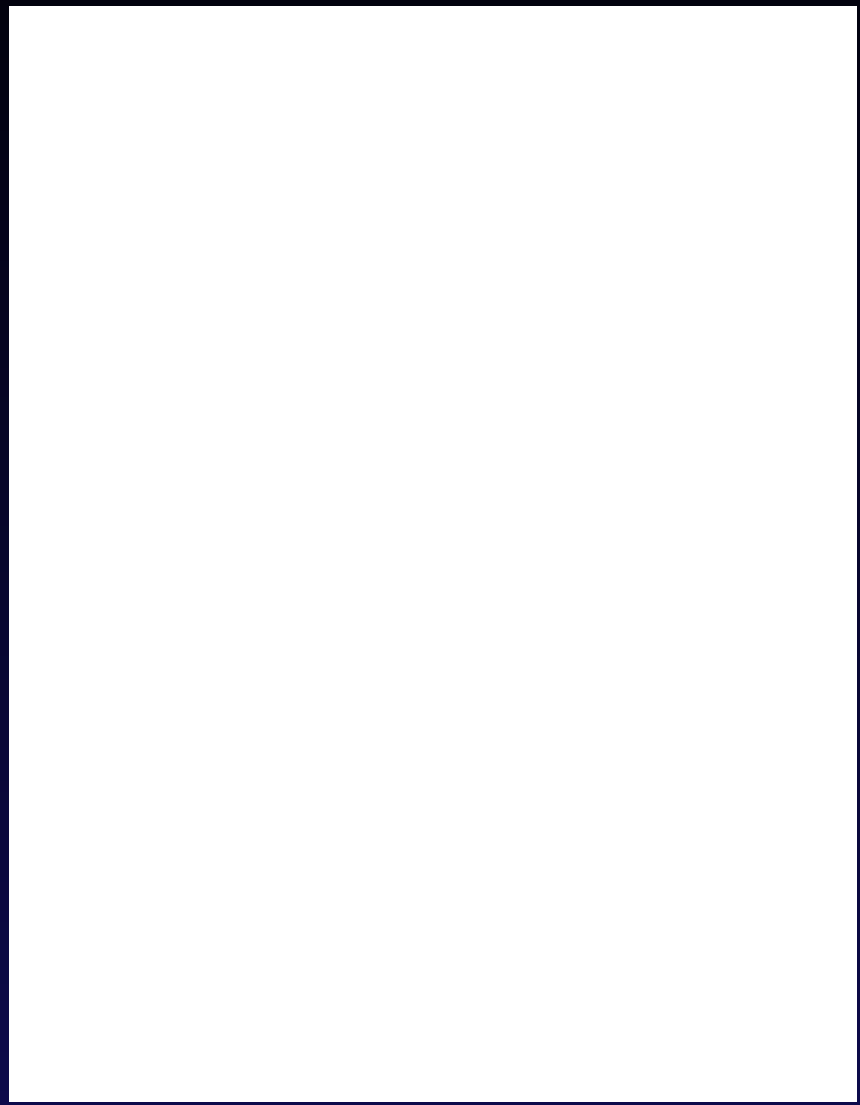
Massachusetts Institute of Technology

McGRAW-HILL BOOK COMPANY, INC.
New York Toronto London
1954

History



Reflection

$x > 4\lambda$

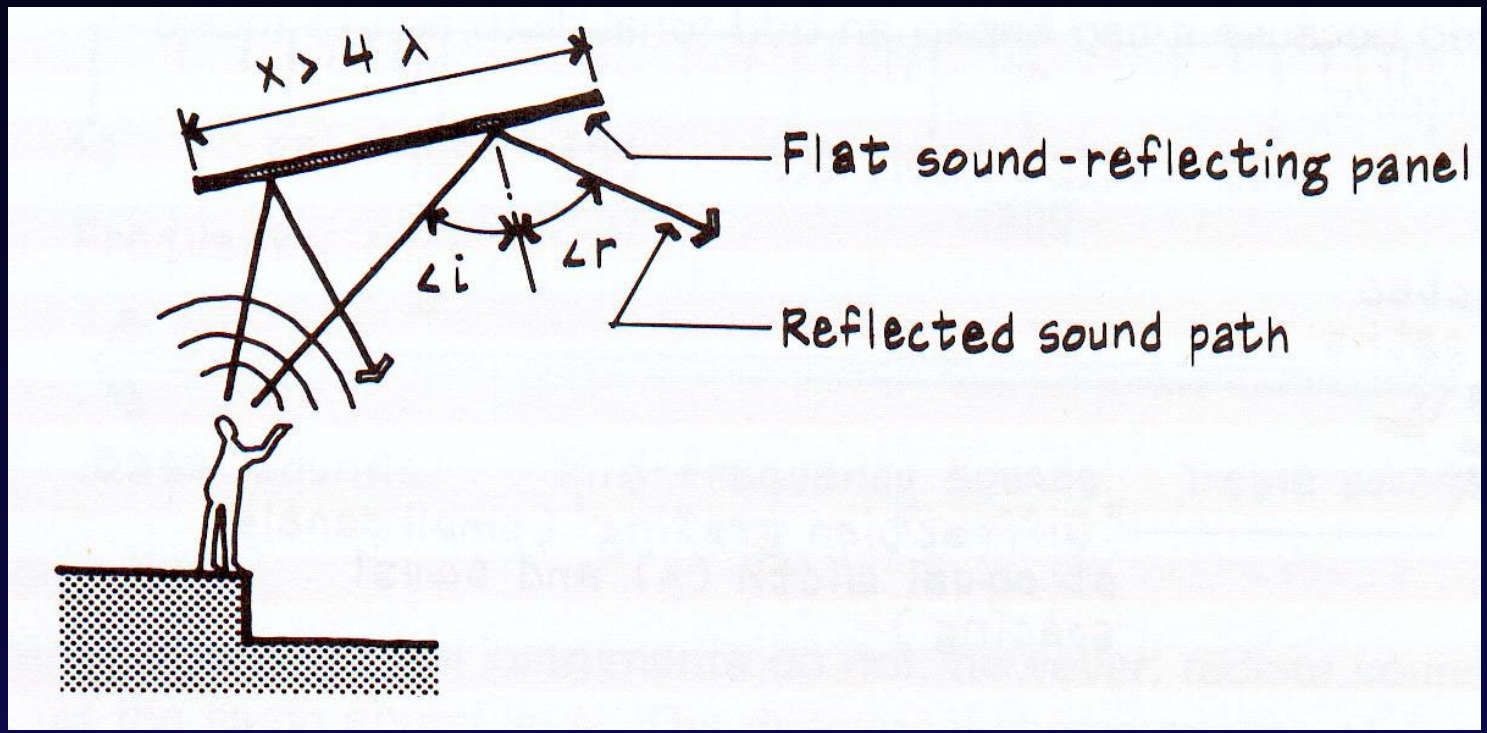


Figure 8

Diffusion

$x \approx \lambda$

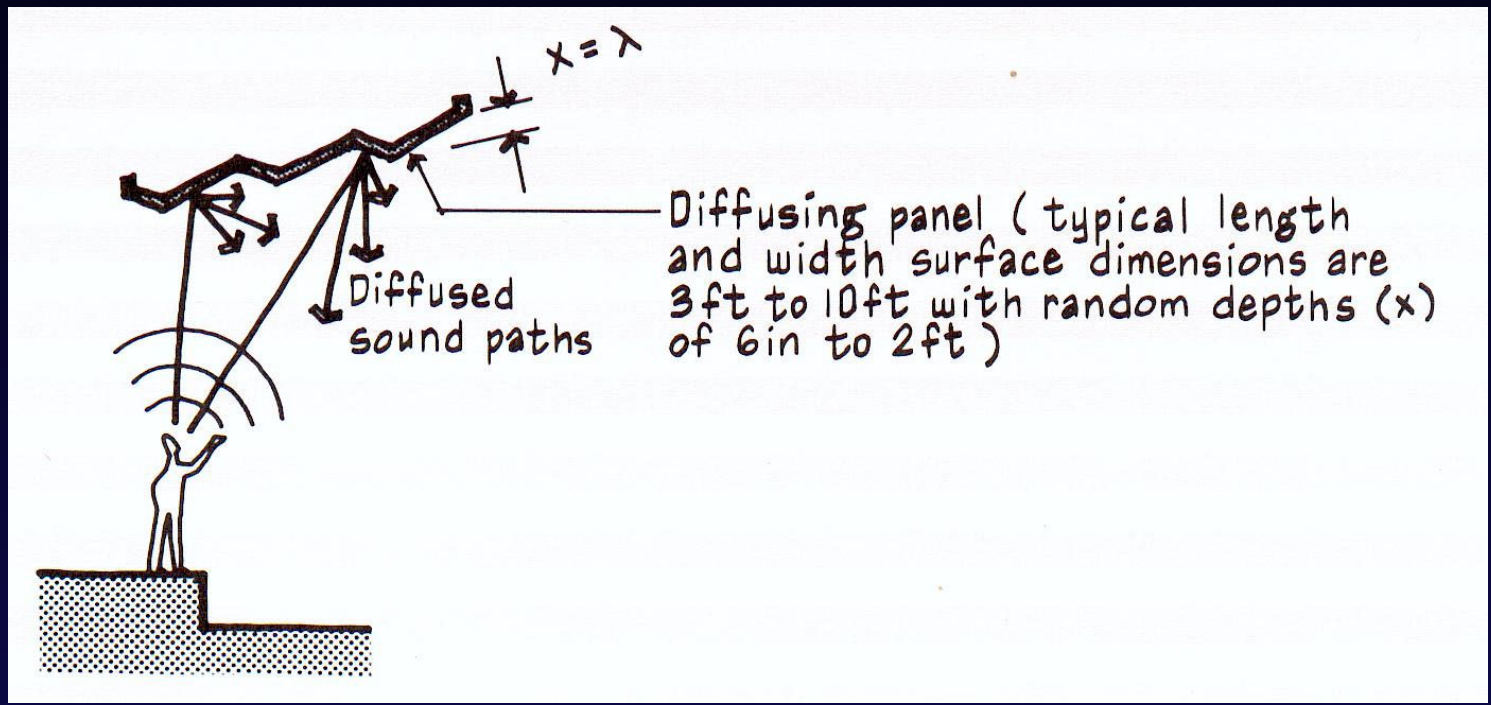


Figure 9

Diffraction

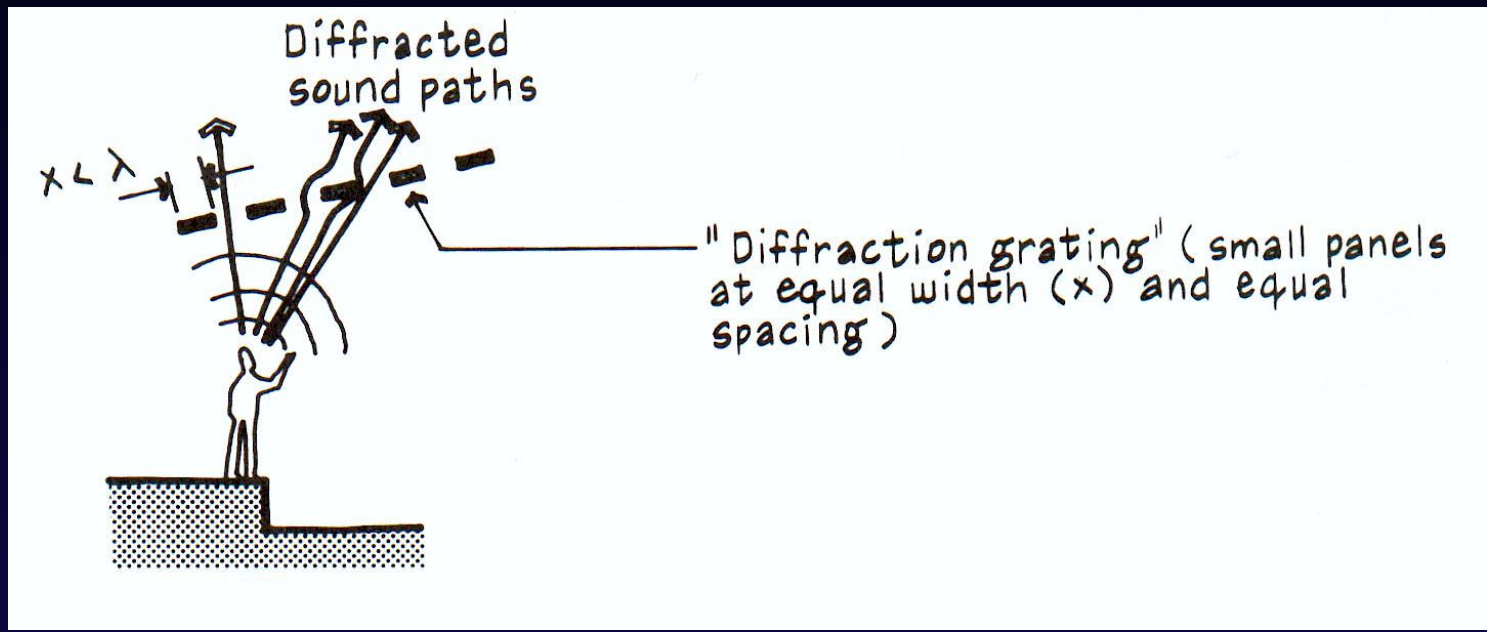


Figure 10

Concave Reflector

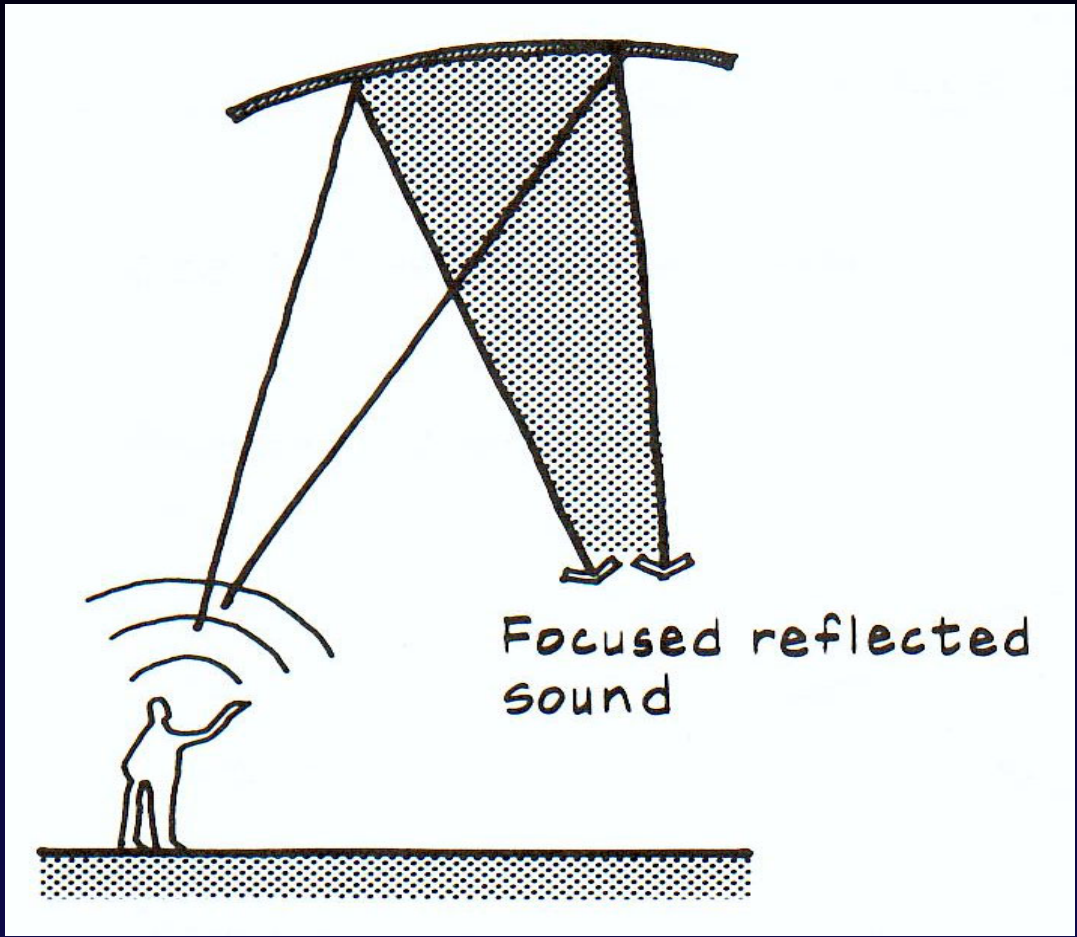


Figure 11

Flat Reflector

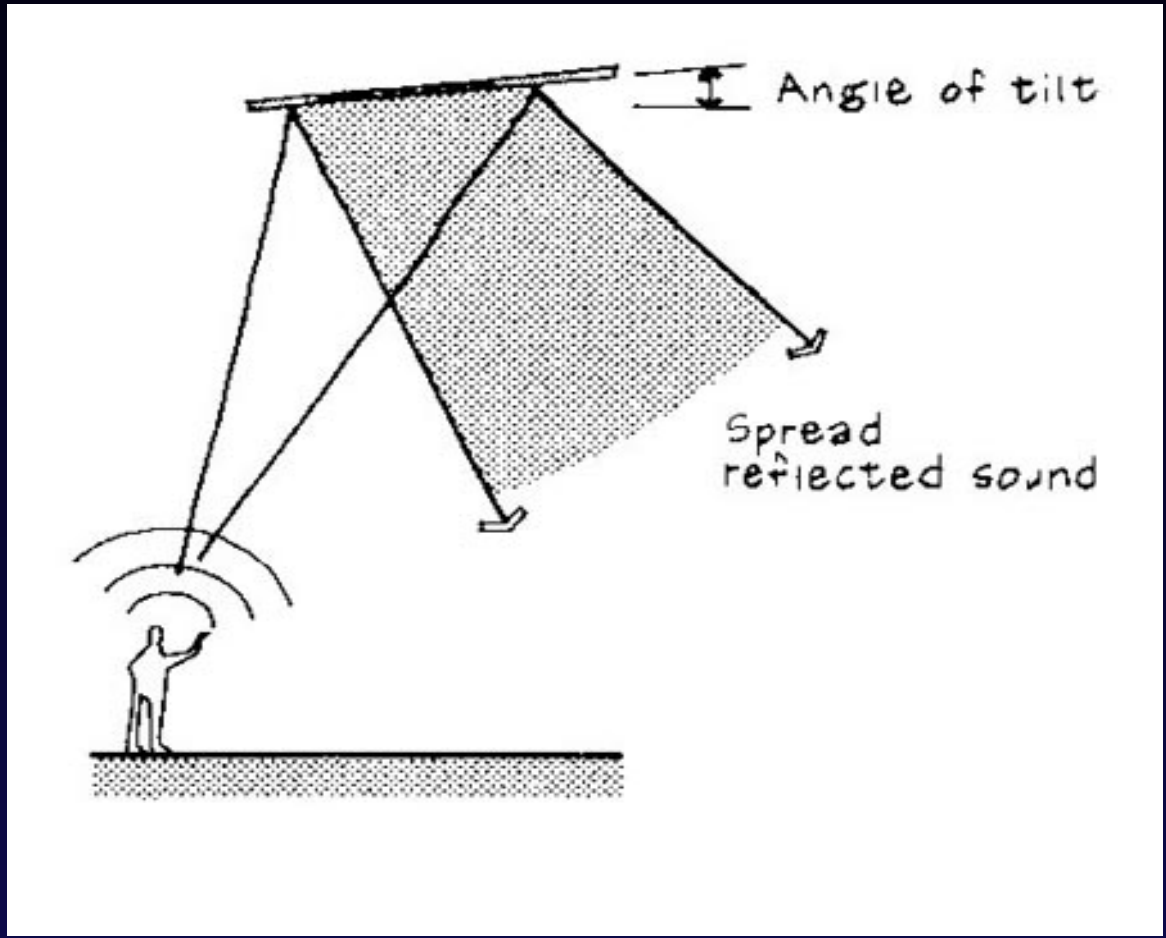


Figure 12

Convex Reflector

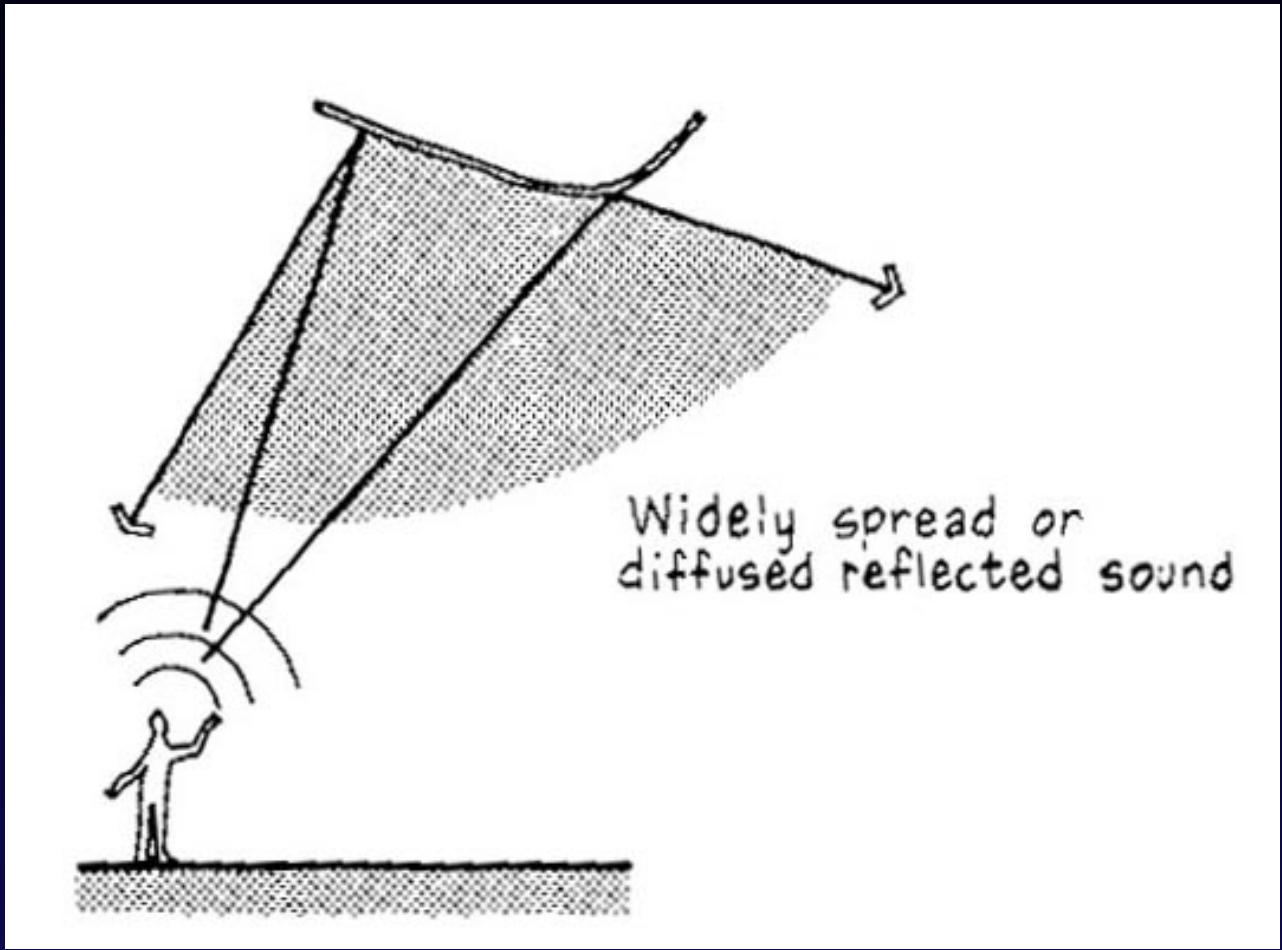


Figure 13

Room Modes

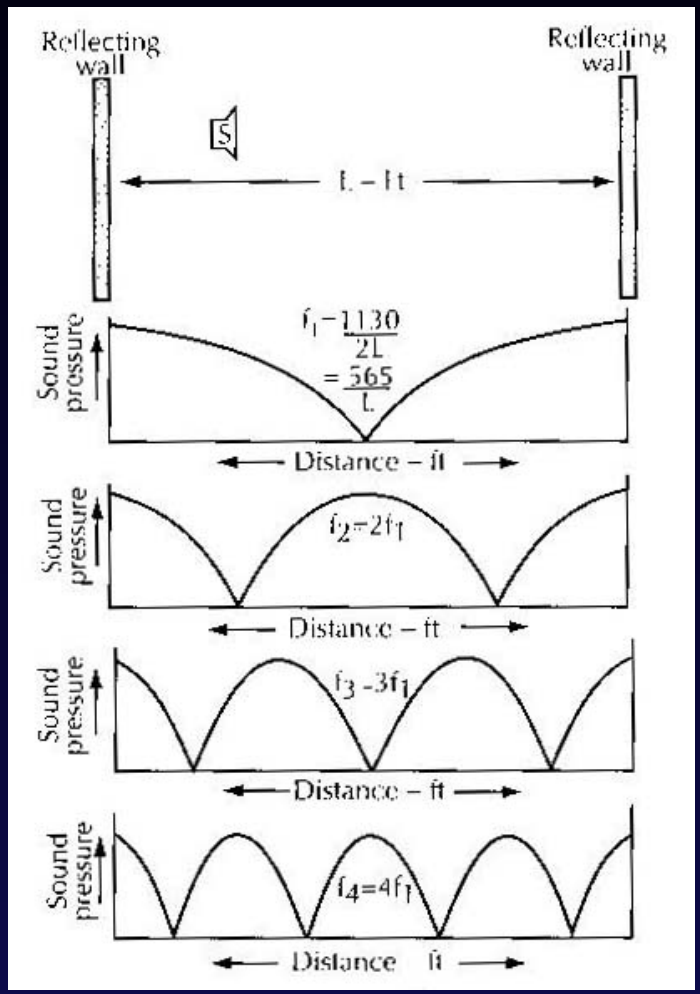


Figure 14

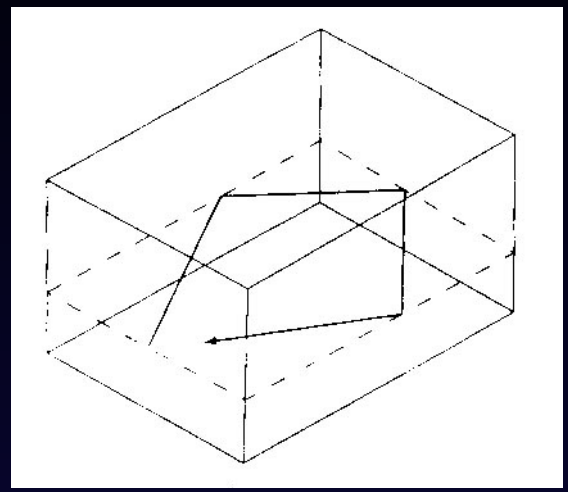


Figure 15

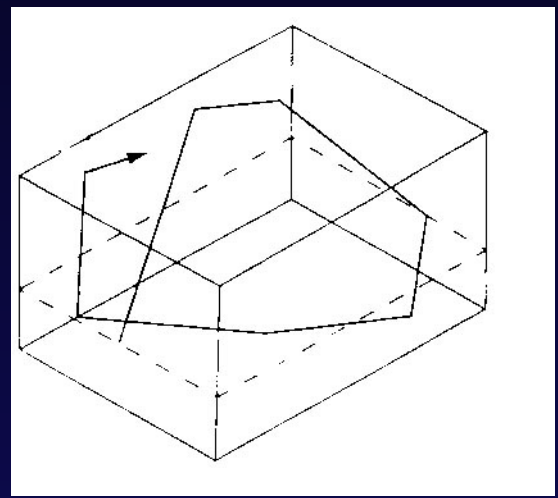


Figure 16

Reverberant Decay

large room

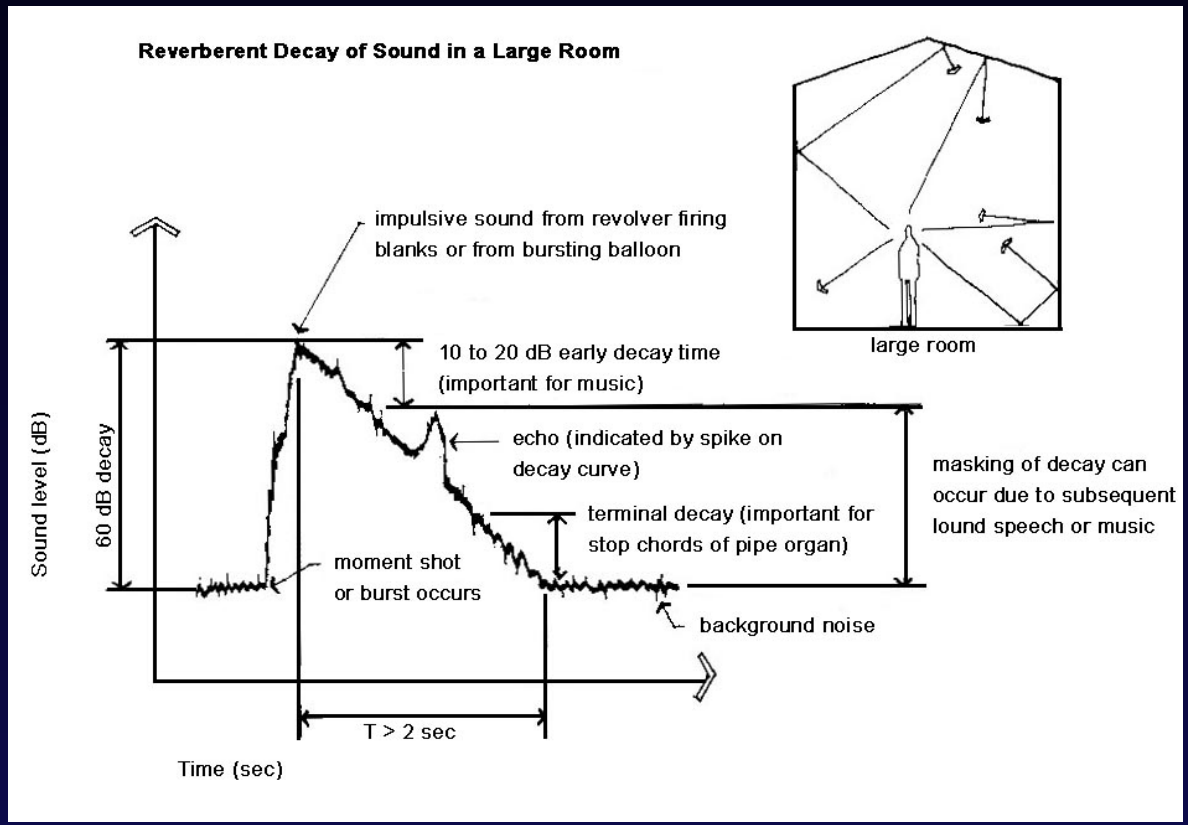


Figure 17

Reverberant Decay

small room

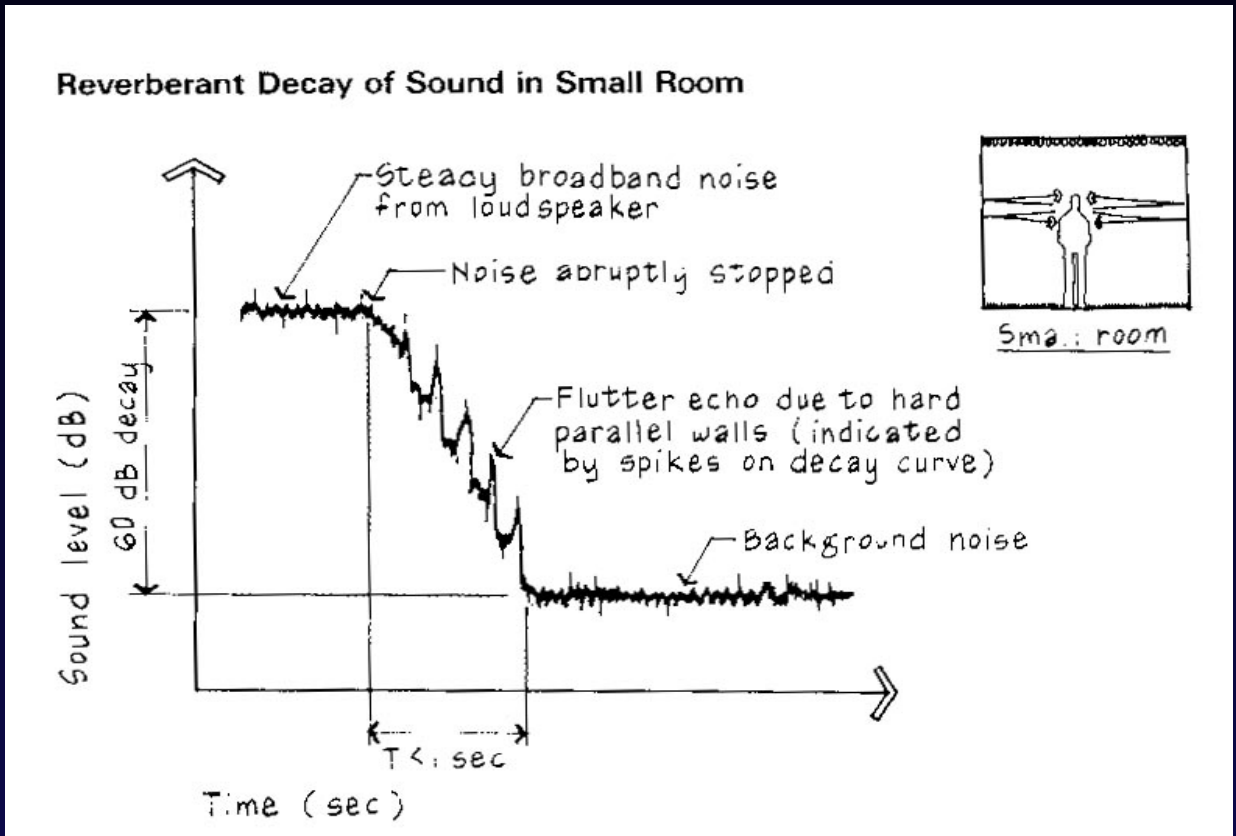


Figure 18

Materials

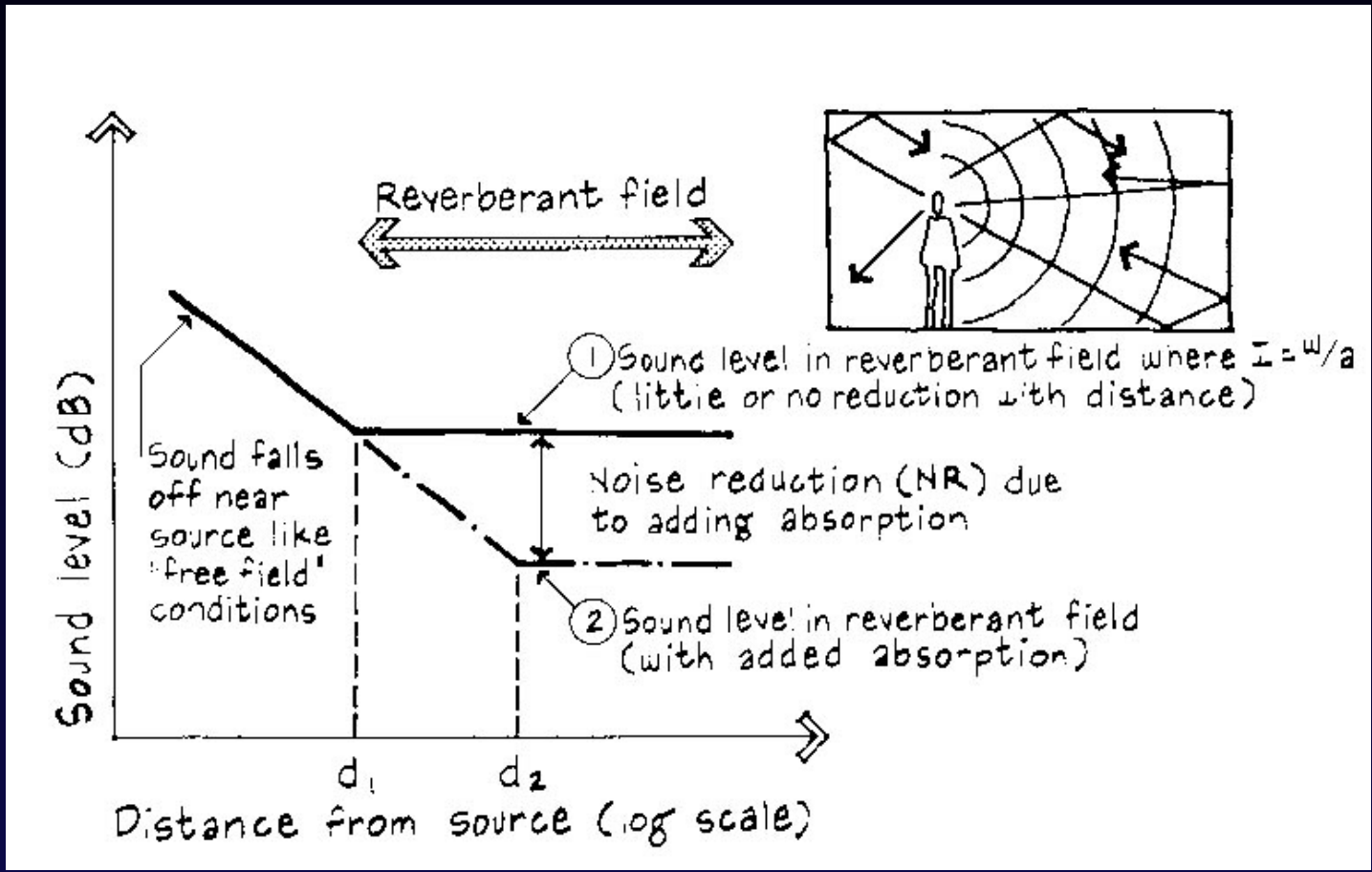


Figure 19

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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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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