First Pan-American/Iberian Meeting on Acoustics
Cancun, Mexico
2 – 6 December 2002
Acoustics


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:** $P_o \approx 100 \text{ kPa}$

$p(t) = \text{instantaneous}$

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

**Frequency/ Wavelength:**

Speed of Sound: $c = \frac{\lambda}{f}$

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

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

Figure 1
SPL (sound pressure level)

\[ L_p = \text{SPL} = 20 \log \frac{p}{p_{\text{ref}}} \]

\[ p_{\text{ref}} = 0.00002 \text{ Pa} \]

\[ \text{Pa} = [\text{N/m}^2] = [\text{Kg} \cdot \text{m/s}^2 \cdot \text{m}^2] = [\text{kg/s}^2 \cdot \text{m}] \]
**SWL (sound power level)**

\[
\text{SWL} = 10 \log \frac{W}{W_{\text{ref}}}
\]

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

\[
W = [\text{kg} \times \text{m}^2 / \text{s}^3]
\]
\( I (\text{intensity}) \)

\[
L_I = 10 \log \frac{I}{I_{\text{ref}}}
\]

\[
I_{\text{ref}} = 10^{-12} \text{ W/m}^2 = 1 \times 10^{-12} \text{ kg/s}^3
\]
Waves

PLANE:

\[ \frac{\partial^2 p}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0 \]

COMPLEX FORM OF THE HARMONIC SOLUTION

\[ P = Ae^{j(wt-kx)} + Be^{j(wt+kx)} \]

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**Waves**

**CYLINDRICAL:** \( \nabla^2 p + k^2 p = 0 \) (\( k = \frac{\nu}{c} \))

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

One solution:

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

\[\rightarrow\]

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

\[\rightarrow\]

\( W \to 0 \quad i \frac{2A}{\pi} \ln(w)e^{-2\pi i vt} \)

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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 \(a << \lambda\) then \(p/r >> \frac{\partial p}{\partial r}\) @ \(r = a\)

\[
P \cong \rho \frac{1}{4\pi} \frac{dS}{dt} \quad \text{at } r = a
\]

\[
p \cong \rho \frac{1}{4\pi r} S' \left( t - \frac{r}{c} \right)
\]

where \(S'(z) = (d/dz)S(z)\)

\(S = \text{Total Flow}\)
Human Factors

RANGE OF AUDIBILITY:

Figure 2
Figure 3
Human Factors

Figure 4

Symphonic Music

Threshold of Feeling

Dynamic Range

For Symphonic Music

Threshold of Audibility

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## Human Factors

### Critical Bands

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

**Figure 5** Critical Bands

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**Common Sounds**

<table>
<thead>
<tr>
<th>Sound Description</th>
<th>Decibels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Plane (100 feet)</td>
<td>140 dB</td>
</tr>
<tr>
<td>Amplified Rock and Roll (6 feet)</td>
<td>130 dB</td>
</tr>
<tr>
<td><strong>Threshold of Pain</strong></td>
<td>120 dB</td>
</tr>
<tr>
<td>Diesel Truck (30 feet)</td>
<td>100 dB</td>
</tr>
<tr>
<td>Food Blender (3 feet)</td>
<td>90 dB</td>
</tr>
<tr>
<td>Motorcycle (30 feet)</td>
<td>80 dB</td>
</tr>
<tr>
<td>Automobile (25 feet)</td>
<td>70 dB</td>
</tr>
<tr>
<td>Loud Singing (3 feet)</td>
<td>70 dB</td>
</tr>
<tr>
<td>Inside Car</td>
<td>70 dB</td>
</tr>
<tr>
<td>Normal Conversation</td>
<td>60 dB</td>
</tr>
<tr>
<td>Quiet Street</td>
<td>50 dB</td>
</tr>
<tr>
<td>Quiet Home</td>
<td>40 dB</td>
</tr>
<tr>
<td>Quiet Whisper (3 feet)</td>
<td>30 dB</td>
</tr>
<tr>
<td>Rustling Leaves</td>
<td>20 dB</td>
</tr>
<tr>
<td>Human Breathing</td>
<td>10 dB</td>
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<tr>
<td><strong>Threshold of Hearing</strong></td>
<td>0 dB</td>
</tr>
</tbody>
</table>

**Figure 6**

- 117 dB Chainsaw (3 feet)
- 115 dB Pneumatic Riveter (3 feet)
- 107 dB Power Mower (3 feet)
- 94 dB Subway (inside)

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## Measurement

<table>
<thead>
<tr>
<th>THIRD OCTAVE BAND NO.</th>
<th>CENTER FREQUENCY (Hz.)</th>
<th>FREQUENCY RANGE (Hz)</th>
<th>CORRESPONDING OCTAVE BAND</th>
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<td>14</td>
<td>25</td>
<td>22 to 28</td>
<td>Sub-Octave</td>
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<td>15</td>
<td>-- 31.5 --</td>
<td>28 to 36</td>
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<td>16</td>
<td>40</td>
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<td>56 to 71</td>
<td>45 to 89</td>
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<td>19</td>
<td>80</td>
<td>71 to 89</td>
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<td>20</td>
<td>100</td>
<td>89 to 112</td>
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<td>21</td>
<td>-- 125 --</td>
<td>112 to 141</td>
<td>89 to 178</td>
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<tr>
<td>22</td>
<td>160</td>
<td>141 to 178</td>
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<td>200</td>
<td>178 to 224</td>
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<td>-- 250 --</td>
<td>224 to 282</td>
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<td>25</td>
<td>315</td>
<td>282 to 355</td>
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<td>26</td>
<td>400</td>
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<td>27</td>
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<td>447 to 563</td>
<td>354 to 709</td>
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<td>28</td>
<td>630</td>
<td>562 to 708</td>
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<td>29</td>
<td>800</td>
<td>708 to 892</td>
<td>5</td>
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<tr>
<td>30</td>
<td>-- 1000 --</td>
<td>891 to 1123</td>
<td>707 to 1414</td>
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<td>31</td>
<td>1250</td>
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<td>1600</td>
<td>1412 to 1779</td>
<td>6</td>
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<tr>
<td>33</td>
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<td>1778 to 2240</td>
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<td>34</td>
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<td>3150</td>
<td>2817 to 3549</td>
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<td>36</td>
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<td>3547 to 4469</td>
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<td>5000</td>
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<tr>
<td>40</td>
<td>10000</td>
<td>8909 to 11225</td>
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</tbody>
</table>

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History

Exodus XXVI

Menlo Scientific Acoustics
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
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

\[ \lambda \approx \lambda \]

**Figure 9**

Diffusing panel (typical length and width surface dimensions are 3ft to 10ft with random depths (x) of 6in to 2ft)
Diffraction

Figure 10

"Diffraction grating" (small panels at equal width \(x\) and equal spacing)
Concave Reflector

Figure 11

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Flat Reflector

Figure 12
Convex Reflector

Figure 13

Widely spread or diffused reflected sound
Room Modes

Figure 14

Figure 15

Figure 16
Reverberant Decay

large room

Figure 17

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Reverberant Decay

small room

Figure 18

Reverberant Decay of Sound in Small Room

- Steady broadband noise from loudspeaker
- Noise abruptly stopped
- Flutter echo due to hard parallel walls (indicated by spikes on decay curve)
- Background noise

Time (sec)

Sound level (dB)

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Materials

Figure 19

Reverberant field

1. Sound level in reverberant field where $l = \omega / a$ (little or no reduction with distance)

2. Sound level in reverberant field (with added absorption)

3. Noise reduction (NR) due to adding absorption

Sound level (dB)

Distance from source (log scale)
Small Rooms

- Modes
- Shape
- Reflection management
Large Rooms

TIME METRICS

Reverberation Time (*RT60*)

Bass Ratio (*BR*)
## Large Rooms

### ENERGY METRICS

<table>
<thead>
<tr>
<th>Energy Metric</th>
<th>Description</th>
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<tbody>
<tr>
<td>Strength ((G))</td>
<td>Speech Time Index ((STI))</td>
</tr>
<tr>
<td>Sound Pressure Distribution ((\Delta L))</td>
<td>Articulation Loss ((AL_{cons}))</td>
</tr>
<tr>
<td>Center Time ((t_s))</td>
<td>Subjective Intelligibility Tests</td>
</tr>
<tr>
<td>Energy Definition Measure ((C_{50}))</td>
<td>Clarity ((C_{80}))</td>
</tr>
<tr>
<td>Register Balance Measure ((B_{R}))</td>
<td>Sound Coloration ((K_t \text{ and } K_h))</td>
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</table>

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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

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References


References


Handbook for Sound Engineers, Glen M. Ballou (editor), Focal Press, Boston, 2002

The Pentateuch and Haftorahs, J. H. Hertz (editor), Soncino Press, London, 1960


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