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: \( P_o \approx 100 \text{ kPa} \)

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

\( p = \text{effective} = \sqrt{<p^2(t)>} \)

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)

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

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

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

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

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

\[
W = [\text{kg} \cdot \text{m}^2 / \text{s}^3]
\]
**I (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

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

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

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

One solution:

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

\[\rightarrow \quad W \rightarrow \infty \quad A \sqrt{\frac{2}{\pi k w}} e^{i k (w - c t)} - i(\pi/4) \quad k = \frac{2\pi \nu}{c} = \frac{2\pi}{\lambda}\]

\[\rightarrow \quad W \rightarrow 0 \quad i \frac{2A}{\pi} \ln(w) e^{-2\pi i \nu t}\]
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 \(a<<\lambda\) then \(p/r \gg \frac{\partial p}{\partial r} \at r = a\)

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

\[
p \approx \frac{\rho}{4\pi r} \left[ S' \left( t - \frac{r}{c} \right) \right] \text{ where } S'(z) = \left( \frac{d}{dz} \right) S(z)
\]

\[
S = \text{Total Flow}
\]
Human Factors

RANGE OF AUDIBILITY:

Figure 2
**Human Factors**

![Figure 3](image-url)
Human Factors

Range

Sound Level (dB)

Frequency (Hz)

4k

Threshold of Feeling

Dynamic Range
For Symphonic Music

Threshold of Audibility

Figure 4

Symphonic Music

Speech

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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>
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<td>50</td>
<td>100</td>
<td>13</td>
<td>1850</td>
<td>280</td>
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<tr>
<td>2</td>
<td>150</td>
<td>100</td>
<td>14</td>
<td>2150</td>
<td>320</td>
</tr>
<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>
</tr>
<tr>
<td>6</td>
<td>570</td>
<td>120</td>
<td>18</td>
<td>4000</td>
<td>700</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>12</td>
<td>1600</td>
<td>240</td>
<td>24</td>
<td>13500</td>
<td>3500</td>
</tr>
</tbody>
</table>

*Figure 5: Critical Bands*
### Common Sounds

<table>
<thead>
<tr>
<th>Sound</th>
<th>Decibels (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Plane (100 feet)</td>
<td>140</td>
</tr>
<tr>
<td>Amplified Rock and Roll (6 feet)</td>
<td>130</td>
</tr>
<tr>
<td><strong>Threshold of Pain</strong></td>
<td></td>
</tr>
<tr>
<td>Diesel Truck (30 feet)</td>
<td>120</td>
</tr>
<tr>
<td>Food Blender (3 feet)</td>
<td>110</td>
</tr>
<tr>
<td>Motorcycle (30 feet)</td>
<td>100</td>
</tr>
<tr>
<td>Automobile (25 feet)</td>
<td>90</td>
</tr>
<tr>
<td>Loud Singing (3 feet)</td>
<td>80</td>
</tr>
<tr>
<td>Inside Car</td>
<td>70</td>
</tr>
<tr>
<td>Normal Conversation</td>
<td>60</td>
</tr>
<tr>
<td>Quiet Street</td>
<td>50</td>
</tr>
<tr>
<td>Quiet Home</td>
<td>40</td>
</tr>
<tr>
<td>Quiet Whisper (3 feet)</td>
<td>30</td>
</tr>
<tr>
<td>Rustling Leaves</td>
<td>20</td>
</tr>
<tr>
<td>Human Breathing</td>
<td>10</td>
</tr>
<tr>
<td><strong>Threshold of Hearing</strong></td>
<td>0</td>
</tr>
</tbody>
</table>

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

Figure 6

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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>
</tr>
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<tr>
<td>14</td>
<td>25</td>
<td>22 to 28</td>
<td>Sub-Octave 22 to 45</td>
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<tr>
<td>15</td>
<td>-- 31.5 --</td>
<td>28 to 36</td>
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<tr>
<td>16</td>
<td>40</td>
<td>35 to 45</td>
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<tr>
<td>17</td>
<td>50</td>
<td>45 to 56</td>
<td>1</td>
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<tr>
<td>18</td>
<td>-- 63 --</td>
<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>
<td>2</td>
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<tr>
<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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<tr>
<td>23</td>
<td>200</td>
<td>178 to 224</td>
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<td>-- 250 --</td>
<td>224 to 282</td>
<td>178 to 355</td>
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<tr>
<td>25</td>
<td>315</td>
<td>282 to 355</td>
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<td>26</td>
<td>400</td>
<td>355 to 447</td>
<td>4</td>
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<tr>
<td>27</td>
<td>-- 500 --</td>
<td>447 to 563</td>
<td>354 to 709</td>
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<tr>
<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>
<td>1122 to 1413</td>
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<td>32</td>
<td>1600</td>
<td>1412 to 1779</td>
<td>6</td>
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<tr>
<td>33</td>
<td>-- 2000 --</td>
<td>1778 to 2240</td>
<td>1411 to 2822</td>
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<tr>
<td>34</td>
<td>2500</td>
<td>2238 to 2819</td>
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</tr>
<tr>
<td>35</td>
<td>3150</td>
<td>2817 to 3549</td>
<td>7</td>
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<tr>
<td>36</td>
<td>-- 4000 --</td>
<td>3547 to 4469</td>
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<td>37</td>
<td>5000</td>
<td>4465 to 5625</td>
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<td>38</td>
<td>6300</td>
<td>5621 to 7082</td>
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<td>39</td>
<td>-- 8000 --</td>
<td>7077 to 8916</td>
<td>5617 to 11234</td>
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<tr>
<td>40</td>
<td>10000</td>
<td>8909 to 11225</td>
<td></td>
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</table>

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History

Exodus XXVI

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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
History
Reflection

\[ x > 4 \lambda \]

Figure 8

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Diffusion

\[ x \approx \lambda \]

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

Figure 9
Diffraction

Figure 10

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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

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Reverberant Decay

large room

Figure 17

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Reverberant Decay

small room

Figure 18
Materials

Figure 19

Sound level (dB)

Reverberant field

1) Sound level in reverberant field where $I = u/a$
   (little or no reduction with distance)

2) Sound level in reverberant field with added absorption

Sound falls off near source like 'free field' conditions

Noise reduction (NR) due to adding absorption

Distance from source (log scale)

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Small Rooms

- Modes
- Shape
- Reflection management
Large Rooms

TIME METRICS

Reverberation Time $(RT60)$

Bass Ratio $(BR)$
### ENERGY METRICS

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


References


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


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

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| Figure 9: Egan, p 89 |
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Menlo Scientific Acoustics, Inc.

Los Angeles Office:
Post Office Box 1610
Topanga, California 90290
fon +310-455-2221
fax +310-455-0923

San Francisco Office:
5161 Raincloud Drive
Richmond, California 94803
fon: +510-758-9014
fax: +510-758-9016

China Office:
c/o Sea Galleon
Jinhaihua Xincun, Chiling,
Houjie, Dongguan, Guangdong
China
fon: +86-769-5887752, 5817646

Taiwan Office:
c/o Kou Ryou Enterprises
2/F, 92 Neihu Road,
Section 1, Taipei
Taiwan
fon: +886-2-2657 1100