Tones in HVAC Systems
(Update from 2006 Seminar, Quebec City)

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Outline

- Review Fundamentals
- Frequency Spectra
- Tone Characteristics
- Tone Detection Methods
- Masking & Critical Bands
- Tone Prominence
- Examples
- ISO 1996 (Part 2)
Characteristics of Noise

- Random or Predictable
- Level or Loudness
- Frequency Content
- Steady, Fluctuating, or Transient
Noise Level

\[ L_p = 20 \log_{10} \left[ \frac{p}{p_{\text{ref}}} \right] \text{ (dB)} \]

Threshold of Hearing = 0 dB

Threshold of Pain = 120 dB
Change in Noise Level

10 dB : Twice as Loud
5 dB : Clearly noticeable
3 dB : Just noticeable
1 dB : Undetectable
Acoustic Frequency

Full Range of Human Hearing

20 Hz to 20,000 Hz

20, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240, 20480 Hz

10 OCTAVES
### Octave Bands

<table>
<thead>
<tr>
<th>Octave Band</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>31 Hz</strong></td>
<td>22 Hz to 44 Hz</td>
</tr>
<tr>
<td><strong>63 Hz</strong></td>
<td>44 Hz to 88 Hz</td>
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<tr>
<td><strong>125 Hz</strong></td>
<td>88 Hz to 177 Hz</td>
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<tr>
<td><strong>250 Hz</strong></td>
<td>177 Hz to 355 Hz</td>
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<tr>
<td><strong>500 Hz</strong></td>
<td>355 Hz to 710 Hz</td>
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<tr>
<td><strong>1,000 Hz</strong></td>
<td>710 Hz to 1420 Hz</td>
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</tbody>
</table>

(CPB = 70% of center frequency)
Octave Bands

Sample Noise Spectra

- One-Third Octave Band Center Frequency (Hz)
- Sound Pressure Level (dB)

- Pink Noise
- RC-45 Noise Criterion
- White Noise
- NC-35 Noise Criterion
1/3-Octave Bands

63 Hz Octave: 50 Hz, 63 Hz, 80 Hz

50 Hz: 44.7 Hz to 56.2 Hz
63 Hz: 56.2 Hz to 70.8 Hz
80 Hz: 70.8 Hz to 89.1 Hz

(CPB = 23% of center frequency)
Frequency Bandwidth

1/1-Octave (70%): 11 bands
1/3-Octave (23%): 33 bands
1/12<sup>th</sup> Octaves (5.9%): 132 bands
1/24<sup>th</sup> Octaves (2.9%): 264 bands
FFT (constant bandwidth): 400 lines
What is broadband noise?

- Random noise that contains a broad range of frequencies simultaneously
- Examples: waterfalls, freeways, electronic masking noise systems
Broadband Noise Characteristics

- Of all sounds, least likely to be detected by the human ear at low levels
- If source is constant, sound level will vary only slightly with time and space (inside a room or in free space)
What is a tone?

- A tone is sound where all or most of the energy is concentrated at a single frequency.

- Examples: musical instruments, sirens, whistles, etc.
Tone Characteristics

- Of all sounds, most likely to be detected by the human ear at low levels
- Can vary dramatically in level with location in a room, but not outside
Spatial variation of 180 Hz Steady Tone in Reverberation Chamber

3D Autospectrum (Mic1) - Input - slice (Real) \ CPB Analyzer (1 sec)

[dB/20u Pa]

80
75
70
65
60

[0] [10] [20] [30] [40] [50] [60]

[s] (Relative Time)
Tones in noise

- Most mechanical noise sources generate tones and broadband noise simultaneously.
- Tones may go unnoticed if masked by broadband noise.
Tones in noise

- Tones usually cannot be detected with octave band analysis
- Tones can sometimes be detected with 1/3-octave band analysis
- Tones can always be detected with narrow band (FFT) analysis
Tone Evaluation Methods

- Audibility (subjective)
- 1/3-Octave Band Method
- Tone to Noise Ratio
- Prominence Ratio
Octave Bands

HVAC Noise in Corridor

Sound Pressure Level (dB)

Octave Band Center Frequency (Hz)

- Measured Noise (62 dBA)
- RC-45 Noise Criterion
1/ 3-Octave Band Method

1. Determine which band tone is located

2. Compare the level of the band with the tone with the arithmetic average of the two adjacent bands: $\Delta$

3. Assume tone is present if:
   - $\Delta > 15$ dB ($f_{\text{tone}} < 125$ Hz)
   - $\Delta > 8$ dB ($125$ Hz $< f_{\text{tone}} < 500$ Hz)
   - $\Delta > 5$ dB ($f_{\text{tone}} > 500$ Hz)
1/3-Octave Bands

HVAC Noise in Corridor

Sound Pressure Level (dB) vs. One-Third Octave Band Center Frequency (Hz)
### 1/3-Octave Method

- Lₚ (20 Hz) = 75.8
- Average of adjacent bands is 61.5 dB \((60.8 + 62.2)/2\)
- 75.8 - 61.5 = 14.3
- 14.3 < 15 dB, Not a Prominent Tone (0.7 dB under)

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<thead>
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<th>Frequency (Hz)</th>
<th>Lₚ (dB)</th>
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<tr>
<td>16</td>
<td>60.8</td>
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<tr>
<td>20</td>
<td>75.8</td>
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<td>25</td>
<td>62.2</td>
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<td>31.5</td>
<td>59.0</td>
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<td>40</td>
<td>57.6</td>
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<td>56.0</td>
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<td>62.5</td>
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<td>54.2</td>
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<td>160</td>
<td>47.4</td>
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<td>250</td>
<td>47.7</td>
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<td>66.4</td>
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<td>500</td>
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1/3-Octave Method

- $L_p (400 \text{ Hz}) = 66.4$
- Average of adjacent bands is 53.0 dB: $(43.8 + 62.2)/2$
- $66.4 - 53.0 = 13.4$
- $13.4 > 8 \text{ dB}$, Tone is **Prominent** (5.4 dB over criterion)

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Sound Masking

Complete masking occurs when one sound overwhelms the original sound so that the original sound is no longer audible.

A tone can be masked by broadband noise, if the broadband noise is loud enough.

Only sound in the frequency region near the tone contributes to the masking effect.
Critical Bandwidth

Concept originally proposed by Fletcher

He postulated that a pure tone is completely masked when the total power in the tone equals the total power of the broadband noise in the critical bandwidth centered on the tone frequency.
Critical Bandwidth

\[ \Delta f_{\text{critical}} = 25 + 75\left[1 + 1.4\left(\frac{f_0}{1000}\right)^2\right]^{0.69} \]
Critical Bandwidth

\[ BW_{\text{critical}} = 100 \text{ Hz} \quad (f < 500 \text{ Hz}) \]

\[ BW_{\text{critical}} = 0.2f \quad (f > 500 \text{ Hz}) \]

note: 1/3-octave bandwidth is 23% \( f_{\text{center}} \)
More recently, Zwicker has found that Fletcher’s assumption was wrong, and a tone is completely masked when the power in the tone is approximately:

\[ \frac{1}{2} \text{ the power of the masker} \quad (f < 500 \text{ Hz}) \]
\[ \frac{1}{4} \text{ the power of the masker} \quad (f > 500 \text{ Hz}) \]
Tone to Noise Ratio
(ANSI S12.10, ISO 7779)

\[ T/N = 10 \log_{10} \left( \frac{W_{\text{tone}}}{W_{\text{noise}}} \right) \]

- \( W_{\text{tone}} \) is the total power in the tone
- \( W_{\text{noise}} \) is the total power of the noise surrounding the tone in the critical band (excluding the tone power)
Prominence Ratio
(ANSI S12.10, ISO 7779)

\[ PR = 10 \log \left( \frac{W_{\text{toneband}}}{W_{\text{noiseband}}} \right) \]

- \( W_{\text{toneband}} \) is the total power in the critical band centered on the tone
- \( W_{\text{noiseband}} \) is the average power in the 2 adjacent critical bands
Prominent Tone (ECMA-74)

Tone Frequency (Hz) vs. Prominence Ratio or Tone/Noise Ratio (dB)

- Prominence Ratio
- Tone to Noise Ratio
Tone to Noise Ratio

HVAC Noise in Corridor

- 20 Hz Tone
- 360 Hz Tone
- 968 Hz Tone
- 2736 Hz
Tone to Noise Ratio (360 Hz)

- **360 Hz Tone (total energy in tone = 70.6 dB)**
- **Critical Band: 310 Hz to 410 Hz**
- **Total energy in Critical Band (without tone) = 51.6 dB**
Tone to Noise Ratio (360 Hz)

- T/N Ratio = 70.6 – 51.6 = 19 dB
- 19 dB > 12 dB, 360 Hz Tone is **Prominent** (7 dB over criterion)
Prominence Ratio (360 Hz)

Total energy in $\text{CB}_{360 \text{ Hz}} = 9182516$

Total energy in $\text{CB}_{260 \text{ Hz}} = 138988$

Total energy in $\text{CB}_{460 \text{ Hz}} = 35567$

Average (260 Hz & 460 Hz) = 87278
Prominence Ratio (360 Hz)

\[ PR = 10 \log_{10} \left( \frac{9182516}{87278} \right) = 20.2 \]

20.2 > 13.6 dB,

Tone is **Prominent**

(6.6 dB over criterion)
Screw Chiller Noise: 1/1-Octave

Screw Chiller Noise in Science Building Lounge

Sound Pressure Level (dB)

Octave Band Center Frequency (Hz)

Measured Data  RC-35 Noise Criterion
Screw Chiller Noise: 1/3-Octave

Screw Chiller Noise in Science Building Lounge

One-Third Octave Band Center Frequency (Hz)

Sound Pressure Level (dB)

- Measured Data
- RC-35 Noise Criterion
1/ 3-Octave Method

- \( L_p (125 \text{ Hz}) = 55.2 \)
- Average of adjacent bands is 46.8 dB \((44.0 + 49.7)/2\)
- \( 55.2 - 46.8 = 8.4 \)
- \( 8.4 < 15 \text{ dB}, \) No Tone \((6.6 \text{ dB under criterion})\)

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**1/ 3-Octave Method**

- \( L_p \) (315 Hz) = 46.1
- Average of adjacent bands is 37.5 dB \((41.8 + 33.1)/2\)
- 46.1 – 37.5 = 8.6
- 8.6 > 8 dB, Tone (0.6 dB over criterion)

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Screw Chiller Noise: FFT

Screw Chiller Noise: (Baseband FFT)

- 120 Hz Tone (30 dB over ISO Threshold)
- 300 Hz Tone (35 dB over ISO Threshold)

Sound Pressure Level (dB) vs. Frequency (Hz)

- Measured Data
- ISO Threshold of Hearing
Screw Chiller Noise: FFT

Screw Chiller Tones: Time History

![Graph showing sound pressure level over time for different tones.](image-url)

- 120 Hz Tone
- 294 Hz Tone
Screw Chiller Noise: Beats

**Screw Chiller Noise: 20 Hz Zoom FFT**

- Frequency Difference = 0.8 Hz
- Beat Rate = 1/0.8 Hz = 1.25 sec

- 119.2 Hz Tone (51.9 dB total energy)
- 120 Hz Tone (51.9 dB total energy)
Screw Chiller Noise: 120 Hz Zoom FFT

Critical Band: 70 Hz to 170 Hz

Total Energy in Critical Band (without tone) = 53.2 dB

120 Hz Tone (55.6 dB total energy)
Tone to Noise Ratio (120 Hz)

- T/N Ratio = 53.3 – 49.7 = 3.6 dB

- 3.6 dB < 15.5 dB,  
  120 Hz Tone is **not Prominent**  
  (11.9 dB under criterion)
Screw Chiller: Zoom FFT

Screw Chiller Noise: 200 Hz Zoom FFT

Critical Band: 248 Hz to 348 Hz

Total Energy in Critical Band (without tone) = 39.5 dB

298 Hz Tone (47.2 dB total energy)
Tone to Noise Ratio (298 Hz)

- T/N Ratio = 47.2 - 39.5 = 7.7 dB

- 7.7 dB < 12 dB, 
  298 Hz Tone is **not Prominent**
  (4.3 dB under criterion)
Prominence Ratio (298 Hz)

- Total energy in CB\textsubscript{298} = 61406
- Total energy in CB\textsubscript{198} = 81126
- Total energy in CB\textsubscript{398} = 3775
- Average CB\textsubscript{198} & CB\textsubscript{298} = 42450
Prominence Ratio (298 Hz)

- PR = 10 log (61406/42450) = 1.6

- 1.6 dB < 14 dB
  
  298 Hz Tone is **not Prominent**
  
  (12.4 dB under criterion)
ISO 1996 (Part 2)

- Ignores prominence ratio

- Analysis based on tone to noise ratio using FFT (Annex C) or alternative 1/3-octave method (Annex D) is allowed, but not preferred
ISO 1996 (Part 2)

- Defines tone audibility $\Delta L_{ta}$ (in dB) as:

$$\Delta L_{ta} = L_{pt} - L_{pn}$$

where: $L_{pt}$ is the power in the tone and $L_{pn}$ is the power in the noise in the critical band centered on the tone.
Instruments to measure tonality

- B&K 2250/2270 has tone assessment option for both FFT and 1/3-octave analysis mode


- Standard setup is 6400 lines, 0-20 KHz with 5 Hz bandwidth (other options OK)
FFT Tone Detection Algorithm

- Detect peaks which represent a possible tone (i.e., noise pause)

- Tone exists when 3 dB bandwidth < CB/10

- $L_{pt}$ includes all energy within 6 dB of tone center frequency
FFT Tone Detection Algorithm

- $L_{pn}$ is calculated from a linear regression of the spectrum within 0.75 CB of tone frequency

- $\Delta L_{ta} = L_{pt} - L_{pn}$
ISO 1996 recommends adding a penalty, $K_t$, to the A-weighted sound pressure level to compensate for the presence of an audible tone. The penalty, $K_t$, is a function of the audibility $\Delta L_{ta}$:

If $\Delta L_{ta} < 4$ dB, $K_t = 0$ dB
If $\Delta L_{ta} > 10$ dB, $K_t = 6$ dB
Otherwise, $K_t = \Delta L_{ta} - 4$ dB
Summary

- Tones are more annoying than broadband noise
- Tones can be accurately measured with narrow band analyzers
- Tone detection algorithms are available, and standardized in ISO 1996-2 (2007)
- Tones should be incorporated into criteria