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A Methodology to Modify Steady State Heating, Ventilating, Air Conditioning and Refrigeration Equipment Noise

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Acknowledgement

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• Also thanks to:
  • Jelena Paripovic and Daniel Carr
1. Objective of the Research
2. Sound Decomposition
3. Sound Modification and Sound Reconstruction
4. Conclusions
5. Future Work
6. References
Objective of the Research

- Long Term Goal:
  - To develop a sound quality model that predicts annoyance due to HVAC&R equipment noise

- Short Term Goals:
  - Understand what sound characteristics are important and affect annoyance
  - Quantify the influence of particular sound characteristics on annoyance
  - Understand interactions between metrics
  - Need to be able to manipulate sound characteristics to develop stimuli for tests
Sound Decomposition

- Objective of Sound Manipulation
- Tonal Component Extraction
- Instantaneous Phase, Amplitude, and Frequency
- Estimated Amplitude of Tonal Components
Objective of Sound Manipulation

- If Loudness and Sharpness are always highly correlated (always vary together) in an application, we only need to use one of these metrics in our model.

- But, if metrics (attributes?) are important in their own right, we need to make sure they are not correlated over the signal set used in the test, so we can model their individual contributions in the model.
Tonal Component Extraction

Recorded Signal

Butterworth Low Pass Filter

Down Sampling

Signal with Low Frequencies Removed

Butterworth Band Pass Filter

Tone Components $y_i(t), i=1, 2, \ldots$

Original Sample Rate 40,960 Hz

Cut-off Frequency 2,000 Hz

New Sample Rate 8,192 Hz

Original Sample Rate 40,960 Hz

Red - Bandpass filtered signal

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>5.5</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>6.5</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>PSD - db ref $(20 \mu P)^2$/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>40</td>
</tr>
<tr>
<td>1000</td>
<td>60</td>
</tr>
<tr>
<td>1500</td>
<td>80</td>
</tr>
<tr>
<td>2000</td>
<td>80</td>
</tr>
</tbody>
</table>
Estimated Amplitude of Tonal Components

- A constant amplitude model of the tonal components

\[
\begin{bmatrix}
    p(t_1) \\
    \vdots \\
    p(t_N)
\end{bmatrix} = 
\begin{bmatrix}
    \cos\{f_1(t_1)\} & \sin\{f_1(t_1)\} & \cos\{f_2(t_1)\} & \cdots & \sin\{f_{nc}(t_1)\} \\
    \cos\{f_1(t_2)\} & \sin\{f_1(t_2)\} & \cos\{f_2(t_2)\} & \cdots & \sin\{f_{nc}(t_2)\} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    \cos\{f_1(t_N)\} & \sin\{f_1(t_N)\} & \cos\{f_2(t_N)\} & \cdots & \sin\{f_{nc}(t_N)\}
\end{bmatrix} \begin{bmatrix}
    A_1 \\
    B_1 \\
    A_2 \\
    \vdots \\
    B_{nc}
\end{bmatrix}
\]

Sampling frequency = 40.96kHz
Spectral resolution = 1.25Hz, Hann window, 50% overlap

Original sound

Sound with tonal components extracted

Original

Modified
Sound Modification
and
Sound Reconstruction
Sound Modification

• Change Loudness
  (Zwicker Loudness Exceeded 5% of the Time)

• Change Tonality (Prominence Ratio)

• Change Roughness (Zwicker Roughness)
Either increase tonal components or broadband components

Also tonality increases

Also roughness increases

Sampling frequency = 40.96kHz
Spectral resolution = 1.25Hz, Hann window, 50% overlap
Change Tonality (Prominence Ratio)

- Change the level of **“all” tones** (less than 2000Hz, max of 50 tones)
- Change the level of the tone that influences the tonality

Sampling frequency = 40.96kHz  
Spectral resolution = 1.25Hz, Hann window, 50% overlap
Change Roughness

- Use equation to add roughness to sound
  \[ x(t) := (1 + \gamma_1 \cos[f(t)]) \times x(t) \]
  \[ f_m(t) = \frac{1}{2\pi} \frac{df(t)}{dt} = 60 + \gamma_2 \alpha(t) \]
  - \( x(t) \) is either the tonal or broadband components
  - \( \gamma_1 \) is a constant that regulates the amount of variation amplitude, level is decided by listening to the sound (typically 0.2 to 0.7)
  - \( \alpha(t) \) is low pass filtered Gaussian distributed white noise (cut-off freq. 200Hz)
  - \( \gamma_2 \) is used to vary the range of the frequency variation (typically \( \gamma_2 \) less than 2.5)

Amplification modification

\[ \begin{align*}
\text{High } \gamma_1 & \quad \text{on average} \\
\text{Low } \gamma_1 & \quad 1/60 \text{ s}
\end{align*} \]
Add roughness to tonal and broadband components

Hard to increase roughness using the tonal components. Roughness mostly affected by broadband components.

Sampling frequency = 40.96kHz
Spectral resolution = 1.25Hz, Hann window, 50% overlap
## Example Sound Modification

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Roughness</th>
<th>Tonality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1. Tonal Comp.</td>
<td>2. Broadband Comp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. “All” Tonal Comp.</td>
<td>4. “One” Tonal Comp.</td>
</tr>
</tbody>
</table>

### Diagrams

- **Tonality vs. Loudness**
- **Roughness vs. Loudness**
- **Tonality vs. Loudness**
Conclusions

- Tonal components were extracted and the instantaneous frequency, phase and amplitude of were calculated

- The amplitude and frequency information was adjusted and components were recombined
  - Using constant amplitudes worked well, but needed instantaneous frequency estimation in modified sound

- Amplifying tonal components increases the loudness and also tonality (sometimes roughness)

- Amplifying broadband components increases loudness and roughness

- Adding amplitude modulation to signal components also increase the roughness metric values (some randomness is desirable in amplitude modulation)

- Adjust individual tonal components differently to keep loudness the same but increase tonality

- Tricky to keep some metrics constant while others vary
Future Work

- Use the sound modification techniques to modify sounds to systematically change particular signal attributes.

- Use the sounds in subjective tests to develop an understanding of how these sound attributes affect people’s annoyance of the sounds.

- Develop a sound quality model that predicts people’s ratings of sounds.
References


- A. McMullen, *Assessment of noise metrics for application to rotorcraft*, MS Thesis. Purdue University, August 2014.


Thank you!