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

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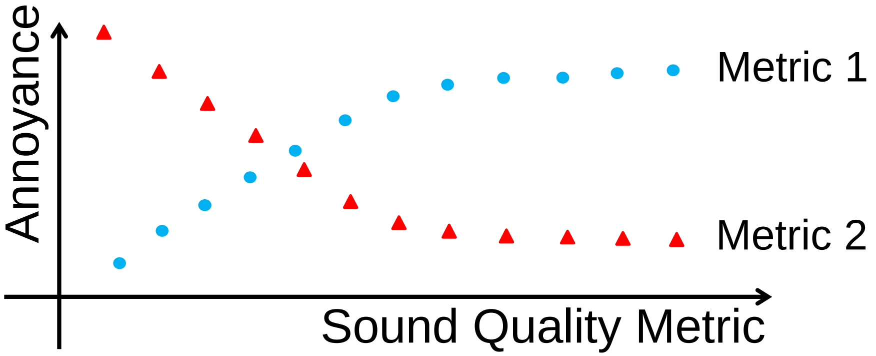
Presentation Contents

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

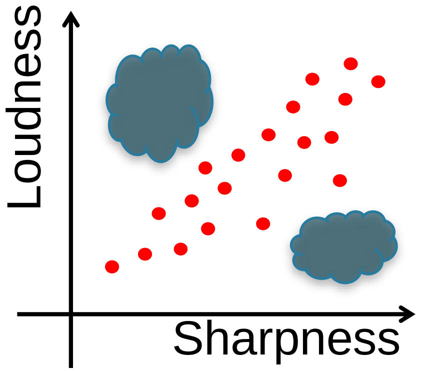


  - Understand interactions between metrics
  - Need to be able to manipulate sound characteristics to develop stimuli for tests

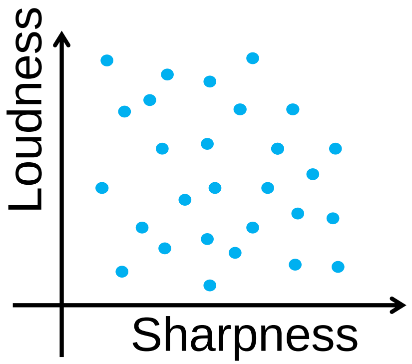
Sound Decomposition

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

Objective of Sound Manipulation

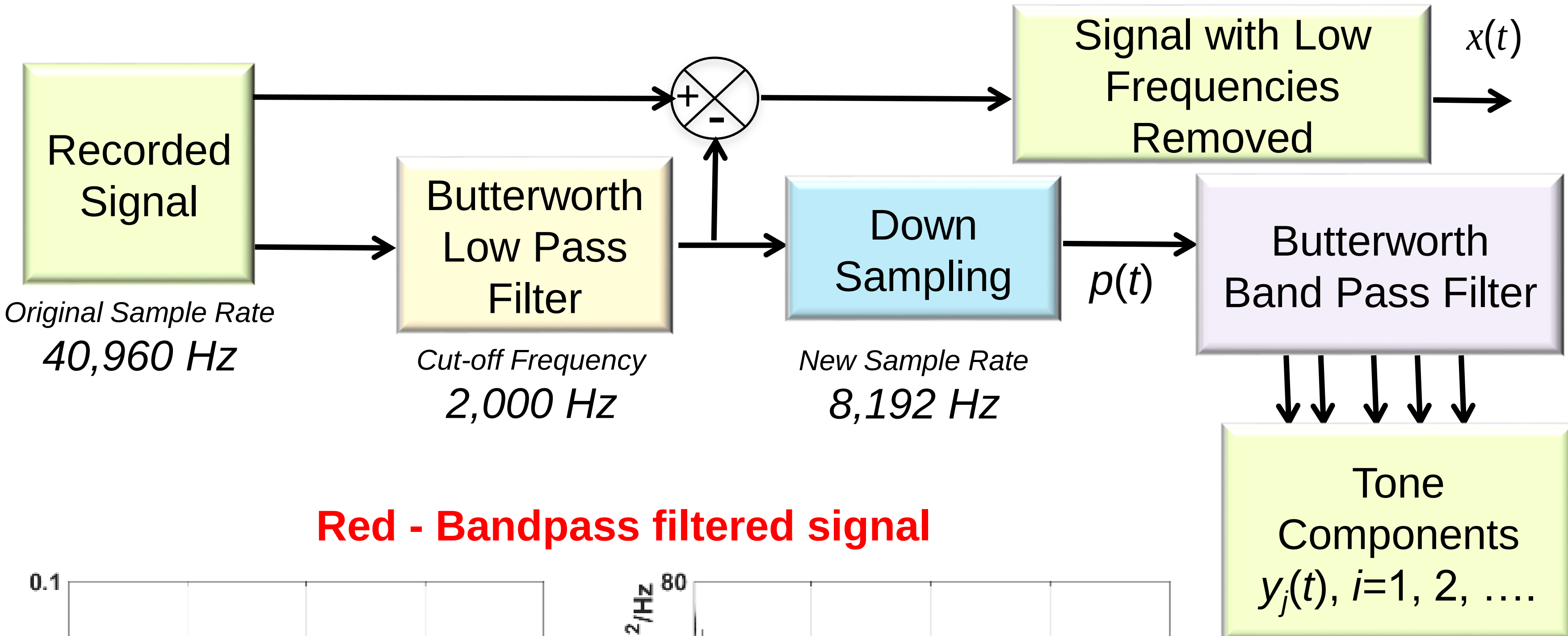


- If Loudness and Sharpness are always highly correlated (always vary together) in an application, we only need to use one of these metrics in our model.

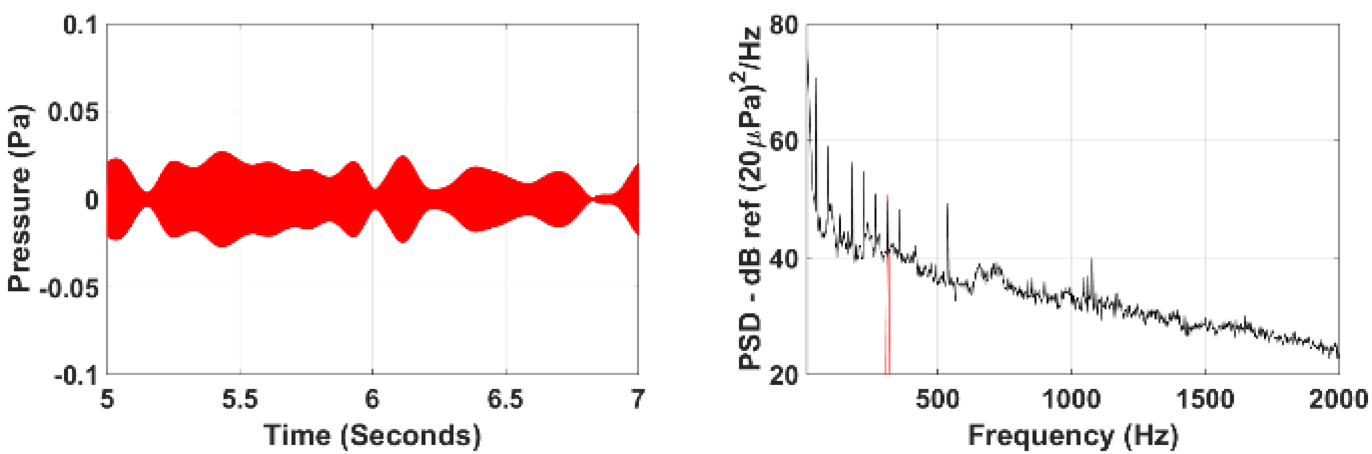


- But, if metrics (attributes?) are important in their own right, we need to make sure they are **not correlated** over the signal set used in the test, so we can model their individual contributions in the model.

Tonal Component Extraction



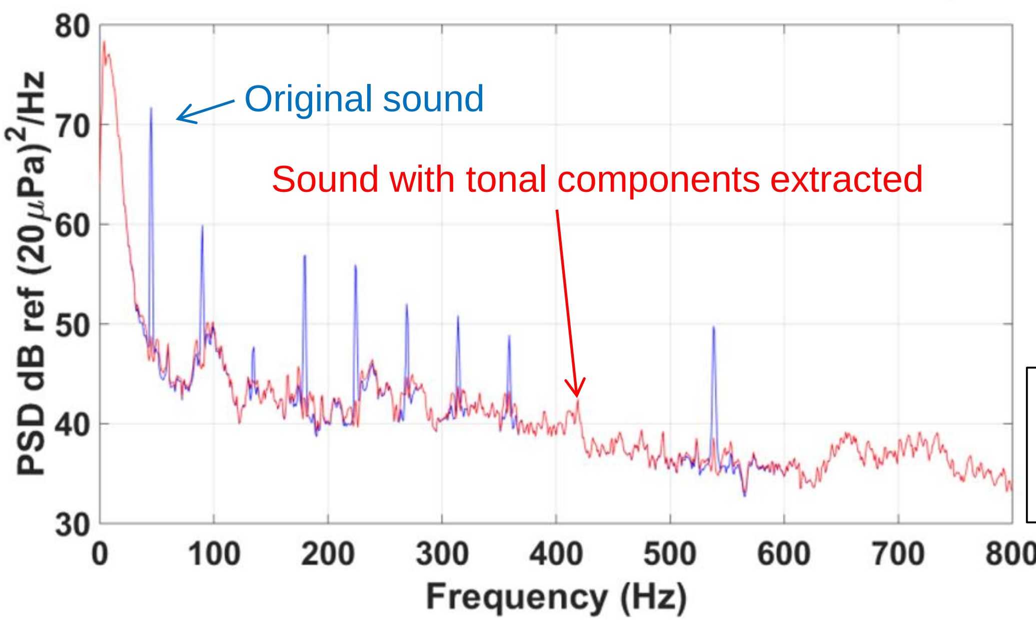
Red - Bandpass filtered signal



Estimated Amplitude of Tonal Components

- A constant amplitude model of the tonal components

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



Original

Modified

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

Sound Modification
and
Sound Reconstruction

Sound Modification

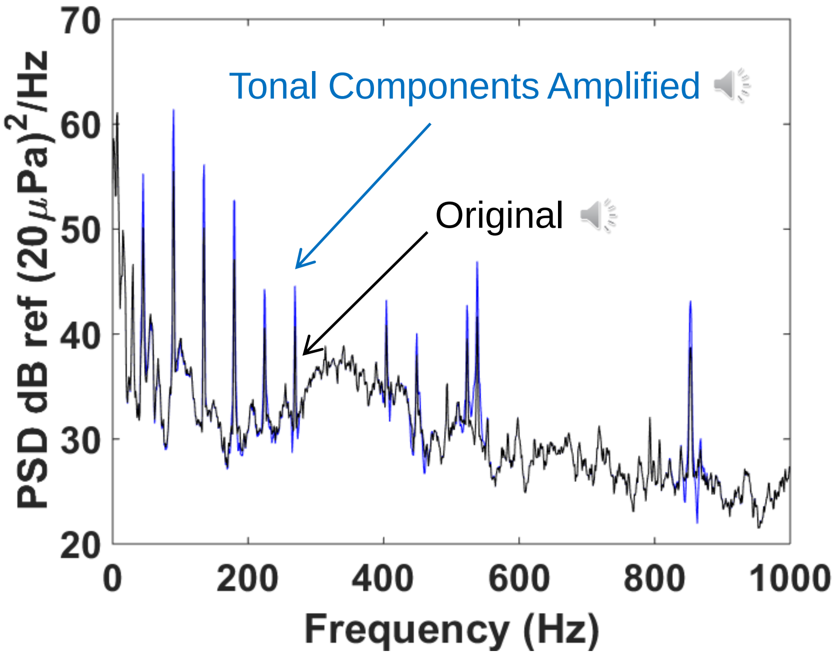
- Change Loudness
  (Zwicker Loudness Exceeded 5% of the Time)

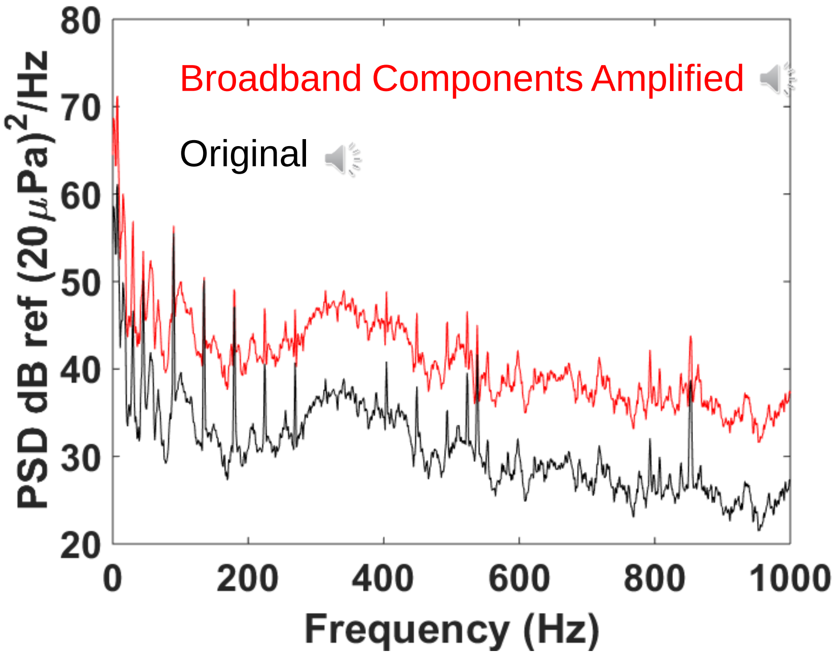
- Change Tonality (Prominence Ratio)

- Change Roughness (Zwicker Roughness)

Change Loudness

- Either increase tonal components or broadband components





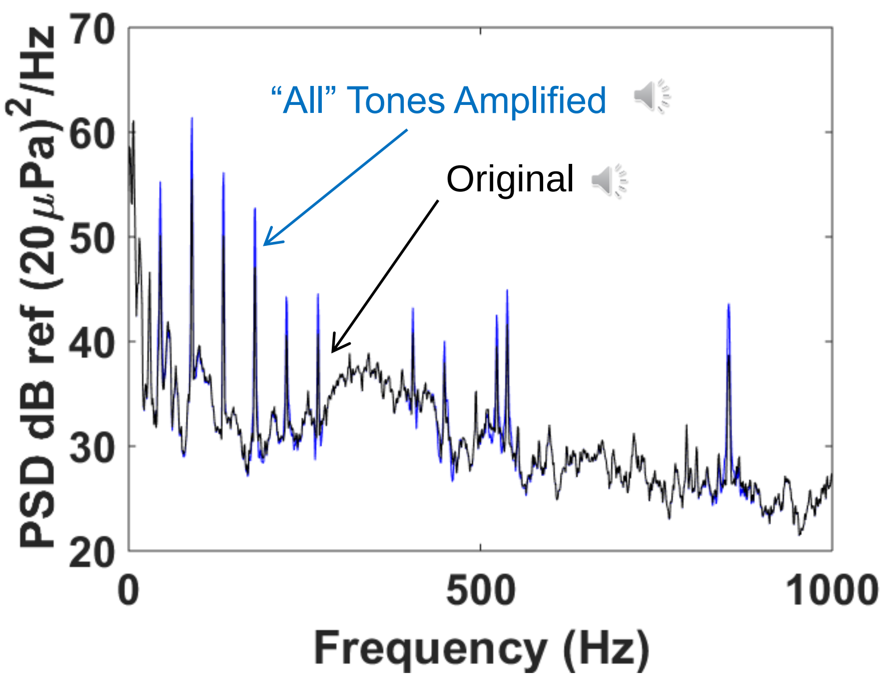
Also tonality increases

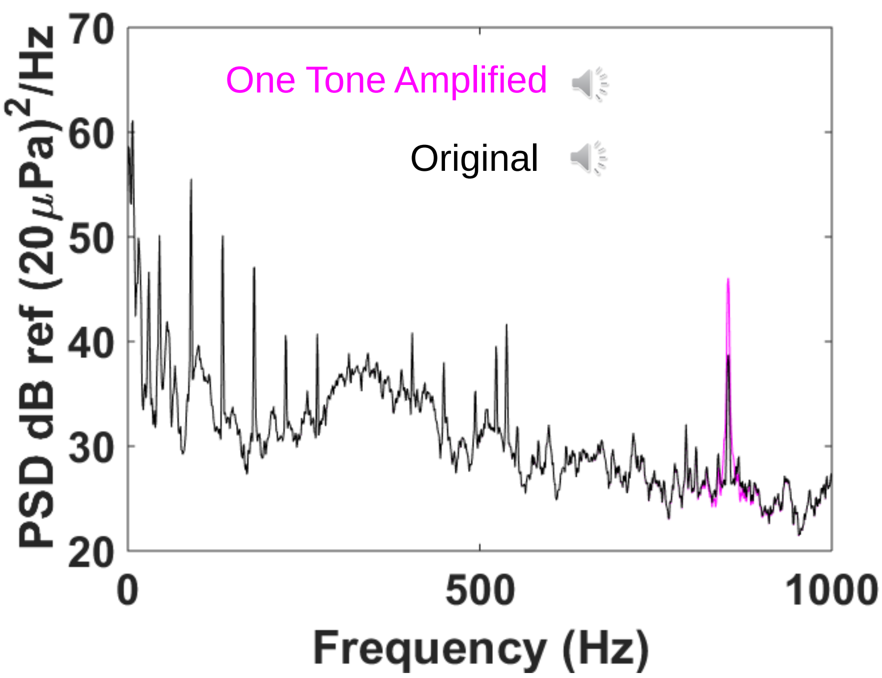
Also roughness increases

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





Also loudness increases

Loudness rarely increases

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

Change Roughness

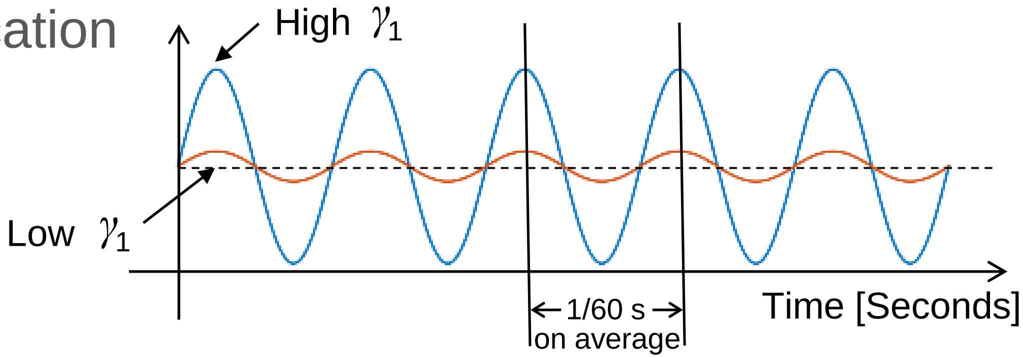
- Use equation to add roughness to sound

$$x(t) := (1 + \gamma_1 \cos[f(t)]) \times x(t)$$

$$f_m(t) = \frac{1}{2\pi}\frac{df(t)}{dt} = 60 + \gamma_2 \alpha(t)$$

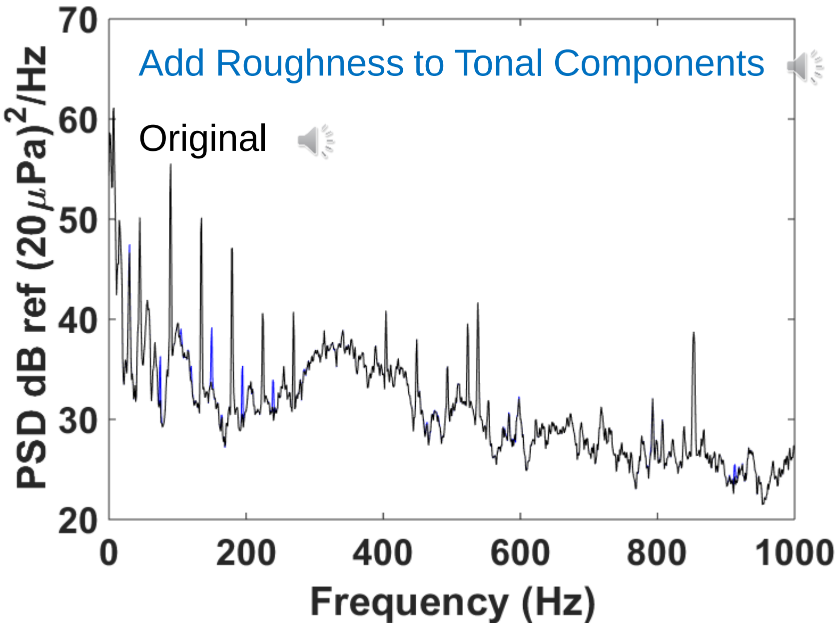
  - $x(t)$ is either the tonal or broadband components
  - γ_1 is a constant that regulates the amount of variation amplitude, level is decided by listening to the sound (typically 0.2 to 0.7)
  - $\alpha(t)$ is low pass filtered Gaussian distributed white noise (cut-off freq. 200Hz)
  - γ_2 is used to vary the range of the frequency variation (typically γ_2 less than 2.5)

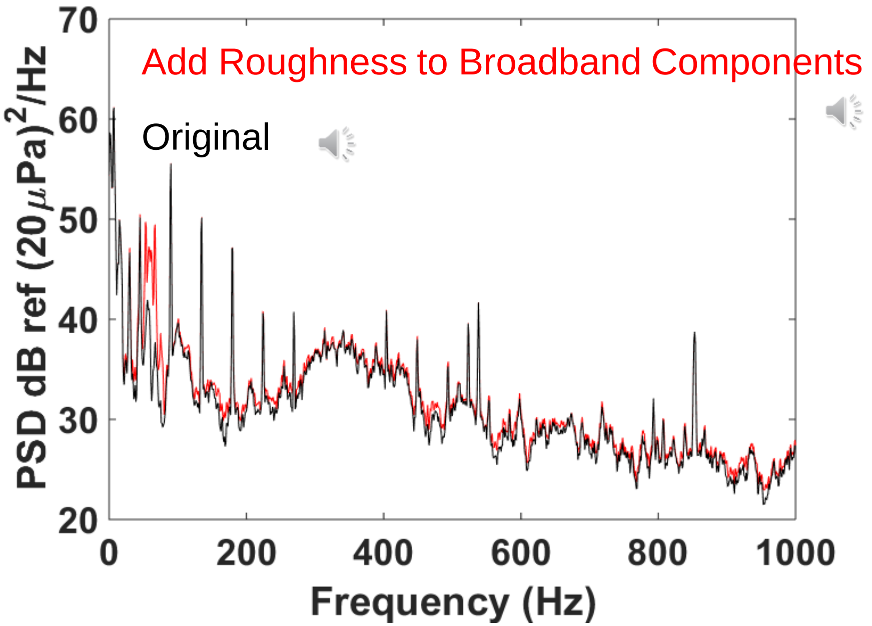
Amplification modification



Change Roughness

- Add roughness to tonal and broadband components



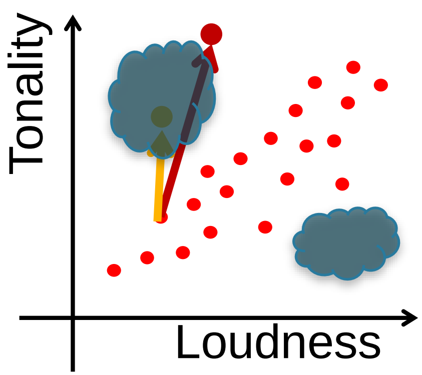


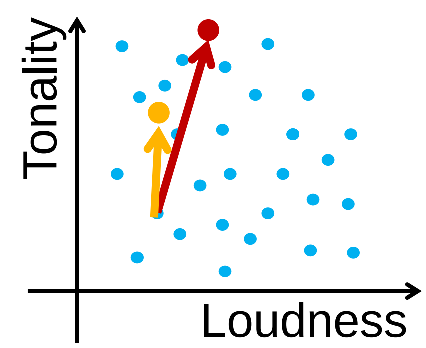
Hard to increase roughness using the tonal components.
Roughness mostly affected by broadband components.

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

Example Sound Modification

Original		
Roughness	1. Tonal Comp.	2. Broadband Comp.
Tonality	3. "All" Tonal Comp.	4. "One" Tonal Comp.





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

- W. Passchier-Vermeer and W.F. Passchier, "Noise exposure and public health", *Environmental Health Perspective* **108 (Suppl 1)**,123, 2000.

- R.P. Leita and S. Paul, "A sounds quality-based investigation of the HVAC system noise of an automobile model", *Applied Acoustics* **70(4)**,636-645, 2009.

- S. Hohls, T. Biermeier, R. Blaschke, and S. Becker, "Psychoacoustic evaluation of HVAC noise", *Proc. of Forum Acusticum Krakow,* Krakow, Poland, 2014.

- *Air-Conditioning, Heating, and Refrigeration Institute,* AHRI/ANSI 1140-2012 Sound Quality Evaluation Procedures for Air-Conditioning and Refrigeration Equipment.

- *Air-Conditioning, Heating, and Refrigeration Institute,* AHRI/ANSI 270 Sound Performance Rating of Outdoor Unitary Equipment.

- M. Schneider and C. Feldmann, "Psychoacoustic evaluation of fan noise", *Proc. of Fan2015,* Lyon, France, April, 2015.

- S. Naji and A. Sanon, "Human perception and fan noise", *Proc. of Fan2015,* Lyon, France, April, 2015.

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

- A.H. Hastings, K.H. Lee, P. Davies, and A.M. Surprenant, "Measurement of the attributes of complex tonal components commonly found in product sound", *Noise Control Engineering Journal* **51(4)**,195-209, 2003.

- E. Zwicker and H. Fastl, *Psychoacoustics, Facts and Models*, Springer, New York, end Edition, 1999.

Thank you!