8th International Conference
on
Wind Turbine Noise
Lisbon – 12th to 14th June 2019

Testing the human response to wind turbine emissions

Peggy Nelson, University of Minnesota, Speech-Language-Hearing Sciences: nelso477@umn.edu

Andrew Bryne, University of Minnesota, Multi-Sensory Perception Lab: byrn0050@umn.edu

Matthew Waggenspack, University of Minnesota, Speech-Language-Hearing Sciences: wagge008@umn.edu

Matthew Lueker, University of Minnesota, St. Anthony Falls Lab: luek0004@umn.edu

Christopher Feist, University of Minnesota, St. Anthony Falls Lab, feist020@umn.edu

Bill Herb, University of Minnesota, St. Anthony Falls Lab: herb0003@umn.edu

Jeff Marr, University of Minnesota, St. Anthony Falls Lab: marrx003@umn.edu

Summary

Our human response laboratory tests participants for their detection, rating, and postural sway during laboratory exposure to wind-turbine generated emissions. Testing of ~70 adults indicated that these participants experienced few symptoms from re-created wind turbine audible (modulated) sound and infrasound emissions. The sample included subjects ages 21-73 years who attended to audible and infrasound signals generated from a wind turbine, recorded at 300 meters and re-created in a laboratory.

During Phase I, stimuli consisted of thirty second \ modulated and unmodulated audible turbine sounds presented at 50 dB SPL, as well as natural and peak-enhanced turbine infrasound at an overall level of approximately 85 dB SPL with peaks up to 100 dB SPL. Infrasound presented was ~40 dB higher than that recorded in the field. This was required as ambient infrasound levels in the lab were higher than wind turbine generated infrasound. Participants were tested for their postural stability, detection, and ratings of audible and infrasound emissions randomly presented in thirty second exposure intervals in the laboratory. Very few and minor adverse effects were noted, mostly ear fullness or pressure. Healthy participants showed no evidence of any change in postural sway in the presence of infrasound for the group tested.

Phase II of testing extended the duration of infrasound to seconds and excluded amplitude modulation to maintain total testing duration. The infrasound used in Phase II was more impulsive than in Phase I yielding clear blade passing and harmonic frequencies in the spectra while maintaining the same presentation level peaks of ~ 100 dB SPL.

Testing of participants who have symptoms of dizziness/imbalance as reported to their ENT specialist is underway. Results from postural sway remain inconclusive; however, these participants report greater symptoms following exposure and a few are reliable detectors of infrasound. Some negative symptoms have been reported even in the absence of infrasound. Testing continues with participants remaining in a seated condition, focusing on detection, sound quality judgments, and pre- and post-exposure symptoms.

Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund.

1. Introduction

The noise produced by wind turbines is a major obstacle for wind energy projects (Oerlemans, Sijtsma, & Lopez, 2007). However, developers and regulators frequently cite that farms are within existing noise limits. A potential discrepancy between these two groups is that wind turbines emit noise that is not covered by typical regulation such as infrasound or amplitude modulation. Typical regulations only cover frequencies in the 20 to 20,000 Hz range. Infrasound is noise below 20 Hz that is generally not sensed through the auditory system. (Moller & Pedersen, 2004). Amplitude modulation (AM) is the sinusoidal modulation of the sound level (amplitude) of an audible carrier frequency. Neither of these types of noise are covered in typical regulations. In this study, participants are subjected to infrasound and amplitude modulation which is recorded and modified from a single turbine site. Balance (sway) is used as a quantitative cochlear or vestibular response to these types of noise along with detection, noise ratings, and symptom surveys.

2. Experimental Setup

Each individual was tested at the Center for Applied and Translational Sensory Science (CATSS) lab at the University of Minnesota with a testing protocol approved by the University of Minnesota Institutional Review Board. The testing room was a 6 foot wide by 15 foot long by 8 foot tall room (Figure 1) with reproduced/modified audible and infrasound recordings obtained from field measurements. The field measurements used in the current study were recorded at the University of Minnesota Eolos Wind Research Station. This site has which has a single 2.5 MW Clipper Liberty Turbine which is primarily used for wind energy research.

Postural stability and sway were measured by having individuals stand on an AMTI AccuSway Optimized™ balance forceplate which measures left-right and front-back sway continuously.

Infrasound stimuli were generated using an Eminent Technologies© rotary subwoofer with a frequency range of 0.01 to 30 Hz. A rotary woofer is a unique subwoofer which utilizes a fan with pitch controlled blades to create the infrasonic pressure waves. Audible stimuli were played through a custom subwoofer with a frequency range of 50-800 Hz simulating the audible turbine noise.

Audible and infrasound signals were recorded from the field site. They are reproduced/modified in the CATSS lab and noise levels are calibrated using an infrasound microphone (Brüel and

Kjær Type 4193 with UC0211 adapter), Infiltec microbarometer, and Brüel and Kjær 2250 sound level meter in the testing room.

Figure 1: Testing room with forceplate, monitor for user interface, and subwoofer enclosure (left) and rotary subwoofer enclosure used to generate stimulus (right). Enclosure was pushed up to door frame after participant enters testing room.

2.1 Testing Protocol

A written general health survey was collected from each subject prior to testing and the generalized testing procedure is outlined below.

1. The subject/monitor/table are in the center of room, with the subject standing on the forceplate and facing the subwoofer with the rotary woofer to their back.

2. Testing
    a. Pre-Test: One set of eyes open and eyes closed conditions, random order.
    b. Main Experiment:
        i. Each stimulus is randomly played with the subject's eyes either closed or shut, the later order also randomly selected
        ii. Repeated for designated repetitions
        iii. Mid-session break halfway through main experiment
    c. Post-Test: one set of eyes open and eyes closed conditions, random order.

    The subject initiates each individual stimulus by clicking a button on the display.

    Subject is given the one of following auditory instructions through subwoofer.
    - "Please close your eyes."
    - "Keep your eyes open."

    The subject is asked to respond to the following questions after each stimulus:
    1. "Did you sense anything besides the sound?"
       "Yes" or "No" buttons for possible responses.
    2. "How would you rate the condition?"

Slider: "Very Negatively" (0) to "Neutral" (0.5) to "Very Positively" (1)

After testing, a post experiment survey was given on symptoms typical of wind turbine noise and the following scale for each.

- 0 = “not at all”
- 1 = “mild”
- 2 = “moderate”
- 3 = “severe”

3. Testing Overview

The original testing plan (Phase I) for human response testing involved a target of ~100 healthy individuals subjected to a combination of amplitude modulated audible and infrasound noise files for a short duration in a controlled laboratory environment. Three repetitions of nine, 30 second combinations of amplitude modulation and infrasound were presented to the individual during testing. Total recorded response time was 13.5 minutes excluding pre/post-test baseline measurements. This excludes time for user input after each condition and stimulus volume ramping. Total testing duration was of 30 to 40 minutes to prevent contamination of results due to fatigue for a standing test.

However, the testing plan was modified twice (Phase II and Phase III) over the course of testing due to lack of human response to stimuli. Phase II investigated longer duration infrasound with a more impulsive infrasound described below and Phase III investigated symptomatic individuals with the same stimulus as Phase II. Symptomatic individuals were told of connection to wind turbine noise for ethical reasons. An overview of the testing phases are summarized in Table 1.

The reasoning for the deviation for the testing plan to Phase II was the lack of human response to the stimulus, updated analysis of field data that revealed impulsive nature of infrasound, and feedback from colleagues about short stimulus duration in testing. To maintain the same approximate total testing time, the amplitude modulation was dropped and the updated “impulsive” infrasound duration was doubled to 60 seconds. Furthermore, amplitude modulation is more likely related to annoyance. Since there was not a significant negative rating to AM conditions from the Phase I population, it seemed unlikely that extending the short term durations to approximately one minute would cause increased response.

The reasoning for Phase III was in response to feedback from colleagues that the general population may contain a very small percentage of people that are affected by infrasound. Also, collaborators in the University of Minnesota Department of Otolaryngology have symptomatic patients who could be invited to testing.

Table 1: Overview of Human Response Testing Phases

	Number of Participants	Number of Stimulus Types	Repetitions	Individual Stimulus Duration (sec)	Measured Response Time (min)	Participants
Phase I	53	9, AM and Infrasound	3 (2 eyes closed and 1 eyes open)	30	13.5 min	Healthy, unaware
Phase II	15	2, Impulsive Infrasound (2 times for each repetition)	4 (2 eyes closed and 2 eyes open)	60	16 min	Healthy, unaware
Phase III	3	2, Impulsive Infrasound (2 times for each repetition)	4 (2 eyes closed and 2 eyes open)	60	16 min	Symptomatic, Aware

3.1 Stimulus

Phase I stimulus are presented in this section. No excessive amplitude modulation had been captured at the field site by the start of human response testing. To resolve this, audible range recordings from the field data were modified to create AM as indicated below and shown in Figure 2. Infrasound frequency recordings were also modified to exaggerate blade passing frequency and five harmonics by adding pure tones at these frequencies with random phases. The raw recordings from the field site were also played as part of the stimulus. “Flat” and “IRec” indicates the unaltered audible and infrasound recorded, respectively. Both recordings were measured 300 meters downwind of the Eolos single turbine site on June 6, 2016.

Background infrasound levels in the testing room were higher than turbine generated infrasound recorded at the field site as shown in Figure 5. To overcome this, the overall amplitude of the reproduced infrasound was increased so that the second (2.4 Hz) and third (3.2 Hz) harmonics were presented at ~95 dB. This level was ~ 10 dB higher than the noise floor which relates to ~40 dB higher than the infrasound recorded in the field in the frequency range of the first five harmonics.

Stimulus was recorded in the testing room during experimental design to compare actual infrasound levels in the testing room to target levels. This is shown in Figure 3.

- Audible Sound (Subwoofer)
  - “White”
    - (Gaussian) white noise.
    - Presentation Level: 40 dBA
  - “Flat”
    - Audible range recording used.
    - Band-pass filtered at 50 and 4000 Hz (3rd order Butterworth).
    - Presentation Level: 50 dBA
  - “AM”
    - “Flat” stimuli with 0.8-Hz modulation imposed on it with a depth of 10 dB (peak-to-trough dB difference).
    - Presentation Level: 50 dBA (measured at the modulation’s peak)
- Infrasound (Rotary Woofer)
  - “IOff”
    - Rotary Woofer (fan) on, but no signal.
  - “IRec”
    - Infrasonic range recording used.
    - Low-pass filtered at 50 Hz (3rd order Butterworth).
  - “IEnh”
    - “IRec” stimuli’s spectra smoothed with 100-(FFT)-point averaging window.
    - Random phases given to all spectral components.
    - Pure tones added to create a 0.8-Hz infrasound signal (with five harmonics).
      - Frequencies = [0.8, 1.6, 2.4, 3.2, 4.0, 4.8] Hz
    - Low-pass filtered at 50 Hz (3rd order Butterworth).

Table 2: Phase I Stimulus Conditions

IOff - White	IRec - White	IEnh - White
IOff - Flat	IRec - Flat	IEnh - Flat
IOff - AM	IRec - AM	IEnh - AM

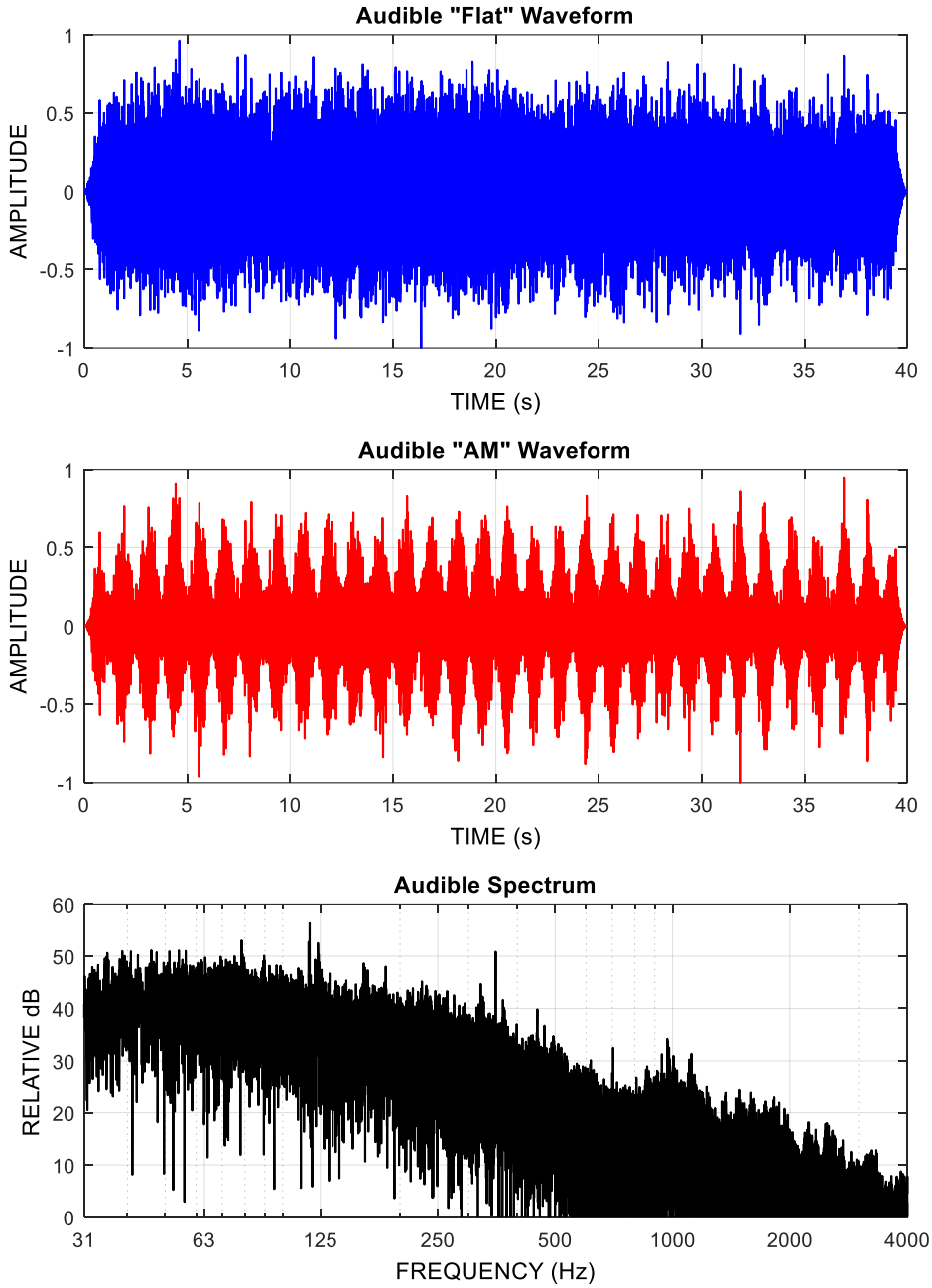

Figure 2: Phase I Field recorded noise audible stimulus and modified AM stimulus prior to amplification

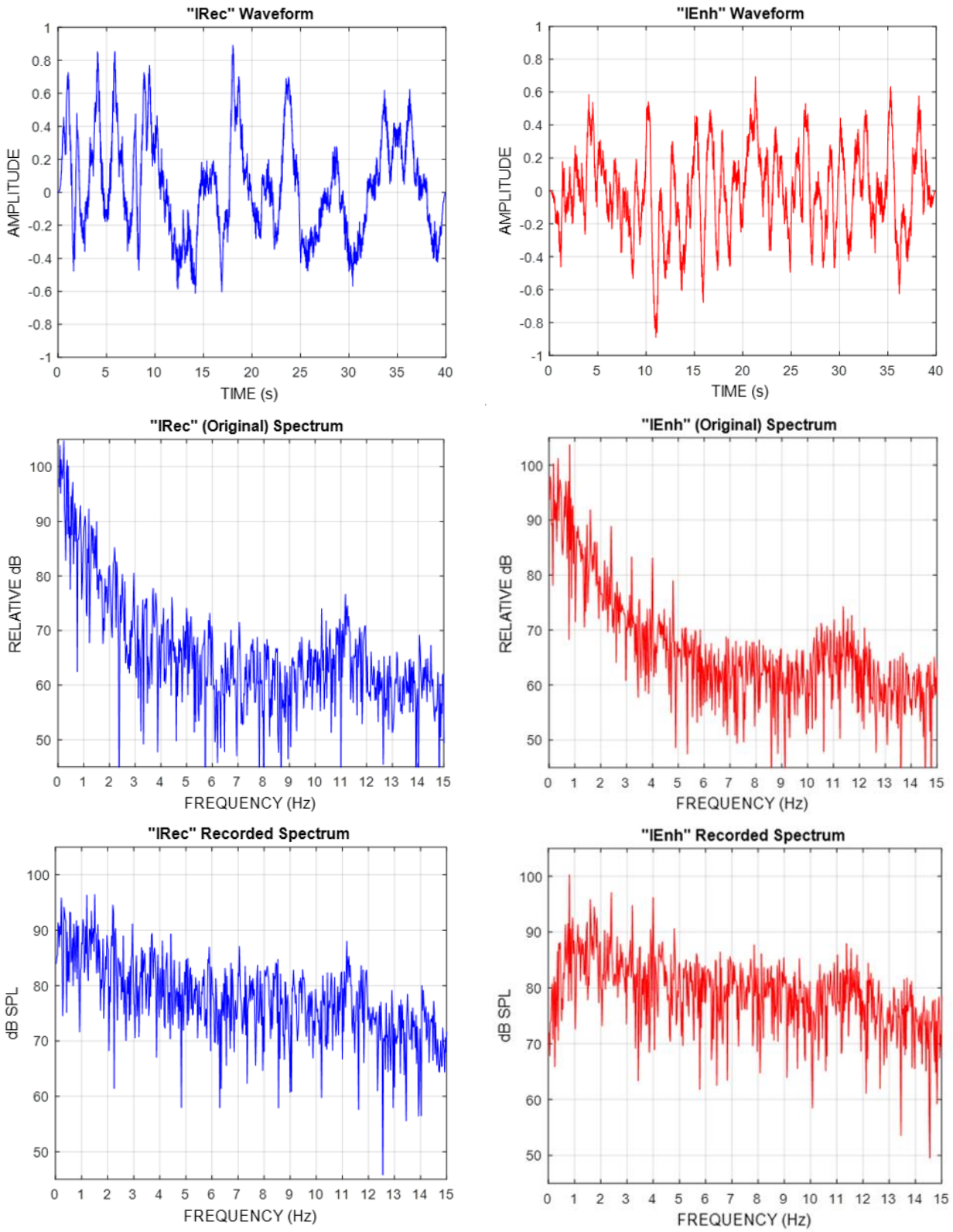

Figure 3:Phase I waveforms and spectra for the original (IRec) and enhanced infrasound stimulus (IEnh)

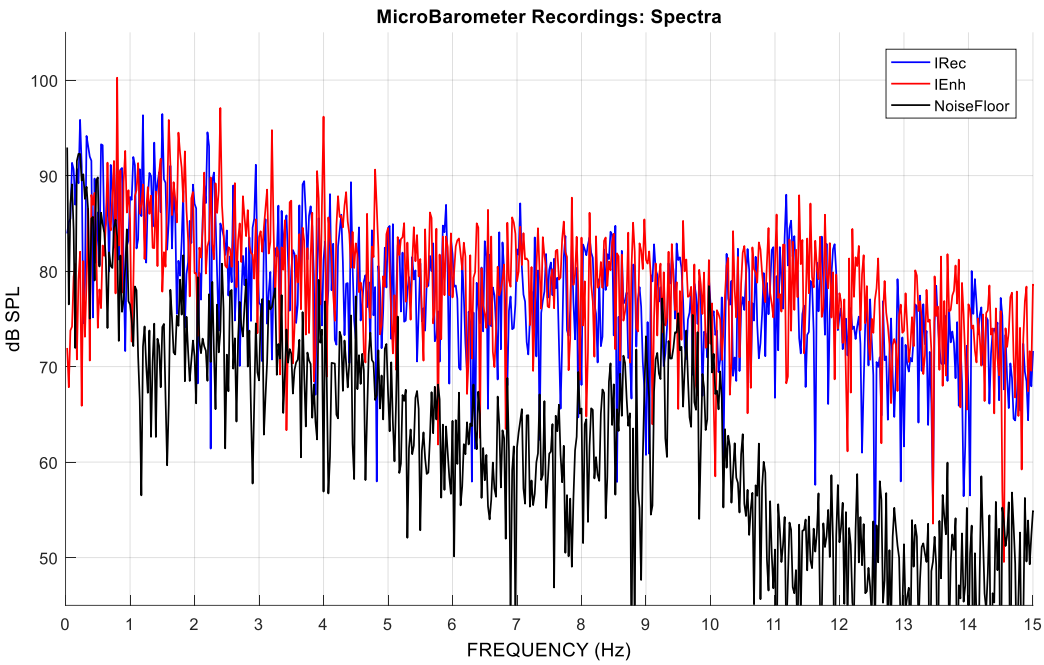

Figure 4: Phase I Spectra of testing room infrasound recordings

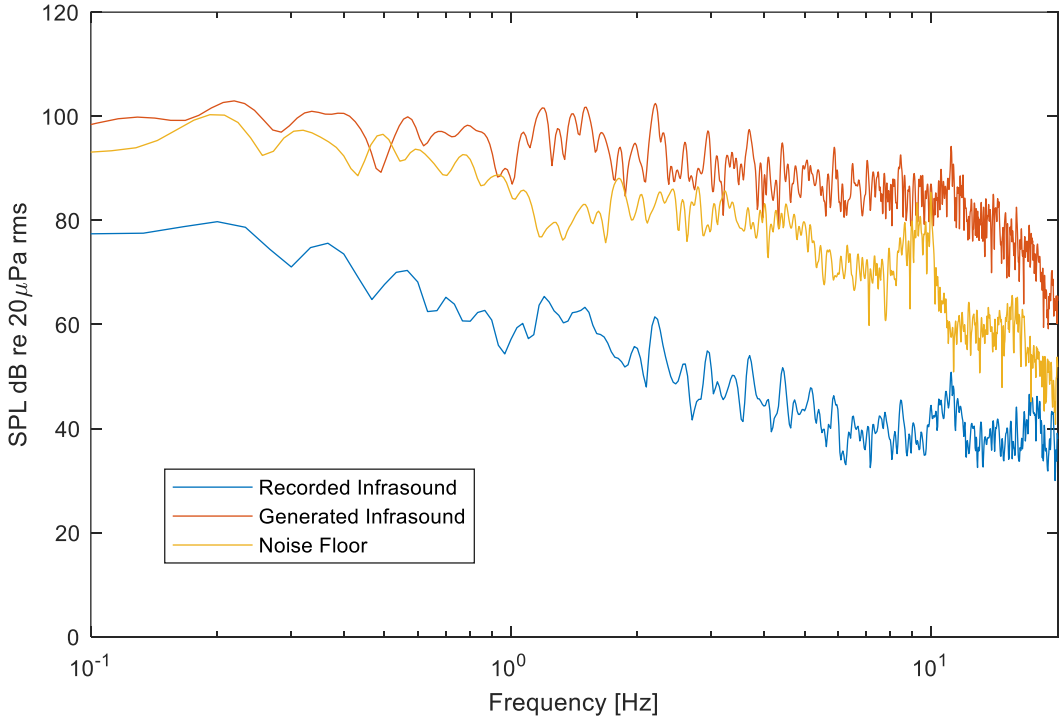

Figure 5: Spectra of infrasound for a 30 s segment of field measurement data (blue), the noise floor in the lab (yellow), and the reproduced infrasound (red)

After 53 participants were tested, the human response results were reviewed. There was a general lack of response to both AM and infrasound. Feedback from conferences indicated that the duration of stimulus may not be long enough. In addition, updated analysis of wind turbine infrasound gave a clear indication of the impulsive nature of wind turbine infrasound emissions as opposed to typical broadband background infrasound.

This updated analysis was based on infrasound collected from the Eolos Wind Research Station on June 10, 2012. For this dataset, turbine hub speed was measured independently

and synced with the noise measurements via a laser tachometer. This allowed resampling of the infrasound to a fixed number of samples per rotation and ensemble averaging in order to remove destructive averaging caused by slight deviations from the design rotor speed of 15.5 rpm. This analysis only used blade rotations ranging from 15 to 16 rpm, or blade passing frequencies of 0.75 to 0.8 Hz. This filtering yielded a dataset of 1328 rotations to ensemble average. The time series and spectrum used for Phase II of human response testing is shown in Figure 7. Compared to the infrasound stimulus played in Phase I, which used random phases for the artificially added blade passing frequency and harmonic tones, the harmonics are much clearer in the spectrum although the presentation level of harmonics was same as in Phase I.

During Phase I testing, the rotary subwoofer was found to emit some extraneous audible noise in addition to the infrasound. To mitigate this artifact, a “masker” audio signal was created by recording audible noise during “IPulse” from the rotary woofer and adding white noise. This masker signal was used for all conditions. The duration of the stimulus was also extended to 60 seconds. There was no AM stimulus for Phase II testing.

- Audible Sound (Subwoofer)
    - “White”
        - (Gaussian) white noise.
        - Presentation Level: 50 dBA
        - Used only for the Pre- and Post-Test conditions.
    - “Masker”
        - Composite audio from:
            - ‘RotaryWoofer.wav' (Microphone recording of the rotary woofer’s fan while playing “IPulse”, for fan pulsation.)
            - 60-dBA (Gaussian) white noise.
        - Band-pass filtered at 50 and 4000 Hz (3rd order Butterworth).
        - Presentation Level: 75 dBA
        - Used on all “Main Experiment” conditions.
- Infrasound (Rotary Woofer)
    - “IOff”
        - Rotary Woofer (fan) on, but no signal.
    - “IPulse”
        - Single rotation ensemble average of a 1328 resampled rotations [0.75<BPF<0.80]
        - The 3.9-s stimulus was resampled to 50 kHz and repeated to create a 70-s total duration.
        - Low-pass filtered at 50 Hz (3rd order Butterworth).

Table 3: Phase I and II Stimuli Conditions

IOff (+Masker)	IPulse (+Masker)

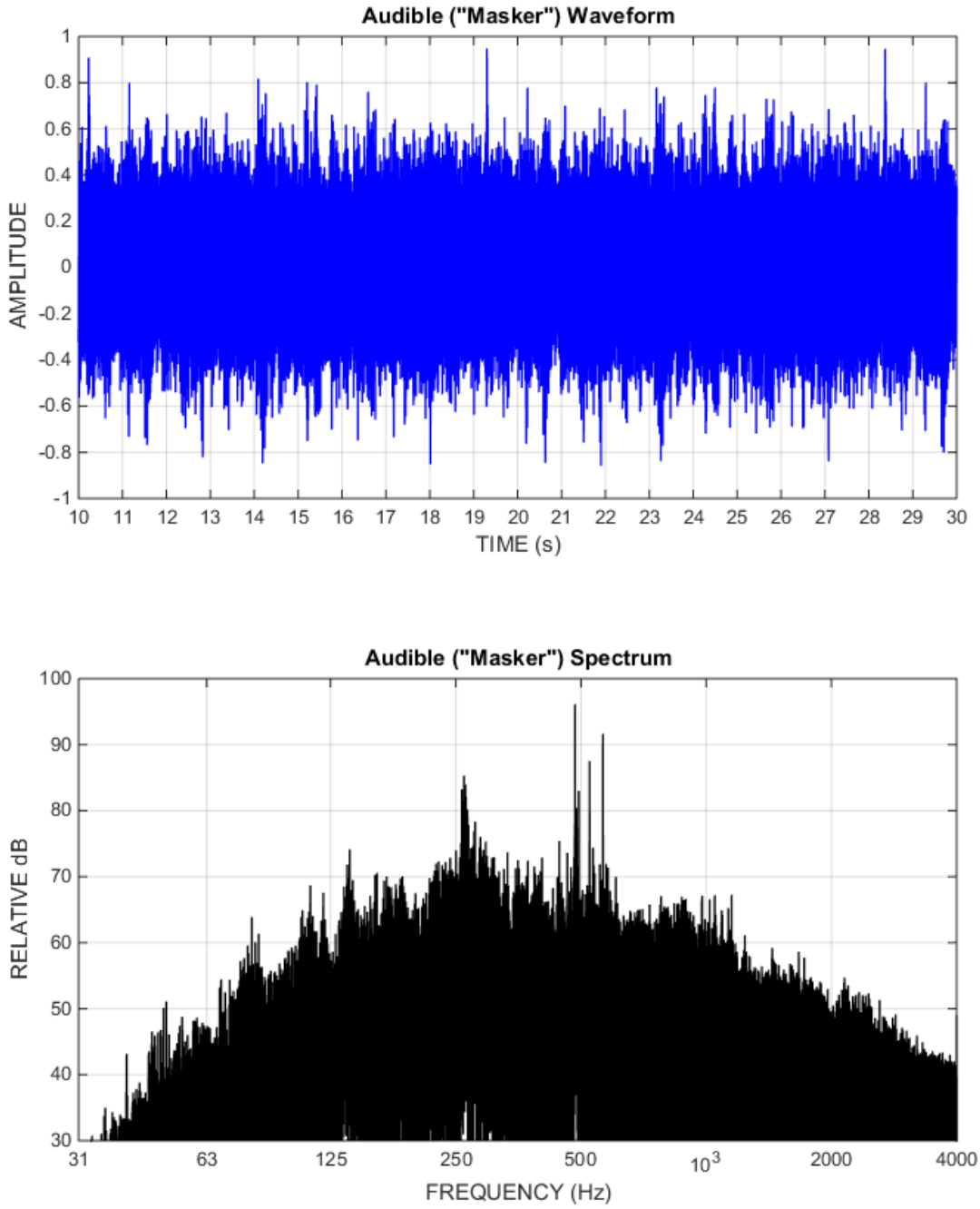

Figure 6: Audible "Masker" waveform and spectra prior to amplification

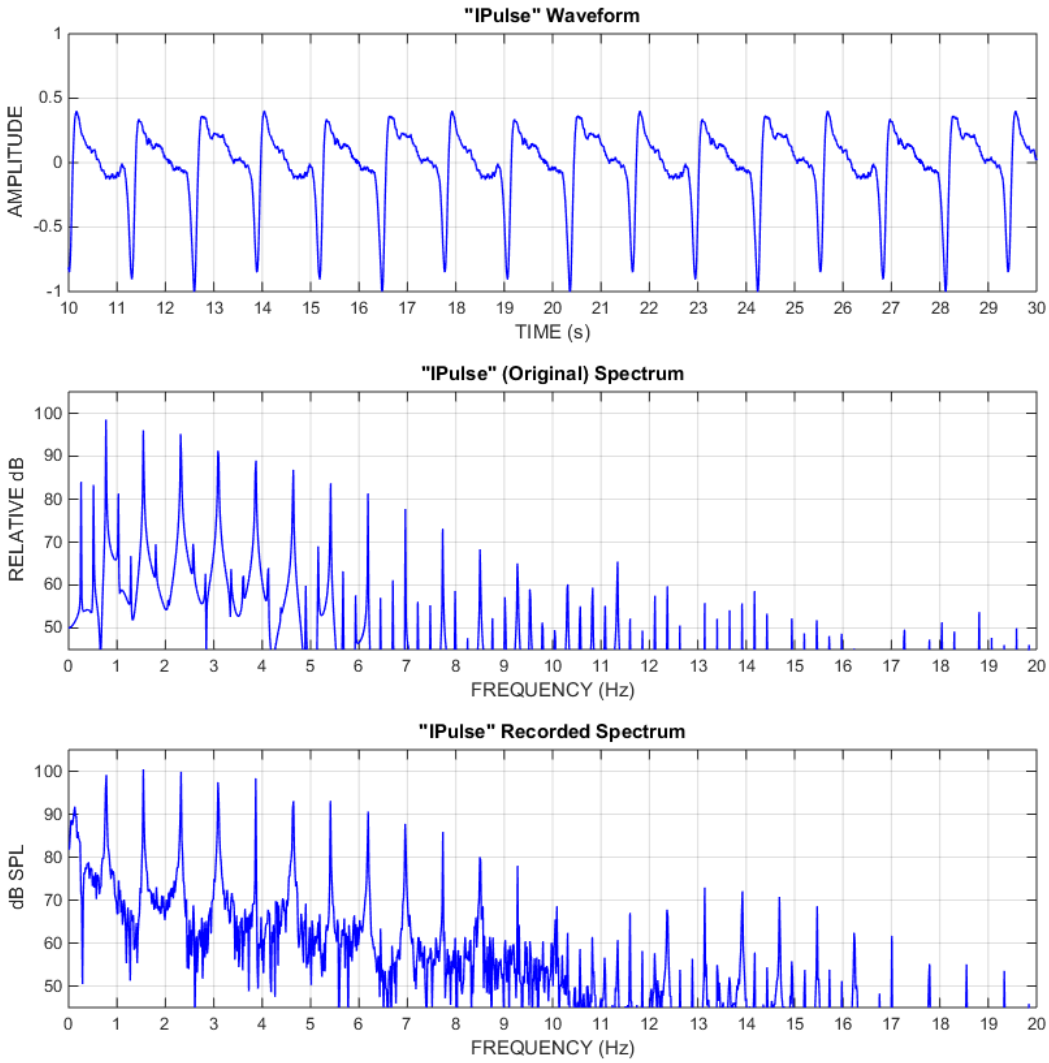

Figure 7: Time series and spectra of original and recorded "IPulse" signal from testing room. This signal was developed by resampling to a fixed number of samples per rotation and ensemble averaging.

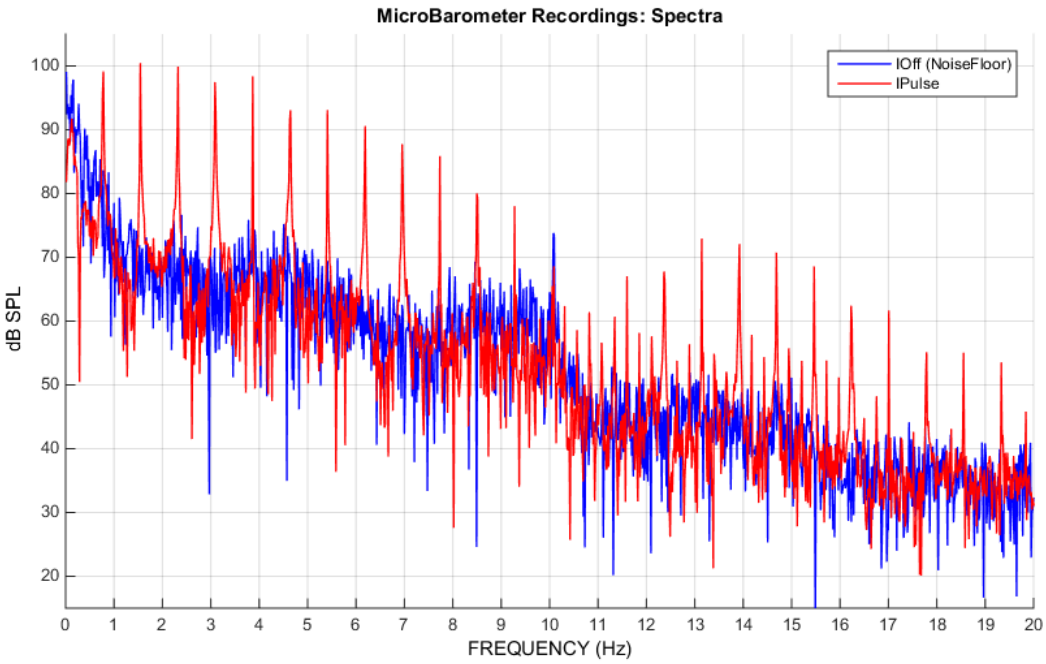

Figure 8: Phase II spectra of testing room infrasound recordings

Phase III testing used the same stimulus as Phase II, but with symptomatic participants who were aware research was related to wind turbine noise.

3.2 Response Analysis

The analysis was primarily performed on population statistics from each testing Phase. The primary metric was from the forceplate comparisons between pre and post testing for a baseline, AM stimulus on versus white noise, and infrasound stimulus on versus off.

Response to the question, *Did you sense anything besides the sound?*, after each individual stimulus was used to quantify the sensitivity index, d', with higher values indicating the signal could be more readily detected.

Response to the question, *How would you rate the condition?,* after each individual stimulus was plotted to give a rating value of the particular stimulus with 0.5 (neutral) being the default.

The post exposure symptoms questionnaire was also reviewed. This questionnaire was given after the testing was over.

4. Results

4.1 Phase I

The results of the sway for each stimulus/eye condition are summarized in Figure 9. It should be noted that there were twice as many eyes closed than eye open conditions which may affect error bars. Figure 10 collapses data by showing the percentage difference of sway during wind turbine noise stimulus (AM or infrasound) from associated references (white noise or infrasound off). The percentage difference combines all eye conditions and X/Y sway for the comparison. The largest percentage difference is post-test to pre-test. There was nothing remarkable about the other percentage differences.

Figure 11 shows the detection and rating for each individual stimulus. The Phase I population correctly detected infrasound for roughly half of the conditions. This may have been due to some an audible artifact of the rotary subwoofer operation. In general, rating values were neutral.

The post exposure questionnaire showed the most prevalent symptom was fullness of head/ears. There were no “severe” (3) ratings given. Fatigue symptoms were also noted but may have been related to the duration of the standing test.

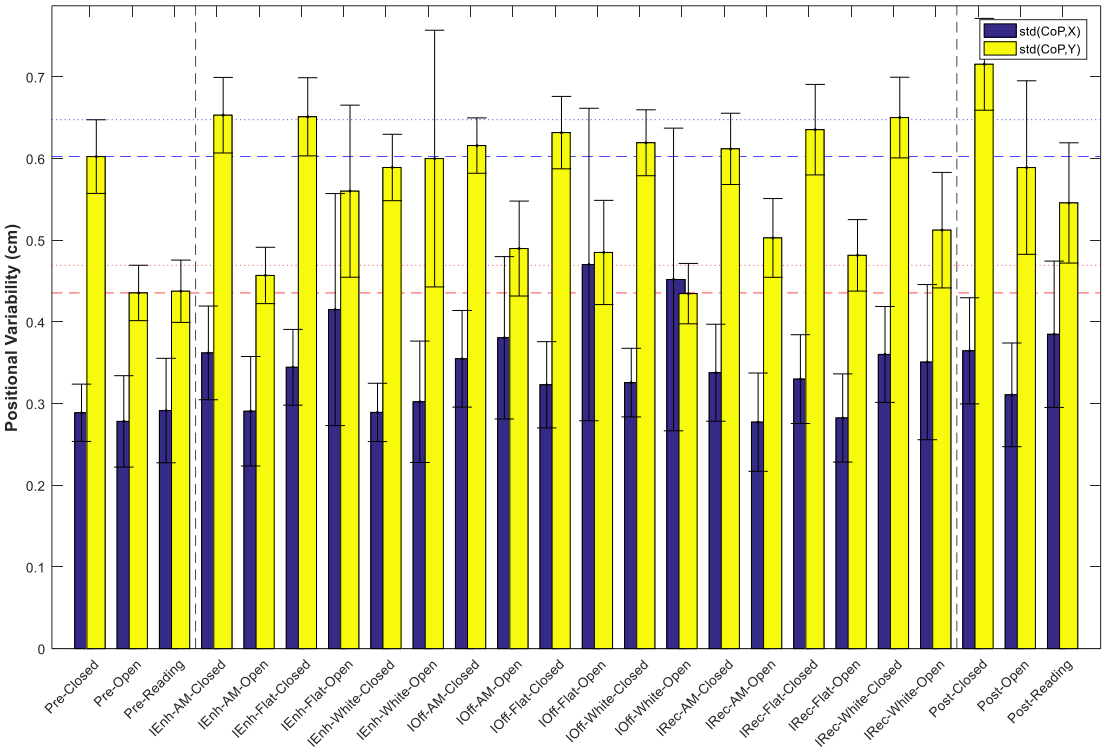

Figure 9: Phase I sway population statistics for each stimulus type/eye condition.

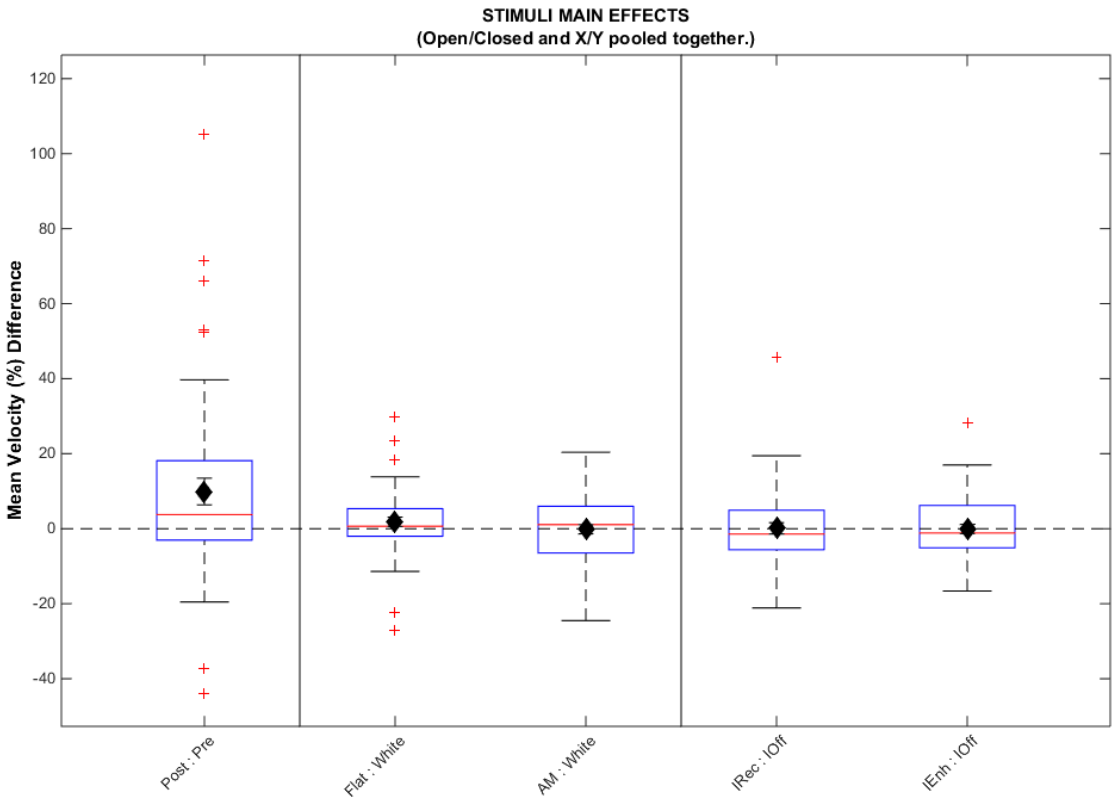

Figure 10: Phase I sway statistics of percentage differences from wind turbine noise stimulus to references

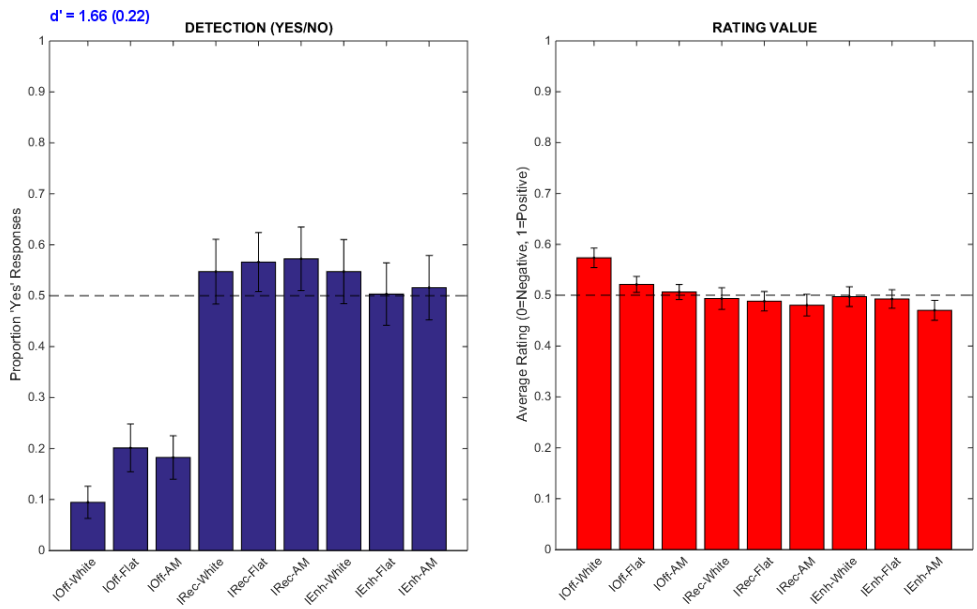

Figure 11: Phase I detection and rating for each stimulus

4.2 Phase II

The results of Phase II was even less remarkable than Phase I results with no significant difference in sway comparing the impulsive infrasound to the infrasound off condition. Figure 12 shows population statistics are nearly identical for both the eyes open and eyes closed conditions regardless of if the impulsive infrasound stimulus was on or off. There were an equal number of eyes closed and open for this Phase.

Figure 14 shows the detection and rating for each individual stimulus. The Phase II population correctly detected for less than half of the conditions. The addition of the “Masker” signal likely

helped mitigate audible artifacts during rotary woofer operation. In general, rating values were neutral and nearly identical for both the infrasound off and on conditions.

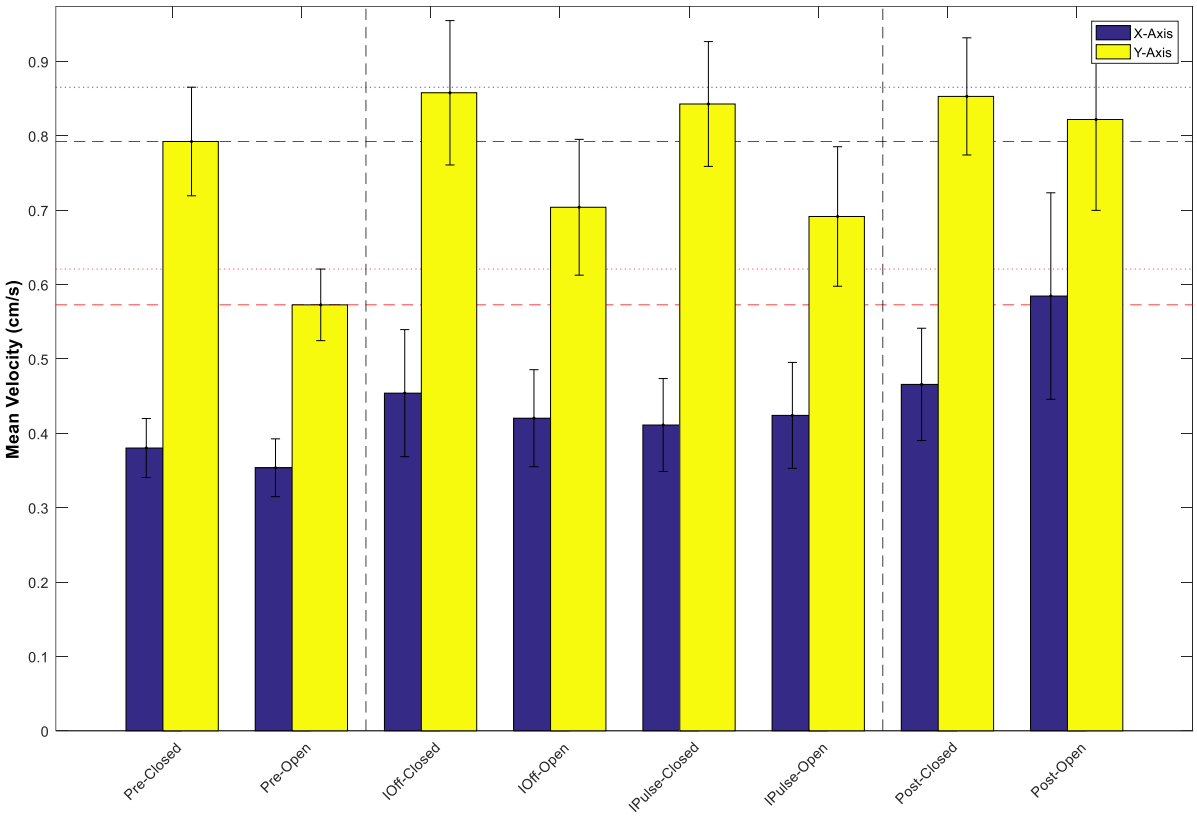

Figure 12: Phase II sway population statistics for each stimulus type/eye condition.

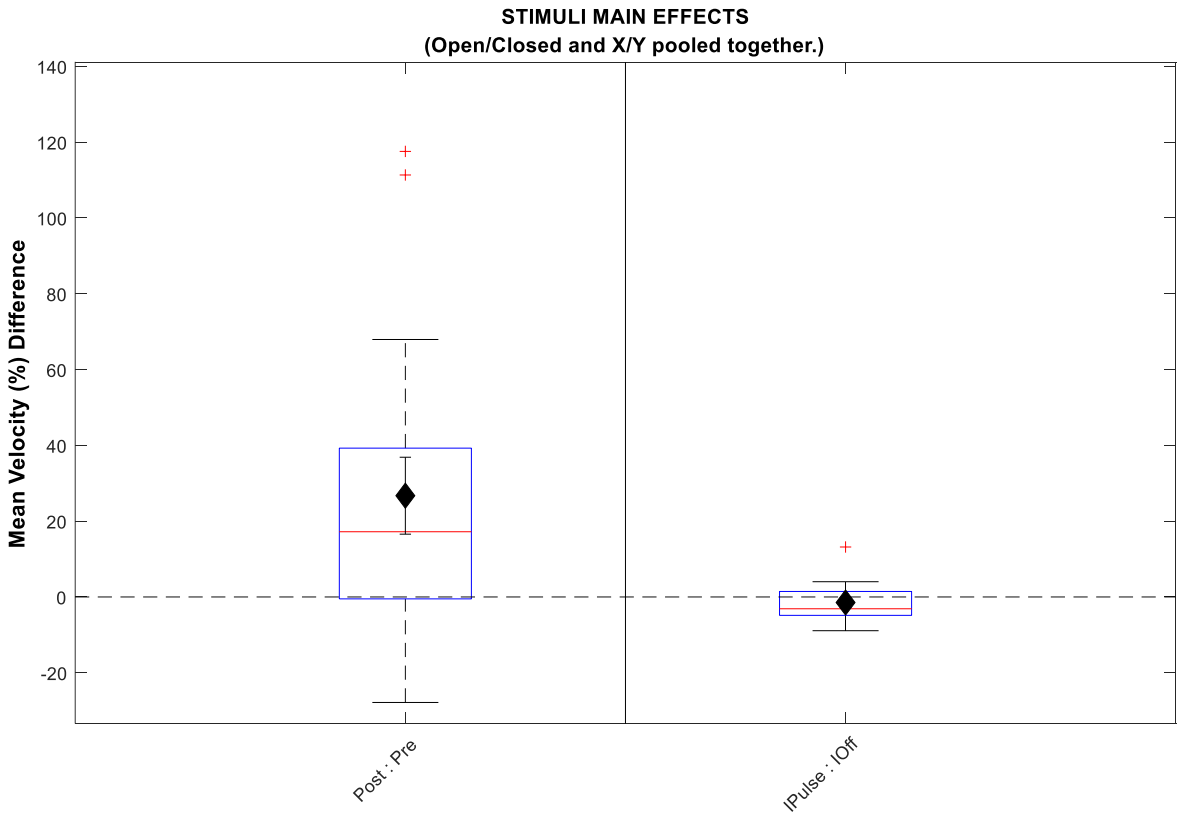

Figure 13: Phase II sway statistics of percentage differences from wind turbine noise stimulus to references

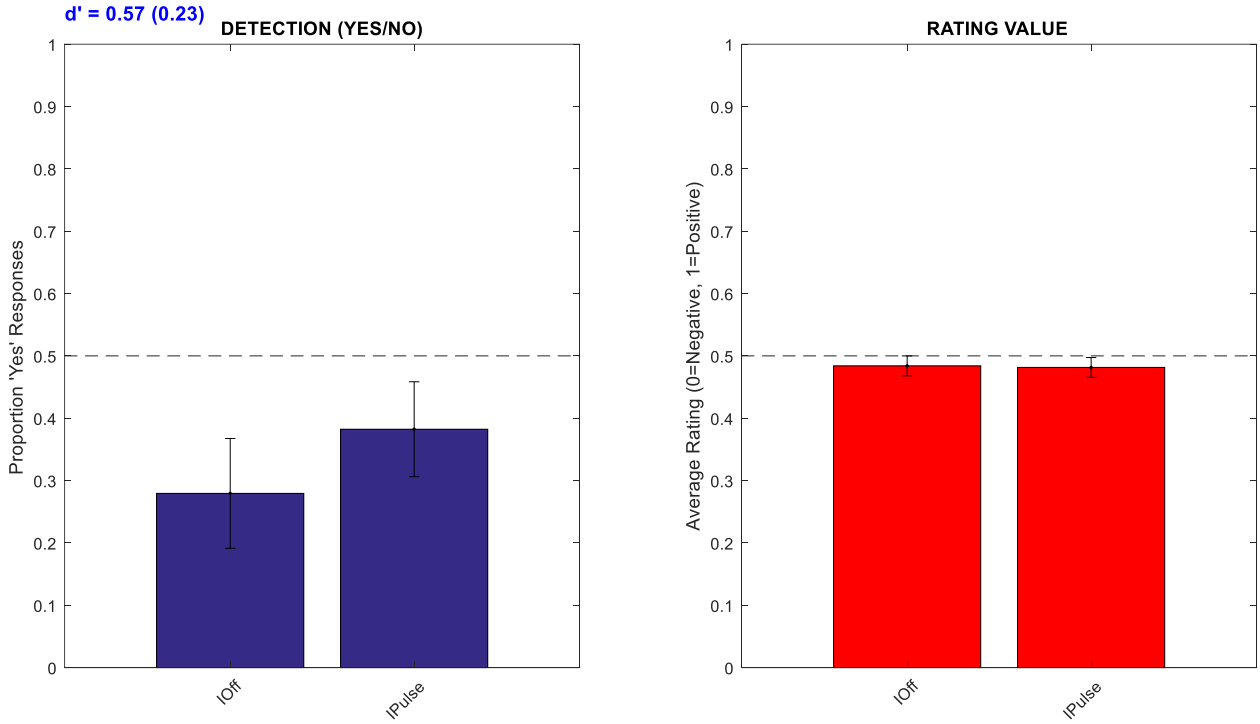

Figure 14: Phase 2 detection and rating for each stimulus

4.3 Outliers/Interesting Individual Results

The outliers in the two phases of testing have yet to be fully investigated. Correlations between sway, detection, rating value, the pre-test general heath survey and the post-test symptom survey should be performed. Some noticeable preliminary individual results are described here. There have only been three symptomatic people tested to date.

- A few participants could detect infrasound with $d' > 2$, but they reported no symptoms and no remarkable sway results. The audible "Masker" was used in Phase II to mitigate any other cues.
- Three out of 54 Phase I individual rated the stimuli with infrasound as slightly negative on sound quality ratings. One of those people was older, took the longest, and reported fatigue. The second reported not liking "airplane-like" sounds and had very high detection ability. The third person showed nothing notable.
- One younger individual with no symptoms and no detection swayed noticeably more on infrasound than other trials
- One symptomatic individual suffered from weakness in the knees and required a break from testing. When testing was restarted, weakness of knees was again reported in the absence of infrasound.

5. Conclusions

From the human response testing completed and analysed, there appear to be no significant relationship between sway or unpleasantness ratings for short stimulus durations of wind turbine noise involving AM or infrasound. After Phase 1, impulsive infrasound was used, duration was doubled, and an audible "Masker" signal was used. The result show even less response to that stimulus. The infrasound presented during human response testing was ~40 dB higher than that recorded in the field in the frequency range of 1 to 5 Hz.

Postural sway did not correlate well with reported symptoms and unpleasantness or detection ratings and may not be a good indicator of symptoms due to wind turbine noise. Longer exposure times with seated participants and relying on self-reporting may be a better approach.

Other general results are listed below.

- Post-exposure symptoms were rated as mild, with a predominance of discomfort, fatigue and head/ear fullness
- No one reported motion sickness
- No significant changes in postural sway in the presence of infrasound or AM sound; only one participant showed greater sway in infrasound conditions, but had no symptoms or negative feedback
- A minority of individuals reliably detected infrasound signals while simultaneously rating the sounds as neutral

Some potential reasons we did not encounter significant human response are listed below.

- Infrasound at levels presented does not cause illness/symptoms
- Illness due to infrasound may have very low prevalence in the healthy population and our sample may not be representative.
- Stimulus duration is short and not representative of the typical length of environmental exposures.
- Testing building and surrounding neighborhood contains background infrasound. Perhaps it is more notable in open areas.
- Our measures may be insensitive to subtle inner ear effects

Future work includes continued testing of patients who may be more susceptible to infrasound effects. Also, electrophysiologic testing including electrocochleography and vestibular evoked myogenic potentials may be utilized in future work to directly measure auditory system response.

References

Oerlemans, S., Sijtsma, P., & López, B. M. (2007). *Location and quantification of noise sources on a wind turbine*. Journal of sound and vibration, 299(4-5), 869-883.

Salt, A. N., & Hullar, T. E. (2010). *Responses of the ear to low frequency sounds, infrasound and wind turbines*. Hearing Research.

Moller, H., & Pedersen, C. S. (2004). Hearing at low and infrasonic frequencies. *Noise and Health, 6*(23), 37-57.

Salt, A., & Lichtenhan, J. (2014). How Does Wind Turbine Noise Affect People? *Acoustics Today*, pp. 20-28.