UNIVERSITY OF MINNESOTA

Twin Cities Campus

Saint Anthony Falls Laboratory
College of Science and Engineering

2 Third Ave SE
Minneapolis, MN 55414
Main Office: 612-624-4363
Fax: 612-624-4398
http://www.safl.umn.edu

Project Title: Wind turbine generated sound: Targeted research to improve measurement, analysis, and annoyance thresholds based on measured human response

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Principal Investigator: Jeff Marr (612) 624-4427
Contract Contact: Bridget Foss (612) 624-5571
Congressional District: (Corporate office) Minnesota 5th
Congressional District: (Project location) Minnesota 1st and 5th

MILESTONE REPORT 8

Executive Summary

Milestone 8 report includes the participant list and synopsis of the third TAP meeting, updates to the human response laboratory study, and future work for both monitoring and human response testing. The complete participant list and synopsis of the meeting is in Appendix A of this report. The updates to the human response laboratory study include updated stimulus focusing specifically on infrasound after initial review of results from the first 53 participants. The updated stimulus testing with 15 people with no response. The future work for the project results from the analysis of the completed work. For the monitoring, the lack of captured amplitude modulation in the field resulted in long-term amplitude modulation monitoring which deploys a noise level meter for continuous recording. For the human response, the lack of human response to stimulus and input from research peers at conferences resulted in an additional phase of testing which will target participants who will more likely respond to wind turbine noise. Outcomes from the future work will be used to write guidelines on noise monitoring and guidelines for impacts of turbine sound and the human response.

The technical advisory panel agreed with our analysis methods and results of noise data, including resampling and ensemble averaging of infrasound data and non-varying amplitude modulation with increasing wind shear. They also agree that long-term amplitude modulation monitoring is required to capture amplitude modulation which occurs under infrequent conditions, thus requiring continuous monitoring. Another phase of human response testing is planned with a more susceptible population of participants and includes electrophysiological metrics as a quantitative measurement. A report from the Minnesota state regulators and resulting discussion revealed regulation issues with existing permissible noise level limits (L_{10} and L_{50}) and the current guidelines should be updated. The guidelines from the current project should address these issues as well as more research level topics such as infrasound and amplitude modulation.

The stimulus for the human response testing after the initial 53 participants was an updated infrasound signal created from resampled, ensemble averaged noise data collected from the Eolos site. Additionally,

the duration of the stimulus was increased from 30 seconds to 60 seconds. To maintain total testing time for each individual, no amplitude modulation stimulus was used. The preliminary analysis of the 15 people showed no human response to the updated infrasound stimulus.

Long-term amplitude modulation monitoring is currently underway. This campaign started at the Eolos site on April 24th and is continuing for the foreseeable future. The current measurement location is 600 meters north of the turbine. The plan is to apply the Institute of Acoustics amplitude modulation methodology to the entire dataset, find times of large amplitude modulation depth and review turbine and atmospheric parameters at these times. Recording during different seasons is also of interest. The stall control on the turbine will also be activated for various atmospheric conditions to help understand how angle of attack may affect amplitude modulation.

Technical Progress

Technical Advisory Meeting

A technical advisory panel meeting was held on April 11th and project results to date were presented including the field analysis and human response testing. The full synopsis of the meeting is located in Appendix A and is summarized below.

- Wind turbine infrasound was discussed and found to be characterized well using the analysis methods discussed in Appendix A. This analysis was implemented in Phase 2 of human response testing.
- The lack of amplitude modulation of significant depth in the far-field was discussed during the measurement campaign. This was due to the relatively short duration of measurements in the new field campaign and the proximity of the microphones to the turbine (100 meter) in the 2012 dataset. Additional far-field measurements are required to capture amplitude modulation of significant depth (>3 dB(A)). Far field is defined as approximately 600 or more meters from the turbine. This led to the long-term amplitude modulation monitoring campaign outlined below.
- The lack of human response in the first 54 people of testing was discussed. Prior to the meeting, the stimulus was modified to longer duration of peakier infrasound. Future phases of human response testing using more at risk participants and electrophysiological measurements was discussed and supported by the technical advisory panel.
- Guidelines were discussed with a focus on current regulation issues in Minnesota and examples of international regulation

Long-term amplitude modulation monitoring

Long-term amplitude modulation monitoring is ongoing since April 24th, 2018. Preliminary results of the application of Institute of Acoustics amplitude modulation methodology are presented in Figure 1Figure 2. Both figures show the amplitude modulation depth on the vertical axis. Figure 1 illustrates results for a duration of 10 minute aggregated from 10 second segments as outlined in the Institute of Acoustics method. Figure 2 shows the amplitude modulation of the raw 10 second segments.

The data shown in the two figures are preliminary and primarily used for gauging the amount of amplitude modulation captured during the long term amplitude modulation monitoring

campaign. In addition to the 100 millisecond L_{eq} data required for the amplitude modulation analysis the complete raw signal is recorded and can be played back. Future analysis of the data will include comparison of times with high amplitude modulation depth to concurrent meteorological measurements and turbine operating conditions. Additionally, raw signals will be listened to ensure that amplitude modulation is related to turbine operation.

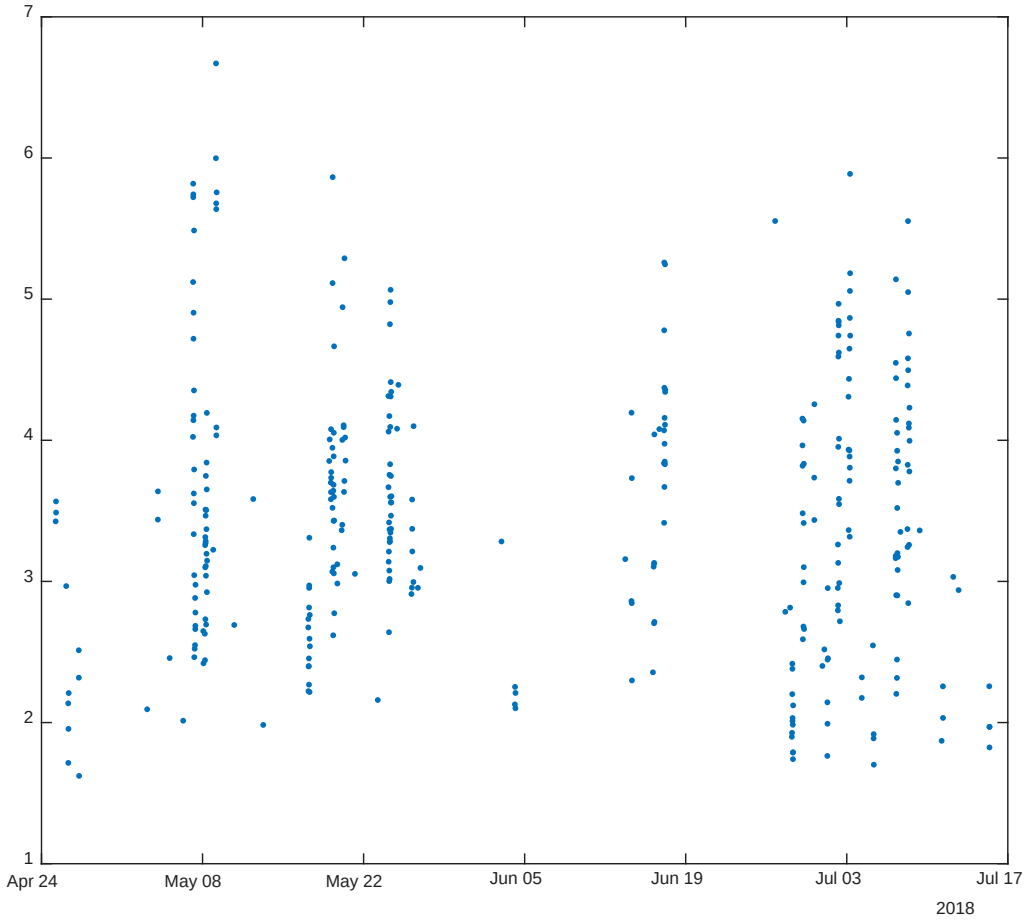


Figure 1: Amplitude modulation depth (y-axis) for 10 minute methodology

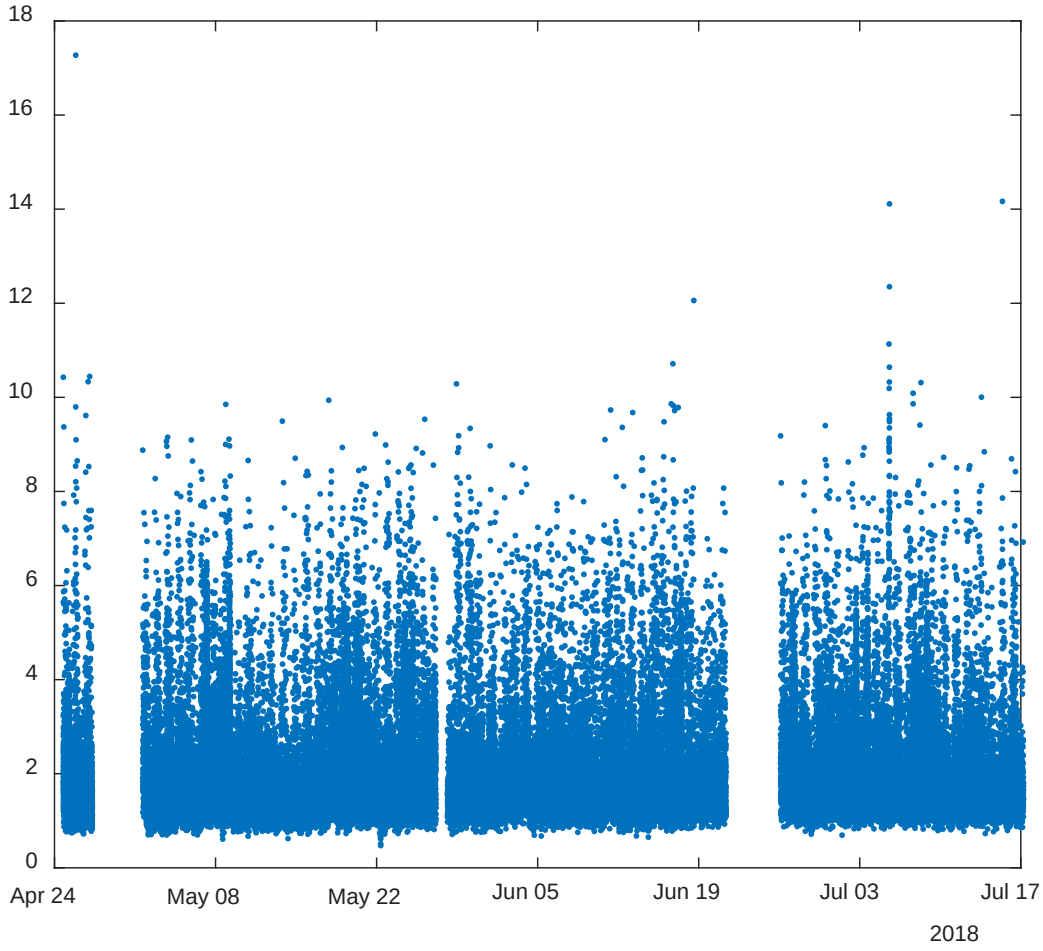


Figure 2: Amplitude modulation depth (y-axis) for 10 second segments

Human Response Testing

Deliverable 7 outlined the preliminary findings of the human response testing at that time. This first phase of testing included results from 52 healthy adult subjects. The preliminary findings at that time found no significant adverse effects or changes in postural sway during testing. Due to this lack of response from study participants, an updated analysis of infrasound data, and peer input from noise conference, the testing and stimuli were modified for a Phase 2 of testing. Overall changes include modifying the infrasound stimulus to be peakier in the frequency domain and representative of the impulsive nature of infrasound generated by wind turbines and increasing stimulus duration from 30 seconds to 60 seconds. To maintain total testing time, the amplitude modulation stimulus was dropped.

Fifteen people participated in Phase 2 with no significant adverse effects or changes in postural sway during infrasound stimulus compared to times without infrasound stimulus. Figures Figure

3Figure 4 show the postural sway results for Phase 1 and Phase 2 of human response testing, respectively. Analysis of the self-reported ratings and questionnaires will be reported in Deliverables 9 and 10.

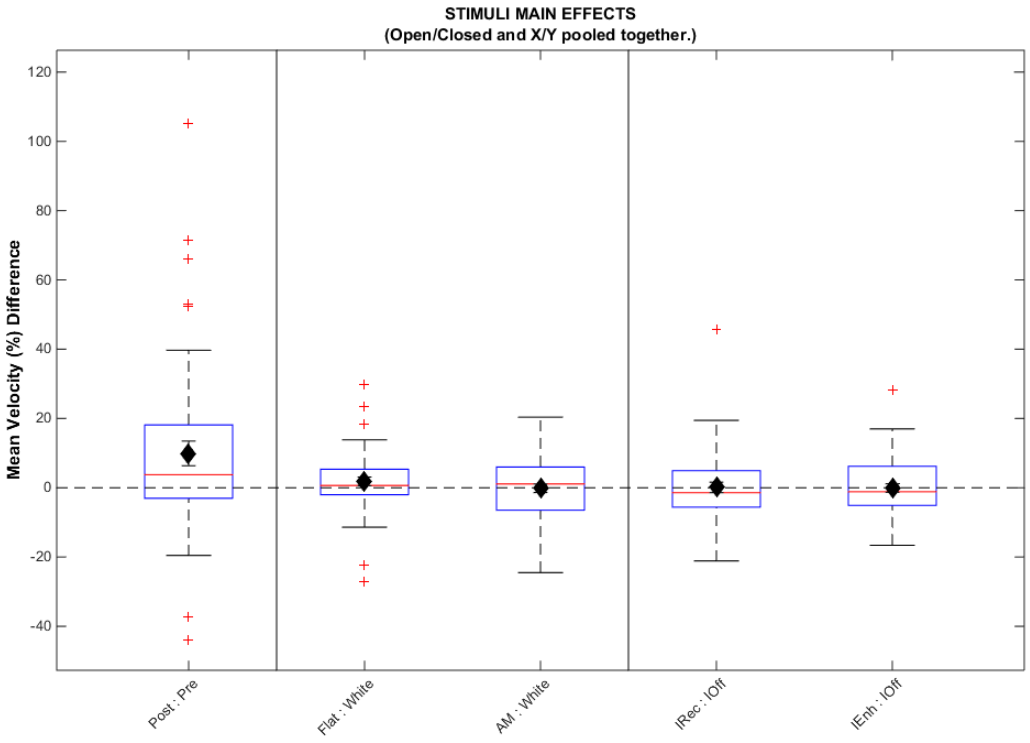


Figure 3: Phase 1 Human Response Postural Sway (52 participants)

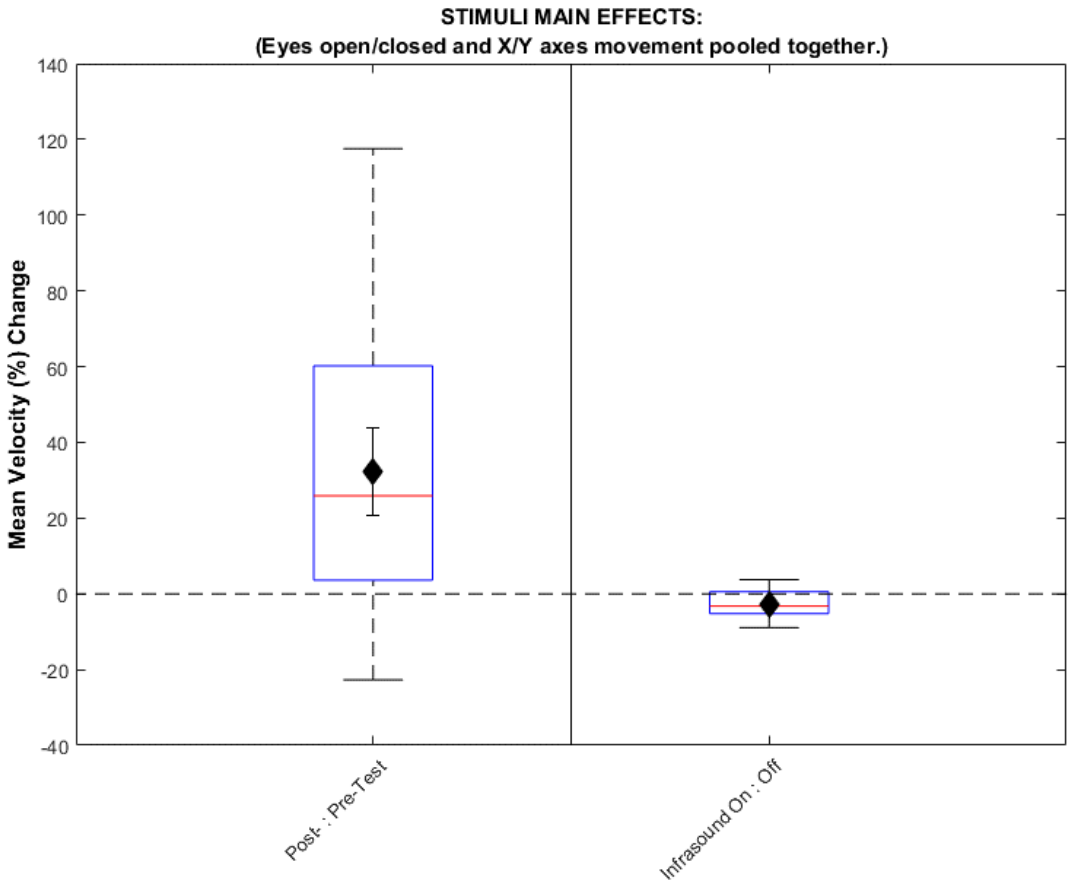


Figure 4: Phase 2 Human Response Postural Sway (14 participants)

Additional Milestones

Analysis of the human response study will be reported on and completed in Milestones 9 and 10, respectively. This analysis is currently underway and will likely include results from Phase 3 of human response testing which targets participants more likely to respond to wind turbine noise than the general population.

Development of guidelines on noise monitoring will be started in Milestone 10 and completed in the Milestone 13. This development of guidelines will utilize methods used during the long term amplitude modulation measurement campaign, which is currently underway. TAP meeting 3 showed that these guidelines should also address more basic noise characteristics currently regulated in Minnesota and should leverage regulations in other national and international areas.

Development of guidelines for impacts of turbine sound and the human response will be started in Milestone 11 and complete in Milestone 13. This development of guidelines will characterize the turbine sound and its potential impacts as well as leverage the results of the human response testing to show any human impacts.

Project Status

The project is behind the original schedule. For this reason, a one year no-cost extension was requested by the University of Minnesota and granted by Xcel Energy. This extension does not require additional funding beyond the original award.

The reason for the delayed schedule is to allow follow up phases of human response testing and deploy long term noise monitoring in the far-field from a turbine. The follow up phases of human response testing are required to address peer input from conference proceeding and ensure initial human response findings are correct. This will aid the guidelines for impacts of turbine sound and the human response. The long term noise monitoring addresses issues with noise measurements required in the far-field as well as providing a large dataset that is more likely to capture infrequent noise issues such as enhanced amplitude modulation. This will aid the guidelines on noise monitoring

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

Appendix A- Technical Advisory Panel – Meeting 3 Synopsis

Subject: Technical Advisory Panel – Meeting 3 Notes April 11th, 2018

Attendees

Research Team	
Jeff Marr	☒
Peggy Nelson	☒
John Wachtler	☒
Michael Sullivan	☒
Meredith Adams	☐
Bill Herb	☒
Chris Feist	☒
Andy Bryne	☒
Matt Lueker	☒
Louise Miltich	☒

Technical Advisory Panel	
Andrew J Oxenham	☐
Chuck Niederriter	☐
Carl Herbrandson	☐
Daniel Shannon	☒
Rita Messing	☐
Dick Bowdler	☒
Mos Kaveh	☐
Corey Juhl	☒
Christopher Hogg	☒
Thomas Stoffregen	☐
Payam Ashtiani	☒

Grant Administrator	
Mark Ritter	☒

Meeting Overview

The third technical advisory panel meeting was well attended by the research team and about half of the technical advisory panel. The grant administrator was also present for the meeting. The primary goals of meeting were to update the TAP and collect input on the path forward for both field measurements and human response testing, discuss current wind energy noise regulation issues encountered by regulators, and start the discussion on the guidelines portions of the project.

Cursory updates on both the field measurements and human response testing were provided to the TAP. Theses updates mostly centered around updated analyses. The path forward for field measurements includes long-term amplitude modulation monitoring and turbine control modifications to potentially create amplitude modulation. The path forward for human response testing are future phases of testing which include clinical human response testing with those who have complained about wind turbine noise and those who have a medical diagnosis which might make them more susceptible to wind turbine noise. This testing will include measuring response with current experimental setup as well as using electrophysiological measurements to directly measure physiological response.

Current issues with Minnesota regulators is generally whether noise limits the Minnesota Pollution Control Agencies set are cumulative noise or the noise levels from modeled single noise sources such as wind turbines. Also, general noise guidelines are not helpful for wind energy as they are designed for regulating noise sources much higher than background noise. Also, they do not deal well with background noise from wind, such as foliage and wind/sensor interactions. The TAP group indicated this is a common problem, Also, it is generally assumed that these limits are cumulative from all sources and are located at the receptor.

A general consensus during the meeting was that the Guidelines on Noise Monitoring should prioritize information on more basic sound characteristics, such as L_{eq} limits, as well as those of infrasound and amplitude modulation. Amplitude modulation is still seen as a research topic followed but not applied by those responsible for creating regulations.

The format or goals of the Guidelines of Turbine Sound and the Human Response were not discussed extensively. Instead, Ontario's complaint assessment protocol for existing wind farms was reviewed. This protocol gives a structured format for regulators for reviewing and responding to wind turbine noise complaints. It includes multiple levels of qualitative and quantitative screening and includes including guidelines on noise measurements.

Items which emerged during the meeting are listed here.

- Resampling noise measurement to a fixed number of samples per full rotation and ensemble averaging gives a good clean view of impulsive infrasound emitted from a wind turbine. This helps remove destructive averaging that can happen with slight changes in rotational speed.

- Amplitude modulation depth is fixed (flat) for a variety of wind shears. This conflicts with the assumption that the amplitude modulation is a function of wind shear alone. This was found in the current project dataset as well as other researcher data sets.
- Long- term amplitude modulation monitoring is needed to capture AM and this will be deployed at the Eolos site. Stall control work will be ongoing with this work.
- The lift coefficient of wind turbine airfoils examined does not abruptly drop after peak lift. This may be a design consideration for wind turbine airfoils and reduce the amount of noise which can be attributed to stall.
- Human response testing has shown no significant response to either infrasound or AM from a general population. A total of 67 people have been tested. Peer reviewers at a noise conference proposed lack of susceptible persons in participant group, too short a stimulus dose for response, high levels of background infrasound in testing environment, and incorrect measurement metrics for response for the lack of response in human testing.
- Future human response testing phase will include targeted population more susceptible to effects by wind turbine noise as well as utilizing electrophysiological metrics for measuring response.
- The current major problem for Minnesota regulators is whether noise limits are cumulative or for the source being permitted. Noise modeling shows that predicted noise levels are very close to limits and may go over when other noise sources or background levels are included. This seems to be a common issue for jurisdictions. Two Canadian provinces assume this is cumulative of all noises sources.
- State guidelines specific to wind farm noise monitoring are accepted and used by developers, but they need to be updated. Ontario requires following the guidelines by specifying guidelines to be used in permit rather other regulation.
- Ontario has a clear complaint assessment protocol with multiple levels of investigation and reporting. This assessment starts with a qualitative assessment based on distance from wind farm and modeled noise levels and ends with detailed acoustic measurement deployed for approximately 6 to 8 weeks to check for non-compliance.
- Guidelines for regulators from this project should include more basic noise measurement metrics such as L_{eq} as well as infrasound and amplitude modulation. There are still issues with the more commonly used metrics that need to be resolved before moving onto using more advanced noise measurement metrics including infrasound, tonality, and amplitude modulation.

Meeting Agenda

9:00 – 9:10 Welcome and Agenda Review

9:10 – 9:20 Introductions

9:20 – 9:50 Field Measurements

- Eolos 2012 Data set
- Updated Eolos Dataset
- Wind Farm Dataset
- Other Testing (Buried Microphone, etc.)
- Distance/Wind Speed Bins Filled
- Final Analysis
- Path forward – Long term noise logger

9:50 – 10:30 Human Response Testing

- Review of testing /stimulus
- Results from first ~50 people (Phase I)
- Updated stimulus and results (Phase (II)
- Future Direction – Additional healthy, clinical, and/or electrophysiological tests

10:30 – 10:40 Break

10:40 – 11:00 Regulation Issues in Minnesota

- Current regulations
- Current regulation issues
- Are sound levels total including background or limited to turbine noise?

11:00 – 11:20 Guidelines on Impacts of Turbine Sound and Human Response

11:20 – 11:50 Guidelines on Noise Monitoring

- Long term amplitude modulation monitoring
- Incorporate stall control to create amplitude modulation
- Post processing with I of A method
- Attended infrasound monitoring

11:50 – 12:00 Look ahead and Adjourn

Appendix B- Phase 2 Infrasound Stimulus Details

Infrasound Project: (Phase 2) Stimuli Details

Audible Sound (Subwoofer)

"White"

(Gaussian) white noise.
Presentation Level: 50 dBA
Used only for the Pre- and Post-Test conditions.

"Masker"

Composite audio from:

1) 'RotaryWoofer.wav' (Microphone recording of the rotary woofer's fan while playing "IPulse", for fan pulsation.)
2) 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.

(See Figure 1 for "Masker" waveform and spectrum.)

Infrasound (Rotary Woofer)

"IOff"

Rotary Woofer (fan) on, but no signal.

"IPulse"

Original file used: 'average_infrasound1a.mat' [0.75<BPF<0.80, (n=1328)]
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).

(See Figures 2 and 3 for infrasound stimuli waveform, original spectrum, and measured spectrum/levels.)

2 Stimuli Conditions

(All stimuli are windowed with 1-s raised cosine on/off ramps.)

IOff (+Masker) IPulse (+Masker)

Miscellaneous Procedural Details

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

Pre-Test:

One set of Eyes Open and Eyes Closed conditions, random order.

Main Experiment:

Four sets of conditions: Open/Closed/Open/Closed *or* Closed/Open/Closed/Open (chosen randomly).
Both stimuli (IOff/IPulse) conditions presented twice in each set, order randomized.
Mid-session break after block 8 (of 16).

Post-Test:

One set of Eyes Open and Eyes Closed conditions, random order.

The subject initiates each block (by clicking a button on the display) and can abort the experiment at this point before each block.

Subject is given auditory instructions (through subwoofer) for the type of condition:

"Please close your eyes."
"Keep your eyes open."

Subject response after each block:

"Did you sense anything besides the sound?"
"Yes" or "No" buttons.
"How would you rate the condition?"
Slider: "Very Negatively" -to- "Neutral" -to- "Very Positively"

FIG. 1.

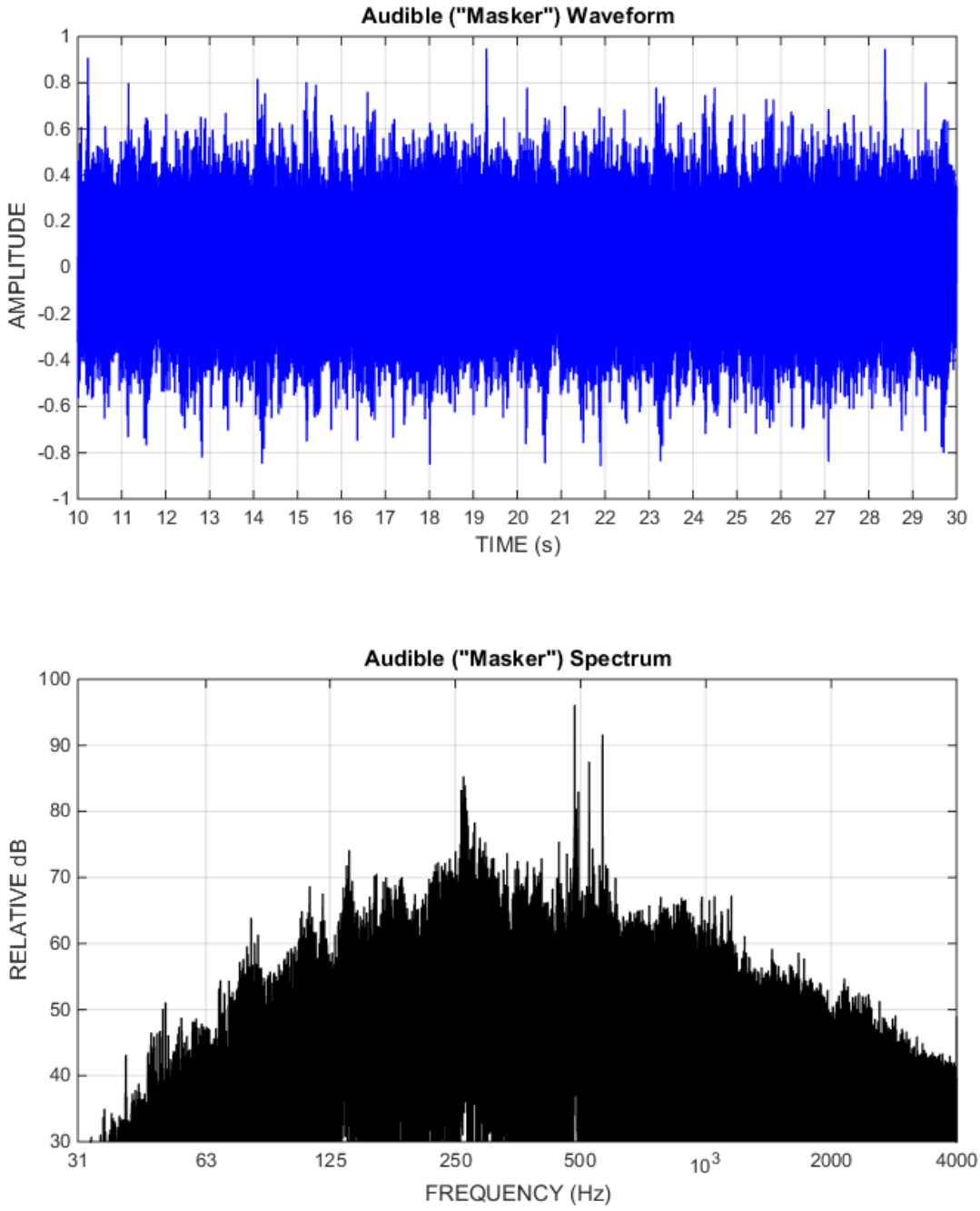

Audible ("Masker") Waveform
AMPLITUDE
TIME (s)
Audible ("Masker") Spectrum
RELATIVE dB
FREQUENCY (Hz)

FIG. 2.

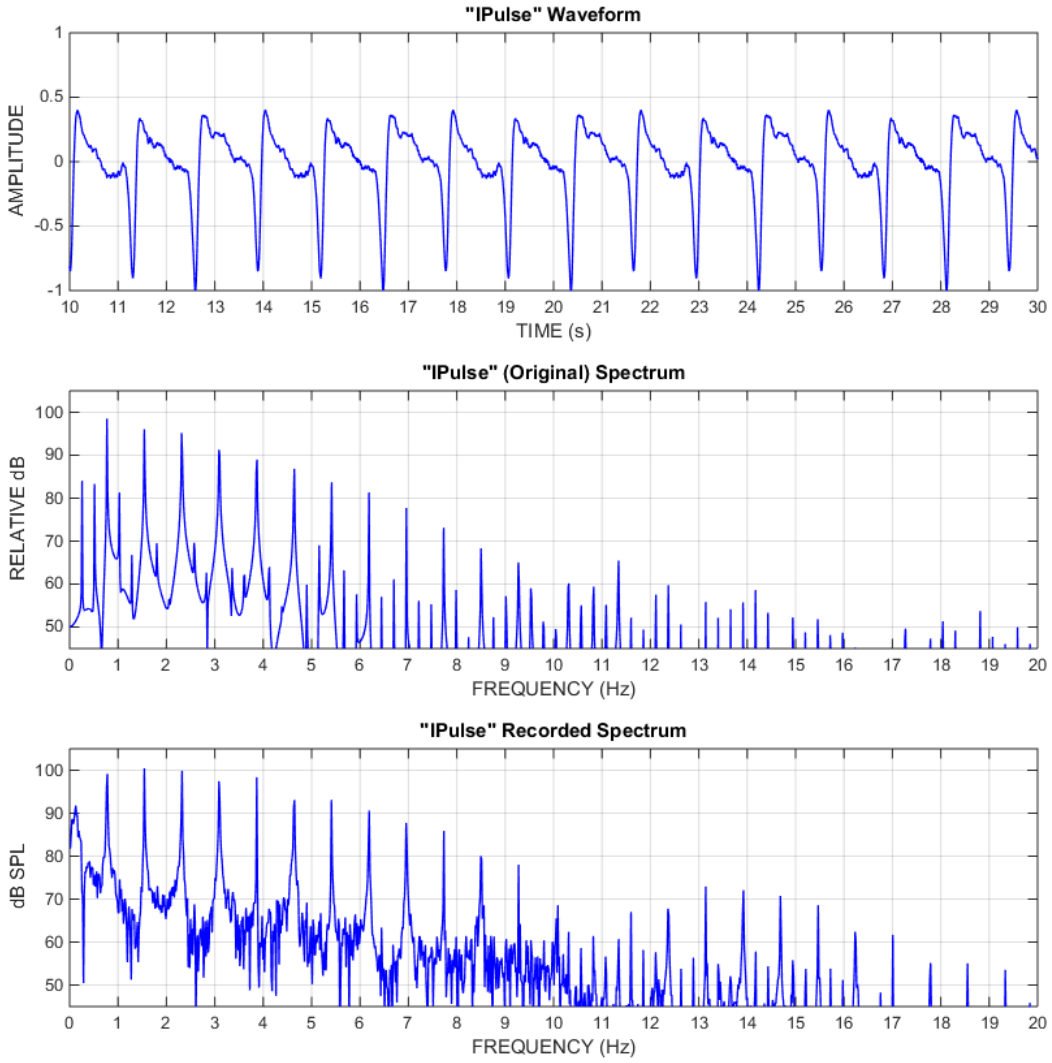
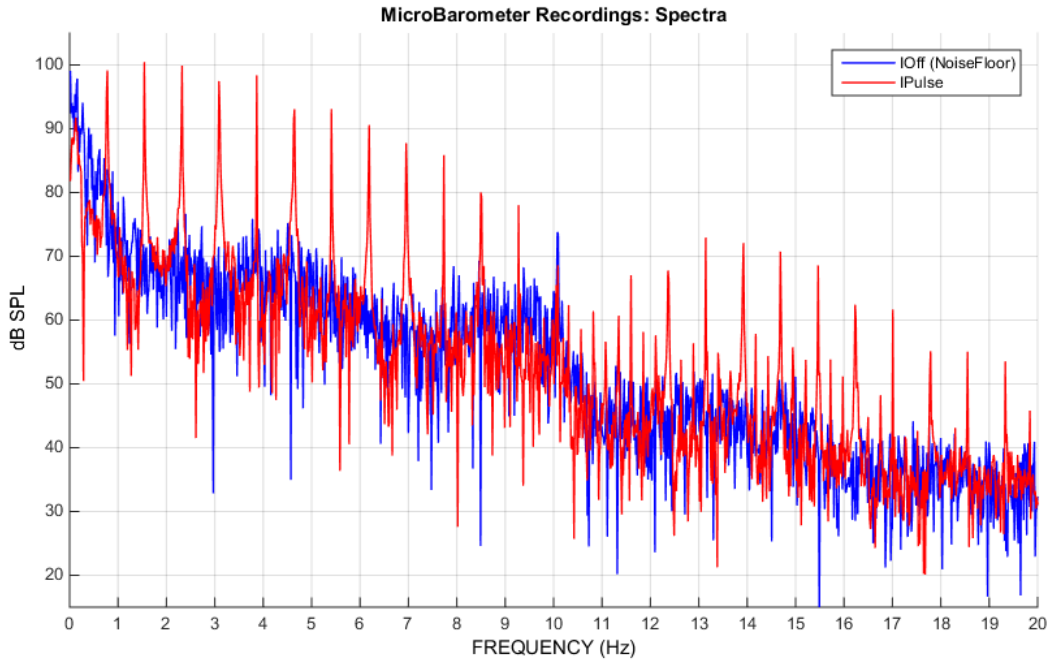

"IPulse" Waveform
AMPLITUDE
TIME (s)
"IPulse" (Original) Spectrum
RELATIVE dB
FREQUENCY (Hz)
"IPulse" Recorded Spectrum
dB SPL
FREQUENCY (Hz)

FIG. 3.


MicroBarometer Recordings: Spectra
IOff (NoiseFloor)
IPulse
dB SPL
FREQUENCY (Hz)
100
90
80
70
60
50
40
30
20
0
1
2
3
4
5
6
7
8
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