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Spatial distribution of acoustic modulation depth around a modern wind turbine

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Abstract

Modulation depth is an important factor associated with human annoyance of wind turbine noise [1]. We model the ground plane associated modulation depth character surrounding a modern wind turbine using a modified version of the National Renewable Energy Laboratory's (NREL) FAST/NOISE models [2]. The modifications to the noise modules permit the estimation of time dependent acoustic spectra using the aero-acoustic source mechanisms described by Brooks, Pope and Marcolini [3] and by Amiet [4]. The modifications also allow input and subsequent predictions for an arbitrarily sized and positioned locus of points defining observer locations. The FAST method estimates the wind turbine full system structural dynamics which allows an accurate determination of the aerodynamic environment of the airfoil segments which are used to represent each blade. This aerodynamic knowledge serves as input into the noise source mechanism models. The turbulent wind environment for forcing the aero-mechanical system was derived from sodar observations for input into the NREL TURBSIM model [5]. We present comparisons of acoustic model results and validation observations from an array of microphones associated with a **Mervento 3.6-118 wind turbine** to serve as a measure of the validity of the methods.

Objectives

- Develop an observation and modeling system for wind turbine (WT) acoustics
- Characterize the nearby spatial variability associated with wind turbine ground plane acoustics focusing on modulation depth
- (In the future) apply the acoustic observation and modeling system to optimization problems associated with noise control by developing novel pitch actuator control schedules

Methods

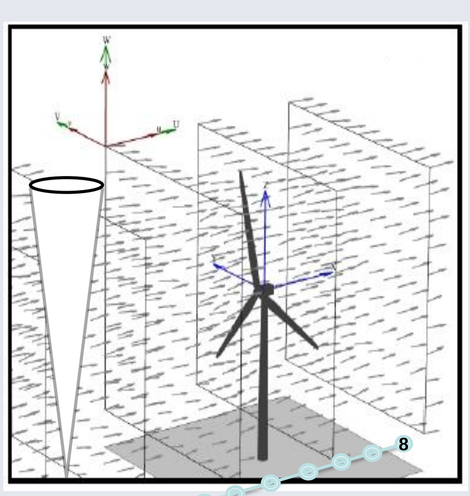

Fig 1. General locations of the microphone array and the sodar's sampling volume (cone) used during acoustic observations.

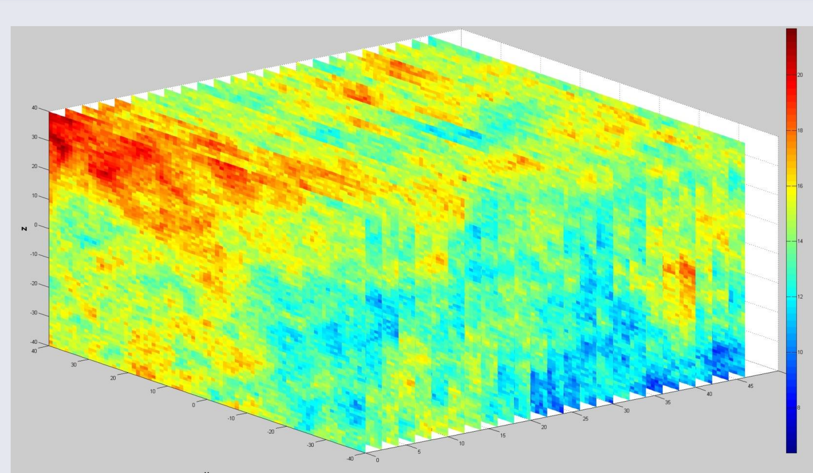

Fig 2. Example time dependent wind fields generated by TURBSIM derived from the wind profile statistics measured by the sodar. The system intends to generate statistically similar not actual turbulent wind fields for use in simulations.

For acoustic observations near the wind turbine we deployed a linear array of eight groundboard positioned microphones (with windscreens). The array's total length was 100m, it was offset from the mast at a distance equal to the rotor disk diameter/4. The direction of the array was chosen to align with the predominant wind direction (220 degrees re. N). Anti-aliasing filters and digitization rates were chosen to acquire narrow band estimates up to 12800 Hz. A sodar instrument was positioned approximately 300m upwind of the wind turbine (in the predominant wind direction, see fig1) to measure the wind speed profile. To estimate a turbulent wind field to force the FAST wind turbine model, sodar data were summarized and used as inputs to the NREL TURBSIM model. The TURBSIM generates time dependent spatial wind fields with random, spatially coherent turbulence and a wind profile. NREL's Upwind Wind Farm Model was used to achieve a high turbulence forcing wind derived from a thin stable atmosphere (Richardson number 0.05, SBL thickness 500m, reference wind speed 13.2 knots, and a log wind profile was used). Outputs from the TURBSIM model (fig 2) were used as inputs for the FAST simulations. Examples from the modified FAST system demonstrate some spatial acoustic characteristics near the WT blades at a single time step (fig 3). This example FAST/NOISE output provides third octave center frequency acoustic energy (400Hz) at arbitrary locations (three major axis planes in this case). Similar results were calculated as a function of time at a rate of 200Hz. Two sampling periods from different days are summarized here. Pre- and post- calibration signals were obtained for each sampling period.

For modelling, the parameterization of **a Mervento 3.6-118 wind turbine** was performed for input into the FAST model. This entailed characterizing the size, mass and elastic scale characteristics of the wind turbine. Also included were the blade definitions characterizing the airfoil shapes, size and twist distributions. In our use, FAST provided coupled aero-servo-elastic dynamics of the aero-mechanical wind turbine system (forced by the wind fields mentioned above). This included blade structural dynamics. The components of the wind turbine were allowed to transition to a steady state in response to the forcing wind fields and then the noise modules were employed to estimate third-octave spectra at desired locations. For the trials here, all noise mechanisms provided by the FAST/NOISE system of modules were included. Also the Mervento 3.6-118 pitch controller module was operated in the default scenario. The modified FAST/NOISE system allows investigations of noise mechanisms and specifically permits an understanding of the acoustic directivity produced by the model. The possibility to visualize the interaction of the noise from each blade is also made possible, for example two of the blades can be "muted" from the display so that the contribution from a single blade only is conveyed. Also temporal evolution of the acoustic fields are possible (fig 3 is a single frame from a movie).

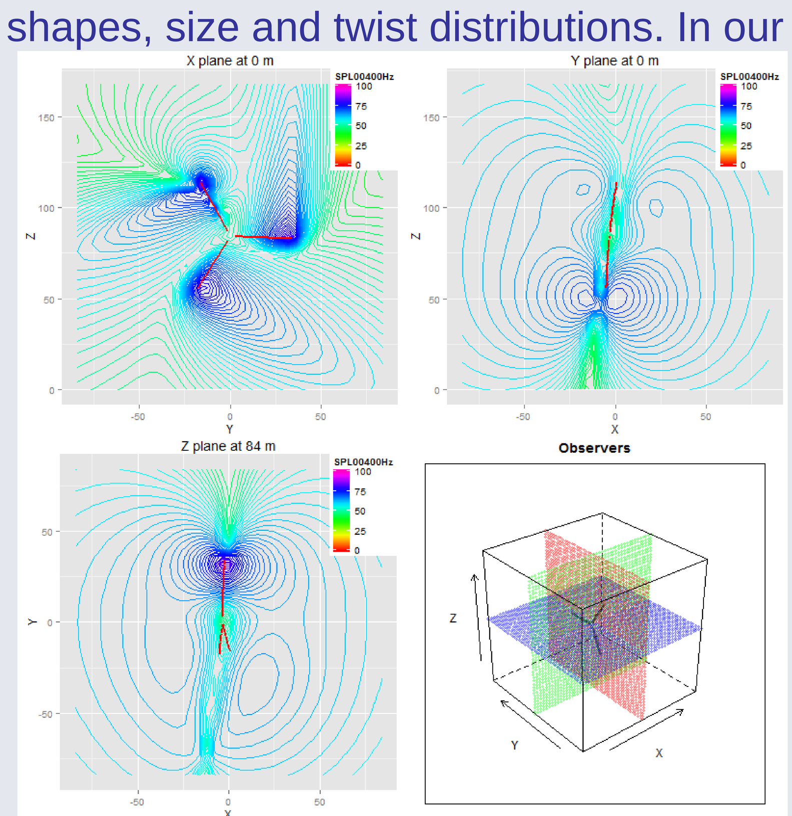

Fig 3. Example output from the modified FAST noise modules showing estimated acoustic levels at arbitrary loci of points near the WT blades. The modifications are programmatic rather than technical, allowing a large number of arbitrarily located points to be processed with a single run. Additionally, modifications allow one to output time dependent spectra in addition to the standard integrated metrics.

Results

Analysis of the calibration signals demonstrate that the acoustic measurement system performed accurately (for an example, see fig 4). But, the system noise floor limited the analysis from 300 to 12800 Hz. An example spectrogram and time series from a microphone location furthest upwind (mic 1) demonstrates blade passage dependent acoustics and the long term variability associated with the turbulent winds experienced during the observation period (fig 5). These data were collected during a gusty and high winds event when the sodar measured a mean wind speed of 10.5 m/sec at the wind turbine's hub height. Since we seek to compare model to observations with the goal of verifying the model no A-weighting of the acoustic data has been performed.

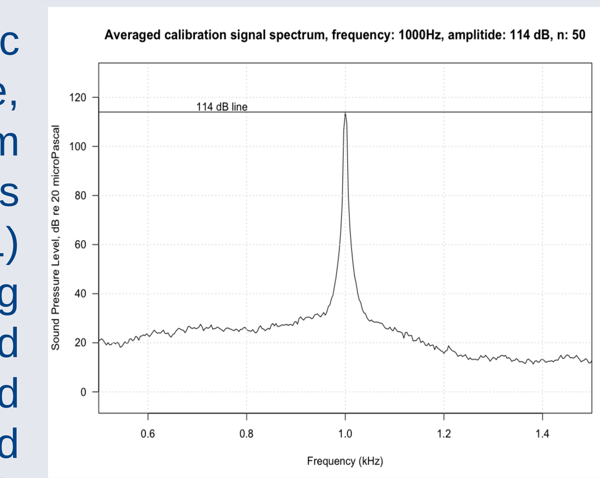

Fig 4. Example calibration spectrum from G.R.A.S. 42AB Sound Calibrator. The calibrator produces 1kHz sinusoidal waveforms with a rms value of 114 dB.

Modulation depth may be assessed by quantifying the difference between blade passage event maxima and minima amplitudes. We do so here subjectively. Within the duration of a single minute (fig 5) we observe the modulation character to vary substantially (at a single wavelength across time, the amplitudes [colors] change) at the lower frequencies (300 to 700Hz.). A modulation of the frequency content is also observed from the time dependent spectra.

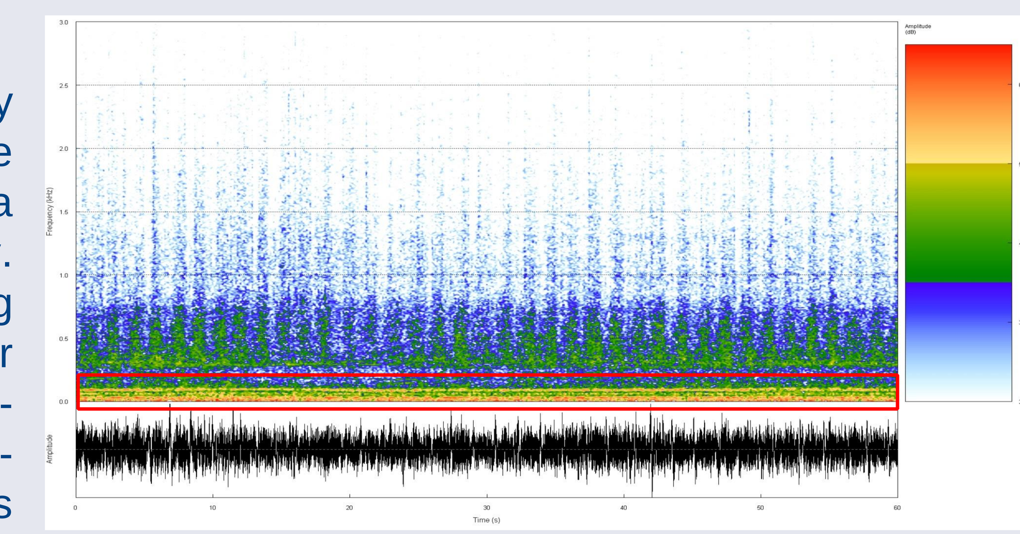

Fig 5. Example time-series and time dependent acoustic spectra from mic 1. Red box indicates the low frequency (0-300Hz) noise floor problem domain.

Since the model produces time dependent third octave spectra, we choose a specific third-octave bin (center frequency (500 Hz) to compare with observations. The FAST/NOISE model results (fig 6) at the microphone locations show a systematic trend in the mean acoustic levels as a function of distance from the rotor disk plane (projected to ground level). The acoustic variability (which is synonymous with modulation depth) about these means also systematically varies levels as a function of distance from the rotor disk plane.

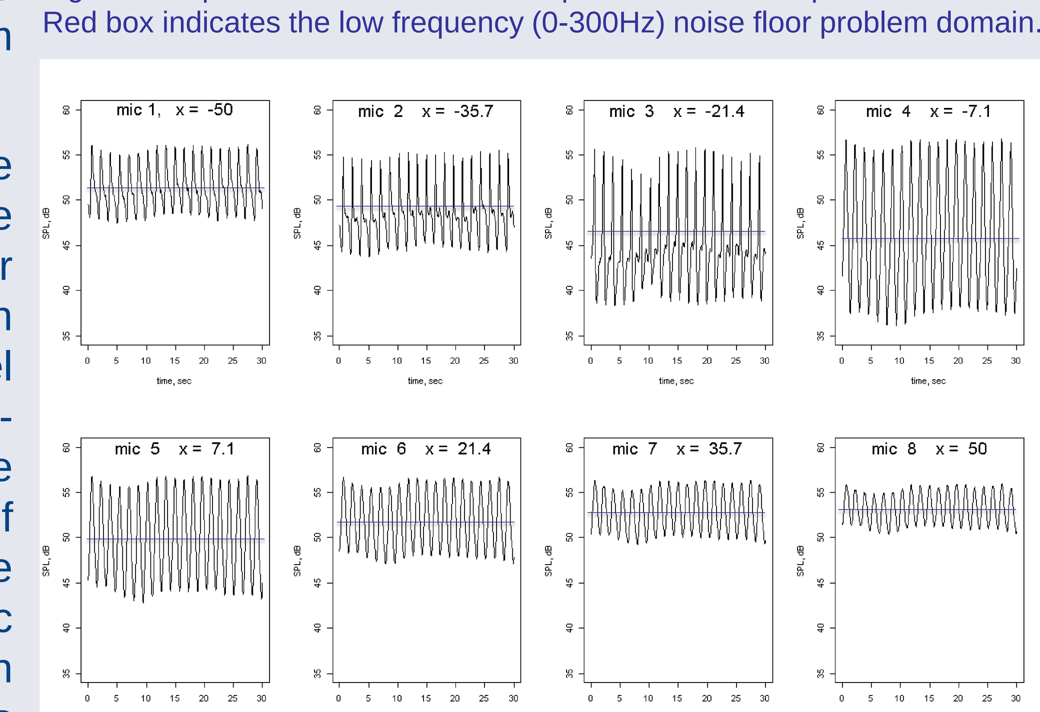

Fig 6. Time dependent third octave band (500Hz center frequency) acoustic energy modeled with the FAST/NOISE system. Horizontal lines represent approximate mean acoustic dB levels for the 30 second duration.

The comparable 500Hz third-octave integrated acoustic time histories show more variability relative to the model results (fig 7). Generally the mean trend for the observations across the mic locations is similar to the model results, both systematically changing as a function of distance from the rotor disk plane. The slopes of these trends are although increased for the observations data. The mic 8 location seems to be an anomaly, This locations proximity to the edge of a forest may be significant.

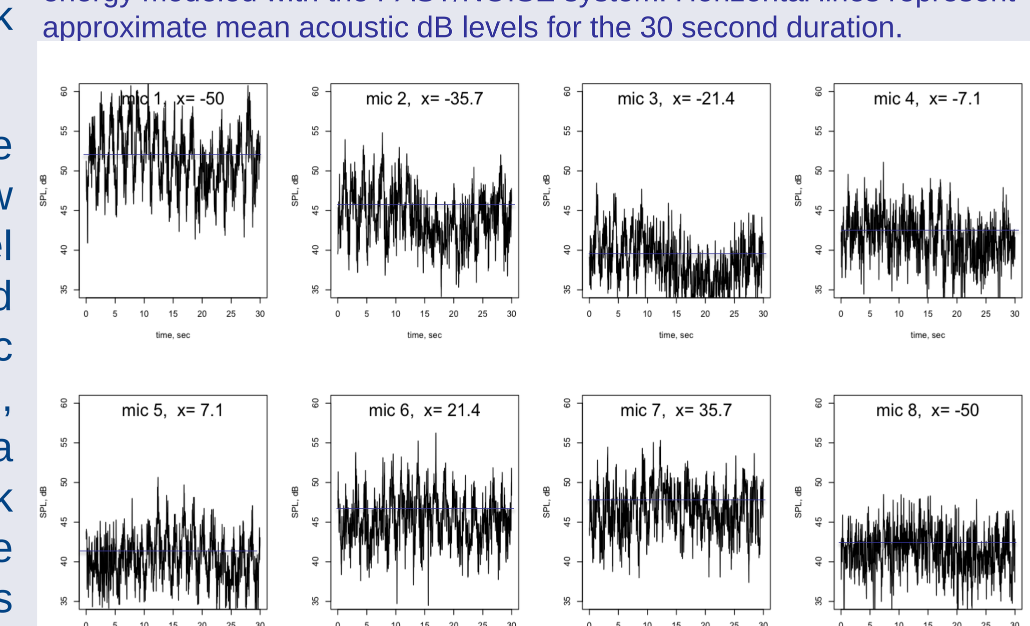

Fig 7. Time dependent third octave band (500Hz center frequency) acoustic energy measured with the acoustic observation system. Horizontal lines represent approximate mean acoustic dB level.

Summary & Conclusions

- An array observation system for wind turbine (WT) acoustics was implemented and accurate calibrations were accomplished. The observation system has a problematic noise floor for low frequencies (0-300 Hz) which will be problematic for future wind turbine acoustic research.
- Spatial variability associated with wind turbine ground plane acoustics was modeled and observed in the field. Data were analyzed to focus on the spatial change of modulation depth near a wind turbine.
- The modeling system captured the mean acoustic level trends associated with the changes across the linear transect researched but the variability in the model results need to be increased to simulate better the observations.
- We speculate more attention needs to be spent with the TURBSIM model so that more accurate (turbulent) winds can be input to the FAST/NOISE system of models.

References

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