**A2e Aeroacoustics Experts Meeting**

January 20 and 21, 2014

Notes from presentations and questions that were raised.

Yellow highlighting indicates uncertainty in what was said.

# Introduction (Pat Moriarty, NREL)

## This meeting was formed for the purpose of determining critical issues for wind energy aeroacoustics. Some expected outcomes include proposed projects and priorities for DOE investments, including timelines and metrics for success.

# A2e (Atmosphere To Electrons) Initiative Overview, Shreyas Ananthan, DOE Wind and Water Power Technologies Office

## Fundamental goal is to achieve cost parity with other energy sources.

## New R&D framework

### Moving from individual turbine focus to wind plant cost and optimization

### Engage national laboratories in a collaborative consortium

### Adapt an open “DOE/SC like” paradigm

## Motivation for a new research initiative

## Loses as high as 20-30% in modern wind plant

### Performance, cost, and risk factors

## 10-20% improvement in forecasting could lead to $100-300 million improvement in operating costs

## Collaboration: Use labs in a ‘hub like’ system

## International collaboration and collaboration with other federal agencies (Office of Science, NOAA, etc.)

## Collaborative R&D Framework, Primary Focus:

### Optimized performance of existing wind plants

### Seamless grid integration @ high deployment rates (~30%)

### Next generation wind plant technology development

#### Reduced acoustic emissions by 5% (intentionally fuzzy metric)

## Strategic Planning (or Thrust) Areas

### 

## LCOE (Levelized Cost of Energy) is heavily influenced by capital cost

### Cost of Uncertainty on LCOE = up to 30% Land

### Cost of Uncertainty on LCOE = up to 30% Offshore

### Based on NREL Cost and Scaling model (?“Wind Levelized Cost of Energy: A Comparison of Technical and Financing Input Variables, “ 2009 ?)

### Sources of uncertainty:

#### 20 year wind forecasting

#### Day/hour ahead wind forecasting

#### Inflow into the wind plant

#### Intra-plant flow (wake recovery, turbine-turbine interaction, interaction with atmosphere at sides and top of wind plant)

## A2e Initiative approved by EERE Assistant Secretary, June 2013

## 12 member External Merit Review Boar/Committee met Feb. 4-5

## Infrastructure

### Sandia National Laboratories SWiFT facility

#### Inflow and wake interaction studies

#### Scaled blade/rotor studies

### NWTC/NREL Field Test Site

#### Utility scale turbine

## Questions

### Where does 5% acoustic emission reduction come from?

#### Ans: “It was intentionally left fuzzy, ie. 55 of what? It was included to represent the idea that acoustic observation and prediction needs to be included in wind plant optimization.

### What is the timeframe?

#### Funding starting FY15

### Funding defined?

#### Can’t commit to long term funding, but can use a long term plan to decide where funding should go as it becomes available.

# History of DOE/EERE Wind Aeroacoustic Research, Pat Moriarty

## Example DOE Project

### Complaints from 12 houses, 1000 home w/I 3km radius.

### Annoyance described as an intermittent ‘thumping’ sound.

## Early history: 1980 Mod1

### Boone, NC. 61m rotor, GE-NASA design

### Different technology and configuration than today: downwind rotor results in tower-blade interaction

#### Effectively killed downwind machines.

### High levels of infrasound and low frequency sound, resonance with building frequencies

### Airfoils operating near stall.

### Predecessor mod 0 was 100 kw and had no noise issues

### For modern turbines, infrasound and audible noise is lower

### Mod1 findings have been getting lots of attention in 2013

#### “Wind Turbine Syndrome”

#### DOE has addressed or published anything to address this.

## DOE research 2002-2013

### Small wind, airfoils - NLR

### Utility scale, Virginia Tech

### CFD/CAA noise modeling: PSU, Florida Staet

### Semi-empirical noise modeling

#### NREL NAFnoise, last updated 2005

### Acoustic array development and measurement

#### Small studies

### Noise mitigation of blades, wind plant propagation

### Research activities curtailed in 2007, nothing in 2014?

### Community Impact: Minimal, talked to people about what was heard and when

## IEC Standards: testing and measurement

### Small wind airfoil testing in Netherlands

### Tip acoustic testing at Virginia tech

### Utility Scale wind tunnel testing at Virginia Tech

## Acoustic Modeling

### Semi-empirical methods

### Computational Physics

## CAA: computational Aeroacoustics

## Blade shape: swept blades change loading through tower shadow

## Acoustic Array version 1.0: Bushland, Texas

### Gearbox noise swamped other sources

### Measurements at NREL/NWTC

## Acoustic Array v. 2.0, better mics, weather resistant

### Turbine Interactions: paper at Wind Turbine Noise Conference

## GE-Stanford-Sandia: LES simulation of trialing edge noise

## Questions:

### Any plans for dissemination of information? Everything here focused on technology.

#### A proposal for work on community/public relations and research could be made in the community Impact breakout session. Some work has been done as part of Wind Powering America.

### Does IEC address this (community impact)?

#### IEA has a general community impact requirement

#### Some areas are talking about new plans for community impact

#### Canadian wind energy association

#### Acoustic (psycho-acoustics?) studied in rotorcraft industry

##### Study showed people were annoyed by perceived rotor noise when they could see a rotor, even though the noise was below perceptible levels

#### There is a worry about an emphasis on complaints as a basis for regulation

##### Don’t just use a survey of 6 people to drive regulation

##### Studies have shown that if people get a share of the wind farm income, then they like or don’t mind the noise

##### IEA has two papers on community acceptance, one U.S. and one International

### Is it true that since we don’t’ have astandard to design to, each country or area is coming up with their own?

#### OEMs spec. a single turibne, but they are installed in farms w/ differing atmospheres and terrain.

#### DOE has focused on acoustic technology w/ community impact and market barriers being ancillary.

#### A lot of states (in the U.S.) have filled a void that DOE ahs left

#### DOE has traditionally been technology focused, but it is open to partnering with other agencies to study perception and health impacts

# Perspectives and Recommendations: Consultant, Mark Bastasch, CH2MHill

### Acoustic consulting in the USA overview,

#### Oregon is the only State with a PE reqt. for acoustical consultants

#### Education and experience varies dramatically

#### Robust experience rate

#### Most have experience with transportation policy

### Sound regulations in the USA

#### Very few noise regulations

#### Permitting challenges

#### Can be emotionally and politically charged, haves vs have nots

#### Fact vs fiction

#### 1000’s of pages can be brought into a hearing, much from internet

#### Infrasound still brought up, still confusion around early DOE 1980’s studies (Mod1)

#### Silence shouldn’t be required nor promised

#### Uniform regulatory framework lacking (for wind and many other sources)

#### Most regulation done on the local level

### The tale of two projects:

#### Proj A, Siting process not opaque, residents taking legal action

#### Proj B, Residents engaged, 6x the number of turbines, residents hear turbines but are not bothered inside or out, rural farmland, acoustics important or not?

### Acoustic Modeling: Engineering Methods Robust

#### Engr models predict A weighted levels reasonably well, but would be expanded, would be desirable to have noise source models that can run on a PC.

### Mitigation Options for Winds are Limited

#### Amplitude modulation, recent research published by Renewable UK worthy of additional review

#### Can sources by further clarified?

#### Are there applicable mitigation strategies?

### Where can DOE assist?

#### Overcoming some of the same measurement challenges identified in the 1980’s

#### Harmonization of methodology and metrics for far field

#### Validation of existing and development of new prediction methods for typical setback distances

#### Nosie and Health addressed similar to the EMF RAPID program?

### Help frame bounds of a reasonable discussion, correct misinterpretations

### Audible sound character/quality metrics could be explored

### Develop reasonable and appropriate analysis techniques

### Proven new metrics will influence vendors to address sound quality (in addition to dBA)

### High quality sound recordings

### May prove useful in developing simulation (and perception?) tools

## If not DOE, then who?

### Industry lacks technical and financial resources to address these issues

### IEC standard not applicable at residential distances, turbine vendors

### Developers lack in-house expertise

### States resources similarly lacking

### Doe has access to technical resources in acoustics and aeroacoustics, authority and credibility with regulators

### Large sociological studies expensive and outside of DOE’s expertise

## Questions

### Q: Consultants taking meas. Using equipment in ways that it wasn’t intended, can you address this?

#### Ans: areas in infrasound are very complicated meas. To be made, particularly in the presence of wind. It is also an issue of a background measurement being made in a corn field in high wind that is then given to a regulator. Best practice is evolving and lacks standardization; any amount that DOE could help this practice would be great.

### Q: Is there a pathway that you could see, like a guidebook, something that could show what your site would look like under certain conditions (a siting tool)?

#### Ans: One of the problems that we have in the States is the variety of regulations. Projects are built to a regulatory limit. IN UK, a best practices guide has been published. Perhaps DOE can help develop a best practices guide, but leave the regulation side looser. List pros and cons of different regulatory concepts. Issues of current IEC standard, which is only for one microphone 400 feet away.

### Q: Far away measurement is difficult, could an extrapolation metric be defined, similar to aircraft?

#### Ans: If a reliable prediction method can be created (from DOE?), then we could take near-field measurements and use it in far-field prediction tools.

#### Comment: This is what OEMs do now using near-field measurements, but there are still issues. Maybe the issue is in how the models are used.

#### Sweden is using similar methods using measurements at MET tower. At distance of 1000 meter, there is a big difference up to 14 dB due to weather conditions.

# Kevin Kinzie, From Turbine to Receptor

## Blade noise is still the main issue, but machine noise can still be an issue.

### Source: blade and machine noise

### Turbine Operation

### Propagation. Measurement noise at 150m and trace it back to the turbine

### Noise perception

## Much misinformation and misinterpretation

### Examples of articles

#### Need to make sure that new tools are tested, as has been done with current tools.

#### Regulators and policy makers need the right data to create proper regulation, mainly siting. Proper siting is key.

#### Need for objective and clear information.

#### Policy makers have the job to sort this all out.

## What is the state of the art?

### Source

#### Blade noise sources are well understood

#### Airfoils and trailing edge devices are OEM’s expertise and highly impact whole turbine system

#### Further noise reductions of a few dB difficult to achieve and probably nor for free (loads, aero)

#### Acoustic impact of turbulence, wakes, shear, still difficult; introduces variation to noise

### Turbine Operation

#### OEM’s pitch and farm control systems are advanced, flexible, even cyclic operation based on wind speed and sector.

#### Advanced NRO’s and farm control possible

### Propagation

#### Standard tools are not capturing the complexity of the problem

#### Many stakeholders with differing methods and margins

#### Inadequate use can lead to +/- 5 d offsets

#### Only limited data about tonality and propogation into far field

### Nosie perception and noise regulations

#### Lack of objective data

## Recommendations

### Best practices for farm noise siting and far field noise predictions including propagation modeling

### Field test data

### Receptor noise measurements guidelines and data

### Mechanisms and mitigation concepts of far field amplitude modulation including stall noise

### Improved inflow turbulence noise model based on field measurements

### Long term testing of several airfoil and blade sizes

### Requires leading edge wall mounted sensors, ground microphones and met-mast

### Objective data on the public annoyance w.r.t. wind farms

### Partners with another agency, ex. EPA and international experts committee

## Questions

### Q: Does this list reflect your priorities?

#### Ans: Would need to think about it more.

#### Comment: Just because it is a social issue doesn’t mean DOE will not study it.

#### Ans: People who study health don’t know science and technology, so need to partner. If DOE doesn’t do it then I don’t know who will.

### Q: What is the risk of doing this? Is the industry at a point that it can address what is found by such a study?

#### Ans: UK Renewables study said here the metrics and the methods. Need to think through the risks and challenges.

### Comment: It’s not so easy to come up with a guidebook with “here’s your standoff under these conditions”, need a probabilistic approach.

#### Ans: We have, but there’s a lot of inputs. Wind direction, shear affect it. Hard to capture in wind tunnel as scale effects it.

# Manjinder Singh, Siemens

## Why is it important (Wind turbine acoustics)?

### Wind turbines being installed closer to homes, even if 1/100 complaints real, that one needs to be addressed

### Local regulations are tending to be more restrictive

### Airfoil noise important, needs to be a design constraint from the beginning

## Importance of rotor size (diameter and tip speed) on noise

## Development of blade shape

### Solidity change from 10% to less than 5%

### Airfoils changed from 1930’s aircraft to modern custom-made shapes

### Blade add-ons yield noise reductions of several dB

### Blade tip design eliminates tip noise

## Low-noise controls

### Smart controls reduce noise at min. energy loss

### Stall regulation replaced by pitch regulation and variable speed

### Control settings can be tailored to specific site conditions

### dB vs pitch setting vs AEP reduction

## If noise is assumed to be the only limiting factor, then 1 dB(A) reduction of noise can improve AEP by 20% based on historical trends (disclaimer: more of a brain exercise)

## Siemens methods of addressing aeroacoustics

### Modeling, Empirical CFD

### Improved measurement tech.

### Control schemes

### Add on

#### Field testing

#### Tunnel

### ?...Field testing

#### 24 mic array in US and 108 mic array in Europe

## Topics of interest

### Better understanding of rotor noise

#### Focus on understanding the acoustic behavior of turbines in field via dedicated experiments

#### Include factors to leading to variability and uncertainty of results

#### Coupling with aerodynamic state of the rotor

#### Simple yet effect computational tools

### Airfoil noise behavior

#### Focus ion airfoil noise measurements in wind tunnel for understanding airfoil noise behavior as a function of relevant variables (Reynolds number, roughness, etc)

### Publically available databases and simulation tools that manufactures can apply to their rotor design tools (eg. NAFNOISE)

### Passive (active?) technologies for noise control

#### Active need to survive for 20 years, doesn’t think that we’re there yet

## Projects that will not be explored in this program

### Low noise rotor design

#### Confidential information may be involved that will not be shared

### Noise mitigation control strategies, this can be very turbine specific

### Farm level modeling:

#### The main challenge is to understand the acoustic source behavior of a single turbine

### Down-wind turbine design

### Concerns: IP Protection

## IP related risks must be addressed before we can consider sharing the data model/designs.

## Questions

### Ques: Why do you say that farm doesn’t matter for modeling?

#### Ans: It’s not that it doesn’t matter, it does, but at this point we feel that our understanding of a single turbine source is not well understood and it is needed before it can be propagated.

#### Comment: I’m trying to understand the separation between the source term and the propagation.

### Ques: On the source term, can’t you separate the terms from the propagation model to do research on the farm propagation level?

#### Ans: When you have a low-level jet, the noise propagates itself and affects it, not just the noise itself. What controls do you need to (mitigate) it?

### Ques: If you see a risk from the IP aspect, what do you think DOE should focus on?

#### Ans: At Siemens there are some controls schemes that we don’t want to give out…

### Ques: The office of science approach is that fundamental research will be done that can be put into the public domain. This is different than work for others under a private agreement.

#### Ans: Refer back to list of what should be left to manufacturers (‘Projects that will not be explored in this program’)

#### Comment: Agreed, those things that are IP specific should not be engaged in this program, and focus should be on fundamental science.

# Peter McPhee, Massachusetts CEC (Clean Energy Center), Program Director

## Background and Motivation

### Some MA wind projects have faced challenges during permitting

### Public and decision-makes have detailed questions on AM, infrasound, nighttime shear events, indoor sound levels, etc.

### Difficult to answer

### Working on pre-project planning, but need to define conditions.

## Research study on wind turbine acoustics

### Research goals:

#### Understand wind turbine sound under operating conditions

#### Understand causation

#### Evaluate accuracy of modeling under varying conditions

#### Help inform MASSDEP on evaluating their compliance method

#### Present results statistically and make available to public

## Methodology

### MassCEC hired Resource Systems Group (RSG) to implement

### Coordinated access to sites, regular shutdowns, power access

### At sites with 1-2 turbines, we deployed for ~2 weeks.

#### Multiple sound level meters in different directions at different distances, sometimes with infrasound meter, some indoor

#### Lidar to collect 40-200 meter wind data

#### 10 meter MET tower

#### SCADA monitoring

#### All collecting ~1 sec or faster data

### Unattended and attended monitoring

### Lots of number crunching and SQL routines.

### Challenges for site access, making data public.

## Deployed to 4 of 6 sites to date

### Collected 120 million records with 150 variables

### Conducted over 100 turbine shutdowns

### First interim report focusing on AM (Ambient) levels, AM frequency contents, and measurement metrics.

### Second interim report in process, focusing on comparing modeled to measured sound levels and comparing metrics

### Full report coming in 2014

### Looking to post some of the data for open access

## Conclusions and Applications

### Receptor-focused instead of technology or development focused research

### Helping to address questions from public and decision-makes

### Good data is part of the soln. for appropriate wind turbine siting

### Working to inform Mass DEP’s effort to consider noise policy revision and a potential permitting role

### Intend for the research to be used beyond Massachusetts.

## Additional research needs:

### Research study could be expanded to more variables and more sites

#### Varied locations, large wind farms, newer technologies

#### Internal measurements (indoor or within farm)

### Tie in with turbine technology: what is the mechanism for wind turbines to produce sound conditions under complex and real-world operational conditions?

#### Tie in with human response: how to people respond to specific noise (conditions)?

### Determine appropriate assessment for metric for AM

### Identify specific, measureable ILFN thresholds

### Expand upon IEC 61400-11 data to include AM, ILFN, etc., possibly through Annex A

### Understand characteristics of other sound sources relative to wind projects (highway vs wind turbine)

### Understand characteristics of ambient better

### -Seasonal, spatial, geography?

### How does traditional?? Missed….

## Questions

### Ques: You said there is a need to frequency response characterization?

#### Ans: Example of infrasound, there is a metric from NASA, infrasound hasn’t been an issue from wind turbines and it would be good for someone to explain.

# International efforts: Con Doolan, University of Adelaide

## Flow and Noise group

### Transitional noise, CAA/DNS, Jet noise, wind noise, trialing edge noise

## RANS-based noise prediction

### Empirical- not good for design

### LES/DNS – too computational demanding

### RANS based: good fit with design process, but needs two-point turbulence statistics with noise model

### RSVM for trailing edge noise, empirically based

## Trailing edge noise

### Passive Control: Serrations, wind tunnel

### Experimentally measured noise reductions are much lower than theory

## Field trails at wind farms

### Simultaneous noise measurements in field and in homes

#### People annoyed from 2.5-8 km from farm in South Australia.

#### Whenever people are annoyed by noise, they press a button and it is recorded and they press a button to rate how annoying the noise.

#### Continuously averaged in 10 minute bins of 3 weeks.

#### Results correlate, but also correlate heavily with ambient wind noise

### SODAR measurements at farm simultaneously with in-home measurements for correlation of wind profile measurements with indoor measurements (2.5-8 km away). Outside measurements as well.

## Opinion on what’s important

### Computational modeling

#### Apply RANS based CA rotor noise prediction tools

#### More detailed, unsteady LES-based CAA tools for more detailed assessment//verification and research

### Trailing edge noise

#### Fundamental studies to resolve issues

#### Passive noise control,, (serrations, etc.)

### Community Acceptance

## Planned research at () university

### More fundamental studies: poro-elastic edges

### Combined NAH and Beamforming of trailing edge noise at high Reynolds number

### Fundamental noise generation studies on rotating blade systems

### RANS based techniques.

## Integrated studies on Social/Health/Physical factors that impact individuals within communities in the vicinity of a wind farm. No individual organization that can fund this, so they are focusing on ‘Physical’.

## Questions

### Ques: How was wind noise correlated?

#### Ans: Correlation of some noise levels with wind speed. Local wind noise on the side of the house.

### Ques: But amplitude could modulation could be hidden in this.

#### Ans: Study needs to be correlated over a number of homes and sites.

# Helge Madsen, DTU Wind – Research on Wind Turbine Aeroacoustics

## Overview of major projects/activities

### 1993-96 PhD on Computational Aeroacoustics (CAA)

### 1996 BPM model (Brooks, Popa, and Marcolini) model for wind turbine noise

### 1996 Tip noise – CFD/full-scale experiment

### 2003-6 start on low frequency noise, industry contract

### 2004-8, Wind turbine noise engineering model

### 2006 First test of measuring high frequency noise sources on blade (inspired by Virginia Tech. work)

### 2007-10 DELTA project on low frq noise

### 2007-10 DANAERO MW project

### 2007-10 Research project with DELTA on noise due to wake operation of turbines

### 2008-11 EUPD project on amplification of noise

### 2 others…

## Low frequency noise,

### Research on tower vortex shedding

### 2006-10, participated in Danish project coordinated by DELTA on low frq. Noise – upwind turbines, comparison to downwind rotor.

#### Upwind rotor only has high level of low frequency noise if the blade gets very close to the tower.

## DANAERO MW

### Inflow measurements, correlation of inflow and acoustic measurements

### Sensor on blade to measure instantaneous inflow on the blade.

### Surface pressure and inflow at 4 radial stations

### 60 high frq. Microphones near tip, next to outer surface press. Measurements.

### All pressure and microphone holes were covered with tape every night.

### Measurement of Shear Profile on a full scale rotor blade, 80m diameter, 2MW

### Pitot probe, show rotor at low point of revolution has more high frequency content and less low frequency, vice-versa for top-point.

#### Implies that atmospheric turbulence has higher frequency content (smaller spatial scale) at bottom of turbine (closer to ground).

### Also LE, and TE spectra - source

## Key research areas:

### Noise mitigation

### MISSED

## Questions

### Ques: Can data be shared?

#### Ans: It would need to be cleaned, would need to remove manufacturer data. Was interesting to have several manufacturers involved in past research, but would be different now.

# Conny Larson, Uppsala University

## Sound propagation outdoor since 1976, airports, line sources (roads, high tensions lines) and point sources (broad band)

### Sound from wind turbines model-measure-validate (2009-2014)

### Farms, flat, heterogeneous

## Dragaliden, 1km

### Turbines on hill with several smaller MET towers and 120m and 140m

### Available power data: electrical effect, 10min.

### Wind and temperature (0.5 - ~ 140m)

### Rel. humidity and air pressure

### Sound immission measurements

## Selected measurements

WT sound (10 min. measurement period) is regarded as the dominant sound source

Sound level calculated > 30 dBA (immision point)

L5 – L95 <= 4 dBA

Spectral requirement to take away noise from wind through vegetation

Enercon 80m 2MW (check?)

deltaL = difference between the measured imission sound level and free field geometrical spreading of sound energy from a spoint source corrected for atmospheric absorption and directivity

Chart: deltaL vs. Effective sound speed gradient (s-1) calculated between 120-0 m, snow cover vs No Snow Cover

Cumulative distribution (%) vs. LA,eq, shouldn’t just look at maximum noise, look at sound due to different disturbances and atmospheric conditions

## AM study, 1 year

### Lundmark, Measurement of swish noise, a new method, Fourth International Meeting….

### Amplitude modulation

### Day vs Night

## AM during 1 year, Dragaliden, Month, House after midnight

### AM more common during specific meteorological conditions

### 2-3 dB at source AM, 8 dB away from source

## Conclusions

### The weather governs the immission sound level even for high elevated sources (Wind Turbine) variations

### AM between 20-30% of time

### Most frequent at evening-night-morning at stable stratification

### Snow covered ground – low SPL (up bending) high SPL (down bending)

### Validation, ISO 9613-2, on for one farm, either under of over predicts dBA for Dragaliden, other method is off for both farms

## Questions

### Somewhere from 500-800 m the noise can be heard because of different methods than at less than 500m.

### Q: How can you distinguish from gusts and WT noise?

#### Ans: I have the biggest wind screen, the forest. The forest and vegetation take it up.

# William Devenport, Virginia Tech – Perspectives and Recommendations, represents a center of people

## Eric Patterson, Ricardo Burdisso, Stewart Glegg, William Devenport

## Part of the PSU/VY Cyber Wind Facility, LES/CFD capability based on OpenFOAM

## VT Stability Wind Tunnel, 6x6x24’ test section. Very low Turulence level, 0.01% to 0.03%, ReNum to 4 million,

## Not too much data out there for Wind Turbine airfoils

### Some data for rotorcraft airfoils, in particular the NACA0012 airfoil trailing-edge (TE) noise, 1.5 to 2.8 million Re Num, resulted in BPM model (Brooks et al., 1989)

### Feels that there is a need for a database of airfoils and conditions relevant to wind turbine airfoils.

### Need for an understanding of Real World Effects on Noise sources needed. TE noise w/o turbulence 36 dB, w/ turbulence 40 dB.

## A2e Aeroacoustics Program

### Acoustic sources at the blade level

#### Robust, practical prediction tools for blade noise,

#### Need a public database with systematic and validated library of blade section acoustic measurements and supporting flow diagnostics at relevant conditions on open (eg. DE) sections

#### Accompanying DNS-level simulations

#### Other…

### Real-turbine and farm effects on acoustic sources

#### Goal: systematic documentation and modeling of the effects of environmental conditions on acoustic sources

#### ABL and upstream rotor wake inflow as an acoustic modifier

#### Three dimensional and separation

#### Blade weathering and fouling (leading edge erosion)

### Assembling the acoustic fingerprint of the farm and its environmental impact

#### Goal: systematic documentation and modeling for wind-farm acoustic impact assessment and operation

#### Integrated aeroacoustic modeling of triune/ABL, turbine/turbine interactions

#### Propagation from a turbine array, integrate with weather/terrain

#### Amplitude modulation

#### Sound into building

### Developing metrics and standards

#### Development of the methodology and metrics for wind farm certifications/ noise standards

#### Development of noise metrics standards that account for the unique character of wind-farm noise

#### Development of simplified tools/codes for operators/consultants to use in planning and operation

## Questions

### Ques: As nice as this VT wind tunnel is, you need to measure the inflow. I’m not sure good the corrections are for infinite effects at high angle of attack.

#### Ans: Have first principle correction method that’s evolved significantly in the last 5 years. Thankfully that’s a solved problem.

### Ques: What size problem can be solved in the high fidelity CFD?

#### Ans: What we’ve been doing in the Cyberwind facility, farm simulation using actuator line is fairly inexpensive compared to blade resolved CFD. To do wind farm isn’t bad, but a full farm LES simulation that could give acoustic source and propagation is a big problem.

# Sanjiva Lele, Stanford; Wind turbine airfoil noise: a computational perspective

## Noise source processes in a wind turbine

### Interaction of ABL and farm

### Etc.

## Nosie propagation from a wind farm

### Propagation through the windy boundary layer

### Scattering form ground terrain vegetation

### Scattering from towers/etc.

### missed

## NACA0012 self-noise

### With careful attention, one can compute unsteady aerodynamics and noise sources from the same calculation

### Numerical results compared to experiments be Sagrado and Hynes.

### Need to make sure that 3d span is big enough and effects are accounted for

### Trailing edge predictions match with experiments by Brooks et al..

### Wolf and Lele AIAA paper 2011

### Trailing edge noise changes with frequency

## CL versus alpha for DU96 airfoil at Reynolds number 1.5 million, project supported by GRC-GE, NREL experiment vs. RANS, LES, Rfoil, wall modeled LES (WM-LES)

### WM-LES of high lift system, J. Bodart et al. AIAA-2013-2724

### Very good predictions of Cl\_Max, high AOA investigations of potential effects, low AOA: blockage effect due to slat cove…

## Future prospects:

### Benchmarks problems for wind turbine aeroacoustics

### Modeling simulations and experiments

### Multi-fidelity Modeling (LES, RANS, hybrid methods, farm-scale models,…)

#### Models with terms that we can understand with parameters calibrated using higher fidelity model results (and experimental data)

### Combined aerodynamic and aeroacoustic optimization

### Control of turbine aerodynamics and aeroacoustics

### Farm-scale aerodynamics and aeroacoustics (modeling, predictions and validation)

### Farm-scale wind noise propagation and validation

### Farm-scale optimization and control

### Experimentation must not be used just for validation but also as a means of discovery.

## Questions

### Ques: If you get the farm scale data at every 10 minutes, can you use it?

#### Ans: If you get wind field and temperature field in three dimensions, can we use it? If we cannot use simpler theory, then we must use wave theory with no assumption that what is propagated is higher frequency.

#### Comment: We had a PhD student who used Ray theory, and it did not work for stable conditions.

### Ques: When we were doing dynamic stall 2D, and tried translating that to a 3D body, and tried translating that to a 3D rotating body, and I still don’t think that we got that right. When thinking about aeroacoustics, is BEMT ok, for example when the flow is separating, or would these methods be needed?

#### Ans: Need to know when the predictions we make with a given model will break down. The only way to know is to have a reference calculation (or measurements of a ‘truth’ model, ie. Experimental data) for comparison. Industry will learn from these tools and improve the tools they have for everyday calculations. Engineers will use what works optimally for the problem at hand. Hybrid methods will catch on more as time goes on, more science will be incorporated into them.

### Ques: I was trying to get at whether the 3D effects of the rotating rotor are important?

#### Ans: root flow and strong flow induced by the tip vortices/vortex wake are important and mean that models, such as the actuator line model, are not applicable. How long do the tip vortices last? Need to know when models are useful and have a flag when they should not be used.

#### Comment: don’t just want to do a farm, want to do 100’s or 1000’s of calculations of cases. Need to do high resolution LES to look at the model and use engineering models with the ‘truth’ model.

#### Ans: May be missing something, need to have real world measurements.

# Jim Manwell, UMass,

## “Not Many Turbines but a lot of Noise”

## History

### US Windpower (forerunner of Kenetech), initially based in Burlington, MA, 1970’s 100kw downwind, pitch controlled, deployed in CA, tip speed ~64 m/s, some informal noise complaints

### Bergey 10 kw with 147 m/s, removed ue to noise

### UMass ESI-80 on Mt Tom, 1990’s, 250 kw, 77 m/s tip-speed, reported hearing at night

### Hull, MA, 2000’s

### Municipal utility, 660kw, 2001 near school and seashore

### 1.8 MW, 2006 on closed land fill, near condominium Tip speeds ~70 m/s, no known noise complaints

## Wind turbine health effects panel

### Initiated by MA Dep. Of Envir. Protection, 2011 to understand what literature says about wind turbine health impacts.

### Informational for DEP as they navigate complaints waged against wind turbines

### Panel made of individuals with expertise in various relevant areas

### Shadow flicker, Ice throw, Noise: audible amplitude modulation & ?

## Summary report in 2012

### Limited evidence from epidemiological studies suggesting an association between noise form wind turbines and sleep disruption. It is possible that …

### ..

### ..

### No evidence that wind turbine syndrome existed

## Best practices for moving forward, used Danish and German guidelines for siting and noise levels

## Aftermath

### Organized opposition to wind turbines has increased throughout the state, less emphasis put on infrasound now

### Wind Turbine Noise Technical Advisory Group (WNTAG), panel set up 2012

### Intended to provide input to DEP, which may modify the regulations regarding noise

### Panelists form varying backgrounds

### Focus on audible and methods for assessing pre and post construction and for compliance

### “Amplitude modulation” has been frequent topic of discussion

## Observations

### Objections increase as distance to turbine decrease (< 1-0.5 mile)

### Audibility of wind turbines triggers negative reactions, but of questionable proportionality

### Hard to distinguish real impacts form those that are self-induced

### -Makes one wonder about hearing sensitivity and how it plays a role

### Wind turbine installations are not equivalent (seems due to both technology and site)

### If there were no amplitude modulation and a more constant tone, might be less (sensitive)

## Recommendations

### Quantify effects demonstrably attributable to wind turbine noise

### Develop procedures to predict circumstances under which wind turbine noise is likely to create problems

### Investigate methods to reduce wind turbine noise

### Develop models which can include amplitude modulation prediction, including high frequency time domain outputs

### Update (Wind Turbine Noise” by Wagner et al. 1996

## Questions

### Q: Do you see these recommendations being scalable to other states?

#### Ans: If you can keep your turbines farther than ~1 mile, then number of objections will decrease. Ownership will also decrease objections: (“that’s the sound of my money” vs. “that’s the sound of someone else’s money”). For example, no or few objections in town where the turbines are community owned. For example in Denmark the turbines have always been around and gradually getting larger, so people there have always been around them.

#### Ans audience: Still have objections in Denmark to the very large turbines. Ownership is very important.

## Ques.: What is the breakdown of power in MA?

### A lot of gas, nuclear, 103 MW of installed Wind in the state, a lot of wind from Maine imported. Coal plants shut down, a lot of natural gas (about 50%). Meeting RPS goals by importing a lot of power, but have 230MW PV and ~100MW wind).

# Ken Brentner, Penn State, (and Phil Morris, Jim Brasseur, Sven Schmitz)

## Acoustic Issues for Wind

### Low blade passage frequency

#### Low frequency sound is relatively unaffected by atmospheric attenuation – propagates long distances

#### Blade passage frequency below threshold of human hearing

#### Modulation of broadband noise by blade passage frequency

### Importance of broadband noise, dominant noise source, scale of large wind turbines lead to broadband noise at relatively low frequencies

### Unsteady flow environment, causes excessive noise

## Cyber wind facility

### Highly resolved 4-D cyber data

### Coupled atmospheric turbulence-blade loadings shaft torque

### Experiments design, test-bed, turbine design, controls concepts and testing

### Advanced correlations for BEM and other design tools using look-up tables

## Cyber-wind overview

### Highly coupled system, ABL, farm, turbine, aeroelasticity, structural dynamics, aeroacoustics and noise

## High fidelity models needed

### ABL turbulence (low dissipation high resolution LES)

#### Atmospheric stability state essential

#### Forced by weather events

#### Blade-boundary-layer-resolved simulations

#### Extreme resolution at boundary later time scales to resolved boundary layer separation dynamics

#### High resolution at blade rotation time scales -> wake dynamics

### Elastic blade deformation

### The actuator line high-fidelity blade model within ABL LES

#### Table lookups from CWF simulation -> higher levels of specificity and accuracy….

### Other high fidelity blade models: partial resolution of blade boundary later

#### Recognition of low reduced frequencies and development of “quasi-steady” models

### Issues with full blade resolved CFD

#### Computational complexity

#### Many practical HPC issues

#### Computational resource problems and the current DOE trend towards GPU

#### Time required

## Needs first principles approaches to sound propagation

### Use as basis for assessment of low order models

## Aeroacoustic sources simulation challenges

### Extraction of representational locations along wind turbine blades from CWF simulation

### Aeroacoustics HPC to establish and quantify characteristics of essential acoustic sources

### Influence of ABL turbulence and resulting changes….

### Missed

## Propagation

#### Issue central to propagation from single wind turbines

#### TTI and noise prediction from wind farms

#### Basic methods to predict and analyze propagation…. missed

#### TTI (turbine-turbine interaction)

### Aerodynamics

#### Concept of representational locations within a lrage wind farm

#### Lower order representation to model wind farms: actuator line vs “low boundary layer resolution” CFD

#### High fidelity representation of wind turbines at representational locations within a wind farm

### Aeroacoustics

#### Modeling strategies for essential noise sources

#### Modeling strategies for acoustic propagation, TTI acoustic, and wind farm aeroacoustic

## Questions

### Q: When you go from actuator line to fully resolved, how much does computational time go up? When you go from just wanting aerodynamics to wanting noise, how much does the comp. requirement go up?

#### Ans: Probably can’t do Sanjiva’s calc. (Stanford) for the entire blade yet. Need to adjust our model fidelity to make it a doable problem, such as the acoustic analogy, Fox-Williams eqn.,

### Ques: How well do these methods work in time and space?

#### Ans: I’ll tell you in 5 years, we don’t know yet, I’m just projecting. Putting our talent on this problem can probably clear things pretty quickly. The consultants need help, just understanding fundamental physics. It reminds me of helicopter noise, we were debating at that time whether we could predict Blade Vortex noise, and now there’s no questions. We can do things by simple modeling to do things fast enough, but we need to validate them with higher fidelity models so that we know what we’re missing; we’re not there yet.

### Ques: If you’re in a farm you may have other parts, so it can be an inviscid solution?

#### Ans: well you may need turbulence (ABL) and complex terrain

### Ques: So it’s inviscid, it seems you could do this with statistical (uncertainty) bounds

## Ans: Well people in this community seem to think very deterministically. And it seems once you get here, we will always ask for more (ABL turbulence, complex terrain).

### Ques: Once we have the model of the effect of turbulent inflow noise, we can estimate…. We found that we got the same noise with turbulent inflow as without. It seems that one should figure out the main issues and focus on them. It seems that we can get stuck at one level if we don’t get pushed, as we do an airfoil and get stuck there. It seems that the farm centricity is a good thing for this community.

**A2e Aeroacoustics final presentations 1-21-14**

# Community acceptance

## What do we need to reduce?

### Is it the A weighted level that is most relevant? How/when is AM important?

### Address the information gap, something to clarify what the community and DOE consider quality information

### PC based modeling, help consultants and regulators.

### Can pre-farm atmospheric data be used to better predict noise?

### Look for specific site characteristics (shear/capping inversion) that create specific noise/AM/OAM conditions

### Margins, If there is a better understanding, the margins (safety factors) can be reduced.

#### More optimal wind farm and/or turbines for mass/AEP (LCOE)

## Outcomes:

### Determination of relevant human factors must begin at the earliest stages of A2e

### Results will guide all other aspects throughout the A2e Aeroacoustics initiative

#### Ensuring that the important characteristics and metrics are considered

#### Continual discussion/feedback with aeroacoustic modeling efforts

### Historical context, review, and comparisons together with the website development can begin as soon as possible

#### Relation/comparison/lessons learned from aircraft and rotorcraft communities

### Ensure that experimental and computational aspects address the most impactful areas.

### What are the most impactful areas and how can measurements be accurately made to meet noise criteria?

## Questions

### Q: How do you quantify the annoyance effect? Is there a study that could address the health-based noise issues? It keeps coming up.

#### A: I think that it does need to be addressed and put in perspective of other community (noise) issues.

### Q: Is there a progression of things that need to be addressed? Such as with avian issues.

#### A: That is basically what you did with property values, health Canada is doing that right now with wind turbine noise. We might just need to get that information out there. I was pushing to do something like that in 2004-5. We have seen 20 studies in that time.

### Q: Does something need to be done, or just a synthesis of information and a website?

#### A: That is the first step, and if that could be done quickly that would be great. The health Canada study should be done by 2015.

### Q/comment: studies on noise and perception, NIH, similar to U.S. studies on aircraft

#### Comment: There is a lot that could be done to study annoyance, FAA is currently doing such a study. The (aircraft/psychology/sociology/social science) community knows how to do that.

#### Ans: I don’t see a need for a new health study, since a lot has been done; more a need to bring together information and (centralize it). Could be a need to study annoyance.

### Q: Would be nice to have a tangible metric: this study shows that noise shouldn’t exceed this level/metric.

#### Comment: There was some research in Australia on community issues and correlating perceived annoyance with measured noise indoors, outdoors, at the farm, and with wind/atmospheric conditions.

#### Comment: It would be useful to understand/quantify what the most annoying noise source is.

#### Ans: It would be useful to quantify this, to understand what are the most useful/relevant acoustic parameters. If we could relate certain annoying conditions to atmospheric conditions, it could lead to new control strategies.

#### (Could also create standard practices for you to study/measure/quantify these effects and best practices/options for how to address them, control, siting, or otherwise).

### Q: Missed

#### Ans: Current models used by vendors is to certify to IEC noise during the warranty period. This does not include propagation (that risk is taken on by developer and/or owner/operator). In real conditions, residents may take measurements that include vegetation noise (or other sources).

#### Comment: It would be useful/important for modelers to experience what the noise is like in the field (such as what Conny has done).

#### “It would be neat to do an acoustics roadshow – get a Winnebago and sleep near a wind turbine.”

# Wind Farm

## Problem: accurate noise propagation models that calculate influences of terrain, vegetation and changing atmosphere are needed.

### Data is needed for validation of such tools,

### Turbine noise (changed inflow/wakes) and cumulative noise interactions not well understood – more than superposition, phasing is important

### Physical mechanism of AM not understood

### Intermittent events, OAM, what creates this noise? Source, conditions (aero., aeroelastic, ABL?)

## Unique noise mechanisms in wind plants

### Noise interaction between turbines:

### Maybe TE noise is important for standalone turbine, but not as much for turbine in wake, DANaero showed TE noise did not change much with wake turbulence

### Behavior of turbines modified in wind plant

### Wake deficit

### Elevated turbulence levels

### If propagation models are improved, how will this benefit developers? Influence on LCOE?

### Future propagation model needs?

### Measure and model influence of changing ABL simultaneous with noise.

### Terrain impacts

### Vegetation

### Physically appropriate and time dependent propagation models to accurately predict amplitude modulation and cumulative phasing of turbines

#### Measurements with detailed turbine and atmos. Observations

### Controlled experiments forcing AM under changing atmos. Conditions – e.g. SWiFT, NWTC, synthetic sources

### Database of noise tests for model development and validation

#### Cover range of physics: turibnes, tones, broadband,

#### Building blocks: wind tunnels, airfoils, subscale turbines, full scale

### Uncertainty bounds of a range of fidelity models

## Measurement Standardization

### Where do you measure noise? On the ground or at perceived height (reflection off ground)

### Over what period of time?

### How to separate wind turbine noise from background? What are the metrics?

### What frequency range? Infrasound?

## More Needs

### Fundamental studies of amplitude modulation creation

#### Turbine behavior?

#### ABL interaction or both?

### What causes intermittent events? What is probability distribution?

### Probabilistic approach? E.g. L10

### New weighting to reflect turbine noise – A weights, C weighting may not be working, overlap comm. Noise

## Wind Plant Noise Control

### Produce tools which include controls?

### Public domain research vs. commercial IP : bracket research space

## Recommendations

### Range of models:

#### Physics based validation model that could be used by OEMs, regulators, design tools

### Place noisier turbines in plant center, already done with controls. Atmospheric propagation conditions where this may still exceed noise?

## Priorities and Timeline

## Overall Comments

### Q: Plan for IEA integration with A2e?

#### Ans: Yes, but it hasn’t been defined what it will be. Seems like Community impact is covered under IEA task 28 (~Social Acceptance of Wind Energy), but it doesn’t seem that there is an IEA task focused on turbine noise work.

### Q: Yes, it seems that there are some interesting work…

## Takeaways:

### Big issues/overview of what things are important to consider, importance of combining source and passing to study AM.

### What’s going to get us the most advancement for the resources available.

### We’ve seen some common themes in terms of annoyance, it would be good to clarify this in terms of what research is needed. It would help clarify things in terms of bringing together documents and previous research.

### Focus on fundamentals, probably get the most bang for your buck.

### Opportunity to understand the sources properly in terms of AM and source propagation. Fundamental physics.

### How can we prioritize these activities in terms of the overall A2e plan?

### Surprise for me was this ambiguity in the measurements, especially for whole wind farms in terms of the annoyance factors are. I think that we’ve heard a lot of studies from other countries in terms of quantifying annoyance. It would be nice if we could have some work done this year to bring together and summarize work that’s already been done.

### In terms of determining what work can be affordable. Need to stand back and say “What is the goal?”. Right now we have three different goals from three different groups.

### Community noise impact and identification of what’s important can hopefully guide to some degree what’s important and the technology development.

### We know little about AM, we don’t have a metric for the community reaction to that, and we don’t’ know the sources in order to be able to predict it properly. While we have understood for year dBA levels, methods to predict turbine noise, what seems to be unique to wind turbines is this AM.

### A lot of things came about from sources, I’m looking forward to the of these in terms of what’s important and what to be done.

### I’d like to thank DOE for saying that they’re finally going to address this and that the states and regions can turn to someone for information. The other thing that DOE could be a leader on is to pull in the other agencies to get some things done, same problem in Australia of too many disparate entities.

### Overall, I’m really impressed that you’re asking so many of the deeper, harder questions. Similar questions coming out of different groups, these aren’t separate areas, they interpenetrate. Looking at sources of where these noises come from and intermittent events on the lookout. Looking at the variability of these events.

### My impressions have altered a bit, it is the intention of the A2e initiative… There is a plethora of opportunities that need to be sorted. Assessment of impacts and regulatory bodies. There needs to be an integrated aeroacoustic plan. Maybe you can’t attack this all together, …but they could be looked at more holistically in terms of the impacts and the engineering that drives these impacts. Look at the impacts that address the human side and come up with a better balance going forward. It’s like going through any systems design piece, fix one thing and another pops up.

### From a farm good to see something going on in this area. AM has a considerable that could be done. The international community should not be forgotten. I’m quite impressed about how this is being driven in the U.S., quite an amazing way of doing it. It gives me hope that my time is well spent in being here. Budgets are tight and it’s impressive to see how things are prioritized.

# Turbine Technology

## How will noise reduction influence LCOE?

### How much wind power is currently curtailed due to noise? (MWhr/year, % fleet)

### What would it take to get 30% power from wind?

### How many projects are delayed or prevented due to noise?

### How much are economics during siting influenced due to noise?

### What if noise could be eliminated for free (at no blade/machine cost)? How quiet could it be?

### Case studies?

## Goal?

### -6dB from 106 dBA – Lwa, by 2020 at same AEP

#### Reduce noise at same power vs. higher power, same noise

#### Or equivalent gain in power at same sound level

#### Currently 10-12% loss in AEP for 100 dB rotor

#### Sensitivity relative to baseline turbine

### Reduce AM

#### Need to define metric for AM

#### Decrease in single rotor noise would decrease AM, not clear by how much (reinforcement/cancellation)

### How to trade AEP for dB

#### 2-4% decrease in AEP per dB decrease due to curtailment

#### Potential gain due to technology

#### Need to keep turbine tonal noise in mind

### Develop tools and knowledge base so that noise can be part of rotor and site optimization (currently noise is a constraint)

#### Would need AM and OAM

#### Statistically uncertainty analysis vs. deterministic (high fid. Modeling)

## State of the Art for Key Source Noise Components

### Low frequency portion of spectrum becoming more important as long range propagation becomes more important

### Trailing edge noise: Pressure fluctuations in the boundary layer scattered by the sharp trailing edge

#### Reasonably well understood in “steady” flow

#### Better understanding of variations and impact of unsteady inflow could improve near and far field predictions (currently modeled as quasi-unsteady)

### Tip noise: Vortex structures at the tip interacting with the blade edges & surfaces

#### Not a relevant noise source for well designed tip

### Inflow turbulence noise: Inflow turbulence inter-acting with blade leading edge

#### Important – more understanding is needed (experiments and predictions)

### Flow separation noise: Large turbulent structures interacting with blade trailing edge and surface

#### Important – more understanding is needed (experiments and predictions)

### Better data and predictions provides insight into physics that can lead to noise reduction concepts – soiling and erosion can have significant influence

### Better data and prediction modules for these components will allow reduction of noise margins that will allow for reducing quoted noise levels

## Critical Issues: How to meet -6dB

### Investigation/Validation of contribution of each noise source

#### How much gain is left from improvements in trailing edge noise?

#### Stall/separation noise?

#### Inflow noise?

#### Systematic study of farm, rotor, scaled farm, 2D/airfoil tests, add-ons

### Trailing Edge Noise

#### How much gain is left from improvements in trailing edge noise?

#### Systematic study of trailing edge noise

#### Fundamental studies experimentally and computationally

#### Expand the database to realistic Reynolds numbers and airfoils, add-ons

#### Systematic study, understand why a different shape produces different noise

#### Influence of roughness/soiling/erosion

### Impact of Unsteady Inflow on Acoustics

#### Sensitivity to inflow turbulence, wind shear, upstream rotor wake/turbine-turbine interaction – especially characterize low frequency noise (LFN) spectral components

#### Blade/airfoil design characterize the minimize sensitivity of LFN to unsteady inflow

#### Describe and quantify atmospheric boundary layer (ABL) and the effect of shear

#### What inflow conditions are likely to create high noise levels that could be mitigated through smart operation?

#### Quantifying the effect of Dynamic Stall and its interaction with acoustics

#### Need to consider range of scales

#### Airfoil, BL

#### Stall, airfoil

#### Turbulence, blade

### Stall/Separation noise

#### Still questions on aerodynamics

#### Scaling rules for progressive separation leading to full stall – can start with 2D airfoil and progress to 3D blade

#### “steady” and dynamic

### Coupling of turbine near-field sources to far-field propagation to receptor

#### How to adequately describe sources for input to propagation modeling? Unsteadiness; spectral content

#### How to characterize turbine/turbine interaction?

#### How to describe wake effects on source generation and propagation?

#### Handoff to far-field propagation modeling

### Scaling Issues

#### How do acoustics scale across size?

#### 2D wind tunnel, SWIFT size, vs. full size rotor

#### How do noise sources change with scale?

#### Fundamental mechanisms of transition, stall, and the associated aeroacoustics change with scale/Reynolds number

#### Need to include/consider 3D effects and rotational effects

## Critical Issues: AM/OAM

### Amplitude Modulation

#### Physics of OAM, lacking fundamental understanding

#### Need metric to differentiate between normal AM and OAM (Other AM); metric also needed for regulations

#### Collect data to characterize OAM and to develop metric

#### Need ability to predict conditions favorable for generation of OAM (statistical vs. deterministic?)

#### Need ability for OEMs to characterize their turbines with respect to OAM (par. for siting)

#### Based on hypothesis that OAM is related to stall related noise, need ability to predict stall noise

## Experiments

### Blade flow conditions, relationship to acoustics

#### 2D airfoil wind tunnel testing

#### 3D (root and tip induced flow effects, stall interaction)

#### Controlled inflow vs field testing

#### Measure aero. properties (transition/stall/flow angle) and acoustic source as well as array measurements on ground

### Airfoil wind tunnel testing: DU family (public)

### Scaling laws – systematic study:

#### Experimental, analytical, and computational

### Stall Noise – related to OAM

#### Scaling rules, Reynolds number limitations

#### Progressive separation

#### Areas of blade where spanwise and induced effects must be included

### Impact of turbine-turbine interaction on receptor noise (acoustics source and propagation)

## Noise Reduction Concepts

### Create noise to level out unpleasant variations

#### Would first need to know “what is good noise?”

### More blades to reduce AM

### Passive control at source – blade flexibility

### Active control – active TE devices

### Morphing airfoils

### Form level control – Sensing?

#### Microphone

#### Inflow conditions

## What tools are most needed?

### Better validation of current methods vs. development of new

### Use airfoil database to influence airfoil design tools, or develop new tools

### Use information from ABL studies to influence design tools (airfoil/rotor/farm)

## Questions

### To be added…