Nikolas Lutzenhiser - Physics 536 - Winter 2023

Biologically Inspired Airfoil Design for Noise Reduction

Image Source: [1]

Introduction

- Our modern era is filled with devices that improve our quality of life.
- They can:
  - Generate clean, renewable energy.
  - Transport us from place to place quickly.
  - Provide search and rescue and life-saving care to those in need.
- However, these devices can also produce an unwanted side effect – noise!

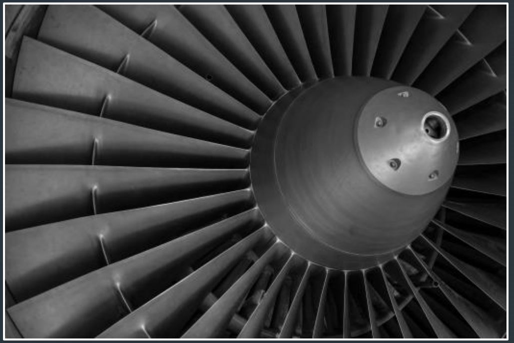


Image Sources: [Getty]

Wind Turbine Blade Noise Characteristics

- General properties of commercial turbine noise, per SNL paper:
  - Blade noise dominates over nacelle gear noise. Trailing edge noise dominates blade noise.
  - Blade noise sources loudest for last 25% radial portion of blade.
  - Measured noise on the ground is loudest for a downward travelling blade.
  - Blade noise intensity scales with rotation speed with the fifth power of relative flow velocity. Slower = quieter.

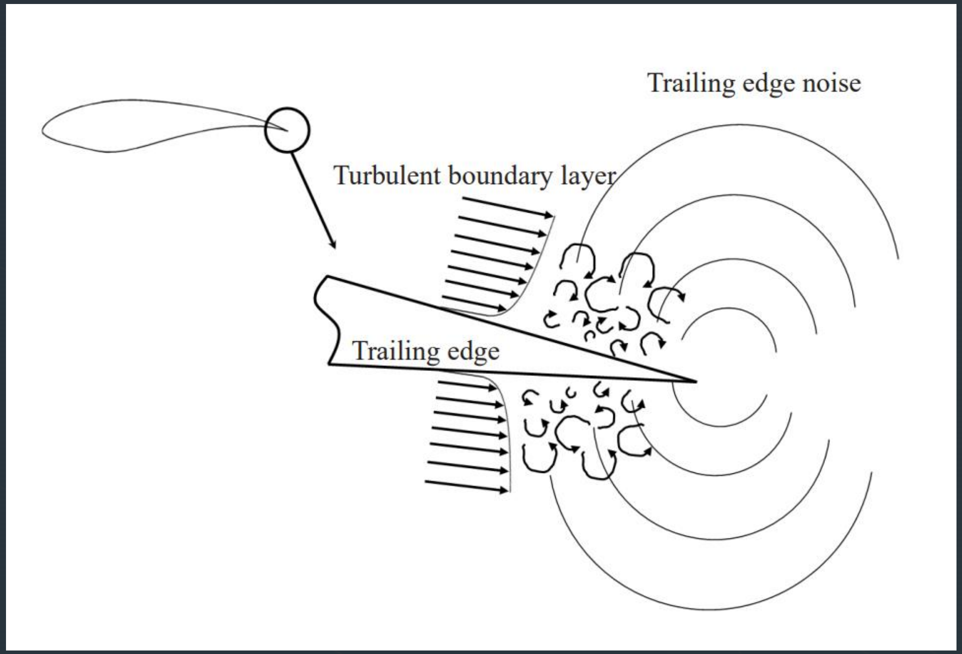
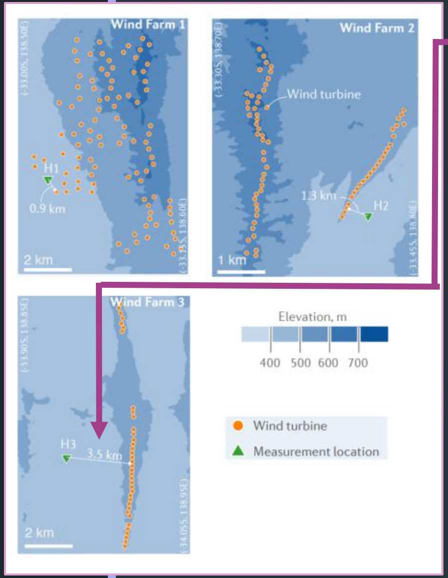


Image Source: [14]

Assessment of Wind Farm Noise (WFM) and Amplitude Modulation (AM)

- One noticeable noise type from Windfarms is Amplitude Modulation (AM), which is a periodic fluctuation at the blade-pass frequency of ~ 0.4 - 2.0 Hz.



- Audible AM noise is detectable indoors up to 3.5km from source.
- Usually seen over turbine power ranges from 40-85%.
- AM levels seem to be higher at night.

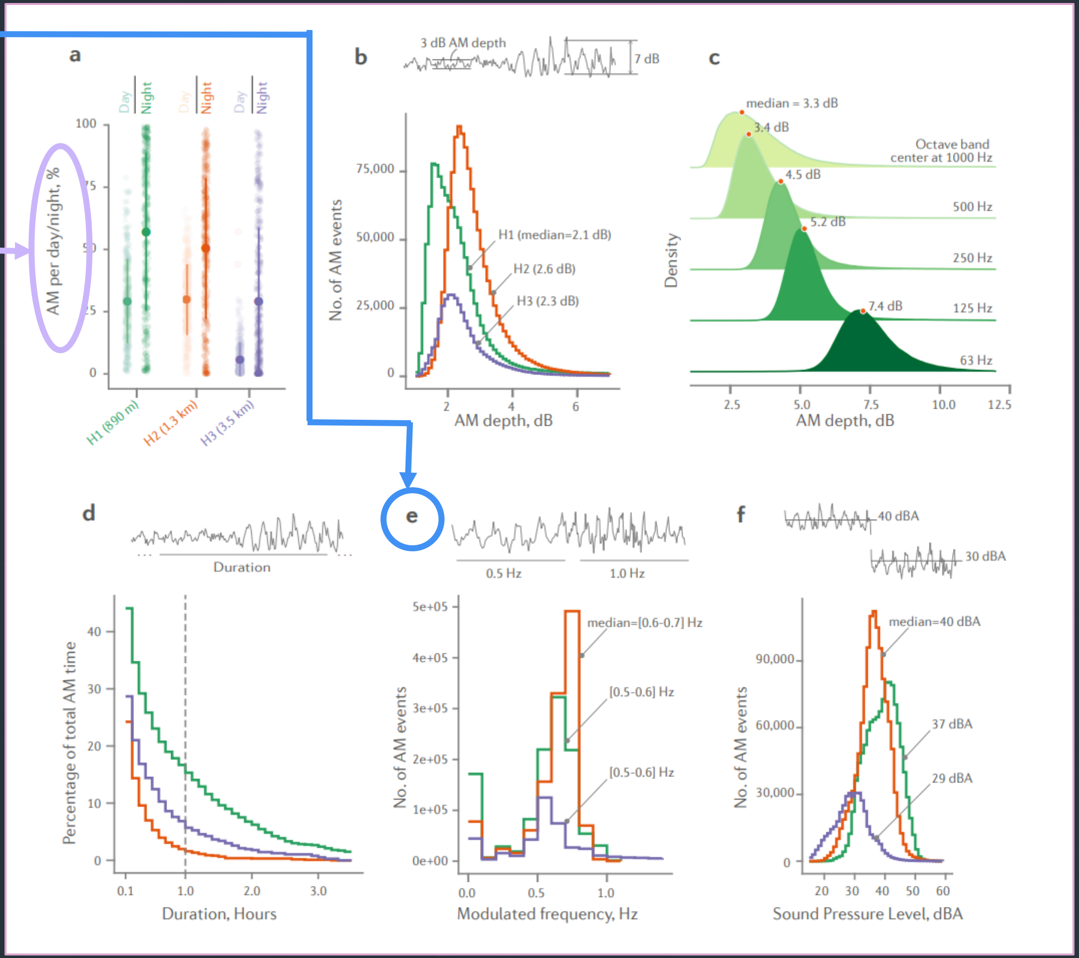


Image Source: [5]

Amplitude Modulation Detail

- Here is a larger/clearer image showing the magnitude of amplitude modulation for a sampled turbine.
- Amplitude Modulation "Depth" can be characterized as either SPL peak to trough range, or as L95-L5 difference (noise level exceeded 95% to 5% of the time, over a selected period).

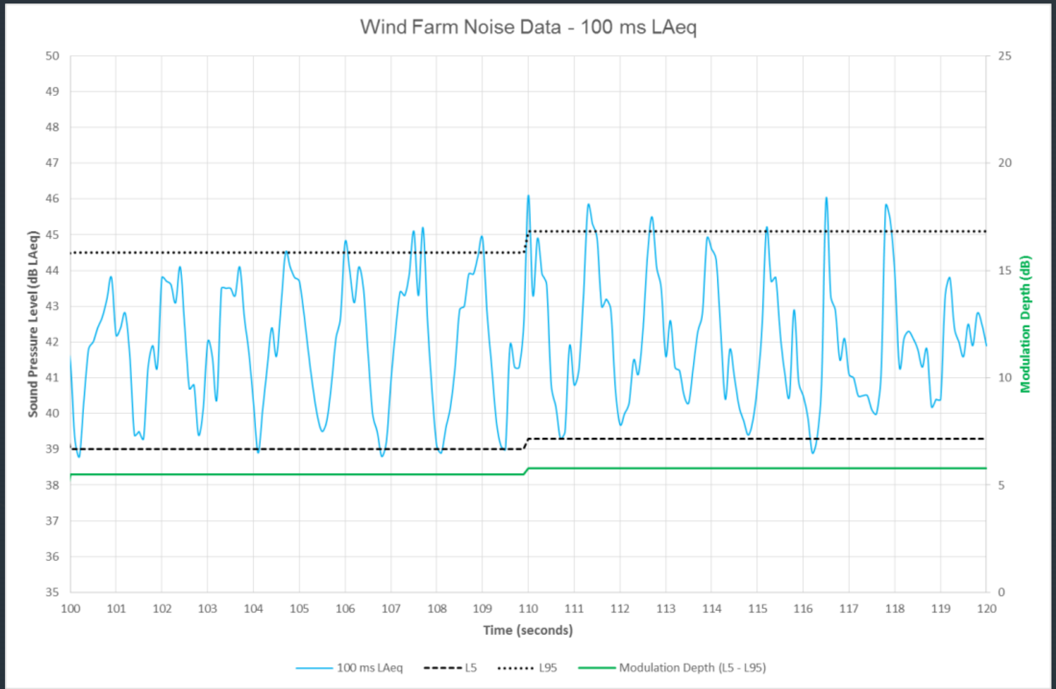
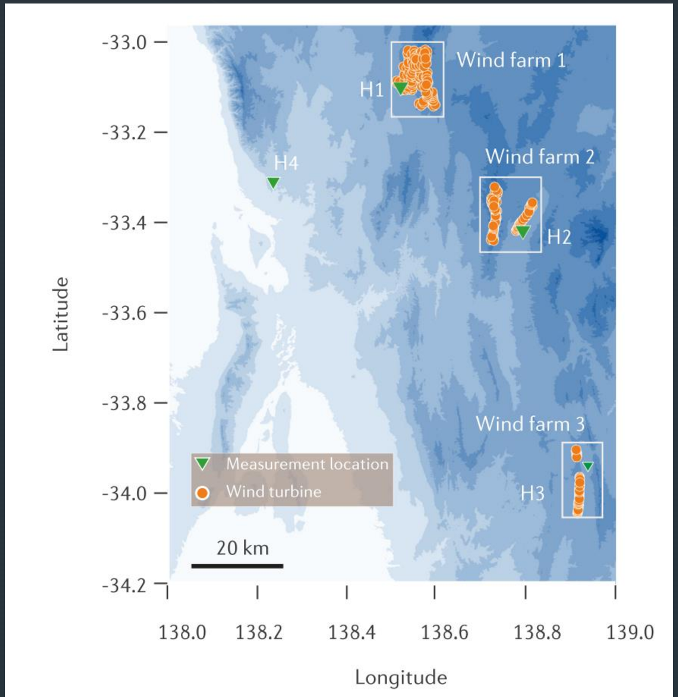
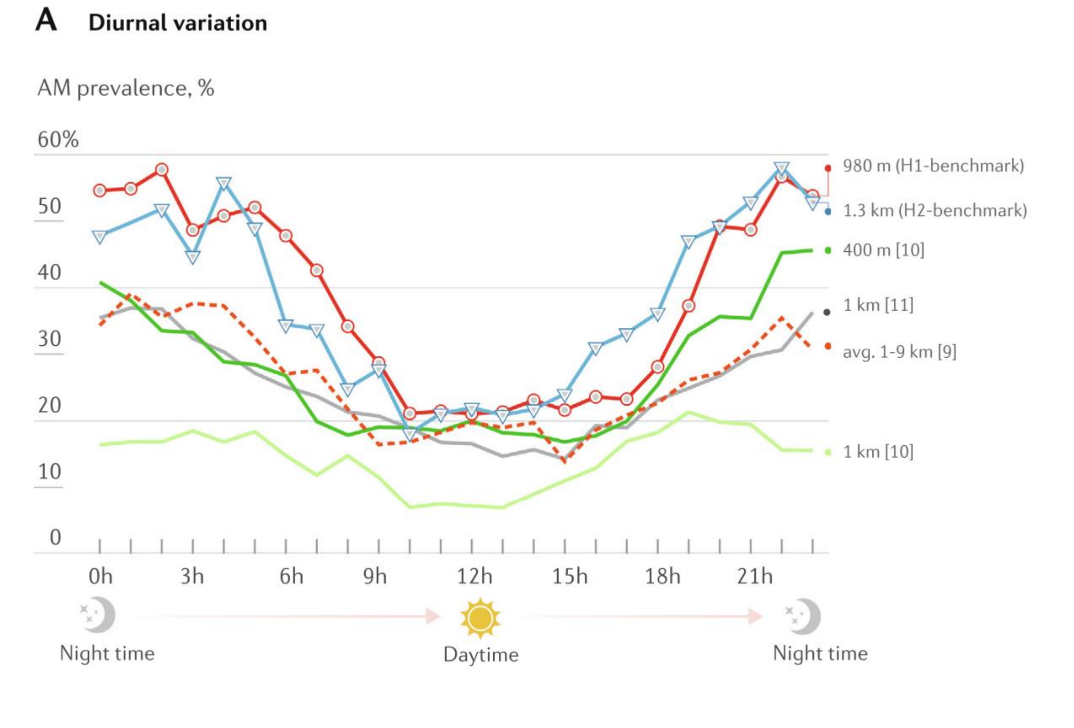


Image Source: [21]

Diurnal Variation in Amplitude Modulation Detection

- This slide shows a second study identifying variation in detected AM by time of day.



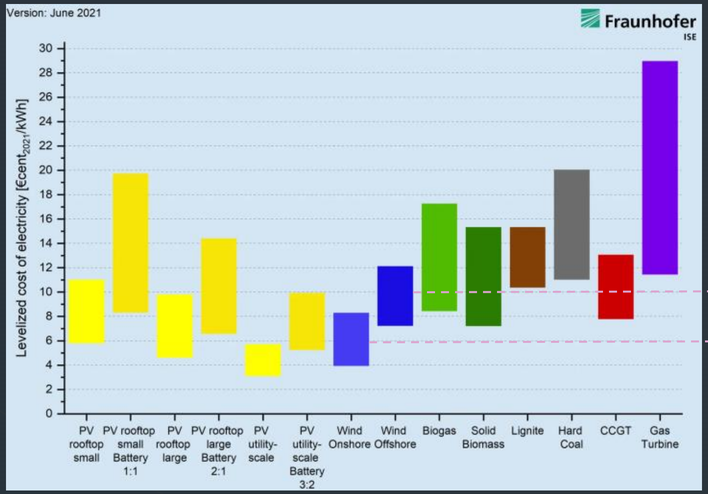


Images Source: [10]

- Median background noise level in this study for AM samples was 38.4 dBA . AM median 'depth' was 2.1 dBA), peaked at 7.0 dBA @ 63 Hz

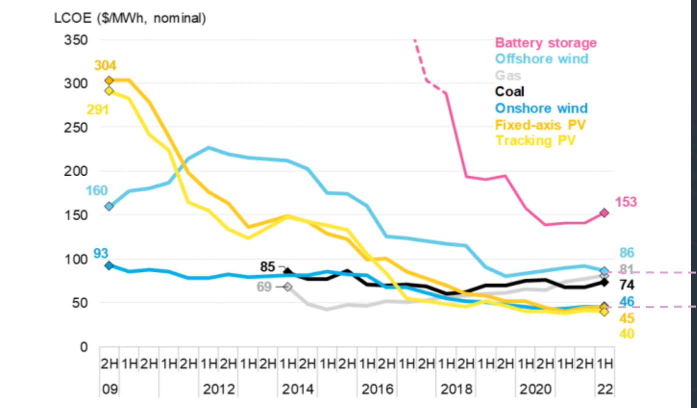
Why do we care? Advantage of terrestrial WF vs. Offshore = $$$

- Terrestrial Wind Farms remain a cheaper option than offshore. However, cost of land can be a challenge.
- Maintenance costs and cost of installation labor are contributing factors.
- So, there is a desire for WFs to be close + quiet (and to run at night).



Δ ~ 4c/kWh

Figure 1: Global levelized cost of electricity benchmarks, 2009-2022



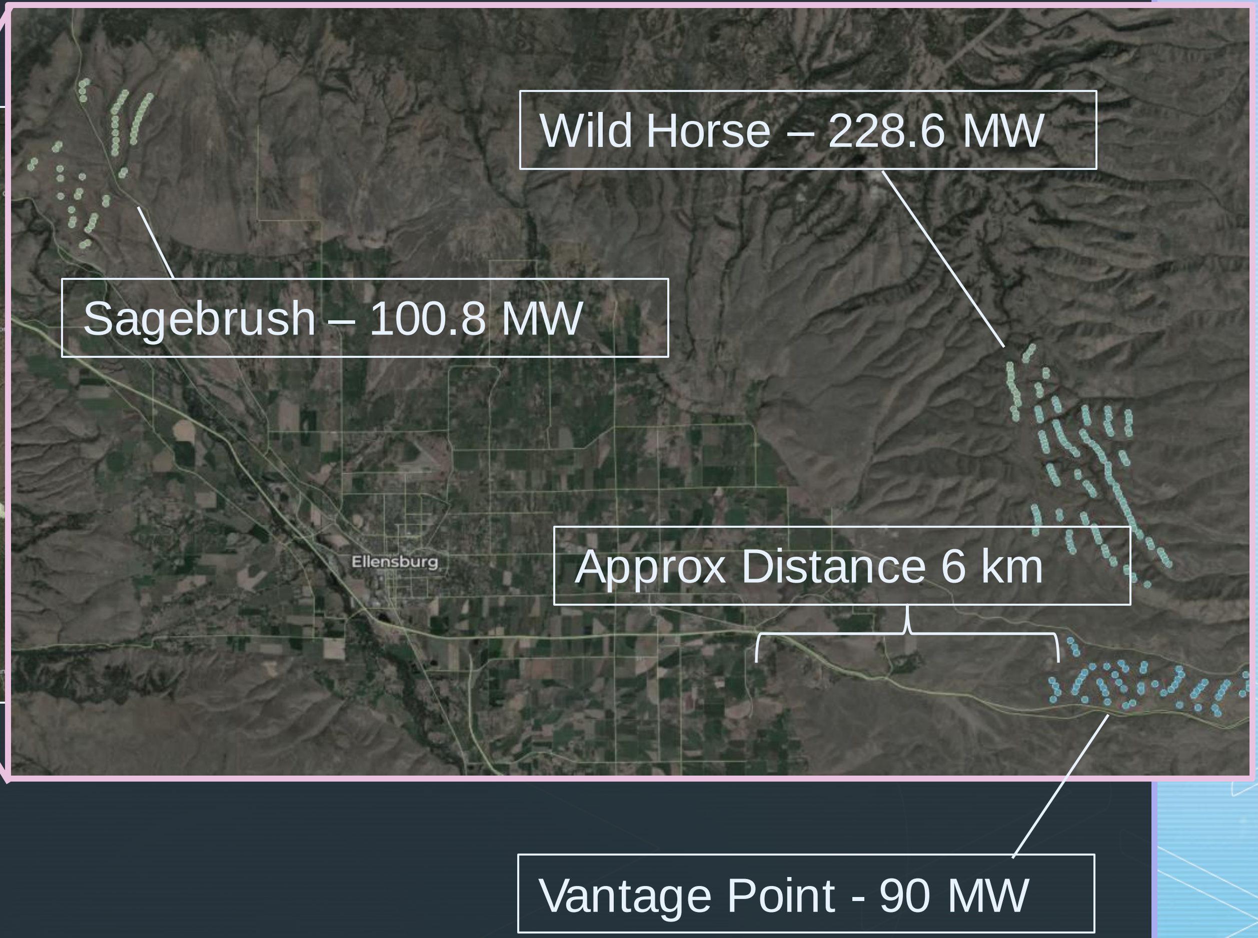
Source: BloombergNEF. Note: The global benchmark for PV, wind and storage is a country-weighted average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system with four-hour duration running at a daily cycle and includes charging costs.

Δ ~ $40/MWh

Image Sources: [7,8]

Case Study Example – Ellensburg, WA

- 3 Wind Farm Projects located with nearest installation close to outskirts of existing mid-size city.



- As renewable energy development continues, we will see more instances of WFs close to residential areas.

Image Source: [6]

Regulatory Controls on WFN

- Washington Laeq < 50 dbA for rural areas, at night (< 60 dbA for day).
- Recall that Laeq = "Equivalent Continuous Sound Pressure Level" = constant noise. Higher SPLs are allowed for shorter times, as shown in the table.
- Irritating WFN can cause reputational and financial damage.

Table 1.8 Noise metrics and threshold limits for Western USA.

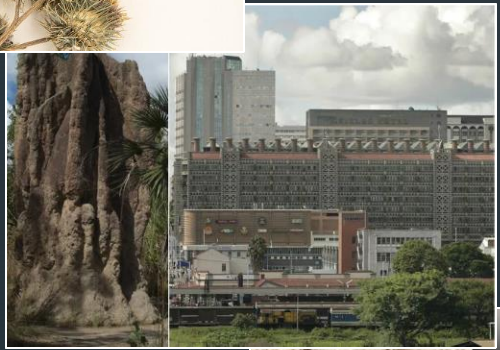
State or county	Setback distance	Noise metric	Rural		Residential		Residential, near industry	
			Day	Night	Day	Night	Day	Night
California (Alameda)	N/A	L_{50}	–	45	–	45	–	45
California (Contra Costa)	N/A	L_{dn}	60	60	60	60	60	60
California (Fairfield)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Fresno)	N/A	L_{50}	–	45	–	45	–	45
California (Kern)	N/A	L_{dn}	50	50	50	50	50	50
California (Kern)	N/A	$L_{A8.3}$	45	45	45	45	45	45
California (Monterey)	N/A	L_{den}	45–55	45–55	45–55	45–55	45–55	45–55
California (Morro Bay)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Riverside)	2–3000 ft	L_{Aeq}	60	60	60	60	60	60
California (Sacramento)	N/A	L_{50}	–	50	–	50	–	50
California (San Bernadino)	N/A	L_{Aeq}	–	45	–	45	–	45
California (San Francisco)	N/A	L_{Aeq}	55	50	55	50	55	50
California (San Joaquin)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Santa Cruz)	N/A	L_{Aeq}	–	40	–	45	–	45
California (Solano)	2000 ft	L_{Aeq}	44	44	44	44	44	44
California (Solano)	2000 ft	L_{den}	50	50	50	50	50	50
Colorado	N/A	L_{Aeq}	50	50	50	50	50	50
Colorado (Arapahoe)[3]	$H + B$	L_{Aeq}	55	50	55	50	55	50
Nevada (Lyon)[3]	$2(H + B)$	L_{Aeq}	55	55	55	55	55	55
New Mexico (San Miguel)[3]	0.5 miles	L_{Aeq}	<bk	<bk	<bk	<bk	<bk	<bk
Oregon[3,13,15]	N/A	L_{A50}	36	36	36	36	36	36
Washington	N/A	L_{Aeq}	60	50	60	50	70	70
Washington	N/A	L_{A25}	65	55	65	55	75	75
Washington	N/A	$L_{A16.7}$	70	60	70	60	80	80
Washington	N/A	$L_{A2.5}$	75	65	75	65	85	85
Wyoming (Laramie)[3]	$5.5H$	L_{Aeq}	50	50	50	50	50	50
Wyoming (Plympton)[3,12]	N/A	$L_{Ceq} - L_{Aeq}$	15	15	15	15	15	15

Background noise is usually measured using the $L_{A90,10min}$ metric. However, the wind farm noise is measured using the metric indicated in column 3 of the table. The term <bk, means that introduced wind farm noise must be less than existing background noise levels, which implies that the introduced noise can increase existing noise levels by a maximum of 3 dB; H is the hub height of the turbine; B is blade length.

Image Sources: [9]

Toward a Solution -Taking a Page from the Book of Nature

- Biologically Inspired design has been successfully implemented in a number of fields, such as:
  - Velcro, based on tree burrs.
  - Office Building designs, based on termite mound cooling.
  - Water collection designs, based on beetle shells.
  - And most importantly for us – noise reduction from Owl Wings. Let's see how.



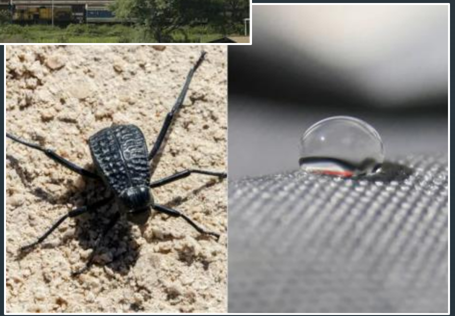


Image Sources: [2,3]

Owl Wing Morphology and Applications

- Owl wing features have applications in the design of:
  - Wind Turbines
  - Drones and small UAVs
  - Fans, Ducts, and HVAC systems
  - Aircraft
  - Turbines / Compressors

We will focus on WTs in this presentation due to existing body of research

Leading and Trailing Edge Serrations

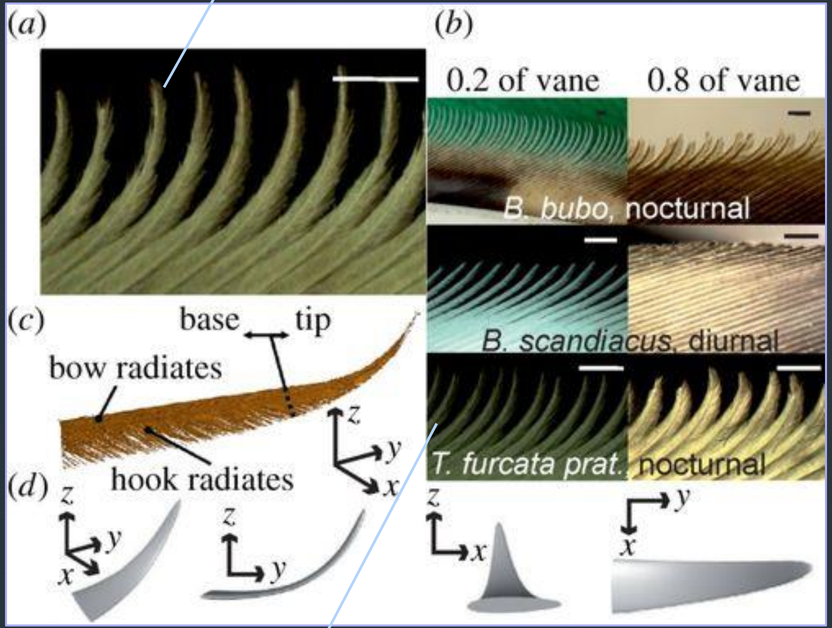


Image Source: [4]

Trailing Edge Porosity due to vane structure

Numerical Investigation - Example Study

Lei Wang (王雷) and Xiaomin Liu (刘小民) , Physics of Fluids, 2021

- In this study, the authors numerically investigated the effects of trailing edge serrations on sound levels.
- Three configurations were studied:
  - A. Smooth Trailing Edge.
  - B. Bionic serrations (Owl-like) "TE 1"
  - C. Straight serrations "TE 2"

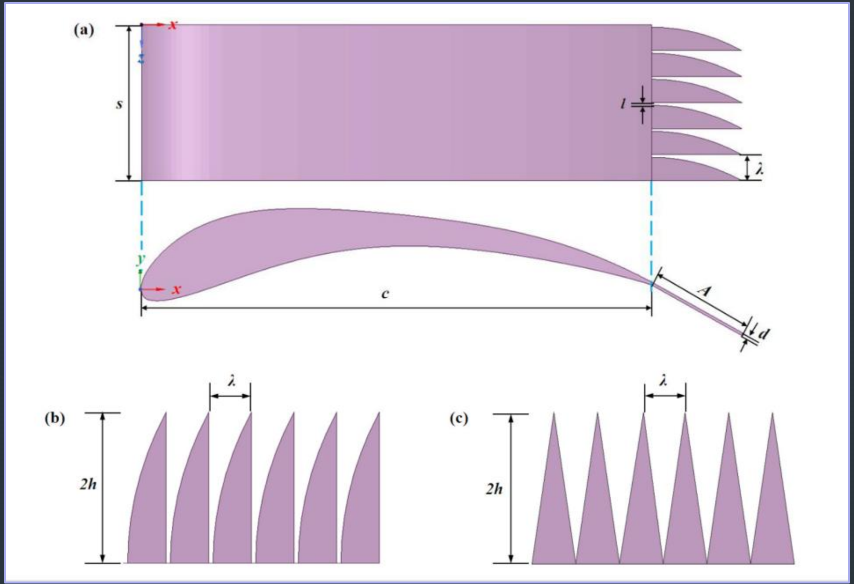


Image Source: [11]

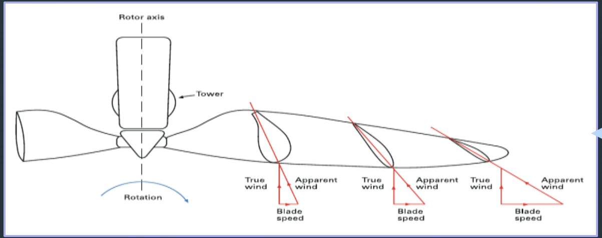
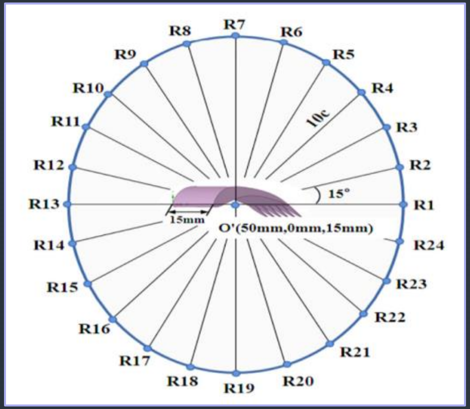


Image Source: [12]

Notably, the airfoil was studied at 0° Angle of Attack. Real blades will have a varying AoA depending on radial distance from hub.

Wang/Liu Study Results and Discussion

- The authors defined 24 "virtual receivers" stationed around the wing section in 15° increments. They then evaluated the sound pressure levels at a distance of 10 chord lengths.



Images Source: [11]

- Results showed a 5.47 dB reduction in SPL for Bionic TE1 configuration, and
  3.68 dB reduction for the TE2 configuration relative to the smooth TE.

- CL / cD is also improved.

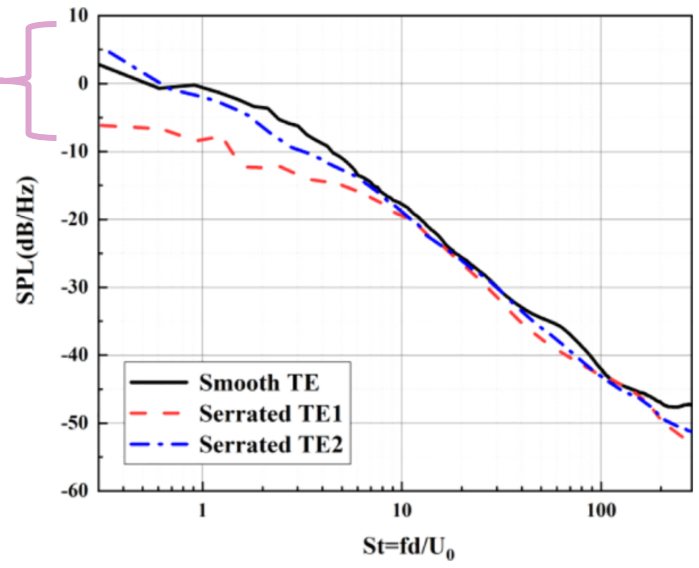


FIG. 16. Spectrum of SPL at receiver with maximum value.

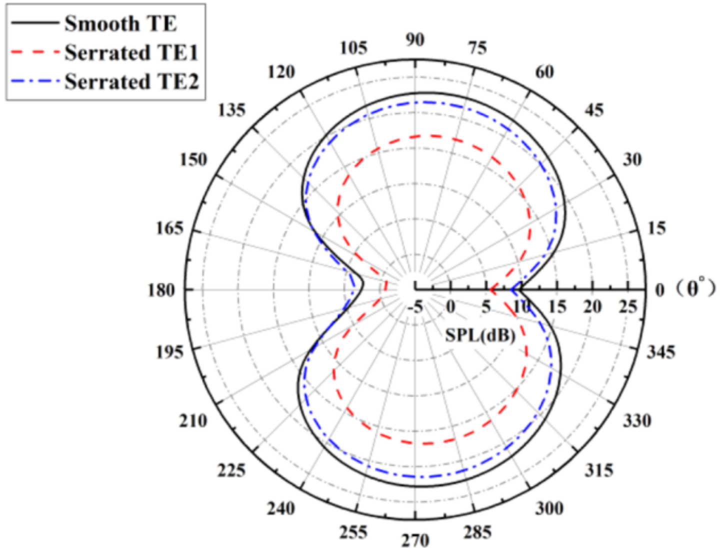
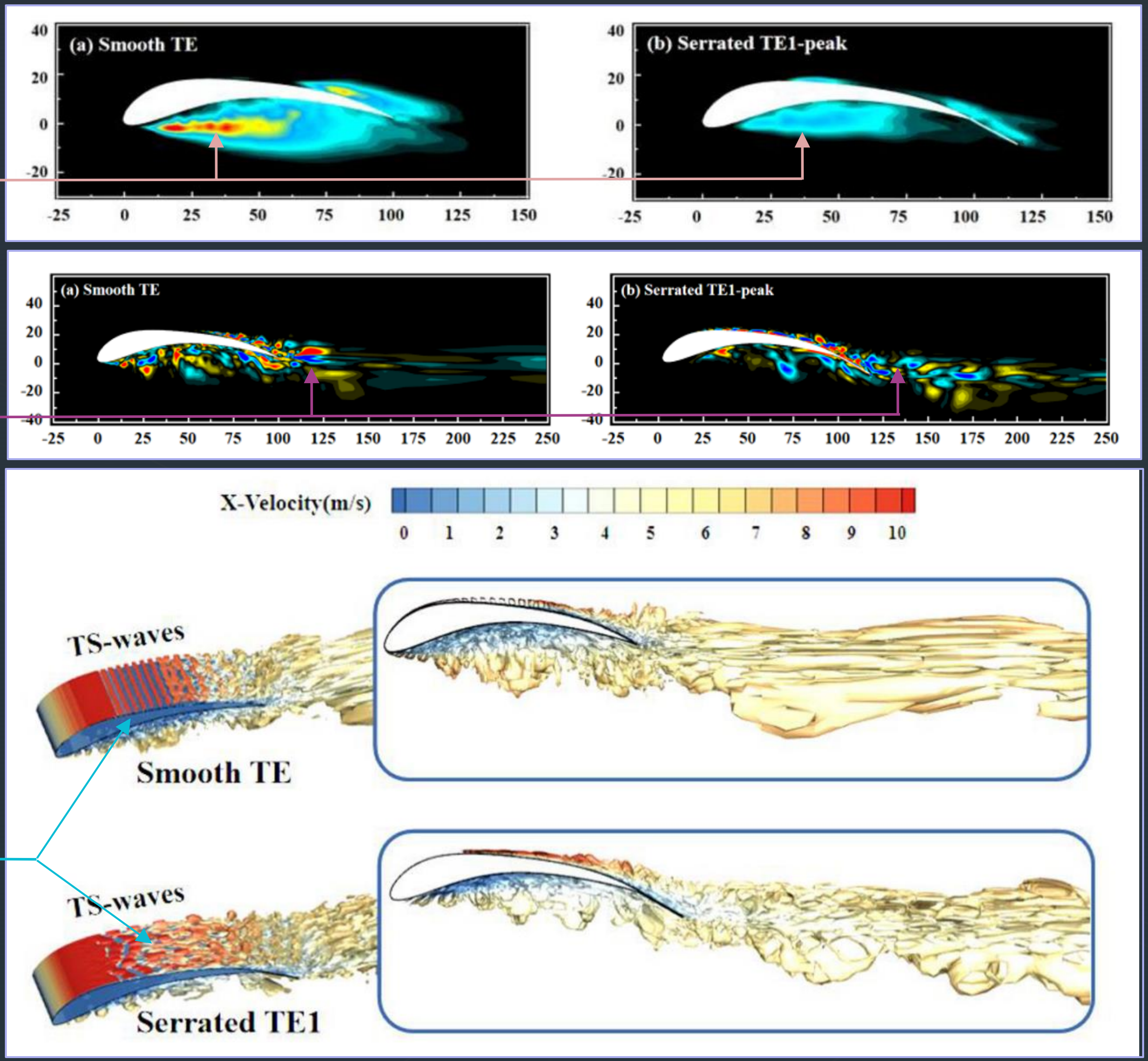


FIG. 18. Spatial distribution of SPL around the airfoils.

Wang/Liu Study Flow Field Visualization

Images Source: [11]

- Theorized mechanisms from authors to explain reduction in sound pressure level include:
  - Reduction in intensity of pressure fluctuations on pressure side of airfoil.
  - Reduction in 'spanwise correlation' parameter associated with vortex strength, as well as helicity on pressure side.
  - Shape of vortices at on suction side of serrated airfoil is 'horseshoe' shaped as opposed to linear 'TS-wave' for smooth trailing edge airfoil – reduces strength of wake vortex shedding.



Experimental Investigation - Sample Study

S. Oerlemans, M. Fisher, T. Maeder, K. Kögler, Report NLR-TP-2009-401

- In this study, the authors experimentally studied turbine trailing edge noise on a commercial GE 2.3 MW turbine by adding a noise-optimized profile to one blade, and adding serrations to a second blade.
- Rotor diameter was 94m.
- Serrations were applied to outer 12.5m of the blade.
- Wind Speed range of study was from 6 m/s to 10 m/s.

Image Source: [15]

Experimental Investigations – Results and Discussion

- Results of Oerlemans study showed a reduction of up to 3.2 dBA in SPL up to around 1250 Hz.
- However, the trailing edge serrations actually caused an *increase* in high-frequency noise (above ~2000-5000 Hz). This is believed to be due to increased tip noise.
- 'Sirocco', low-noise optimized blade profile had minimal effect (<0.6 dBA).
- TE brushes also had an ~3dBA effect in separate WT testing.

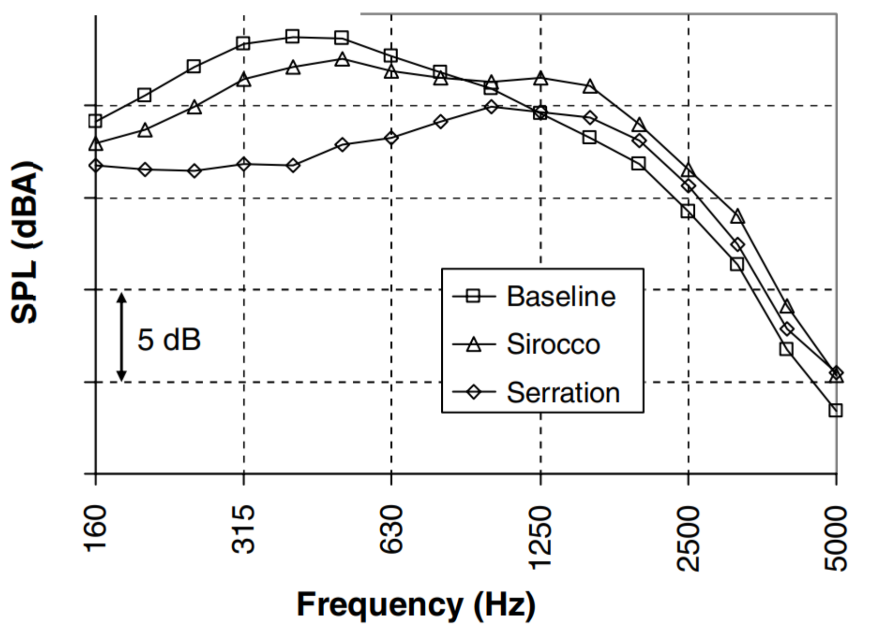


Fig. 13 Average blade noise spectra for state 2a.

Image Source: [15]

Conclusion and Next Steps

- Both Numerical and Experimental studies show meaningful noise reduction effects from adoption of Owl-wing like structures such as TE serrations and high-roughness surface finishes.

- Next steps – Commerical integration!
  - Challenges include manufacturing costs, high-frequency noise.
  - Already being adopted by some MFRs, e.g. Siemens Gamesa. SG7.0-170 with "Dinotails"
- More study is needed to pave to way to a quieter future for wind power.

Image Source: [19]

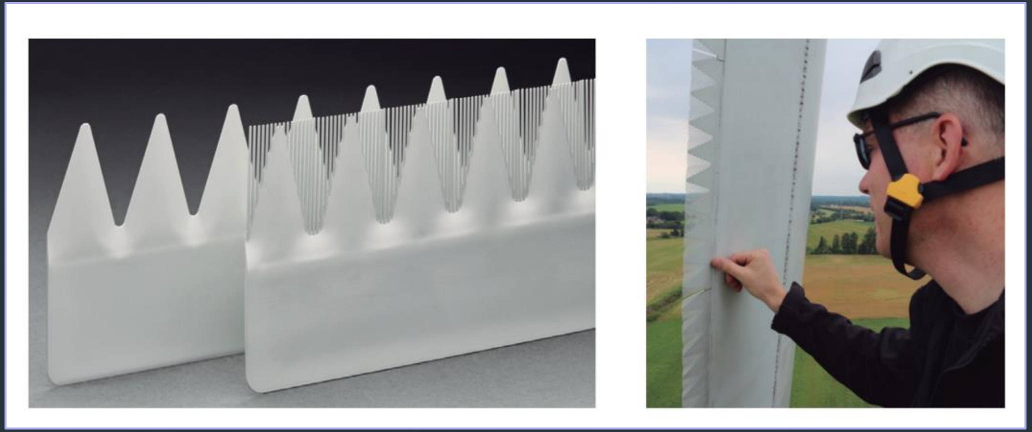


Image Source: [19]

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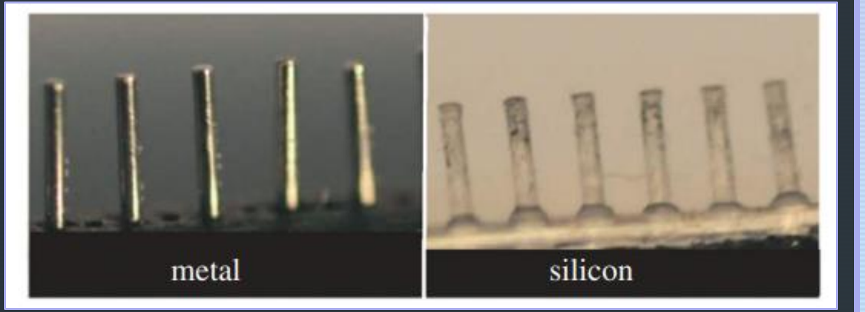
Backup Content – Cut for Time

Experimental Investigations – LE Serrations and Surface Roughness

- Studies conducted by Klan et al. & Winzen et al, using model leading edge serrations have shown some noise reduction effects, but magnitudes are uncertain. Ref. Japanese Shinkansen Bullet Train for example of real-world application of this type of structure.
- The same authors also conducted studies of a simulated 'velvet-like' surface which was shown to reduce the separation bubble size on the suction side of a model airfoil, allowing for reduced stall speed.



Images Source: [4]