Comparison of Loads and Aeroacoustics Between Upwind and Downwind Wind Turbine Rotors

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National Renewable Energy Laboratory

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Why Downwind?

Most wind turbines fly upwind rotors. However, downwind is a recurring R&D theme:

- Reduction in turbine capital expenditures thanks to relaxed blade-tower clearance constraint
- Increase in farm power for flow-aligned rows of turbines
- Increase in rotor-swept area for floating applications.

Downwind for Floating?

Downwind floating may yield benefits:

- Increase rotor-swept area under platform pitching (turbine greedy approach)
- Enhance platform yaw stability.

Image from x1wind

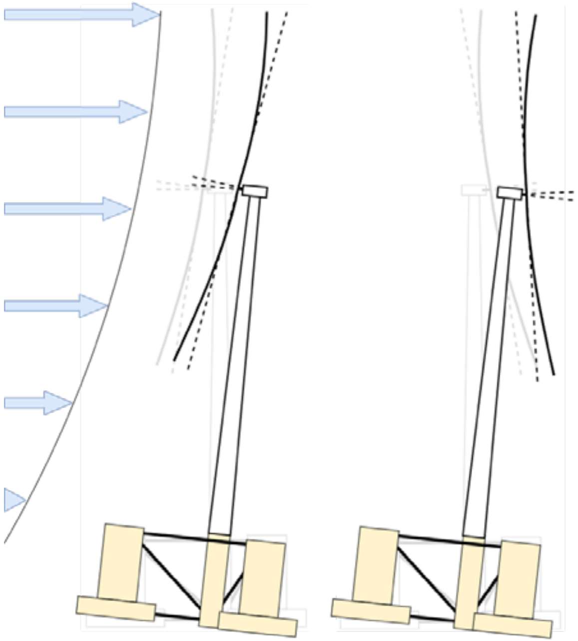
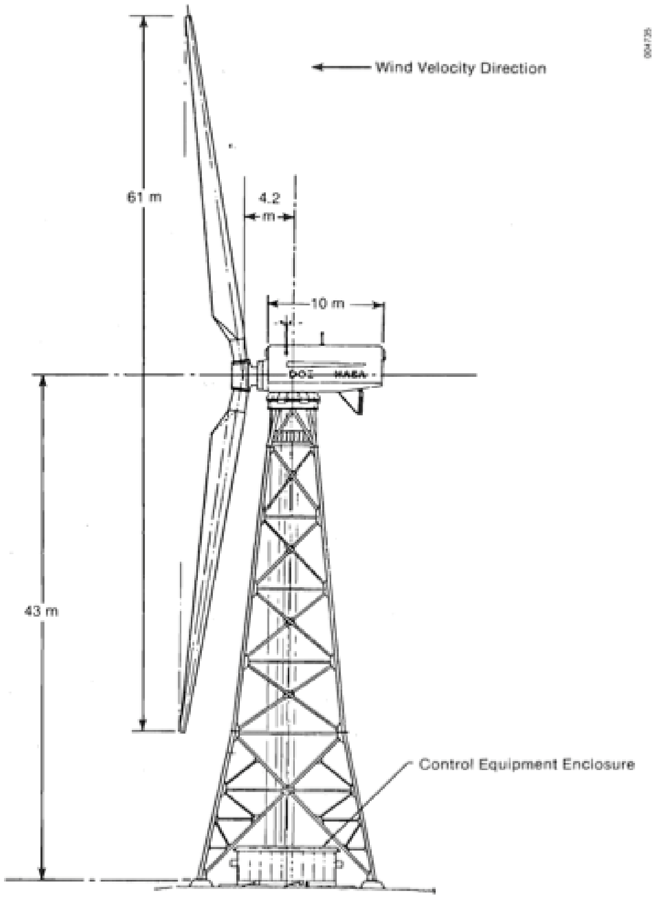


Illustration by M. Chetan, NREL

Why NOT Downwind?

- Combination of unproven advantages and historical issues.
- Tower shadow loading
- In 1980s, downwind wind turbines suffered from excessive noise.

- However, these turbines had truss towers with high aspect ratios and stiff blades.
- Modern turbines look a lot different.



MOD-1 downwind turbine from
https://www.nrel.gov/docs/legosti/old/1166.pdf

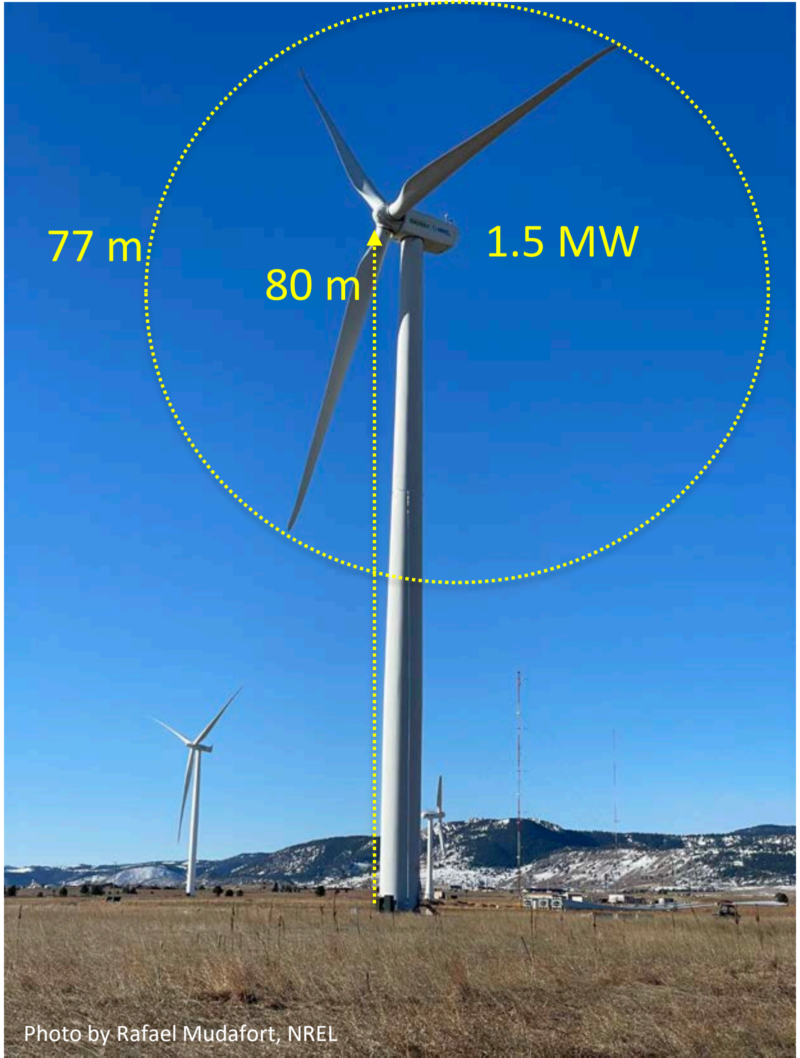
Goal of the Experiment

Generate a unique dataset to validate noise and aerodynamic models, and advance understanding of barriers of downwind wind turbine technology.

- Validate positive anecdotal experience around downwind (Hitachi, CART)

- Where: NREL Flatirons Campus, DOE 1.5 MW
- How: pitch and yaw 180 deg, and rotate counterclockwise
- When: Winter/Spring 2024

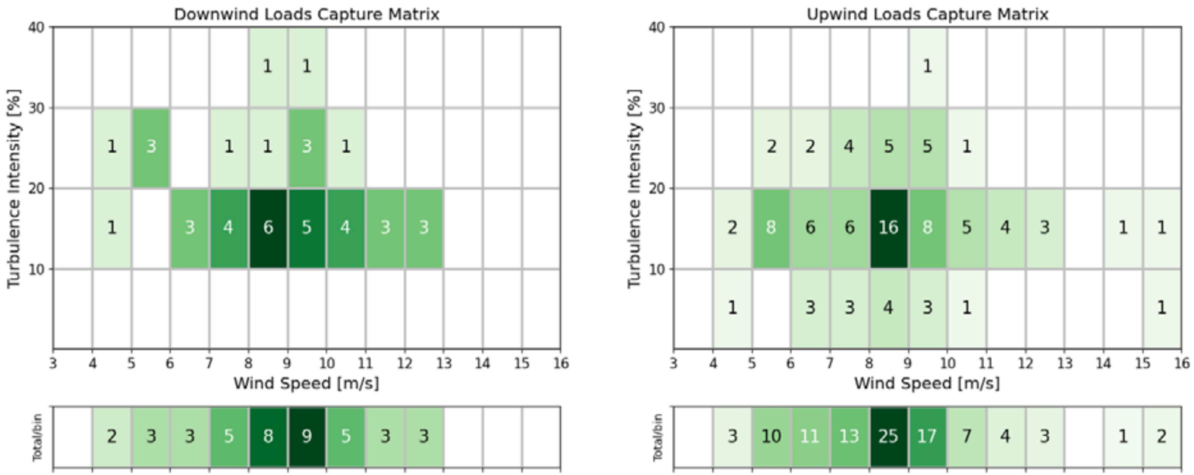
- Turbine is now back upwind—no damage to the turbine during the experiment.



Loads

Load Dataset

	Start	End	10-Minute Samples
Downwind	2024-04-13	2024-06-04	41
Upwind	2024-06-29	2024-07-19	96



Numerical Simulations

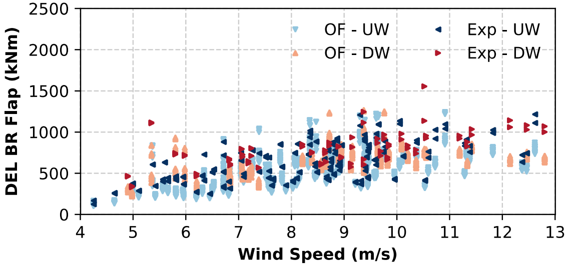
1:1 numerical/experimental validation

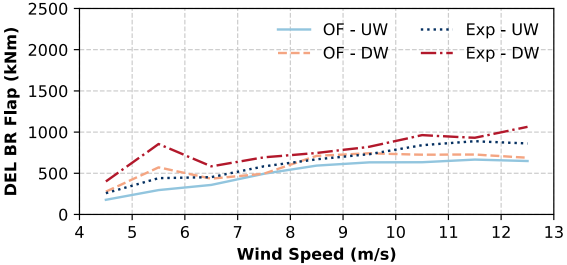
- 6 turbulent seeds per experimental 10-min sample in TurbSim, matching
  - Average wind speed
  - Turbulence intensity
  - Exponential shear exponent
  - Air density.
- OpenFAST v3.3
  - Blades modeled in ElastoDyn
  - Unsteady aerodynamic effects included.
- GE precompiled controller.

DEL Blade Root Flap

- Statistics averaged across three blades.
- Scatter in the data is due to turbulence.
- OpenFAST is underpredicting damage equivalent load (DEL) by as much as 50%.
- Numerical predictions and experimental observations show DEL increases between 10% and 20% in downwind (more at low wind speeds, where fewer experimental samples are available).

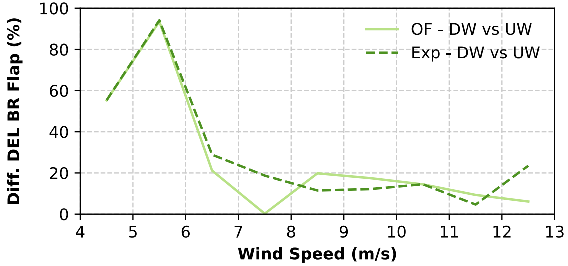
scatter plot of the raw experimental and numerical data

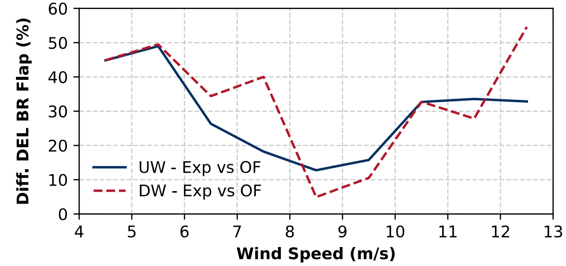




average of binned data

difference in binned averages between downwind and upwind (1st: numerical data, 2nd: experimental data)



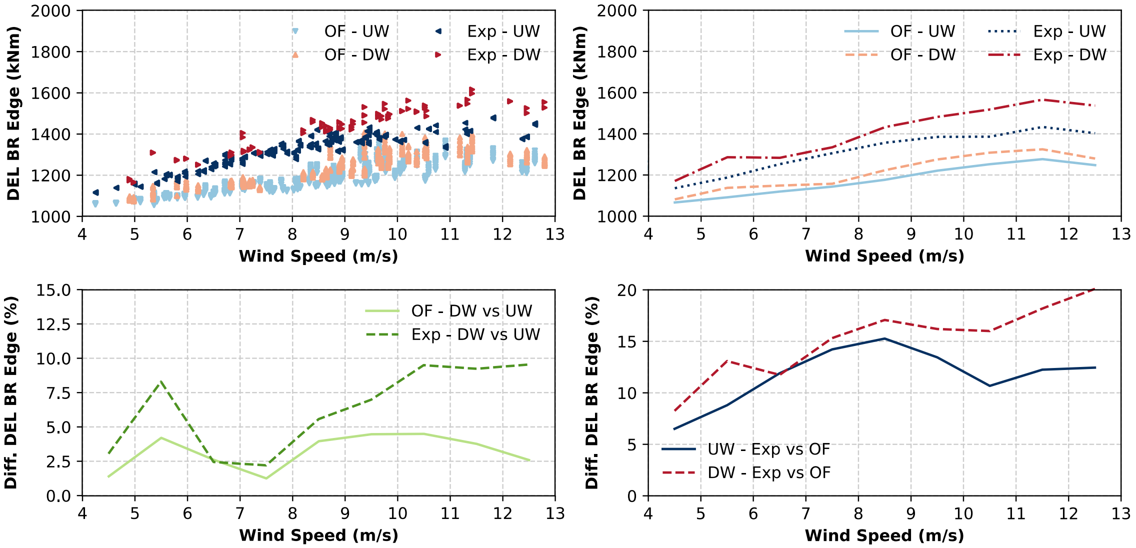


difference in binned averages between experimental and numerical data (1st: upwind data, 2nd: downwind data)

OF = OpenFAST; Exp = experimental; UW = upwind; DW = downwind

DEL Blade Root Edge

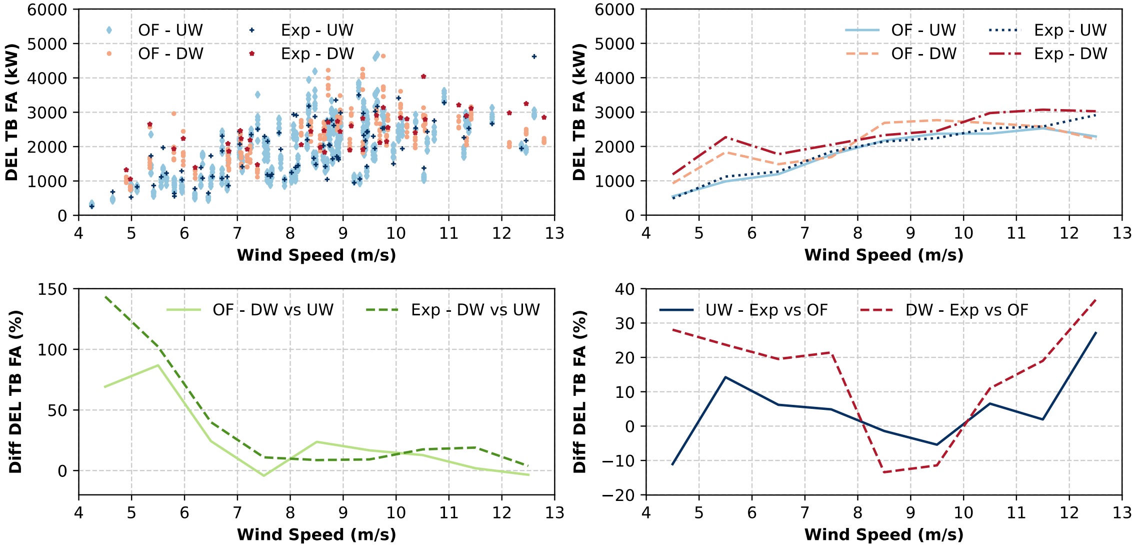
- Statistics averaged across three blades.
- OpenFAST underpredicts DEL by as much as 15% in upwind and 20% in downwind.
- Numerical predictions show DEL increases between 2.5% and 5% in downwind.
- Experimental observations show DEL increases between 2.5% and 10%.



OF = OpenFAST; Exp = experimental; UW = upwind; DW = downwind

DEL Tower Base Fore-Aft

- Similar trends to DEL of blade root flap.
- Scatter in the data is due to turbulence.
- Numerical predictions and experimental observations show DEL increases between 10% and 20% in downwind (more at low wind speeds, where fewer experimental samples are available).



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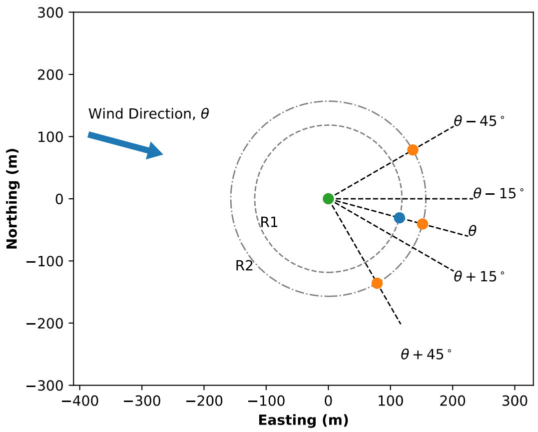
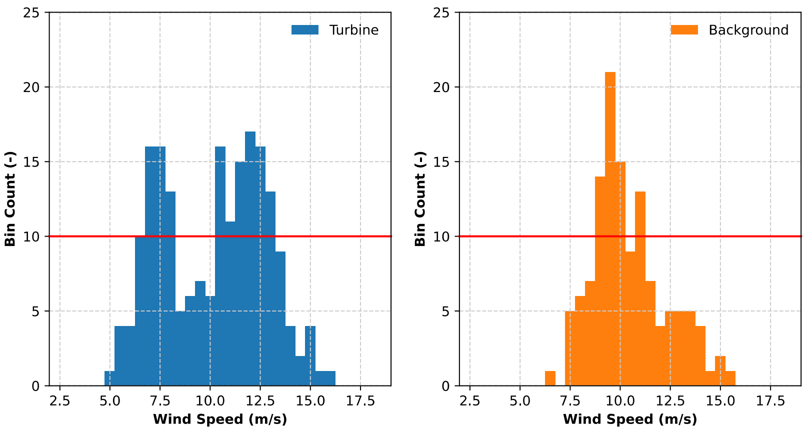
Experimental Aeroacoustics

Acoustic Data

- All data are listened to and qualified for interruptions.
- Red line is the minimum required data in each bin according to International Electrotechnical Commission (IEC) 61400-11, 2018.





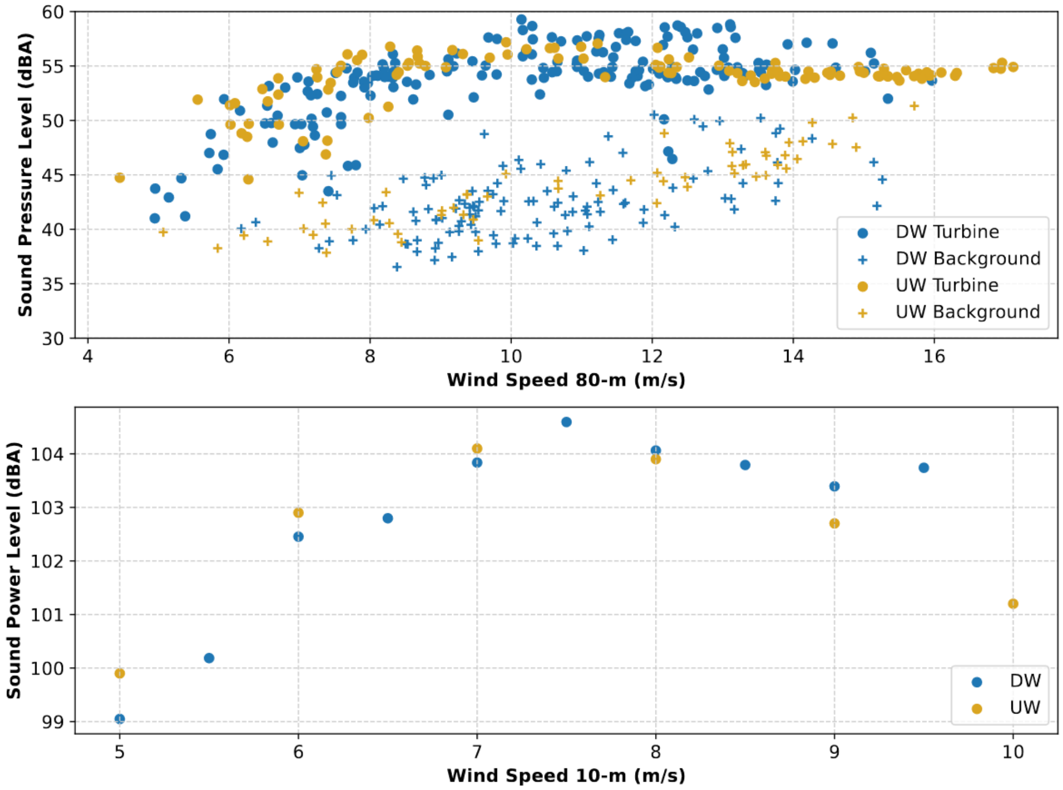
Histograms of valid turbine and background data.

IEC Results

- Overall sound pressure and sound power levels between the downwind and upwind IEC test performed in 2011.

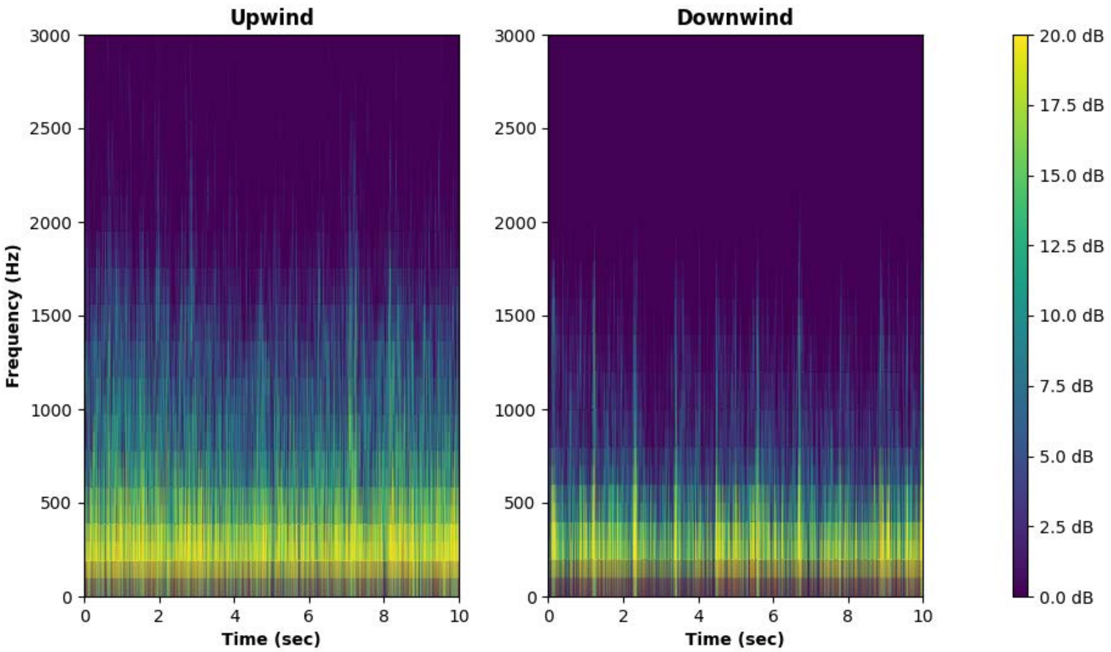
- Data largely overlap.

- Additional variation in downwind at the higher wind speeds.



Spectrograms

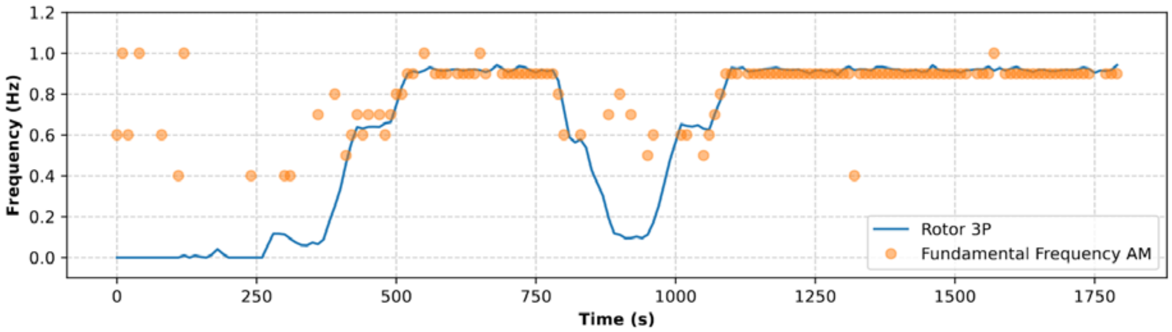
- Audible amplitude modulation
- Periodic spikes and striations in the downwind data
- Rotor harmonics could not be detected in fast Fourier transforms (FFTs) of the data
- Instead, we opted for the method defined in the IEC 61400 -11-2 for amplitude modulation to detect audible variations.

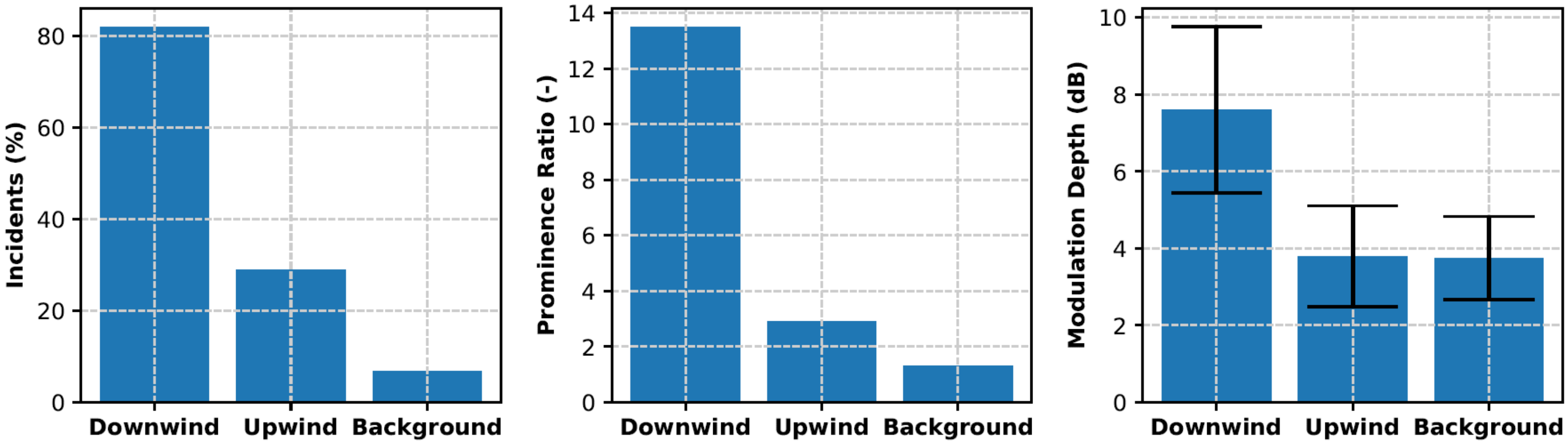


Amplitude Modulation

Amplitude modulation performed according to IEC 61400-11-2

- Fundamental frequency in line with rotor 3P when operating





How Severe is This Amplitude Modulation?

In Collaboration with Tom Levet & Robin Woodward, Hayes McKenzie Partnership Ltd, UK

- Somewhat subjective. Moderate?
- Certainly nowhere near as extreme as the accounts of the MOD-1.
- 7.6 dB mean modulation depth. 2-3dB where humans perceive some annoyance.
- The level measured during BAR is fairly comparable to the highest measured on <u>upwind</u> machines by Tom and Robin.
- EC TS 61400-11-2:2024 with an AM penalty scheme for 3db-10dB+. Plenty of periods where <u>downwind</u> would be penalized.

→ Moderate?

Conclusions

Conclusions

- Experiment completed successfully
- No known damage to the turbine
- OpenFAST trends match experimental trends
- Downwind operation causes a (modest?) increase in fatigue loads
- Overall sound levels similar between upwind and downwind
- Moderate amplitude modulation experienced in downwind.

Q&A

www.nrel.gov

NREL/PR-5000-91567

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