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The Future of Land-based Wind Turbine Rotor Technology: The Perspective From NREL

Pietro Bortolotti

Senior Researcher and Project Lead

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Photo by Dennis Schroeder, NREL 55200

Agenda

1. The BAR Project
2. Controlled Flexing of Blades During Rail Transport
3. Distributed Aero Controls
4. Aeroelastic Stability and RAAW Project
5. Downwind Rotors
6. Research Foci Beyond BAR
7. Key Takeaways and References

The BAR Project

A high level overview

BAR Mission

Mission of the Big Adaptive Rotor project:

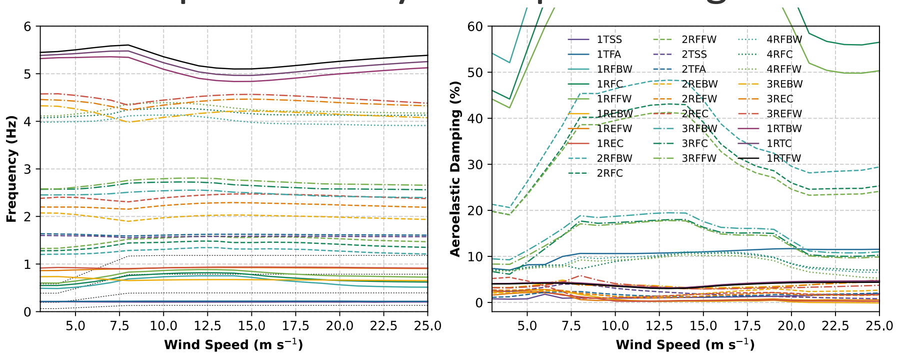
Identify and develop novel technologies to support the next generation of **high-capacity land-based** wind turbines

5 megawatt (MW), 200+ meter (m) rotors

How BAR Started…
Downselection of Technologies

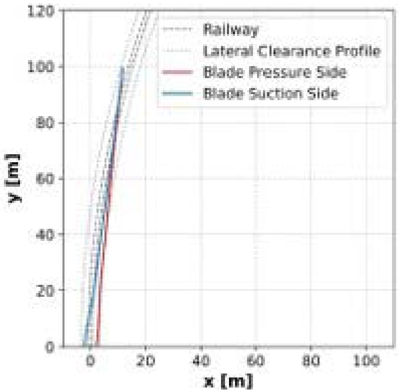
DNV-led Supersized Blades workshop (Smith and Griffin 2019)

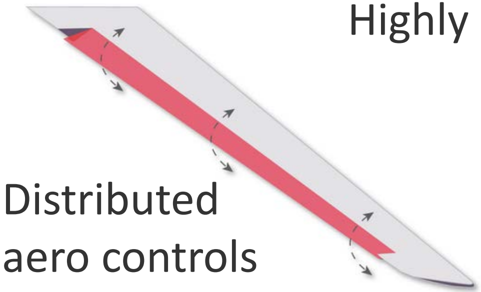
National-Renewable-Energy-Laboratory (NREL)/Sandia-National-Laboratories (Sandia)-led workshop to identify most promising technologies (Johnson et al. 2019)



Highly flexible rotors

Controlled flexing during rail transport





Distributed aero controls

Downwind rotors

Some Concepts That Were Left Behind

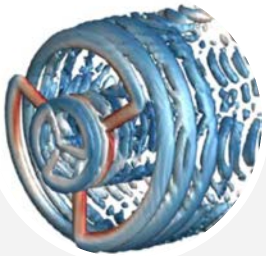
Disclaimer
Not enough data to make strong, facts-based decisions! Value could be there. Strategically, we decided to prioritize the concepts from slide #4.

Highly Coned Downwind

Lower annual energy production (AEP)

Multirotor

Higher operational expenditures (OpEx)
Patents and high technology readiness level (TRL)



Dual Rotor

Higher capital expenditures (CapEx) and OpEx

Two (and Five) Bladed Rotors

Unsteady loads (2)

Higher CapEx (5)

Blades-Hub Integration

Higher CapEx

Not a lab core competence

Photos and drawings from Johnson et al. (2019)

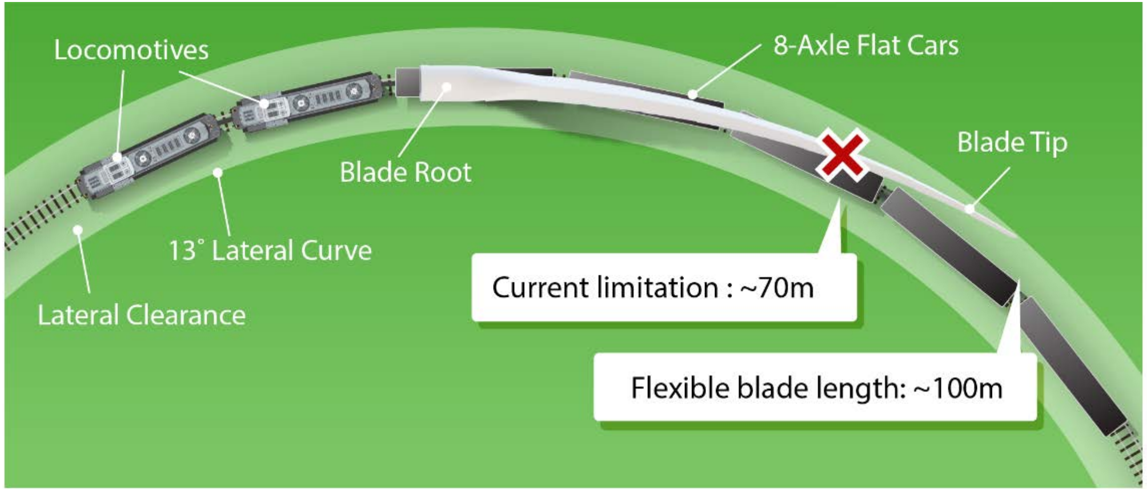
Controlled Flexing of Blades During Rail Transport

See the references for more details

Rail Transport

Controlled flexing of blades during rail transport was first proposed by DNV in Smith and Griffin (2019) to soften logistic constraints of 100-m-long blades.

The study in Carron and Bortolotti (2020) shows that the idea is less unrealistic than it sounds!



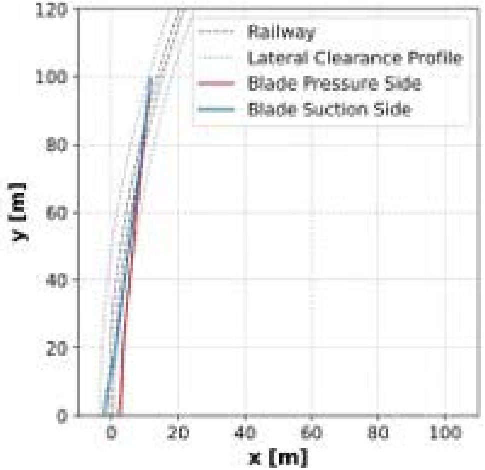


Illustration and plots from NREL

Distributed Aero Controls

See the references for more details

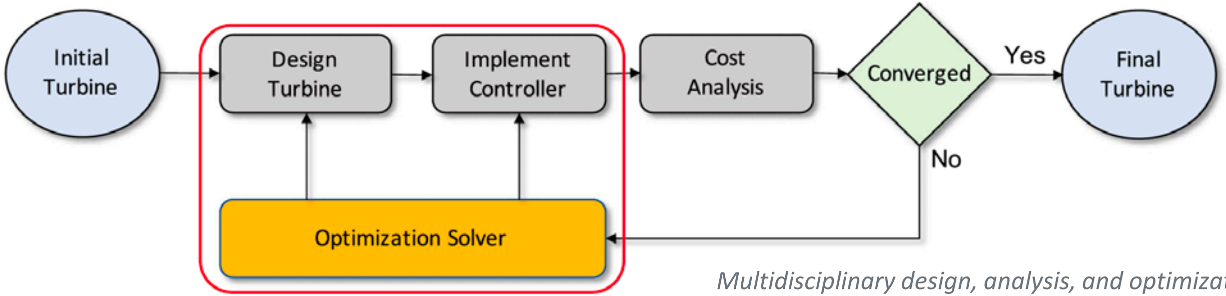
Distributed Aero Controls

Investigations into both leading- and trailing-edge devices to minimize ultimate loads.

Approach and results are thoroughly described in Abbas et al. (2023)

Key takeaways:

- Sophisticated fully open-source optimization toolchain wrapped around OpenFAST
- Flaps reduce loads and blade deflection but need to be large and actuate often
- The value story remains very challenging (higher OpEx is likely to cancel out the small levelized cost of energy benefits).



Multidisciplinary design, analysis, and optimization workflow adapted by Abbas et al. (2023)

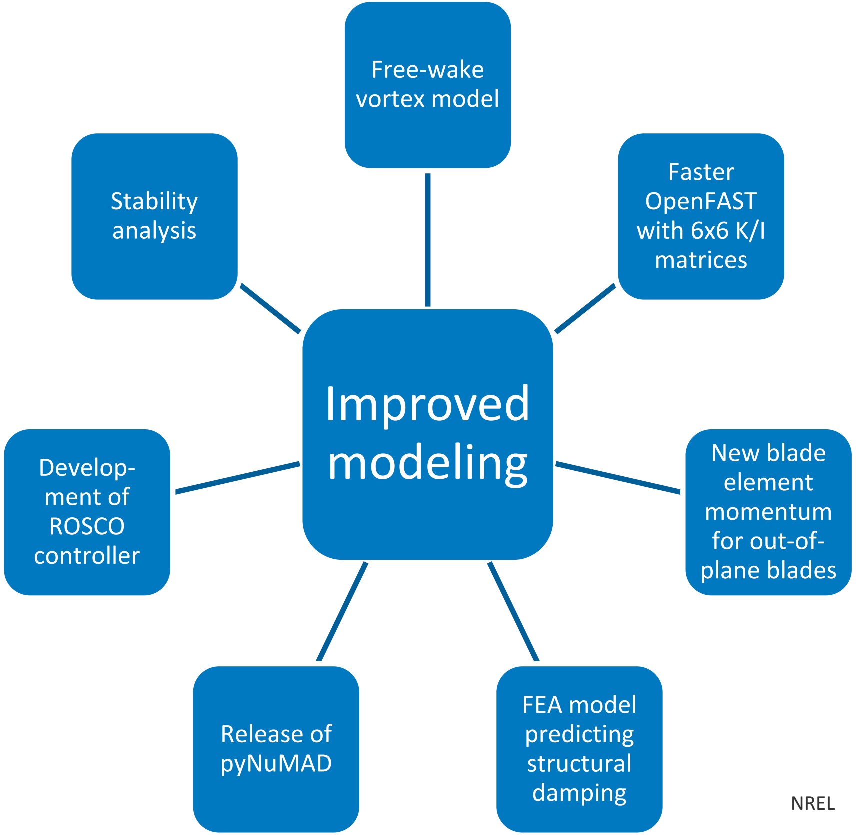
Aeroelastic Stability and RAAW Project

Ongoing activities

Flexible Rotors

Modern numerical models struggle to accurately **predict** the aeroelastic behavior of highly flexible rotors (and flexible turbines).

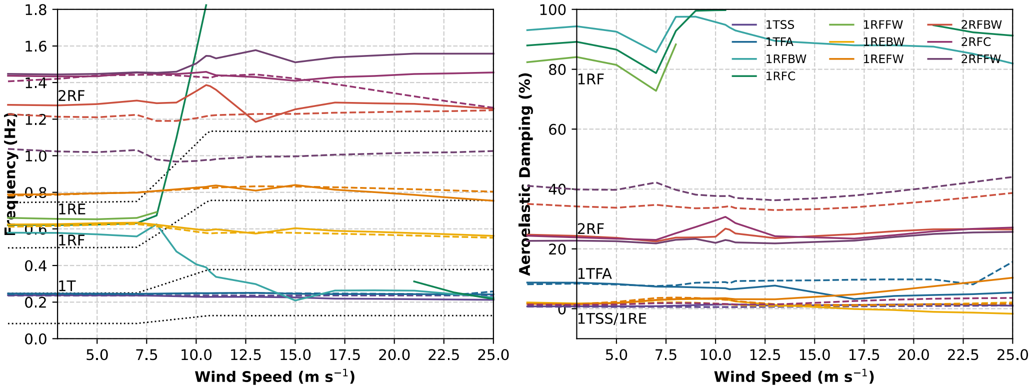
This topic area directly addressed the **second grand challenge of wind energy** identified by Veers et al. (2019) in "Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines."



Aeroelastic Stability

Modern turbines increasingly suffer from aeroelastic instabilities.

- The trend is worsening for larger and more flexible machines.
- Podium presentation on paper at TORQUE 2024 conference will discuss stability analysis in OpenFAST.
- Verification against HAWCStab2 showed:
  – Structural-only comparisons return good match
  – Discrepancies emerge when aero effects are included
  – Edge modes match much better than flap ones.

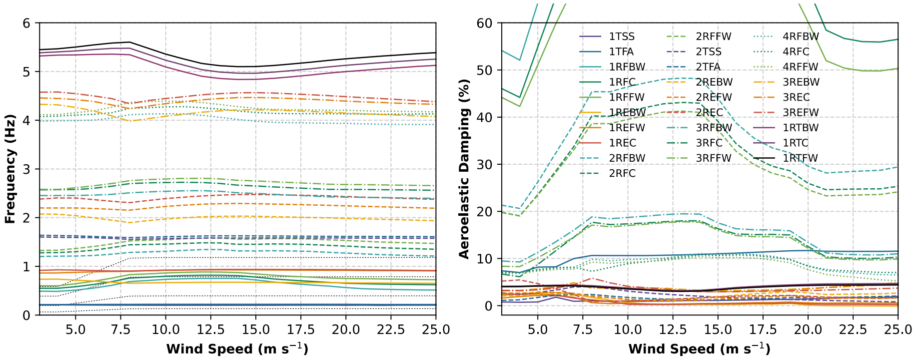


Campbell diagram of the International Energy Agency (IEA) 15-MW reference wind turbine. Full results will be presented at TORQUE 2024. Legend: Solid lines show results from OpenFAST, dashed lines show results from HAWCStab2. Legend: 1/2 = order of mode, TSS/TFA = tower side-side/fore-aft, RF/RE = rotor flap/edge, FW/C/BW = forward whirling/collective/backward whirling.

Aeroelastic Stability

The paper to be presented at TORQUE 2024 also discusses the impacts of different design choices on the stability of a flexible rotor.

- Baseline design is barely stable.
- Choice of values of structural damping is key.
- Torsional stiffness is a second key.
- Spanwise joint lowers damping lines.
- Chordwise airfoil placement is a third key.
- Solution is not very sensitive to prebend shapes, but prebent blades are more stable than straight ones (bad news for logistics).



Campbell diagram of a flexible rotor designed within BAR. Full results will be presented at TORQUE 2024. Legend: 1 (solid)/2 (dashed)/3 (dash-dotted)/4 (dotted) = order of mode, TSS/TFA = tower side-side/fore-aft, RF/RE/RT = rotor flap/edge/torsion, FW/C/BW = forward whirling/collective/backward whirling.

Stability analysis shall be integrated in **automated** design optimization processes.

RAAW Experiment

Rotor Aerodynamic, Aeroelastic, and Wake (RAAW) experiment

- Collaboration between NREL, Sandia, and GE Vernova
- Highly instrumented 2.8-MW (127 m) wind turbine
- Same rotor of the wind farms from the American WAKE experiment (AWAKEN) campaign.

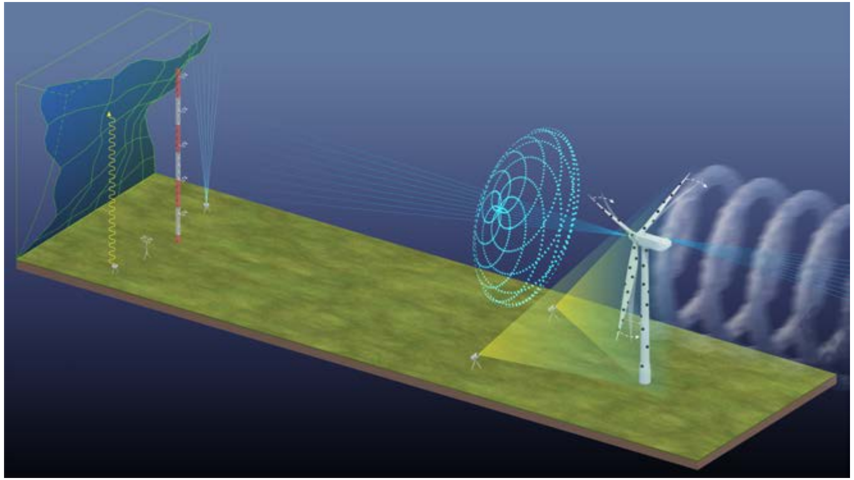


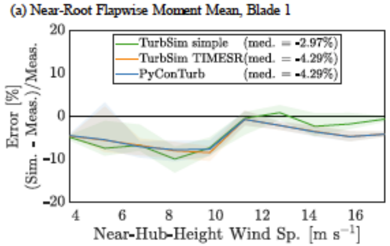
Illustration from NREL

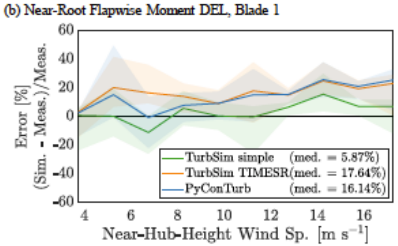
Photo from GE

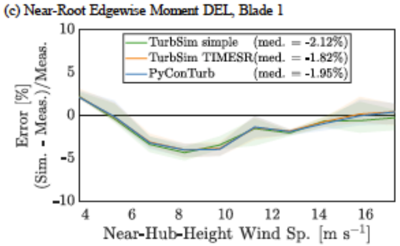
RAAW Experiment

Recently published journal article (Brown et al. 2024) describes the most complete validation of the aeroservoelastic solver OpenFAST coupled to open-source controller ROSCO to date.

Plots from Brown et al. (2024)







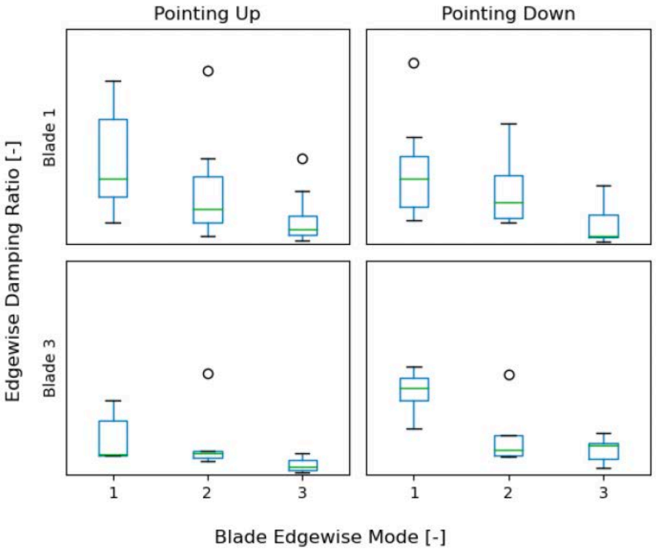
Some key conclusions:

- Satisfactory match, with a few concerns
  - Values of blade structural damping need to be high in OpenFAST
  - Mismatch in blade flapwise and tower fore-aft damage equivalent load
- Design at the edge of aeroelastic stability.

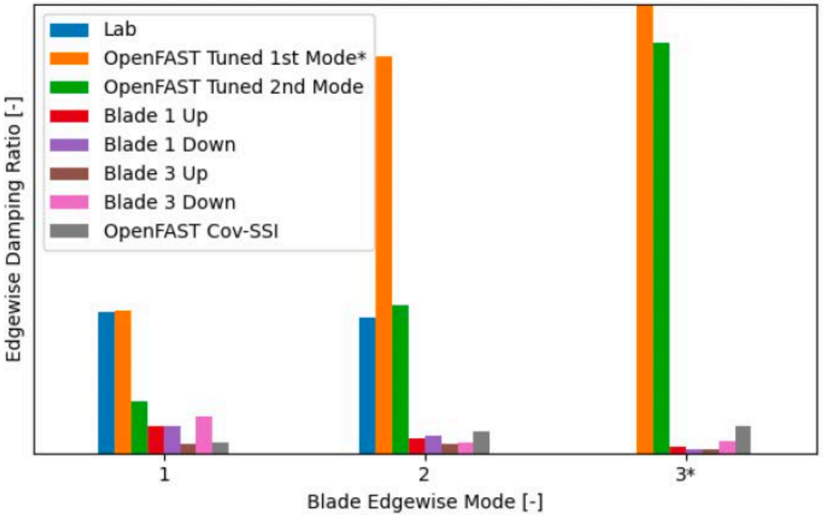
Structural Damping

Yaw impulse tests performed during RAAW

Classic aeroelastic tools seem to overpredict structural damping above first (or second) modes.



Plot from Mayank Chetan, NREL



Plot from Mayank Chetan, NREL

Downwind Rotors

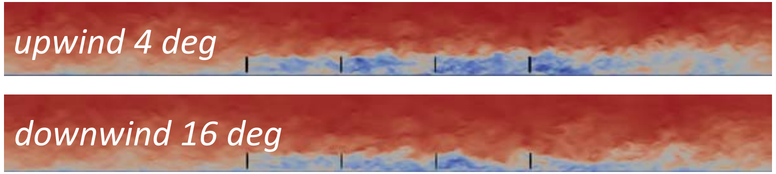
An ambitious experiment

Why Downwind?

Most wind turbines fly upwind rotors; however, downwind is a recurring research and development theme.

- ~~Reduction in capital expenditures (CapEx)~~
- Increase in ~~turbine and/or farm~~ AEP
- Advantages in floating wind applications.

Plant AEP of Land-Based Downwind



- At the plant level, literature shows promising results (Cossu 2021).
- At NREL, new results return lights and shadows:
  - Great improvements when turbines are aligned with inflow
  - AEP loss for a 4-by-4 wind farm with a uniform wind rose
  - Potential for bigger wind farms or different atmospheric boundary layers?
  - Cory Frontin will present the full story at TORQUE 2024.

Flux of stream-aligned momentum at 0- and 10-degree inflows for downwind wind farm with 20-degree tilt
Illustrations by C. Frontin, NREL

Downwind for Floating?

Downwind floating may yield benefits:

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

Photo from x1wind

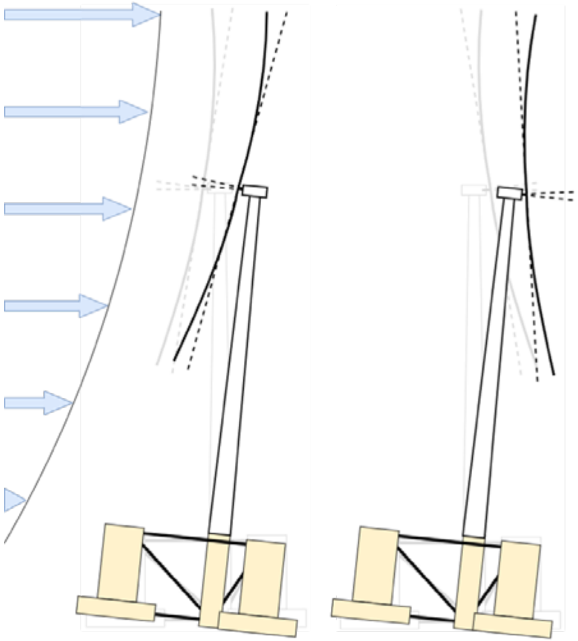
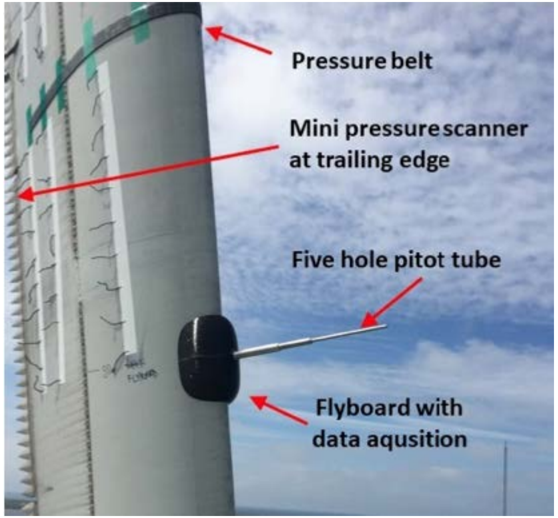


Illustration by M. Chetan, NREL

Feasibility of Downwind Rotors

We are turning the rotor of our GE1.5 downwind to characterize loads and aeroacoustic emissions.

Simultaneously, we will deploy three pressure belts to characterize blade (2) and tower (1) aerodynamic properties.



Technical University of Denmark (DTU) belts deployed on Siemens Gamesa wind turbine in Denmark. Photo from Madsen et al., 2022

GE1.5 wind turbine located at NREL's Flatirons Campus. Photo by Jeroen van Dam, NREL

Timeline Downwind Experiment

Now
- Six new pitch bumpers installed
- Controller accepted 180- to 270-deg pitch range

February
- Turbine offline
- Swap generator phases and flip wind vane

March
- Obtain final approvals
- Start testing

April
- Deploy DTU pressure belts
- Deploy aeroacoustic array

Summer
- Complete testing
- Disseminate findings

GE1.5 wind turbine located at NREL Flatirons Campus. Photo from NREL

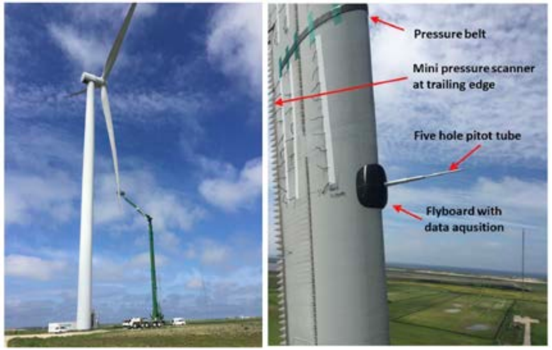
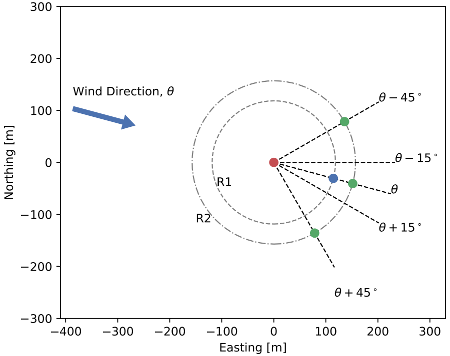


Photo from Madsen et al., 2022



Locations of acoustic measurements

Research Foci Beyond BAR

How to make impactful research at U.S. National Labs

Beyond BAR
Future Rotor Research at the Labs

- Aero-servo-hydro-elasticity
- Probabilistic design
- Manufacturing advancements
- Rotor sentience.

NREL technical report to be published

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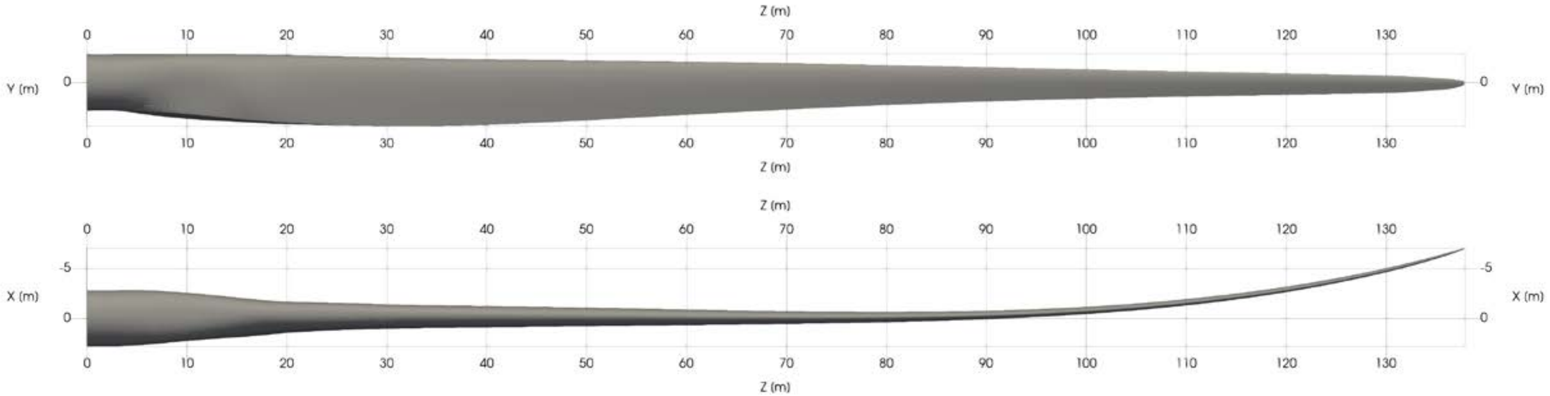
A First Teaser: New IEA 22-MW Reference Wind Turbine

IEA Wind Task 55 REFWIND just released v1.0 of the new 22-MW reference wind turbine.

Design is available at https://github.com/IEAWindTask37/IEA-22-280-RWT.

Technical report will appear online in the coming weeks.

NREL, DTU, and DNV will host a webinar about the design.



Illustrations from Frederik Zahle, DTU

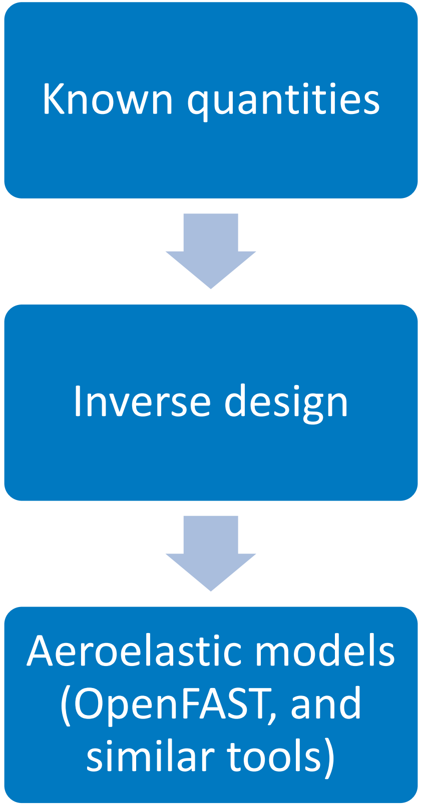
A Second Teaser: Inverse Rotor Design

There is a growing need to generate accurate aeroelastic models for generic wind turbine rotors from

- Wind turbines already installed
- Installations of known wind turbines
- Future installations of turbines that do not yet exist

NREL's design optimization tools can be reversed to target quantities such as:

- Rated power, rotor diameter, hub height
- Rotor and tower natural frequencies
- Loads and performance metrics



Key Takeaways and References

To wrap up

Conclusions

- NREL and the U.S. Department of Energy Wind Energy Technologies Office are supporting the next generation of wind turbine rotors
- Multiple active fronts
  - Improvement of predictive aeroelastic tools, especially when it comes to stability; the next generation of land-based (and offshore!) rotors requires improvements to the multidisciplinary design, analysis, and optimization tools
  - Experimental and numerical research into downwind rotors
- Portfolio of publications discussing
  - Controlled flexing during rail transport (promising, it might work!)
  - Distributed aerocontrol devices (very challenging value proposition)
  - Open-source family of tools freely available to use.

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Q&A

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Photo from iStock-627281636

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A Teaser: New IEA 22 Reference Wind Turbine

Quantity	Value
Rated Elec. Power [MW]	22.0
Rated Mech. Power [MW]	23.266
Specific power [W m^{-2}]	351.410
Wind Class	1B
Rotor orientation	Upwind
Number of blades	3
Control	Variable speed, collective pitch
Cut-in wind speed [m/s]	3.0
Rated wind speed [m/s]	11.0
Cut-out wind speed [m/s]	25.0
Design tip-speed ratio	9.153
Min. rotor speed [rpm]	1.807
Max. rotor speed [rpm]	7.061
Max. blade tip speed [m/s]	105.0
Rotor diameter [m]	284.0
Blade length [m]	137.8
Blade prebend [m]	7.0
Blade mass [t]	82.301
Airfoil series	FFA-W3
Blade root diameter [m]	5.8
Rotor precone angle [deg.]	4.0
Shaft tilt angle [deg.]	6.0
Hub height [m]	170.0
Drive train	Direct drive
Nacelle assembly mass [t]	821.2
Tower mass [t]	1,574
Monopile mass [t]	2,097

Table 1: Overview of the main properties of the IEA 22MW Reference Wind Turbine.