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

Pietro Bortolotti
Senior Researcher and Project Lead
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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
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
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!
Distributed Aero Controls

See the references for more details
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).
Aeroelastic Stability and RAAW Project

Ongoing activities
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.”
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.

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).

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.
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.

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.
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.
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 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
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.
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

Locations of acoustic measurements

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

Photo from Madsen et al., 2022

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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
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
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

A Second Teaser: Inverse Rotor Design

Known quantities -> Inverse design -> Aeroelastic models (OpenFAST, and similar tools)
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.


Q&A

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Photo from iStock-627281636
A Teaser: New IEA 22 Reference Wind Turbine

<table>
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<tr>
<th>Quantity</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rated Elec. Power [MW]</td>
<td>22.0</td>
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<tr>
<td>Rated Mech. Power [MW]</td>
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<td>Specific power [W m⁻²]</td>
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<td>Wind Class</td>
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<td>Rotor orientation</td>
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<td>Number of blades</td>
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<tr>
<td>Control</td>
<td>Variable speed, collective pitch</td>
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<tr>
<td>Cut-in wind speed [m/s]</td>
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<td>Rated wind speed [m/s]</td>
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<td>Cut-out wind speed [m/s]</td>
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<td>Max. blade tip speed [m/s]</td>
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<td>Rotor diameter [m]</td>
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<td>Blade length [m]</td>
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<td>Tower mass [t]</td>
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<td>Monopile mass [t]</td>
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Table 1: Overview of the main properties of the IEA 22MW Reference Wind Turbine.