U.S. DEPARTMENT OF ENERGY

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The Big Adaptive Rotor (BAR) Project

Novel Technologies for the Next Generation of Land-Based Wind Turbine Rotors

Pietro Bortolotti, PI @ NREL
Josh Paquette, PI @ SNL
Sandia Blade Workshop 2022
Albuquerque, NM, October 18-19, 2022

Agenda

1. Intro & Background
    1. What is BAR?
    2. Summary of BAR Phase I
2. Task 1 of BAR Phase II – Advanced TEA
3. Task 2 of BAR Phase II – Modeling Gaps and Validation
4. Task 3 of BAR Phase II – Experiments
    - Downwind Experiment
    - Overview of RAAW Project & Instability Experiment
    - Structural Experiments
5. Q&A

BAR Mission & Timeline

Identify and develop novel technologies that can enable large (>100 m) blades for low-specific-power wind turbines

2018 DNVGL leads workshop and report on supersized blades

May 2018 BAR Phase I kicks off with SNL, NREL, and LBNL

August 2018 Expert workshop to identify innovative technologies (report)

November 2018 First BAR EAB in person at CU Boulder

2019 - 2021 18 peer-reviewed publications

Summer 2021 Phase I wraps up and Phase II starts

September 2022 Year 1 of Phase II completed. Moving into year 2

The BAR Teams in Phase II

NREL — NATIONAL RENEWABLE ENERGY LABORATORY

- Pietro Bortolotti — PI
- Mayank Chetan — Aeroelasticity
- Emmanuel Branlard — Aeroelasticity
- Scott Hughes — Materials & Testing
- Derek Berry — Manufacturing
- Jason Roadman — Aeroacoustics
- Andy Platt — Aeroelasticity
- Jason Jonkman — Aeroelasticity
- Paul Veers — Science Challenges

Sandia National Laboratories

- Josh Paquette — PI
- Evan Anderson — DAC & NuMAD
- Ernesto Camarena — NuMAD
- Ryan Clarke — Structures & Materials
- Evan Sproul — TEA
- Ken Brown — Aeroacoustics

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- Ben Hallissy — Technology manager
- Ben Murray — Project manager
- Mike Derby — Program manager
- Mike Robinson — A2e Program manager

EAB

- Anurag Gupta — DIS - CREADIS
- Carlo Bottasso — TUM
- David King — Gulf Wind Technology
- Frederik Zahle — DTU Wind Energy
- Kristian Dixon — Envision Energy
- Kyle Wetzel — Wetzel Wind
- Joyee Zhu — LM / GE
- Scott Johnson — SGRE
- Stephen Nolet — TPI

Summary of BAR Phase I

2018 – 2021

Tasks 1, 2, 3, and 5 of BAR Phase I

Task 1 – Assessed the trends, impacts, and value of low-specific-power wind turbines

- Opportunities for and Challenges to Further Reductions in the "Specific Power" Rating of Wind Turbines Installed in the United States (link)
- The Hidden Value of Large-Rotor, Tall-Tower Wind turbines in the United States (link)

Task 2 – Developed a wind turbine blade cost-reduction road map study

- A Detailed Wind Turbine Blade Cost Model (link)
- Investigation of Innovative Rotor Concepts for the Big Adaptive Rotor Project (link)

Task 3 – Completed research-and-development opportunity screening

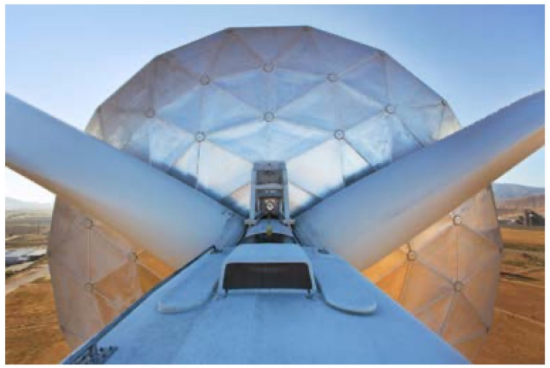
- Supersized Wind Turbine Blade Study: R&D Pathways for Supersized Wind Turbine Blades (link)

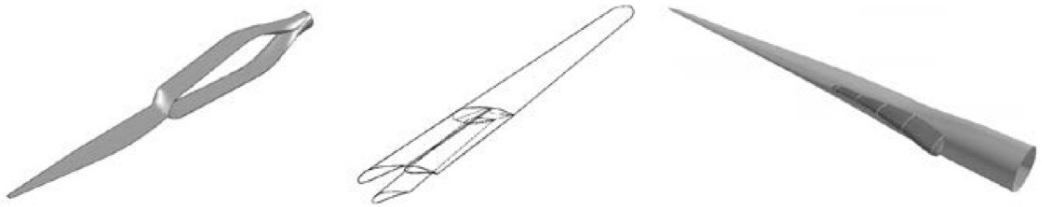
Task 5 – Assessed low-cost carbon fiber

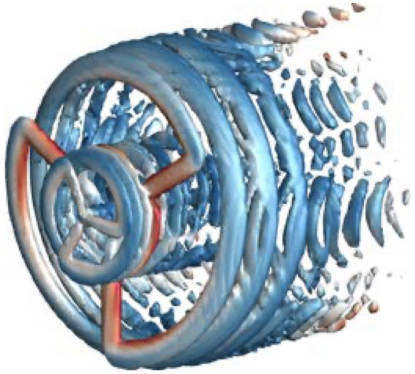
- Optimized Carbon Fiber Composites in Wind Turbine Blade Design (link)

What we Left Behind

Why? Investigation of Innovative Rotor Concepts for the Big Adaptive Rotor Project (link)







a)

b)

What we Brought Ahead

Task 4 – Detailed Design Studies

Aerodynamics and aeroacoustics

- Aeroacoustics Noise Model of OpenFAST (link)
- OLAF User's Guide and Theory Manual (link)
- Investigation of the Nacelle Blockage Effect for a Downwind Turbine (link)

Aeroelasticity of flexible blades

- A Cross-Sectional Aeroelastic Analysis and Structural Optimization Tool for Slender Composite Structures (link)
- Investigation of Flutter for Large, Highly Flexible Wind Turbine Blades (link)

Rail transport logistics

- Innovative Rail Transport of a Supersized Land-Based Wind Turbine Blade (link)
- Land-Based Wind Turbines with Flexible Rail Transportable Blades – Part I: Conceptual Design and Aeroservoelastic Performance (link) Part 2: 3D finite element design optimization of the rotor blades (link)

Distributed aerodynamic controls

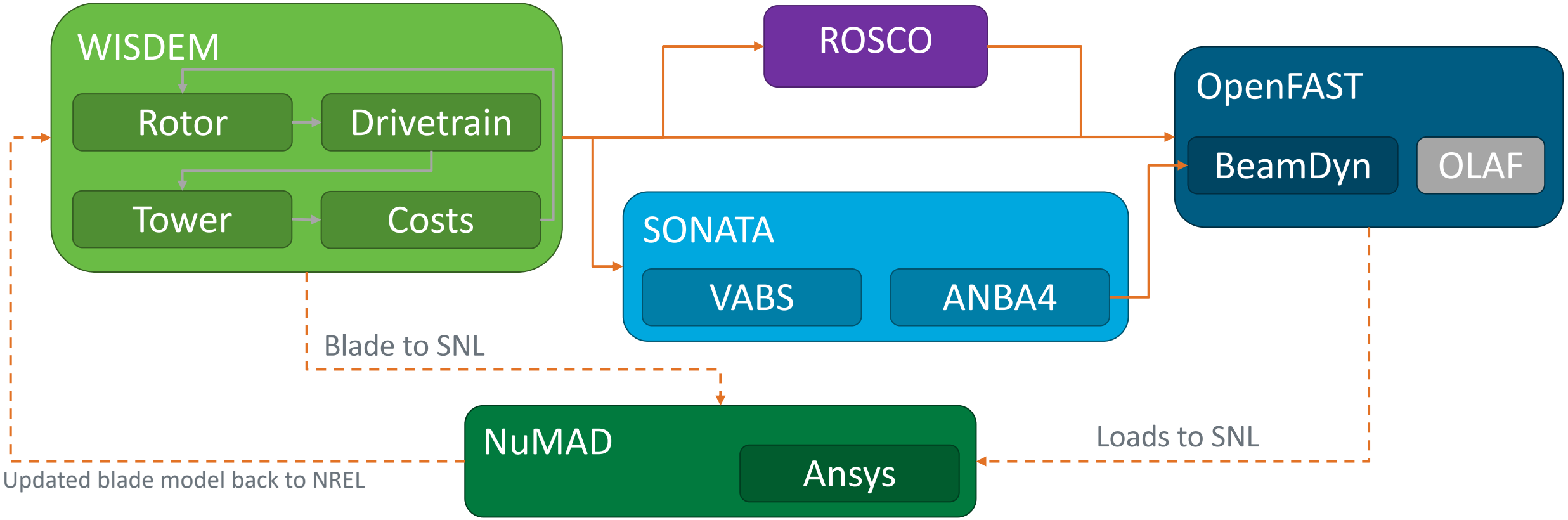
- Distributed Aerodynamic Control using Active Trailing-Edge Flaps for Large Wind Turbines (link)

Innovative concepts

- Conceptual Designs of the Structure of Inflatable Blades for Enabling Larger Turbines (link)

The Design Process used in BAR Phase I

Sequential design process at increasing fidelity, using open-source tools



Key Conclusions of BAR Phase I

Techno-economic analyses

1. The **rotor diameters** of land-based wind turbines will keep **growing** to lower specific power and increase capacity factors
2. Highly **flexible** blades help **reducing LCOE** but present technical challenges in the areas of **aeroservoelasticity** and **materials**
3. Downwind offers a promising pathway to lower costs, but suffers loss in AEP, and **similar LCOE**
4. Blade logistics constraints are alleviated by **segmentation** but also **controlled-flexing** during rail transport
5. Low-cost **carbon** fiber is a promising material for spar caps
6. Newer technologies (**DACs**, **inflatable**) offer promising pathways but also require extra efforts

Modeling & validation

1. Highly-flexible rotors suffer from **modeling gaps** across disciplines and fidelity levels
2. Strong need for experimental datasets to run **model validation**

BAR Phase I Final Report (link)

BAR Phase II

2021 - 2024

Three Tasks in Phase II

1. **Techno-Economic Analysis** – Continue the investigation into the value of upwind and downwind flexible rotors
2. **Modeling Gaps & Validation** – Improve the understanding of the dynamics and structures of large and flexible rotors at low-mid fidelity, strengthen links to high fidelity modeling
3. **Field Experiments** – Four experiments relevant to land-based wind technology
    - Downwind
    - Instability
    - Coupons, subcomponents, and scaled blade structures
    - Support to RAAW experiment

Task 1 – Technoeconomic Analysis of Flex Rotors

Phase I suggests that there is value in **highly flexible rotors**:

- These can fly upwind at high values of cone and tilt, or downwind
- Downwind offers a pathway to reduce costs, but suffers loss in AEP
- An experiment to address the historical skepticism behind downwind is planned in Task 3

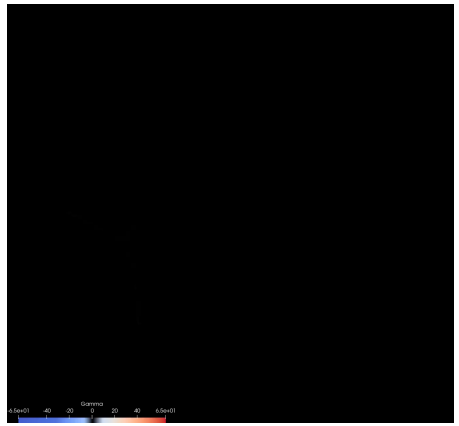
First, we tried answering the following questions:

- What do aerodynamic models at higher fidelity predict?
- What if we had advanced control strategies that could minimize the blade deflections toward the tower?
- What happens at the farm level?

Effect of Higher Fidelity Models on AEP

- BAR URC, USC, DRC blades were modelled in OpenFAST, and simulated from cut-in to cut-out wind speed
- Inflow was limited to steady inflow with shear
- Comparison of USC and DRC to URC:
  - USC is a stiffer blade and generates higher AEP
  - Downwind does not show significant advantage over upwind configuration in BEM nor OLAF

- BD doesn't change conclusions
- Need to rethink ED/BD coupling



AEP (GWh)			
	USC	URC	DRC
AD15-ED	24.57	24.55	24.39
OLAF-ED	24.41	24.37	24.24
AD15-BD	24.17	23.59	23.60
OLAF-BD	24.07	23.44	23.55

Comparison to URC (%)		
	USC	DRC
AD15-ED	0.047%	-0.654%
OLAF-ED	0.184%	-0.517%
AD15-BD	2.449%	0.033%
OLAF-BD	2.671%	0.434%

Comparison to AD15-ED (%)			
	USC	URC	DRC
OLAF-ED	-0.637%	-0.772%	-0.636%
AD15-BD	-1.611%	-3.918%	-3.253%
OLAF-BD	-2.015%	-4.520%	-3.474%

Acronyms:
- URC – Upwind rail-transportable with CFRP
- USC – Upwind segmented blade with CFRP
- DRC – Downwind rail-transportable with CFRP
- BEM –Blade element momentum
- OLAF - Free vortex wake model
- ED – ElastoDyn, modal-based beam model using two flapwise and one edgewise mode
- BD – BeamDyn, geometrically exact beam theory

Effect of Advanced Control Strategies on Downwind

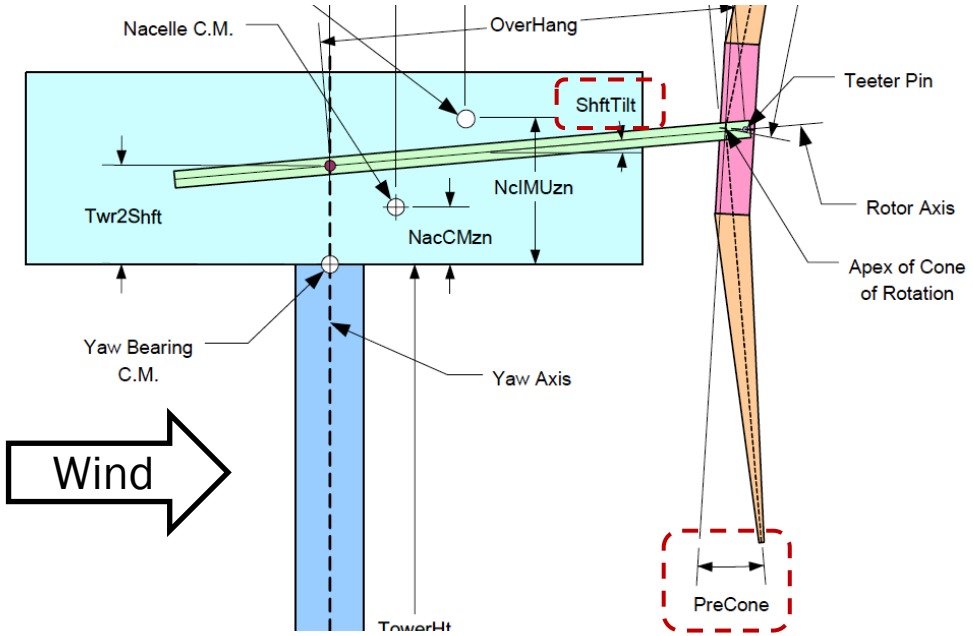
- The downwind rotor was simulated with lower precone and shaft tilt angles to emulate availability of advanced control strategies

- On the turbine level:
  - Tilt has modest effect
  - Coning towards the tower increases AEP by 1%
  - This has the potential to close the AEP gap compared to upwind flexible (URC)

- What happens at the farm level?

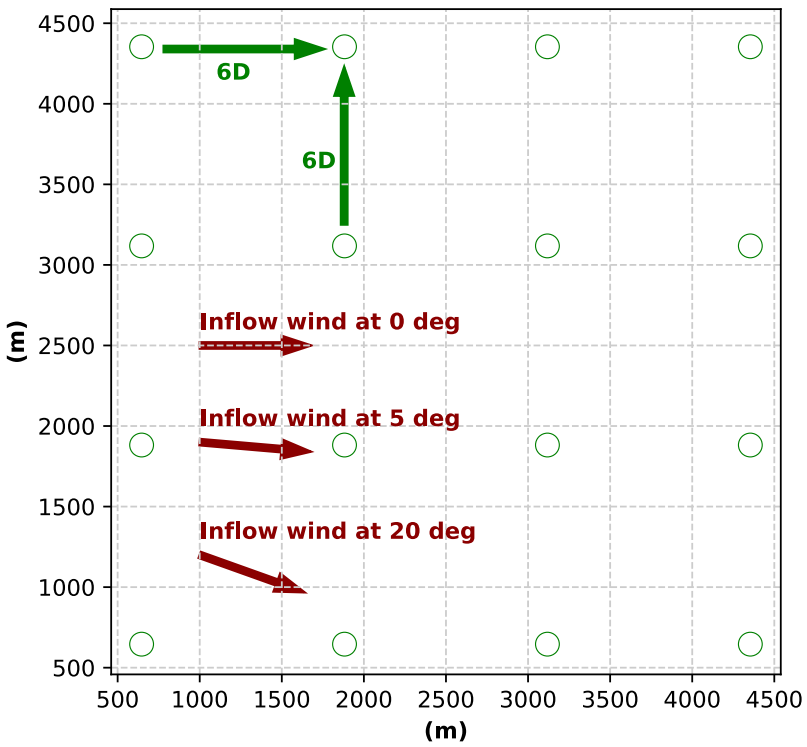
AEP (GWh)		Precone Angle (deg)		
		-2	0	2
Shaft tilt angle (deg)	2		24.56	24.40
	5	24.64	24.54	24.39

Comparison to Baseline (%)		Precone Angle (deg)		
		-2	0	2
Shaft tilt angle (deg)	2		0.688%	0.024%
	5	1.018%	0.603%	Baseline

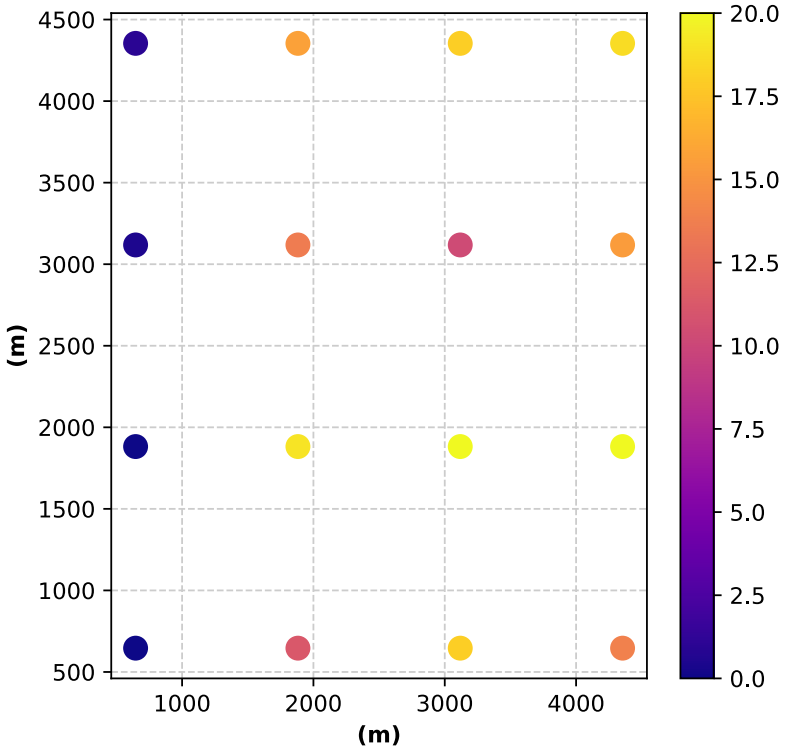


Simulations in AMR-Wind

Wind farm layout for tilt study.

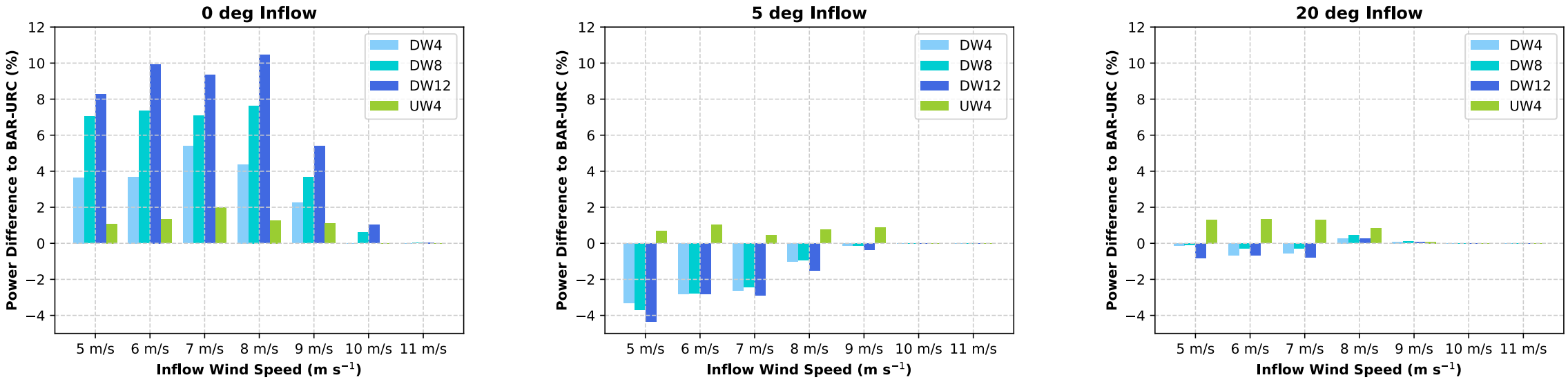


Percent change in turbine power for the downwind case with 12 degrees tilt for an inflow speed of 8 m s^{-1} and an inflow direction of 0 deg relative to the upwind case with 8 deg tilt.



[1] C. Bay et al., Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation, 2019

Strong Gains when Turbines Operate in Waked Conditions



Turbine rated wind speed: 8 m/s

More numerical simulations will be running soon to

1. Expand the numerical domain
2. **Quantify AEP**

Weibull-weighted power gains

Inflow Angle	0 deg	5 deg	20 deg
4 deg downwind	1.54	-0.77	0.38
8 deg downwind	2.66	-0.75	0.02
12 deg downwind	3.67	-0.94	-0.14
4 deg upwind	0.50	0.38	0.44

Task 2: Modeling Gaps & Validation

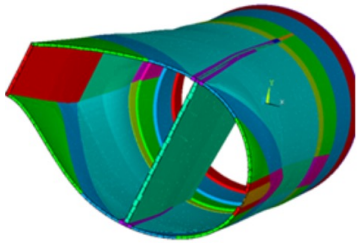
Develop tools that will support the next generation of wind turbines

Work toward addressing the second grand challenge of wind energy science*: Aerodynamics and structural dynamics of enlarged wind turbines

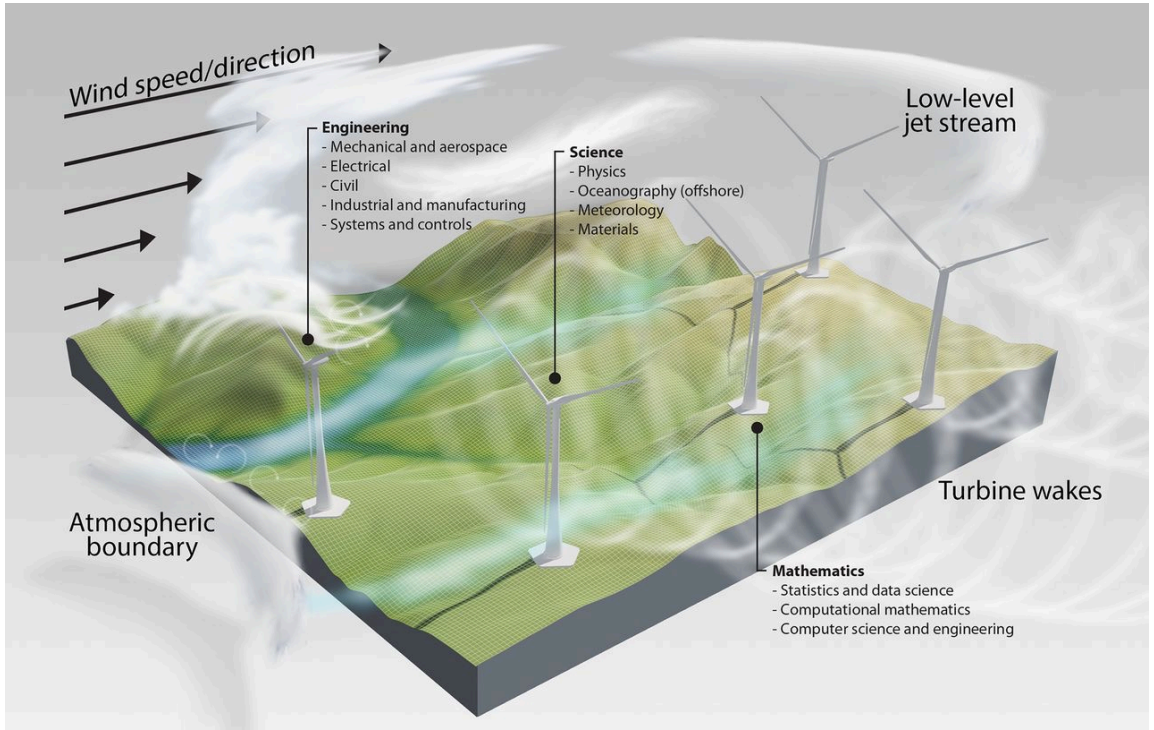
Sub-tasks modeling

- Improve BEM and vortex tools in OpenFAST
- Speed-up BeamDyn within glue code
- Define LCOE+ scenarios and LCOE+ optimum wind turbine designs
- Improvements to NuMAD (brick elements, in-house mesh code, python based, maintenance of GitHub page ...)

Sub-tasks validation



- Validation from RAAW
  - OpenFAST
  - OLAF
- Beam and cross-sectional analysis from structural experiment
  - NuMAD
  - BeamDyn and ANBA4

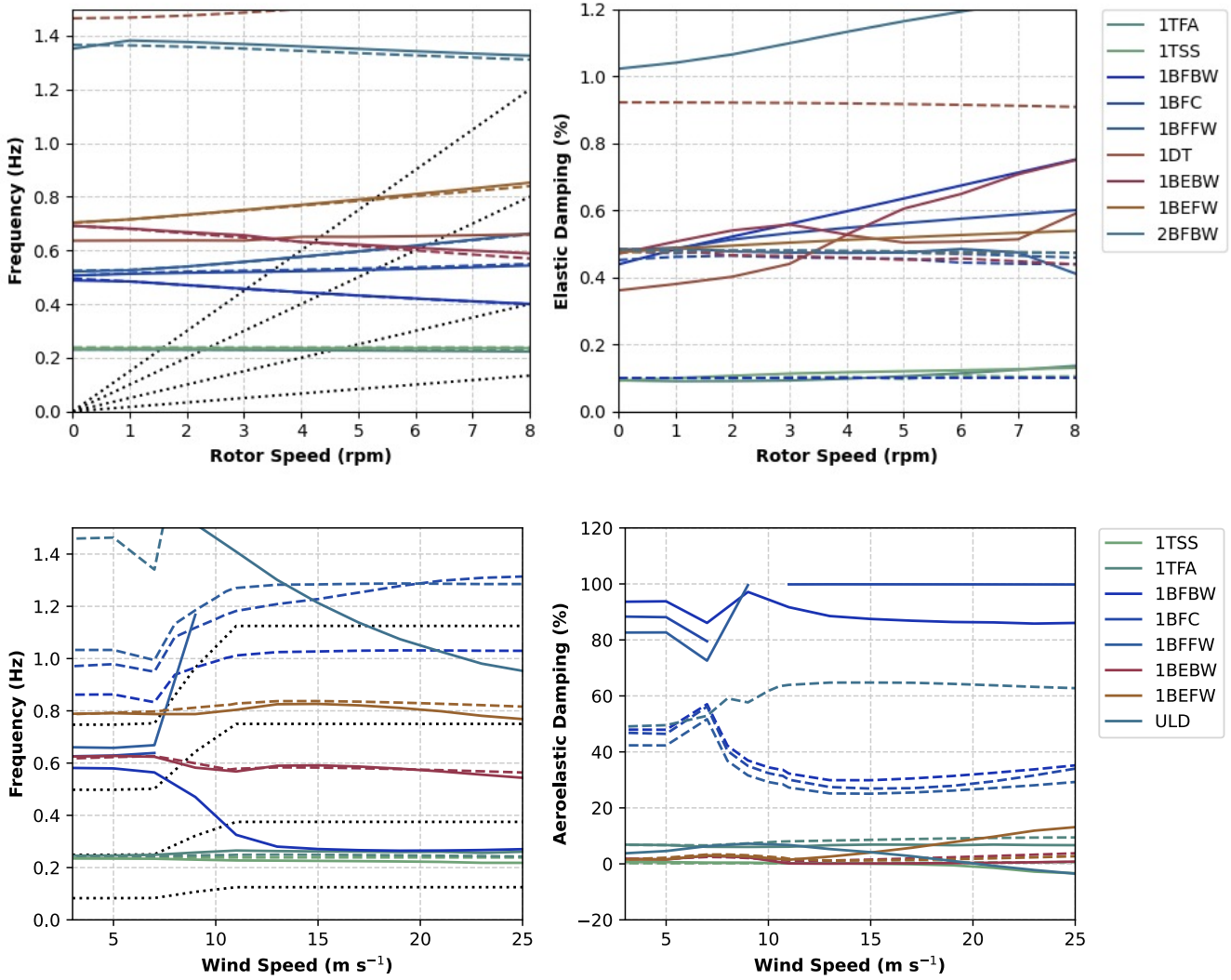


Veers et al., 2019, DOI: 10.1126/science.aau2027

Numerical Aeroelastic Stability Analysis in OpenFAST

Verification of OpenFAST vs HAWCStab2

- NM80 with and without aerodynamics using the results from IEA Wind Task 29
- IEA15 blade only, turbine no aerodynamics, and full turbine (land-based configuration)
- It took time, but elastic response now matches well in frequency and ok in damping
- Large discrepancies in flap response when aero is on

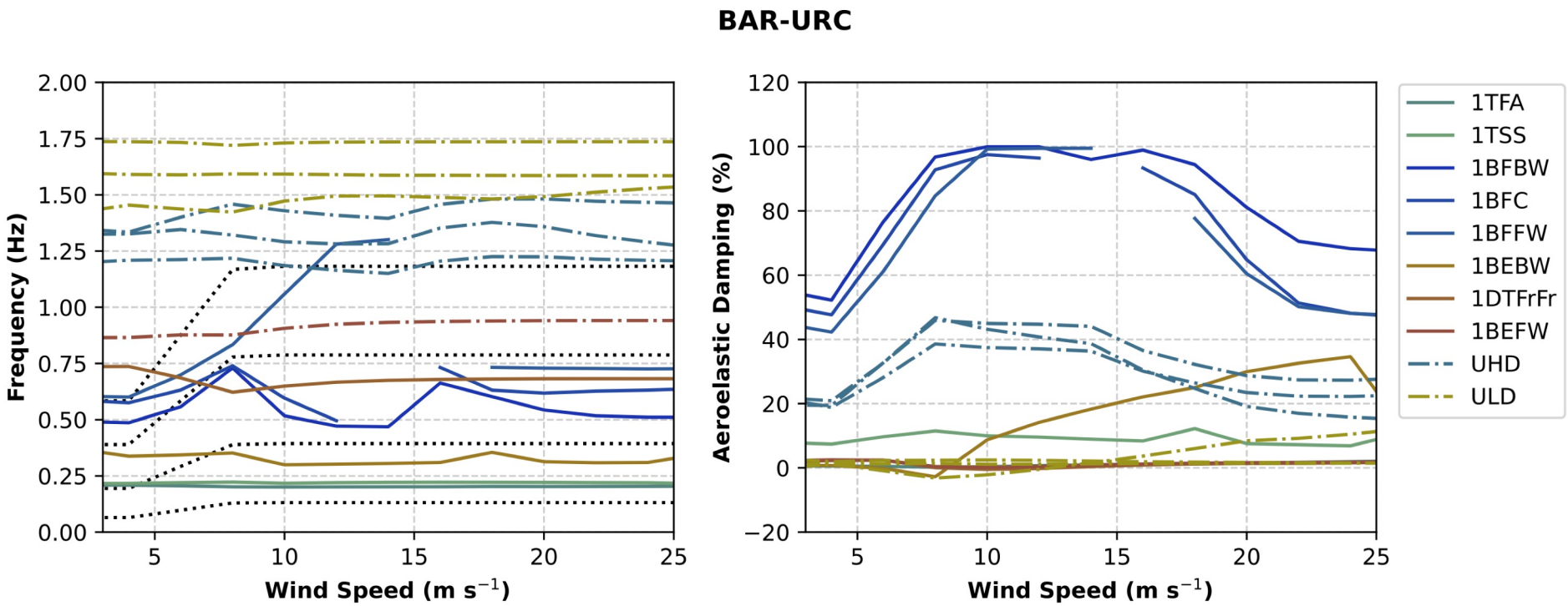


BAR Results

OpenFAST v3.2 is used to predict instabilities of the highly-flexible **BAR** rotors, showing dangerous negatively-damped modes around rated wind speed at 8 m s^{-1}

Next steps

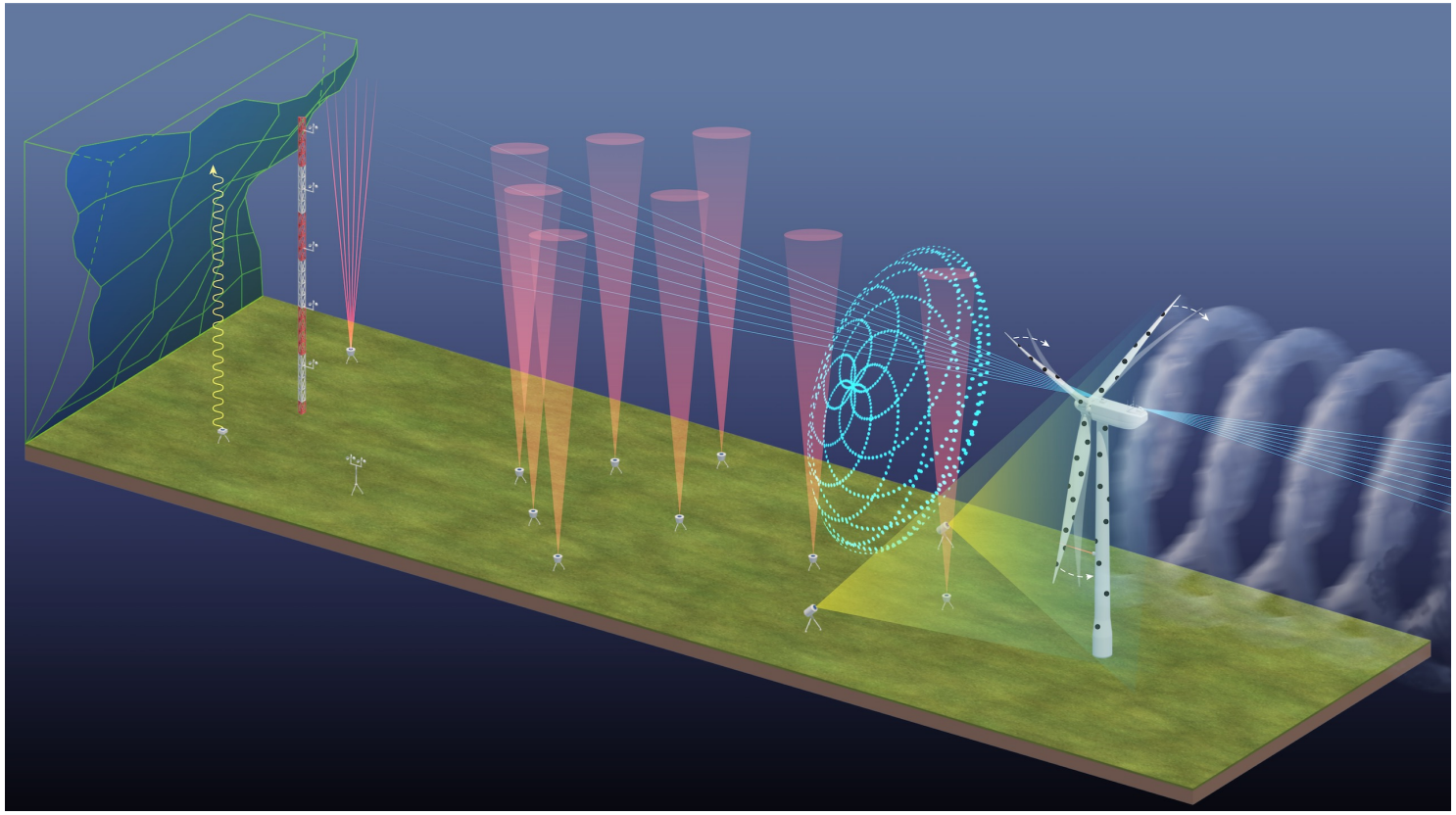
1. Compare different strategies to correct design
2. Characterize instabilities in time domain



RAAW

Rotor Aerodynamic, Aeroelastic, and Wakes experiment

- GE Renewables, NREL, and SANDIA
- Experimental campaign on GE prototype
- Full access to aeroelastic model
- No access to the controller, but we've tuned **ROSCO** and a **rotor position** control
- Innovative measurements
  - SCADA
  - Met mast & surface flux station
  - Scanning, spinning, and profiling lidars
  - DIC and strain gauges on blades
  - Pressure belts on the blades
  - Laser measurements for blade/tower clearance
  - Thermodynamic profiler (temperature and humidity)
- Experimental campaign ongoing until July 2023
- Deployment of DTU pressure belts scheduled in February 2023

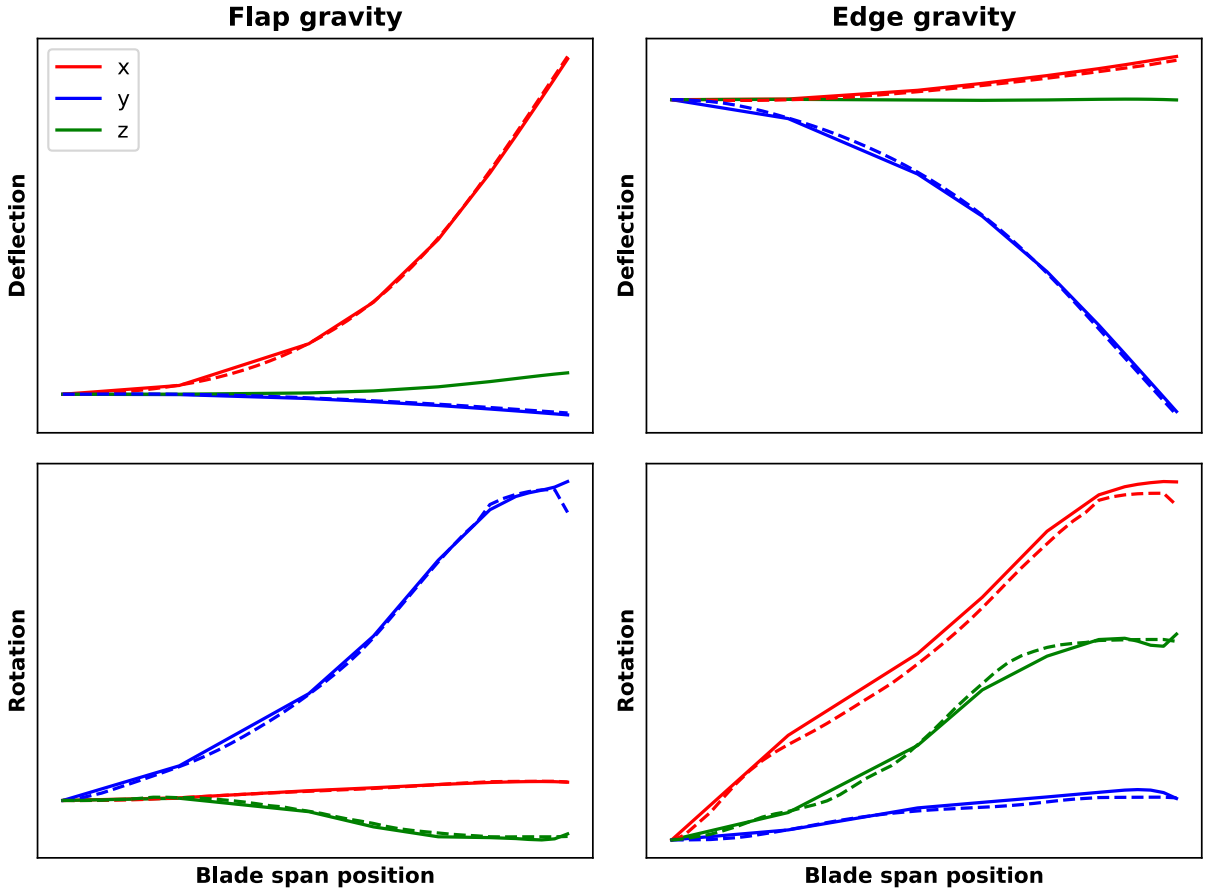


RAAW Results

A code-to-code verification is also ongoing between OpenFAST and Simpack using a **2.8MW wind turbine** from GE Renewable Energy from the DOE-funded project RAAW

On the right, the comparison of deflections and rotations for the blade clamped at blade root and subjected to gravity (solid OF, dashed Simpack)

In steady-state, models match well



RAAW Results

The results of the **modal analysis** of the **blade clamped at blade root** are compared against lab results and Simpack predictions

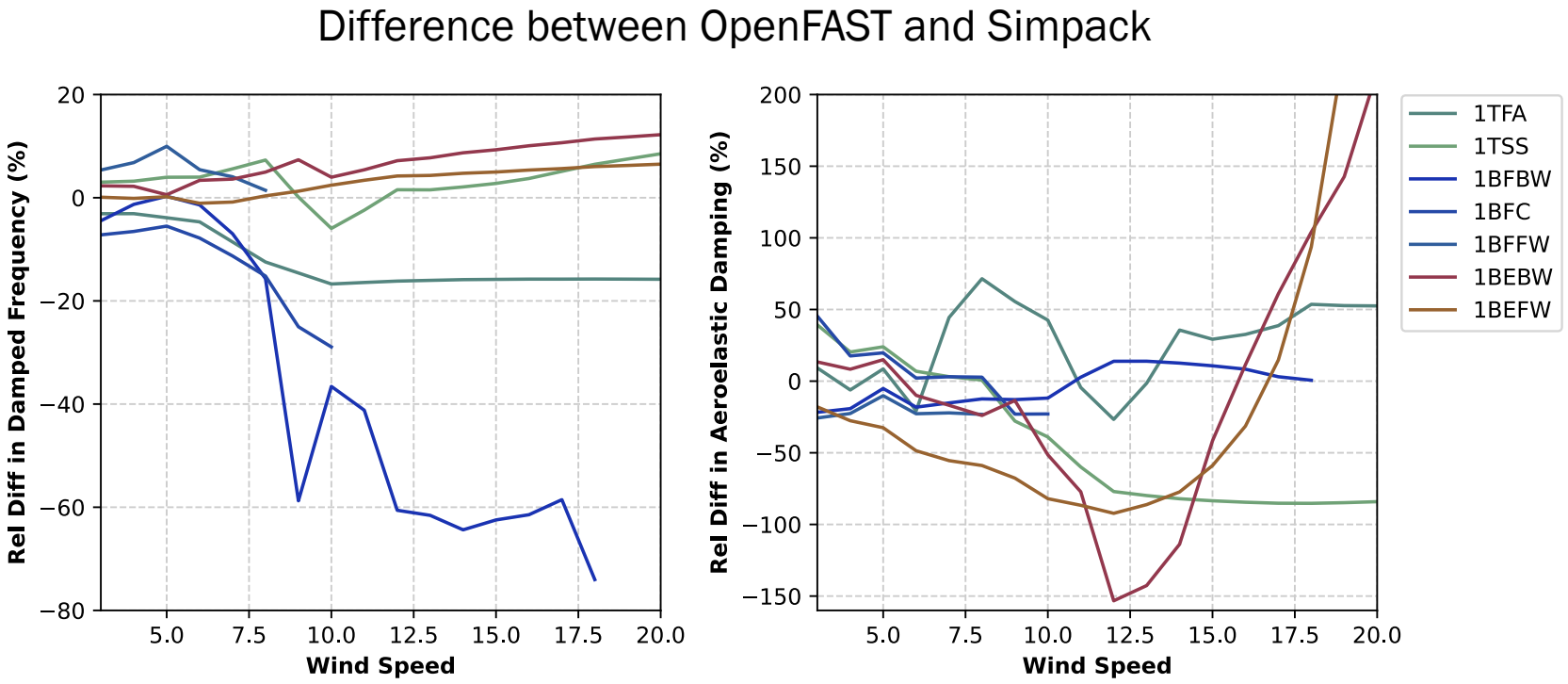
Good comparison for the first modes except for first flap, growing deltas above 2nd modes

Significant deltas also on damping values

	Nat. Frequency		Damping Ratio	
Relative difference w.r.t. BeamDyn	Lab	Simpack	Lab	Simpack
1st flap	-5.1%	0.0%	-5.9%	-5.3%
1st edge	-1.1%	-0.1%	1.3%	16.2%
2nd flap	0.1%	0.5%	416.4%	0.3%
2nd edge	-1.2%	3.0%	192.7%	29.0%
3rd flap		2.3%		2.7%
4th flap		2.3%		-57.1%
3rd edge		11.3%		341.6%
5th flap		12.7%		-7.9%
1st torsion		-0.6%		-69.1%

RAAW Results

When the **whole system** is modeled and aerodynamic effects are included, the **discrepancies** between OpenFAST, Simpack, and measurements **grow**



Task 3: Downwind Experiment

Scope: address the historical skepticism affecting downwind

- Fatigue damage
- Aeroacoustics emissions
- AEP

Work in progress:

- FMEA in preparation of the experiment
  - Address all concerns (loads, controller, generator cooling system,
  - Compare loads and deflections upwind vs downwind. Blades are prebent toward the tower…
- Experiment scheduled in spring of 2023
  - Yaw 180 deg, pitch 180 deg. Rotor will spin backwards w.r.t. nacelle
  - Deploy aeroacoustics array
  - Monitor loads and performance on SCADA

Task 3: Instability Experiment

What is too flexible?

Goal: Validate aeroelastic models when rotor harmonics cross system natural frequencies

Actions:

- Mode identification from field data of RAAW turbine
- Define experiment in agreement GE
- Support measurement campaign
- Post-process data and provide validation dataset (OpenFAST, AMR-Wind)
- Support improvements to numerical models (automate modal identification, streamline visualization, closed loop linearization in ROSCO, include instability into design procedures)

Task 3: Blade Structural Experiment

Goal: Reduce uncertainty, increase reliability in material and structural deformations and failure in wind blade design.

Coupon level

What: Multi-axial static failure characterization of common wind blade composite laminates

Why: Lack of available test data for wind energy composites in multi-axial stress, leading to uncertainty in failure criteria and design limits

Subcomponent level

What: Multi-axial fatigue characterization of wind blade structural subcomponents

Why: Large flexible rotors induce significant combined loading in critical load carry parts of wind blade structure such as the spar cap

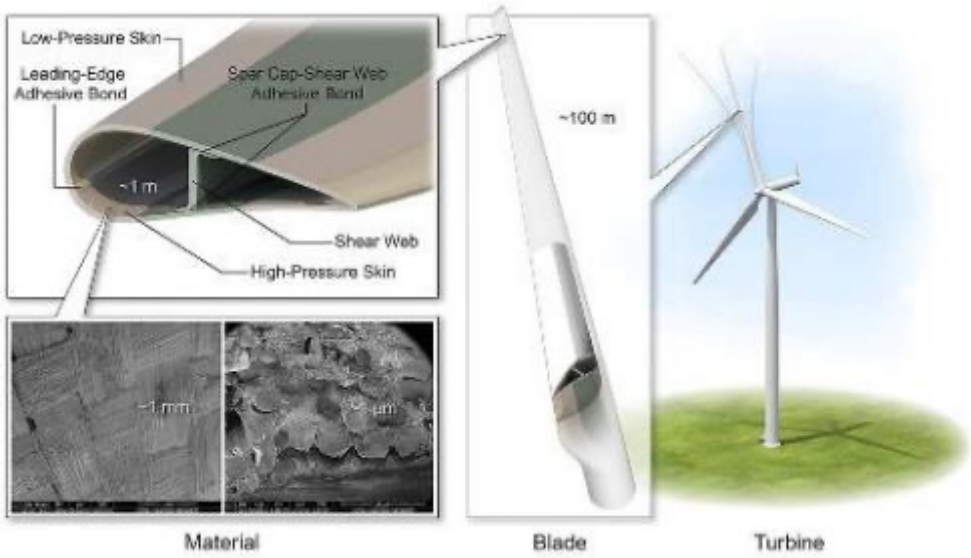
Scaled-blade level (NREL)

What: Modal and large deflection static characterization of elastically scaled very flexible wind blades

Why: Need for validation data and to quantify uncertainty of modern blade models with very large, nonlinear deflections

New task: investigate material and geometric damping, connection to projects focusing on thermoplastics and recyclable blades

Are we fully using the composite material limits?



Source: Veers et al., 2019, DOI: 10.1126/science.aau2027

Key Takeaways of BAR

- **Value in highly flexible rotors**
  - Obvious capital cost reductions
  - New room for logistics solutions
  - AEP increase opportunities at the farm level by going downwind
- **Modern wind turbines push existing numerical models to and beyond the limit**
  - Design models need to rely on high-fidelity solvers
  - Need for fast, accurate, and validated 6x6 beam models
  - NuMAD will support 3D FE models with solid elements
  - Unsteady aerodynamic models become crucial
  - OpenFAST is verified in the linearized domain against DTU flagship tool HAWCStab2. Discrepancies in aerodynamics require validation studies
- **Ongoing large-scale experiments**
  - Downwind experiment to characterize impact of tower shadow on loads and aeroacoustic emissions
  - Aeroelastic stability experiment to study nonlinear instabilities of modern flexible rotors
  - Structural experiment to characterize ultimate and fatigue failure criteria and start the investigation into high-damping materials, such as thermoplastics

Thank you!

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