Research Overview and Cognitive Approaches

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Mechanical Engineering

WESEP 594 Seminar
1/30/2014

CV: Education

- **PhD**, 2008–2012
  Structural Engineering
  University of California, San Diego
  "*Fluid–Structure Interaction Analysis of Wind Turbines*"

- **MSE**, 2006–2008
  Aerospace Engineering and Engineering Mechanics
  The University of Texas at Austin

- **BS & MS**, 1999–2003 & 2003–2005
  Engineering Science and Ocean Engineering
  National Taiwan University, Taipei, Taiwan

CV: Academic Experience

- **Assistant Professor**: August 2013 – Present
  Department of Mechanical Engineering
  Iowa State University

- **Postdoctoral Fellow**: August 2012 – July 2013
  Institute for Computational Engineering and Sciences
  The University of Texas at Austin

CV: Research Interests

- Fluid–Structure Interaction (FSI)
- Computational Mechanics
- Computational Fluid Dynamics (CFD)
- Isogeometric and Finite Element Analysis (IGA & FEM)
- High-Performance Computing
- **Wind Turbine Modeling and Simulation**
- Renewable Energy Applications
- Biomedical Applications
- Cardiovascular Mechanics

How I do research…

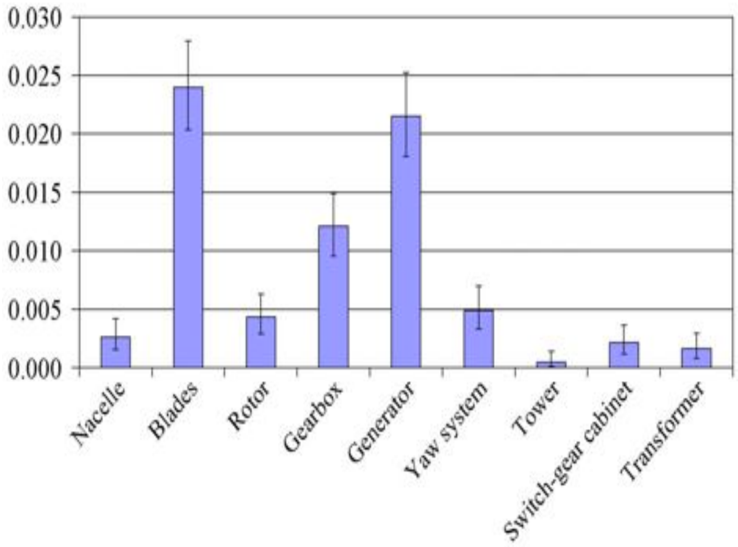
“*Computational Fluid–Structure Interaction Analysis of Wind Turbines*”

Motivations

- Countries are putting substantial effort behind the development of wind energy technologies
  - Alternative energy source
  - Clean and sustainable
  - The least expensive renewable energy source
- US Government established an objective of 25% electricity from wind by 2025
  - Requires 1200% increase in capacity
  - Leading-edge wind energy R&D is necessary to achieve this goal
    - Improve manufacturing efficiency
    - Address blade failure issues
    - Challenges remain great

Motivations: Issues

- The present costs for wind energy are dominated by **Operations** and **Maintenance**
- A typical wind turbine may have **2.6** component failures per year during the first 10 years of operation[1]
- The industry is currently unable to predict these failure mechanisms – **unscheduled downtime** and **reduced capacity**
- Offshore wind turbines are receiving increased attention
  - Stronger and more sustained wind
  - Exposed to harsh environments
  - Rotor blades of much larger diameter (> 120 m)



[1] *E. Echavarria et al., J Sol Energy Eng, 130 (2008) 031005-1–8*

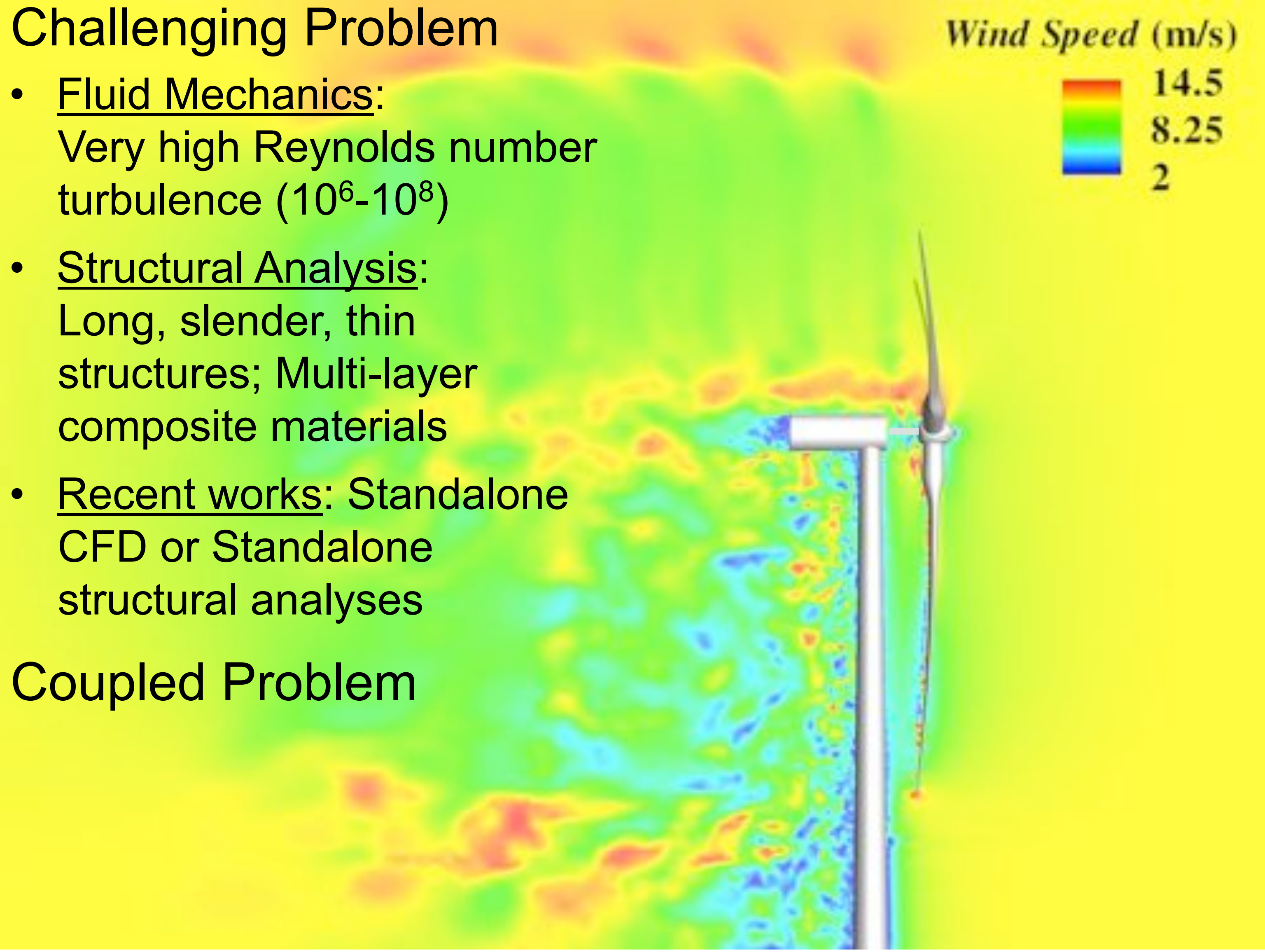
Advanced Simulation for Wind Turbines

- These are significant engineering challenges that must be addressed through advanced research and development.
- Advanced simulation are used in
  - Automobile crash analysis
  - Design of commercial and military aircraft
  - Ship building
  - Assessment and design of medical devices
- However, advanced simulation tools for wind turbines are notably lacking

Advanced Simulation for Wind Turbines

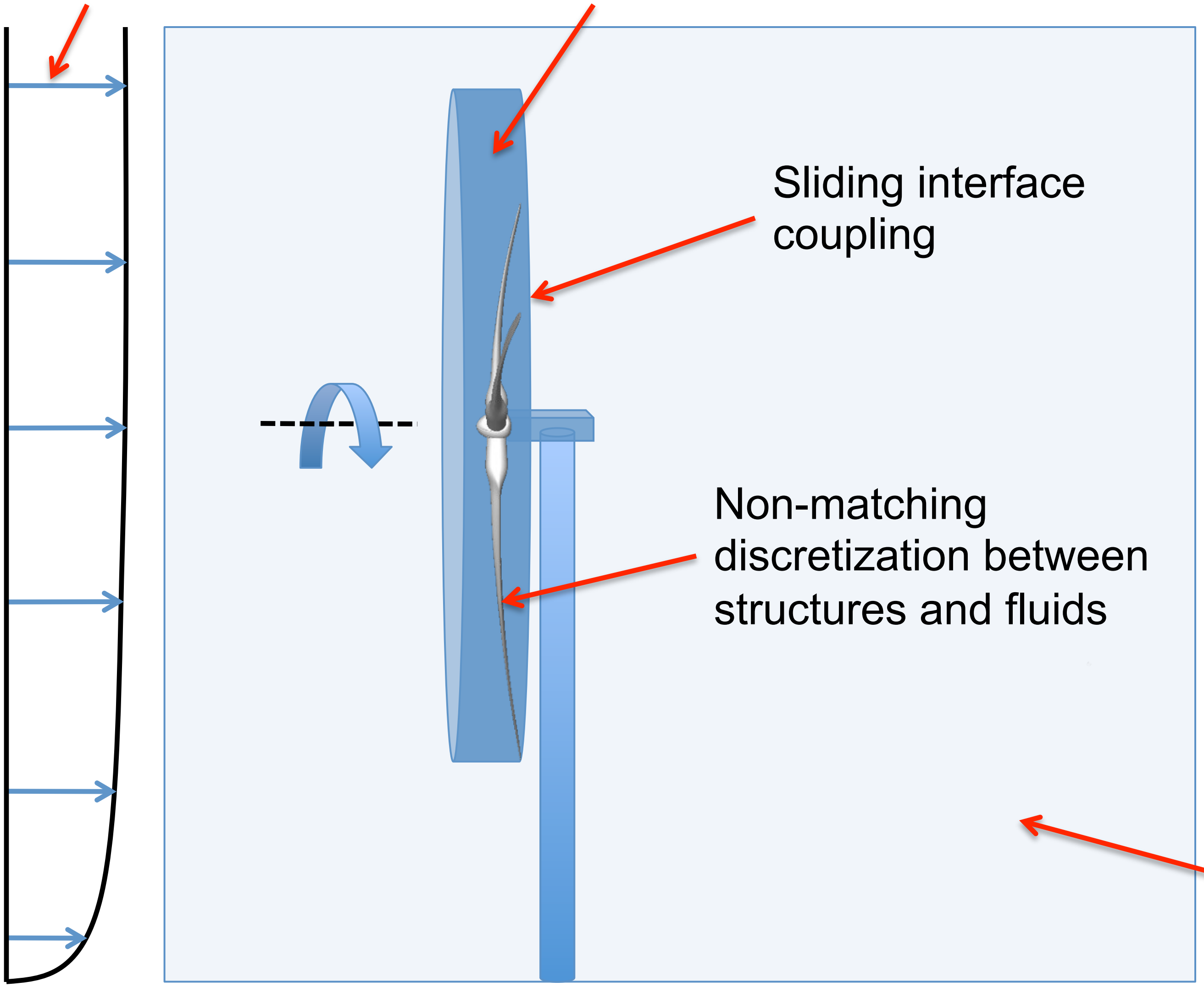
- The current practice in wind turbine simulation
  - Steady (time independent)
  - 2D lumped-parameter aerodynamic models for airfoil cross-sections
  - 1D beam-type structures
  - Evaluate wind turbine blade designs and aerodynamic performance
- Unable to represent 3D time-dependent and complex mechanical phenomena
  - Flow separation and reattachment
  - Detailed blade deformations and stress distributions

FSI Simulation of Full Wind Turbine



- Challenging Problem
  - Fluid Mechanics: Very high Reynolds number turbulence (10^6-10^8)
  - Structural Analysis: Long, slender, thin structures; Multi-layer composite materials
  - Recent works: Standalone CFD or Standalone structural analyses
- Coupled Problem

Full Wind Turbine Simulation



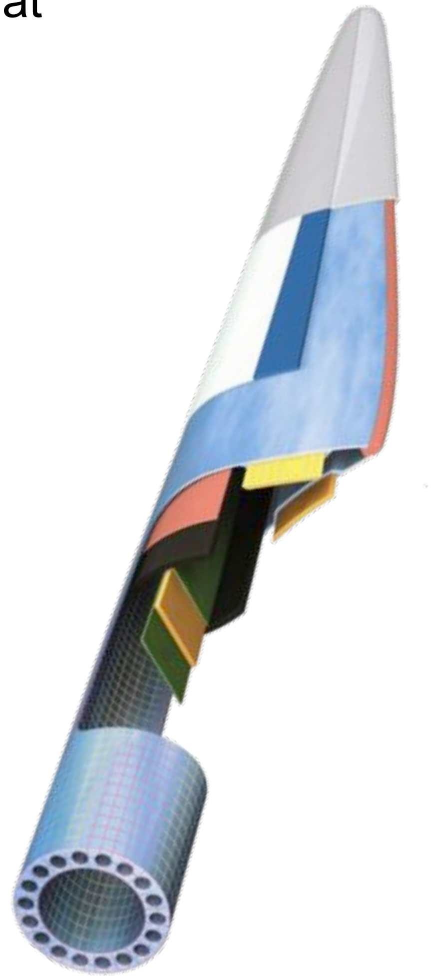
Boundary layer inflow (offshore, inland, etc.)

Rotating/deforming subdomain that encloses the wind turbine rotor

Sliding interface coupling

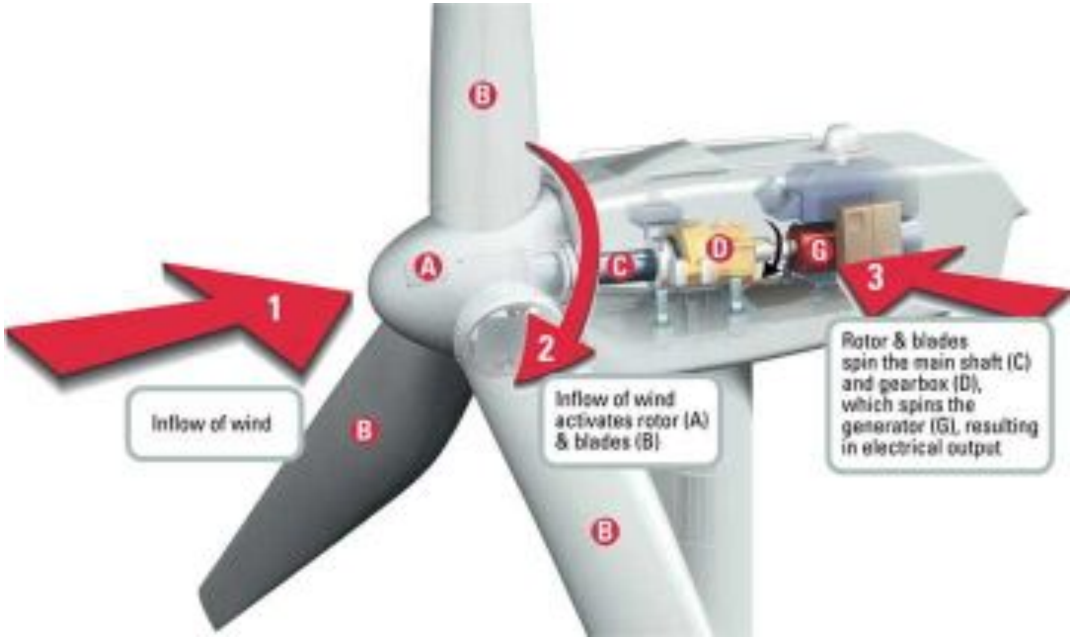
Non-matching discretization between structures and fluids

Stationary exterior flow domain



How Does Wind Turbines Work?

How does a wind turbine work?



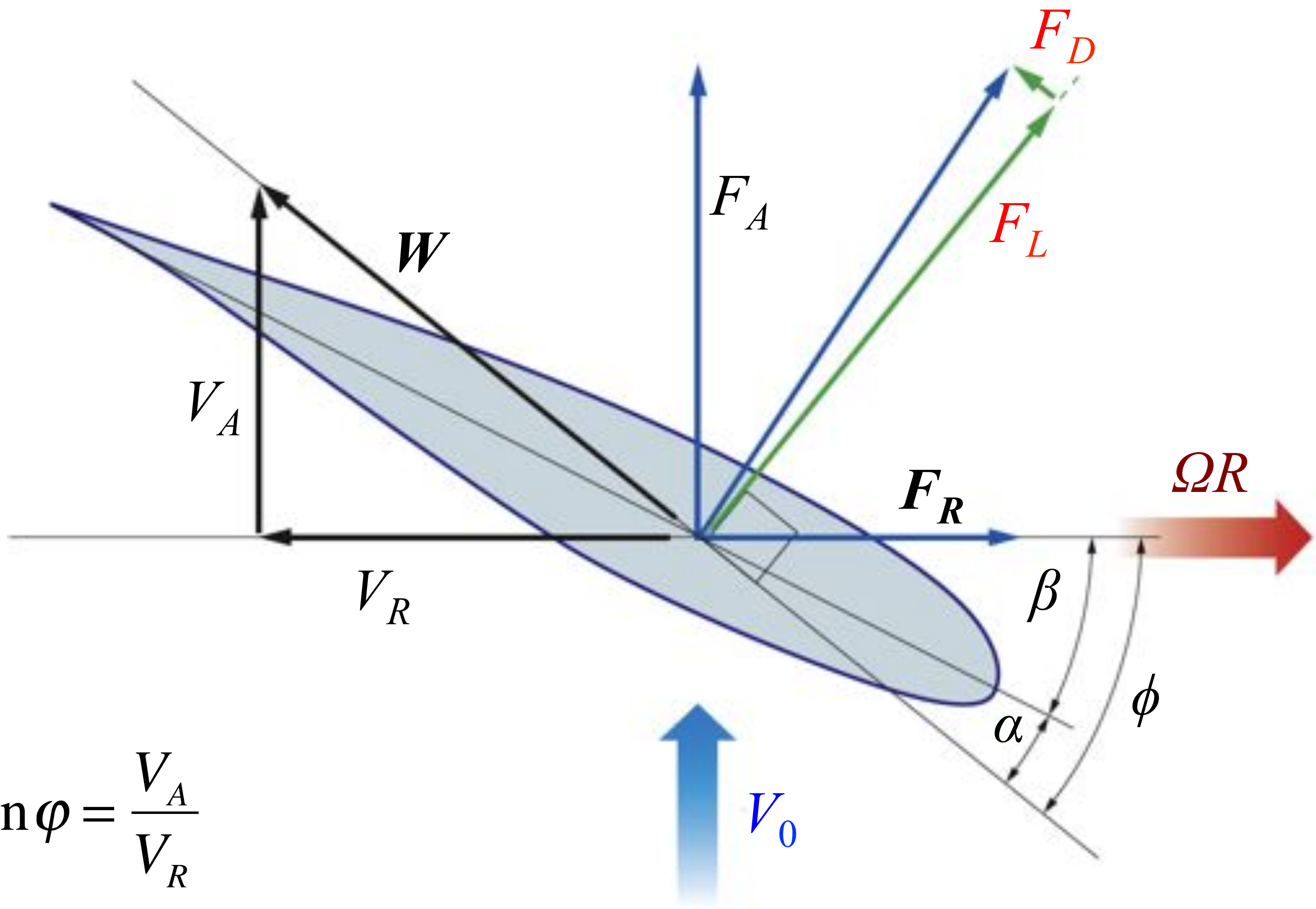
Inflow of wind

Inflow of wind activates rotor (A) & blades (B)

Rotor & blades spin the main shaft (C) and gearbox (D), which spins the generator (G), resulting in electrical output

Three-blade **H**orizontal-**A**xis **W**ind **T**urbine (HAWT)

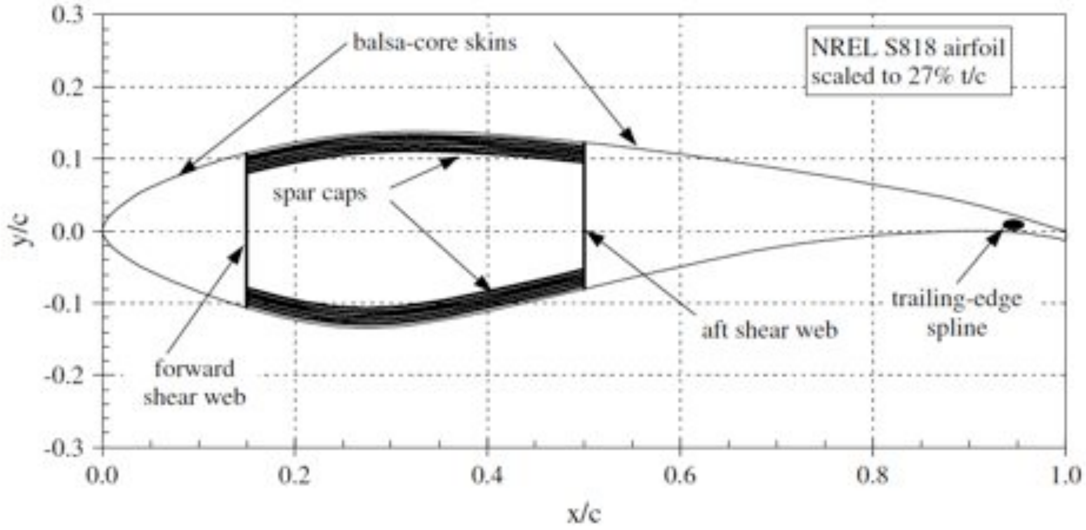
Wind Turbines: Aerodynamics



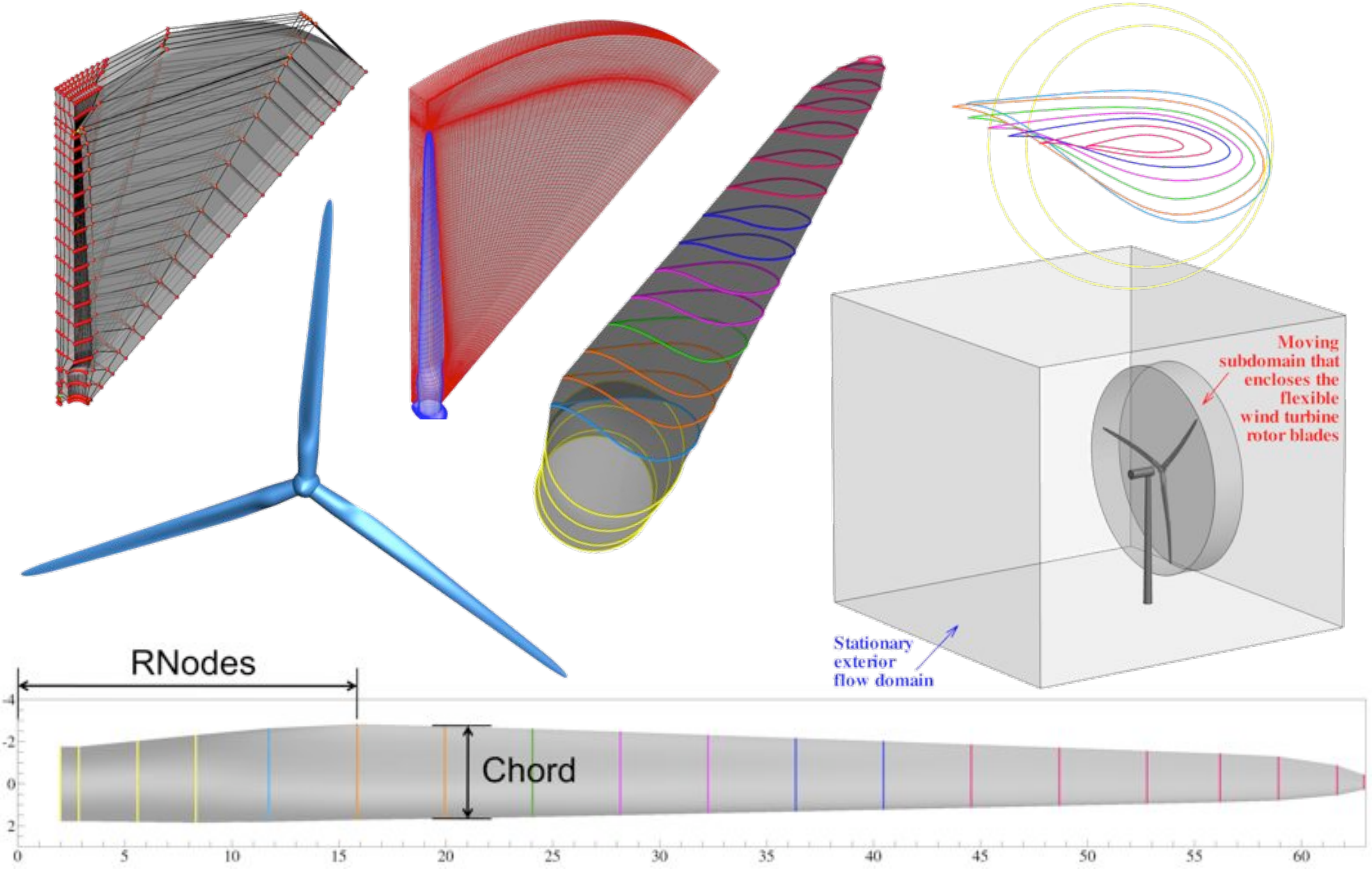
$$\tan\varphi = \frac{V_A}{V_R}$$

Wind Turbines: Blade Structure

- Spar caps and webs:
  - Thick laminate with unidirectional fibers
  - Carry the flapwise bending loads
- Blade skins or shells:
  - Double-bias or triaxial fiberglass
  - With balsa or foam core



NREL 5 MW Offshore Wind Turbine



Aerodynamics Modeling: ALE–VMS

Find $\mathbf{u}^h \in \mathcal{S}_u^h$ and $p^h \in \mathcal{S}_p^h$, such that $\forall \mathbf{w}^h \in \mathcal{V}_u^h$ and $q^h \in \mathcal{V}_p^h$:

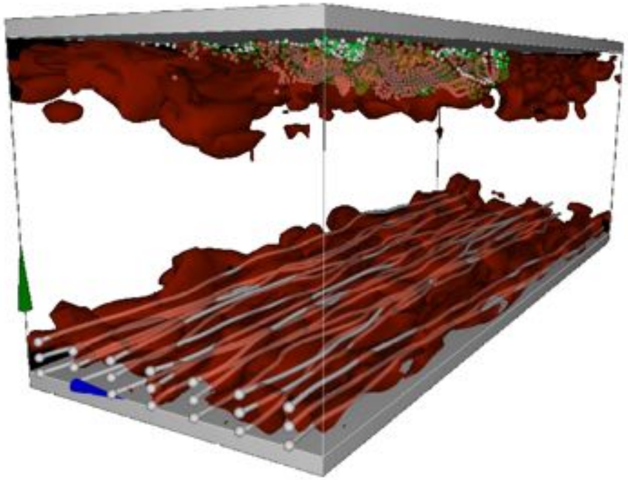
$$\text{Galerkin}\left\{\begin{aligned} &\int_{\Omega_t} \mathbf{w}^h \cdot \rho\left(\left.\frac{\partial \mathbf{u}^h}{\partial t}\right|_{\hat{x}} + \left(\mathbf{u}^h - \hat{\mathbf{u}}^h\right)\cdot\nabla\mathbf{u}^h - \mathbf{f}^h\right)\mathrm{d}\Omega + \int_{\Omega_t} \boldsymbol{\varepsilon}\left(\mathbf{w}^h\right):\boldsymbol{\sigma}\left(\mathbf{u}^h, p^h\right)\mathrm{d}\Omega \\ &-\int_{(\Gamma_t)_\mathrm{h}} \mathbf{w}^h \cdot \mathbf{h}^h \,\mathrm{d}\Gamma + \int_{\Omega_t} q^h \nabla\cdot\mathbf{u}^h \,\mathrm{d}\Omega \end{aligned}\right.$$

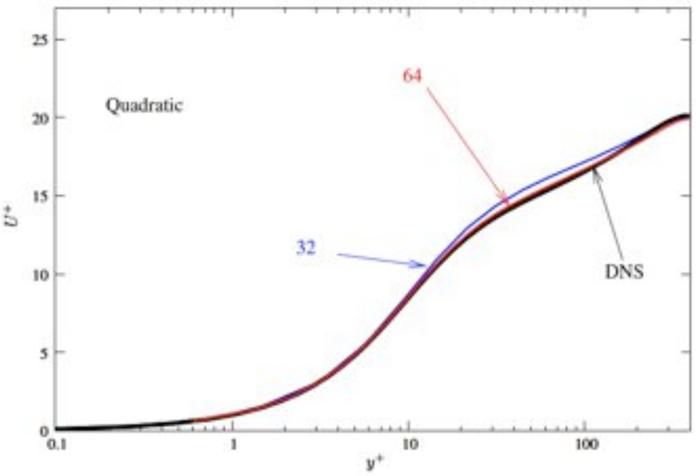
$$\text{Multiscale}\left\{\begin{aligned} &\left.\begin{aligned} &+\sum_{e=1}^{n_{el}}\int_{\Omega_t^e} \tau_{\mathrm{SUPG}}\left(\left(\mathbf{u}^h - \hat{\mathbf{u}}^h\right)\cdot\nabla\mathbf{w}^h + \frac{\nabla q^h}{\rho}\right)\cdot\mathbf{r}_{\mathrm{M}}\left(\mathbf{u}^h, p^h\right)\mathrm{d}\Omega \\ &+\sum_{e=1}^{n_{el}}\int_{\Omega_t^e} \rho\nu_{\mathrm{LSIC}}\nabla\cdot\mathbf{w}^h r_{\mathrm{C}}\left(\mathbf{u}^h\right)\mathrm{d}\Omega \end{aligned}\right\}\text{SUPG} \\ &-\sum_{e=1}^{n_{el}}\int_{\Omega_t^e} \tau_{\mathrm{SUPG}}\mathbf{w}^h \cdot \left(\mathbf{r}_{\mathrm{M}}\left(\mathbf{u}^h, p^h\right)\cdot\nabla\mathbf{u}^h\right)\mathrm{d}\Omega \\ &-\sum_{e=1}^{n_{el}}\int_{\Omega_t^e} \frac{\nabla\mathbf{w}^h}{\rho}:\left(\tau_{\mathrm{SUPG}}\mathbf{r}_{\mathrm{M}}\left(\mathbf{u}^h, p^h\right)\right)\otimes\left(\tau_{\mathrm{SUPG}}\mathbf{r}_{\mathrm{M}}\left(\mathbf{u}^h, p^h\right)\right)\mathrm{d}\Omega = 0 \end{aligned}\right.$$

\+ Weakly enforced essential boundary conditions

Verification: Turbulent Flow

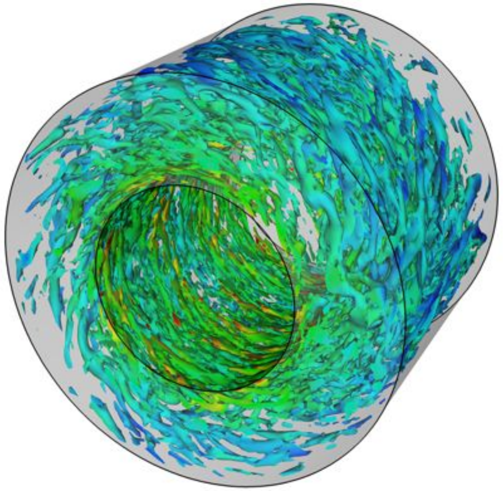
Channel Flow

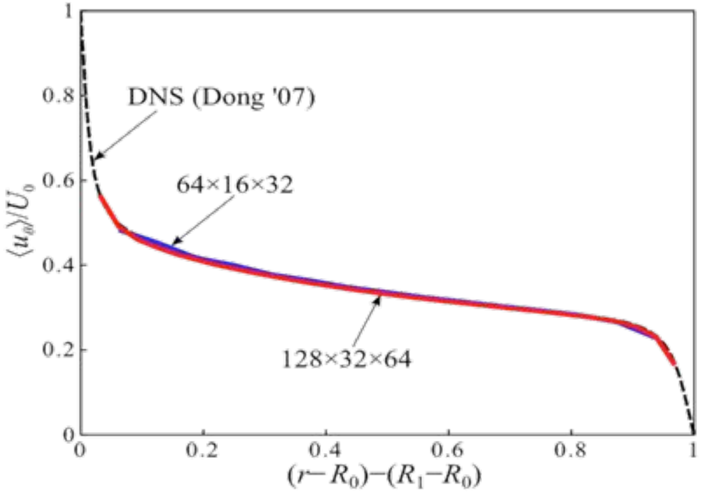




Y. Bazilevs et al. / Comput. Methods Appl. Mech. Engrg. 197 (2007) 173–201

Taylor–Couette Flow

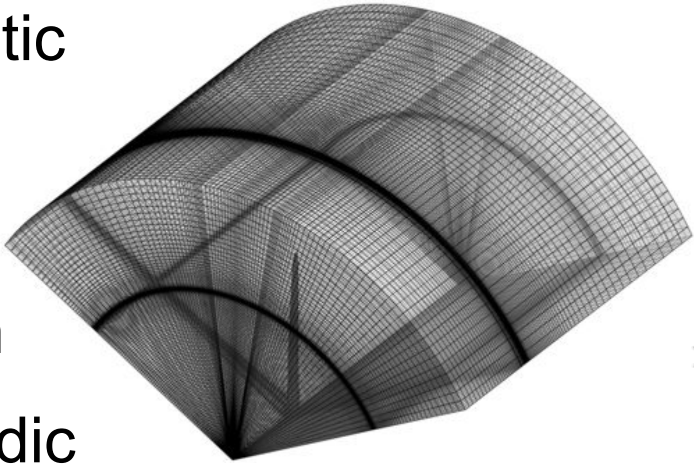


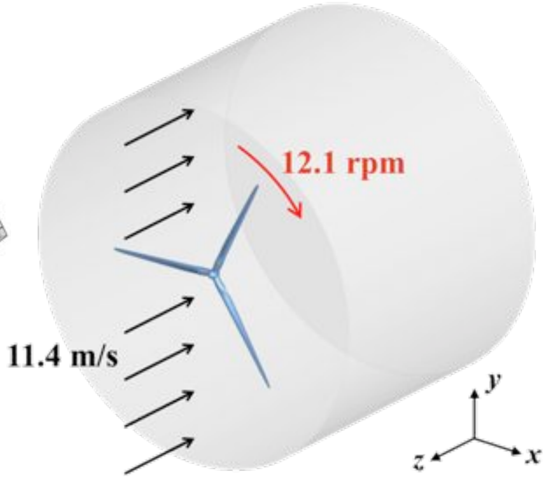


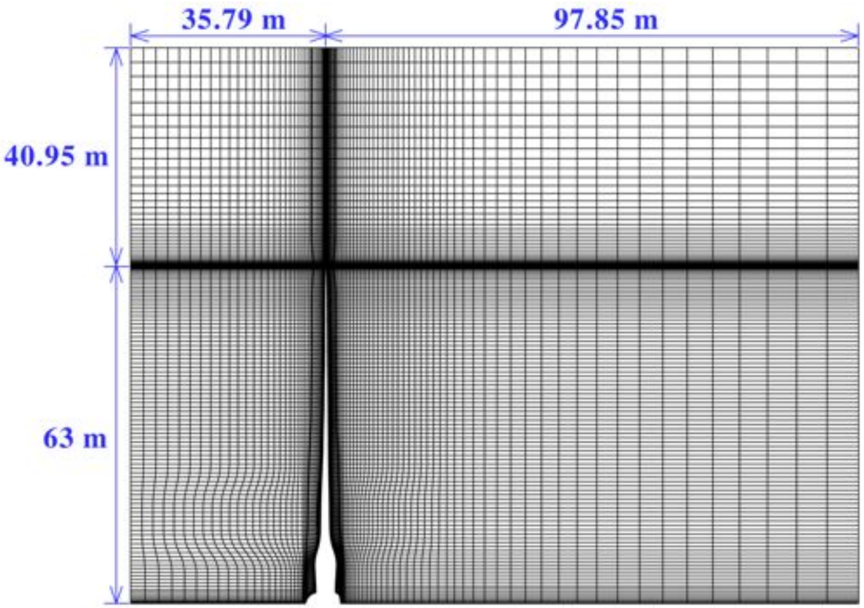
Y. Bazilevs, I. Akkerman / J. Comput. Phys. 229 (2010) 3402–3414

Computational Setup

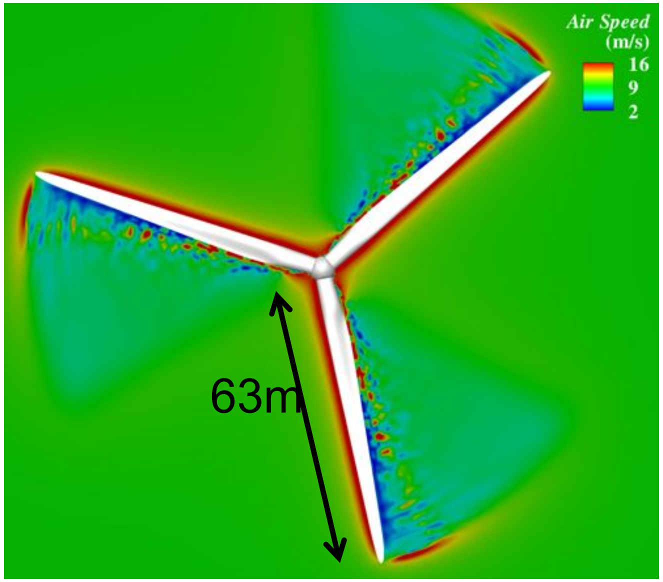
- 1,449,000 quadratic NURBS elements
- 240 processors
- Conforming mesh
- Rotationally periodic boundary condition
- Blade diameter: 126 m
- Wind speed: 9-12 m/s
- MPI for parallel processing
- In-house research software

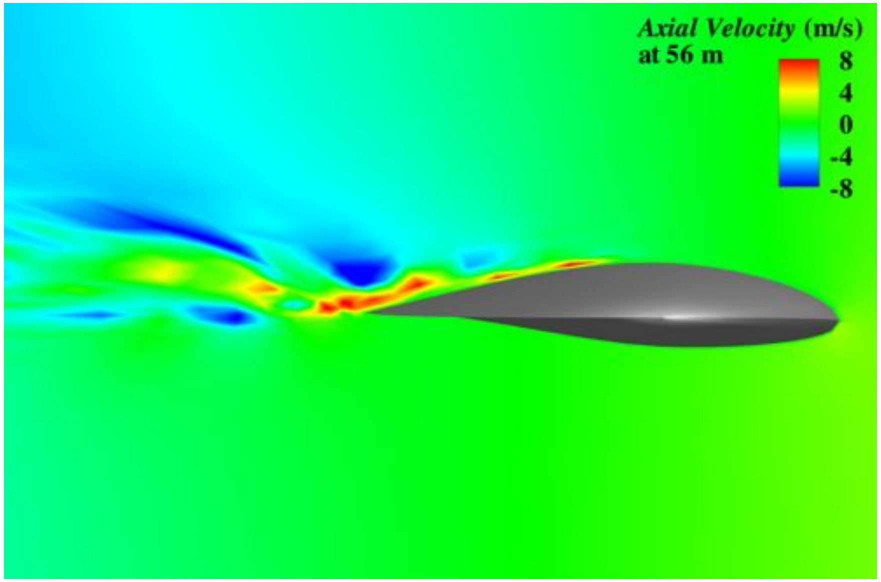


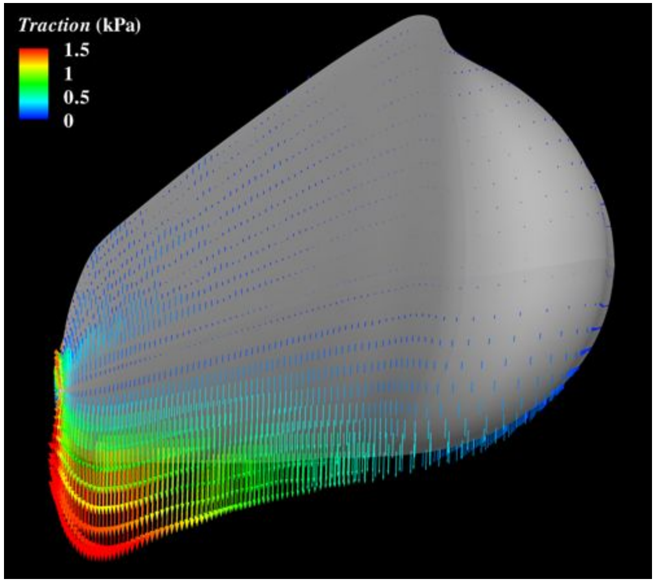


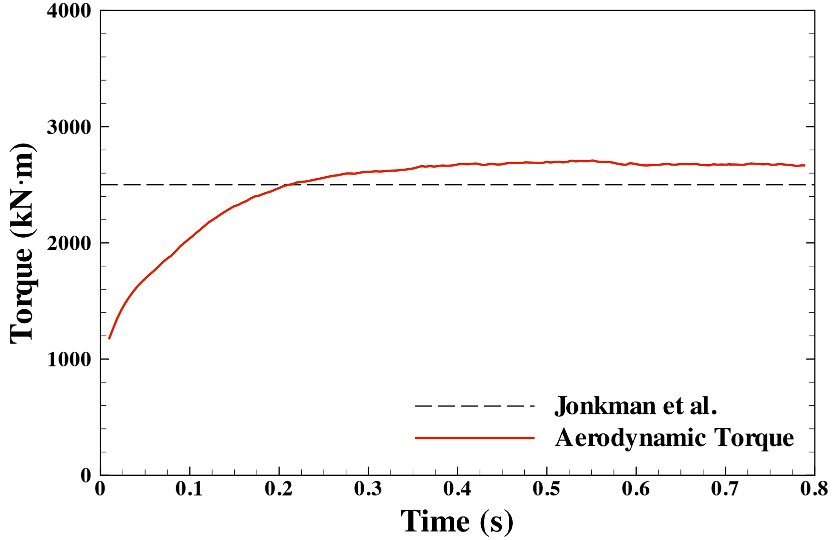


NREL 5 MW Wind Turbine Aerodynamics





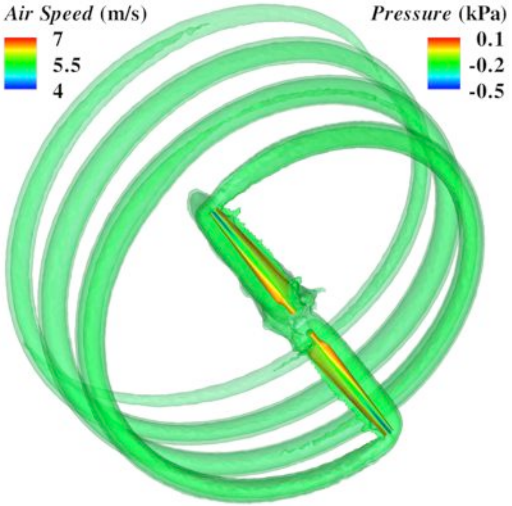


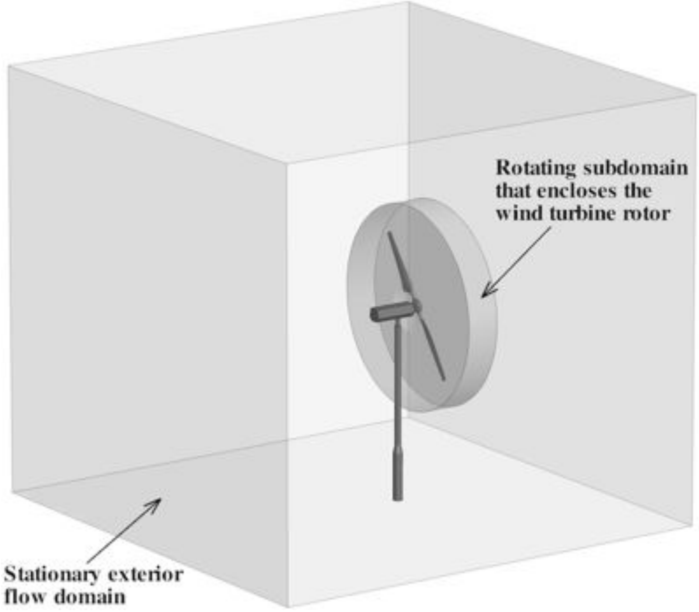


Validation: NREL Phase VI

- Rated Power: **19.8kW**
- Rotor Diameter: **10.058m**
- Cases selected:
  - Blade tip pitch angle: 3°
  - Wind speed: 5m/s ~ 25m/s
  - Rotational speed: 72rpm

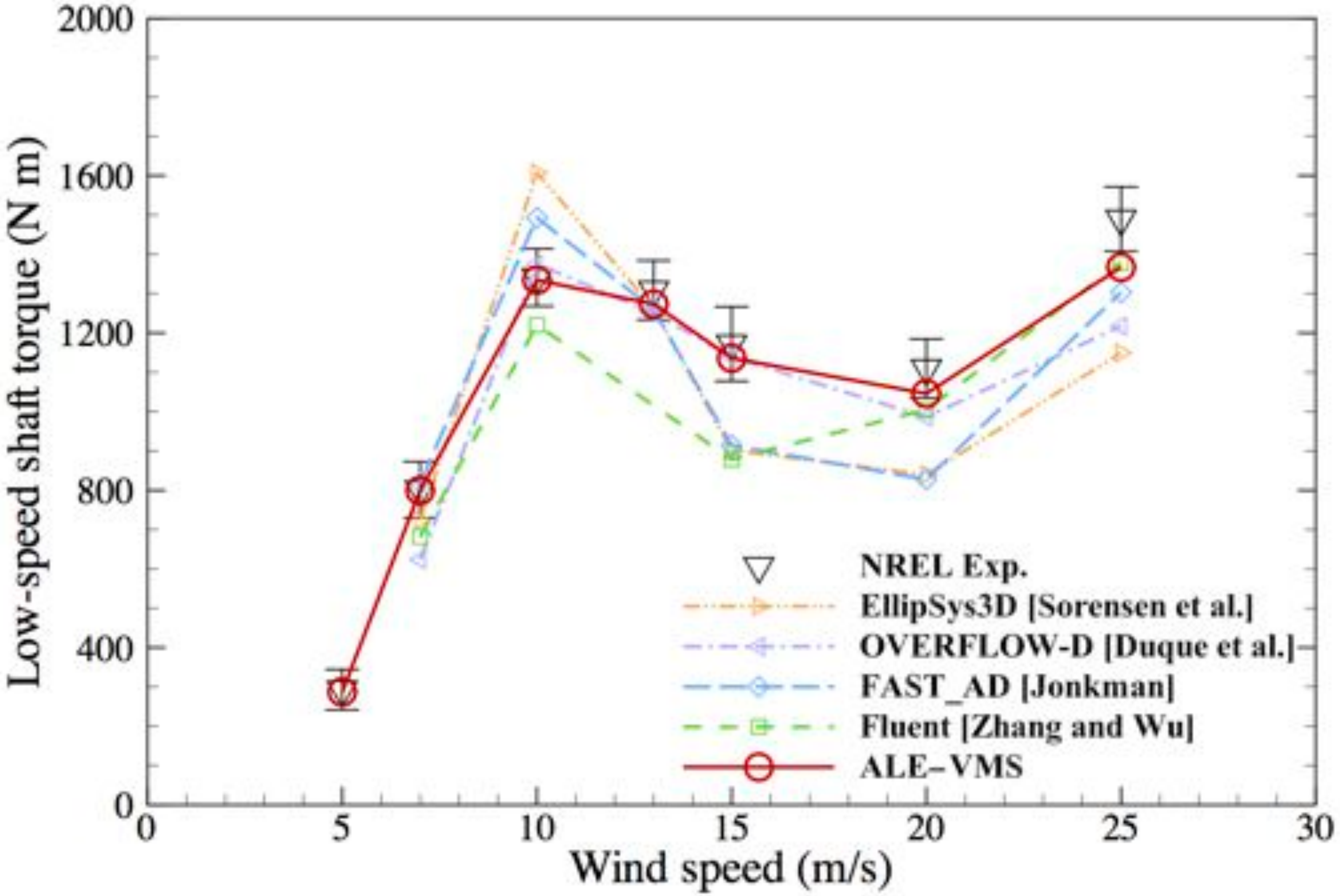
Tested in NASA Ames 80’×120’ Wind Tunnel (2000)



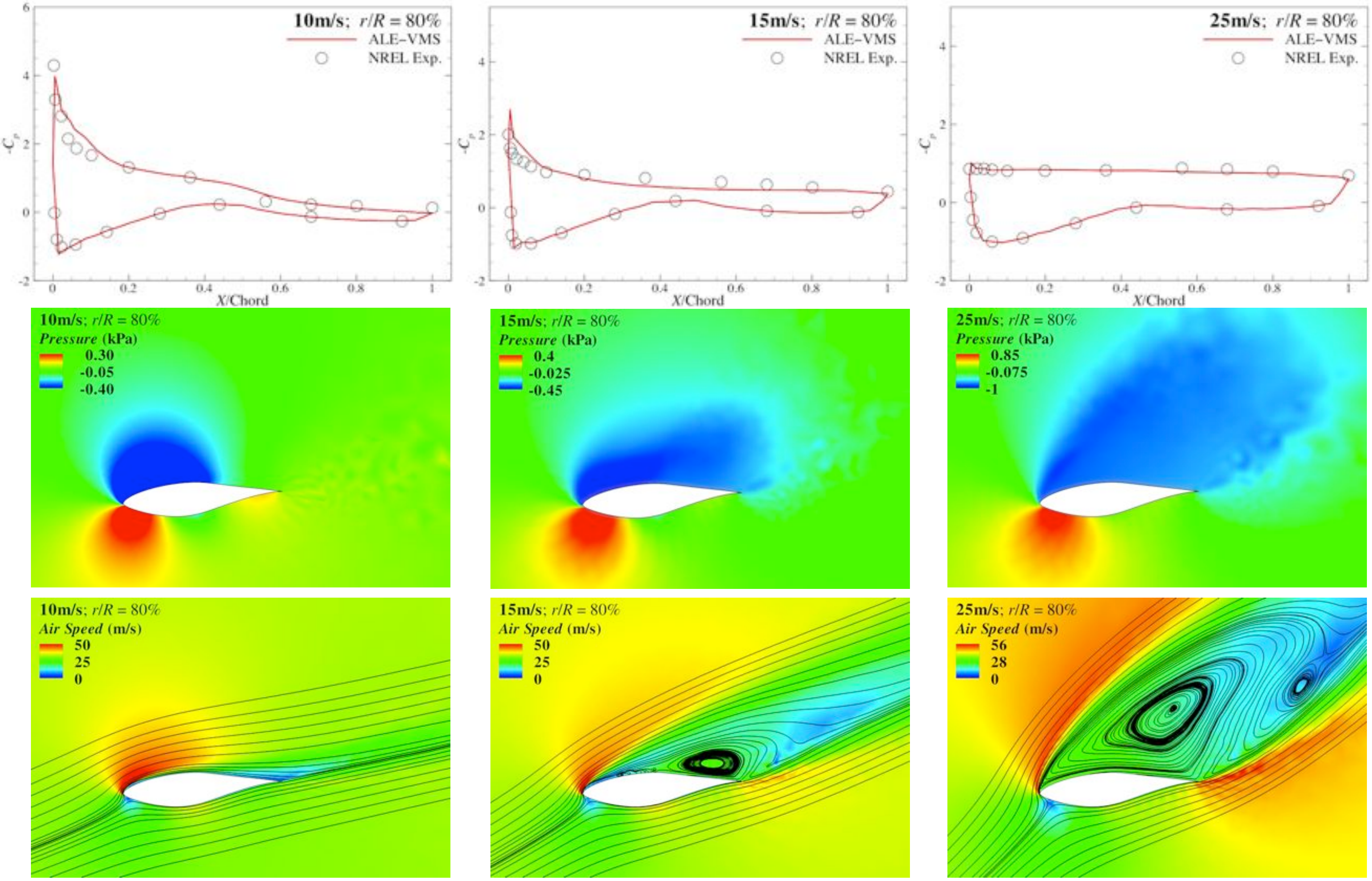


Results: Aerodynamic Torque

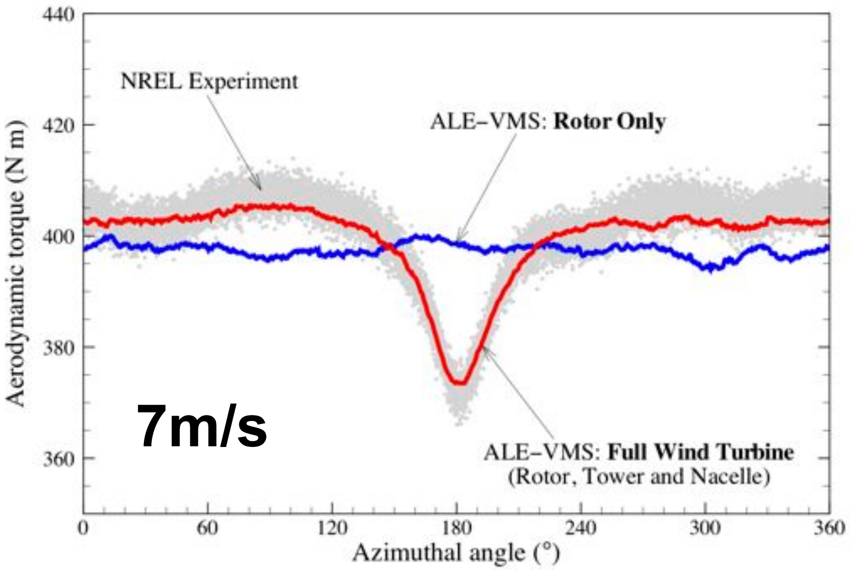
- "I" represents ±1 experimental standard deviation

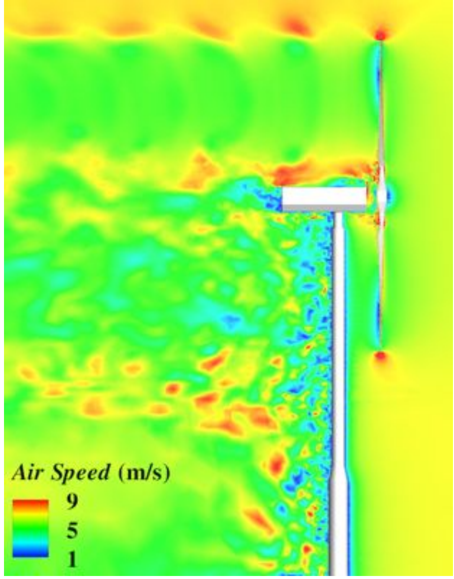


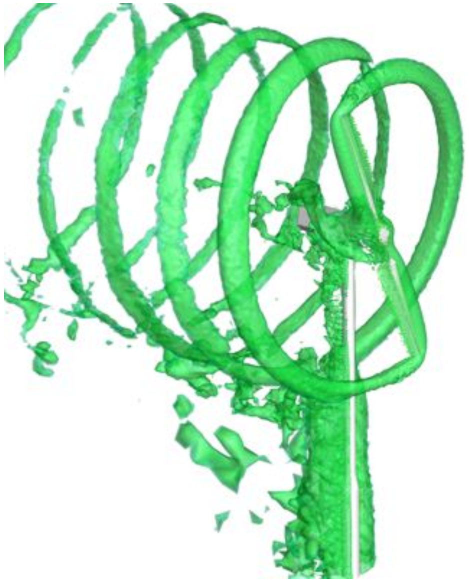
Pressure Coefficient

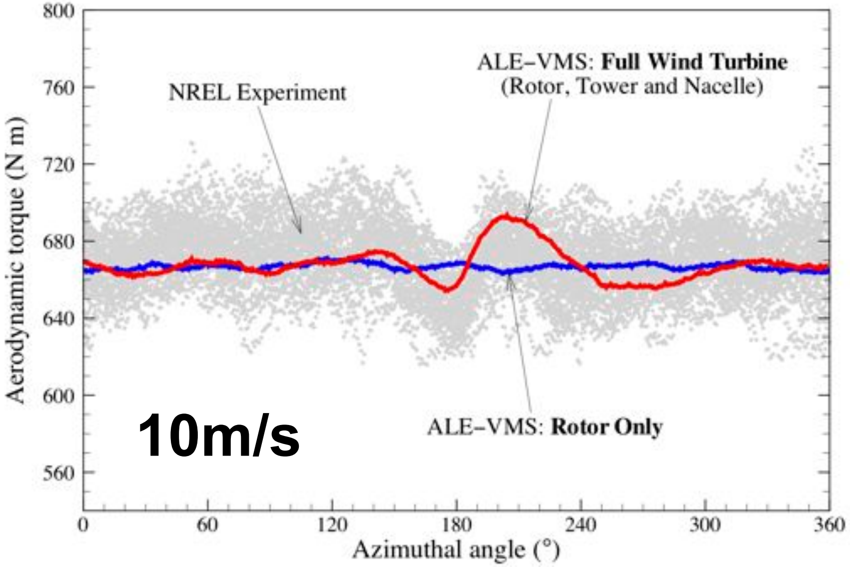


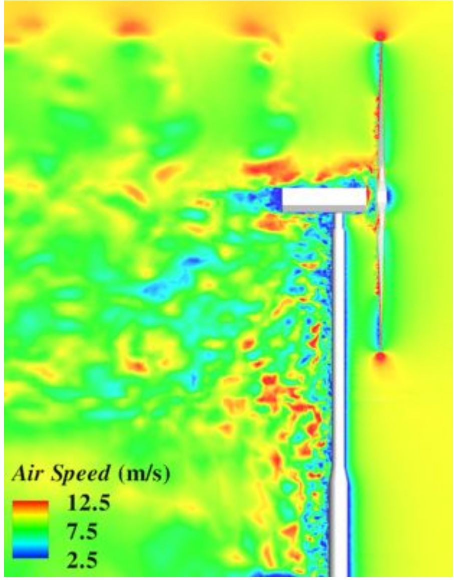
Rotor–Tower Interaction

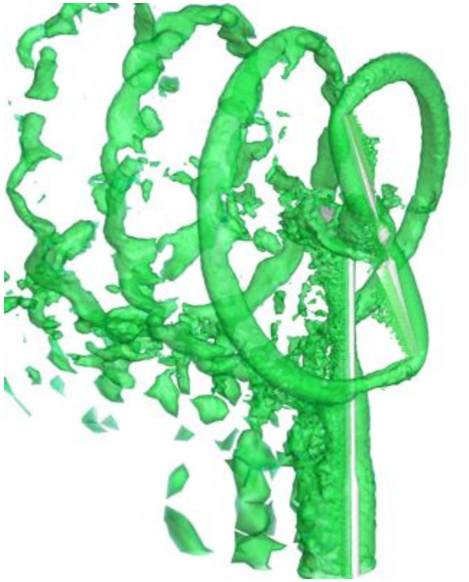












Structures: Isogeometric Kirchhoff–Love Shell

Find shell midsurface displacement $\mathbf{y} \in \mathcal{S}_y$, s.t. $\forall \mathbf{w} \in \mathcal{V}_y$:

$$\int_{\Gamma_0^s} \mathbf{w} \cdot h_{\text{th}} \bar{\rho}_0 \left(\frac{\mathrm{d}^2 \mathbf{y}}{\mathrm{d}t^2} - \mathbf{f} \right) \mathrm{d}\Gamma$$

$$+ \int_{\Gamma_0^s} \delta \bar{\boldsymbol{\varepsilon}} \cdot \left(\mathbf{K}_{\text{exte}} \bar{\boldsymbol{\varepsilon}} + \mathbf{K}_{\text{coup}} \bar{\boldsymbol{\kappa}} \right) \mathrm{d}\Gamma$$

$$+ \int_{\Gamma_0^s} \delta \bar{\boldsymbol{\kappa}} \cdot \left(\mathbf{K}_{\text{coup}} \bar{\boldsymbol{\varepsilon}} + \mathbf{K}_{\text{bend}} \bar{\boldsymbol{\kappa}} \right) \mathrm{d}\Gamma - \int_{\left(\Gamma_t^s\right)_{\text{h}}} \mathbf{w} \cdot \mathbf{h} \, \mathrm{d}\Gamma = 0$$

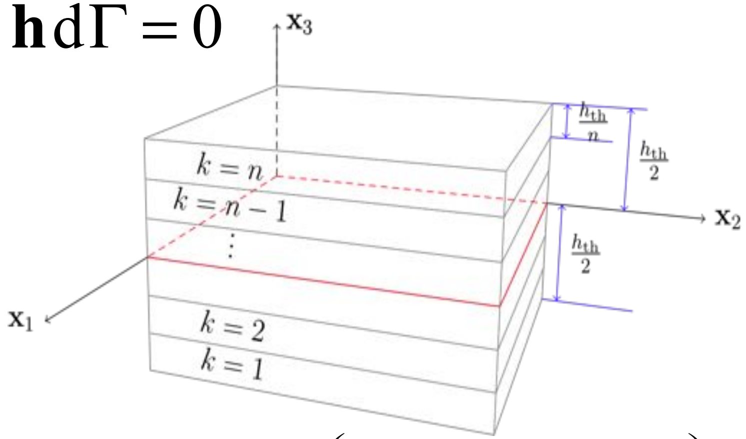
Membrane strains
(in the local coordinate system)

Curvature changes
(2^{nd} order derivatives)

$$\delta W_{\text{int}} = -\int_{\Omega} \mathbf{S} : \delta \mathbf{E} \, \mathrm{d}\Omega$$

$$\mathbf{S} = \mathbb{C}\mathbf{E}$$

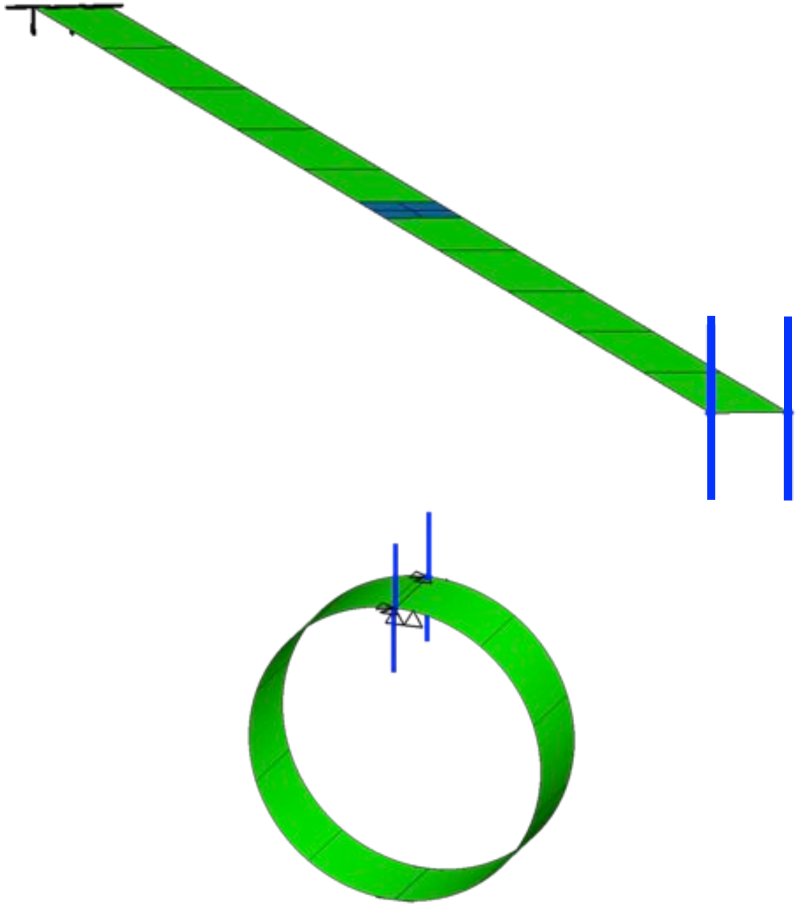
$$E_{\alpha\beta} = \varepsilon_{\alpha\beta} + \xi_3 \kappa_{\alpha\beta}$$



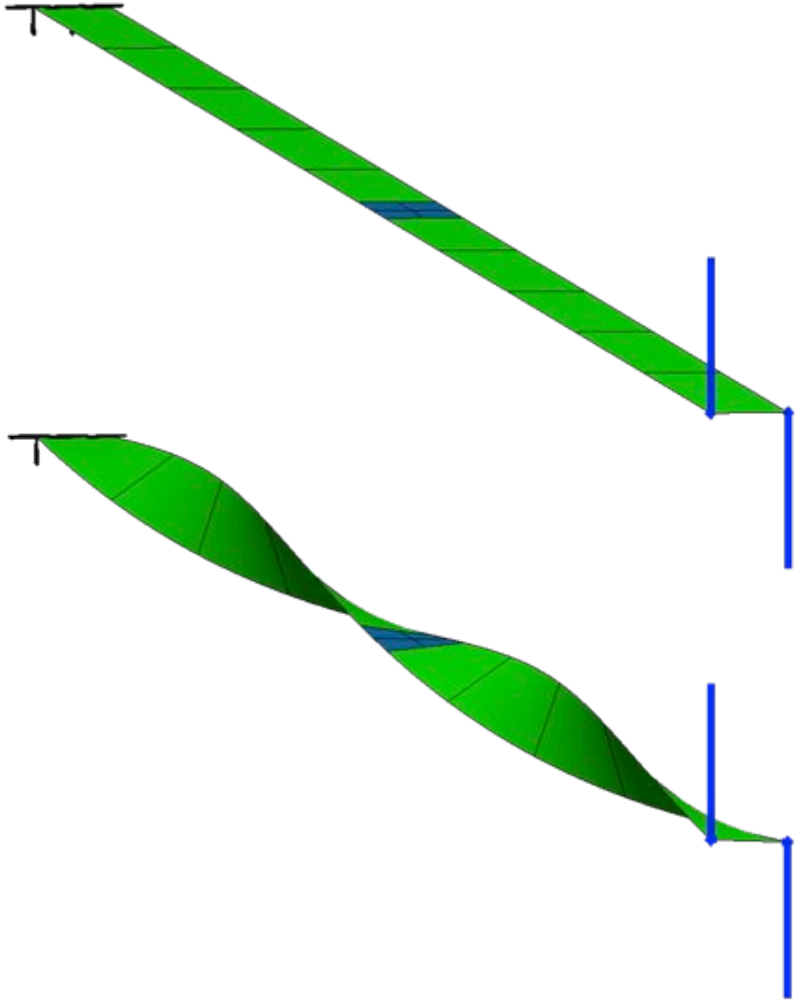
$$\mathbf{K}_{\text{bend}} = \int_{h_{\text{th}}} \xi_3^2 \mathbb{C} \, \mathrm{d}\xi_3 = \frac{h_{\text{th}}^3}{n^3} \sum_{k=1}^{n} \bar{\mathbb{C}}_k \left(\left(k - \frac{n}{2} - \frac{1}{2} \right)^2 + \frac{1}{12} \right)$$

Verification: Large-Deformation

Bent Plate

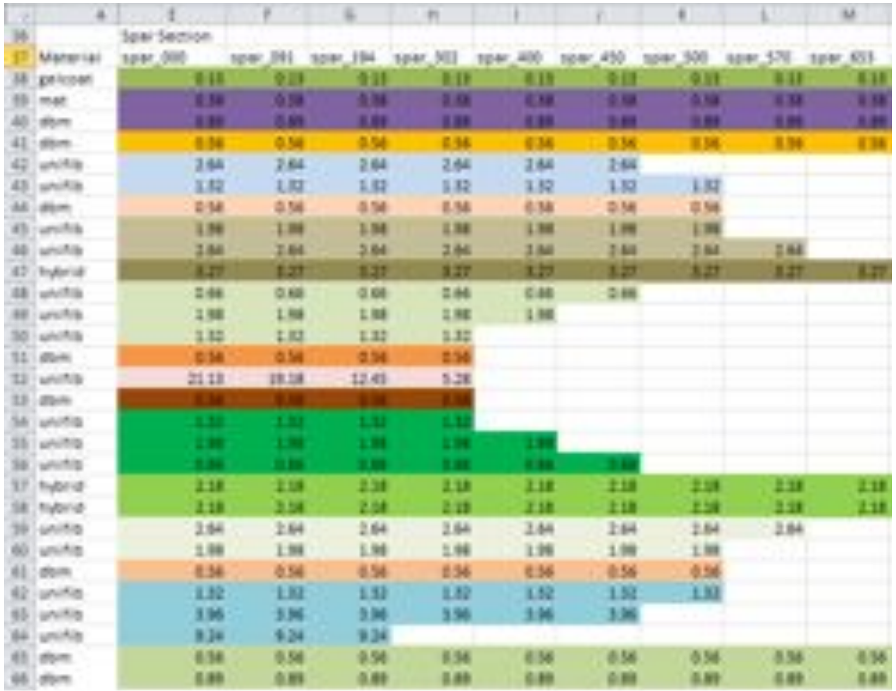


Twisted Plate



Structural Validation (Sandia CX-100)

Material layup and sections:



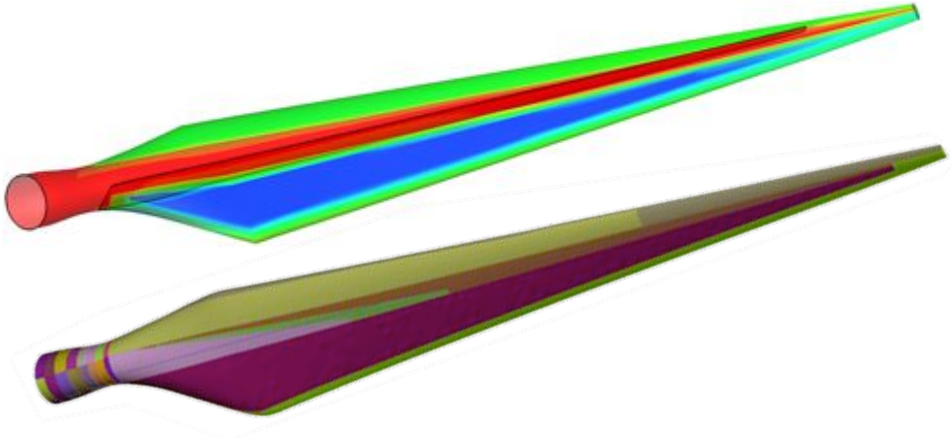
	Experiments	**Computations**
Mass (kg)	175.54	**173.34**
CG (m)	2.38	**2.22**

Sandia CX-100 9-m blade:

ndeshm-lab.ucsd.edu

IGA (NURBS) Model:

1879 Nodes; 1472 Elements



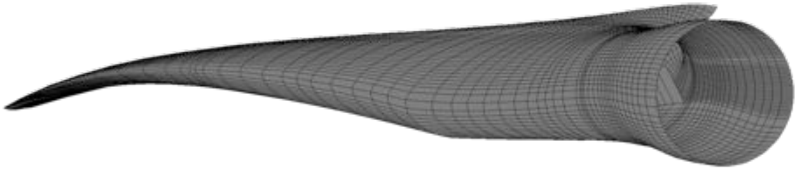
Comparison of Frequency Results

Clamped:

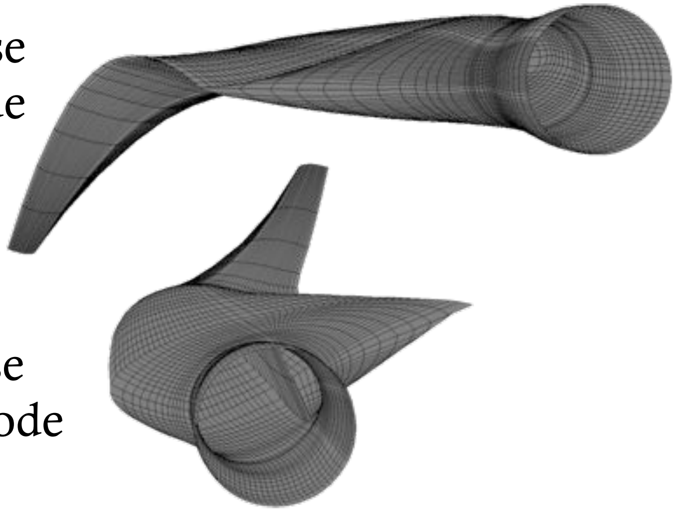
Mode	Experiments of NREL (Hz)	**Computations (Hz)**
1st Flapwise Bending	4.35	**4.33**
2nd Flapwise Bending	11.51	**11.82**
3rd Flapwise Bending	20.54	**19.69**

Free:

Mode	Experiments of SNL, LANL, and SDASL (Hz)	**Computations (Hz)**
1st Flapwise Bending	7.9 – 8.2	**8.28**
1st Edgewise Bending	16.0 – 18.1	**15.92**
2nd Flapwise Bending	20.2 – 20.8	**19.26**



1st Flapwise Bending Mode



1st Flapwise Bending Mode

1st Edgewise Bending Mode

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[1] *T. Marinone et al., Modal Testing of 9 m CX-100 Turbine Blades, (2012), DOI:10.1007/978-1-4614-2422-2_31*

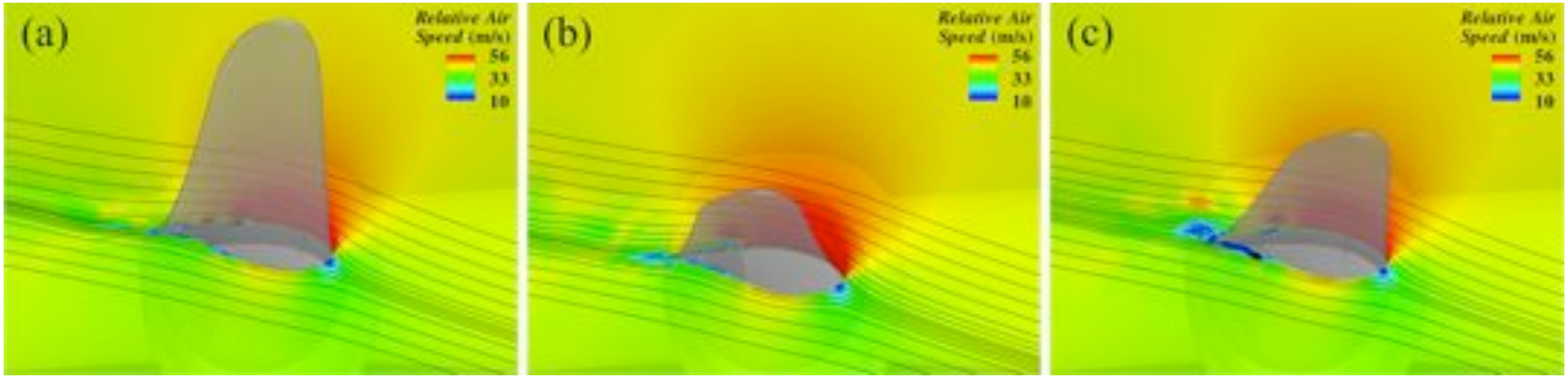
Non-Matching FSI Formulation

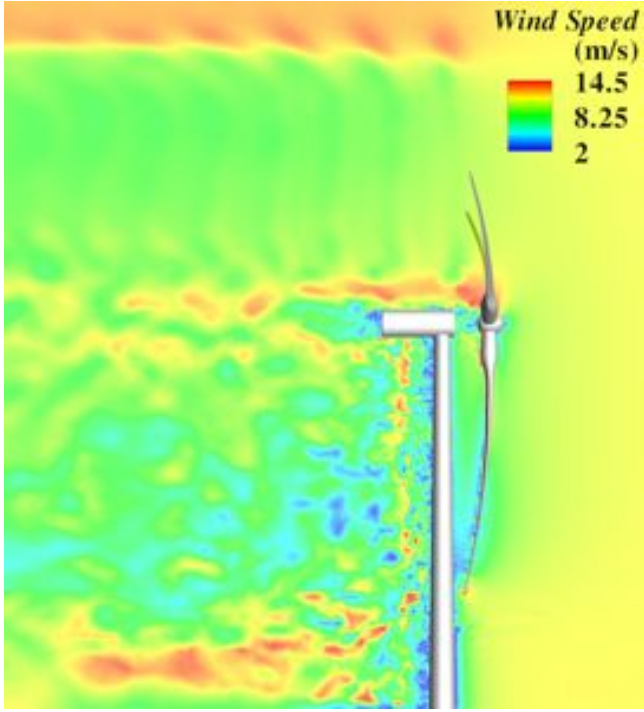
Find $\mathbf{u}_1 \in S_u,\ p \in S_p,\ \mathbf{u}_2 \in S_d,$ s.t. $\forall \mathbf{w}_1 \in \mathcal{V}_u,\ q \in \mathcal{V}_p,\ \mathbf{w}_2 \in \mathcal{V}_d$

$$\overbrace{B_1\left(\{\mathbf{w}_1, q\},\ \{\mathbf{u}_1, p\}\right) - F_1\left(\{\mathbf{w}_1, q\}\right)}^{\text{Fluids}} + \overbrace{B_2\left(\mathbf{w}_2, \mathbf{u}_2\right) - F_2\left(\mathbf{w}_2\right)}^{\text{Structures}}$$

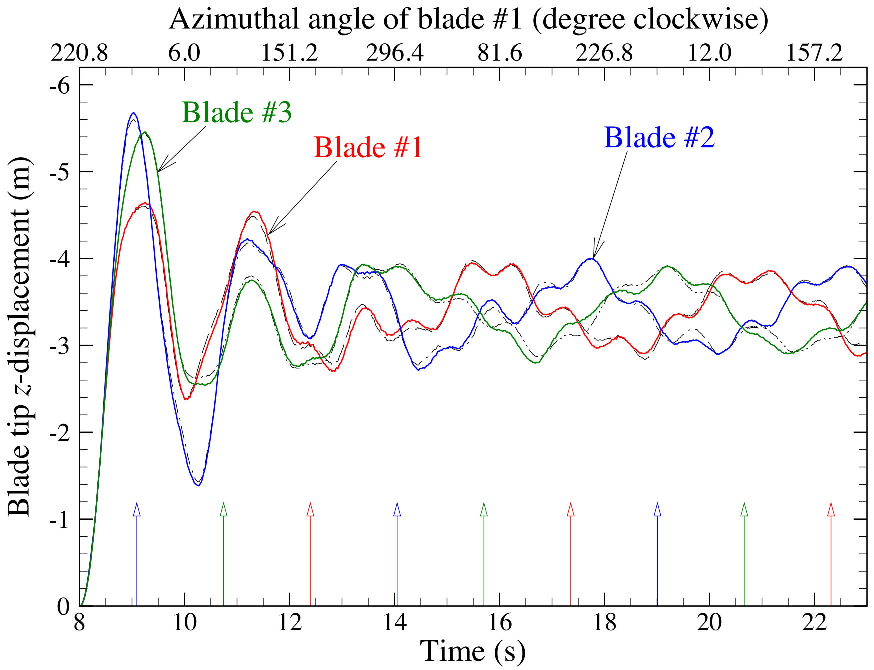
$$\left.\begin{aligned}
&-\int_{(\Gamma_t)_\mathrm{I}} \left(\mathbf{w}_1 - \mathbf{w}_2\right) \cdot \boldsymbol{\sigma}_1\left(\{\mathbf{u}_1, p\}\right)\mathbf{n}_1 \,\mathrm{d}\Gamma \\
&-\int_{(\Gamma_t)_\mathrm{I}} \left(\delta_{\{\mathbf{u}_1, p\}} \boldsymbol{\sigma}_1\left(\{\mathbf{w}_1, q\}\right)\mathbf{n}_1\right) \cdot \left(\mathbf{u}_1 - \mathbf{u}_2\right) \mathrm{d}\Gamma \\
&+\int_{(\Gamma_t)_\mathrm{I}} \left(\mathbf{w}_1 - \mathbf{w}_2\right) \cdot \beta\left(\mathbf{u}_1 - \mathbf{u}_2\right) \mathrm{d}\Gamma = 0
\end{aligned}\right\} \text{FS Interface}$$

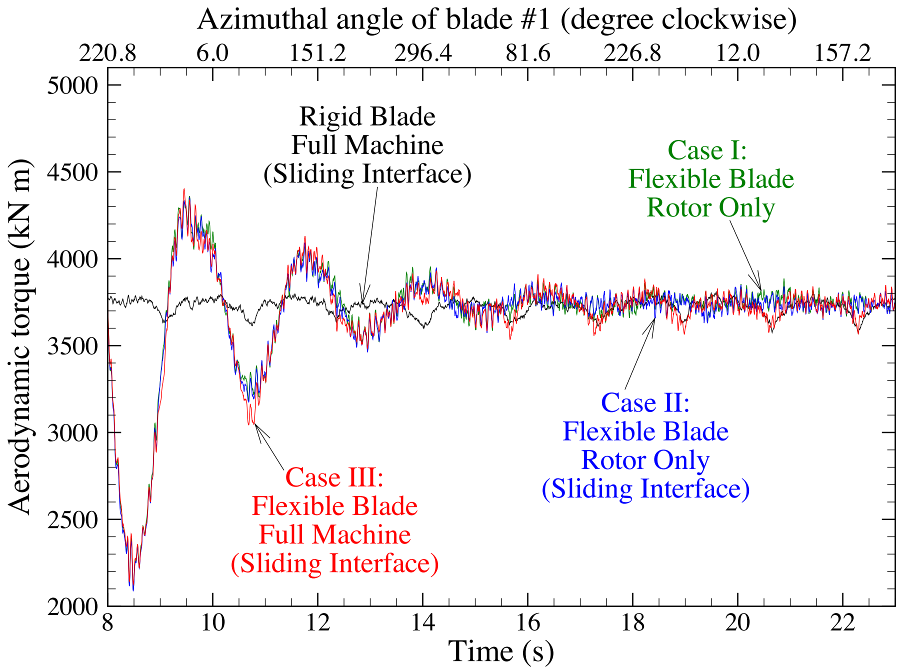
FSI Simulation Results





FSI Simulation Results

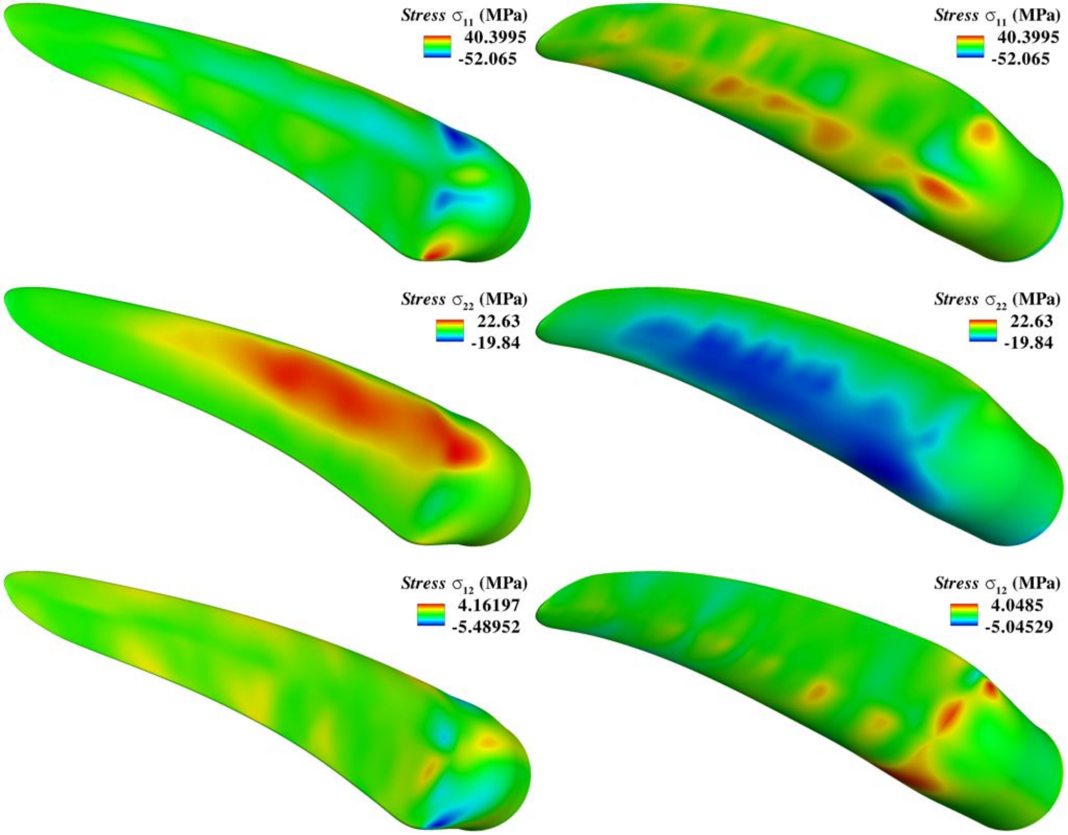


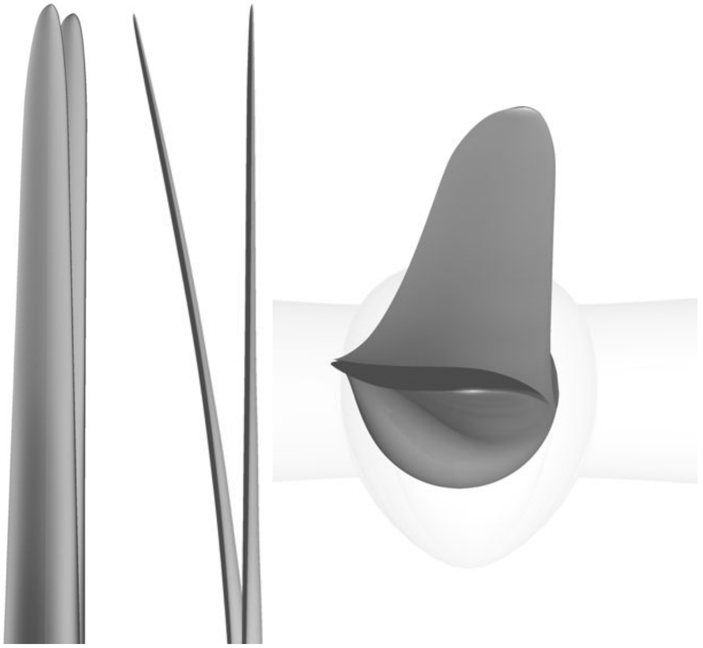


- Without considering any power loss, the energy generated by this wind turbine design is 4.73 MW.
- According to the Betz' law, the maximum power that can be extracted at this wind and rotor speeds is 6.57MW.
- This leads to the aerodynamic efficiency of 72%, which is quite good for modern wind turbine designs.

Stress Analysis

- Stress components (in local material coordinates) for ply number 14 (0°)





Conclusions

- We has developed a unique, validated computational framework and software, which combine geometry modeling, aerodynamics, structural mechanics, and fluid–structure interaction (FSI) analysis of full-scale wind turbines.
- The framework is implemented in large-scale high-performance computing environment.
- Advanced computational methods are adopted and employed in industrial-scale applications

Future Possibilities

- We continue to extend our interests to several important topics, including
  - Atmospheric boundary layer effect
  - Wake effect of wind turbines
  - Wake effect in wind farms
  - Wind shear and turbulence effects
  - Wind turbine blade and rotor design
  - Multiple rotor system
  - Vertical axis wind turbines
  - Rotor–tower interaction
  - Tower design and modeling
  - Airborne wind turbines

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Selected Publications

- M.-C. Hsu, I. Akkerman and Y. Bazilevs, “**Finite element simulation of wind turbine aerodynamics: Validation study using NREL Phase VI experiment**”, *Wind Energy*, (2014). doi:10.1002/we.1599.
- M.-C. Hsu and Y. Bazilevs, “**Fluid–structure interaction modeling of wind turbines: simulating the full machine**”, *Computational Mechanics*, 50 (2012) 821-833.
- A. Korobenko, M.-C. Hsu, I. Akkerman and Y. Bazilevs, “**Aerodynamic simulation of vertical-axis wind turbines**”, *Journal of Applied Mechanics*, 81 (2014) 021011.
- A. Korobenko, M.-C. Hsu, I. Akkerman, J. Tippmann and Y. Bazilevs, “**Structural mechanics modeling and FSI simulation of wind turbines**”, *Mathematical Models and Methods in Applied Sciences*, 23 (2013) 249-272.
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- Y. Bazilevs, M.-C. Hsu and M.A. Scott, “**Isogeometric fluid–structure interaction analysis with emphasis on non-matching discretizations, and with application to wind turbines**”, *Computer Methods in Applied Mechanics and Engineering*, 249-252 (2012) 28-41.

Selected Publications

- Y. Bazilevs, M.-C. Hsu, K. Takizawa and T.E. Tezduyar, "**ALE–VMS and ST–VMS methods for computer modeling of wind-turbine rotor aerodynamics and fluid–structure interaction**", *Mathematical Models and Methods in Applied Sciences*, 22 (2012) 1230002.
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- Y. Bazilevs, M.-C. Hsu, I. Akkerman, S. Wright, K. Takizawa, B. Henicke, T. Spielman and T.E. Tezduyar, "**3D simulation of wind turbine rotors at full scale. Part I: Geometry modeling and aerodynamics**", *International Journal for Numerical Methods in Fluids*, 65 (2011) 207-235.

Broaden Cognitive Approaches

- How do we become aware of the problems we work on?
- What are the attributes of a “good research problem”?
- To what extent can research be planned?
- What is the interplay between creativity and literature review?
- What is the desired “end-product” of a research project (paper? “contribution”? patent? technology transfer? impact? graduated student?); how in the research process does choice of “end-product” affect what happens?
- How are solution approaches identified?
- What constitutes acceptable evidence that a problem is indeed solved?

What’s Important?

- Collaborations and discussions
- Literature review and understand the problem
- Be very organized when you conduct research.
- Publish and advertise your work
- Go to conferences and interact with people
- Give organized presentations
- Research what you love and enjoy the process
- Set up short term goals