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Design Challenges for Bend Twist Coupled Blades for Wind Turbines: and application to standard blades

2012 Sandia Wind Turbine Blade Workshop

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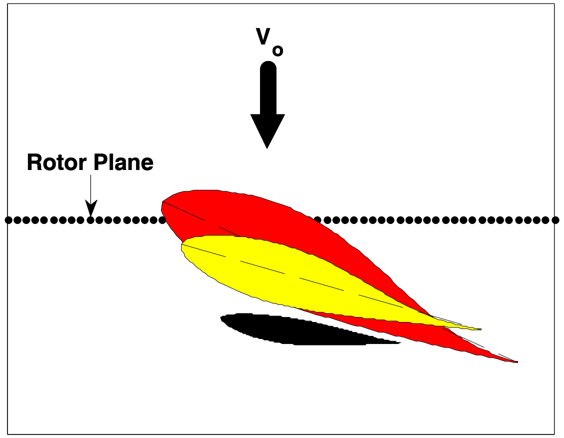
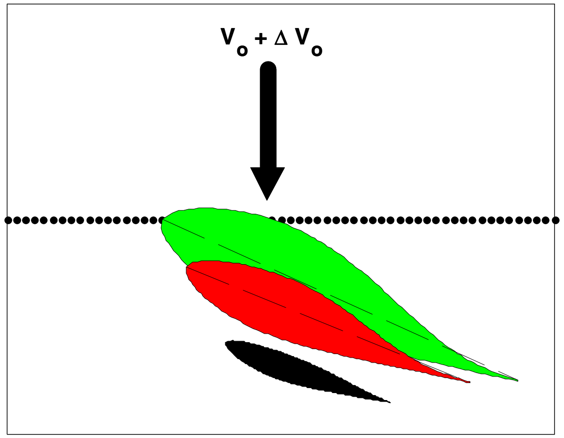
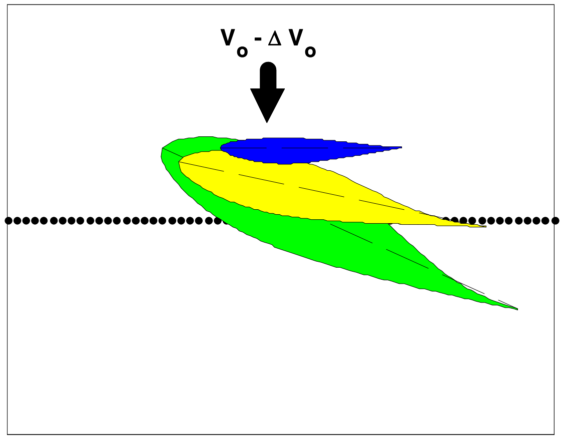






Who (1): Mark Capellaro

- Visiting researcher Sandia National Labs
- Doctoral Candidate from the University of Stuttgart Faculty of Aerospace Engineering and Geodesy (Diss. Submittal 3/12).
    - Topic: BTC Blades
- Master of Science in Wind Energy from the Danish Technical University/Risoe
- Bachelor of Science Mechanical Engineering, University of Washington
- Bachelor of Arts, Economics and South Asian Studies, University of Wisconsin – Madison.
- Design Engineer, Wind Turbine Company, Seattle, WA (2000-2002)
- Vestas Intern/Test Engineer, IOW UK (2005)

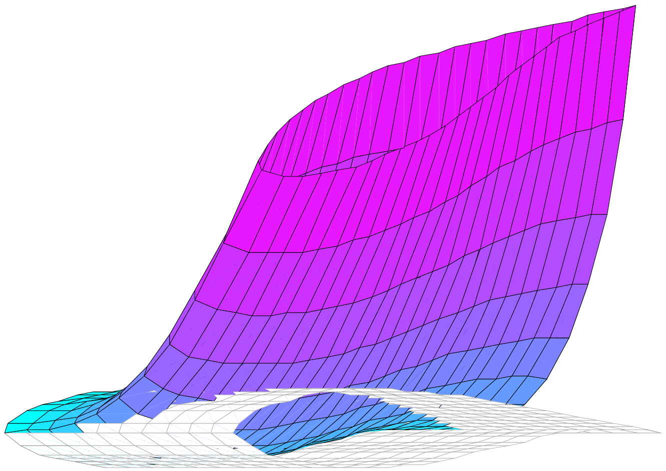
Bend Twist Coupling: Explained

The coupling between the bending and torsional deflection of a wind turbine blade.

Also known as ‘aero-elastic tailoring‘.

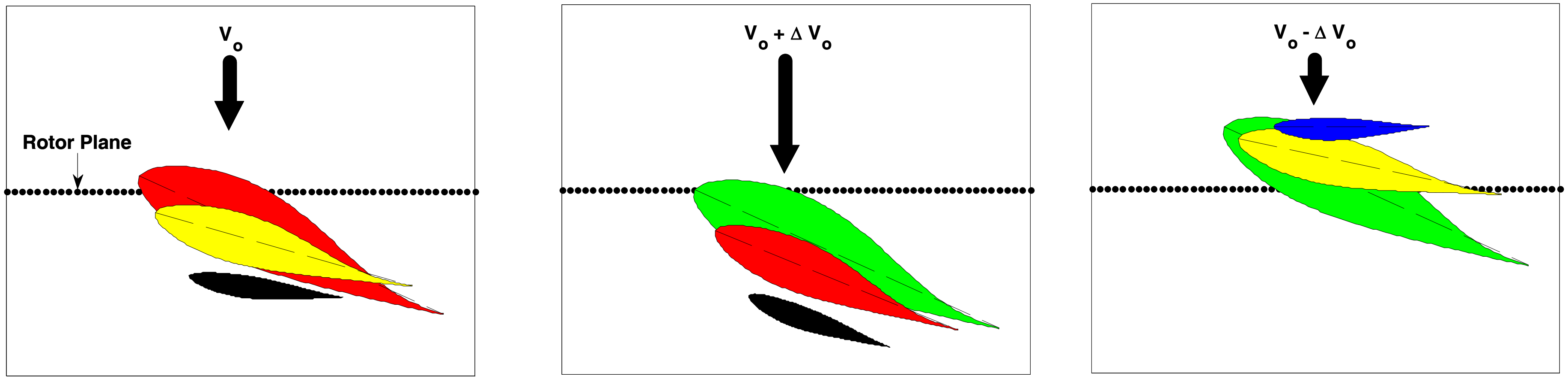
In wind turbine applications, we want the flap or out of plane bending to force the blade to twist along the long axis of the blade (torsion).

The torsional deflection towards feather, can be used to lower the loads.



Blade bend twist coupling towards feather – lowering the angle of attack

Bend Twist Coupling: Explained



Equilibrium Condition   Vo + ΔVo (+ Gust)   Vo - ΔVo (- Gust)

The rotor will twist or pitch itself with a change in wind conditions.

\+ Positive Gust (more wind) blade twists to lower the angle of attack.

\- Negative Gust (less wind) blade twists to increase angle of attack.

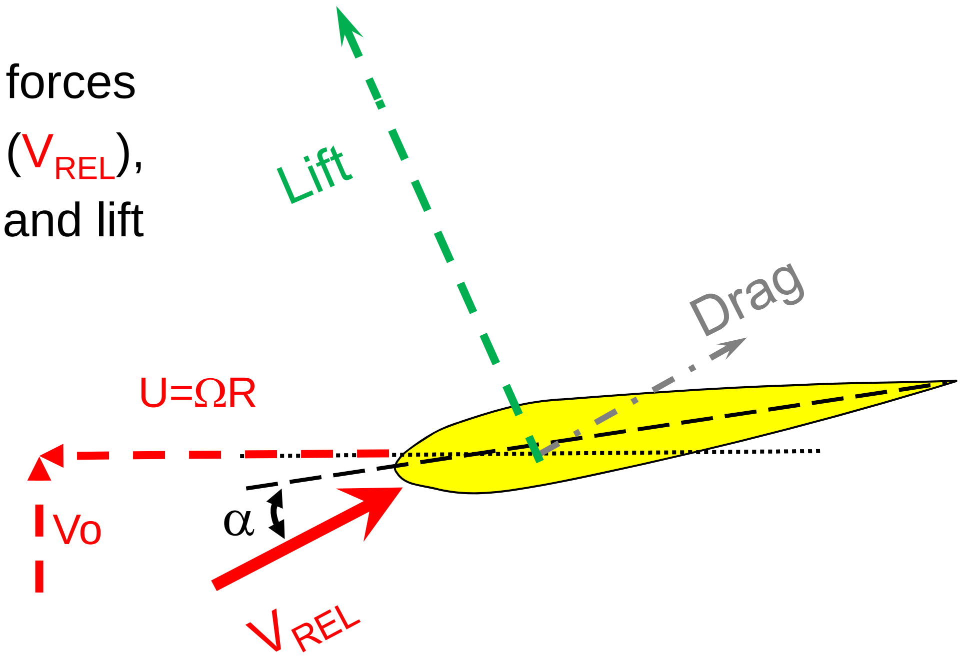
Bend Twist Coupling: Explained

An airfoil generates Lift and Drag forces based on the relative wind speed (V_{REL}), length of airfoil (c), air density (ρ) and lift and drag coefficients (C_L, C_D).

Formulas:

$$Lift = \frac{1}{2} \cdot \rho \cdot C_L \cdot c \cdot v_{REL}^2$$

$$Drag = \frac{1}{2} \cdot \rho \cdot C_D \cdot c \cdot v_{REL}^2$$



Aero loads directions along blade.

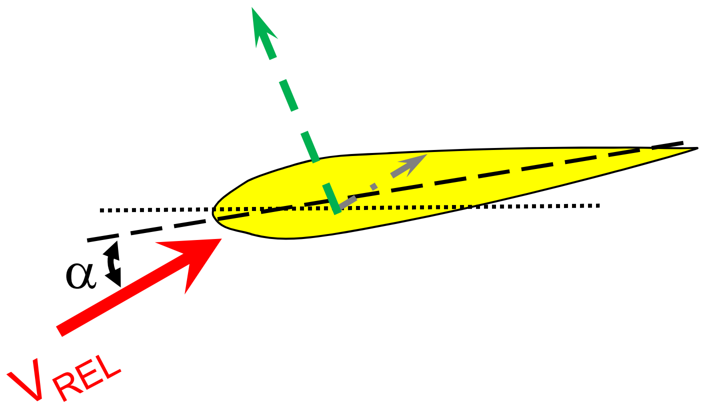
Bend Twist Coupling: Explained

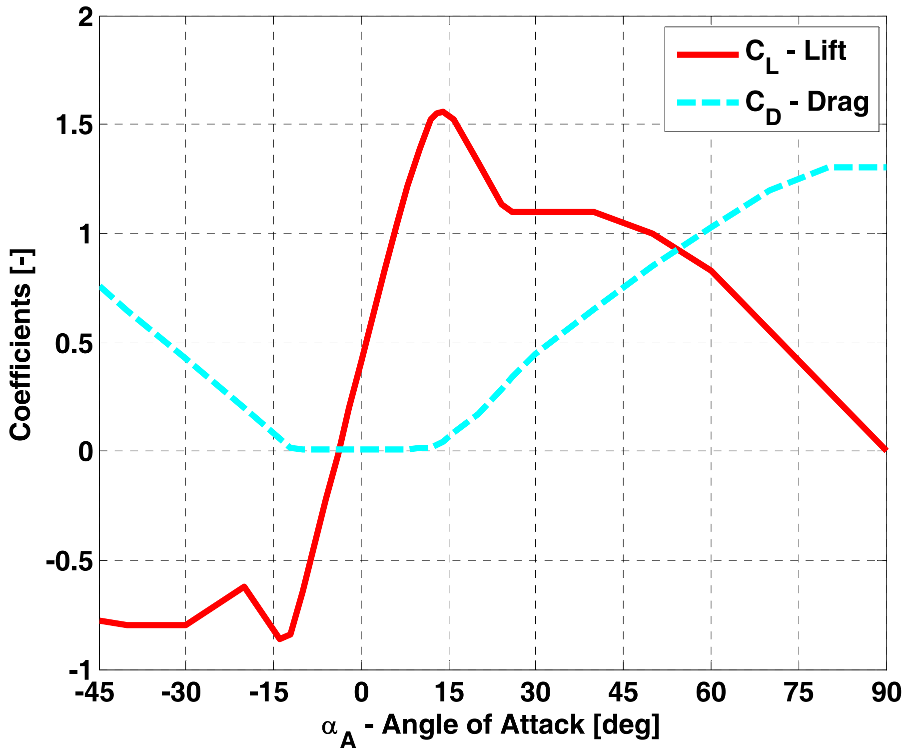
Formulas:

$$Lift = \frac{1}{2} \cdot \rho \cdot C_L \cdot c \cdot v_{REL}^2$$

$$Drag = \frac{1}{2} \cdot \rho \cdot C_D \cdot c \cdot v_{REL}^2$$

The coefficients of Lift and Drag are dependent upon the angle of attack (α) the airfoil chord line makes with the wind (V_{REL}).





Typical aero properties for wind turbine blade tip section profile (~18% thick NACA)

Bend Twist Coupling: Explained

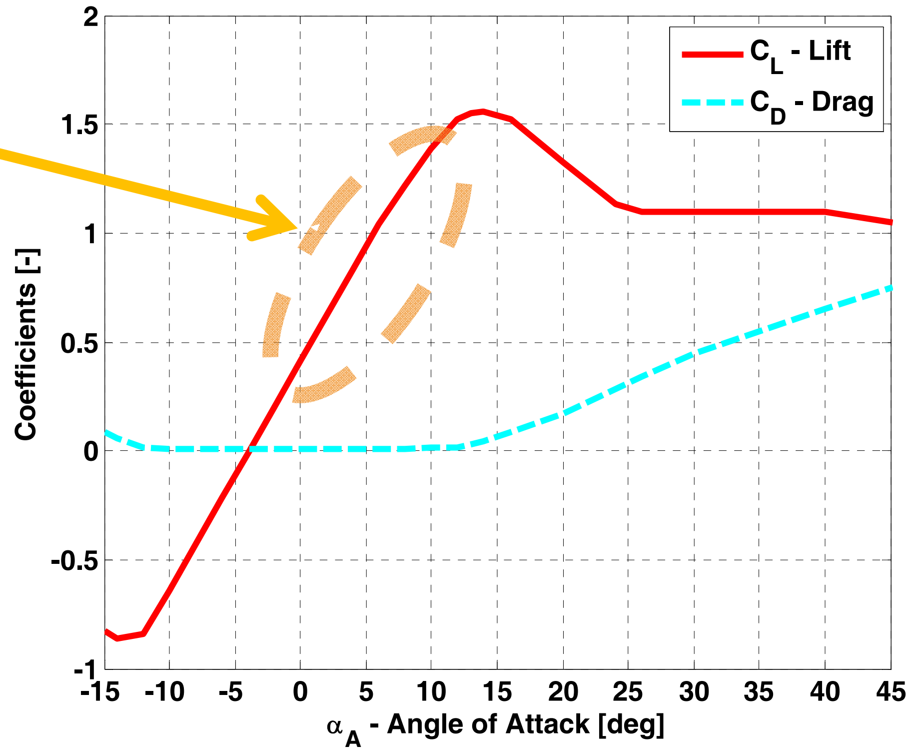
A wind turbine blade operates in this region of angles of attack under normal operating conditions.

Lowering the angle of attack lowers the lift, lowering the blade loading.

Formulas:

$$Lift = \frac{1}{2} \cdot \rho \cdot C_L \cdot c \cdot v_{REL}^2$$

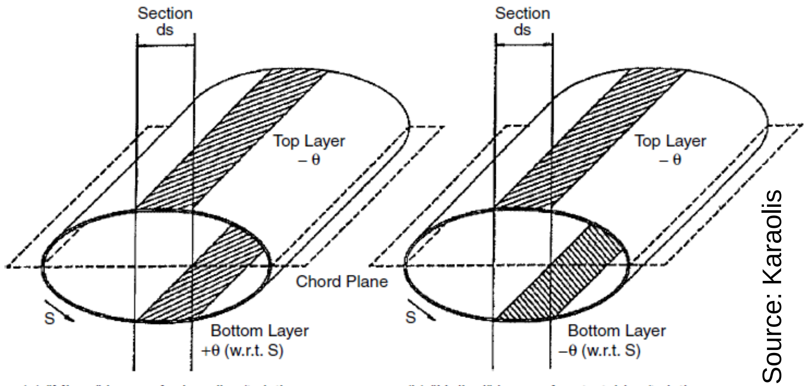
$$Drag = \frac{1}{2} \cdot \rho \cdot C_D \cdot c \cdot v_{REL}^2$$



Typical aero properties for wind turbine blade tip section profile (~18% thick NACA)

Background Research:

- First suggested by Karaolis – UK in 1988 as a method for control of a small turbine.
- Stoddard et al. - USA found bend twist coupling in existing blades (1989).
- ECN – Netherlands studied the use of twist to stall blades for increasing power production (ca. 1996).
- Sandia – USA various models for pitch and stall turbines (1996-2003)
    - aero instability check (flutter and divergence)
    - Use on modern turbines with pitch systems



(a) "Mirror" lay–up for bending/twisting coupling (θ changes sign below chord)

(b) "Helical" lay–up for stretching/twisting coupling (θ has same sign around S)

- Sandia/Wetzel Engineering/GEC – USA finite element calculation of potential twisting based on composite bend twist coupled blades (2002-2005)

Background Research:

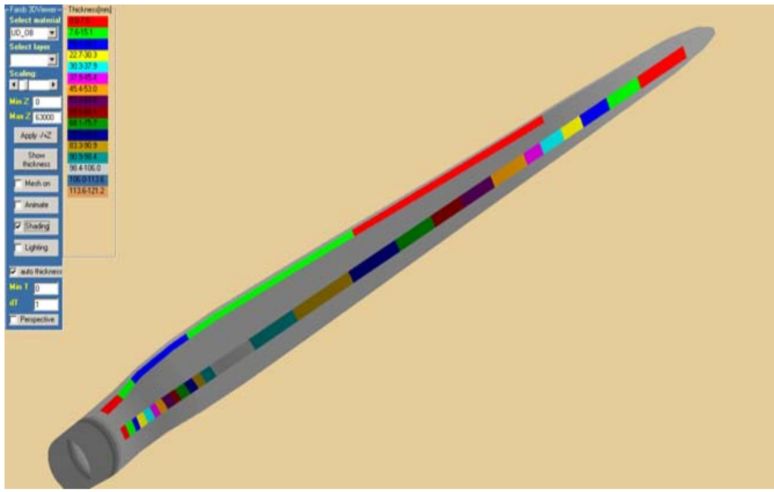
The Sandia papers determined that coupling to stall was not a very good idea and that towards feather could increase power production (if the blade was lengthened) without increasing loads.

The FE modeling determined that the lay up and twisting was limited based on theoretical limits and material limits.

Wetzel/Griffin did the most work in designing composite lay ups for bend twist coupled blades.

Recommendations:

- Twist towards feather
- Load reduction instead of turbine control
- Only outer portion of blade to be coupled.



FE blade model (FAROB WMC/ECN)

Bend Twist Coupling: How

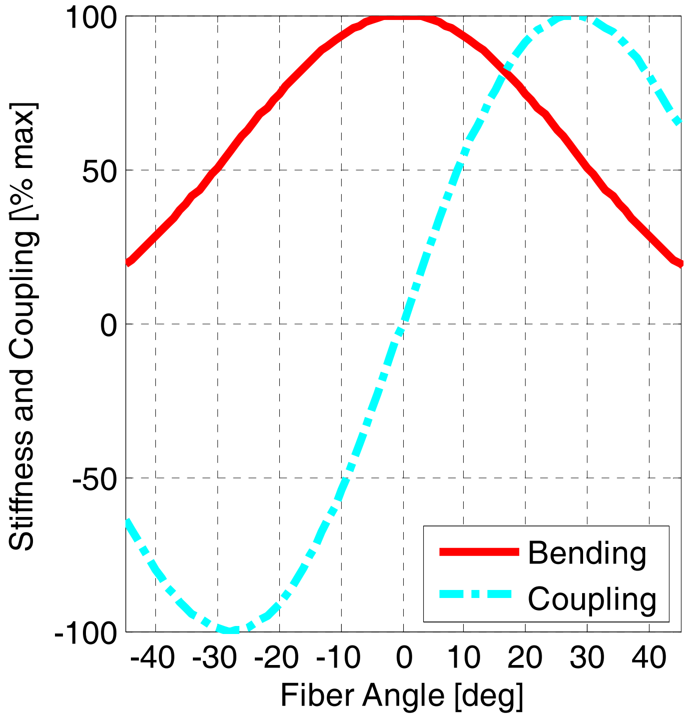
Classical Laminate Theory

The anisotropic properties of fiber composite materials can be used to create coupled lamina materials.

The amount of coupling in a lamina or simple laminate can be calculated with Classic Laminate Theory.

Coupling is inversely correlated with bending stiffness in a lamina*.

*Above a certain angle, the coupling decreases, along with the bending stiffness.



Bend Twist Coupling: How

The more anisotropic the material, the more potential for coupling.

The limit of coupling (α) is based on the bending stiffness and torsional stiffness.

$$\alpha = \frac{g}{\sqrt{EI \cdot GJ}}$$

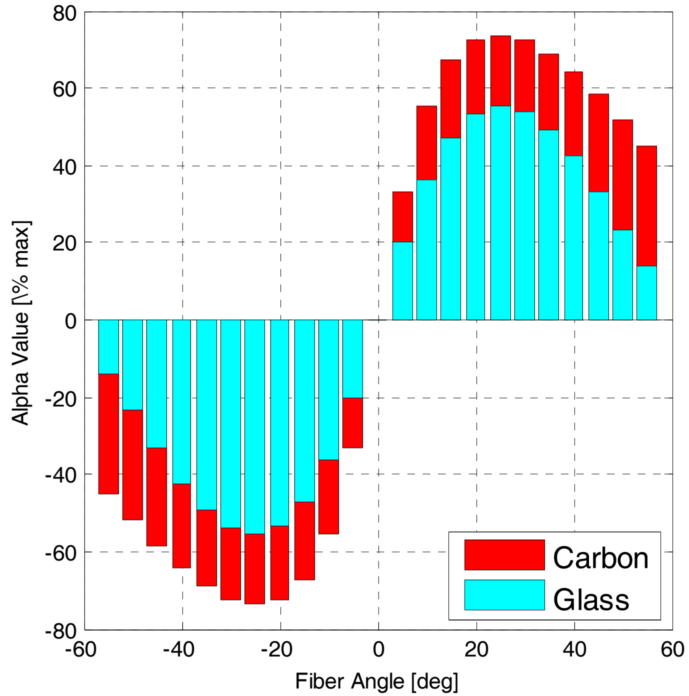
$$-1 \leq \alpha \leq 1$$

$$g = \alpha \sqrt{EI \cdot GJ}$$

Early simulations used α to estimate the coupling.

$$\begin{bmatrix} EI & -g \\ -g & GJ \end{bmatrix} \begin{bmatrix} b \\ t \end{bmatrix} = \begin{bmatrix} M_b \\ M_t \end{bmatrix}$$

Lamina Analysis
(simple UD material)



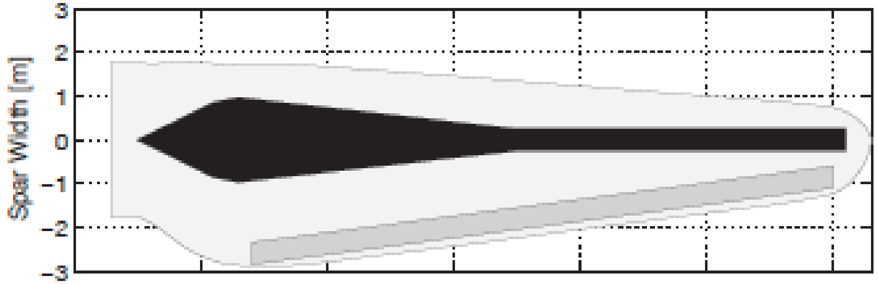
Here α is reverse engineered from the g value in the stiffness matrix.

Bend Twist Coupling: Turbine Modelling

Blade models were created with various fiber angles, based on recommendations from previous research.

Blades created in VABS and converted to Phatas wind turbine aerodynamic simulation code from ECN.

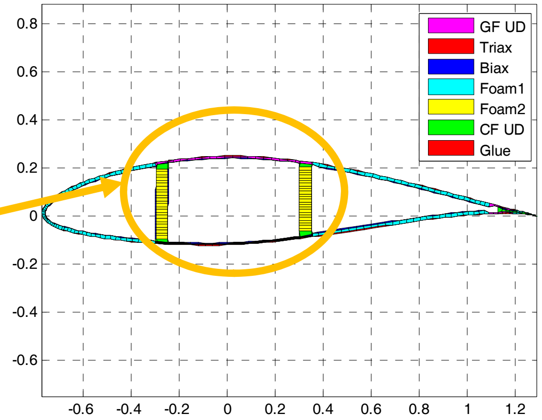
Model Name	**Spar Cap UD Fiber Angle**
M0C2 P00	0 degree (baseline blade)
M0C2 N05	-5 degrees
M0C2 N10	-10 degrees
M0C2 N15	-15 degrees
M0C2 N20	-20 degrees



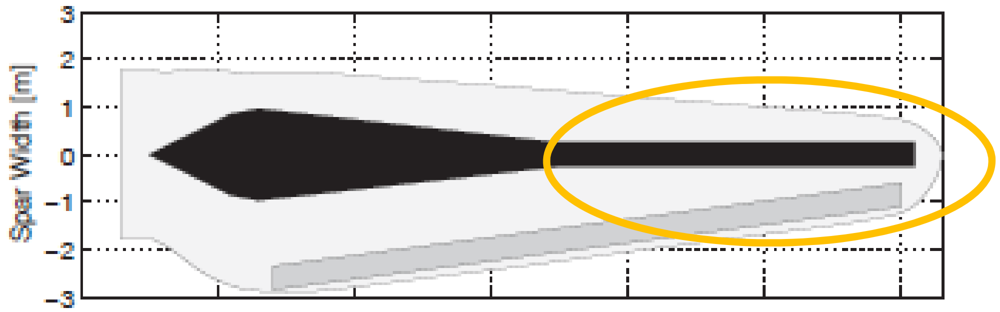
Bend Twist Coupling: How

Coupling in a wind turbine blade is created by creating an asymmetric lay up in the fibers.

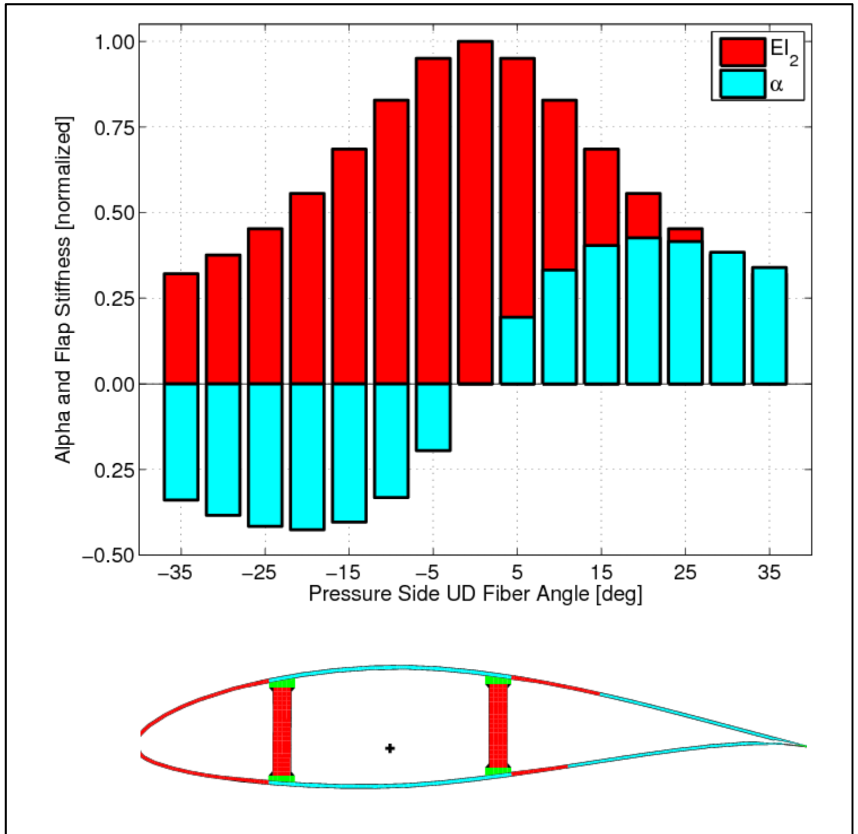
The spar cap uni directional material is used in these models to create the asymmetry and coupling.



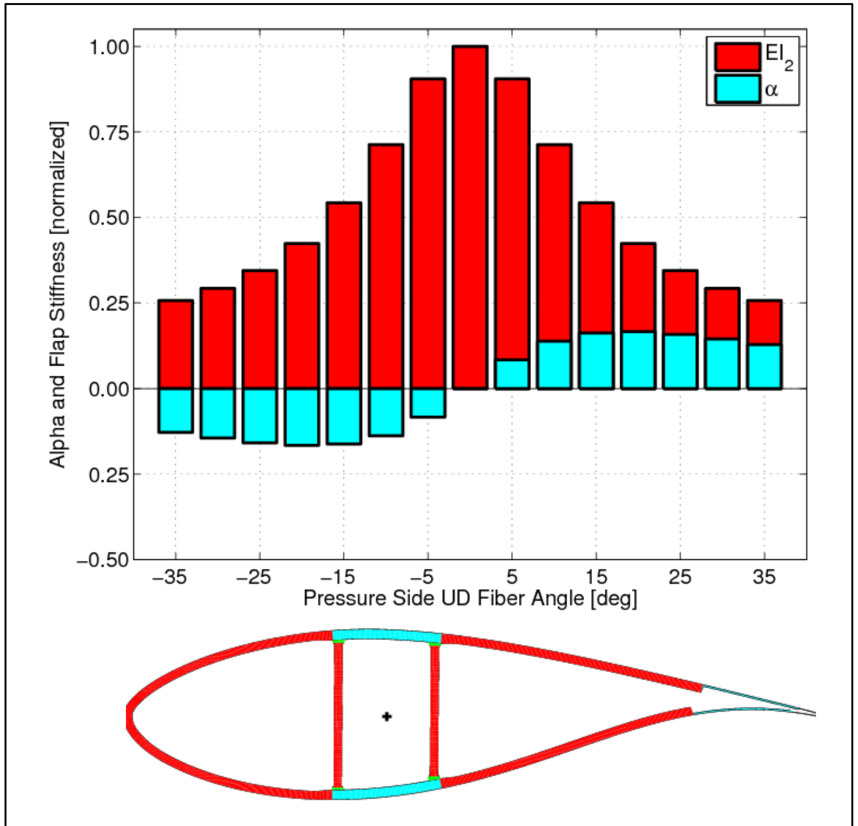
Using the recommendations from previous research, only the outer section was coupled.



Bend Twist Coupling: How



R=60m



R=35m

The potential coupling is dependent upon the material (anisotropic properties), geometry of section and fiber placement.

Better potential near the tip (thinner profiles are used).

Wind Turbine Blade Structural Analysis

Variational Asymptotic Beam Solver (VABS)

FE code developed in the US originally to model helicopter rotor blades.

VABS Inputs:

- Geometry
- Material data (E1, E2, Angles..)
- Thicknesses
- Locations

VABS Outputs (Beam Element inputs)

- Stiffness (Flap EI_2, Edge EI_1 and Torsion GJ)
- Couplings (full matrices for each section[1])
- Mass/m
- Shear center, neutral axes, mass properties

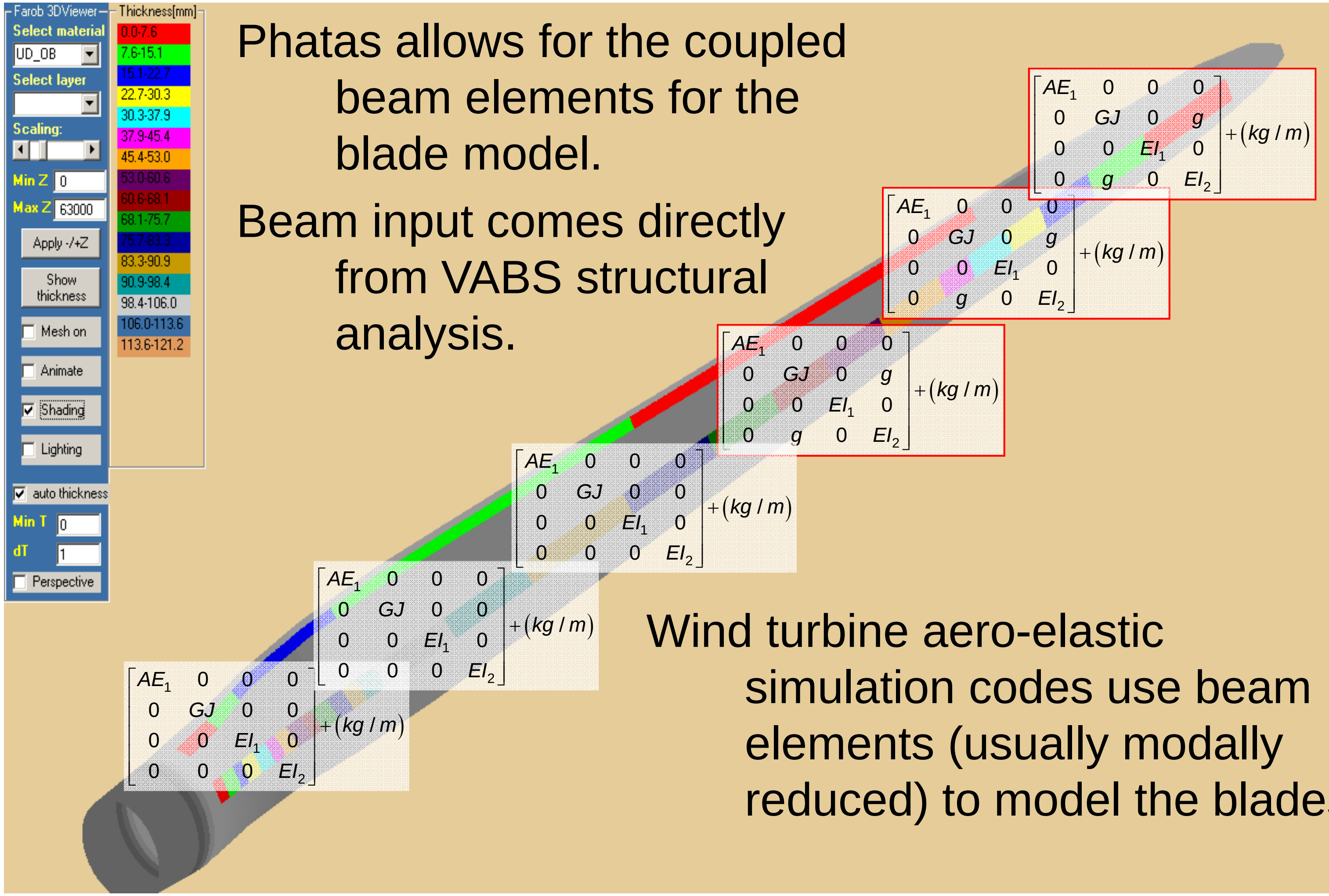
$$\begin{bmatrix} AE_1 & 0 & 0 & 0 \\ 0 & GJ & 0 & g \\ 0 & 0 & EI_1 & 0 \\ 0 & g & 0 & EI_2 \end{bmatrix}$$

$$\begin{bmatrix} 3.93E+09 & 0.00E+00 & 3.56E+08 & -5.26E+08 \\ 0.00E+00 & 3.50E+07 & 0.00E+00 & 0.00E+00 \\ 3.56E+08 & 0.00E+00 & 2.27E+08 & -4.87E+07 \\ -5.26E+08 & 0.00E+00 & -4.87E+07 & 1.13E+09 \end{bmatrix}$$

VABS Output Example – classic stiffness matrix

*Note that the PHATAS code uses axial, flap and edge twist couplings only.

Wind Turbine Blade Model



Phatas allows for the coupled beam elements for the blade model.

Beam input comes directly from VABS structural analysis.

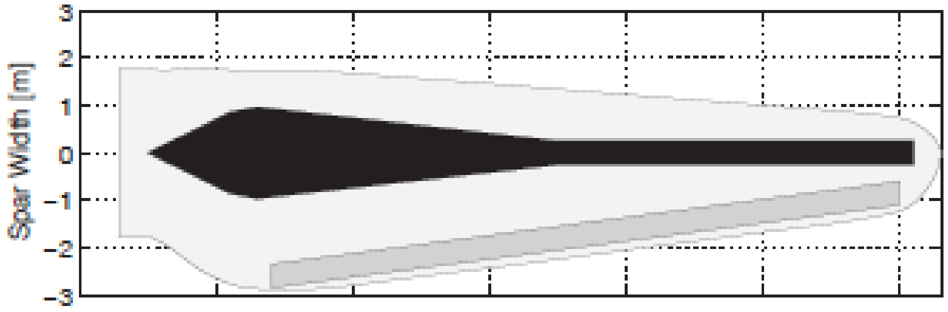
Wind turbine aero-elastic simulation codes use beam elements (usually modally reduced) to model the blades.

Bend Twist Coupling: Turbine Modelling

The NREL 5MW reference turbine was used as the baseline turbine model for the blade properties.

The lay-up was estimated from the blade properties to create the reference lay-up blade.

Wind Regime	IEC Class 1B	
Rotor Orientation	Clockwise rotation - Upwind	
Control	Variable Speed Collective Pitch	
Cut in wind speed	4	[m/s]
Cut out wind speed	25	[m/s]
Rated power	5	[MW]
Number of blades	3	[-]
Rotor Diameter	126.0	[m]
Hub Diameter	3.0	[m]
Hub Height	90.0	[m]
Rated Rotor Speed	12.1	[rpm]
Rated Generator Speed	1,173.7	[rpm]
Gearbox Ratio	97.0	[-]
Maximum Tip Speed	80.0	[m/s]
Hub Overhang	5.0	[m]
Shaft Tilt Angle	5.0	[deg]
Rotor Precone Angle	-2.5	[deg]



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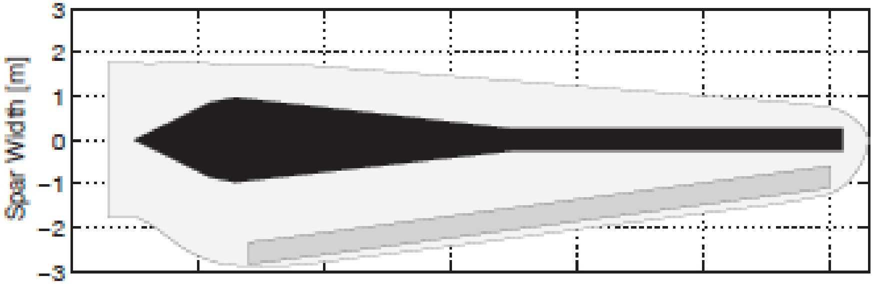


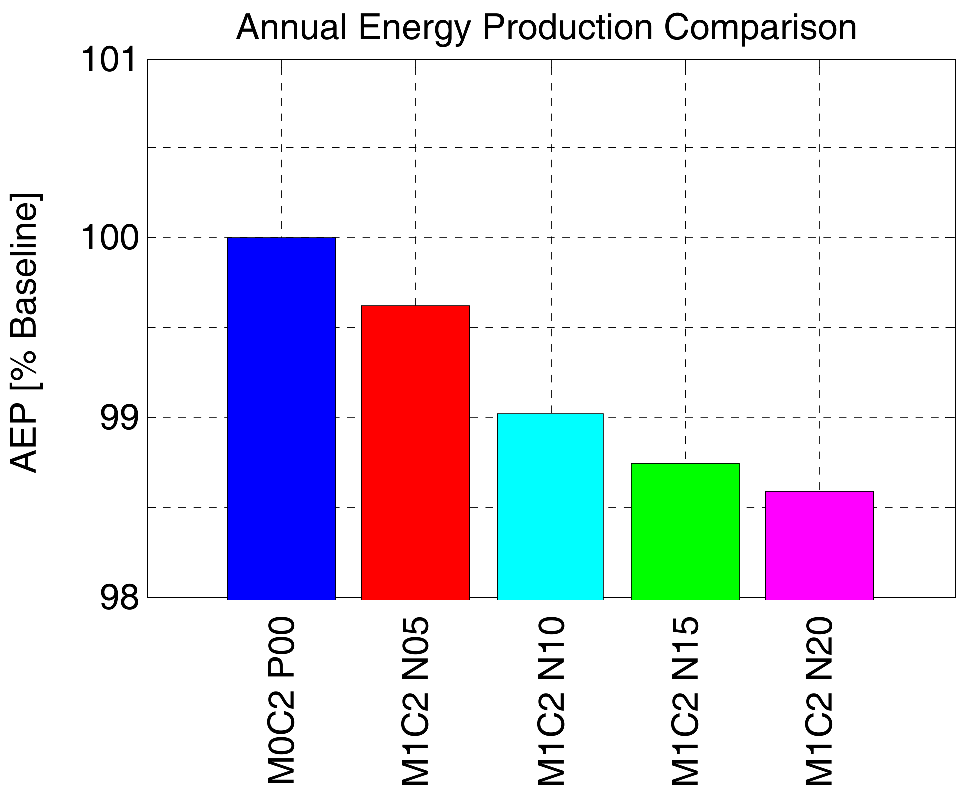
Results: Power Production (Stationary Analysis)

When the blade twists under loading, the angle of attack changes.

This lowers the C_P and power if the blade is not re-tuned for the dynamic twist angle.

Here a standard Weibull wind speed distribution is used to calculate the AEP.

$A = 8$, $k = 1.9$

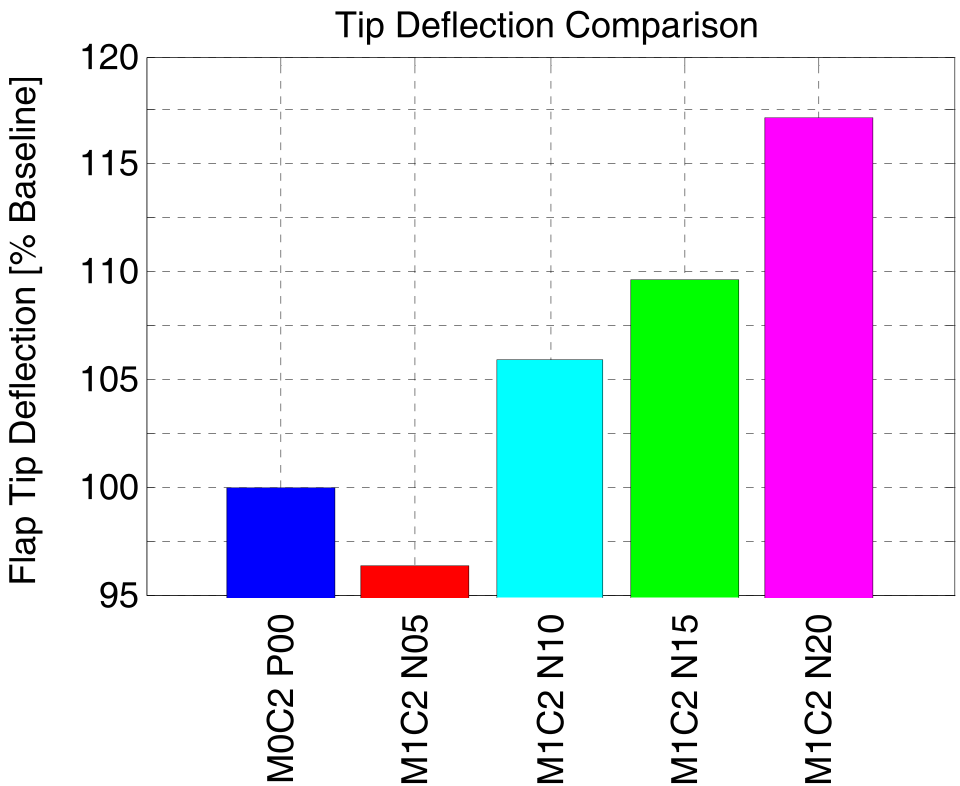


Results: Tip Deflection (Stationary Analysis)

The rotation of the fiber angle away from the blade axis lowers the bending stiffness (if not reinforced).

The loading decreases, but not at the same rate as the bending stiffness.

Blades with larger fiber angles (> 5 degrees) have more tip deflection.

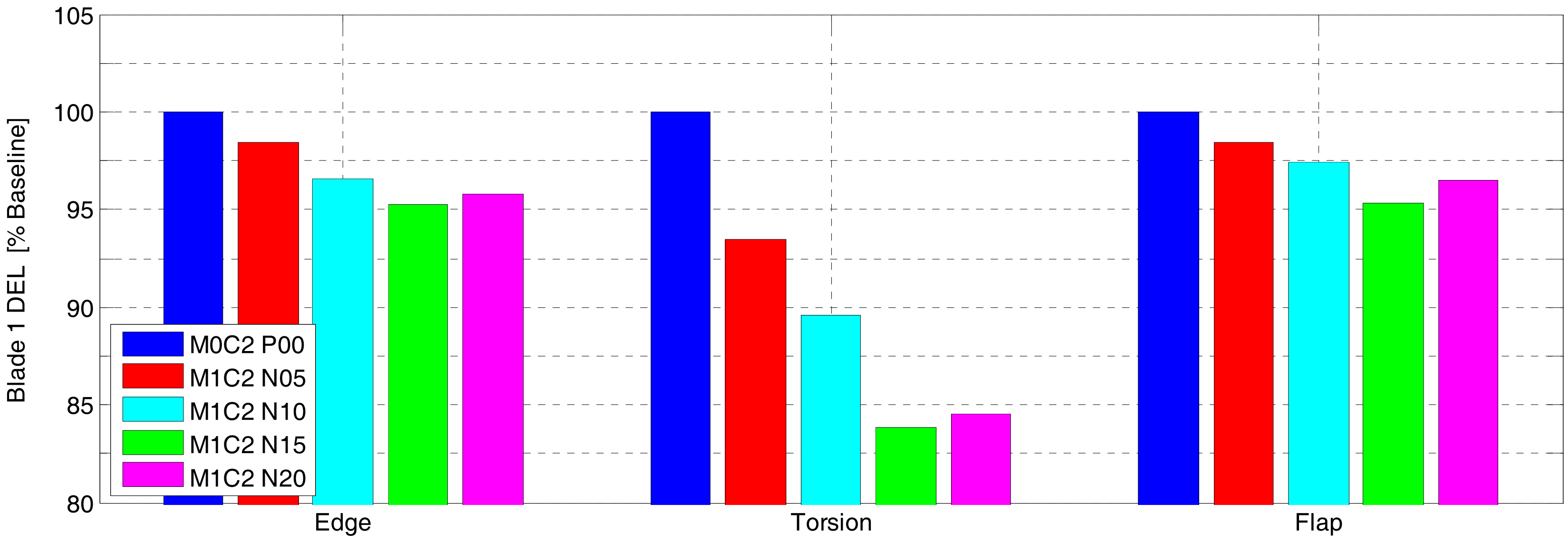


Results: Load Reduction (Dynamic Analysis)

The damage equivalent loading is reduced for the increasing fiber angle.

The flap load reduction is reduced by ~4% for the M1C2N15 model.

The stress reduction would be greater due to the superposition of both the torsion and bending loads.



Discussion of Results

Most of the previous results were confirmed (re-learned).

However, the detailed composite modeling (possible with VABS) and aero-elastic simulation (PHATAS) showed limits that were not clarified with earlier research.

1.Coupling reduces bending stiffness* increasing tip deflection

2.Bend Twist DOF in simulation reduces expected C_P unless blade is retuned.

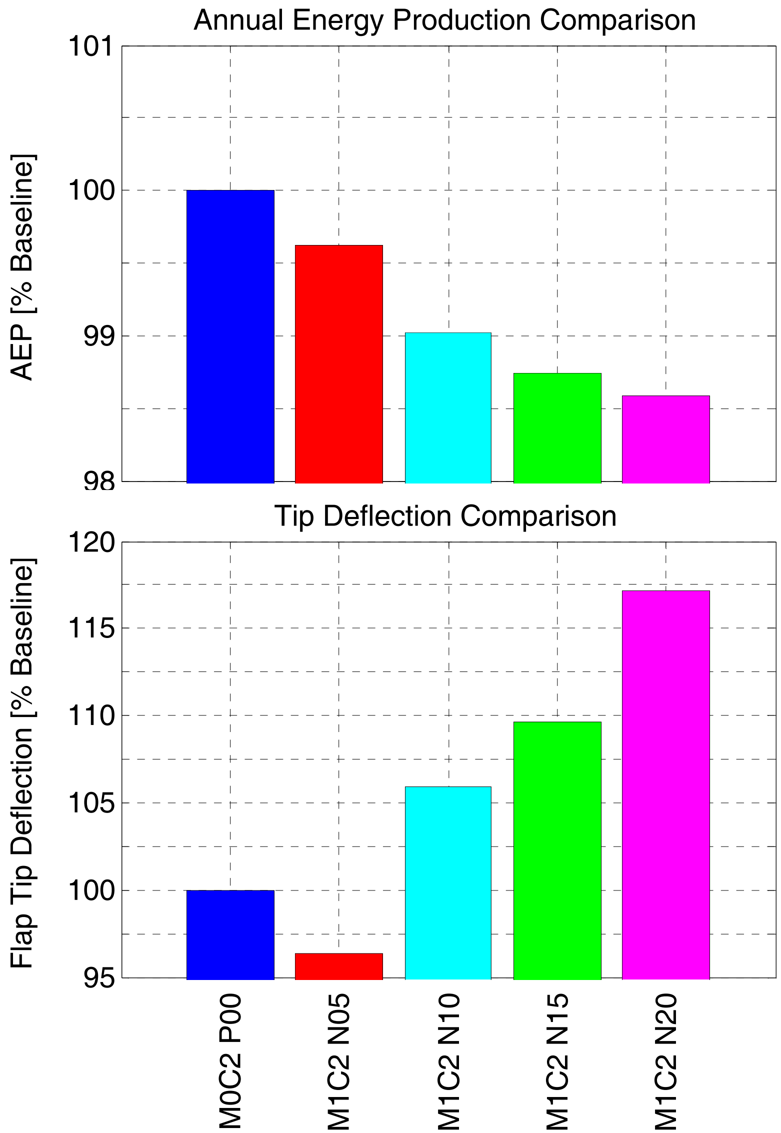
3.Load reduction is not strictly correlated with fiber angle.

Proposed Solutions

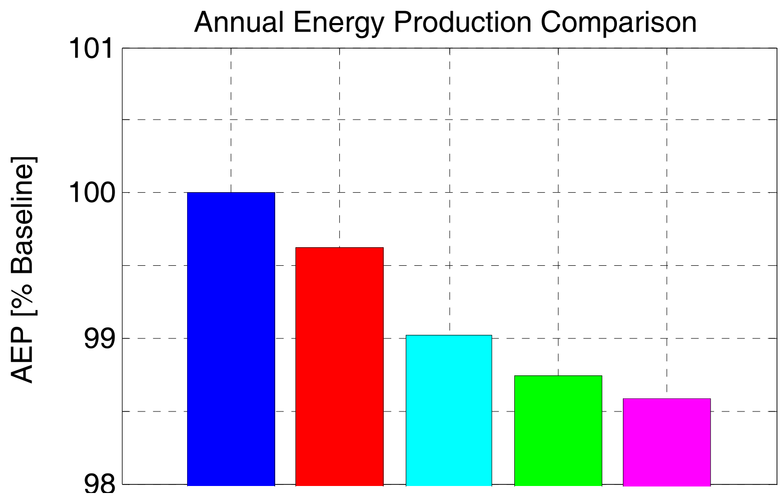
1. Stiffening the blade increases the cost and changes the coupling parameters (and benefit is hard to calculate).
2. Blade can be re-tuned (twist angle) for induced deflection (ongoing work with FE-Aeroelastic simulation/optimization)
3. Coupling is only beneficial in the range where tip deflection is decreased and/or overall blade root loading with minimal power decrease (AEP).
4. Increase blade length to meet DEL from uncouped blade (‚grow the rotor')

Discussion of Results

- The small angles provided load reduction, reduced or equivalent tip deflection and approximately the same AEP.
- Larger angles had more load reduction, but increased tip deflection and decreased AEP.
- Ignoring the changing structural properties with changing fiber angle can lead to overly optimistic results.

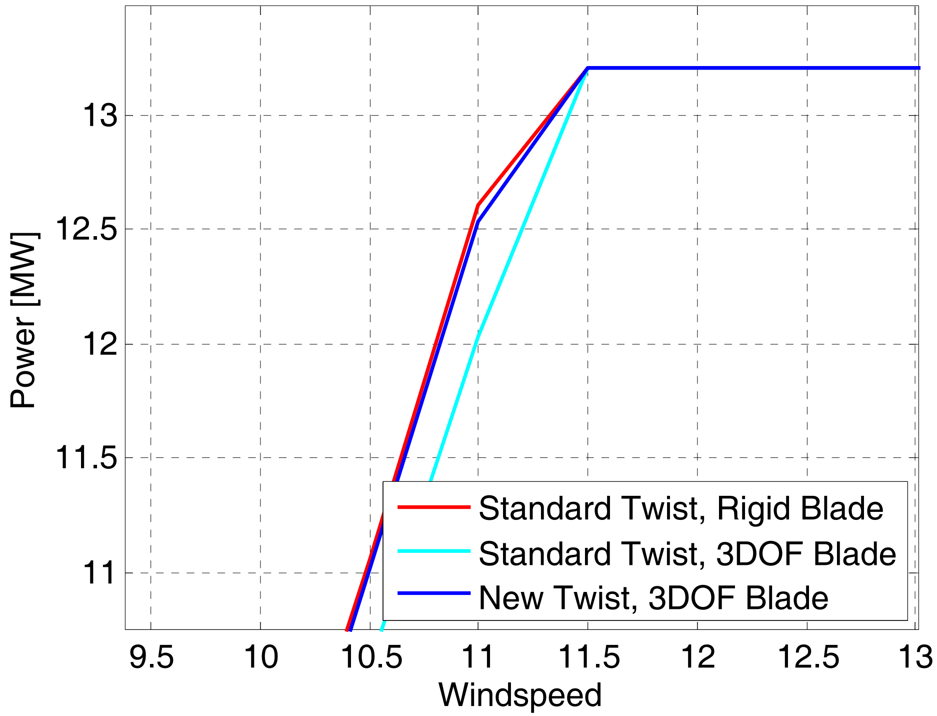


Lessons learned and applications for wind energy.



The decrease in annual energy production is due to the torsional deflection of the BTC blade.

Some improvement in the Cp curve is possible by dynamically calculting the structural twist for the blade.



Blade Shape Improvement: Proposed Method

Preliminary:

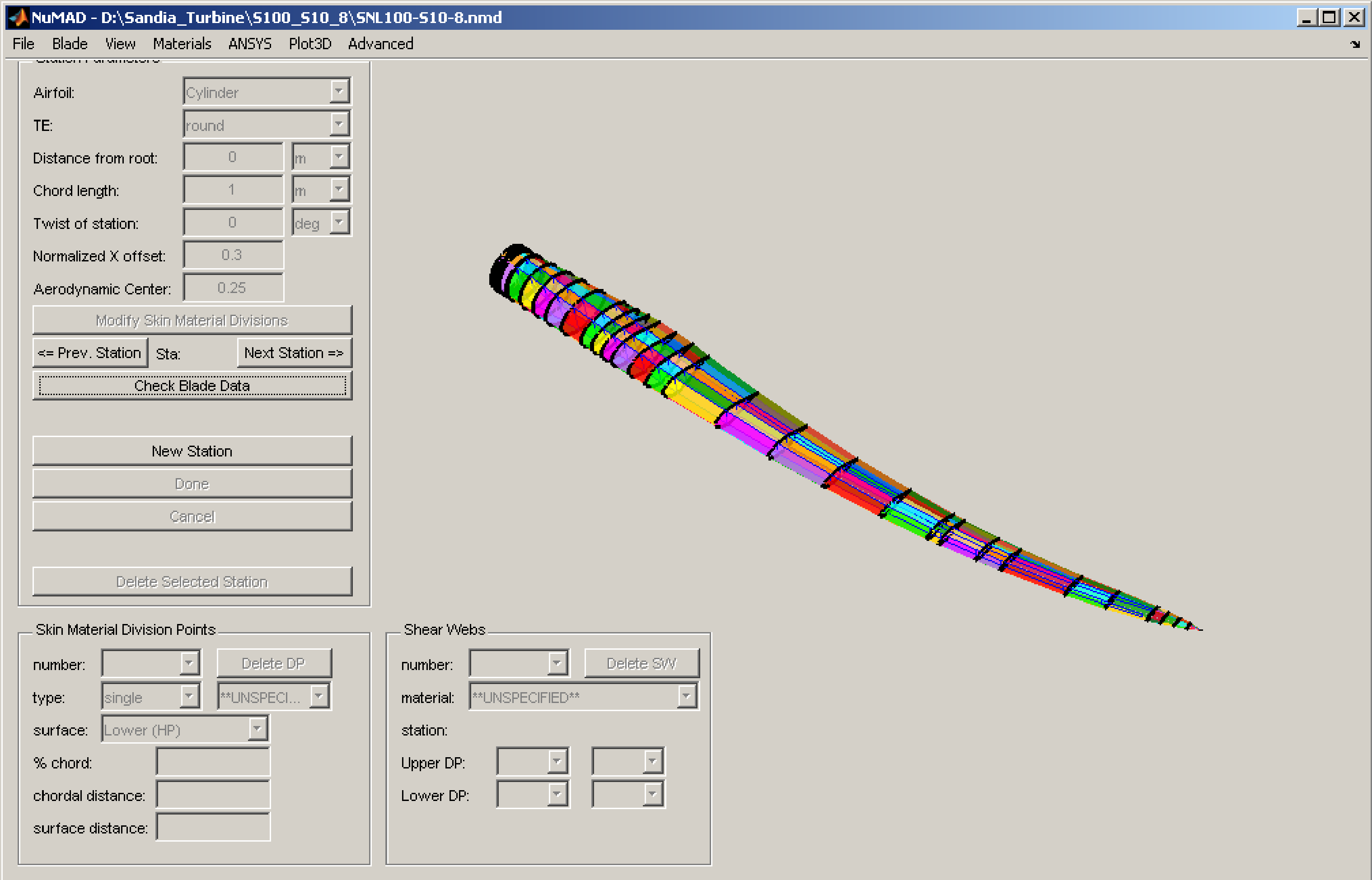
- The blade shape (twist angle) should be at the optimal angle of attack under load (when deflected).
- The best wind speed or point of optimization is the peak power density (Weibull distribution x power curve).
- Simple loading (BEM) can be used since the blade twist angle is to be optimized for steady inflow.
- Method should be valid for any blade with torsional deflection (ie, all blades).

Challenges:

- If you generate a BEM loading, load a blade model and observe torsional deflection, then your preliminary load was wrong.
- Your deformed shape is also wrong (but probably closer to reality).

ABIT example, swept blade to emphasize twist

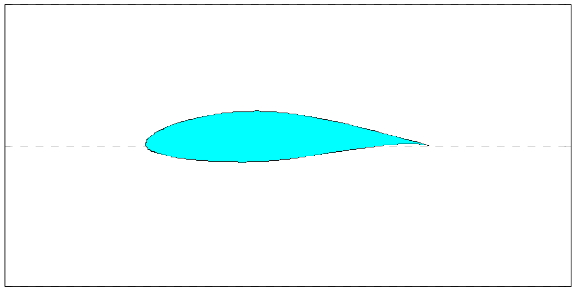
Numad (Sandia) used to modify S100 blade



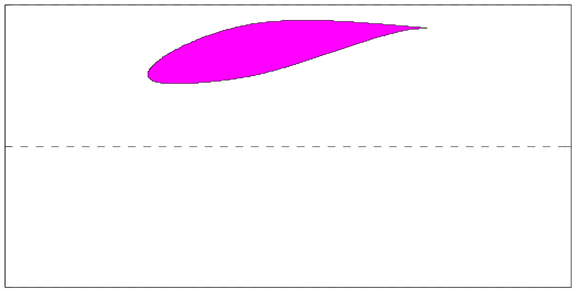
Blade Shape Improvement: Methodology

Step 1: Generate a more accurate deformed shape.

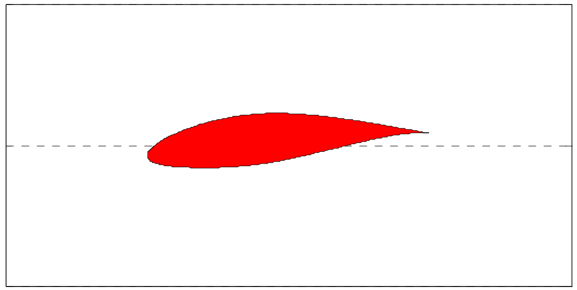
- Load blade model (NuMAD) and data (airfoil lift/drag...)
- Generate BEM load (ANSYS APDL)
- Load blade model
- Determine induced twisting along blade (LE and TE nodes)
- Correct load by altering the blade twist angle but only in the BEM calculation (for speed).



Twist 1 (Betz, Schmitz..)



Induced twisting

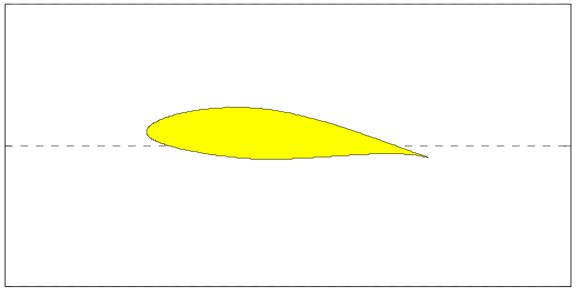


Corrected twist (iteration 2)

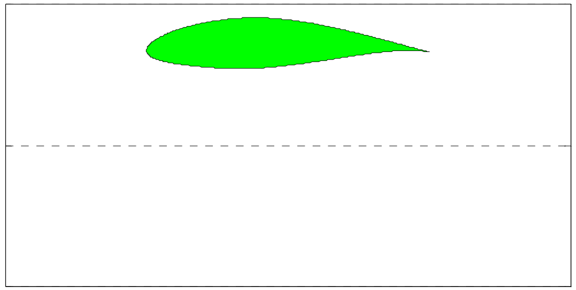
Blade Shape Improvement: Methodology

Step 2: Iterate towards a optimal deformed blade shape (twist).

- Generate BEM load (ANSYS APDL) with
- Load blade model
- Determine induced twisting along blade
- Correct load by altering the blade twist angle but only in the BEM calculation (for speed).
- Correct blade shape (iterated) should be same as first (undeflected) shape.

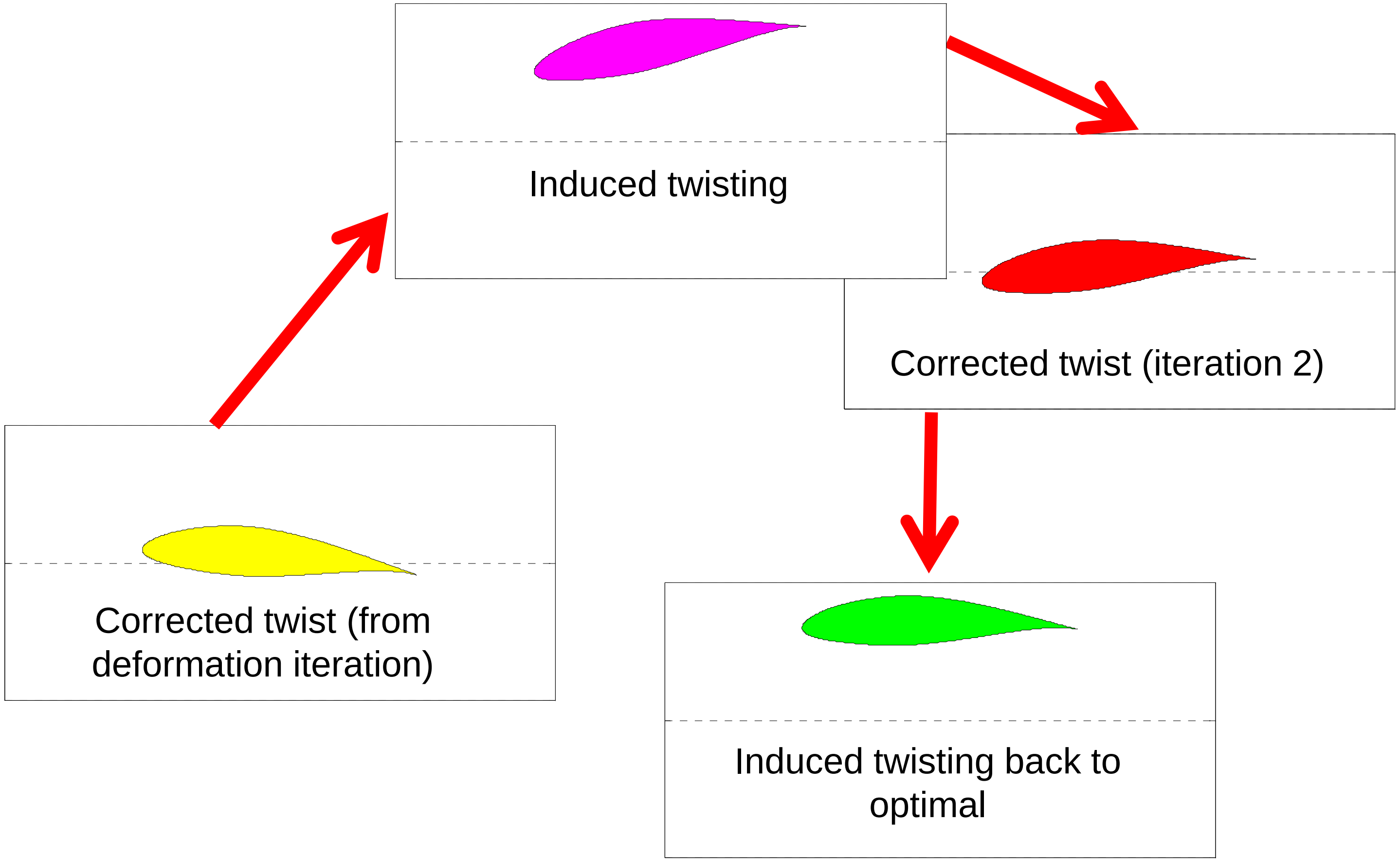


Corrected twist (from deformatoin iteration)



Induced twisting back to optimal

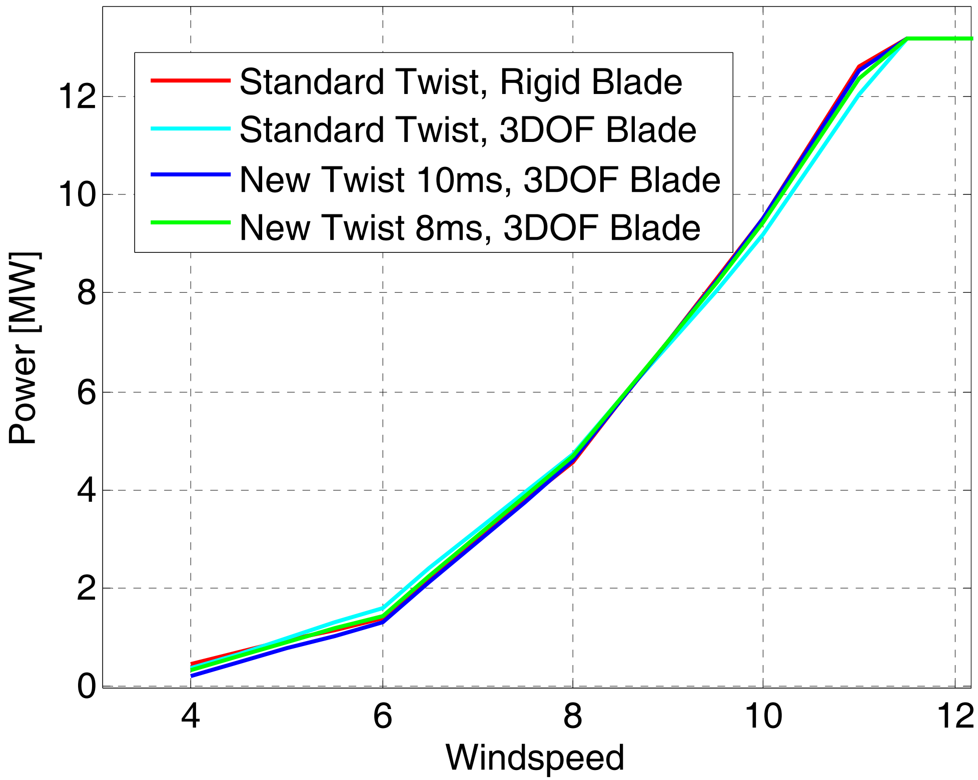
ABIT: Aero-elastic Blade Improvement Tool



ABIT: Tune the blade shape for the max power density.

The blade can be optimized for power production if the deformed shape is optimal for the peak of the power density (power curve x wind distribution).

This becomes a site specific turbine.



Thank you for your attention!

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Special thanks to the Sandia team!