NAWEA
NORTH AMERICAN WIND ENERGY ACADEMY

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Investigation of Dynamic Loading for 13.2 MW Downwind Pre-Aligned Rotor

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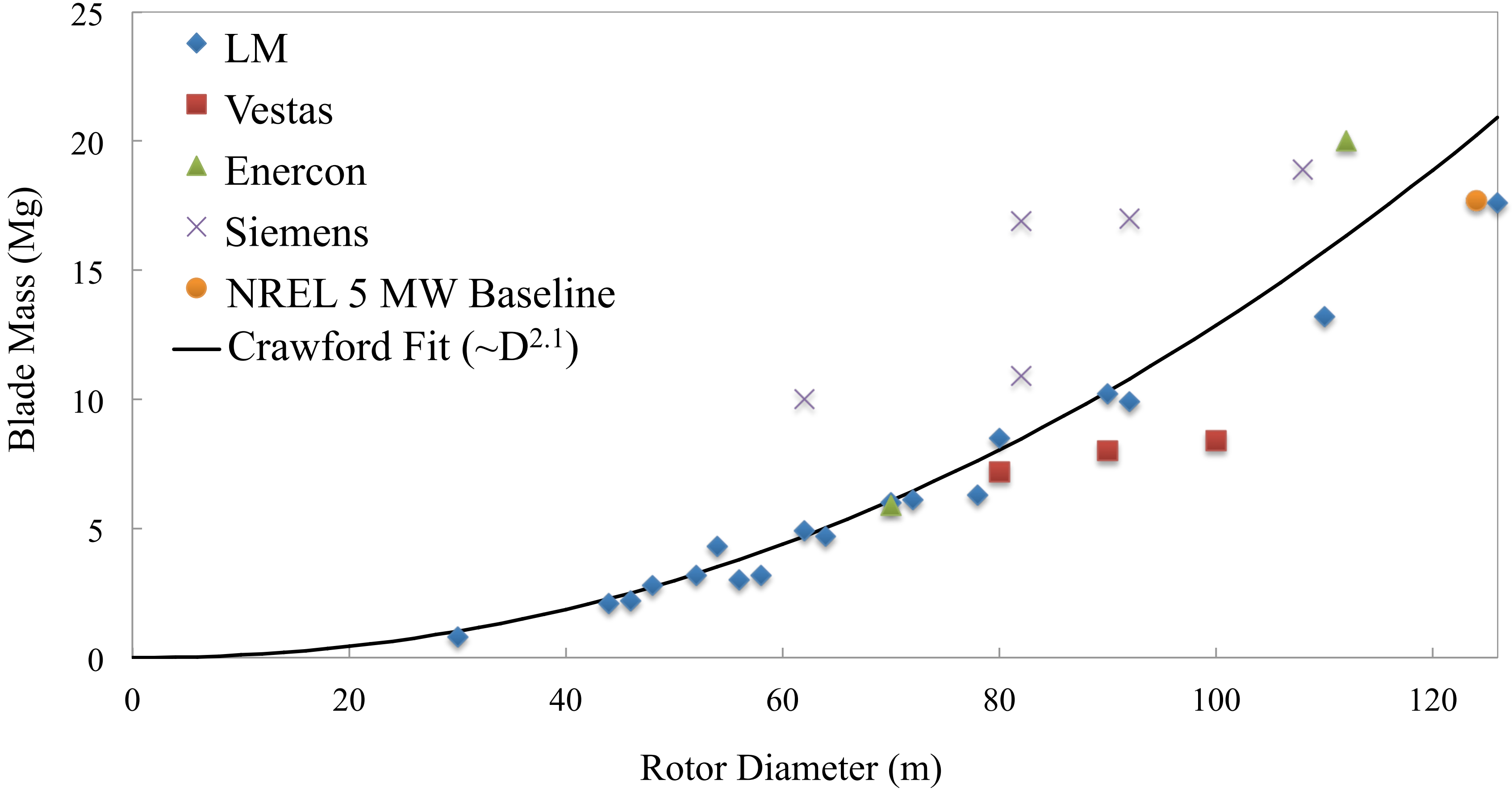
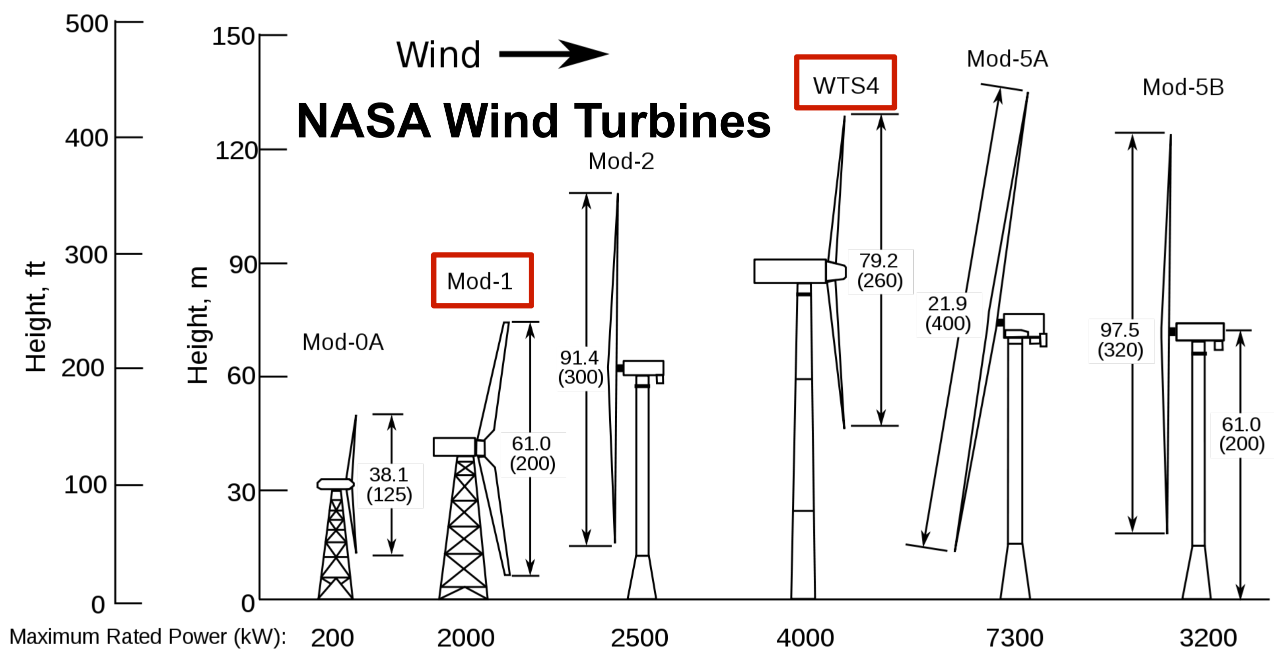
Outline

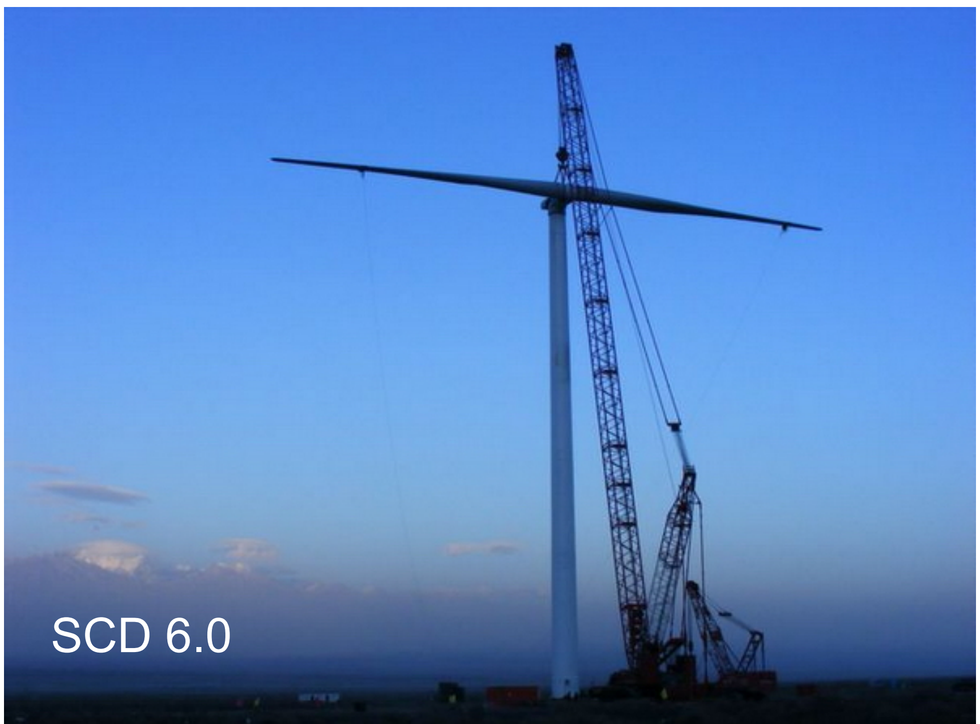
- Extreme-scale issues & Force alignment
- Pre-Alignment & Impact of this design
- FAST simulations & main results
- Discussion & Conclusion

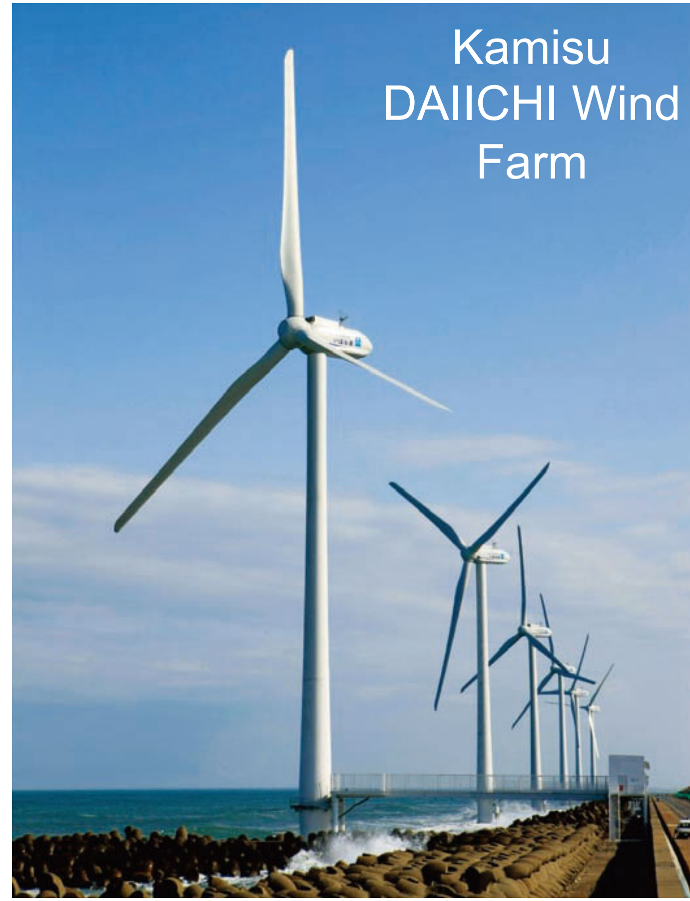
Increasing sizes lead to increasing mass & increasing exponents (2.5+) once gravity loads start to dominate




NASA Wind Turbines
Wind
Height, ft
0
100
200
300
400
500
Height, m
0
30
60
90
120
150
Mod-0A
38.1
(125)
Mod-1
61.0
(200)
Mod-2
91.4
(300)
WTS4
79.2
(260)
Mod-5A
21.9
(400)
Mod-5B
97.5
(320)
61.0
(200)
Maximum Rated Power (kW):
200
2000
2500
4000
7300
3200


SCD 3.0


SCD 6.0


Kamisu
DAIICHI Wind
Farm


Hitachi
2.0/80

Rotor size trends

Larger turbines mean more energy captured
Increased MW reduces “plant” &“utility-integration” costs
Next great frontier: “extreme-scale” off-shore wind turbine systems

Reduce the rotor mass and satisfy tower clearance requirement

Early evaluations of new wind turbine concept

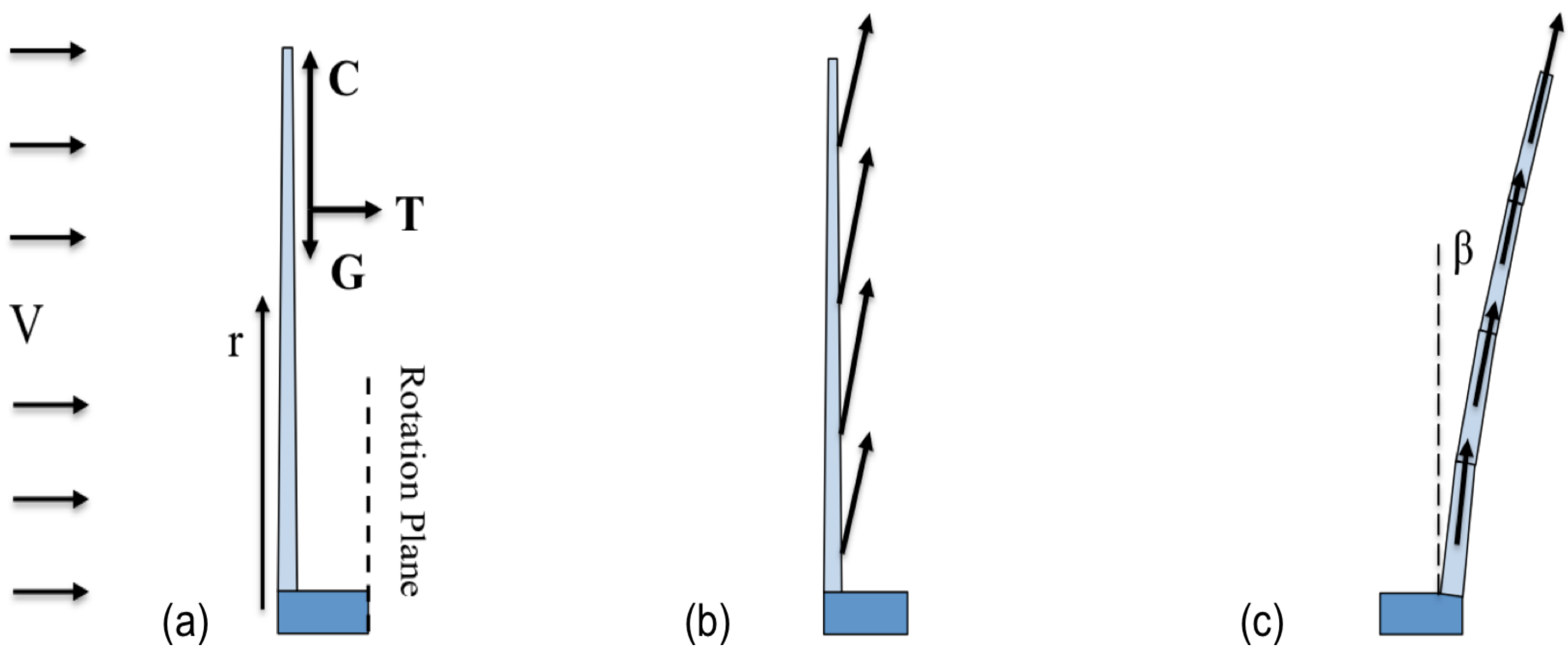
Pre-Aligned Concept

Bio-Inspiration

Fix load alignment to reduce cantilever moments

Wind Turbine Forces

Conventional vs. Load-Aligned



Load combination of centrifugal (C), gravity (G), and thrust (T) aligned along the blade path via downwind coning

Method & Test Conditions

Methodology

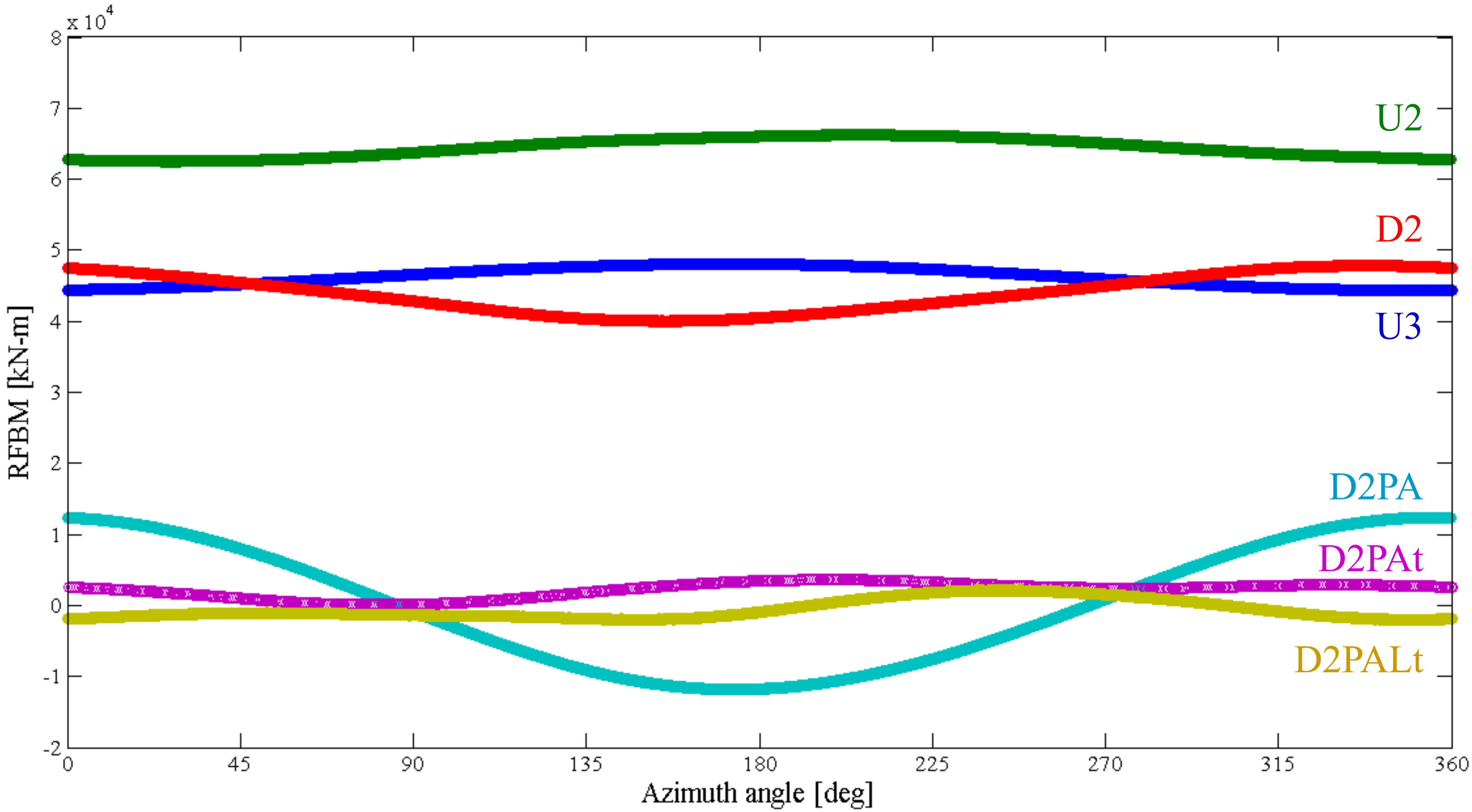
- Aeroelastic simulator FAST, an open source code developed at NREL, is employed to predict loads acting on HAWT blades
- Reference turbine is Sandia 13.2 MW upwind turbine with 100 m blades
- Damage equivalent loads (DEL) of the blades, calculated by MLife code, are used to address impacts of different designs on fatigue

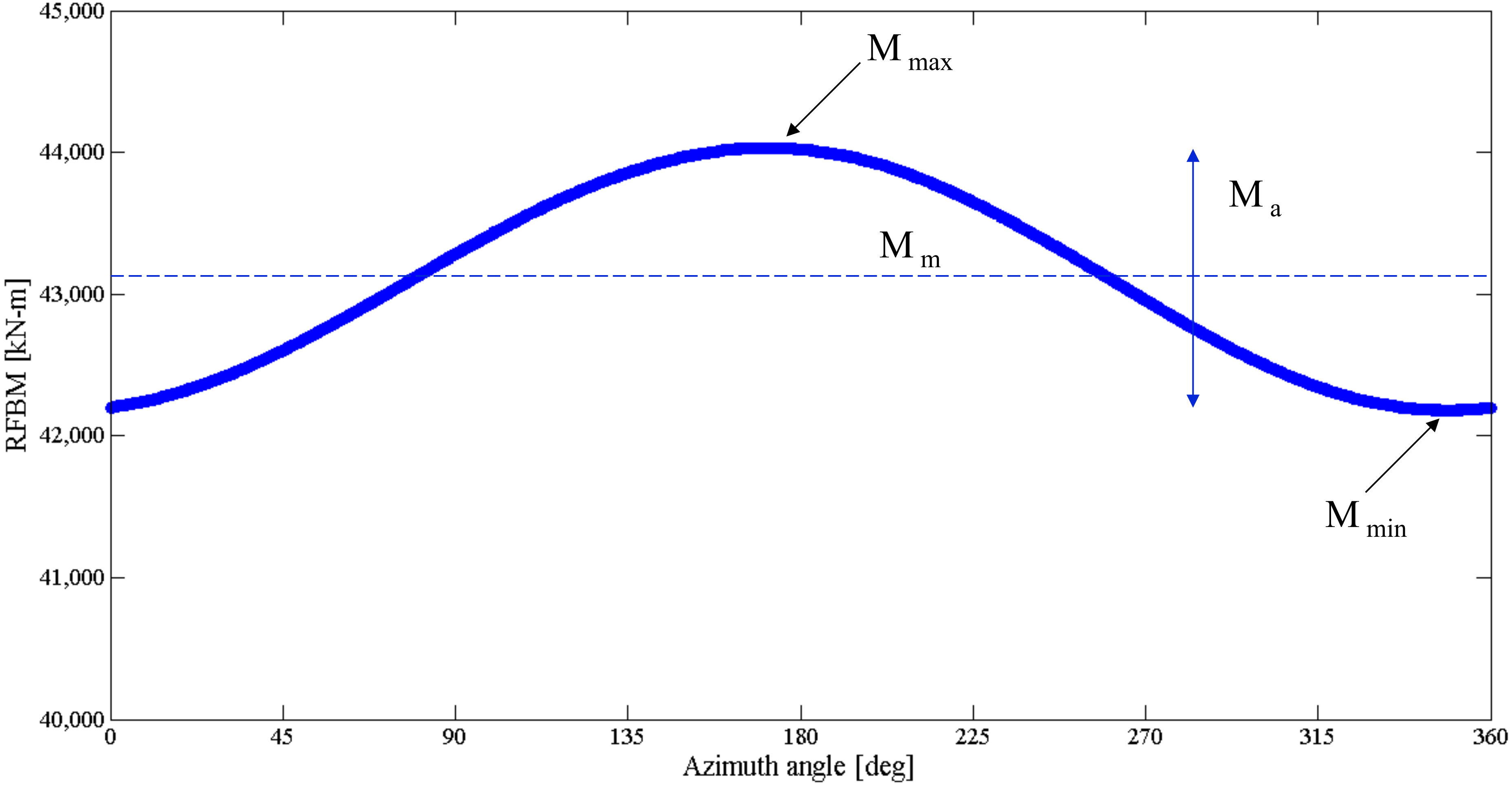
Sandia 13.2 MW Reference

- Rated wind speed V_{rated}, = 11.3 m/s
- Blade: SNL100-00 (117 Mg)
- Conventional design: U3, U2, D2
- Pre-aligned design: D2PA, D2PAL
- Modify Drivetrain and control system
- Turn on pitch and variable-speed controllers
- Turn off tower shadow and potential flow
- Calculate damage equivalent loads (DELs)

Case parameters and main outputs in FAST Simulation

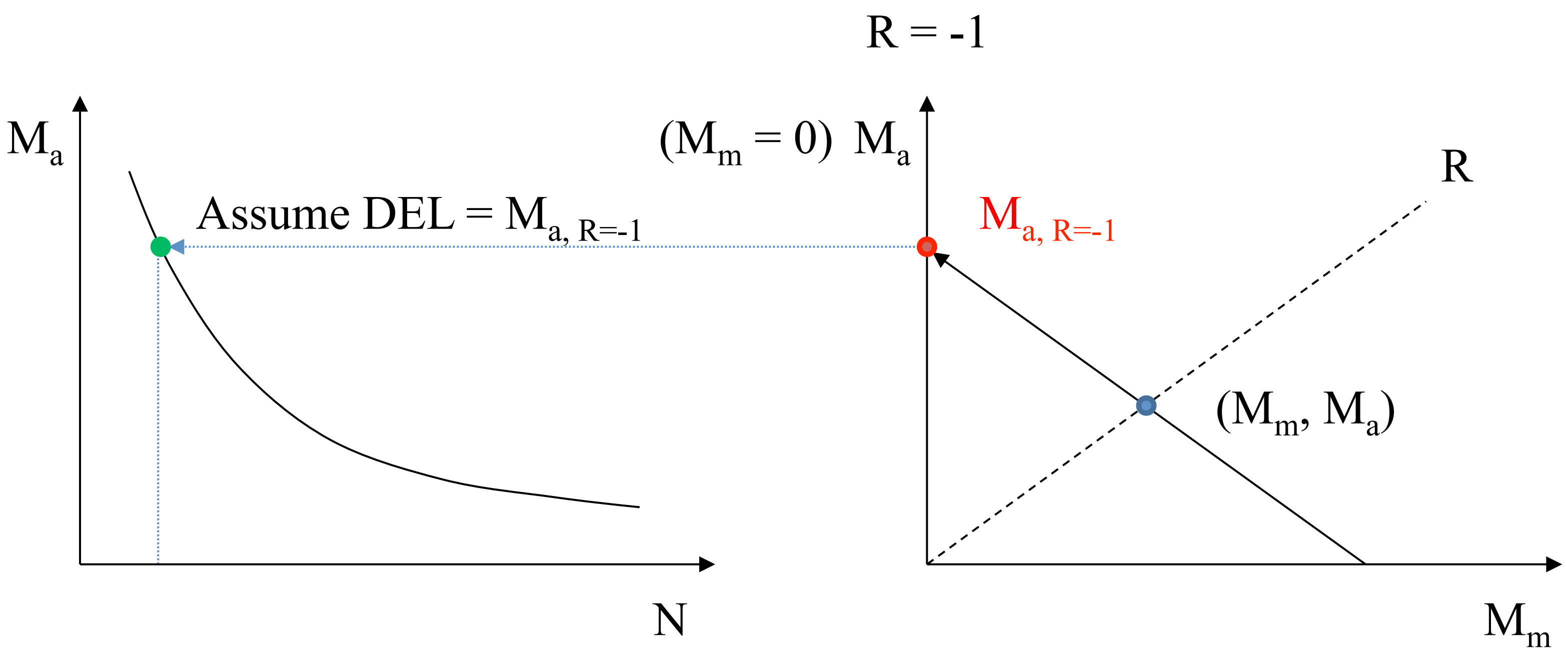
Case	Blade Mass (Mg)	Rotor Mass (Mg)	Cone (deg)	α (deg)	Teeter	ω (rpm)	Cp (-)	λ (-)
U3	114.2	342.6	-2.5	0.0	No	7.44	0.459	7.06
U2	114.2	228.4	-2.5	-1.8	No	8.93	0.458	8.47
D2	114.2	228.4	2.5	-1.8	No	8.93	0.458	8.47
D2PA	114.2	228.4	17.5	-1.8	No	8.93	0.418	7.90
D2PAt	114.2	228.4	17.5	-1.8	Yes	8.67	0.388	7.86
D2PALt	125.6	251.2	Stretch blade by 10%			8.93	0.395	8.93


x 10^4
8
7
6
5
4
3
2
1
0
-1
-2
RFBM [kN-m]
0
45
90
135
180
225
270
315
360
Azimuth angle [deg]
U2
D2
U3
D2PA
D2PAt
D2PALt



M max
M a
M m
M min
45,000
44,000
43,000
42,000
41,000
40,000
RFBM [kN-m]
0
45
90
135
180
225
270
315
360
Azimuth angle [deg]

M-N Curve + Goodman Diagram



$$Ma = Mu \times N^{(-1/m)}$$

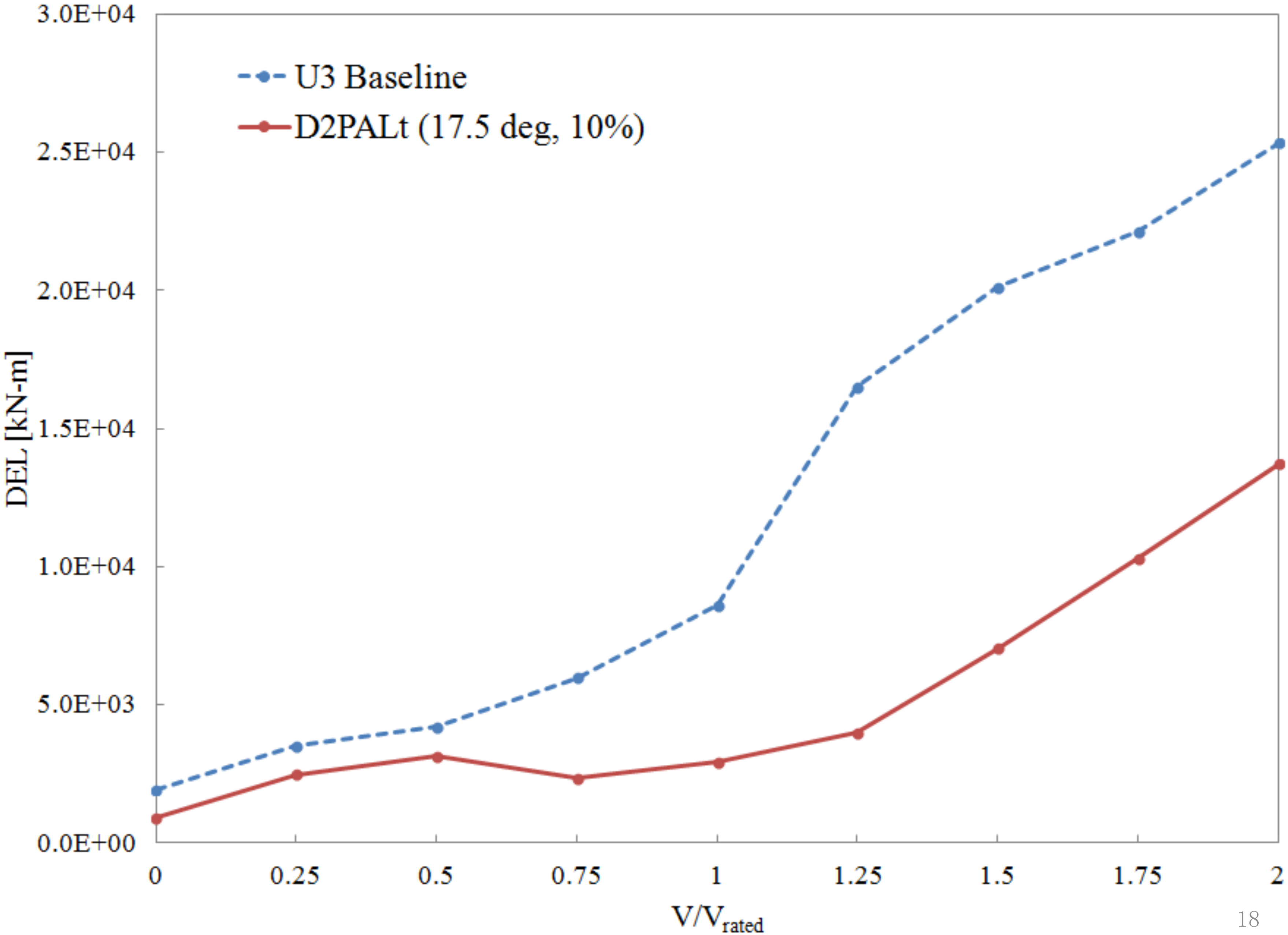
$$R = \frac{M\,min,1cycle}{M\,max,1cycle} = \frac{Mm - Ma}{Mm + Ma}$$

Where,

Ma	Amplitude moment in one load cycle	Mmin,1cycle	Minimum moment in one load cycle
Mu	Ultimate moment of the blade	Mmax,1cycle	Maximum moment in one load cycle
N	Allowable cycles to failure		
m	Slope of the curve		

Case parameters and main outputs in FAST Simulation

Case	Rotor Mass (Mg)	Cone (deg)	α (deg)	Teeter	ω (rpm)	Cp (-)	Pwr (MW)	RFBM (kNm)	DEL (kNm)
U3	342.6	-2.5	0.0	No	7.44	0.459	13.20	4.62E4	8.84E3
U2	228.4	-2.5	-1.8	No	8.93	0.458	13.20	6.44E4	3.79E4
D2	228.4	2.5	-1.8	No	8.93	0.458	13.20	4.39E4	1.73E4
D2PA	228.4	17.5	-1.8	No	8.93	0.418	11.09	155	2.01E4
D2PAt	228.4	17.5	-1.8	Yes	8.67	0.388	10.29	606	2.85E3
D2PAL t	251.2	Stretch blade by 10%			8.93	0.395	13.20	-581	3.41E3


U3 Baseline
D2PALt (17.5 deg, 10%)
DEL [kN-m]
3.0E+04
2.5E+04
2.0E+04
1.5E+04
1.0E+04
5.0E+03
0.0E+00
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
V/V_{rated}

CONCLUSIONS

Steady-state analysis of D2PAt allows substantial reduction in flapwise bending moment for 13.2MW wind turbine blades at rated wind condition

Stretching blade length by 10% can make up the power losses

Pre-aligned design has lower DELs at different steady wind speeds than conventional three-bladed design, but it has two blades that requests rotor running at a higher rpm

Much more work needed to determine relative feasibility for force-aligned downwind systems

Tower shadow
Turbulent wind condition
Control system
IEC standard tests
SNL100-02 blades

University of Virginia

Question and Comment

<table>
<tr><th colspan="2">Manufacturer & Model</th><th>Year</th><th>Commercial Availability</th><th>Location</th><th>Rated Power (MW)</th><th>Blade Number</th><th>Rotor Diamter (m)</th><th>Comments</th></tr>
<tr><td colspan="2">Smith-Putnam</td><td>1941</td><td>Prototype</td><td>Castleton, VT</td><td>1.25</td><td>2</td><td>53</td><td>First MW wind turbine. 1100 hrs. Blade failure.</td></tr>
<tr><td colspan="2">GE MOD-1</td><td>1979</td><td>Prototype</td><td>Howard Knob, NC</td><td>2</td><td>2</td><td>61</td><td>World's second multi-MW wind turbine. Sponsored by DOE and administered by NASA. Operated at least 18 months but full operating history is unknown.</td></tr>
<tr><td colspan="2">Hamilton-Standard WTS-3</td><td>1981</td><td>Prototype</td><td>Sweden</td><td>3</td><td>2</td><td>78</td><td>Sucessfully operated for 11 years.</td></tr>
<tr><td colspan="2">Hamilton-Standard WTS-4</td><td>1982</td><td>Prototype</td><td>Wyoming</td><td>4</td><td>2</td><td>79.2</td><td>World record for power output for over 20 years.</td></tr>
<tr><td colspan="2">GROWIAN I</td><td>1983-1988</td><td>Prototype / FAILURE</td><td>Germany</td><td>3</td><td>2</td><td>100</td><td>The most famous, most discussed and criticised German federal research project.</td></tr>
<tr><td colspan="2">Wind Turbine Company WTC-1000</td><td>Around 2000</td><td>Unknown / 250, 500kW Prototype</td><td>Colorado / California</td><td>1</td><td>2</td><td>54.3</td><td>A modern update of Smith-Putnam. Compared to 3-blade upwind ones, head weight reduces by one-half and manufacturing costs reduce by one-third.</td></tr>
<tr><td rowspan="3">Aerodyn / Ming Yang</td><td>SCD 3.0</td><td>2011</td><td>Available</td><td>South China Sea</td><td>3</td><td>2</td><td>110</td><td rowspan="3">Off-shore. Designed by Aerodyn and manufactured by Chinese licencee Ming Yang.</td></tr>
<tr><td>SCD 6.0</td><td>2013</td><td>Prototype</td><td>China</td><td>6.5</td><td>2</td><td>140</td></tr>
<tr><td>SCD 8.0</td><td></td><td>Prototype in Development</td><td></td><td>8</td><td>2</td><td>168</td></tr>
<tr><td colspan="2">Carter Wind Energy</td><td></td><td>Planned</td><td></td><td>10-50</td><td>2</td><td></td><td>Scale-up 300-500kW products.</td></tr>
<tr><td colspan="2">Hitachi HTW 2.0/80</td><td>~2010</td><td>Available</td><td>Fukushima, Japan</td><td>2</td><td>3</td><td>80</td><td>Experimental off-shore floating wind farm project begins in 2012. In second term, 7-MW wind turbines will be added between 2013 and 2015.</td></tr>
<tr><td colspan="2">Hitachi HTW 5.0/126</td><td>2013-2015</td><td>Prototype in Development</td><td>Kamisu City, Japan</td><td>5</td><td>3</td><td>126</td><td>A demonstration prototype is under construction.</td></tr>
<tr><td colspan="2">Nautica Windpower AFT</td><td>2017</td><td>Concept / Prototype</td><td></td><td></td><td>2</td><td></td><td>Advanced Floating Turbine. Digital prototype. A 1/3-scale version with a 35- m rotor is expected by 2013.</td></tr>
<tr><td colspan="2">Subaru 80/2.0</td><td></td><td>Available</td><td></td><td>2</td><td>3</td><td>80</td><td>Manufactured by Fuji Heavy Industries. Designed for strong wind. Special attention is being given to withstand the heavy typhoon in Japan.</td></tr>
<tr><td colspan="2">SWAY</td><td></td><td>Prototype</td><td>Norway</td><td>2.5-12</td><td>3</td><td></td><td>NREL is collaborating with SWAY. The SWAY 1/5 scale prototype has a 13-m rotor on a 29-m tower, with a large portion of the tower beneath the ocean surface.</td></tr>
</table>

Planed Simulation Progress

Generate Wind Input Profile

- TurbSim
- IEC Standards

FAST Simulation

- Sandia 13.2 MW wind turbine
- SNL100-02 blades
- Upwind /downwind
- Controller from NREL 5 MW turbine
- Pre-cone angles

Fatigue Analysis

- MLife
- Rainflow cycles
- Weibull distribution
  Goodman Correction
- Short-term DELs
- Life-time DELs