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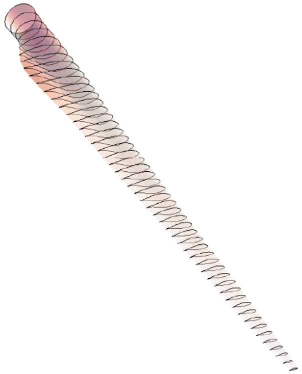

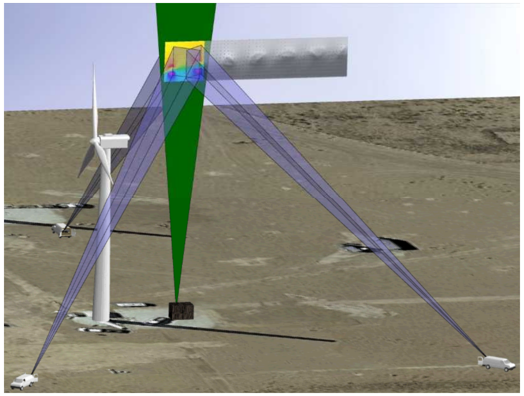

Rotor Structural / Aeroelastic Design

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Presentation Outline

- Standard Blade Requirements
  - IEC DLC discussion
  - Structural Optimization
    - Design A6S0; all glass blade
  - Blade/Turbine survivability
    - Compare to turbine loads
    - Compare to foundation loads
- Additional Blade Requirements
  - Flapwise Stiffness Analysis
  - Torsional Stiffness Analysis
- Structural Design Recommendation

Standard Requirements

- **Turbine Survivability**
  - Meet IEC Design Load Case Requirements
  - Tip Deflection
    - Allowable tip deflection toward tower is 1.328 meters, this includes total safety factor of 1.485
  - Flap Frequencies
    - Flap frequencies not in the ranges of 2.9P—3.1P or 5.95P—6.05P
  - Edge-Flap
    - The ratio of blade edgewise first natural frequency to flapwise first natural frequency shall be greater than 1.3
  - Blade mass
    - The manufactured blade mass shall be compared to the average weight of current OEM blades, 660 kg
  - Rotor Inertia
    - The manufactured blade first moment of inertia shall be compared to the average moment of inertia of current OEM blades, 27,653 kg-m

Design Load Cases

- IEC analysis currently employs DLC 1.2, 1.3, 1.4, 1.5, 6.1, 6.3
- Why only these???
  - These DLC's are what the department has known historically to be the most critical DLC's
  - Final NRT turbine controller does not currently exist.
  - Blade length, thrust, and rotational inertia are less than or equal to OEM blade
  - Rotor not intended for 20-year operation

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0,7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

SWiFT Site Classification

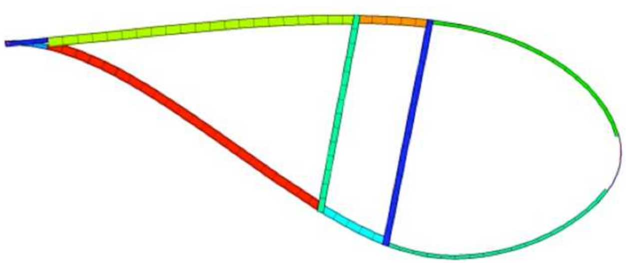
- Classification defined in terms of wind speed and turbulence parameters at the installation site.

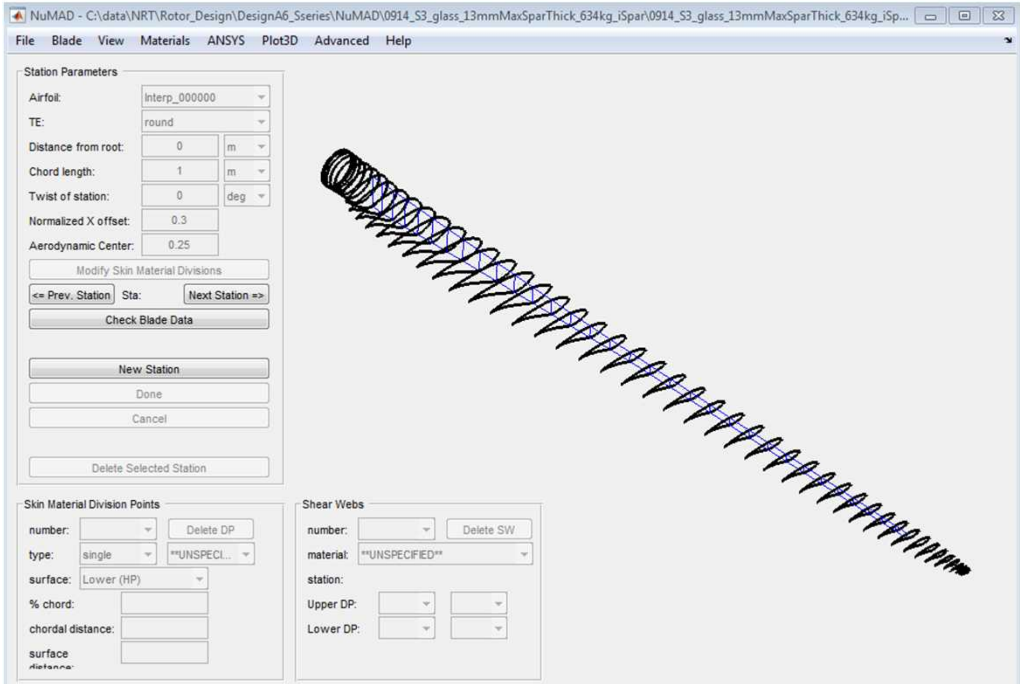
Wind Turbine Class	I	II	III
V_{avg} (m/s):	10	8.5	7.5
A	$I_{ref\ @\ 15\ m/s}$: 0.16		
B	$I_{ref\ @\ 15\ m/s}$: 0.14		
C	$I_{ref\ @\ 15\ m/s}$: 0.12		

- Using 2-years of historical meteorological tower data from Texas Tech University at the site
  - 32m hub height (SWiFT Turbines)
  - SWiFT site determined to be **III-C**

Structural Optimization

- Structural optimization performed using NuMAD to manage the material changes and PreComp and BModes to estimate the blade structural properties
- Design Load Cases 1.2, 1.3, 1.4, 1.5, 6.1, and 6.3 were analyzed using FAST aeroelastic wind turbine simulator with the structural blade representation.





Structural Optimization

- Spar Cap Width
  - Allowed to vary between [100, 700] mm
- Root Build-up
  - Thickness at inner span location; [10, 40] mm @ 0.05-0.14 span
  - Outer span location; [1] mm @ 0.15-0.19 span
- Spar Cap Thickness
  - Beginning of spar; [1, 13] mm @ 0.05 span
  - Inner thickness; [1, 13] mm @ 0.20 span
  - Inner thickness; [1, 13] mm @ 0.50 span
  - End of spar; [1, 13] mm @ 0.95 span

Structural Optimization

- Shell
  - Thickness; [2] mm
  - Foam Core; [1] mm @ 0.05, [15] mm @ 0.20, [10] mm @ 0.50 and [1] mm @ 1.0 span
- Single Shear Web
  - Fiber Thickness; [2] mm @ 0.05-0.90 span
  - Core Thickness; [10] mm @ 0.05-0.90 span
  - Fiber Thickness; [2] mm @ 0.05-0.90 span
- Carrot Material
  - Carrot Thickness; [40] mm @ 0.0-0.0154 span
  - Mass adjusted density, centered on blade bolt circle
- Leading-edge and Trailing-edge panel core
  - [1] mm @ 0.05 span; [15] mm @ 0.20 span; [10] mm @ 0.50 span; [1] mm @ 1.0 span

Structural Optimization

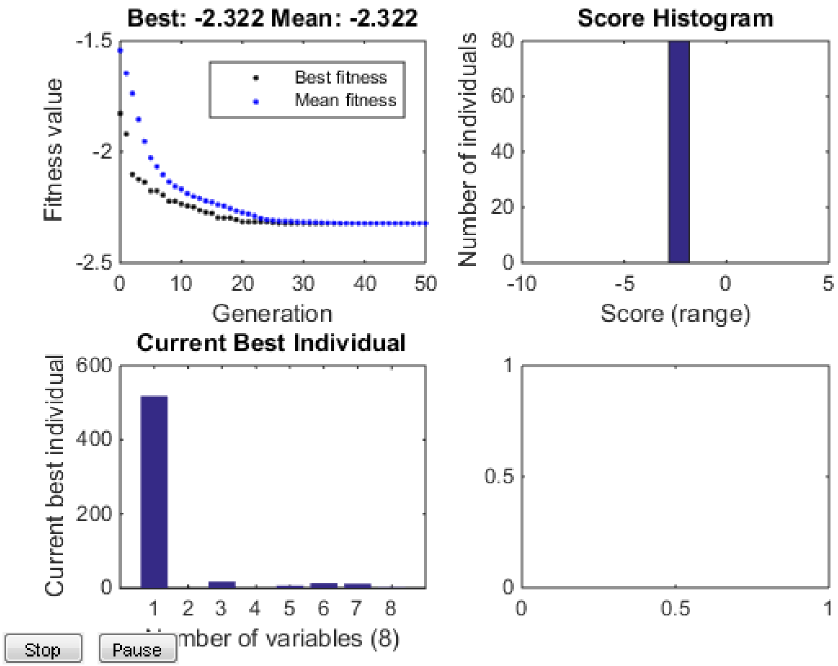
- Material Properties

Material	Type	Ex [MPa]	Ey [MPa]	Gxy [MPa]	PRxy	Density [kg/m3]	UTS [MPa]	UCS [MPa]
Gelcoat	isotropic	3440		-	0.3	1235	1	1
ELT_5500	orthotropic	47835	18197	2826	0.3	1950	875.6	-592.9
EBX_2400	orthotropic	17183	17183	9202	0.3	1900	455.1	-455.1
ETLX_2400	orthotropic	20333	9305	4756	0.3	1900	530.9	-530.9
Airex_C70_200	isotropic	175	175	75	0.3	200	1	1

- Shell: EBX_2400 (bi-axial glass)
- Shell Panel Core: Foam
- Root build-up: ETLX_2400 (tri-axial glass)
- Spar: ELT_5500 (uni-axial glass)
- Shear Web: EBX_2400 (bi-axial glass)
- Shear Web Core: Foam

Structural Optimization Results

A6S0; All glass blade



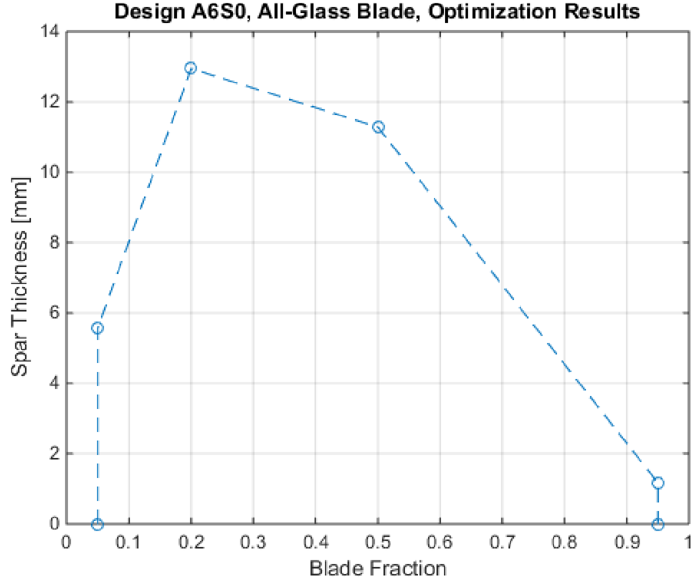
	NRT S0 - All Glass	SWiFT OEM (model)	SWiFT OEM (measured)
First Flap Frequency	2.32 hz (3.2p)	2.28 hz (3.2p)	2.34 hz (3.2p)
First Edge Frequency	4.74 hz (edg/flp = 2.04)	3.40 hz (edg/flp = 1.49)	3.81 hz (edg/flp = 1.62)
Weight (kg)	632 kg	597 kg*	659 kg
Rotor Inertia (kg-m^2)	20,141	22,881	n/a

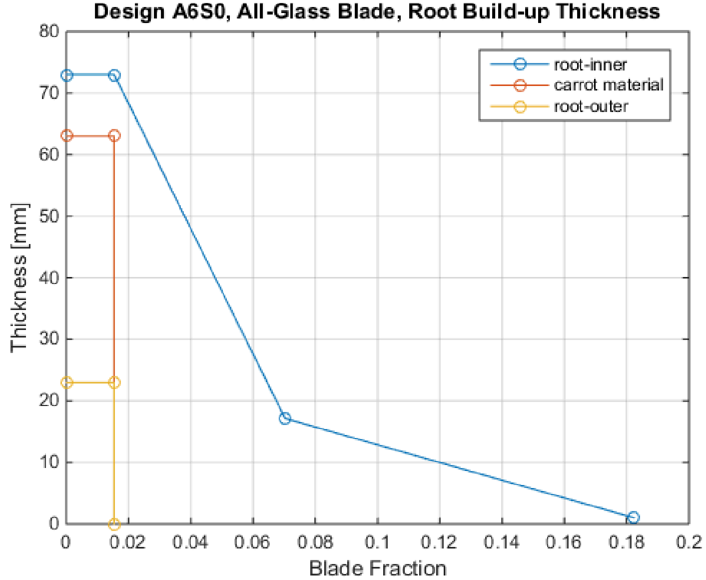
*does not include 40kg of root hardware

Structural Optimization Results

A6S0; All glass blade

Spar Cap Width: 518 mm





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Weight (kg)	632 kg	597 kg*	659 kg
Rotor Inertia (kg-m^2)	20,141	22,881	n/a

*does not include 40kg of root hardware

SWiFT Turbine Loads Analysis

Load Direction	Coordinate	Allowable Loads	Driven By:
Blade Root Bending	Mxb,i	210 kN-m	Pitch Bearings static
Blade Root Bending	Myb,i	210 kN-m	Pitch Bearings static
Blade Tip Deflection	OoPDefl	1.328 m	Tower Clearance
Nacelle Yaw Moment	Mzn	n/a	Yaw System
Tower Base Moment (side-side)	Mxt	4510 kN-m	Foundation
Tower Base Moment (fore-aft)	Myt	4510 kN-m	Foundation

Turbine Partial Safety Factors

$$F_d = \gamma_F F_k$$

- F_d, Design load
- γ_F, partial safety factor
- F_k, Characteristic load

- Turbine is designed to not exceed the characteristic load, using partial safety factors from IEC 61400-1
- For loads compared, a $\gamma_F = 1.35$ is used
- Following results are compared for Design Strength and Design Loads
- For critical displacements, a $\gamma_F = 1.35 * 1.1 * 1.0 = 1.485$ is used

Loads Analysis – Blade Loads

Load Direction	Allowable Loads	NRT Rotor Design Loads	SWiFT Rotor Design Loads
Root Edge Bending	210 kN-m	67.9 kN-m (DLC 1.3 ETM; 15 m/s)	83.8 kN-m (DLC 1.3 ETM; 13 m/s)
Root Flap Bending	210 kN-m	177.1 kN-m (DLC 6.1 EWM50; +15 deg)	181.7 kN-m (DLC 6.1 EWM50; +15 deg)
Blade Tip Deflection	1.97 m	0.68 m (DLC 1.3 ETM, 19 m/s)	0.97 m (DLC 1.3 ETM, 15 m/s)
Nacelle Yaw Moment	n/a	93.7 kN-m (DLC 1.3 ETM, 23 m/s)	132.6 kN-m (DLC 1.3 ETM, 21 m/s)

Loads Analysis – Foundation Loads

Load Direction	Allowable Loads	NRT Rotor Design Loads	SWiFT Rotor Design Loads
Tower Base Moment (side-side)	4510 kN-m	988.4 kN-m (DLC 6.1 EWM50, +15 deg)	1388.3 kN-m (DLC 6.1 EWM50, 15 deg)
Tower Base Moment (fore-aft)	4510 kN-m	1191.3 kN-m (DLC 1.3 ETM, 15 m/s)	1716.1 kN-m (DLC 1.3 ETM, 19 m/s)

Additional Requirements

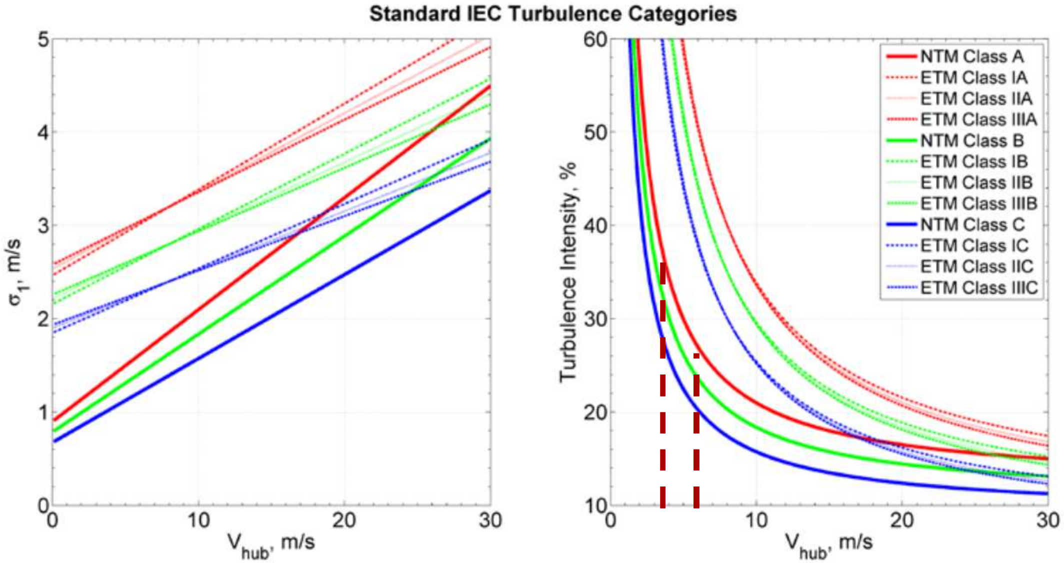
- **Ensure Model Predictability**
  - Sufficient flap stiffness
    - The blade shall have sufficient flap stiffness such that section body velocities do not induce dynamic changes in section angles of attack which vary more than 1 degree from nominal, steady design values for Region II operation.
  - Sufficient torsional stiffness
    - The blade shall have sufficient torsional stiffness such that the blade sections do not experience dynamic changes in section angles of attack which vary more than 1 degree from nominal, steady design values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.
  - No twist coupling
    - The blade structure shall be designed such that there is minimal coupling of twist deflection with any other blade elastic degrees of freedom.

Additional Requirements

- **Ensure Model Predictability**
  - Structural Linearity
    - The blade tip shall not deflect more than 5% of blade length under any normal operating loads. A blade structure which does not deflect more than 5% of its length is assumed to have linear elastic behavior.
  - Design for loaded operation (static twist)
    - Static blade twist distribution shall be designed to match a target distribution at a single operating point of U_{∞}=6 m/s (a middle wind speed in Region II). Deviation from nominal twist design at other operating points in Region II shall not exceed 0.5 degrees. This requirement is meant to ensure that the blade performs as intended under steady aeroelastic loading at the stated operating wind inflow speed.

Analysis Approach

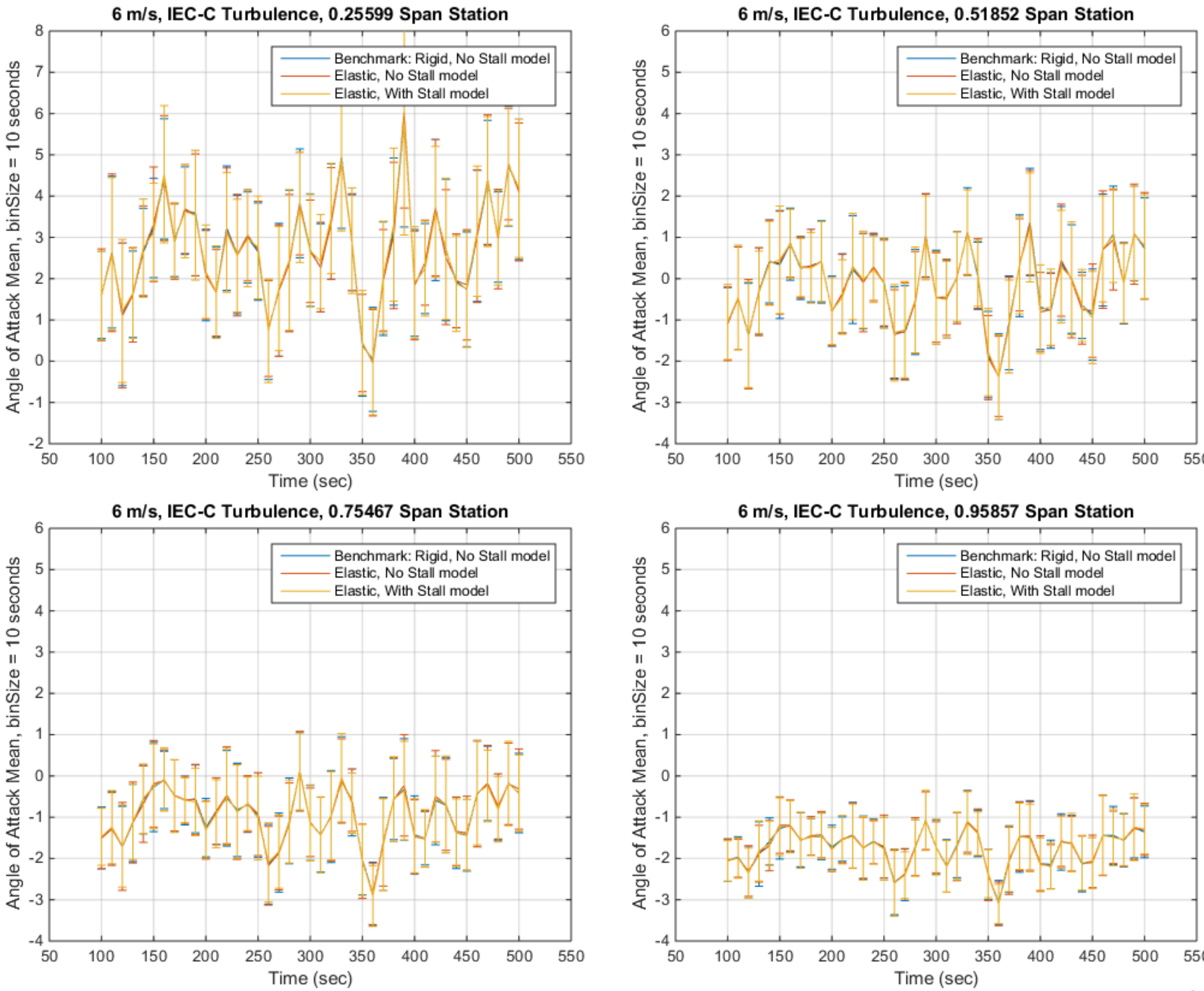
- FAST simulations using the S0 NRT structural blade design
- Tested with TurbSim generated turbulence input files for high (class A) and low (class C) turbulence.
  - Bottom of Region II: 4 m/s (TI = [25, 35]%)
  - Top of Region II: 6 m/s (TI = [18, 25]%)



Effect of Flap/Edge Stiffness

FAST simulation results of model angle of attack in turbulence for A6S0 blade compared to rigid blade (blade DOFs disabled)

- 6 m/s, NTM – C
- Shown with stall model enabled and disabled



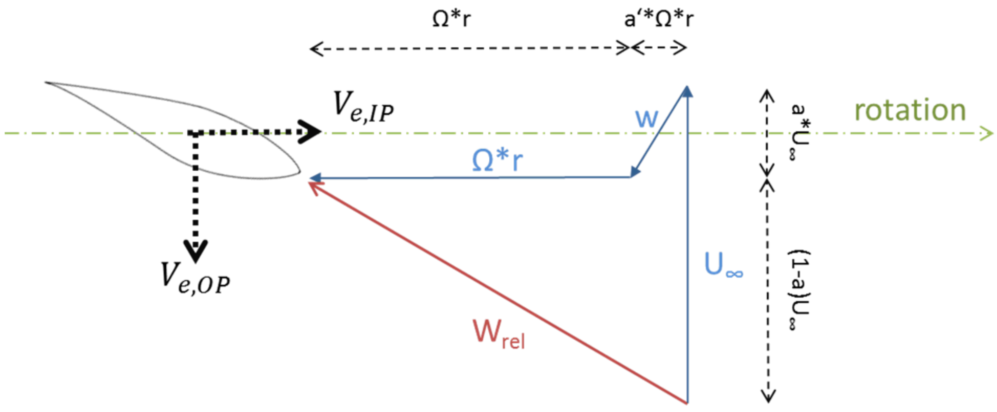
Simulation Results:

- For the 3.2p blade, there is no noticeable difference in angle of attack for rigid blade
- Turbulence effects dominate the AoA effect due to elasticity and body velocities

Effect of flap/edge stiffness

As a check of the FAST simulation results, an analytical method is used to calculate the angle of attack from FAST output values for tip in-plane and out-of-plane velocities

- Body velocities are a function of the blade flap and edge stiffness
- Due to higher rotational velocity (TSR=9) and higher edge stiffness, the greatest contribution to angle of attack changes due to elasticity will be from Out-of-plane deflections.
- Twist due to torsion is not included in this analysis
- Calculations do not directly include the time history of Angle of Attack effects



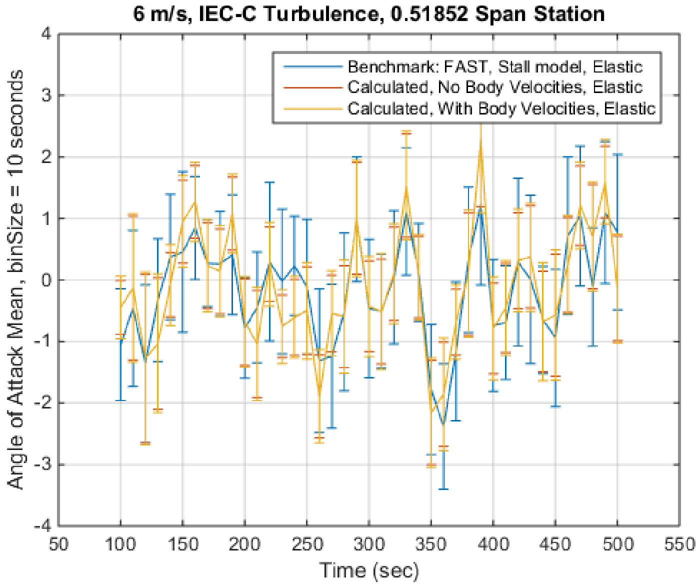
$$\tan(\alpha+\beta) = \frac{U_\infty(1-a)+V_{e,OP}}{\Omega r(1+a')+V_{e,IP}}$$

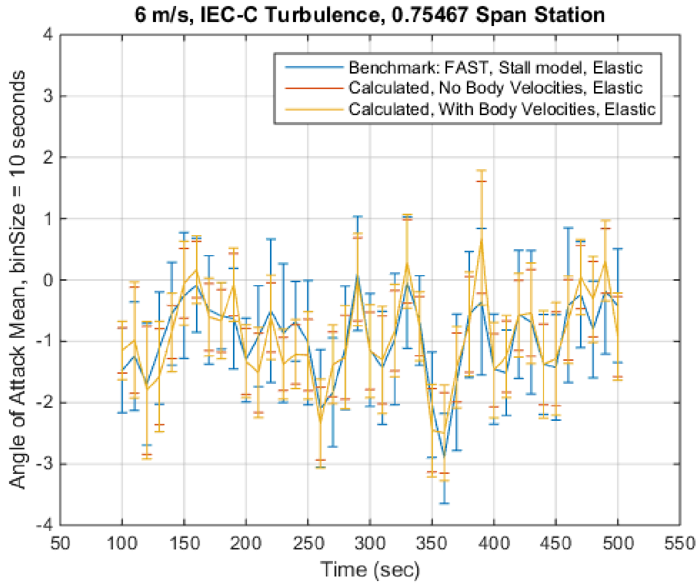
$$\alpha = \tan^{-1}\left[\frac{1}{TSR\,{}^{r}/_{R}} \times \frac{1-a+{}^{V_{e,OP}}/_{U_\infty}}{1+a'+{}^{V_{e,IP}}/_{\Omega r}}\right]-\beta$$

Effect of Flap/Edge Stiffness

FAST simulations are compared with analytical calculation of angle of attack using FAST outputs (both with and without inclusion of body velocities). For this 3.2p blade,

- FAST predictions of AoA are on the same order as the analytical method
- Analytical method also shows little variation between the calculation using the FAST body velocities and the calculation ignoring them.
  - For a reduced stiffness blade these calculations deviated with inclusion of body velocities adding +/- 0.5 deg to the AoA calculation.
- This analysis reveals no significant uncertainty added to AoA with the 3.2p blade



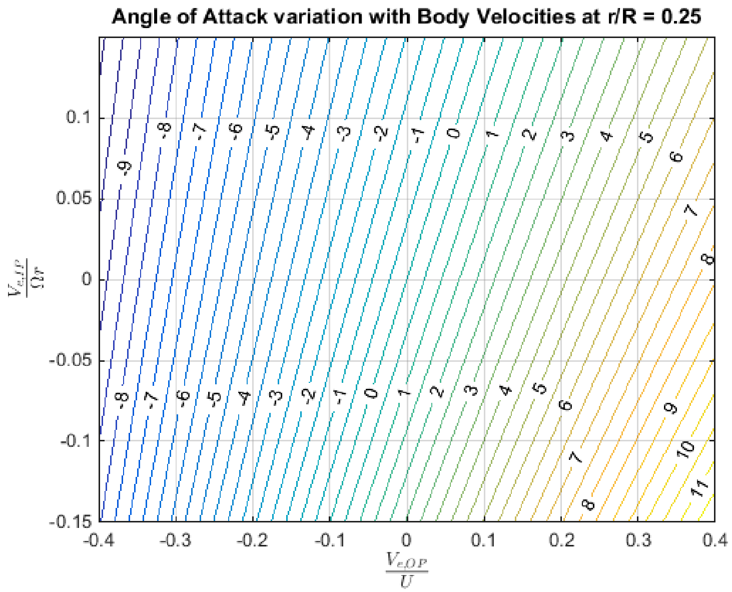


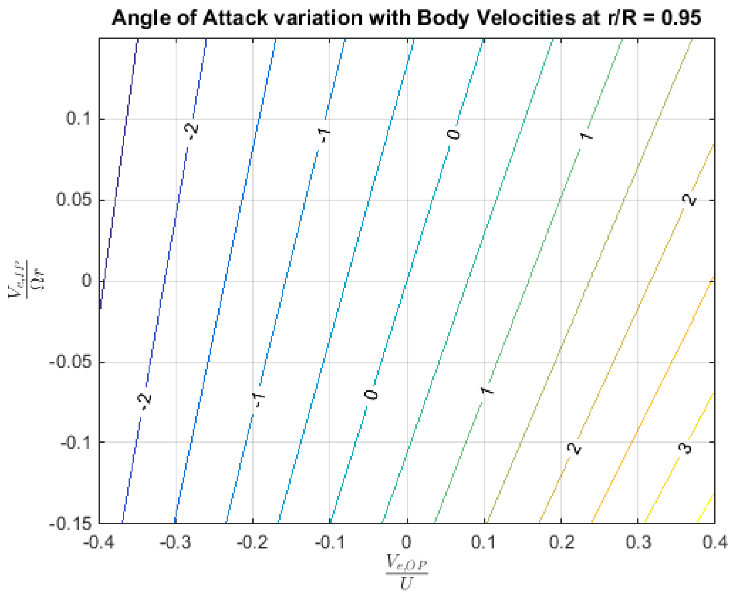
AoA variation with body velocities

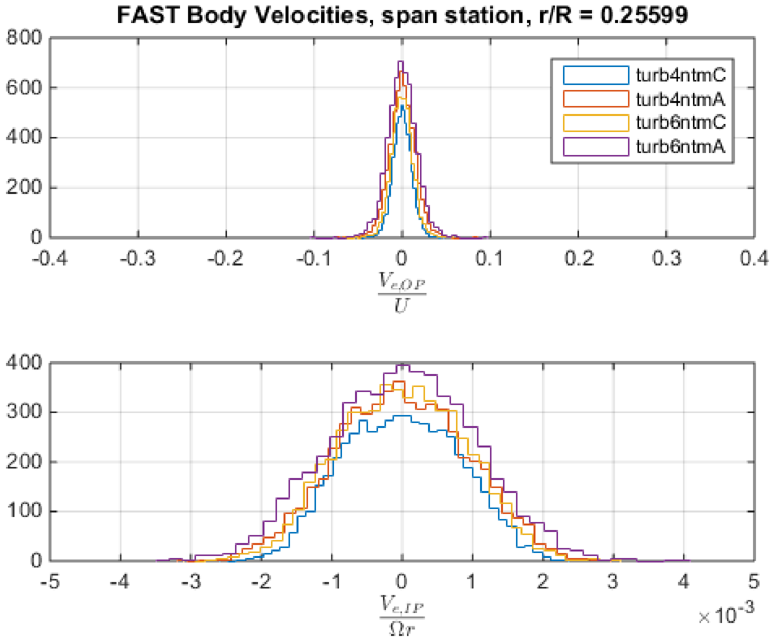
Analytical calculation of the variation in Angle of Attack due to body velocities was performed as another check of elasticity on performance

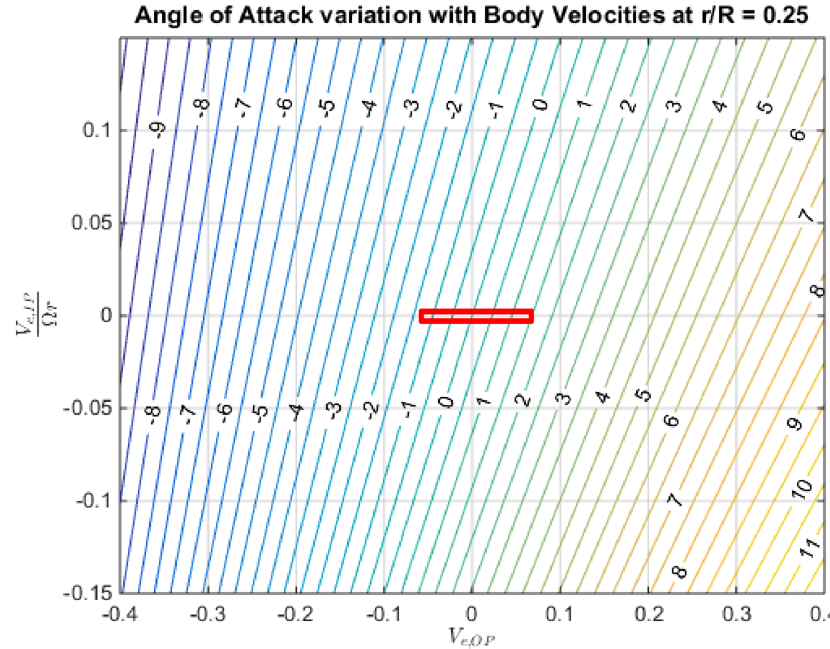
- Assumes controller maintains the turbine at a constant TSR
- Assumes the body velocities do not cause a change in rotor induction (small amplitude, high frequency).

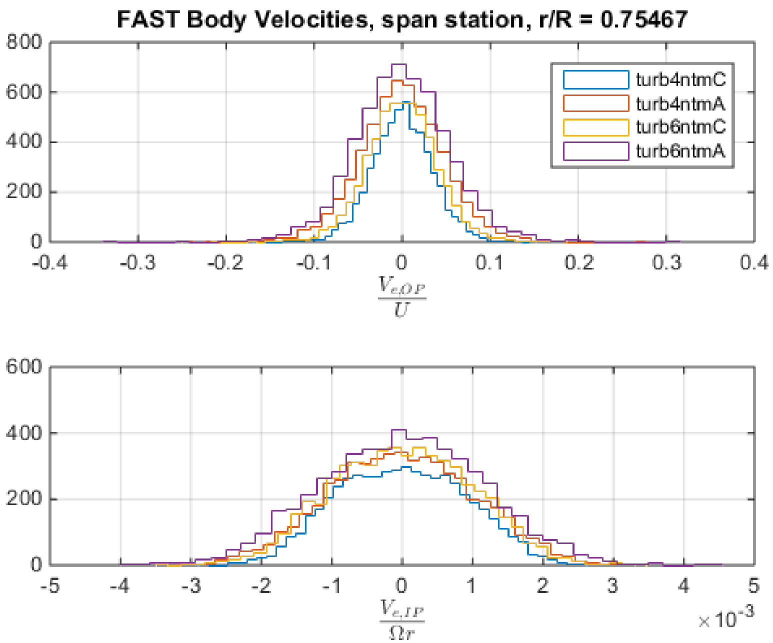
$$\alpha = \tan^{-1}\left[\frac{1}{TSR\ {}^{r}\!/_{R}} \times \frac{1 - a + {}^{V_{e,OP}}\!/_{U_\infty}}{1 + a' + {}^{V_{e,IP}}\!/_{\Omega r}}\right] - \beta$$

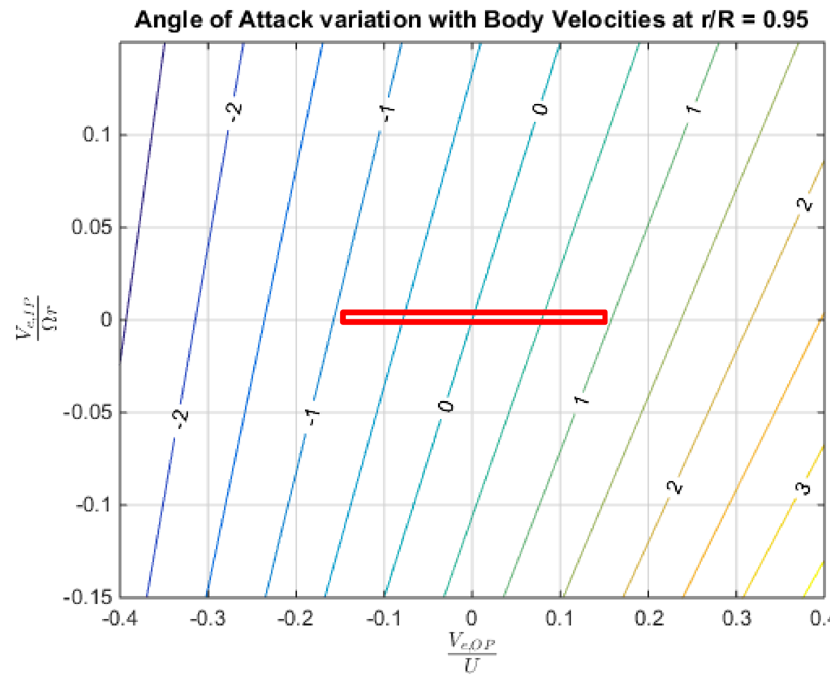


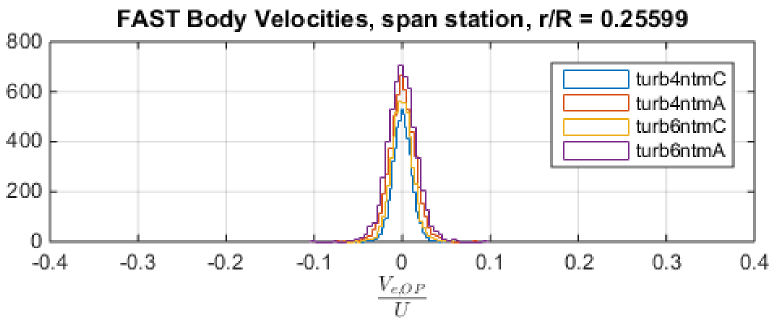



FAST Body Velocities, span station, r/R = 0.25599
turb4ntmC
turb4ntmA
turb6ntmC
turb6ntmA
$\frac{V_{e,OP}}{U}$
$\frac{V_{e,IP}}{\Omega r}$
$\times 10^{-3}$


Angle of Attack variation with Body Velocities at r/R = 0.25
$\frac{V_{e,IP}}{\Omega r}$
$V_{e,OP}$


FAST Body Velocities, span station, r/R = 0.75467
turb4ntmC
turb4ntmA
turb6ntmC
turb6ntmA
$\frac{V_{e,OP}}{U}$
$\frac{V_{e,IP}}{\Omega r}$
$\times 10^{-3}$


Angle of Attack variation with Body Velocities at r/R = 0.95
$\frac{V_{e,IP}}{\Omega r}$
$\frac{V_{e,OP}}{U}$



Result:

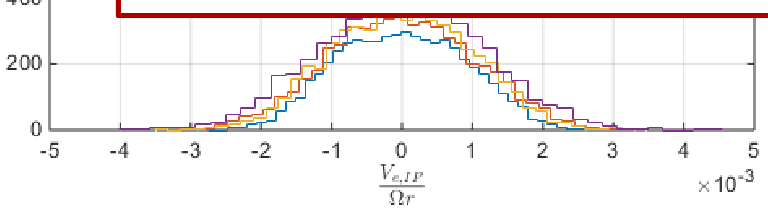
25% Span:

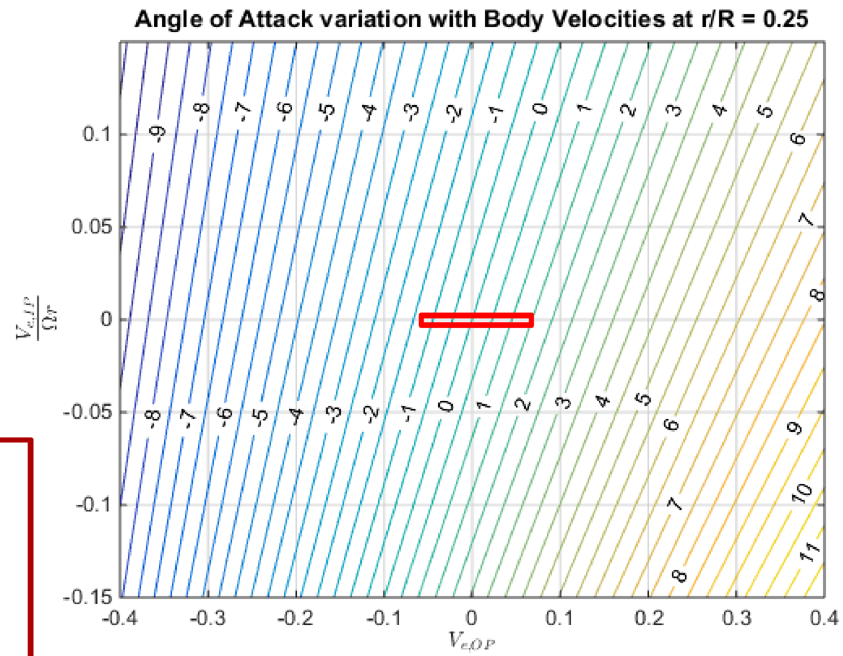
- Maximum AoA variation due to elasticity ~ +/- 1.25 degrees

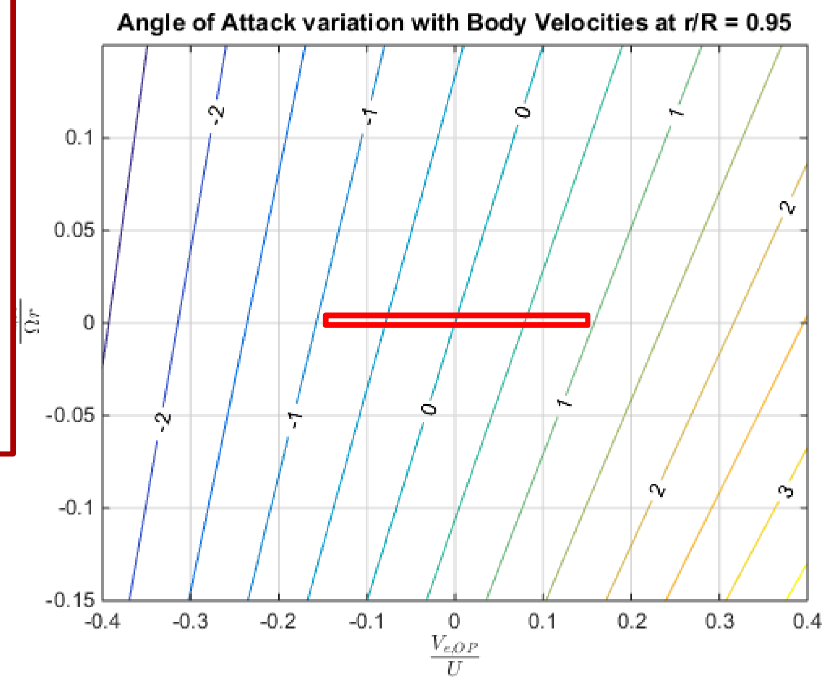
95% Span:

- Maximum AoA variation due to elasticity ~ +/- 1 degree

Approximated effects are due to turbulence + elasticity

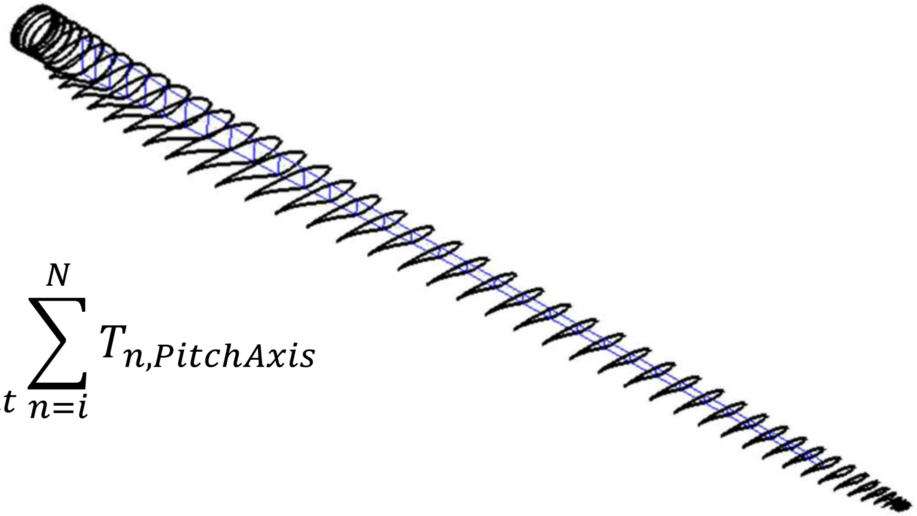






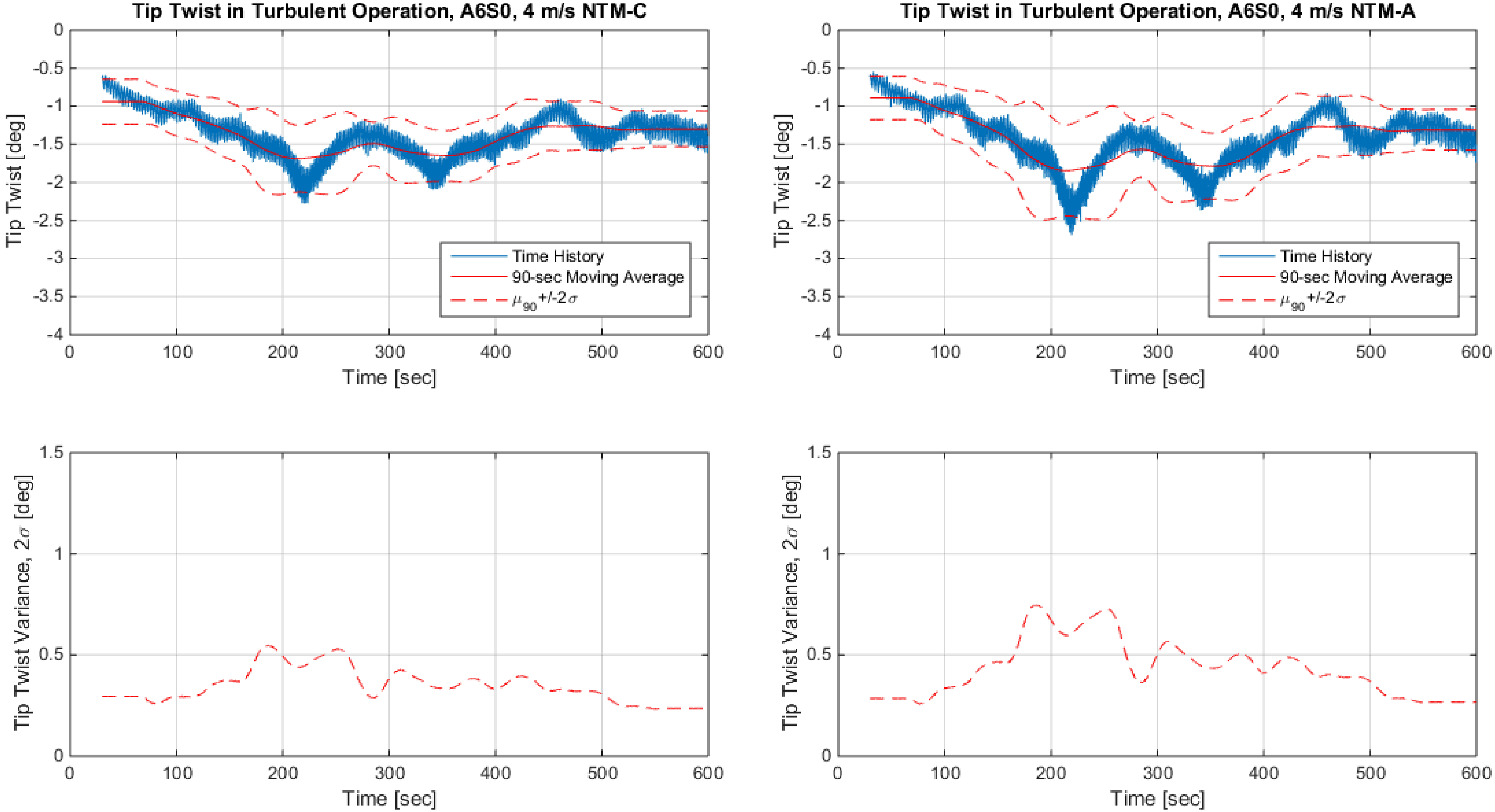
Effect of Torsional Stiffness

- Calculation of twist using FAST output forces and moments at the element stations, and stiffness properties from Bmodes blade structure.
  - Torsion from each airfoil station about the pitch axis calculation from airfoil moment coefficient, lift and drag, with sweep and prebend
  - Does not include the time history
  - Results are thought to be conservative due to twist unloading the blade

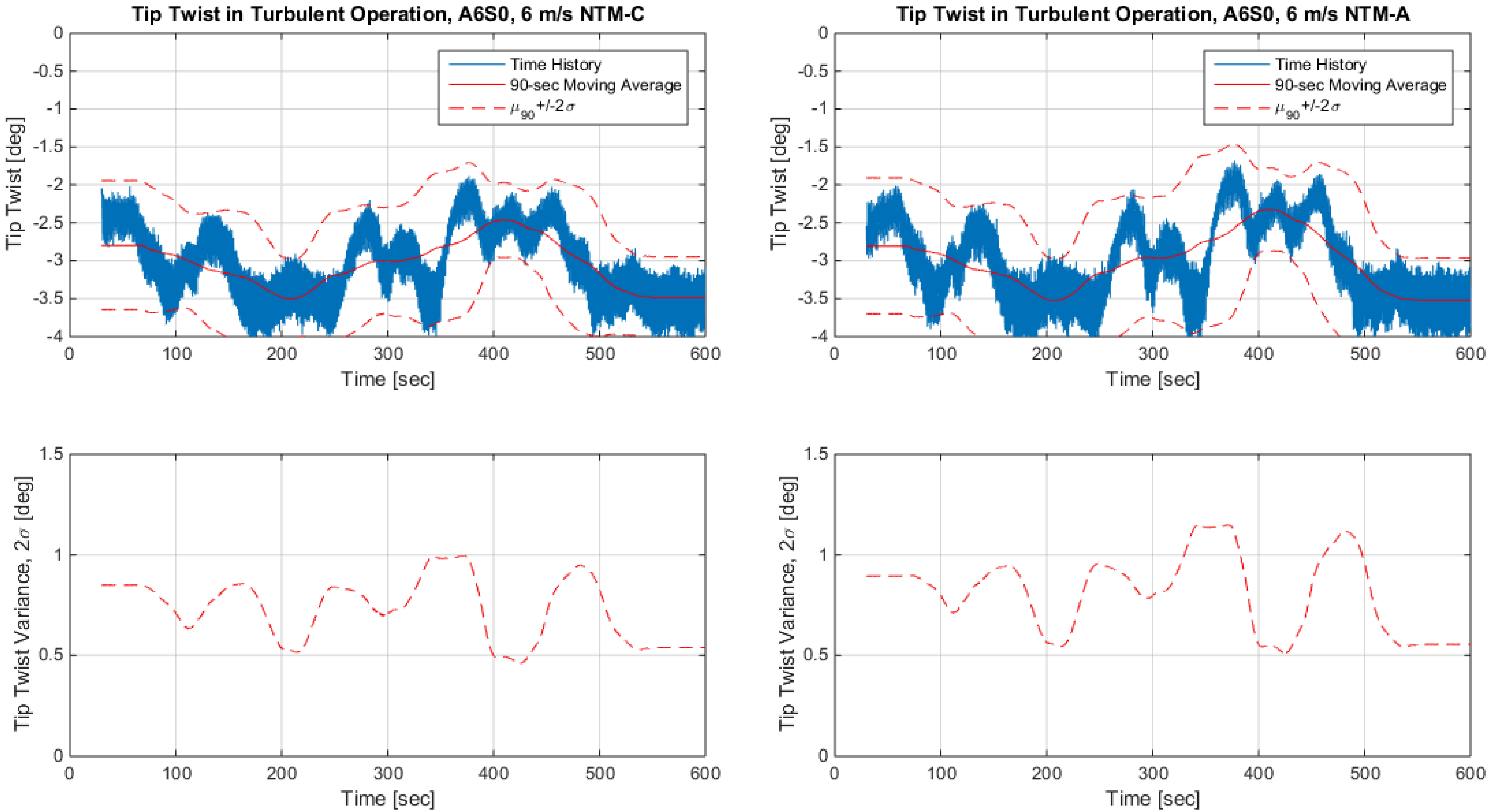


$$\theta_i = \left(\frac{l}{GJ}\right)_{element} \sum_{n=i}^{N} T_{n,PitchAxis}$$

Effect of Torsional Stiffness

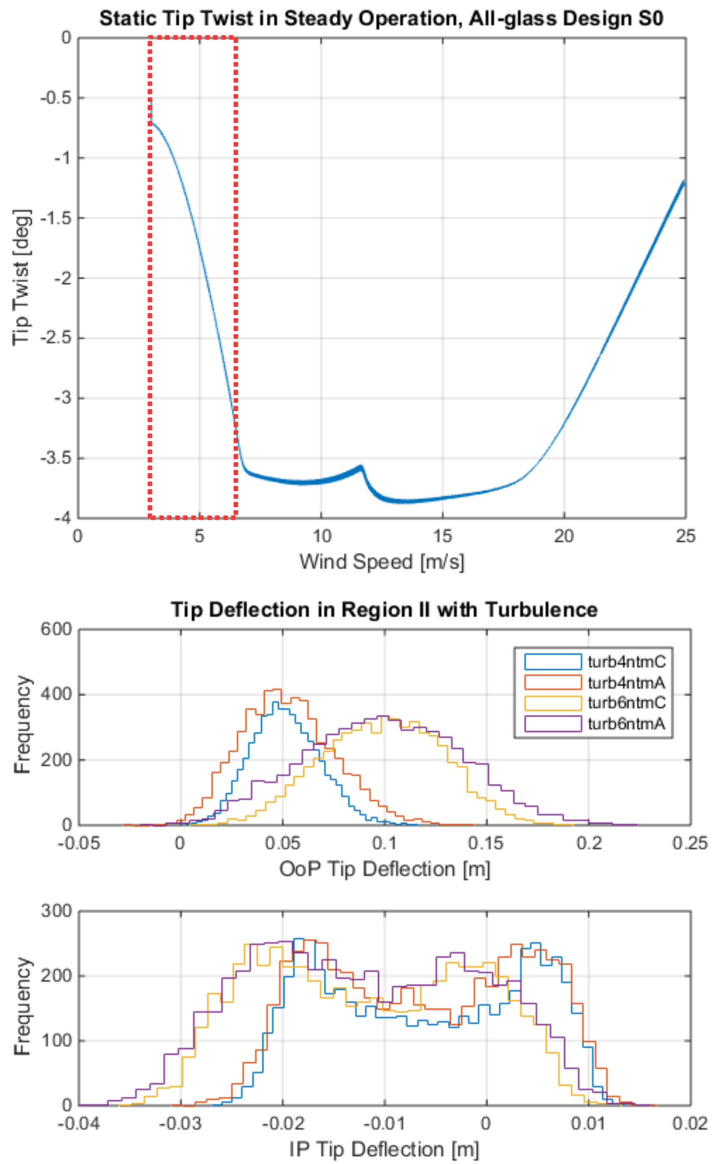


Effect of Torsional Stiffness



Additional Requirements

- Design for Static Loading
  - Static twist in Region II varies from 0.75 to 3.5 deg
- Structural Linearity
  - 5% bending limit = 0.65m
  - This is greater than the maximum characteristic bending in the IEC DLC analysis
  - In Region II the maximum tip deflection is less than 0.2m



Structural Blade Summary

- All-glass Blade, design S0, satisfies the standard requirements
  - Design Load Cases are below the loads envelope, with OEM reference
  - 3.2p first flap frequency, 2.0 edge-flap frequency ratio

- All-glass Blade, design S0, satisfies the additional requirements for ease of modeling
  - change in angle of attack due to bending is dominated by turbulence, difference due to blade elasticity is around +/- 1 degree in Region-II
  - Dynamic change in angle of attack due to torsion is less than 1 degree in Region-II

Thanks!

Back-up Slides

Design Load Cases

- DLC 1.xx: Power Production
  - Wind turbine is running and connected to the grid
- DLC 1.2
  - Fatigue resulting from atmospheric turbulence that occurs during normal operation during its lifetime
  - Performed at [V_{in}:2:V_{out}] m/s using 6 random seeds for turbulence wind input files
  - Normal Turbulence Model for turbulence

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
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	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Design Load Cases

- DLC 1.xx: Power Production
  - Wind turbine is running and connected to the grid
- DLC 1.3
  - Ultimate strength test resulting from operation with extreme turbulence conditions
  - Performed at [V_{in}:2:V_{out}] m/s using 6 random seeds for turbulence wind input files
  - Extreme Turbulence Model for turbulence

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Design Load Cases

- DLC 1.xx: Power Production
  - Wind turbine is running and connected to the grid
- DLC 1.4
  - Ultimate strength test resulting from operation near rated wind speed with extreme coherent gust (15 m/s) with direction change of (720/V_{hub} deg) over a period 10 sec.
  - Performed at {V_r-2, V_r, V_r-2} m/s for both +/- direction change

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Design Load Cases

- DLC 1.xx: Power Production
  - Wind turbine is running and connected to the grid
- DLC 1.5
  - Ultimate strength test resulting from operation with a transient extreme wind shear event, horizontal and vertical
  - Performed at [5:1:25] m/s for both positive and negative vertical wind shear.

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Design Load Cases

- DLC 6.xx: Parked Turbine
  - Wind turbine is parked and rotor is either locked or idling
- DLC 6.1
  - Ultimate strength test for parked turbine with 50-year wind gust event and yaw misalignment.
  - Performed at (V_{50}) m/s with yaw misalignment of +/- [0, 5, 15] deg.
  - $V_{50}(z) = 1.4\, V_{ref} \left({}^{z}/_{z_{hub}} \right)^{0.11}$

Table 2 – Design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year recurrence period		U	N
	6.2	EWM 50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM 1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM 1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM V_{maint} to be stated by the manufacturer		U	T

Design Load Cases

- DLC 6.xx: Parked Turbine
  - Wind turbine is parked and rotor is either locked or idling
- DLC 6.3
  - Ultimate strength test for parked turbine with 1-year wind gust event and yaw misalignment.
  - Performed at (V_1) m/s with yaw misalignment of +/- [0:5:30] deg.
  - $V_1 = 0.8\,V_{ref}(z)$

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Loads Analysis – Characteristic Loads

Load Direction	Allowable Loads	SWiFT Rotor Design Loads	NRT Rotor Design Loads
Blade Root Shear	(-700,700) kN if Mxb,i = 0	19.8 kN (DLC 1.3 ETM, 23 m/s)	
Blade Root Shear	(-700,700) kN if Myb,i = 0	19.8 kN (DLC 1.3 ETM, 23 m/s)	
Blade Root Pullout	? kN	93.0 kN (DLC 1.3 ETM, 23 m/s)	
Blade Root Bending, Mxb,i	(-210,210) kNm if Fxb,i = 0	(-44.5, 62.1) kNm (DLC 1.3 ETM; 23 m/s / 13 m/s)	(-28.0, 50.3) kNm (DLC 1.3 ETM; 21 m/s / 15 m/s)
Blade Root Bending, Myb,i	(-210,210) kNm if Fyb,i = 0	(-104.7,134.6) kNm (DLC 6.1 EWM50; -10 deg / +15 deg)	(-88.7, 131.2) kNm (DLC 6.1 EWM50; -15 deg / +15 deg)
Blade Root Pitching	? kNm	(-2.39, 2.38) kNm (DLC 1.4 ECD, V_r+2 / DLC 6.1, -15 deg)	
Blade Tip Deflection	1.328 m (Characteristic)	0.65 m (DLC 1.3 ETM, 15 m/s)	0.46 m (DLC 1.3 ETM, 19 m/s)
Yaw Moment	n/a	(-102.0, 77.7) kNm (DLC 1.3 ETM, 21 m/s / 23 m/s)	(-69.4, 60.9) kNm (DLC 1.3 ETM, 23 m/s, 11 m/s)

Loads Analysis – Characteristic Loads

Sandia National Laboratories

Load Direction	Allowable Loads	SWiFT Rotor Design Loads	NRT Rotor Design Loads
LSS Inline Force	(0,57.6) kN	39.0 kN (DLC 1.3 ETM, 15 m/s)	34.1 kN (DLC 1.3 ETM, 17 m/s)
LSS tip horizontal shear	(0,0) kN	(-32.6, 20.3) kN (DLC 6.1 EWM50, +15 deg / -15 deg)	(-29.2, 22.3) kN (DLC 6.1 EWM50, +15 deg / -15 deg)
LSS tip vertical shear	(0,126.4) kN	(-37.4, -18.8) kN (DLC 1.3 ETM, 23 m/s / 23 m/s)	(-34.6, -21.3) kN (DLC 1.3 ETM, 23 m/s / DLC 6.1 EWM50, -15 deg)
LSS torque	(0,55) kNm	(-102.2, 82.7) kNm (DLC 6.1 EWM50, 0 deg / DLC 1.3 ETM, 23 m/s)	(-17.9, 72.9) kNm (DLC 6.1 EWM50, 0 deg / DLC 6.3 EWM1, -30 deg)
LSS tip non-torque, Mys,i	(-9,9) kNm	(-74.4, 101.6) kNm (DLC 1.4 ECD, V_r+2 / DLC 1.3 ETM, 21 m/s)	(-56.4, 75.9) kNm (DLC 1.3 ETM, 19 m/s / 21 m/s)
LSS tip non-torque, Mzs,i	(-9,9) kNm	(-98.9, 84.1) kNm (DLC 1.3 ETM, 21 m/s / 23 m/s)	(-68.0, 63.3) kNm (DLC 1.3 ETM, 23 m/s / 11 m/s)

Loads Analysis – Characteristic Loads

Load Direction	Allowable Loads	SWiFT Rotor Design Loads	NRT Rotor Design Loads
Tower Base Shear	190 kN	(-23.5, 41.7) kN (DLC 1.3 ETM, 5 m/s / 13 m/s)	(-18.5, 40.4) kN (DLC 1.3 ETM, 5 m/s / 15 m/s)
Tower Base Shear	190 kN	(-32.5, 20.2) kN (DLC 6.1 EWM50, +15 deg / -15 deg)	(-29.1, 22.2) kN (DLC 6.1 EWM50, +15 deg / -15 deg)
Tower Base Vertical	260 kN	-223.6 kN (DLC 1.3 ETM, 23 m/s)	(-221.4, -207.3) kN (DLC 1.3 ETM, 23 m/s / DLC 6.1 EWM50, -15 deg)
Tower Base Overturning	4510 kNm	(-661.1, 1028.4) kNm (DLC 6.1 EWM50, -15 deg / 15 deg)	(-705.2, 988.4) kNm (DLC 6.1 EWM50, -15 deg / +15 deg)
Tower Base Overturning	4510 kNm	(-704.1, 1271.2) kNm (DLC 1.3 ETM, 5 m/s / 19 m/s)	(-573.0, 1191.3) kNm (DLC 1.3 ETM, 5 m/s / 15 m/s)

Loads Analysis – Design Loads

Load Direction	Allowable Loads	NRT Rotor Design Loads	SWiFT Rotor Design Loads
LSS Inline Force	n/a	46.0 kN (DLC 1.3 ETM, 17 m/s)	52.7 kN (DLC 1.3 ETM, 15 m/s)
LSS tip horizontal shear	n/a	(-39.4, 30.1) kN (DLC 6.1 EWM50, +15 deg / -15 deg)	(-44, 27.4) kN (DLC 6.1 EWM50, +15 deg / -15 deg)
LSS tip vertical shear	n/a	(-46.7, -28.8) kN (DLC 1.3 ETM, 23 m/s / DLC 6.1 EWM50, -15 deg)	(-50.5, -25.4) kN (DLC 1.3 ETM, 23 m/s)
LSS torque	n/a	(-24.2, 98.4) kNm (DLC 6.1 EWM50, 0 deg / DLC 6.3 EWM1, -30 deg)	(-138, 111.6) kNm (DLC 6.1 EWM50, 0 deg / DLC 1.3 ETM, 23 m/s)
LSS tip non-torque, Mys,i	n/a	(-76.1, 102.5) kNm (DLC 1.3 ETM, 19 m/s / 21 m/s)	(-100.4, 137.2) kNm (DLC 1.4 ECD, V_r+2 / DLC 1.3 ETM, 21 m/s)
LSS tip non-torque, Mzs,i	n/a	(-91.8, 85.5) kNm (DLC 1.3 ETM, 23 m/s / 11 m/s)	(-133.5, 113.5) kNm (DLC 1.3 ETM, 21 m/s / 23 m/s)

AoA variation with body velocities