Design tools for Distributed Wind

NREL CIP Fall Workshop
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with contributions from R. Damiani, B. Summerville, D. Davis, R. Preus

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Outline

- Loads modeling options for DWT
  - simplified load methodology
  - aeroelastic modeling
- Loads validation
- More about aeroelastic modeling
  - Options for different types of turbines
  - Getting into aeroelastic modeling
  - Pre and post-processing
- Other useful tools

Simplified loads model

- Simple, conservative equations
- Only applicable for
  - Horizontal axis
  - 2+ cantilevered blades
  - Coordinated blade movement
  - Rigid hub
- Example: Load Case A

$$\Delta F_{zB} = 2 m_B R_{cog} \varpi^2_{n,design}$$

$$\Delta F_{x-shaft} = \frac{3}{2} \frac{\lambda_{design} Q_{design}}{R}$$

$$\Delta M_{xB} = \frac{Q_{design}}{B} + 2 m_B g R_{cog}$$

$$\Delta M_{x-shaft} = Q_{design} + 2 m_r g e_r$$

$$\Delta M_{yB} = \frac{\lambda_{design} Q_{design}}{B}$$

$$\Delta M_{shaft} = 2 m_r g L_{rb} + \frac{R}{6} \Delta F_{x-shaft}$$

Table 2 – Design load cases for the simplified load calculation method

Design situation	Load cases		Wind inflow	Type of analysis	Remarks
Power production	A	Normal operation		F	
	B	Yawing	$V_{hub}=V_{design}$	U	
	C	Yaw error	$V_{hub}=V_{design}$	U	
	D	Maximum thrust	$V_{hub}=2{,}5\ V_{ave}$	U	Rotor spinning but could be furling or fluttering
Power production plus occurrence of fault	E	Maximum rotational speed		U	
	F	Short at load connection	$V_{hub}=V_{design}$	U	Maximum short-circuit generator torque
Shutdown	G	Shutdown (Braking)	$V_{hub}=V_{design}$	U	
Extreme wind Loading	H	Extreme wind loading	$V_{hub}=V_{e50}$	U	The turbine may be parked (idling or standstill) or governing. No manual intervention has occurred.
Parked and fault conditions	I	Parked wind loading, maximum exposure	$V_{hub}=V_{ref}$	U	Turbine is loaded with most unfavourable exposure
Transport, assembly, maintenance and repair	J	To be stated by manufacturer		U	

Key

F analysis of fatigue loads

U analysis of ultimate loads

Ref. International Electrotechnical Commission, Wind turbines - Part 2: Small wind turbines, EN 61400-2:2014.

Inputs and calculations

Description	Input Value	Units	Symbol
Air density	1.2250	kg/m^3	ρ
Gravitational acceleration	9.8100	m/s^2	g
Reference Wind Speed	37.5000	m/s	V_ref
Average Wind Speed	7.5000	m/s	V_ave
Number of Blades	3	n/a	B
Blade Tip Radius	0.9700	m	R
Total Planform Area of the Blade	0.2310	m^2	A_proj,B
Drag Coefficient of the Blades	1.5000	n/a	C_d
Max Lift Coefficient of the Blades	2.0000	n/a	C_l,max
Thrust Coefficient	0.5000	n/a	C_T
Maximum Rotor Speed	1000.0000	rpm	n_max
Design Rotor Speed	700.0000	rpm	n_design
Second Moment of Inertia for each Blade	0.0633	kgm^2	I_B
Single Blade Mass	0.4000	kg	m_B
Rotor Mass (All Blades plus Hub)	3.9800	kg	m_r
Distance from Blade centre of gravity to rotor axis	0.3790	m	R_cog
Distance Between Rotor Centre and First Bearing	0.0260	m	L_rb
Distance Between the Rotor Centre and the yaw axis	0.2180	m	L_rt
Gearbox Ratio (enter 1.0 for no gearbox)	1.0000	n/a	Gear
Enter "Y" if brake is on high speed side of gearbox, otherwise "N"	N	n/a	n/a
Brake torque (enter 0.0 for no brake)	0.0000	Nm	M_brake
Design Power	0.5000	kW	P_design
Short Circuit Torque Factor	2.0000	n/a	G
Type "Y" if blades are stationary during parking, otherwise "N"	Y	n/a	n/a
Diameter of the Shaft	2.5000E-02	m	
Cross Sectional Area of the Blade Root	1.4600E-03	m^2	A_B
Ixx for the blade	2.7900E-08	m^4	I_xxB
x-distance from blade centroid to the maximum stress point	9.1900E-03	m	c_xB
Iyy for the blade	1.1990E-06	m^4	I_yyB
y-distance from blade centroid to the maximum stress point	7.7800E-03	m	c_yB
Ultimate Material Strength for the Blades	1.2000E+02	MPa	f_kB
Ultimate Material Strength for the Shaft	2.5000E+02	MPa	f_k-shaft
Design life of the turbine	20	Years	
	631152000	s	T_d
Number of Cycles to Failure as a Function of Stress (Shaft)	1.00E+10	n/a	N_shaft
Number of Cycles to Failure as a Function of Stress (Blade)	1.23E+13	n/a	N_blade

Description	Value	Units	Symbol
Design Wind Speed	10.50	m/s	V_design
50 year extreme wind speed	52.50	m/s	V_e50
50yr extreme tip speed ratio	1.93	n/a	λ_e50
Design Tip Speed Ratio	6.77	n/a	λ_design
Drive Train Efficiency	0.60	n/a	ή
Design Torque	11.32	Nm	Q_design
Projected Area (turbine swept area)	2.96	m^2	A_proj
Design Rotational Speed of the Rotor	73.30	rad/s	ω_n,design
Maximum Possible Rotor Speed	104.72	rad/s	ω_n,max
Max Yaw Rate	2.99	rad/s	ω_yaw,max
50yr extreme tip speed ratio	1.93	n/a	λ_e50
Ecentricity of the Rotor Centre of Mass	4.85E-03	m	e_r
Effective brake torque	0.00	Nm	M_brake
Cross Sectional Area of the Shaft	4.9087E-04	m^2	A_shaft
The second moment of inertia for the shaft	1.9175E-08	m^4	I_x-shaft
Section modulus for the shaft	1.5340E-06	m^3	W_shaft
Blade x-section modulus	3.0359E-06	m^3	W_xB
Blade y-section modulus	1.5411E-04	m^3	W_yB
Number of Fatigue Cycles	2.21E+10	n/a	n_i

Wood, David, "Small Wind Turbines: Analysis, Design, and Application", Springer-Verlag, London, 2011.

SLM results

Loads from SLM				
Load Case A - Fatigue Loads on Blades and Rotor Shaft				
Equation	Description	SLM Value	Units	Symbol
	Blade Loads			
9.4 (IEC 21)	Centrifugal Force at the Blade Root (z-axis)	1629.23	N	ΔF_zB
9.5 (IEC 22)	Lead-lag Root Bending Moment (x-axis)	6.75	Nm	ΔM_xB
9.6 (IEC 23)	Flapwise Root Bending Moment (y-axis)	25.55	Nm	ΔM_yB
	Shaft Loads			
9.7 (IEC 24)	Thrust on shaft (x-axis)	118.55	N	ΔF_x-shaft
9.8 (IEC 25)	Shaft Moment about x-axis	11.70	Nm	ΔM_x-shaft
9.9 (IEC 26)	Shaft Moment	21.20	Nm	ΔM_shaft
Load Case B - Blade and Rotor Shaft Loads during Yaw				
Equation	Description	SLM Value	Units	Symbol
9.16 (IEC 28)	Flapwise Root Bending Moment (y-axis)	40.83	Nm	M_yB
9.11,12 (IEC 29,30)	Bending moment on the shaft	61.81	Nm	M_shaft
Load Case C - Yaw Error Load on Blades				
Equation	Description	SLM Value	Units	Symbol
9.13 (IEC 31)	Flapwise Root Bending Moment (y-axis)	422.82	Nm	M_yB
Load Case D - Maximum Thrust on Shaft				
Equation	Description	SLM Value	Units	Symbol
9.14 (IEC 32)	Maximum Thrust on Shaft	318.25	N	F_x-shaft
Load Case E - Maximum Rotational Speed				

9.11,12 (IEC 29,30)	Bending moment on the shaft	61.81	Nm	M_shaft
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9.14 (IEC 32)	Maximum Thrust on Shaft	318.25	N	F_x-shaft
Load Case E - Maximum Rotational Speed				
Equation	Description	SLM Value	Units	Symbol
9.15 (IEC 33)	Centrifugal Force at the Blade Root (z-axis)	1662.48	N	F_zB
9.16 (IEC 34)	Bending Moment on the shaft	6.52	Nm	M_shaft
Load Case F - Short at Load Connection				
Equation	Description	SLM Value	Units	Symbol
9.17 (IEC 35)	Bending Moment on Shaft	22.64	Nm	M_x-shaft
9.18 (IEC 36)	Lead-lag Root Bending Moment (x-axis)	7.55	Nm	M_xB
Load Case G - Shutdown Braking				
Equation	Description	SLM Value	Units	Symbol
9.19 (IEC 37)	Bending Moment on Shaft	n/a	Nm	M_x-shaft
9.20 (IEC 38)	Lead-lag Root Bending Moment (x-axis)	n/a	Nm	M_xB
Load Case H - Parked Wind Loads during Idling				
Equation	Description	SLM Value	Units	Symbol
9.23,24 (IEC 39,40)	Flapwise Root Bending Moment (y-axis)	283.71	Nm	M_yB
9.25,26 (IEC 41,42)	Maximum Thrust on Shaft	1754.89	N	F_x-shaft

Wood, David, "Small Wind Turbines: Analysis, Design, and Application", Springer-Verlag, London, 2011.

SLM applicability and safety factors

	Micro wind turbines up to 1 kW Peak Power	1-30 kW Peak Power	30-65 kW Peak Power	65-150 kW Peak Power
STRUCTURAL DESIGN				
SLM	Not required	Not recommended for turbines with Peak Power greater than 10 kW	Not allowed	Not allowed
Aeroelastic model	Not required	Allowed with validation through power, rotor speed. Validate weight of major components.	Allowed with validation through power, rotor speed, blade first flapwise (static) natural frequency*. Validate weight of major components.	Allowed with validation through power, rotor speed, blade first flapwise (static) natural frequency, tower loads*. Validate weight of major components.
Structural Analysis	Not required	Required	Required	Required

Ref. ANSI/ACP 101-1 2021 The Small Wind Turbine Standard

Table 7 – Partial safety factors for loads

Load determination method (see 5.2)	Fatigue loads, γ_f	Ultimate loads, γ_f
1. Simplified equations	1,0	3,0
2. Simulation model	1,0	1,35
3. Full scale load measurement	1,0	3,0

Ref. International Electrotechnical Commission, Wind turbines - Part 2: Small wind turbines, EN 61400-2:2014.


ANSI

ANSI/ACP 101-1 2021
The Small Wind Turbine Standard

ANSI Approval Date
December 21, 2021

AMERICAN CLEAN POWER ASSOCIATION
Standards Committee

AMERICAN CLEAN POWER STANDARDS

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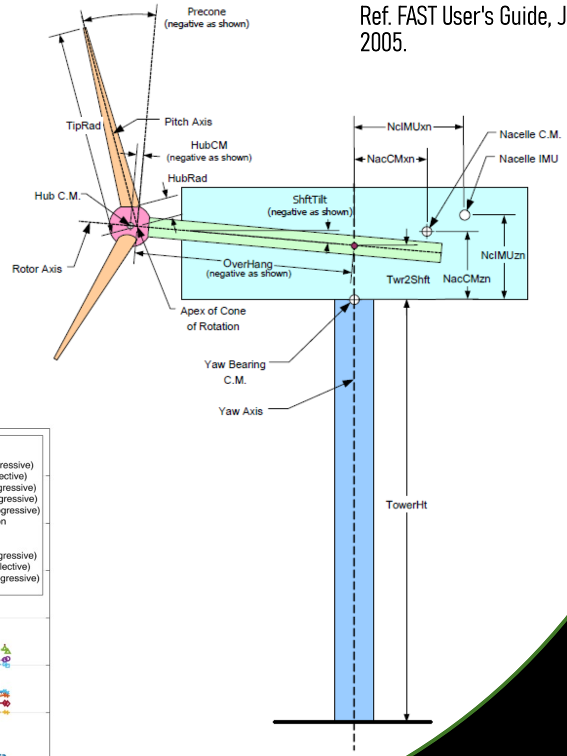
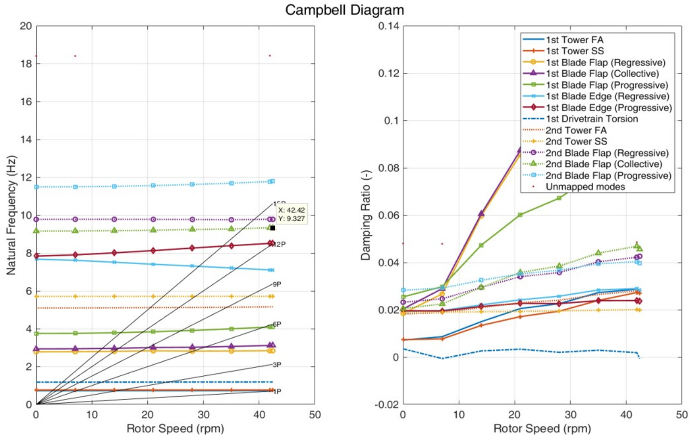
Aeroelastic modeling

- Combines aerodynamics, structural dynamics, and controls into a single integrated simulation for holistic analysis
- Time marching simulations calculate real-time response to any inflow: uniform, turbulent, shear, gusts



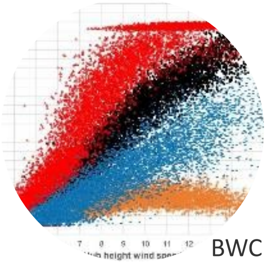
Ref. FAST User's Guide, Jonkman, Buhl, 2005.

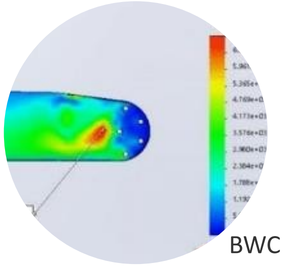
- Captures structural dynamics and vibration mode coupling



Ref. R. Damiani (2021)

Aeroelastic modeling pros & cons


BWC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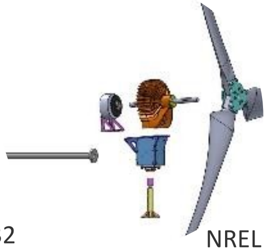
NREL PIX 17523


NREL PIX 43632


NREL PIX 39503

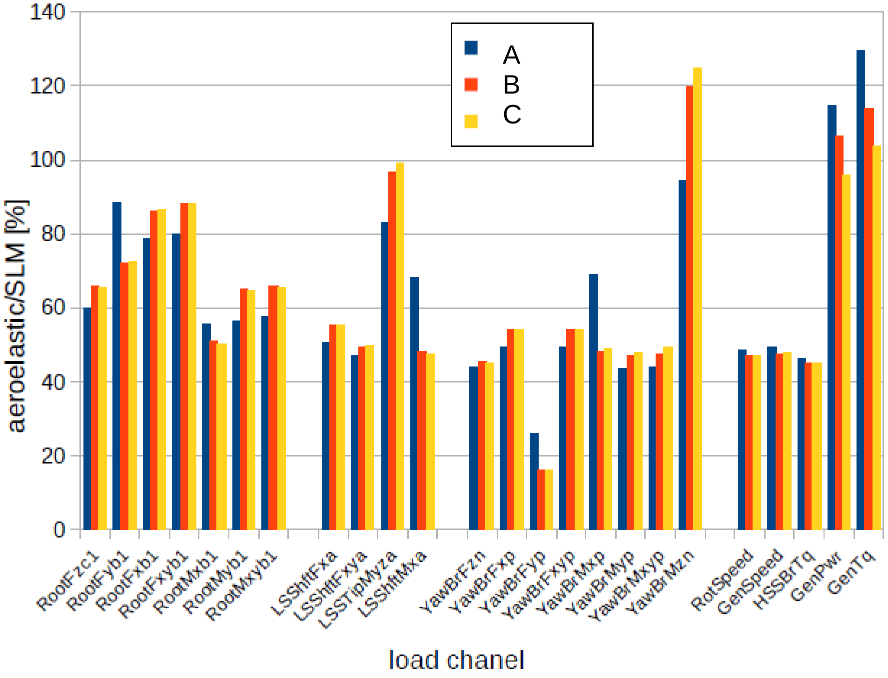
Understand the load and power behavior of the turbine before witnessing it in the field	Control parameters that have the highest impact on design	Optimize the configuration most efficiently	Provide a more realistic basis for design certification	Simplify conformity assessment following a change in the turbine architecture

Ref. R. Damiani, D. Davis, B. Summerville (2021): Aeroelastic Modeling for Distributed Scale Wind Turbines.

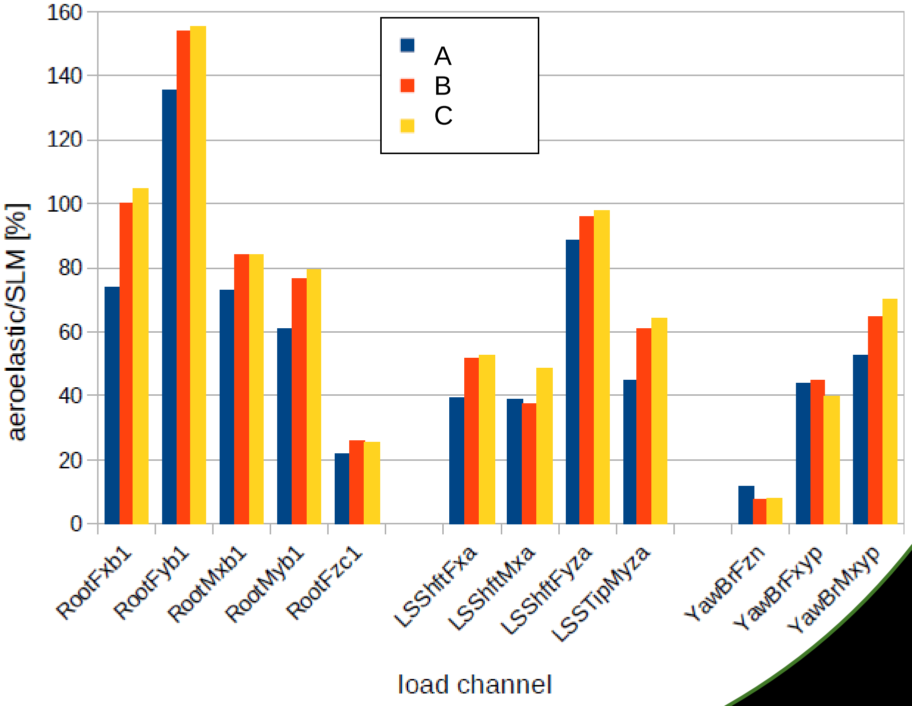
- Disadvantages
  - Mostly HAWT-centric
  - Steep learning curve, labour intensive
  - Computationally expensive
  - License fee for some codes

Aeroelastic vs. SLM

Extreme w/ SF



Fatigue



- Aeroelastic generally results in reduced loads

Tests to verify design data and validate model

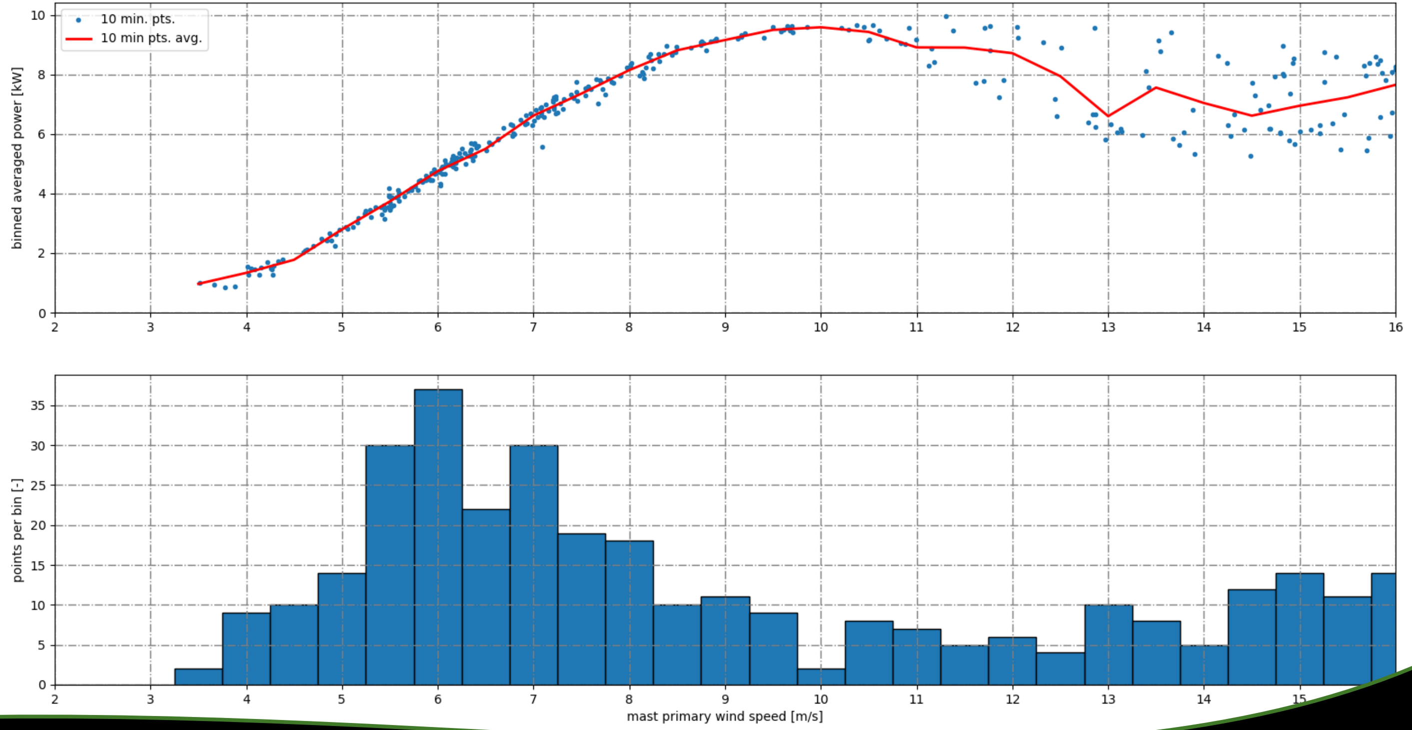
According to ANSI/ACP-101-1

		Design values @ 1.4V_{ave}			maximums		Weights of major components	Blade first flapwise (static) natural frequency	Tower loads
		power	Rotor speed	Shaft torque*	Rotor speed	Yaw rate			
SLM		X	X	X	X	X			
Aeroelastic	1 – 30 kW	X	X	X	X	X	X		
	30 – 65 kW	X	X	X	X	X	X	X	
	65 – 150 kW	X	X	X	X	X	X	X	X

*May be calculated from power and rotor speed

Validation measurements requirements

- Measured data shall be binned into 0.5 m/s wind speed bins
- Each bin from 1 m/s below V_{in} to $2V_{ave}$ shall contain at least 10 data points

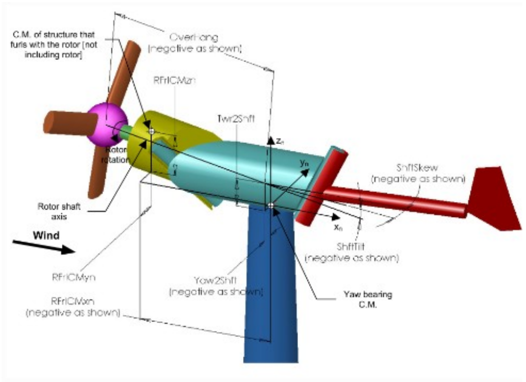


Validation measurements requirements

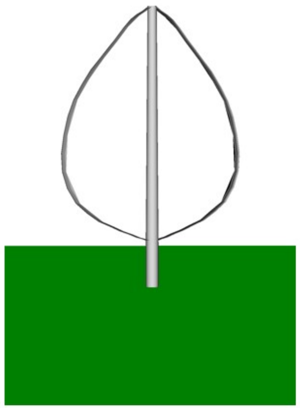
- Max yaw rate
  - Passive yaw: Measured value cannot be used for SLM (use 61400-2 eq. 27)
  - Semi-active / damped yaw
    - Measured value may be used in SLM
    - Must see an upper limit in measured values
- Max rotor speed
  - Shall be measured during condition most likely to give highest speed (e.g. loss of load or wind gust)
  - Wind speeds from 10 m/s – 20 m /s
  - 2h of data
  - At least 1/2 h below 15 m/s and 1/2 h above
  - Max speed shall be extrapolated to V_{ref}

Aeroelastic modeling – Code options

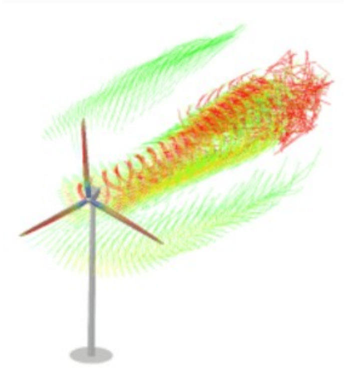
	OpenFAST	HAWC2	MSC.Adams	Bladed	QBlade	Flex5	OWENS	SimPack	SamCef	ASHES	alaska/ Wind
HAWT	X	X	X	X	X	X		X	X	X	X
VAWT		X			X		X				
General purpose			X					X	X		X
free	X	trial available			trial available					trial available	



Ref. FAST User's Guide, Jonkman, Buhl, 2005.



Ref. "Study of Design Load Cases for Multi-Megawatt Onshore Vertical Axis Wind Turbines", DTU Wind Energy, June 2015.

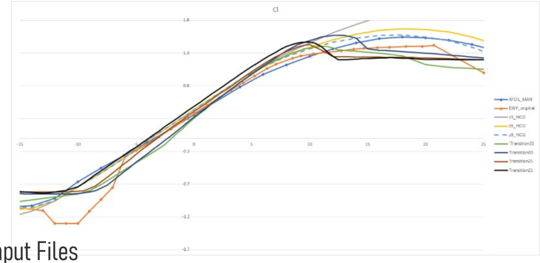


Ref. D. Marten, J. Saverin, R. Behrens de Luna, S. Perez-Becker. 2021.

Aeroelastic modeling workflow

Preprocessing

- Blade/tower structural definition, eigenmodes
- Airfoil Aerodynamics
- RNA properties
- Controller settings



Model Creation

- Assemble Input Files

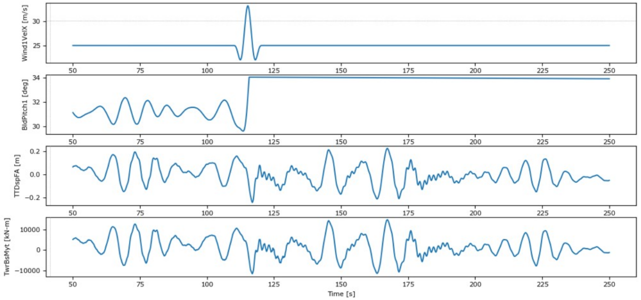
Preliminary Validation

- Assess major properties (mass, eigenfrequencies, steady-state power, RPM, etc.)

Design Basis

- Select DLCs and Environmental Conditions
- Create wind files, batch runs, PC req.ts

Design situation	DLC	Wind condition	Other conditions	Type of analysis
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		F, U
	1.2	ECD $V_{hub} < V_{design}$		U
	1.3	EOG_{50} $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		U
	1.4	EDC_{50} $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		U
	1.5	ECG $V_{hub} = V_{design}$		U
2) Power production plus occurrence of fault	2.1	NWP $V_{hub} = V_{design}$ or V_{out} or $2,5 \times V_{ave}$	Control system fault	U
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Control or protection system fault	F, U
	2.3	EOG_1 $V_{in} < V_{out}$ or $2,5 \times V_{ave}$	Loss of electrical connection	U
3) Normal shutdown	3.1	NTM $V_{in} < V_{hub} < V_{out}$		F
	3.2	EOG_1 $V_{hub} = V_{out}$ or $V_{max,shutdown}$		U
4) Emergency or manual shutdown	4.1	NTM To be stated by the manufacturer		U
5) Extreme wind loading (standing still or idling; or spinning)	5.1	EWM $V_{hub} = V_{e50}$	Possible loss of electrical power network	U
	5.2	NTM $V_{hub} < 0,7\ V_{ref}$		F
6) Parked and fault condition	6.1	EWM $V_{hub} = V_{e1}$		U
7) Transport, assembly, maintenance and repair	7.1	To be stated by the manufacturer		U



Simulation Runs

Postprocessing

- Extract ULS, FLS, SLS driving loads, deflections, etc.
- Assess resonance & instability risk

Ref. R. Damiani (2021)

Publicly available models

Archetype coverage table (HAWTs)

Active Yaw	Passive Yaw	Stall	Pitch	VarSpd	FixedSpd	Down-Wind	Up-Wind	
			✓	✓	✓		✓	Active Yaw
		✓		✓	✓	✓	✓	Passive Yaw
				✓	✓	✓	✓	Stall
				✓		✓	✓	Pitch
						✓	✓	VarSpd
						✓	✓	FixedSpd
								Down-Wind
								Up-Wind

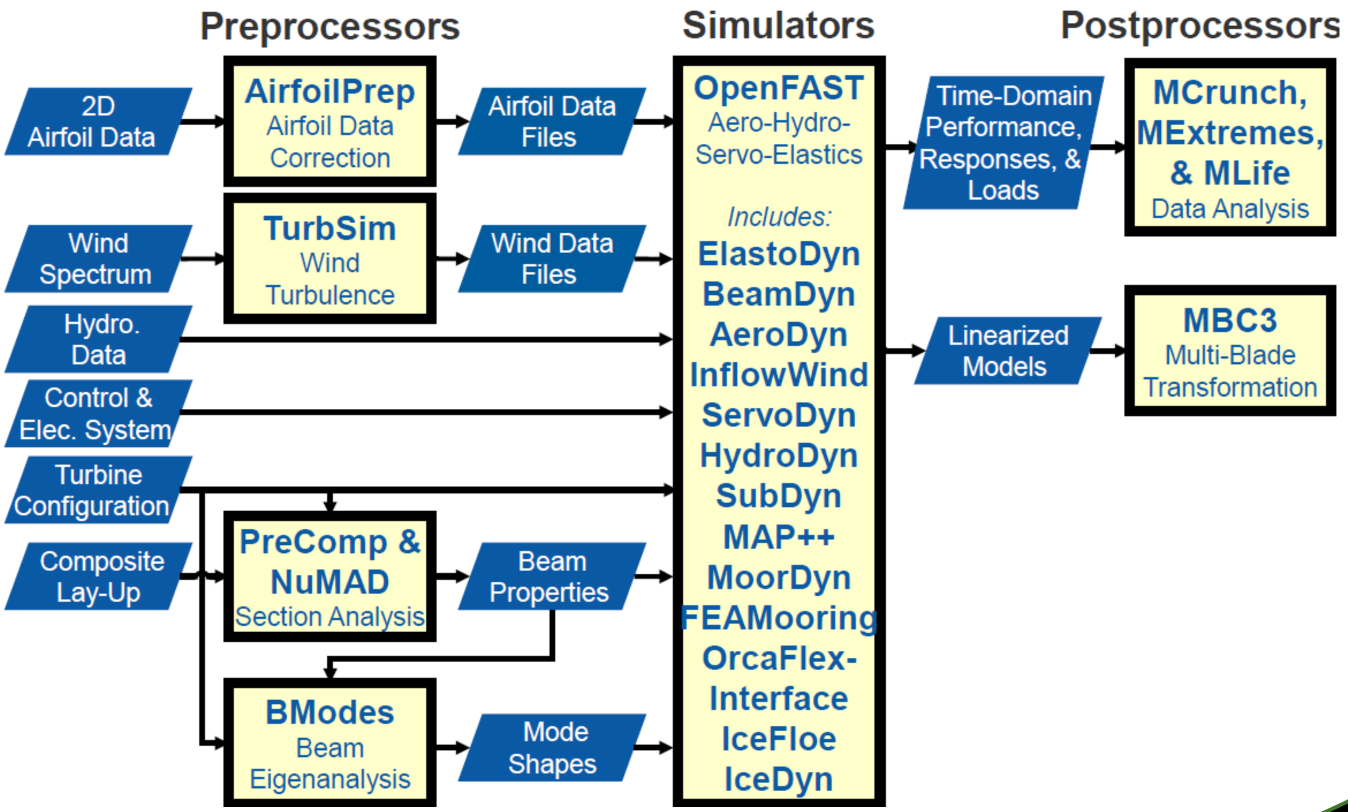
Where:

Gray = N/A
Green = common in the current market
Yellow = rare in the current market
White = not seen in the current market
✓ = aeroelastic model template available

Ref. R. Damiani, D. Davis, B. Summerville (2021): Aeroelastic Modeling for Distributed Scale Wind Turbines.

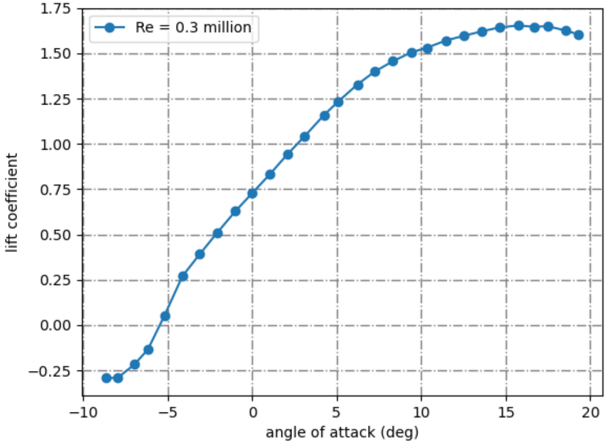
- Other features included
  - Furling
  - Teetering
  - Tip brakes
  - Tail
  - Guyed tower
  - Lattice tower

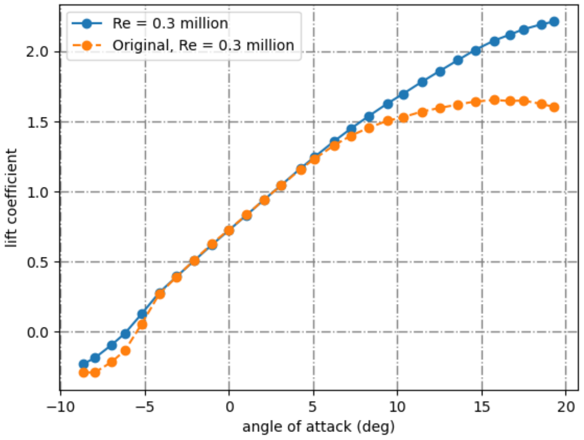
OpenFAST workflow

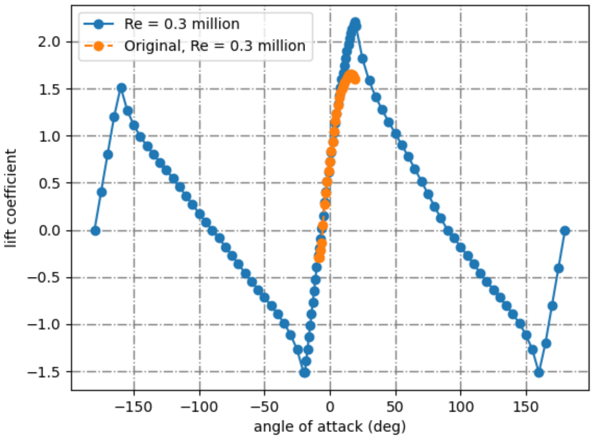


Credit: Dr. J. Jonkman

Preprocessing – airfoil data



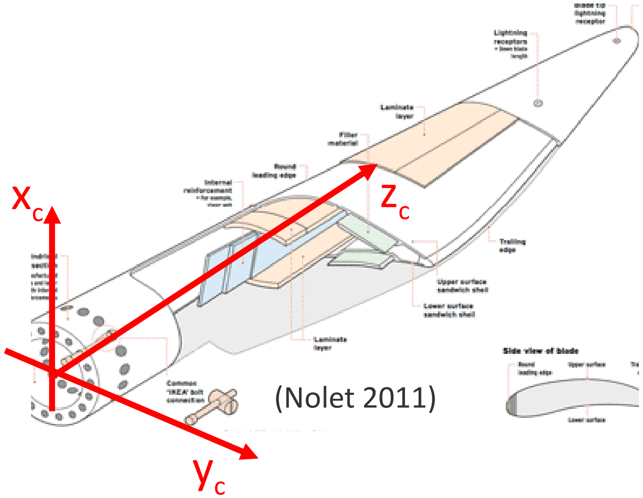


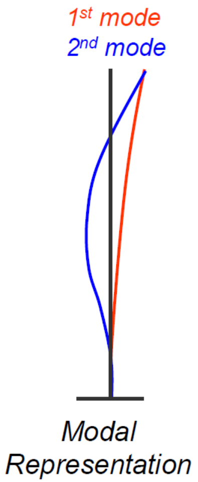


Linear region*	3D correction	360° extrapolation
XFoil**	AirfoilPreppy***	AirfoilPreppy
UIUC airfoil tests database		

* Use data at correct Reynolds number(s)
** Be sure of data at low Reynolds numbers (<5E5). Measurements are best.
*** Also calculates unstable aerodynamics model coefficients

Preprocessing – structure files

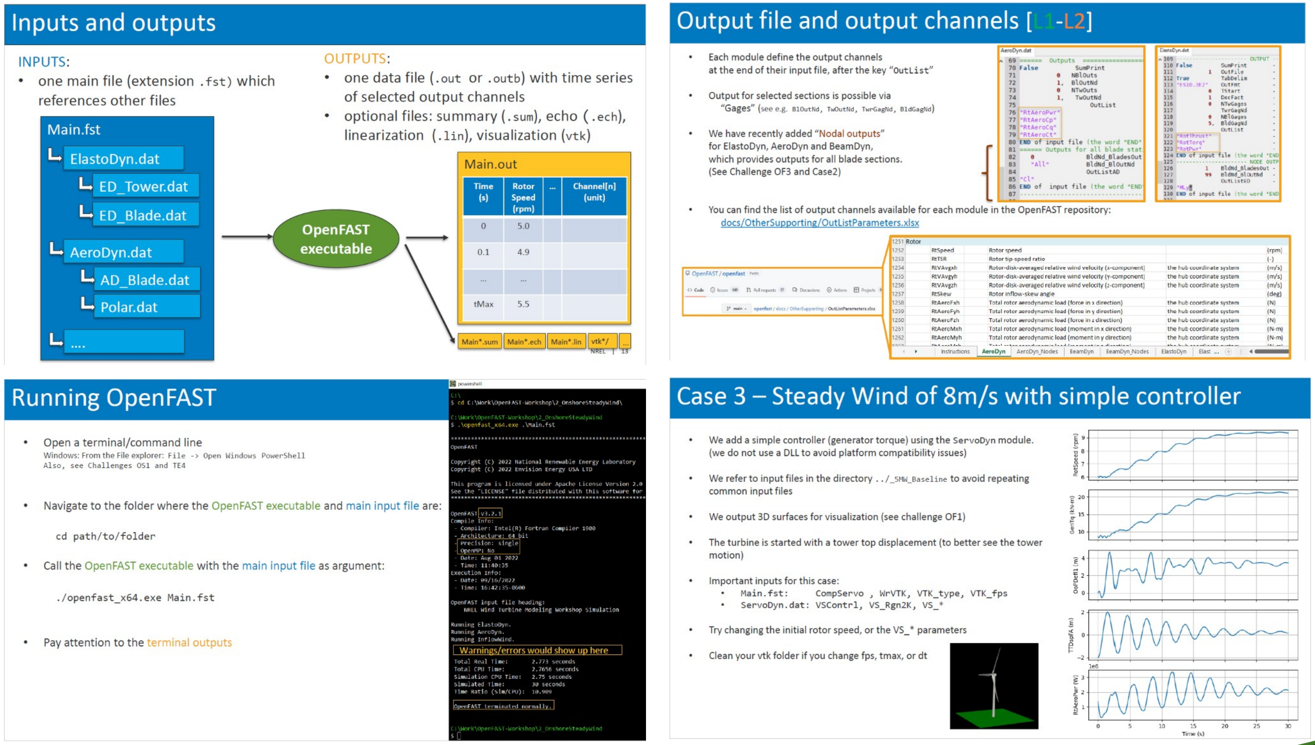




Cross-sectional properties	Eigenfrequencies and mode shapes
PreComp	BModes
VABS	FEM
Sonata	Mode shape polynomial curve fitting

Running OpenFAST

Excellent material for learning OpenFAST from NAWEA 2022 OpenFAST workshop

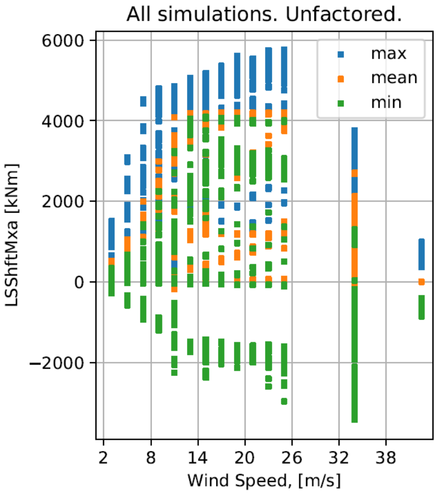


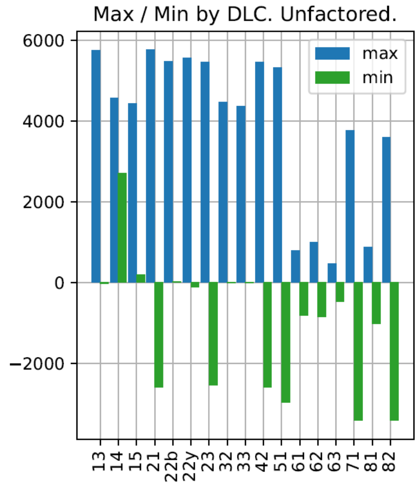
Modeling trip ups

- Time step
- Initial conditions
- Aerodynamic models
  - Disable induction when parked/idling
  - Be aware of high AOAs and yaw errors
- Airfoil polars
  - 3D correction
  - 360° extrapolation
- Drivetrain frequency and damping
- Structural data issues
  - Tune mass, CM, natural frequencies to match reference data
  - Mode shapes
- Geometry and topology
  - Use visualization tools to check

- The NREL forum is full of great tips and support from the developers

Postprocessing – Ultimate limit state (ULS)

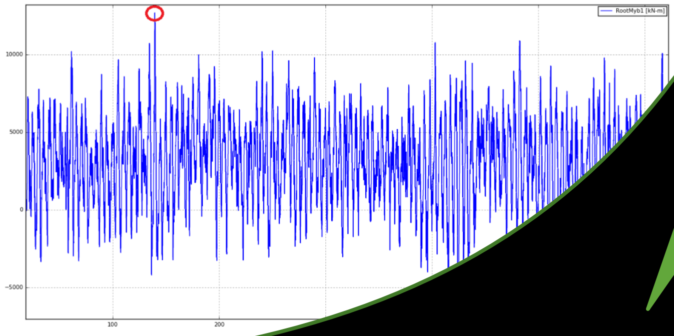




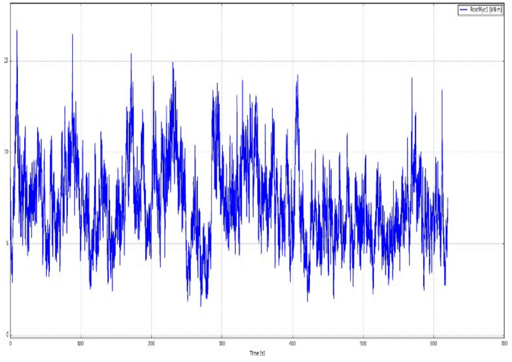
Contemporaneous load table: Blade 1 Root. Unfactored.

			RootFxc1	RootFyc1	RootFzc1	RootFxyc1	RootMxc1	RootMyc1	RootMzc1	RootMxyc1
			kN	kN	kN	kN	kNm	kNm	kNm	kNm
RootFxc1	Max	DLC22y_10020_19_300	4.84e+02	-1.89e+02	4.36e+02	5.19e+02	4.82e+03	1.78e+04	-7.61e+01	1.84e+04
RootFxc1	Min	DLC23_EOGO_55	-3.38e+02	5.74e+01	8.64e+02	3.43e+02	-3.33e+03	-1.40e+04	1.85e+02	1.44e+04
RootFyc1	Max	DLC62_12008_42.5_300	4.50e+01	4.40e+02	-1.49e+02	4.42e+02	-1.18e+04	6.94e+02	1.59e+02	1.18e+04
RootFyc1	Min	DLC62_12003_42.5_45	-7.26e+01	-4.84e+02	-1.70e+02	4.89e+02	1.30e+04	-1.91e+03	-3.95e+01	1.32e+04
RootFzc1	Max	DLC42_EOGO_56	-4.83e+00	-8.41e+01	1.07e+03	8.42e+01	5.42e+01	-2.63e+03	-1.27e+02	2.63e+03
RootFzc1	Min	DLC71_13002_34_30_0	-4.12e+01	-2.74e+02	-1.81e+02	2.77e+02	9.62e+03	-1.43e+03	1.88e+01	9.72e+03
RootFxyc1	Max	DLC22y_10023_25_300	4.65e+02	-2.55e+02	4.88e+02	5.30e+02	6.72e+03	1.64e+04	-5.83e+01	1.77e+04
RootFxyc1	Min	DLC71_13005_34_210_30	-3.73e-04	1.78e-02	-1.46e+02	1.79e-02	-1.01e+03	1.39e+02	9.19e+01	1.02e+03
RootMxc1	Max	DLC62_12003_42.5_45	-7.28e+01	-4.83e+02	-1.70e+02	4.89e+02	1.30e+04	-1.91e+03	-3.98e+01	1.32e+04
RootMxc1	Min	DLC62_12006_42.5_270	3.35e+01	4.38e+02	-1.60e+02	4.39e+02	-1.26e+04	6.75e+02	2.28e+02	1.26e+04
RootMyc1	Max	DLC22y_10020_19_300	4.84e+02	-1.89e+02	4.36e+02	5.19e+02	4.82e+03	1.78e+04	-7.61e+01	1.84e+04
RootMyc1	Min	DLC23_EOGO_55	-3.36e+02	5.00e+01	8.69e+02	3.40e+02	-3.12e+03	-1.41e+04	1.89e+02	1.44e+04
RootMzc1	Max	DLC62_12003_42.5_225	1.20e+01	3.96e+02	-1.68e+02	3.96e+02	-1.16e+04	4.28e+02	3.41e+02	1.17e+04
RootMzc1	Min	DLC62_12010_42.5_150	-8.92e+01	-3.53e+02	-1.72e+02	3.65e+02	1.03e+04	-1.72e+03	-3.33e+02	1.05e+04
RootMxyc1	Max	DLC22y_10020_19_300	4.84e+02	-1.89e+02	4.36e+02	5.19e+02	4.82e+03	1.78e+04	-7.61e+01	1.84e+04
RootMxyc1	Min	DLC21_10033_21_350	9.53e+00	-2.70e+01	-1.54e+02	2.86e+01	-3.77e-01	-1.79e-01	-1.88e+01	4.17e-01

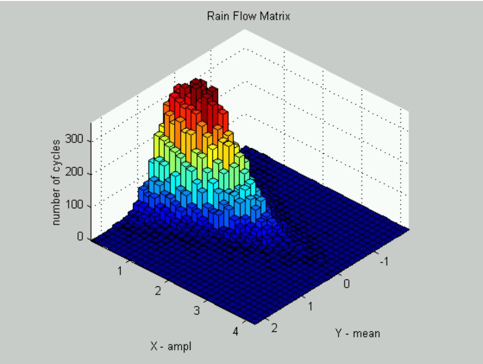
- Extract ultimate loads, deflections, clearance
  - MExtremes or Pcrunch
- Contemporaneous loads tables
- Apply binning, safety factors according to standards

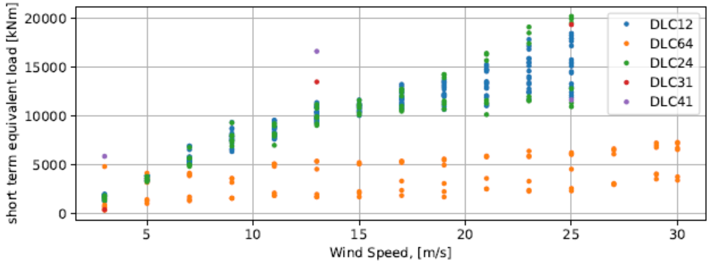


Postprocessing – Fatigue limit state (FLS)

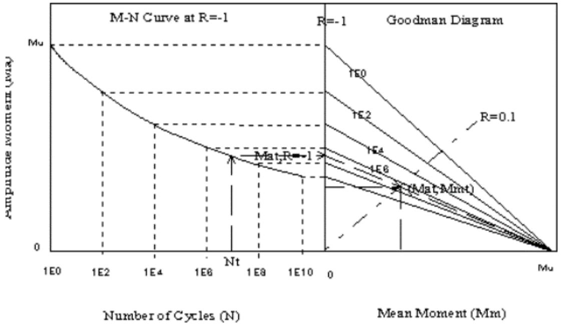


Rainflow counting





Goodman correction

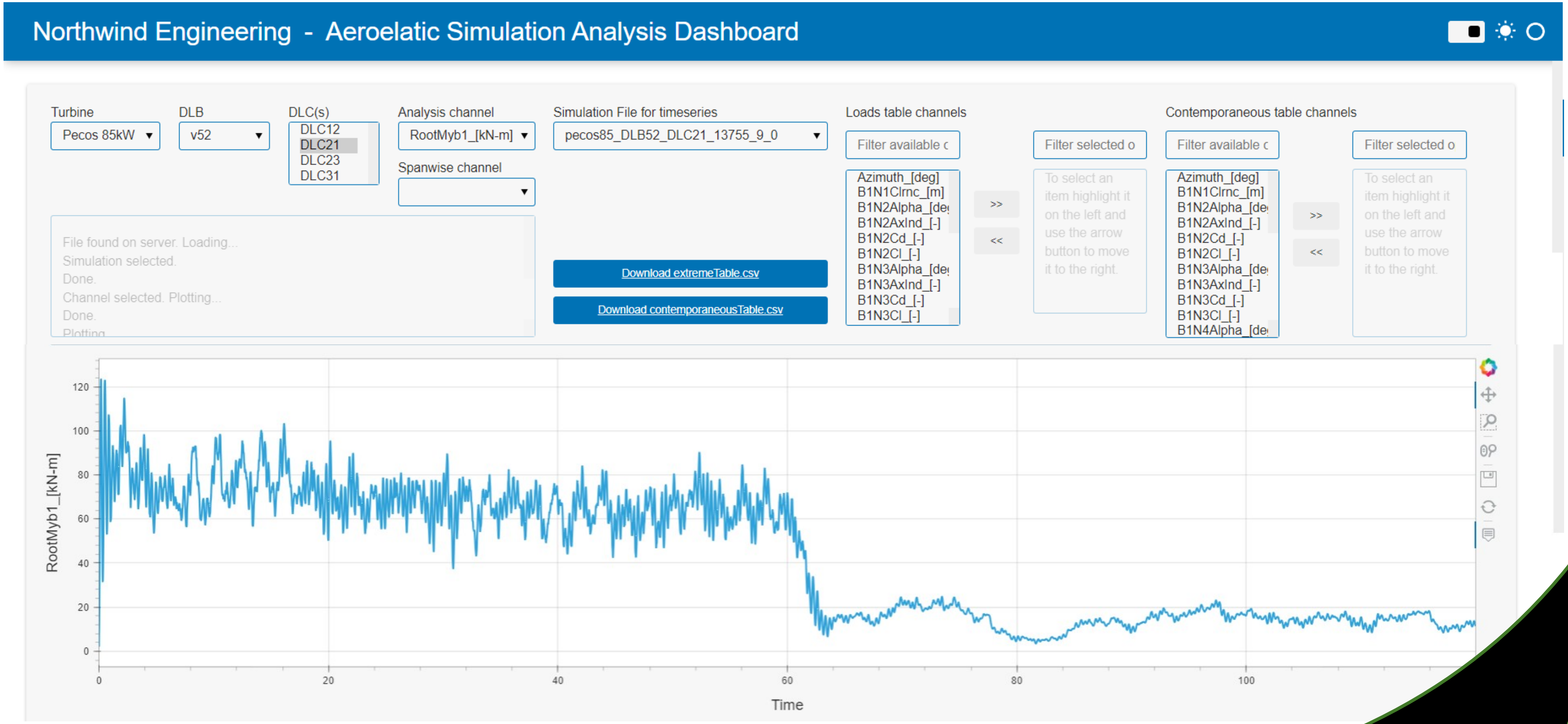


$$DEL = \frac{\sum_i n_i S_i^m}{n_{ref}}$$

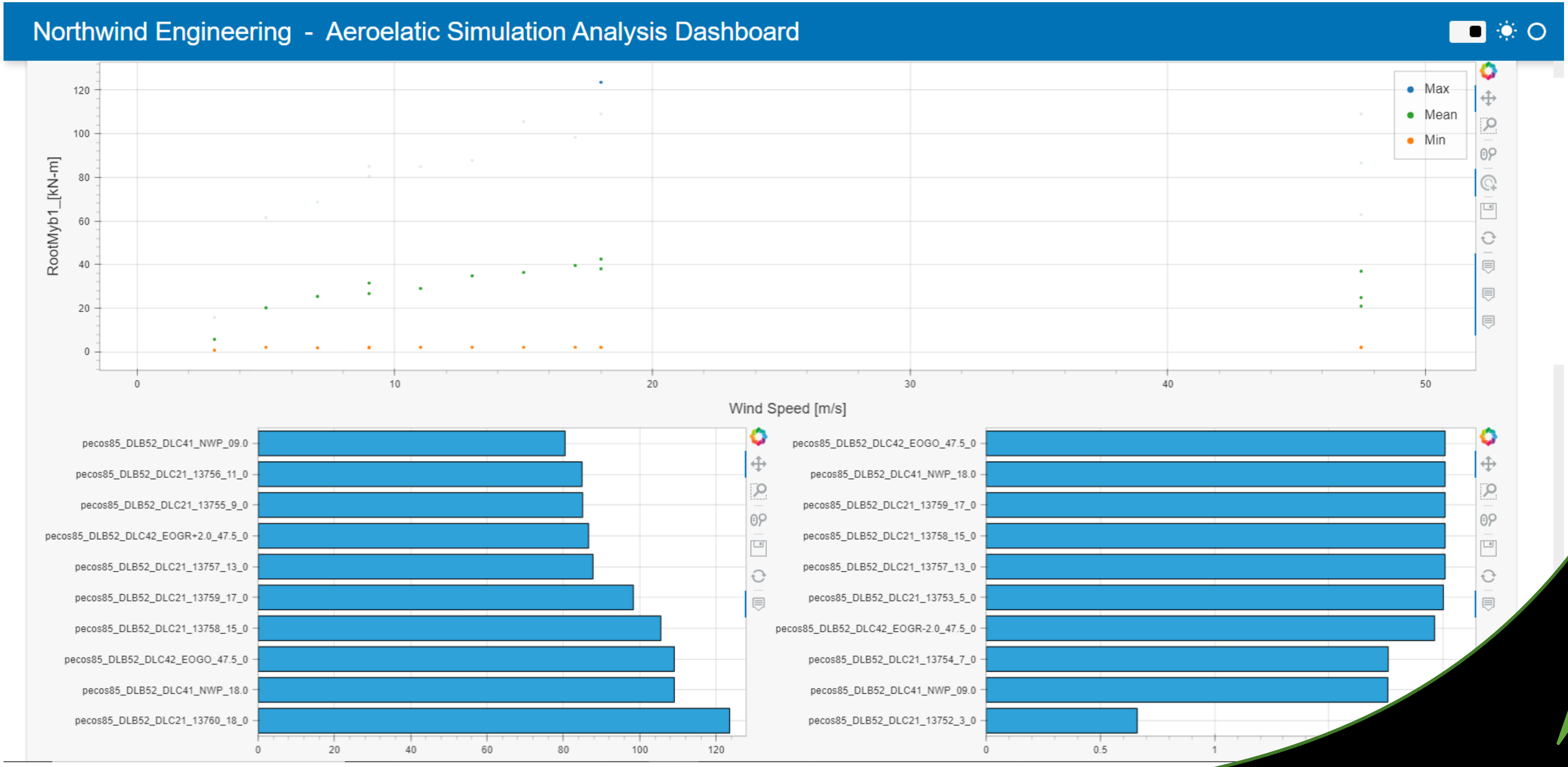
Damage Equivalent Load (single m)

- Calculate damage equivalent loads/stresses
  - MLife or openfast-toolbox

Interactive simulations analysis dashboard

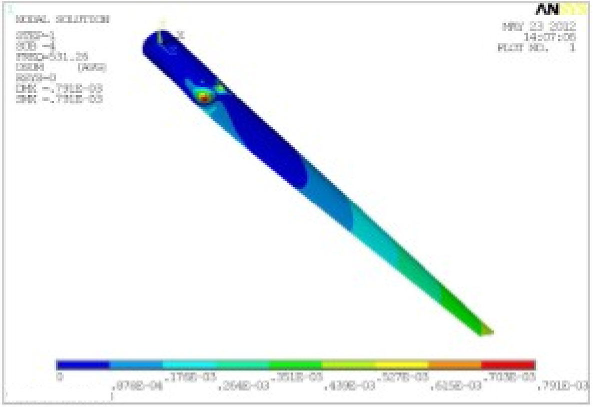


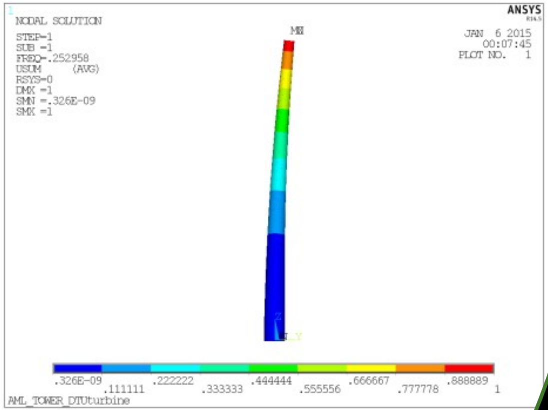
Interactive simulations analysis dashboard



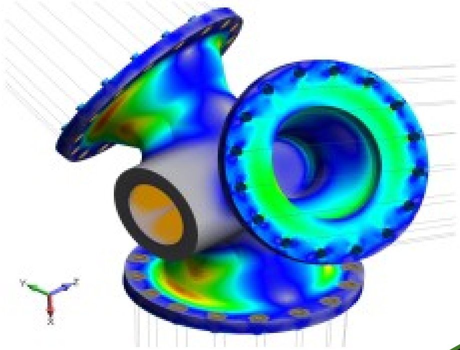
Structural verification of components

- Things to watch out for:
  - Sensitivity to Mesh
  - Boundary Conditions
  - Load Distribution
  - Failure Criteria (e.g. Tsai-Wu)
  - Buckling (linear vs. nonlinear)
  - Welds and stress concentrations
  - Bolts





Ref. R. Damiani (2021)



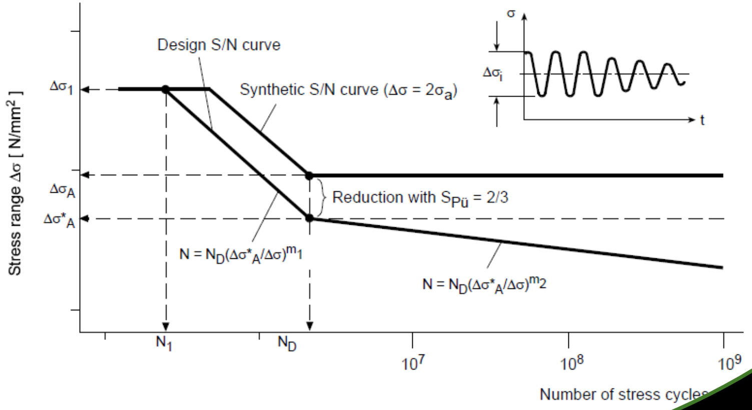
Hub FEA, Source Predictive Engineering

Structural verification of components

- Analytical options

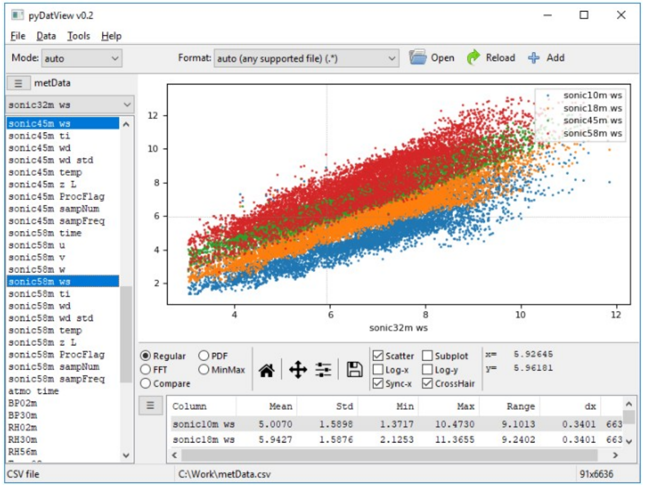
	Circular blade root	Rectangular blade root	Rotor shaft
Axial load	$\sigma_{zB} = \frac{F_{zB}}{A_B}$	$\sigma_{zB} = \frac{F_{zB}}{A_B}$	$\sigma_{x-shaft} = \frac{F_{x-shaft}}{A_{shaft}}$
Bending	$\sigma_{MB} = \frac{\sqrt{M_{xB}^2 + M_{yB}^2}}{W_B}$	$\sigma_{MB} = \frac{M_{xB}}{W_{xB}} + \frac{M_{yB}}{W_{yB}}$	$\sigma_{M-shaft} = \frac{M_{shaft}}{W_{shaft}}$
Shear	Negligible	Negligible	$\tau_{M-shaft} = \frac{M_{x-shaft}}{2W_{shaft}}$
Combined (axial + bending)	$\sigma_{eqB} = \sigma_{zB} + \sigma_{MB}$		$\sigma_{eq} = \sqrt{(\sigma_{x-shaft} + \sigma_{M-shaft})^2 + 3\tau_{M-shaft}^2}$

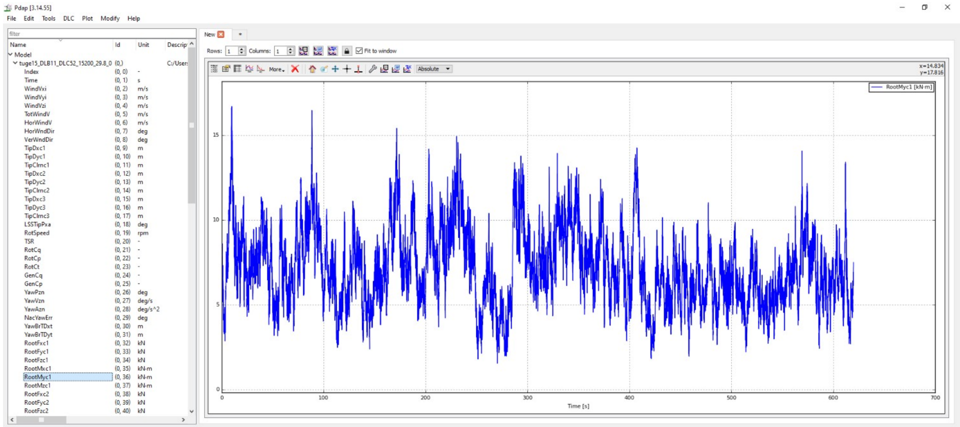
- Evaluate damage and check for safety
  - Eurocodes, AISC
  - GL Guideline for the certification of wind turbines



Other useful tools

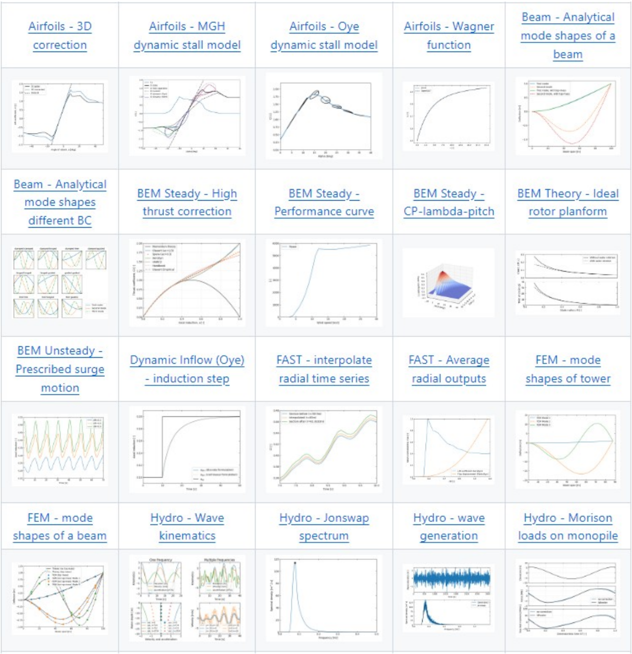
- Scripts to setup models, run simulations and postprocess the results
  - openfast_toolbox   DTU Wind Energy Toolbox
- Visualization of simulation results (and more)
  - PyDatView   Pdap



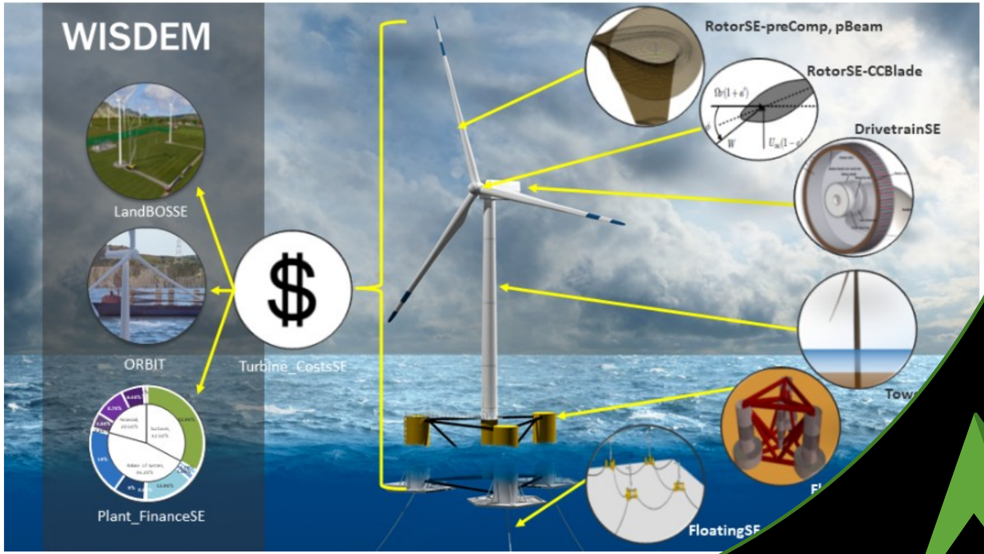


Other useful tools

- Wind Energy Library (welib)
  - Suite of python and matlab tools aerodynamics, controls, structure/elasticity



- WISDEM
  - A set of models for assessing overall wind plant cost of energy (COE)
  - Component and system optimization



Thanks!

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