Wind Turbine Load Calculations with Non-linear Flexible Rotor Blades

Tech Talk, 20.10.2021

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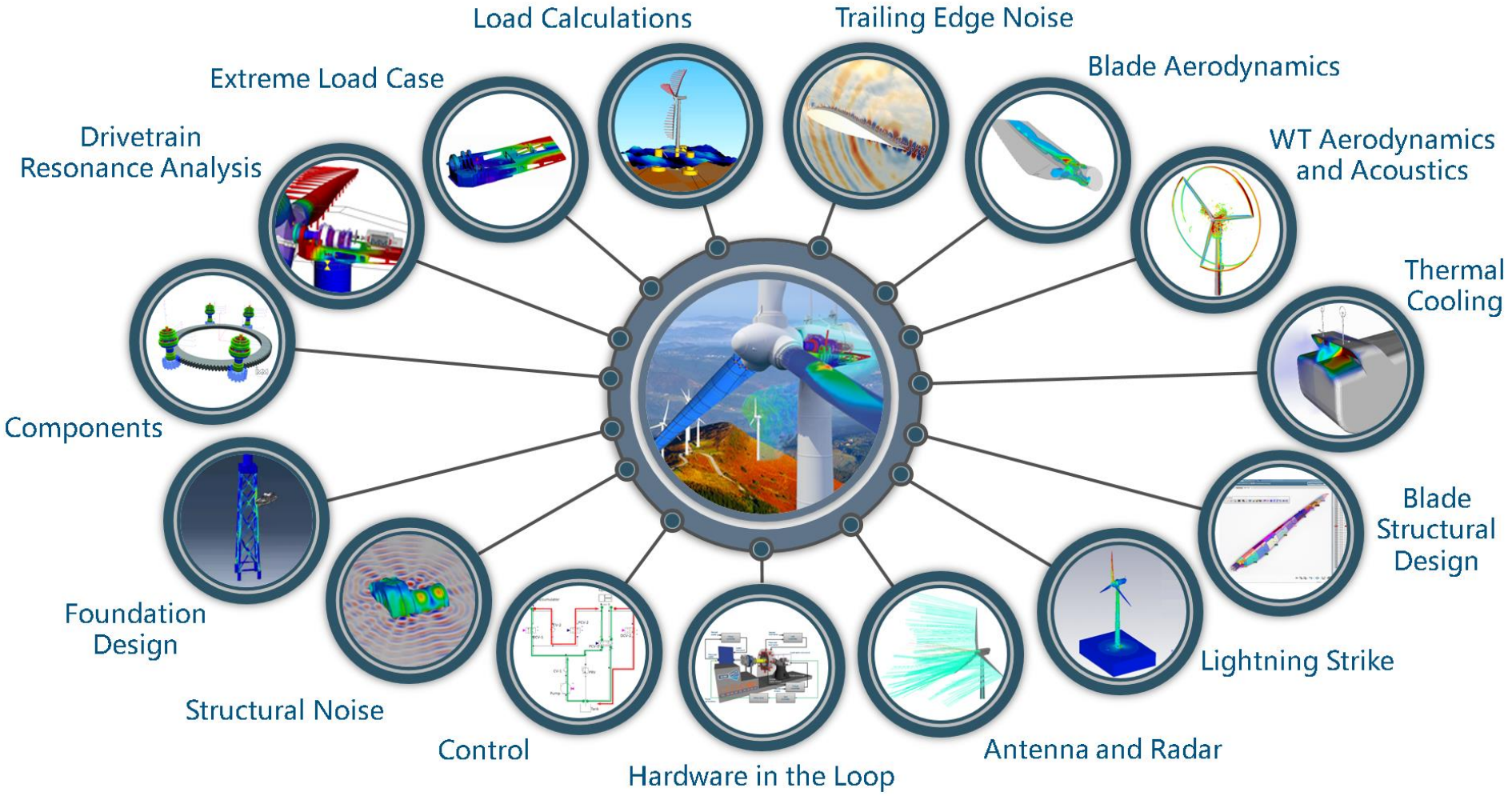
Wind Turbine Engineering

Dassault Systèmes Workflows

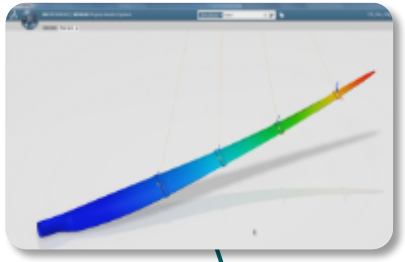


Wind Turbine Engineering | **Avoid Risk**

3DEXPERIENCE **Platform** - The Digital Thread

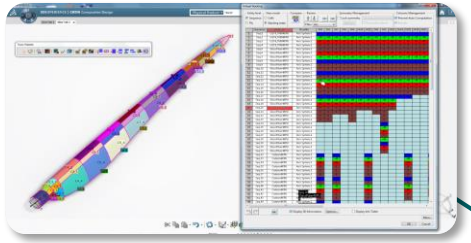
Full digital continuity from design to validation to manufacturing eliminates translations and other sources of data loss.

Detailed Verification



Manufacturing

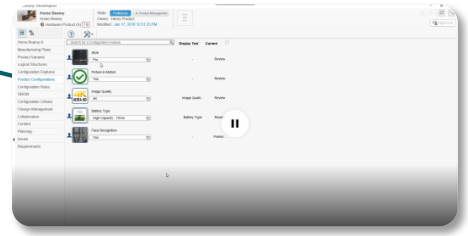
Component Validation



Operations

Design

Requirements



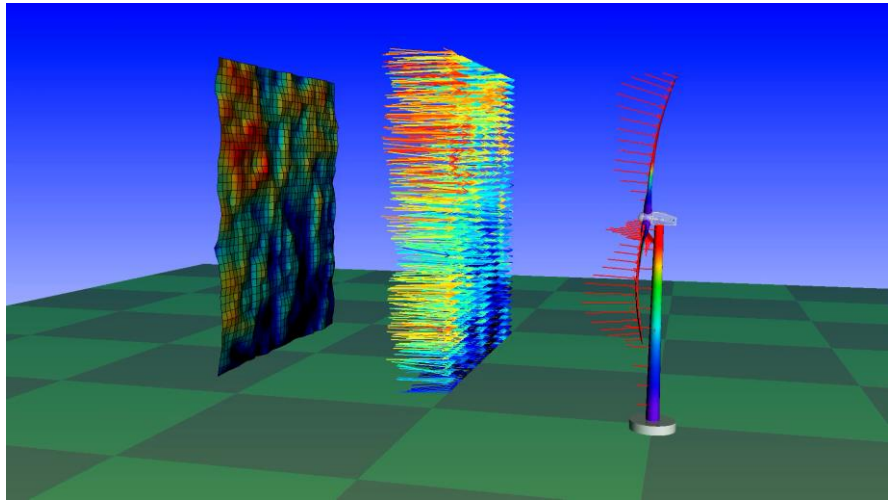
- **Single Source of Truth**
- **Traceability**
- **Versioning**
- **Collaboration**
- **Configuration**
- **Automated Workflows**

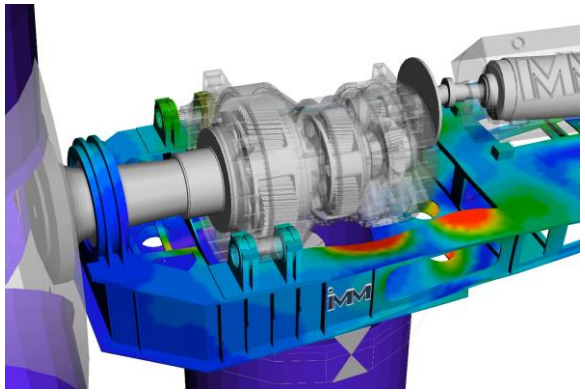
DASSAULT SYSTEMES

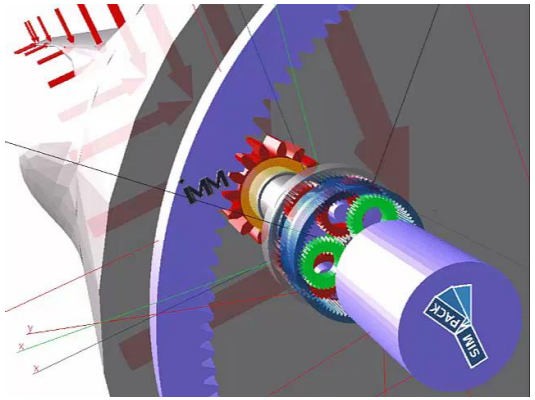
Simpack – Multibody Systems (MBS) Simulation Software

Dynamic analysis and Load Prediction of any wind turbine, any design

- ✓ Load Calculations
- ✓ Drivetrain Resonance Analysis
- ✓ Detailed component analysis
- ✓ Extreme events
- ✓ Stress and durability
- ✓ Optimization
- ✓ Test-rigs, transportation, assembly, maintenance, …





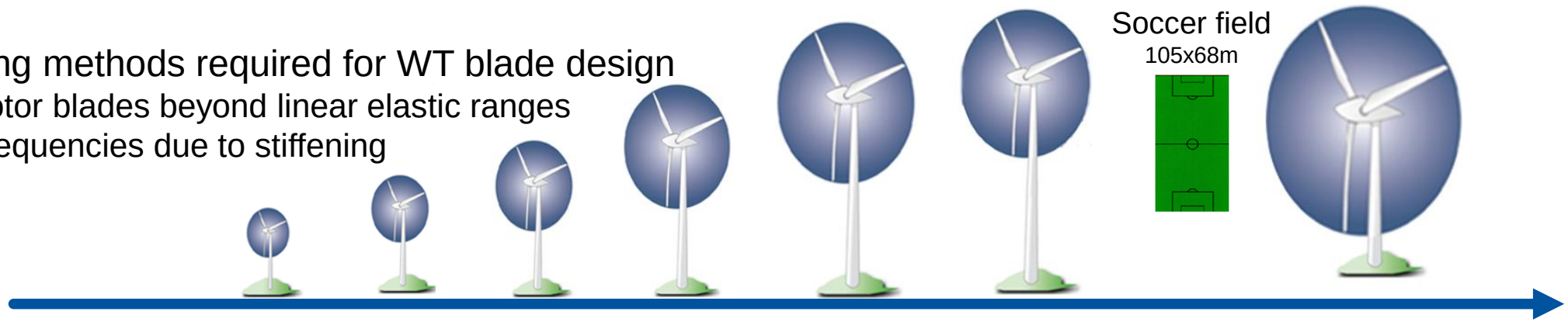


Courtesy of IMM TU Dresden

DASSAULT SYSTEMES

Motivation

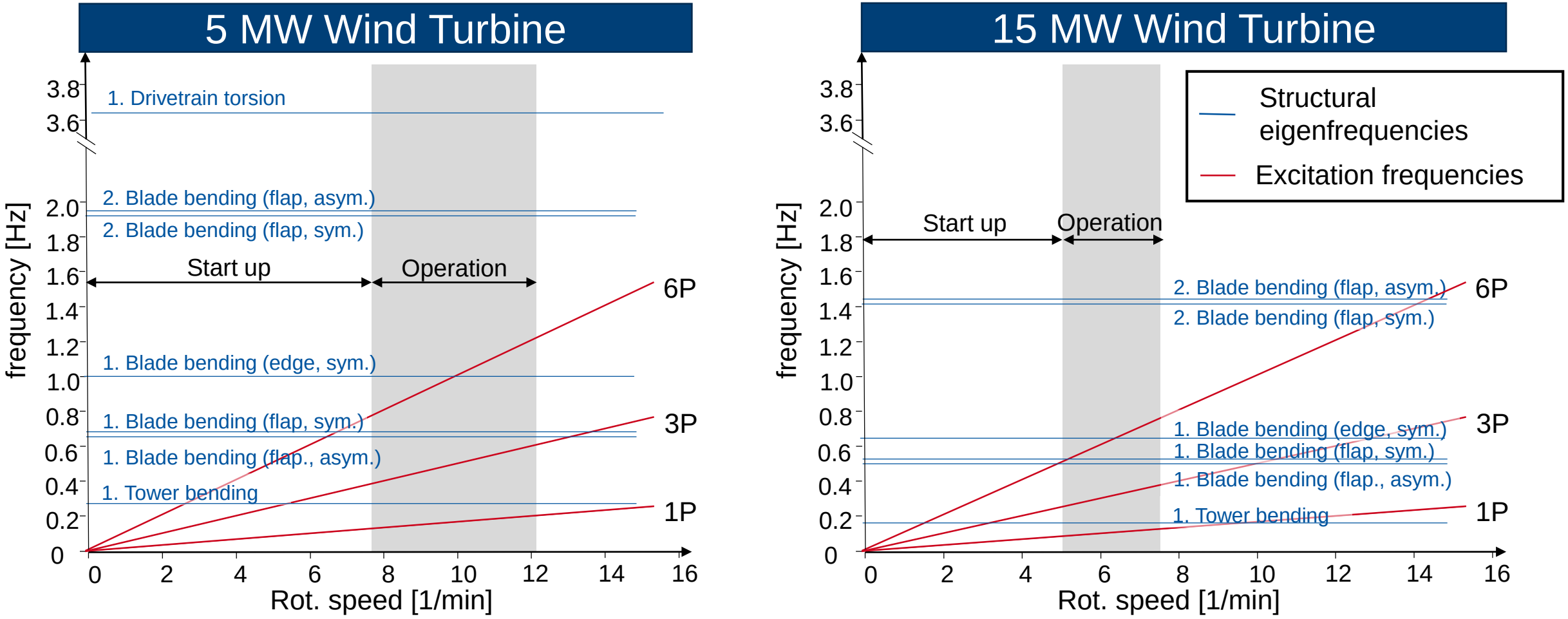
- Wind Turbines (WT) are getting bigger in power and size continuously
- Larger rotorblades to capture more wind energy
  - Increased weight
  - Increased loads
  - Decreased speed
- Precise modeling methods required for WT blade design
  - Deflection of rotor blades beyond linear elastic ranges
  - Shift in eigenfrequencies due to stiffening



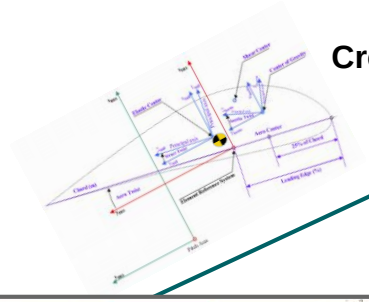
		1985	1990	1995	2000	2005	2010	2014	2018	2020
Rated power	kW	80	250	600	1500	3000	7500	8000	9500	13.000
Rotor diameter	m	20	30	46	70	90	127	164	164	220
Rotor area	m^2	314	707	1.662	3.848	6.362	12.668	21.124	21.124	38.000
Powerdensity	W/m^2	255	354	361	390	472	592	379	450	342.1
Hub height	m	40	50	78	100	105	135	105	105	150

Motivation

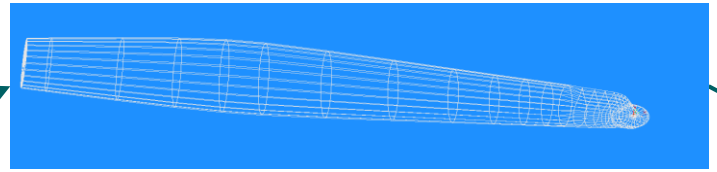
- Margins in the structural-dynamic design become smaller



New method for direct use of nonlinear FE models

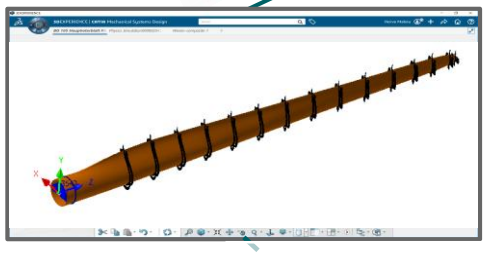


Cross-section analysis



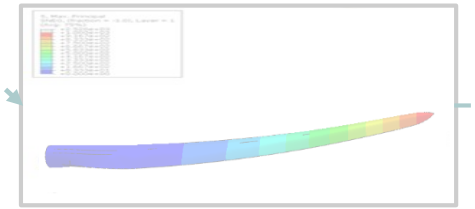
Linear beam for small deformation (modal)
- **5-10 DOF**

Non-linear beam for large deformation (nodal)
- **108 DOF**



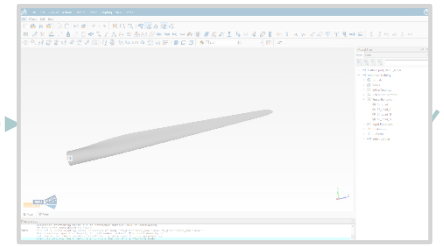
CAD model

FE modeling



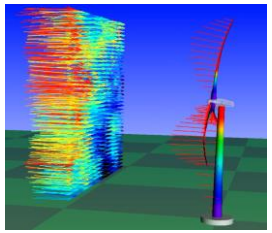
FEA model
- **60000 DOF**

Non-linear Model Order Reduction



Reduced FEA for MBS
- **40 DOF**

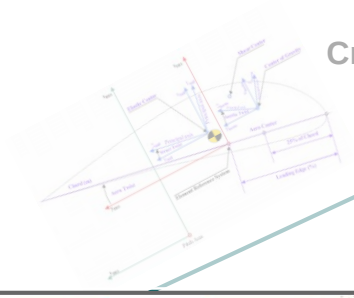
MBS System Model



Natural frequencies, Loads, Deformation, Stress, Fatigue,

MBS

New method for direct use of nonlinear FE models



Cross-section analysis

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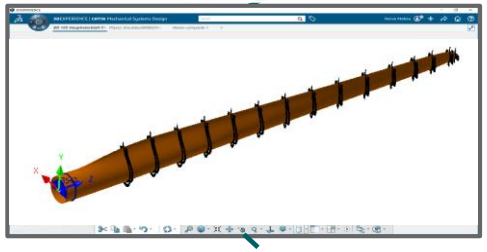
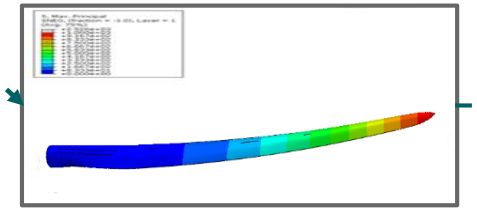
- 5-10 DOF

Non-linear beam for large deformation (nodal)
- 108 DOF



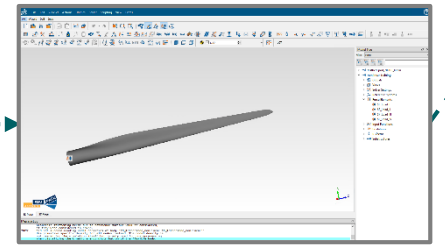
CAD model

FE modeling



FEA model
- 60,000 DOF

Non-linear Model Order Reduction



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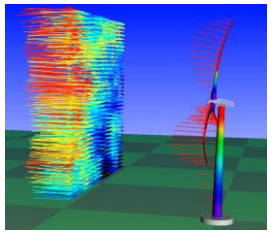
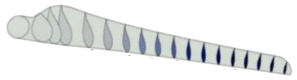
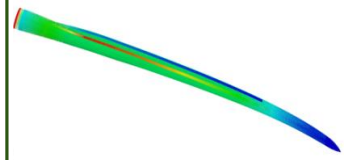


Natural frequencies, Loads, Deformation, Stress, Fatigue,

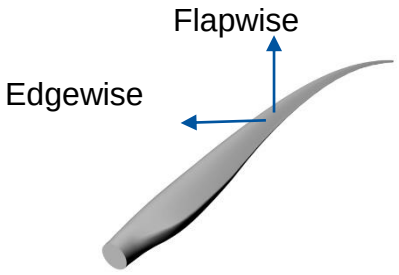
MBS

Workflow - Rotor blade modeling

- **1 Setting up the model**
  - Automated model generation tool for Abaqus

Aerodynamic blade definition	CAD structure	Structural definition FEM
		
▪ Aerodynamic profiles ▪ Defintion of rotor-blade surface	▪ Rotorblade CAD model	▪ Definition of composite layup ▪ Structural analysis

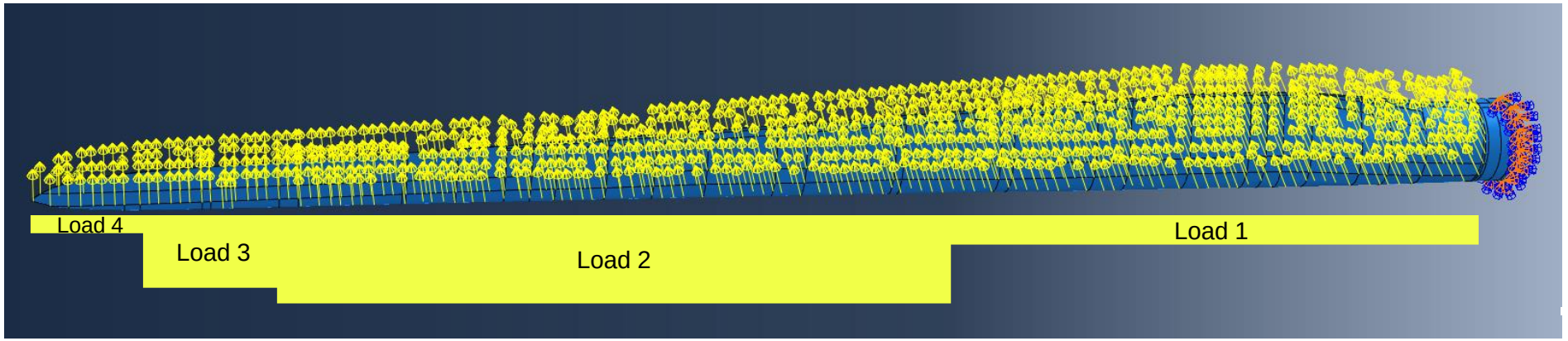
- **2 Identifying the dominant deformation movement**
  - Flapwise deflection/out of plane deflection

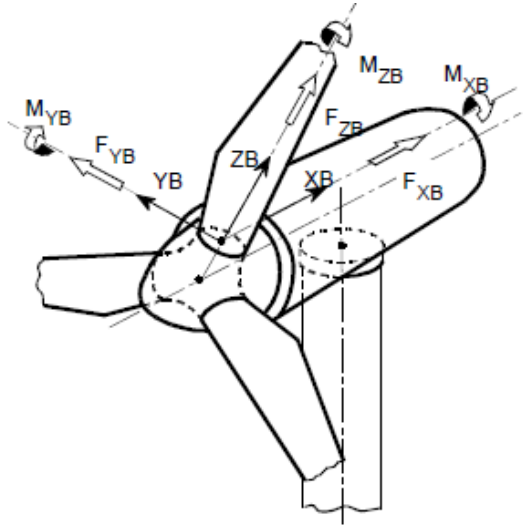


Source: Hau, Windkraftanlagen, 2008

Workflow – Preparing the reduction

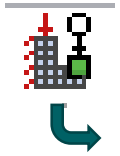
- **3 Defining boundary conditions and loads**
  - Wind load distribution approximated with 4 load zones
  - Fixed at blade root





XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

- **4 Set up the nonlinear deformation space**
  - Single FE job
  - Nonlinear static load calculation
  - Defining snapshots at 35 equidistant steps



```
38  *OUTPUT, FIELD, NUMBER INTERVAL=35
39  *NODE OUTPUT
40   U, UR, TF, CF, RF
41  *ELEMENT OUTPUT
42   S
43  *RESTART, WRITE, NUMBER INTERVAL=35
```

Workflow – Generating the flexible body input

- **5 Generating the reduced model**
  - Simpack fbi file generator started via console commands
  - Writing mass, stiffness and damping matrices for each snapshot
  - Performing linear eigenvalue analyses at each snapshot for secondary deformation
  - Generating the nonlinear flexible body input (fbi) file

Body Properties: $B_Rotorblade_nonlinear

Name: $B_Rotorblade_nonlinear

Description:

Type: Nonlinear flexible <prel>

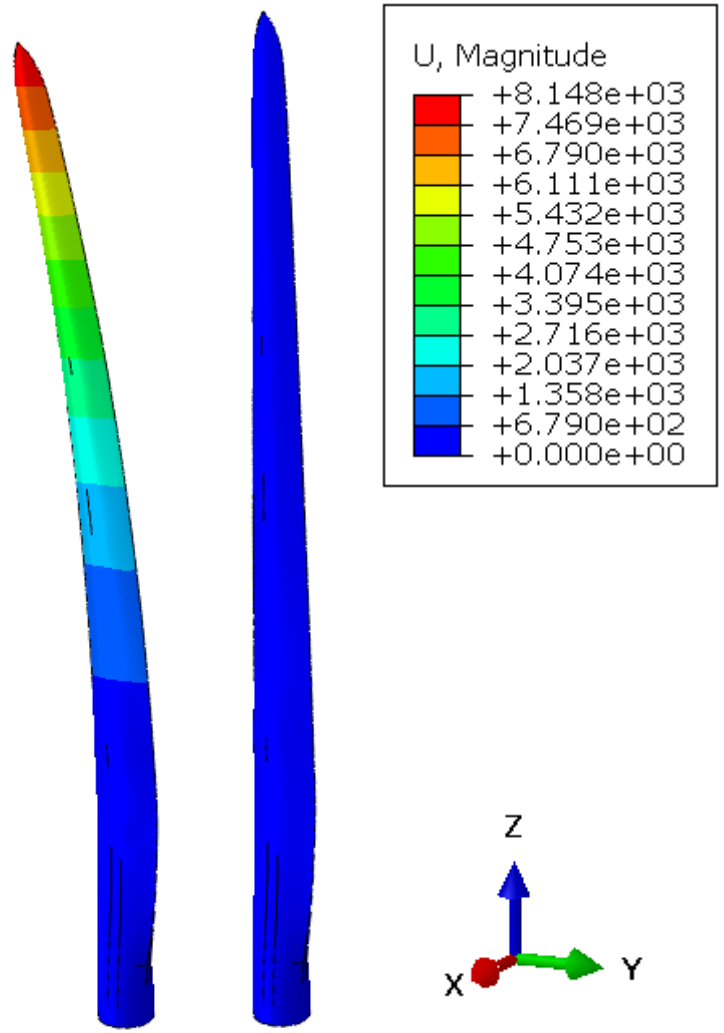
FE Properties | Mass Properties | Position | Modes | Options | Outputs

Damping type: Critical

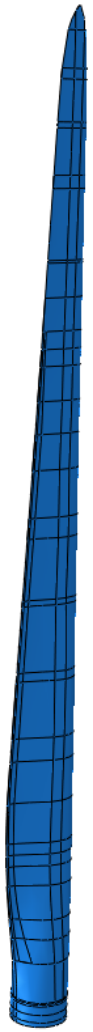
Damping input method: All modes | Damping 0.01

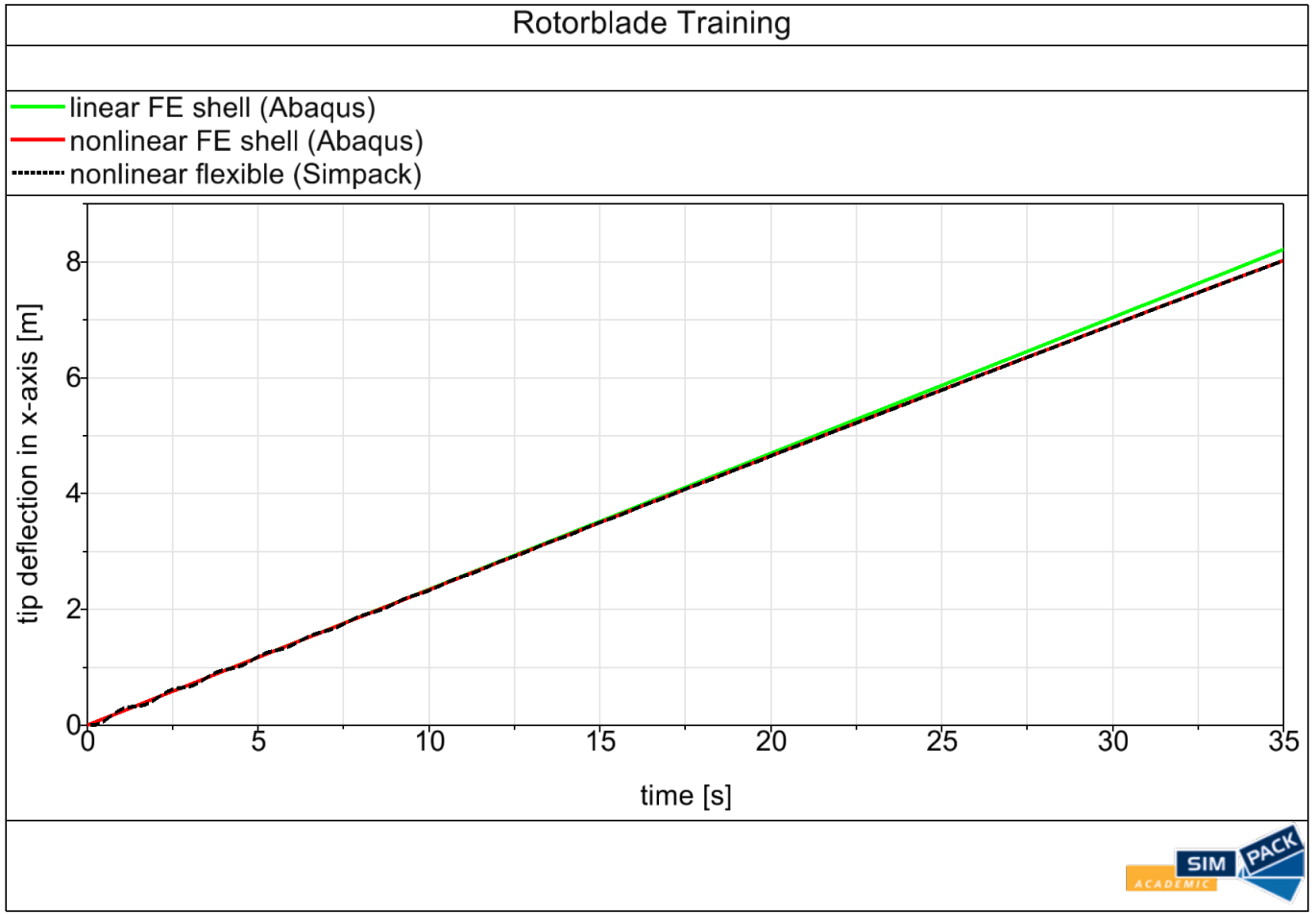
	Description	Damping	Position	Velocity	Pre-Stress Forces	Dependent	Dep. (active)	Active
1	Deformation mode 1 (Damping @ 0.7258 Hz)	0.01	0	0	0	automatic	independent	yes
2	Deformation mode 2 (Damping @ 1.092 Hz)	0.01	0	0	0	automatic	independent	yes
3	Residual mode 1 (Damping @ 1.996 Hz)	0.01	0	0	0	automatic	independent	yes
4	Residual mode 2 (Damping @ 3.217 Hz)	0.01	0	0	0	automatic	independent	yes
5	Residual mode 3 (Damping @ 4.086 Hz)	0.01	0	0	0	automatic	independent	yes
6	Residual mode 4 (Damping @ 5.755 Hz)	0.01	0	0	0	automatic	independent	yes
7	Residual mode 5 (Damping @ 6.515 Hz)	0.01	0	0	0	automatic	independent	yes
8	Residual mode 6 (Damping @ 7.102 Hz)	0.01	0	0	0	automatic	independent	yes
9	Residual mode 7 (Damping @ 9.21 Hz)	0.01	0	0	0	automatic	independent	yes
10	Residual mode 8 (Damping @ 9.653 Hz)	0.01	0	0	0	automatic	independent	yes
11	Residual mode 9 (Damping @ 10.74 Hz)	0.01	0	0	0	automatic	independent	yes
12	Residual mode 10 (Damping @ 11.16 Hz)	0.01	0	0	0	automatic	independent	yes
13	Residual mode 11 (Damping @ 11.58 Hz)	0.01	0	0	0	automatic	independent	yes
14	Residual mode 12 (Damping @ 11.85 Hz)	0.01	0	0	0	automatic	independent	yes
15	Residual mode 13 (Damping @ 12.32 Hz)	0.01	0	0	0	automatic	independent	yes
16	Residual mode 14 (Damping @ 14.36 Hz)	0.01	0	0	0	automatic	independent	yes
17	Residual mode 15 (Damping @ 15.49 Hz)	0.01	0	0	0	automatic	independent	yes
18	Residual mode 16 (Damping @ 18.26 Hz)	0.01	0	0	0	automatic	independent	yes
19	Residual mode 17 (Damping @ 25.46 Hz)	0.01	0	0	0	automatic	independent	yes

- **6 Integration into Simpack**
  - Type nonlinear flexible via fbi-File
  - Mode selection
  - Modal damping



Validation of the nonlinear flexible – training results

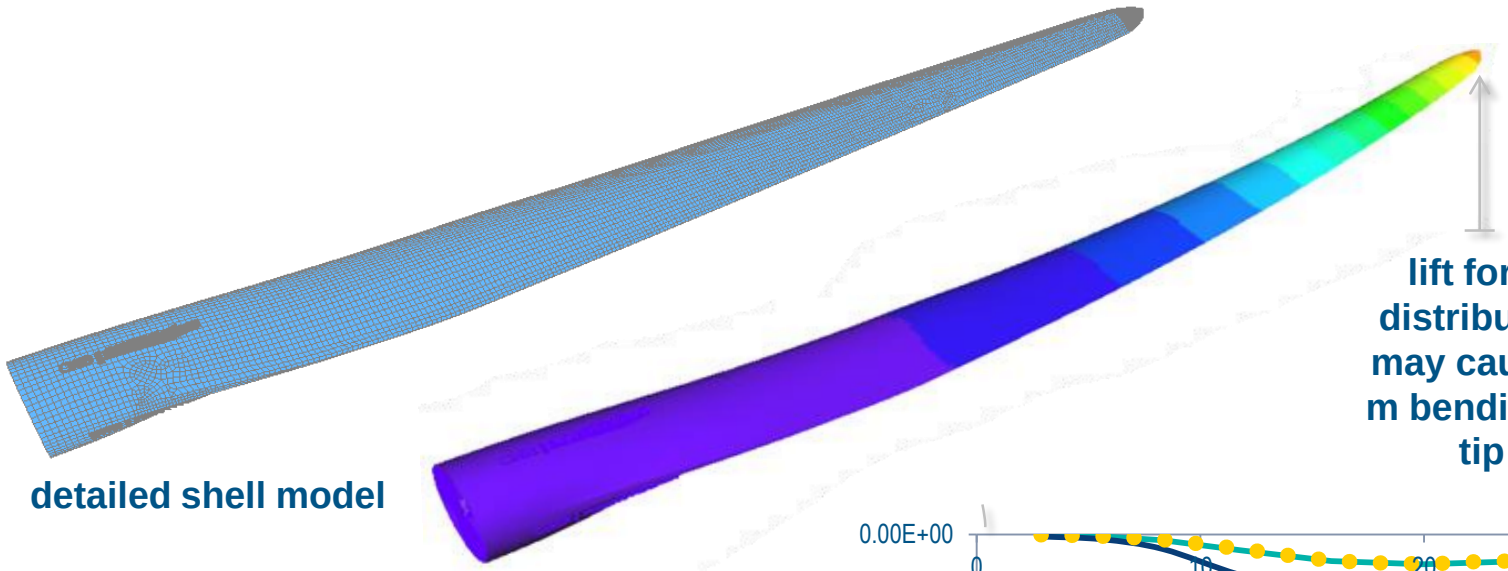




Workflow summary:

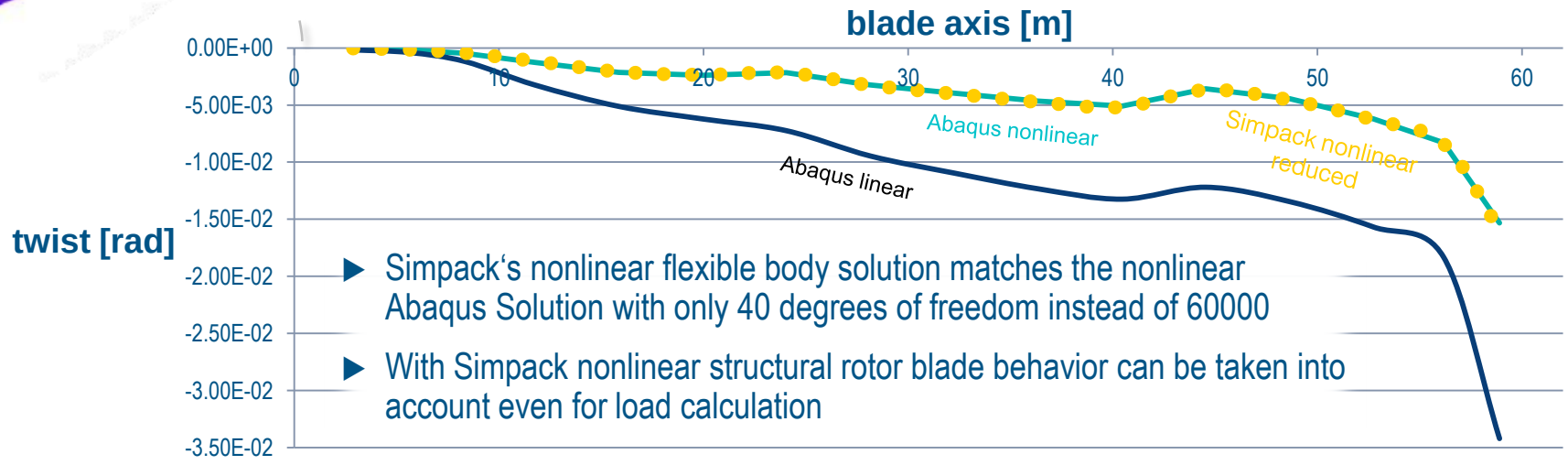
1. Setting up the model
2. Identifying the dominant deformation movement
3. Defining boundary conditions and loads
4. Set up the nonlinear deformation space
5. Generating the reduced model
6. Integration into simpack

Validation of the nonlinear flexible – training results



detailed shell model

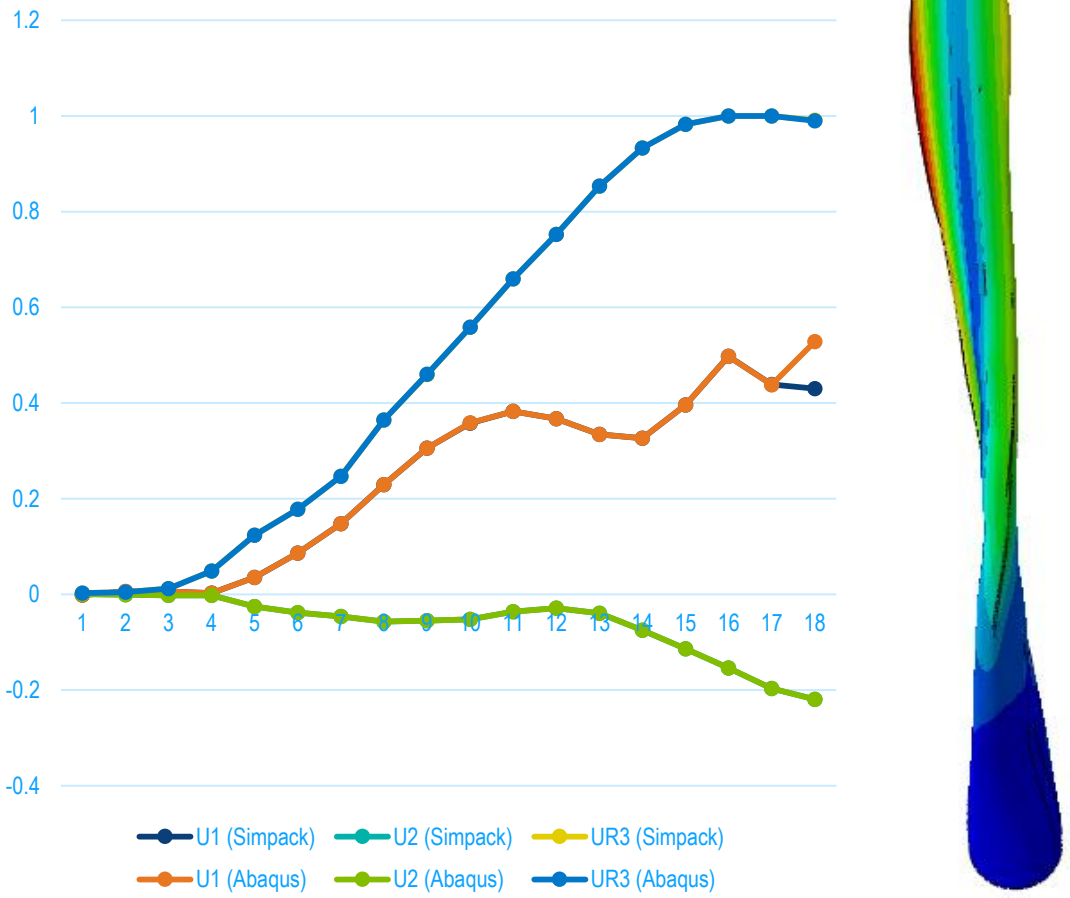
lift force distribution may cause 8 m bending at tip



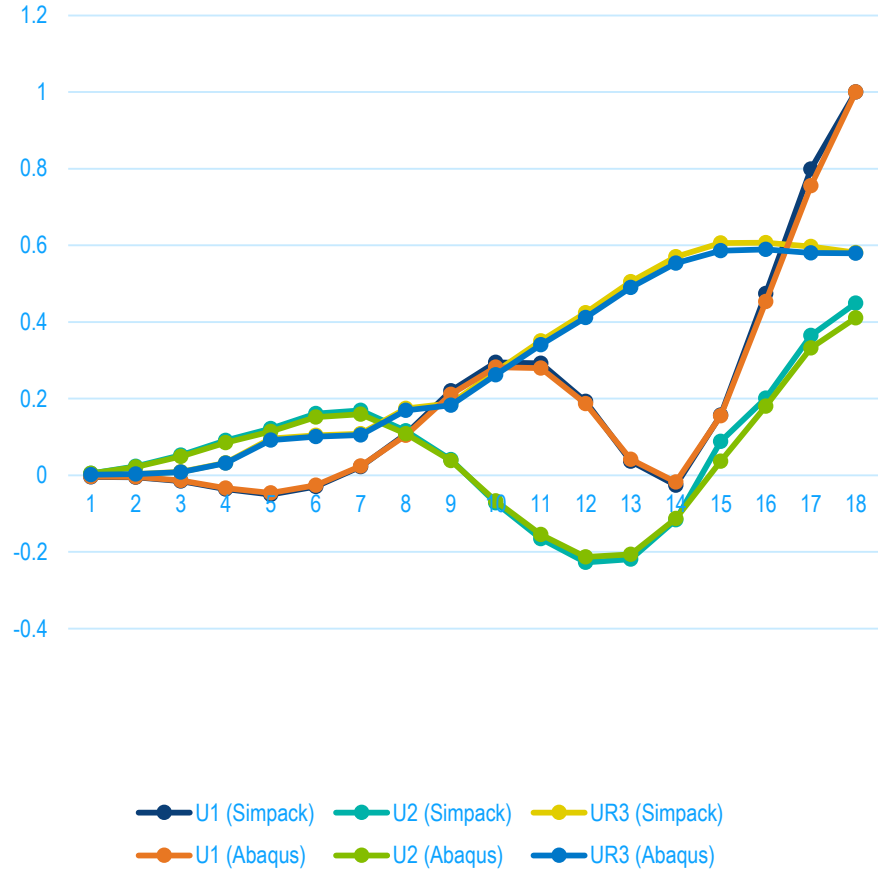
- Simpack's nonlinear flexible body solution matches the nonlinear Abaqus Solution with only 40 degrees of freedom instead of 60000
- With Simpack nonlinear structural rotor blade behavior can be taken into account even for load calculation

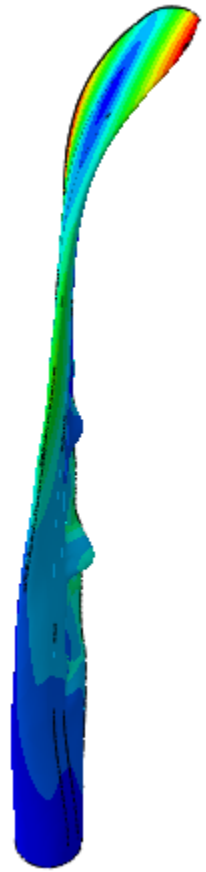
Validation of the nonlinear flexible – training results

Mode 6 @ 5.72 Hz in undeformed state

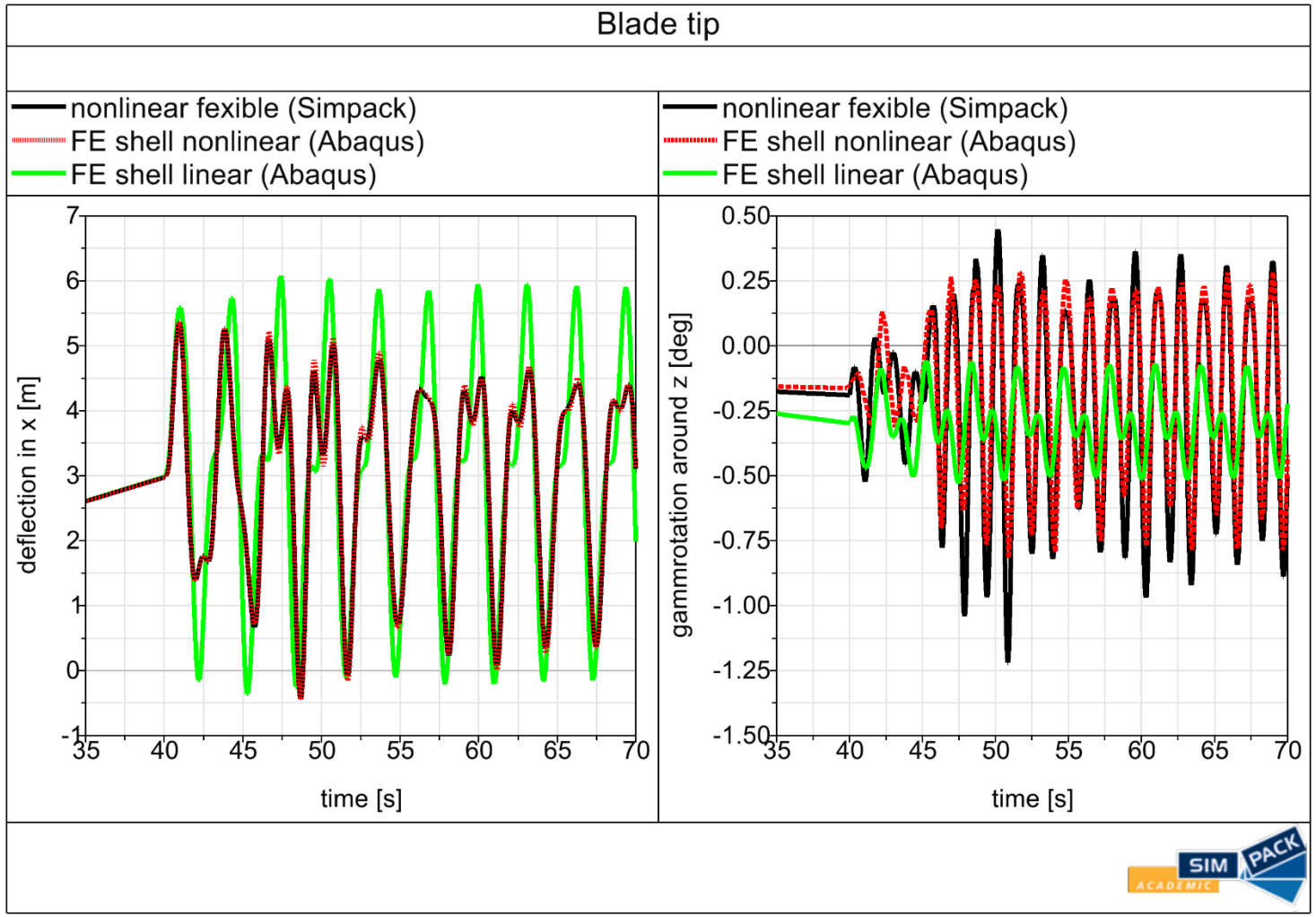


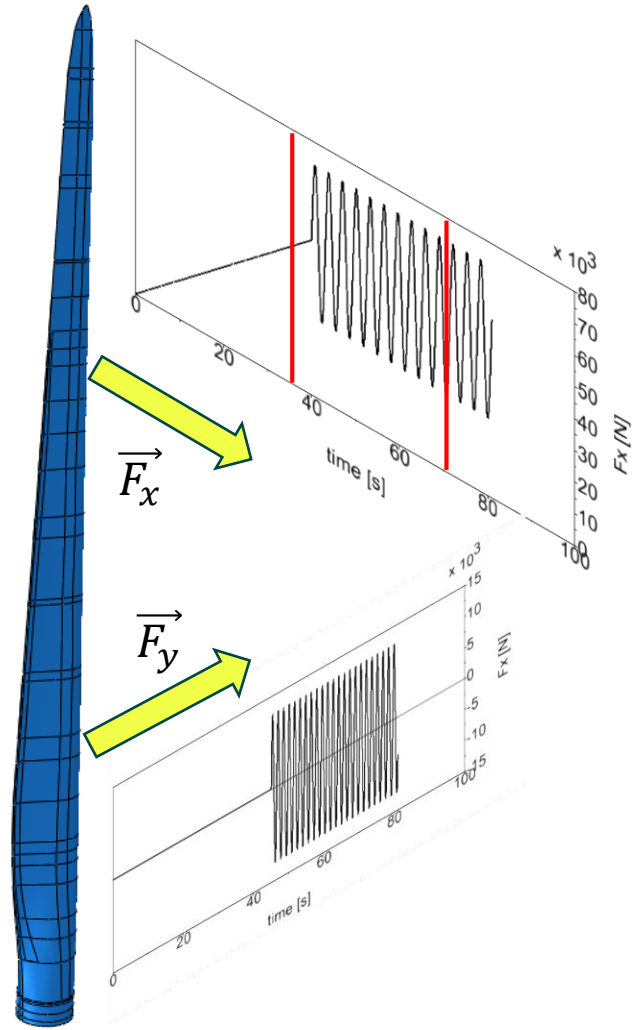
Mode 6 @ 6.13 Hz in deformed state (bending near rated power)





Validation of the nonlinear flexible – load excitation



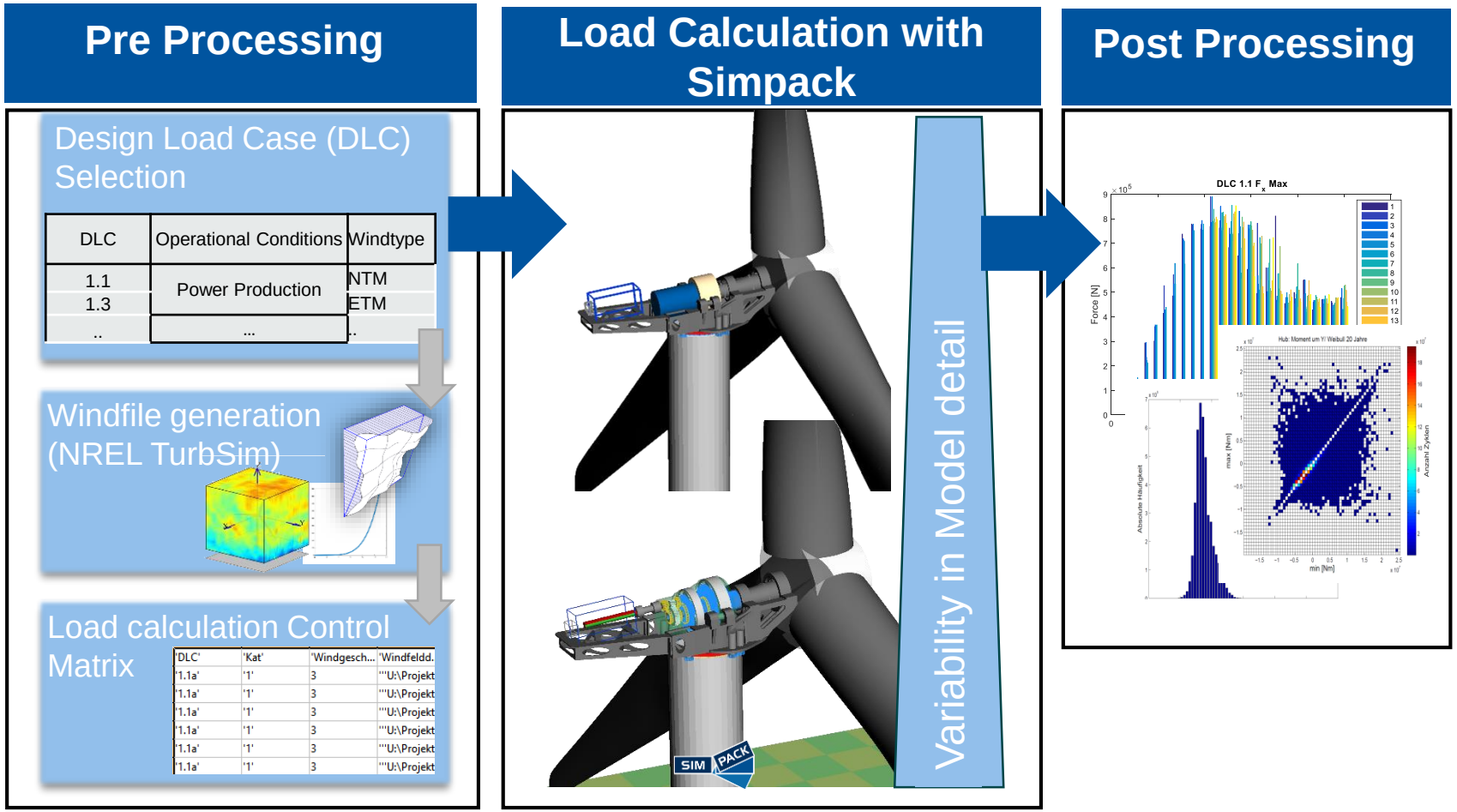


Validation of the nonlinear flexible

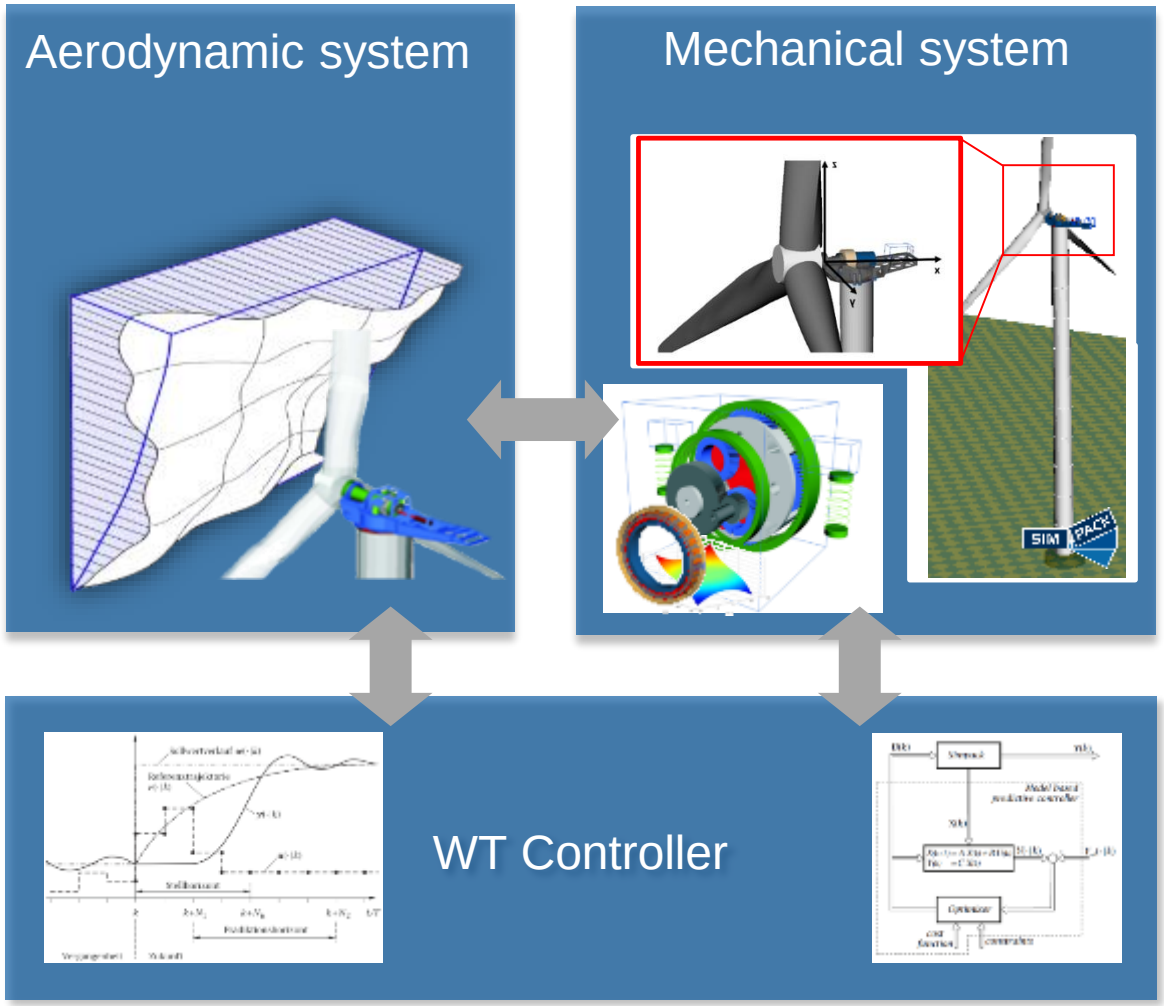
- Other investigated loadcases:
  - Rotation of blade in rotor plane under gravity
  - Rotation of blade around blade axis
  - Load and Release
  - Dynamic excitation at blade root
- Nonlinear elastic behavior of FE models can be reproduced in Simpack with significant reduction of DOF
- Significance increases with deformation scale

DLC calculations - Simpack Load Calculation Workflow

- Load calculations according to IEC 61400
- Automated wind field generation and load calculation via co-simulation
- Automated post processing
- Adjustable controller and modeling depth

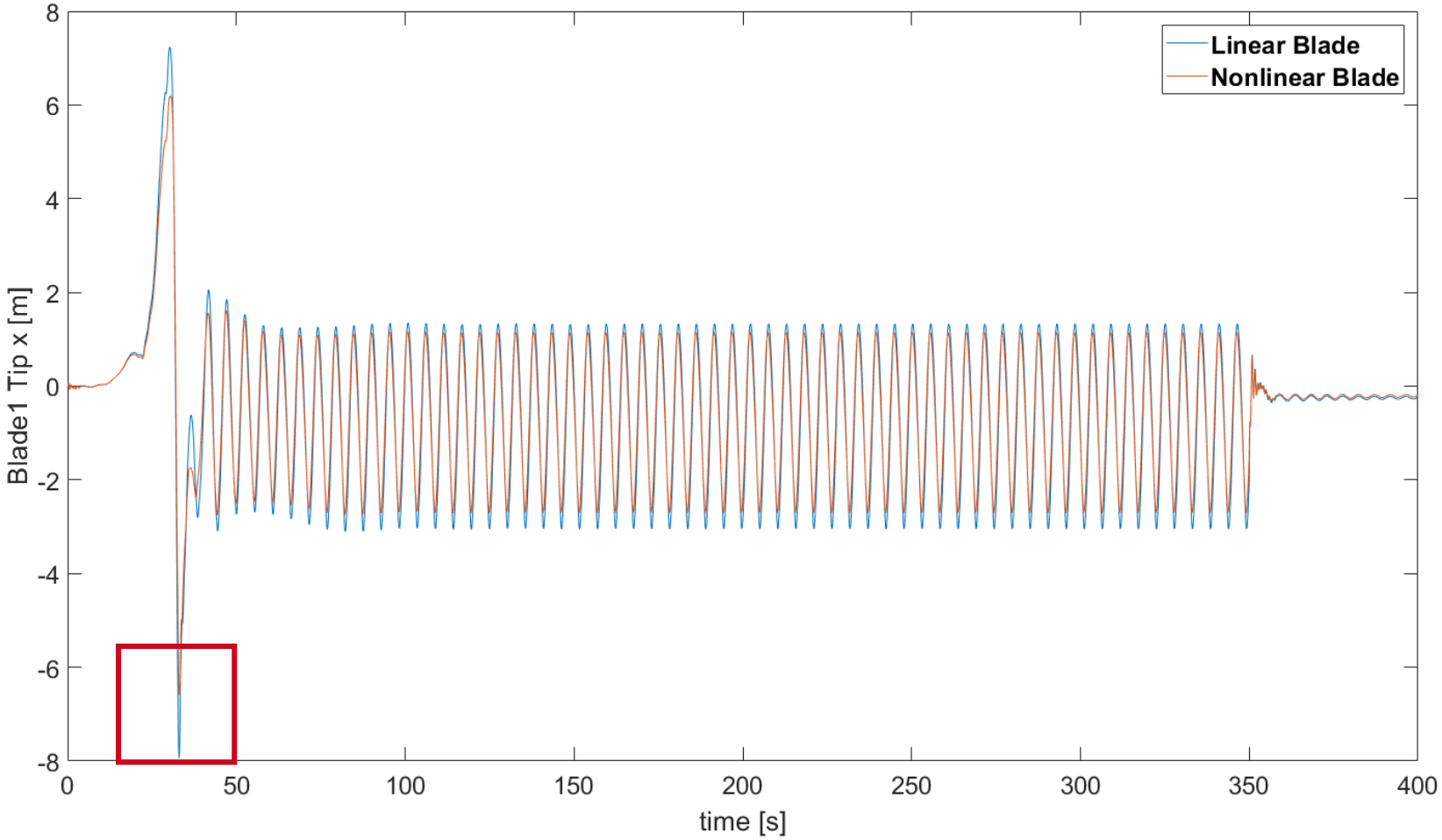


DLC calculations - Simpack WT model



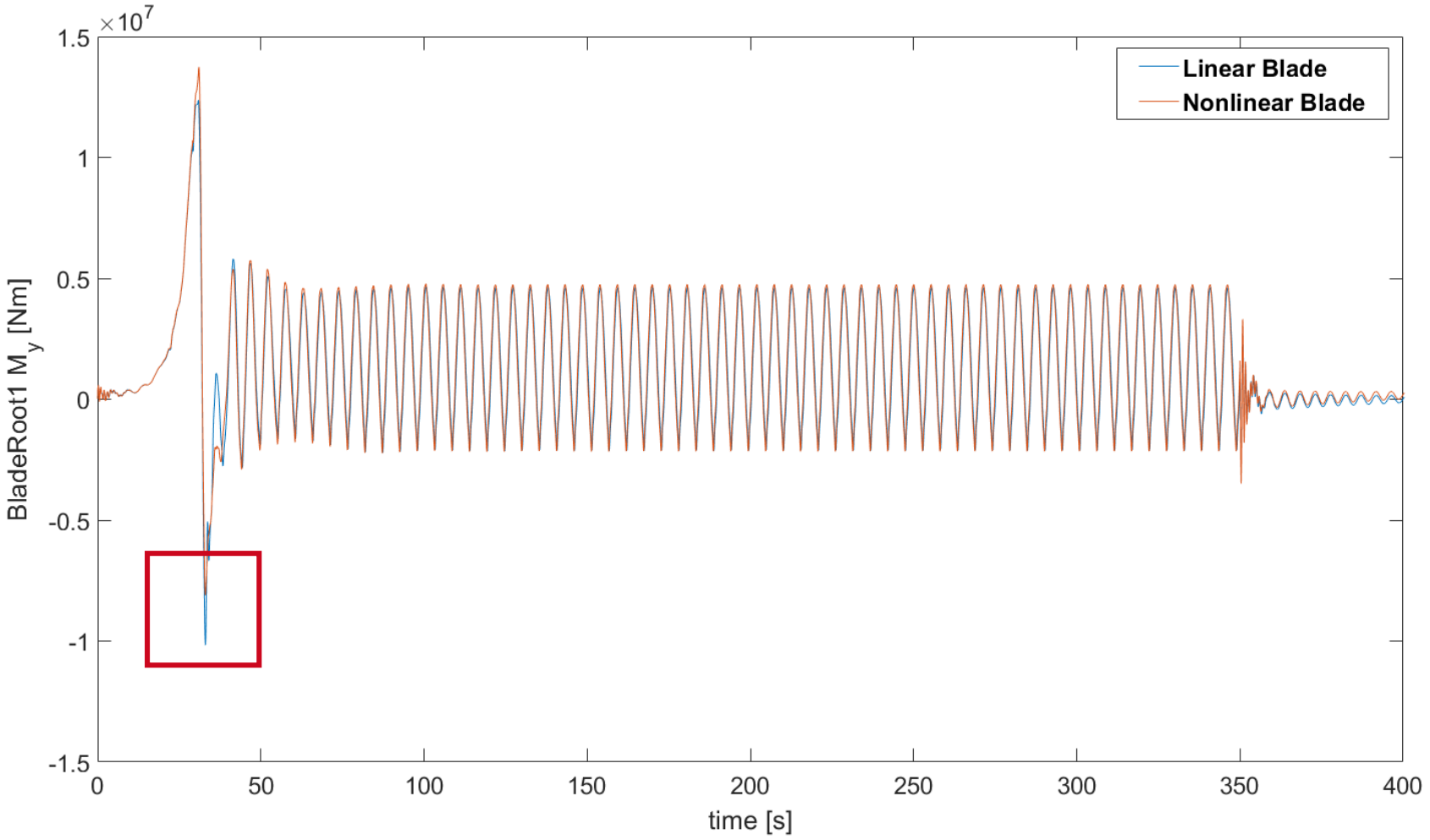
- WT data:
  - 3MW output power
  - 115m hub height
  - 11 m/s rated wind speed
  - 3 m/s Cut-in wind speed, 25 m/s Cut-out wind speed
  - 6° tilt angle
  - 3 point suspension with 1:92 gearbox ratio
- Identical wind fields for linear and nonlinear WT
  - 6 turbulent seeds per wind speed
- Identical controller for linear and nonlinear WT
- Drivetrain reduced to 2 mass oscillator

DLC calculations – extreme conditions



- Extreme operating gust (@30s)
- Emergency shutdown (@350s)
- Blade tip deflection
  - Peak deflection difference: +1.3m (+20%) for linear

DLC calculations – extreme conditions



- Extreme operating gust (@30s)
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- Blade root moment
  - Peak moment difference: +2 MNm (+25%) for linear

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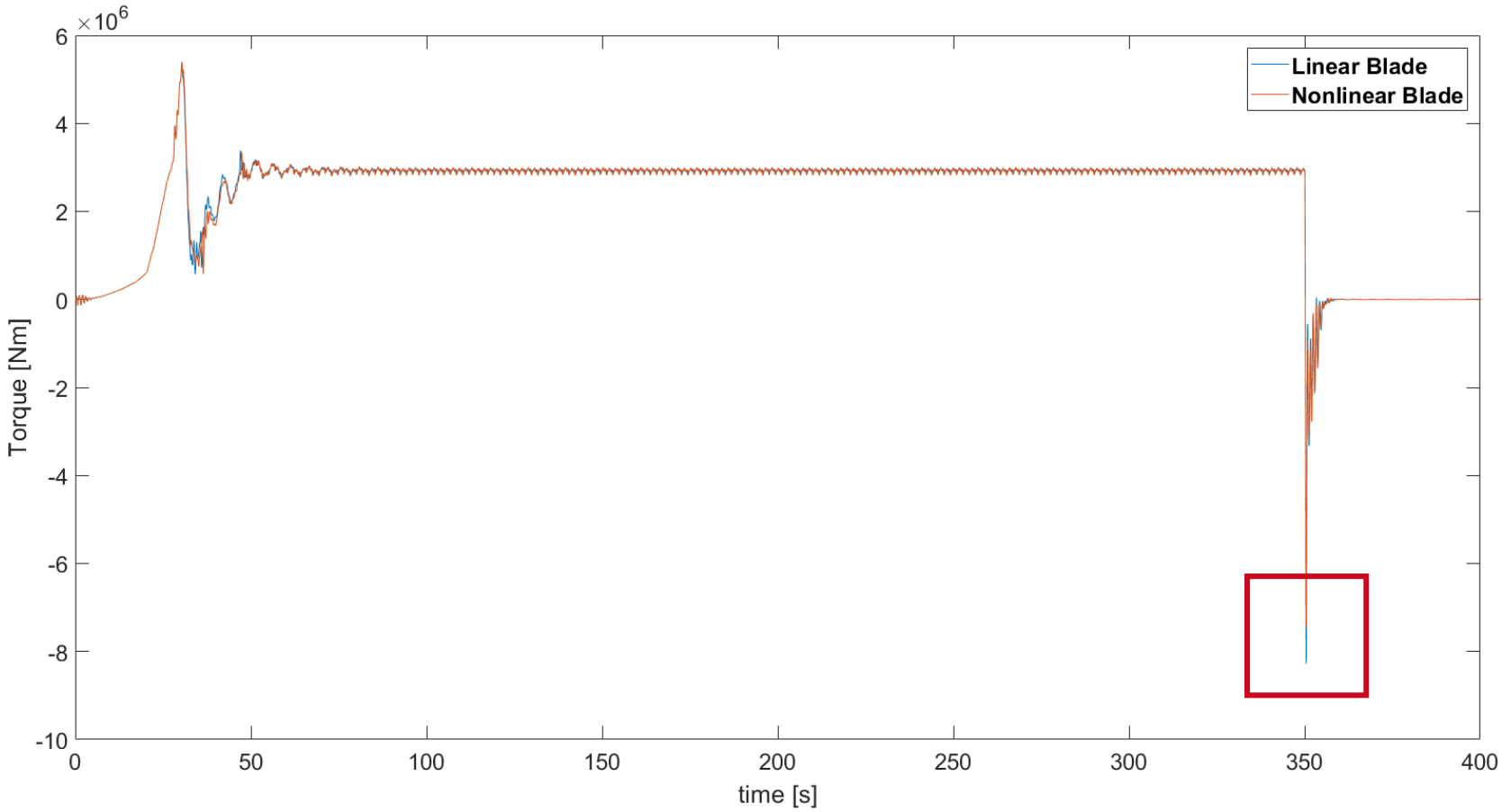
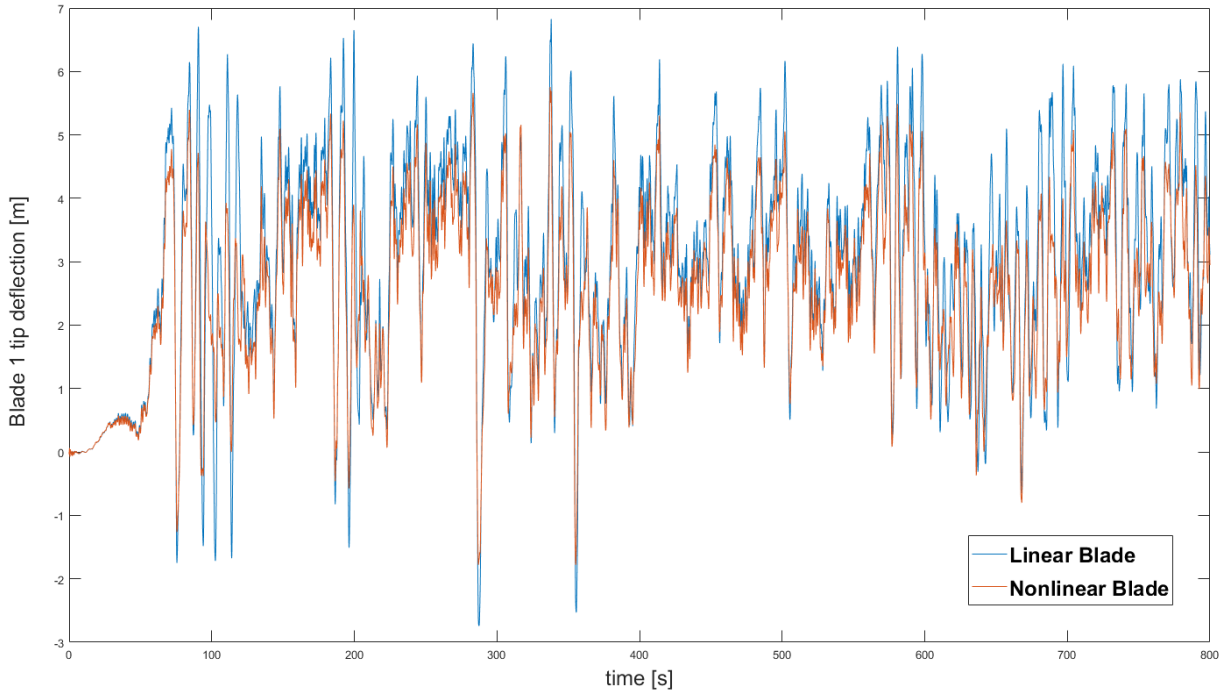
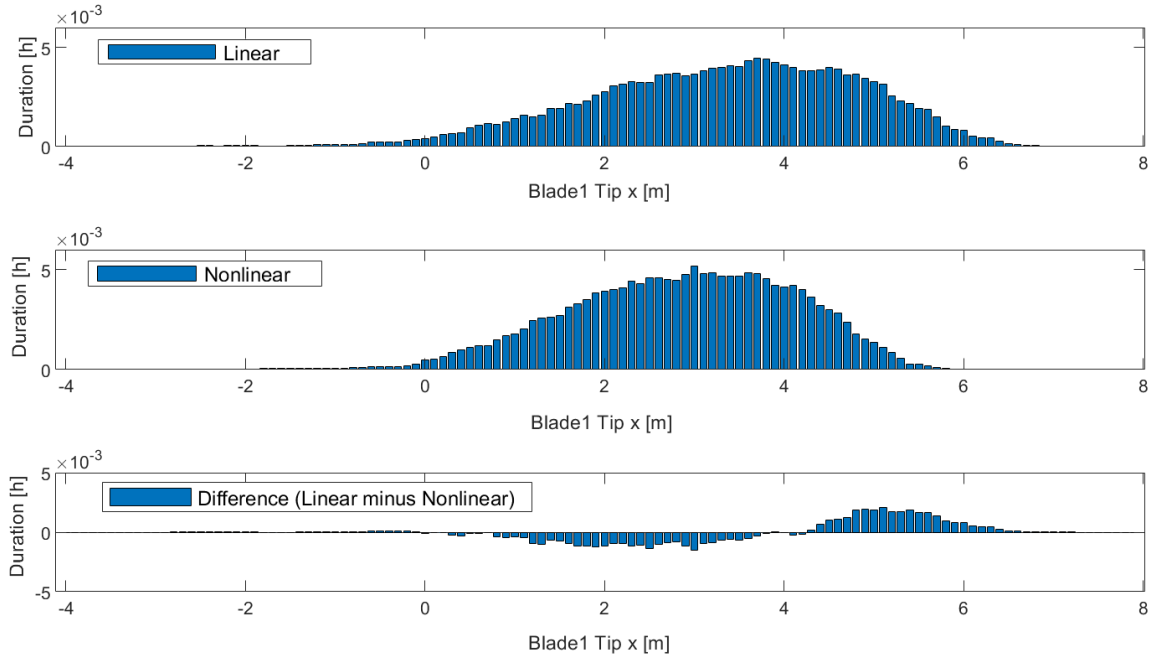


- Extreme operating gust (@30s)
- Emergency shutdown (@350s)
- Blade tip deflection
  - Peak deflection difference: +1.3m (+20%) for linear
- Blade root moment
  - Peak moment difference: +2 MNm (+25%) for linear
- Torque
  - Peak moment difference: +0.8 MNm (+11%) for linear

DLC calculations – normal operation

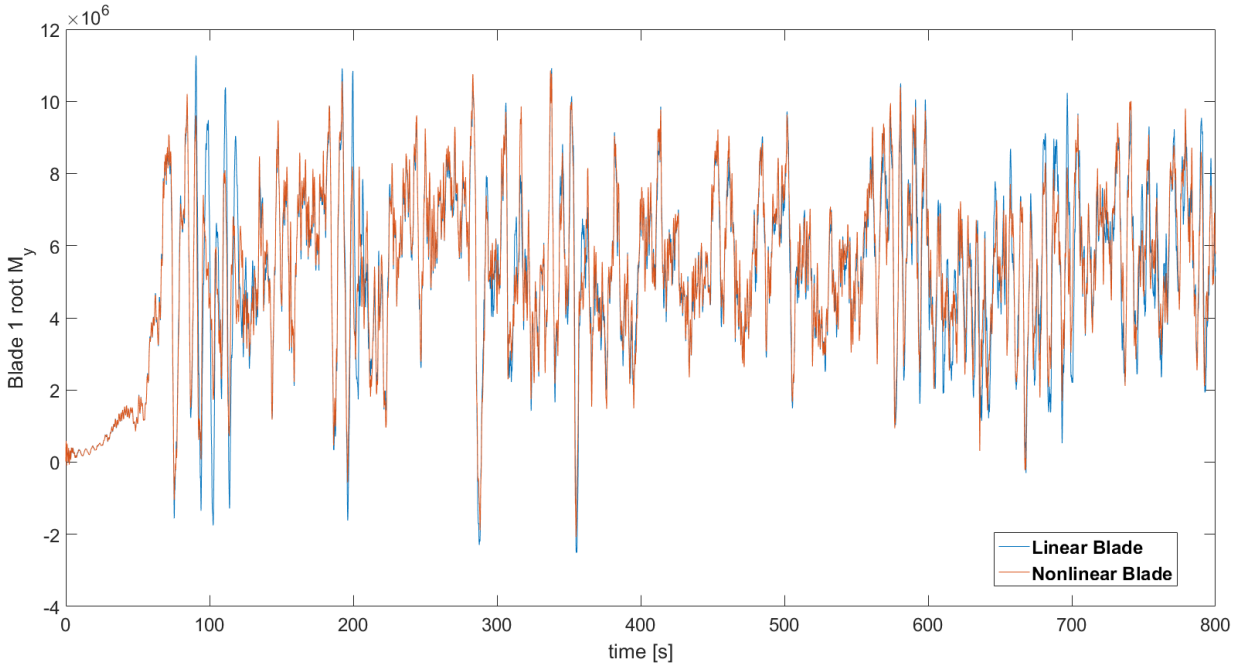
- Evaluation of blade tip deflection in x-direction
- Rated wind speed (11m/s)

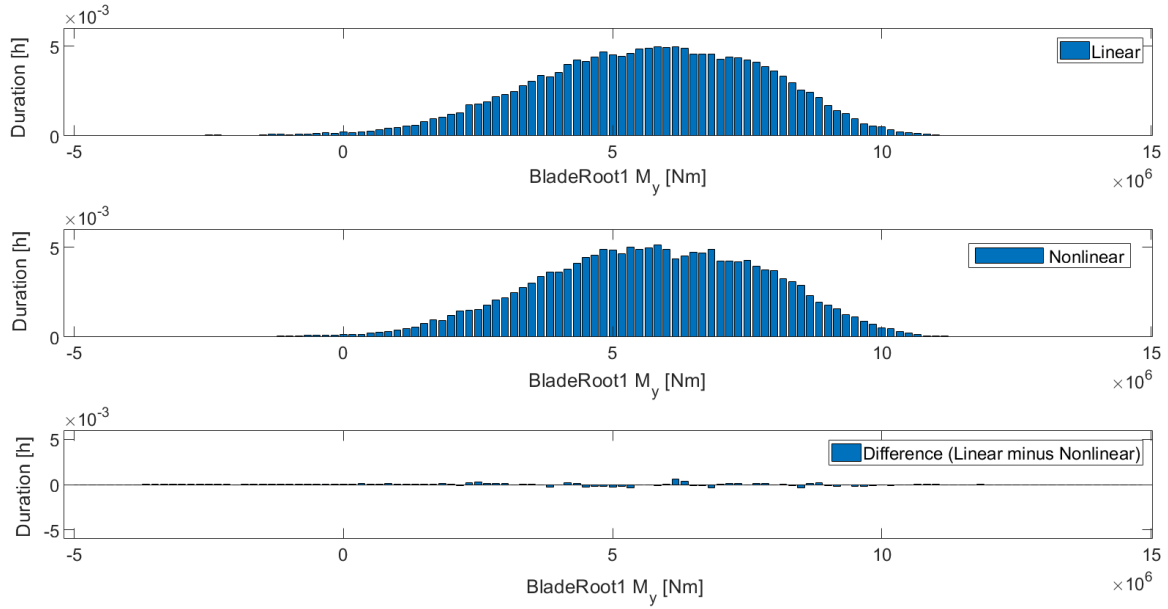




DLC calculations – normal operation

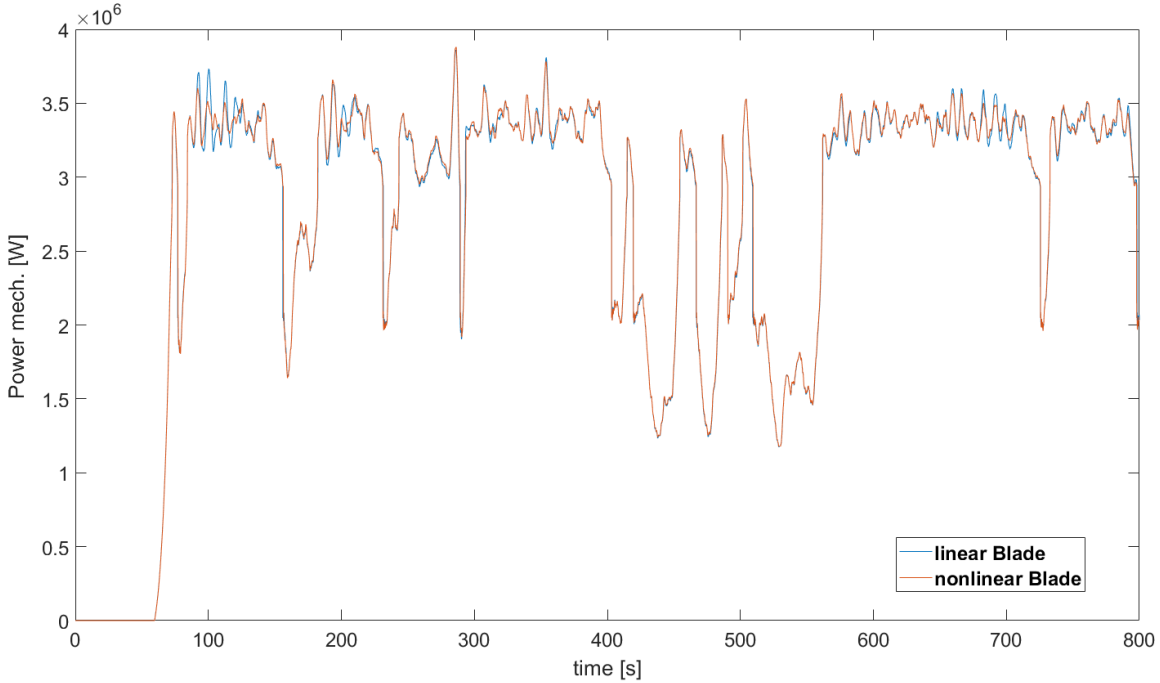
- Evaluation of blade root moment around y-axis
- Rated wind speed (11m/s)

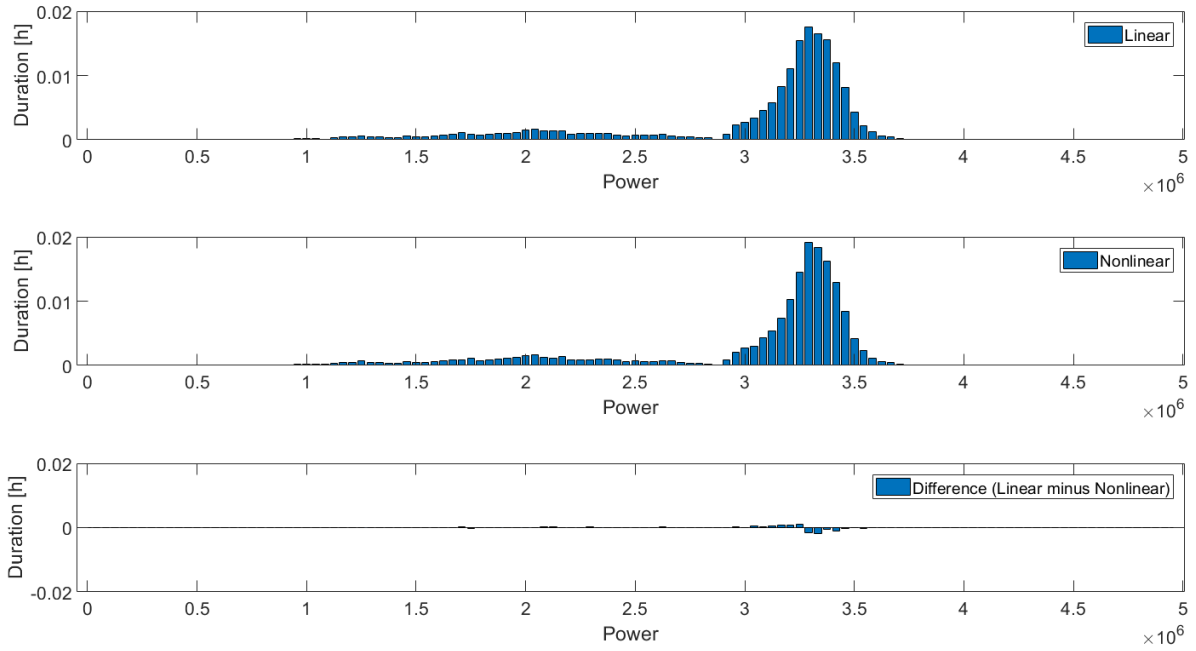




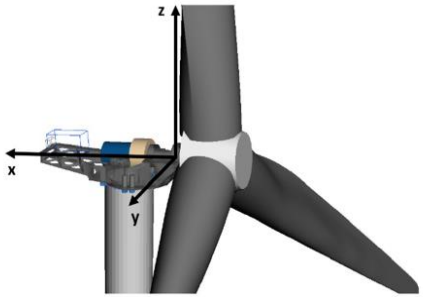
DLC calculations – normal operation

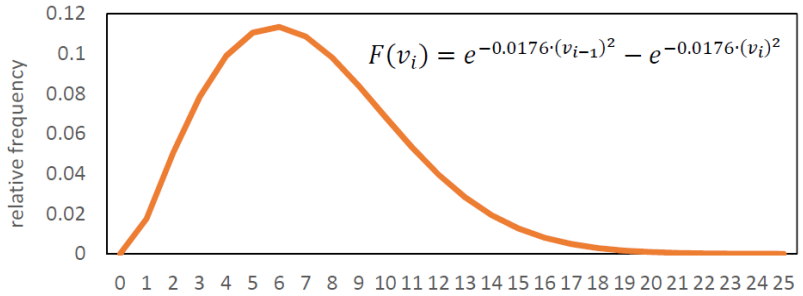
- Evaluation of mech. generator power
- Rated wind speed (11m/s)

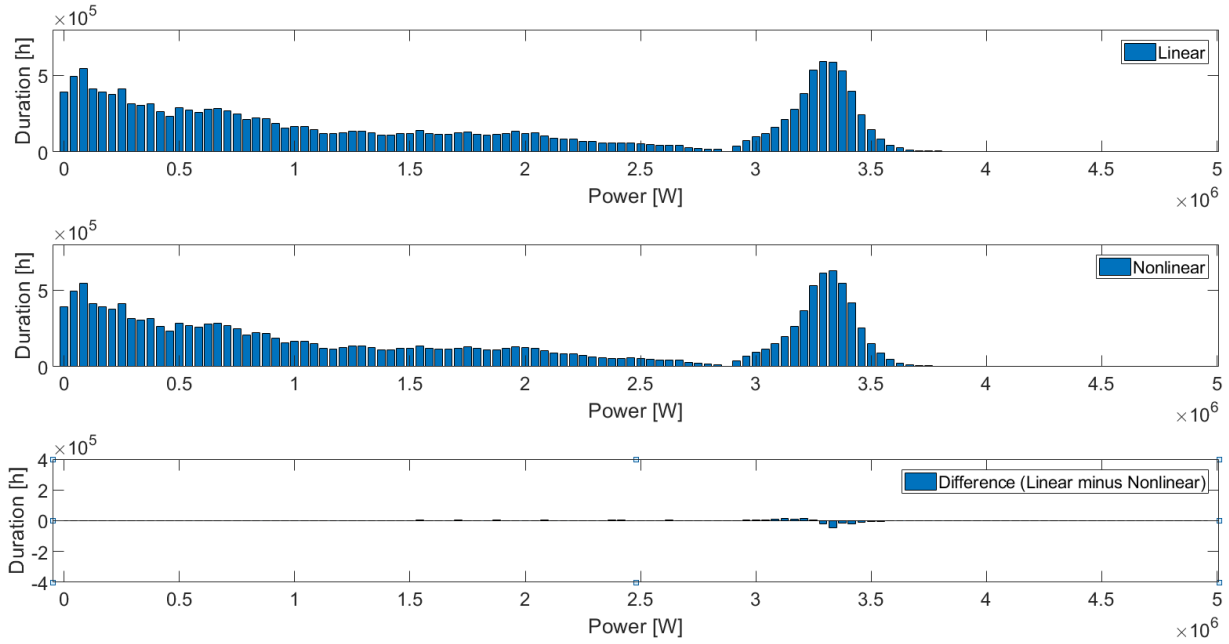




DLC calculations – WT lifetime production





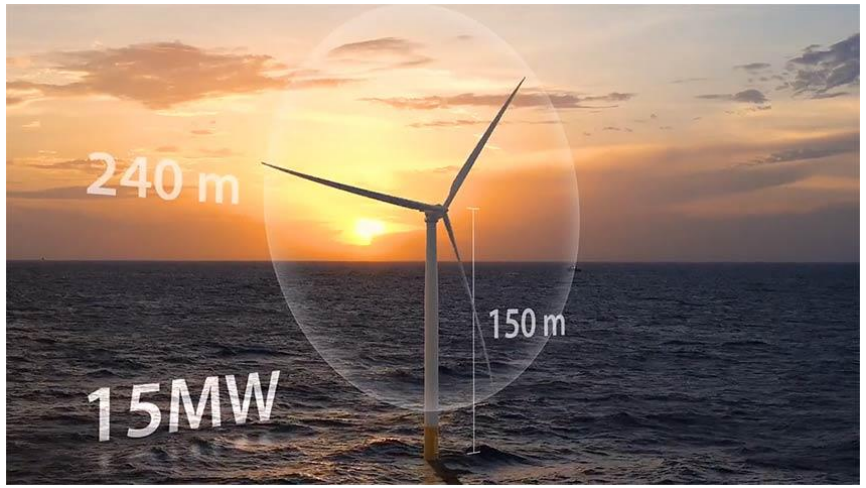


- Reference site from EEG
- 25 years timespan
- Total difference in power production: +836 MWh (+0.3%) with nonlinear blades
- Computational costs increased eightfold with nonlinear flexible rotor blades
- Preferably to be used in extreme operation conditions

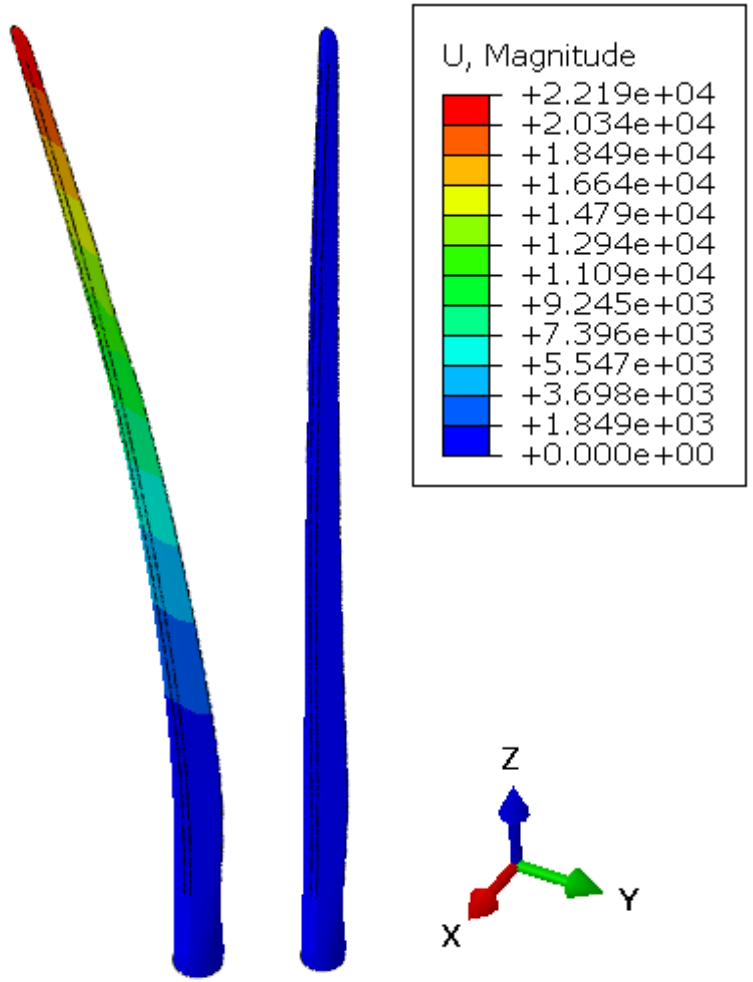
New 15 MW Rotorblade

- Derivation of a blade model from the new NREL 15MW Reference WT
  - Using linear and nonlinear SIMBEAM structures derived from FE model

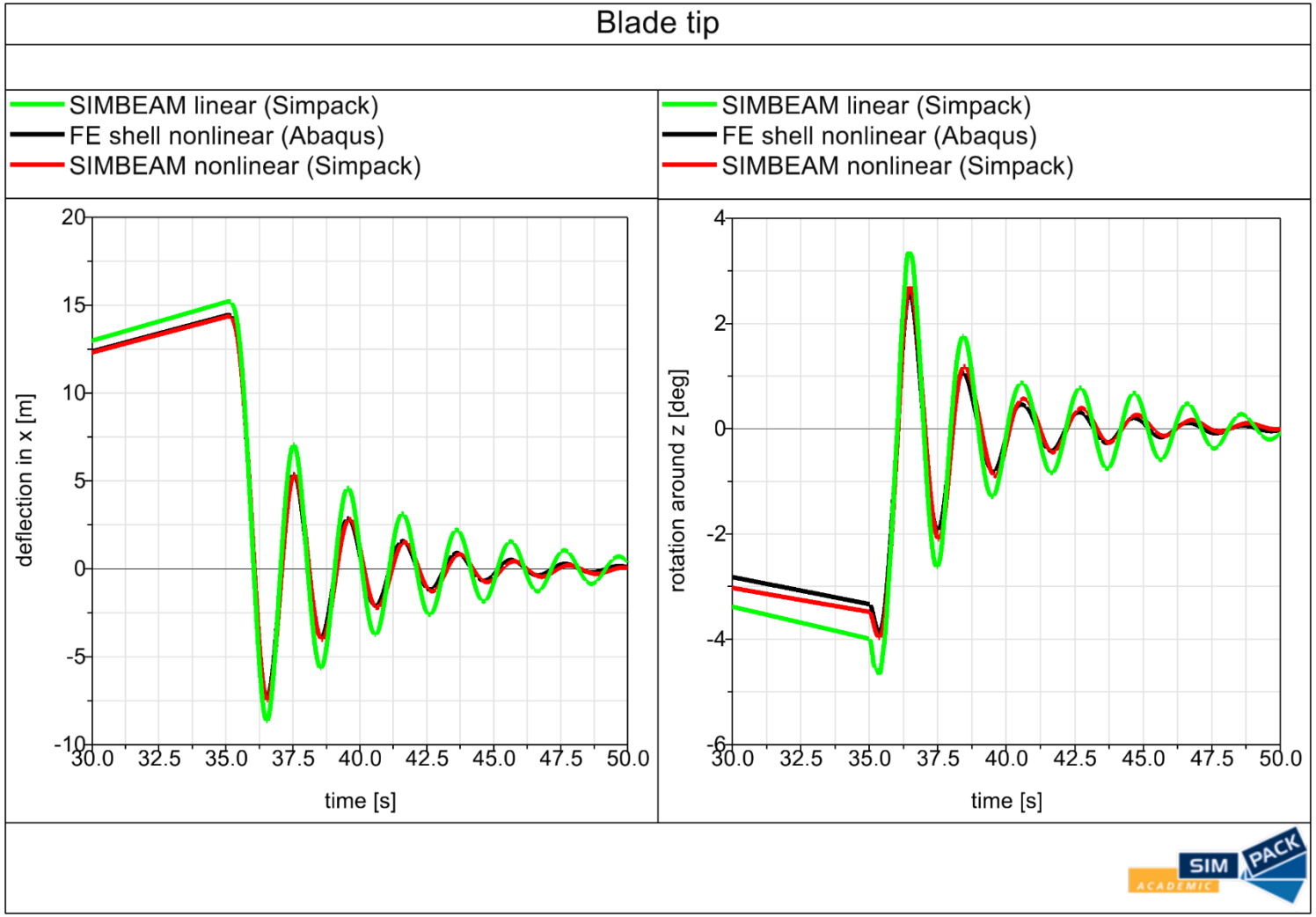
Description	15 MW RB	5 MW RB
Blade length	117 m	61.5 m
Blade mass	65.25 t	17.7 t
Frist flapw. natural frequency	0.555 Hz	0.724 Hz
Frist edgew. natural frequency	0.642 Hz	1.074 Hz

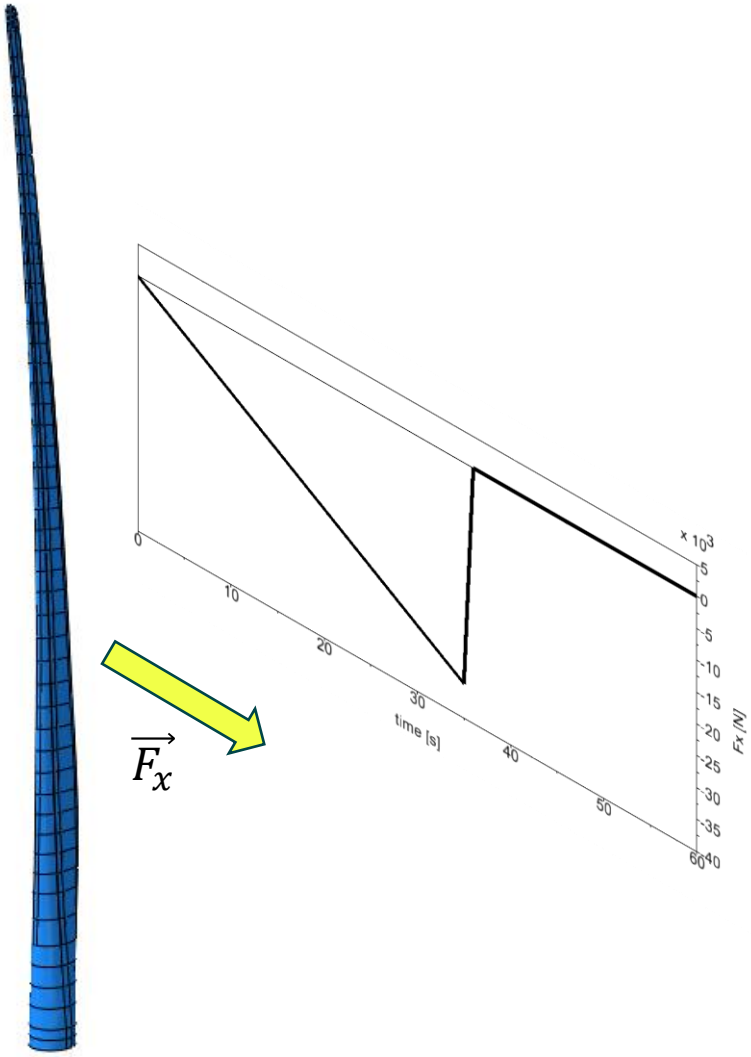


Source: NREL



New 15 MW Rotorblade - Load cases





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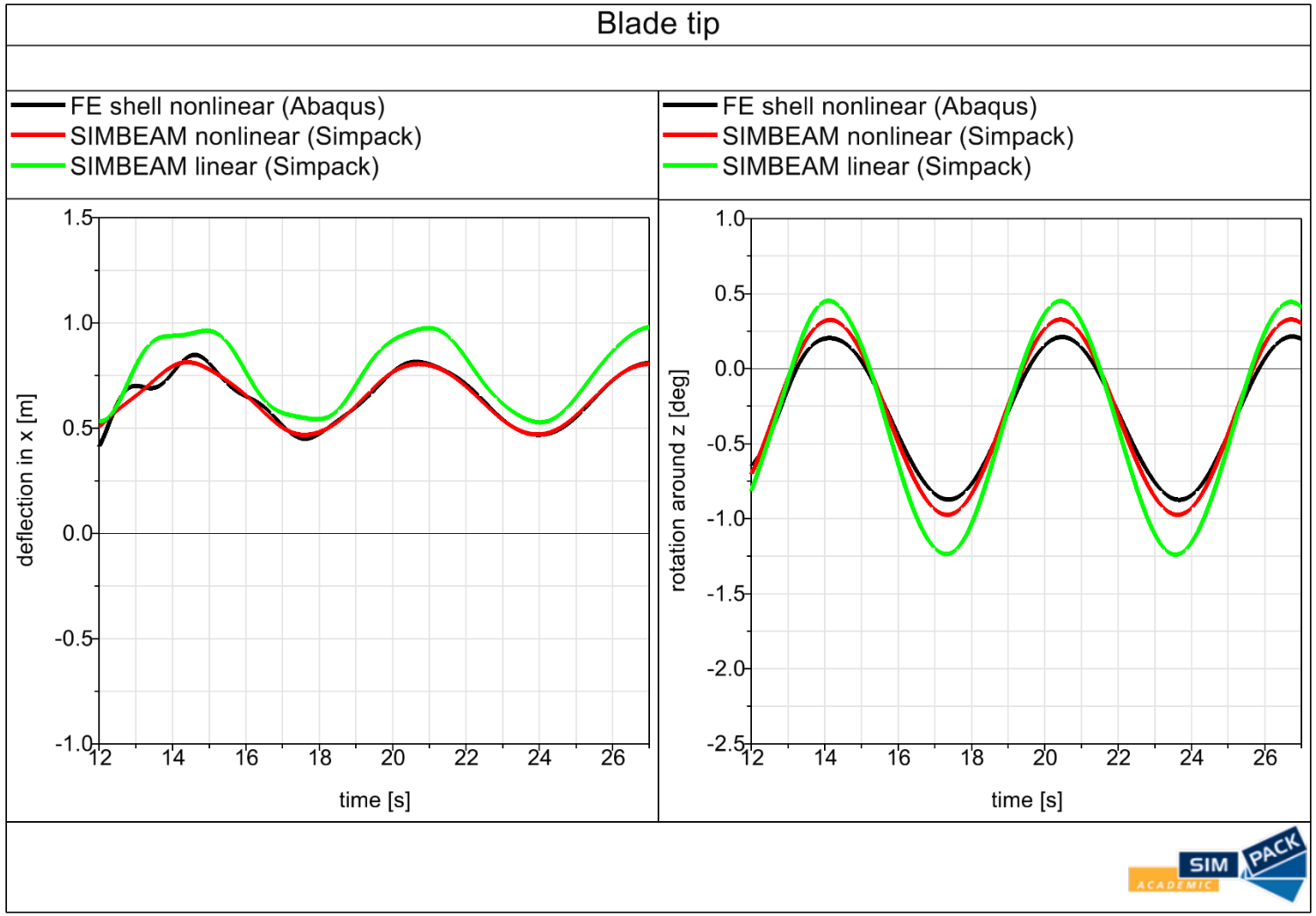
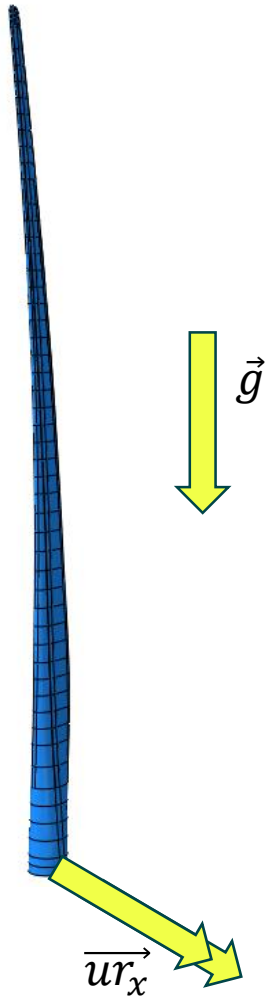
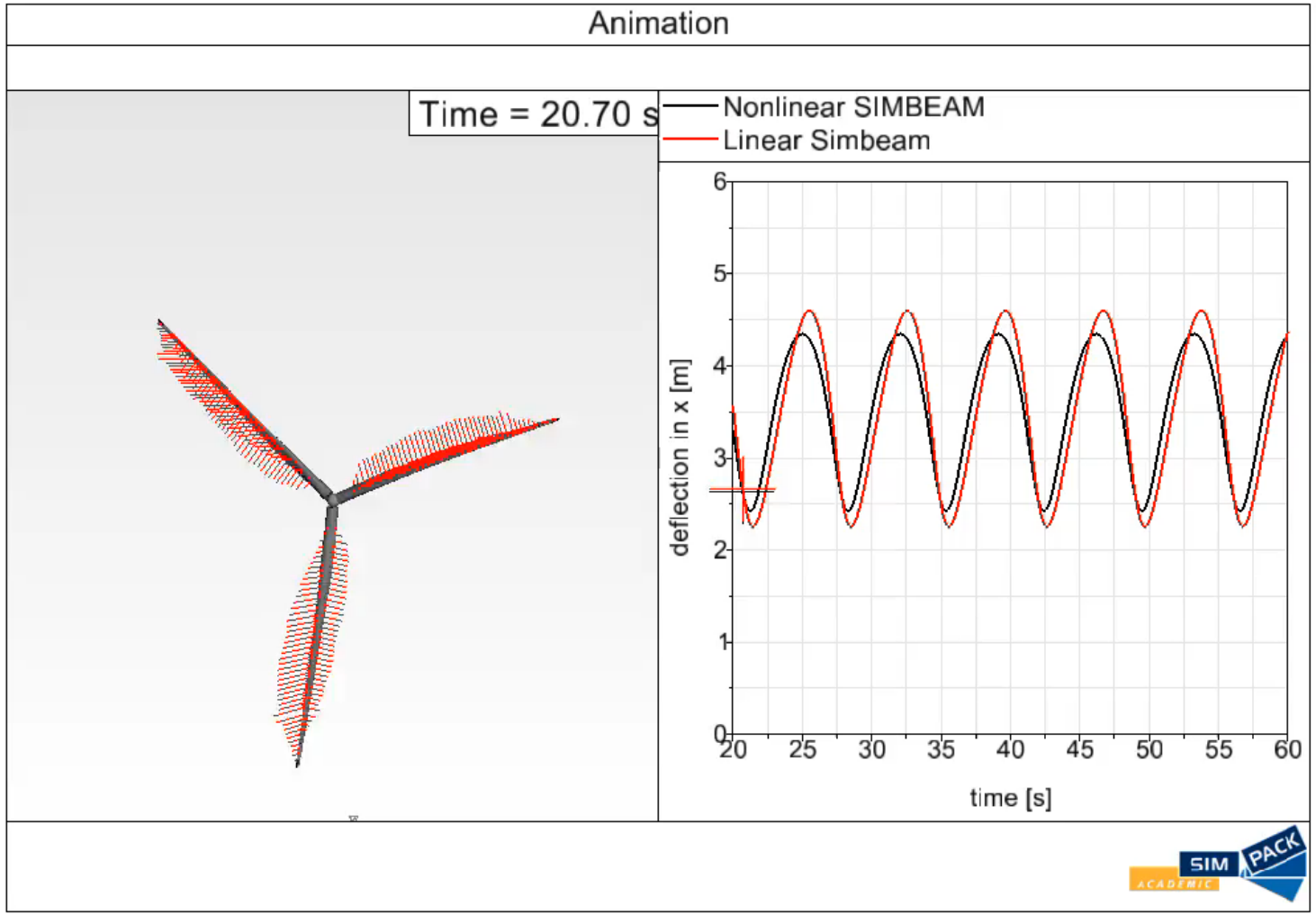


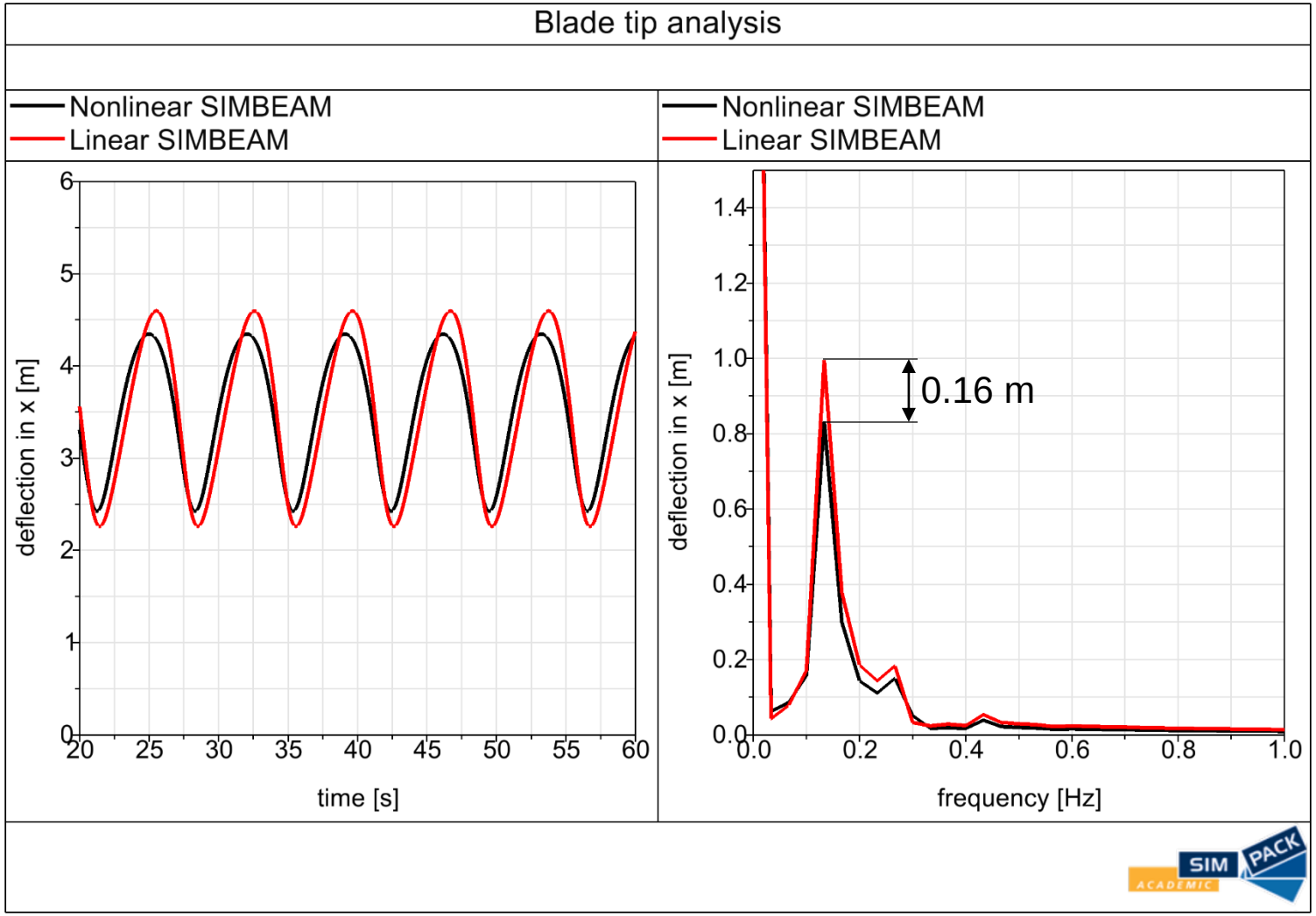


New 15 MW Rotorblade – Wind field simulation



- Blade tip deflection
  - Amplitude difference: +0.16m (+19%) for linear
  - phase shift in peak rotor angle: 33.2°

New 15 MW Rotorblade – Wind field simulation



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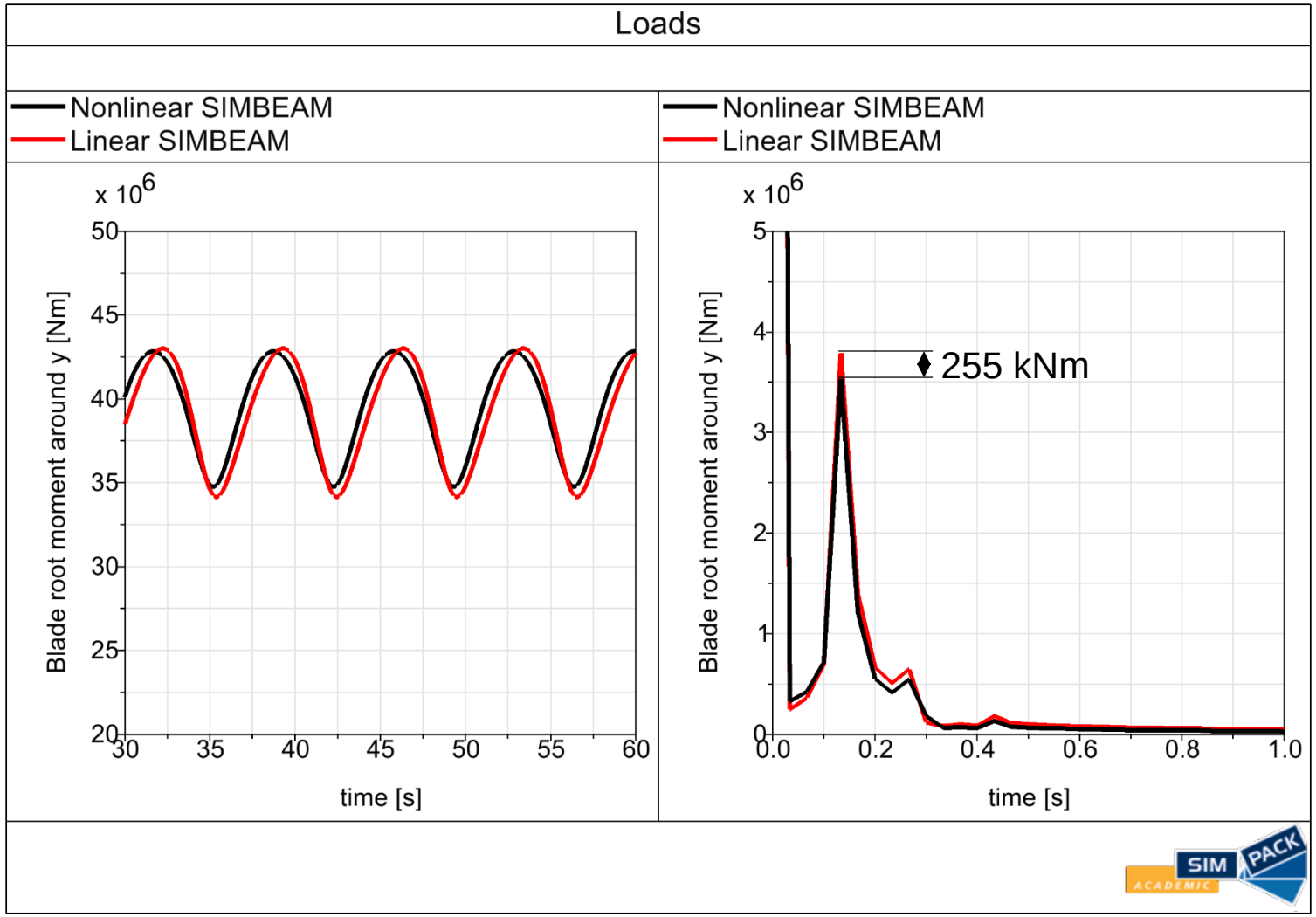
New 15 MW Rotorblade – Wind field simulation



- Blade tip deflection
  - Amplitude difference:
    +0.16m (+19%) for linear
  - phase shift in peak rotor angle: 33.2°
- Blade root moment
  - Amplitude difference:
    +255 kNm (+7%) for linear
  - phase shift in peak rotor angle: 28.1°
- Mechanical Rotor Power
  - Mean difference:
    +73 kW (+0.6%) for nonlinear
    => doubled effect w.r.t. 3 MW WT

Conclusion

- Taking nonlinear behavior into account is suggested for load calculations
  - For extreme load conditions
  - When high accuracy is required

- New method for direct use of FE model in dynamic simulations
  - Reduced modeling effort compared to SIMBEAM
  - Reduced computational costs compared to nonlinear SIMBEAM

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Thank you for your attention.