Multibody-System-Simulation of Offshore Wind Turbines

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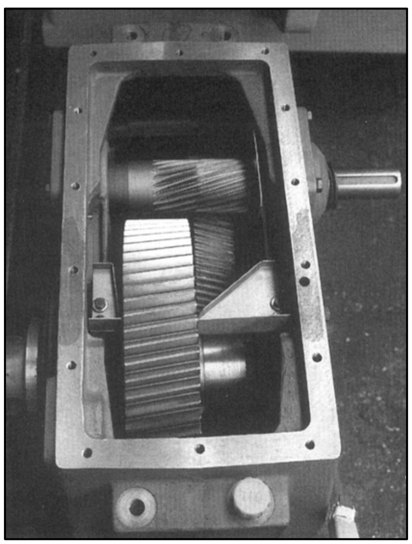
Topics

- State of the art
- Different model types: torsional vibration analysis, rigid MBS-Models or flexible MBS-Model
- Necessary complexity: gearbox, drive train, overall model with structure, electromechanical model, test rig configuration, ...
- Example models and some general results in frequency and time domain
- Model validation and result verification
- Development trends (simulation in the development phase, dynamically optimized drive train constructions by simulation, ...)
- Conclusion - Further Development

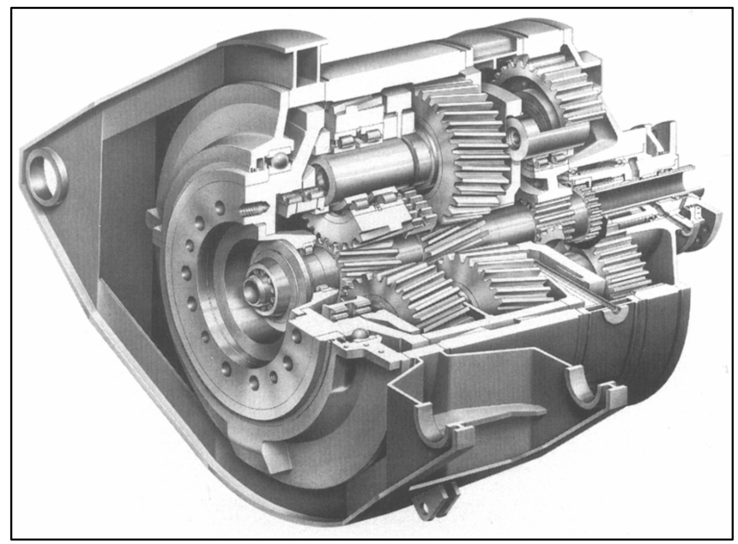
State of the art - Motivation

- The changing relations of mass and stiffness in the Multi-Megawatt-Drives will lower the natural frequencies of the drive train in the area of the natural frequencies of the structure.
- Comparison of the different drive train concepts
- Simulation model of the complete drive train with rotor hub, generator, structure and control of Wind Turbines
- For calculating the right load conditions it's necessary to have an adequate simulation model of the hole turbine with consideration of all needed parameters



2-stage spur gear
with 200 - 400 kW

3-stage planetary gear
2000 - 3000 kW



State of the art – Motivation because of Damages

- The exactly knowledge of all natural frequencies is an absolutely must
- A complete Multibody-System-Simulation can provide the correct load conditions for dimensioning of bearings and toothings

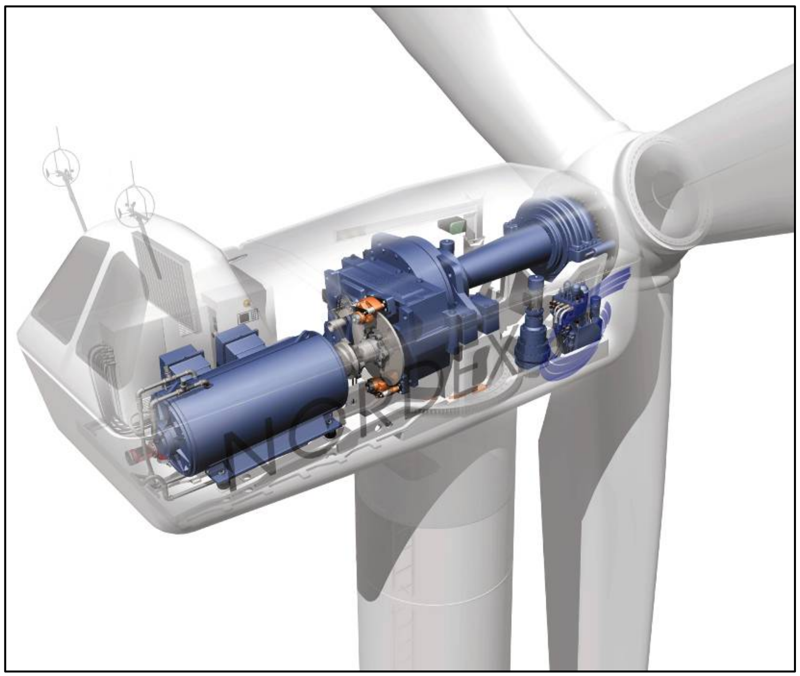
planetary gear damage

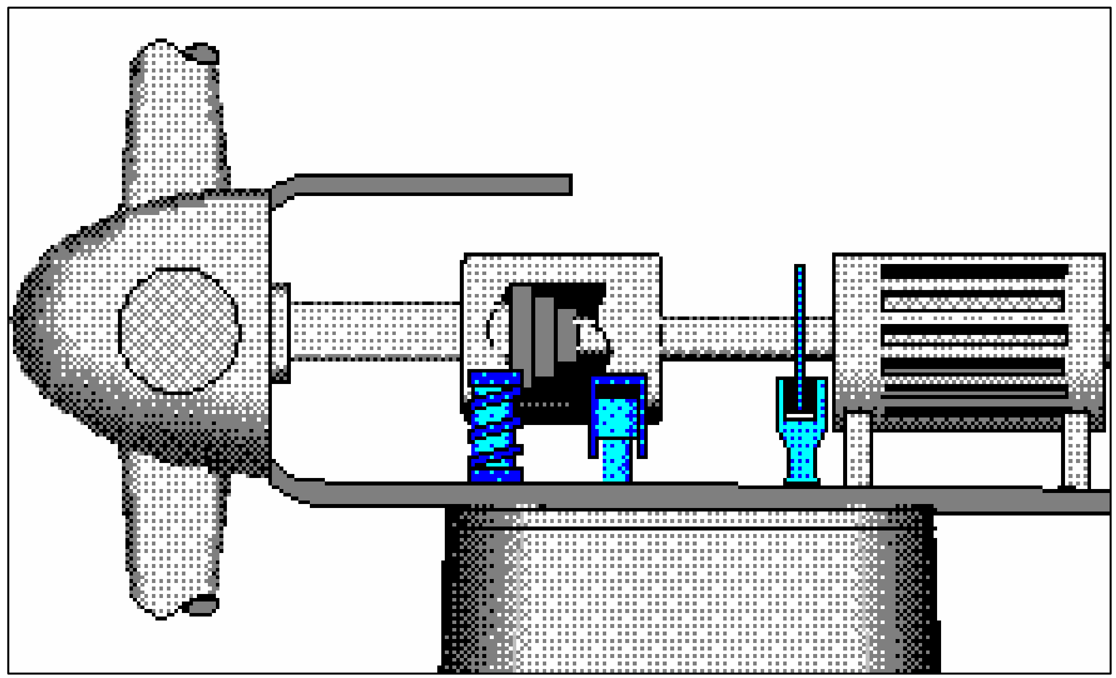
main bearing damage

bearing damage

Multibody-System Simulation vs. Torsional Simulation

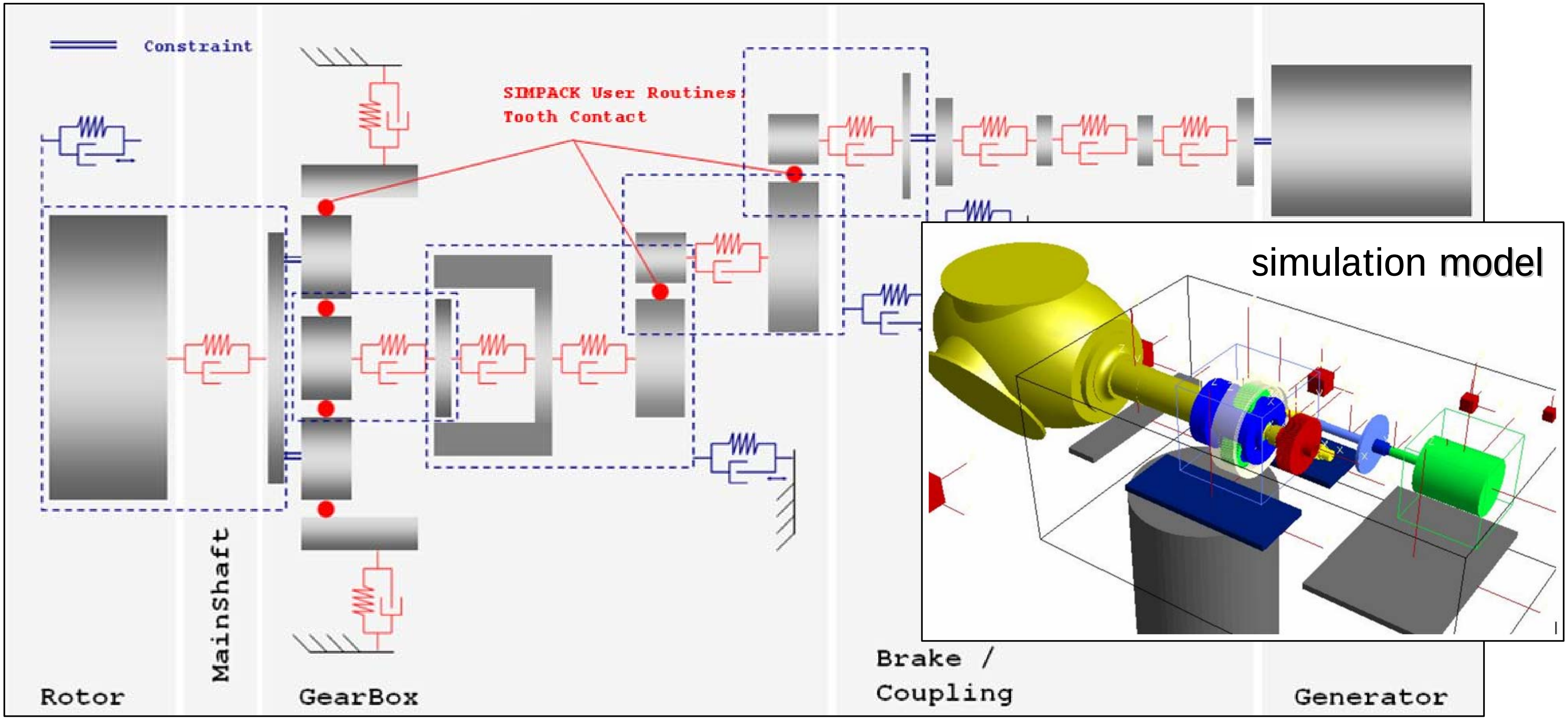
The momentarily common wind load calculation tools, which are used by all turbine manufacturers, use detailed aeroelastic codes for the rotor but work with simple 3-mass torsional oscillators to show the complex vibratory structure “drive train”.





Different model types

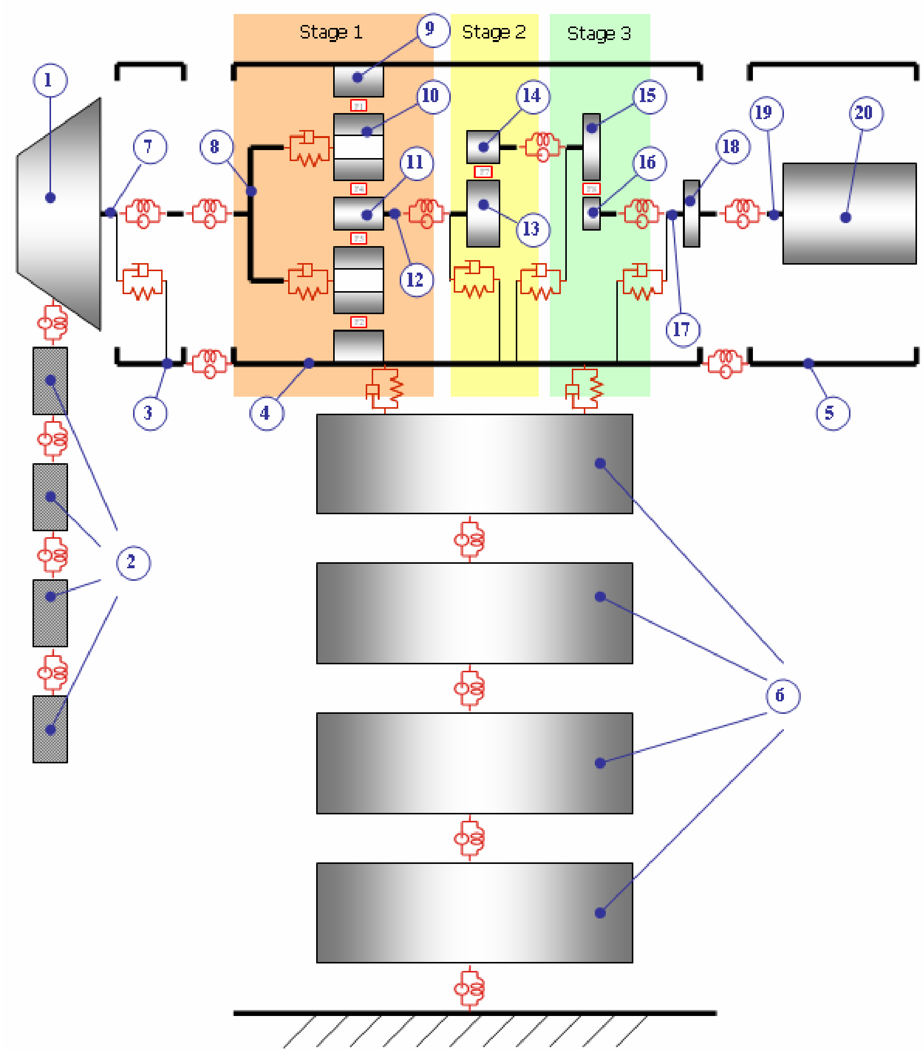
In the case of the following drive train the modeled torsional vibration model was extended by essential translatory degrees of freedom in axial direction. In the next step a main frame, discretized in four masses, was taken into consideration.



Creating a Model - Overview

Mechanical System consists of:

1. Hub
2. Blade Elements
3. Nacelle Frame Bearing
4. Nacelle Frame Gear Box
5. Nacelle Frame Generator
6. Tower Segments
7. Main Shaft (LSS)
8. Planetary Carrier Stage 1
9. Hollow Wheel Stage 1
10. Planets Stage 1
11. Sun Wheel Stage 1
12. Intermediate Shaft Planetary Gear
13. Bull Gear Stage 2
14. Pinion Stage 2
15. Bull Gear Stage 3
16. Pinion Stage 3
17. High Speed Shaft (HSS)
18. Brake / Coupling
19. Generator Shaft
20. Generator



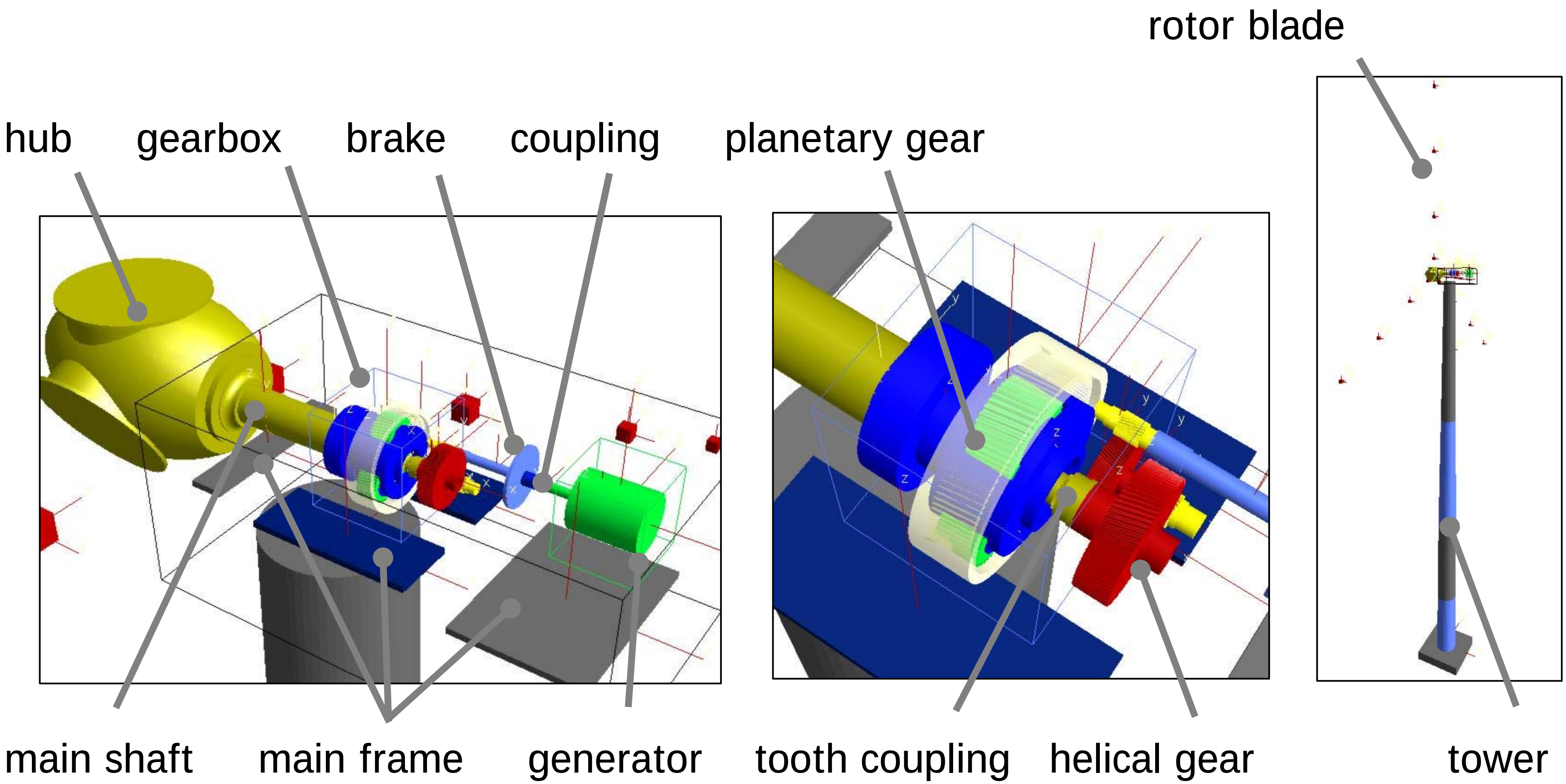
Multibody-System Simulation vs. Torsional Simulation

Degrees of Freedom and results for the Torsional Model and the Multibody Model

	Torsional Vibration	Multibody
Position	1 Rotation	3 Rotation Axes 3 Linear Displacements
Speeds	1 Rotation	3 Rotation Axes 3 Linear Displacements
Accelerations	1 Rotation	3 Rotation Axes 3 Linear Displacements
Internal Forces	---	3 Directions
Internal Moments	1 Rotation Axis	3 Rotation Axes
Bearing Forces	---	Tangential, Radial, Axial
Gearing Forces	1 Tangential	Tangential, Radial, Axial

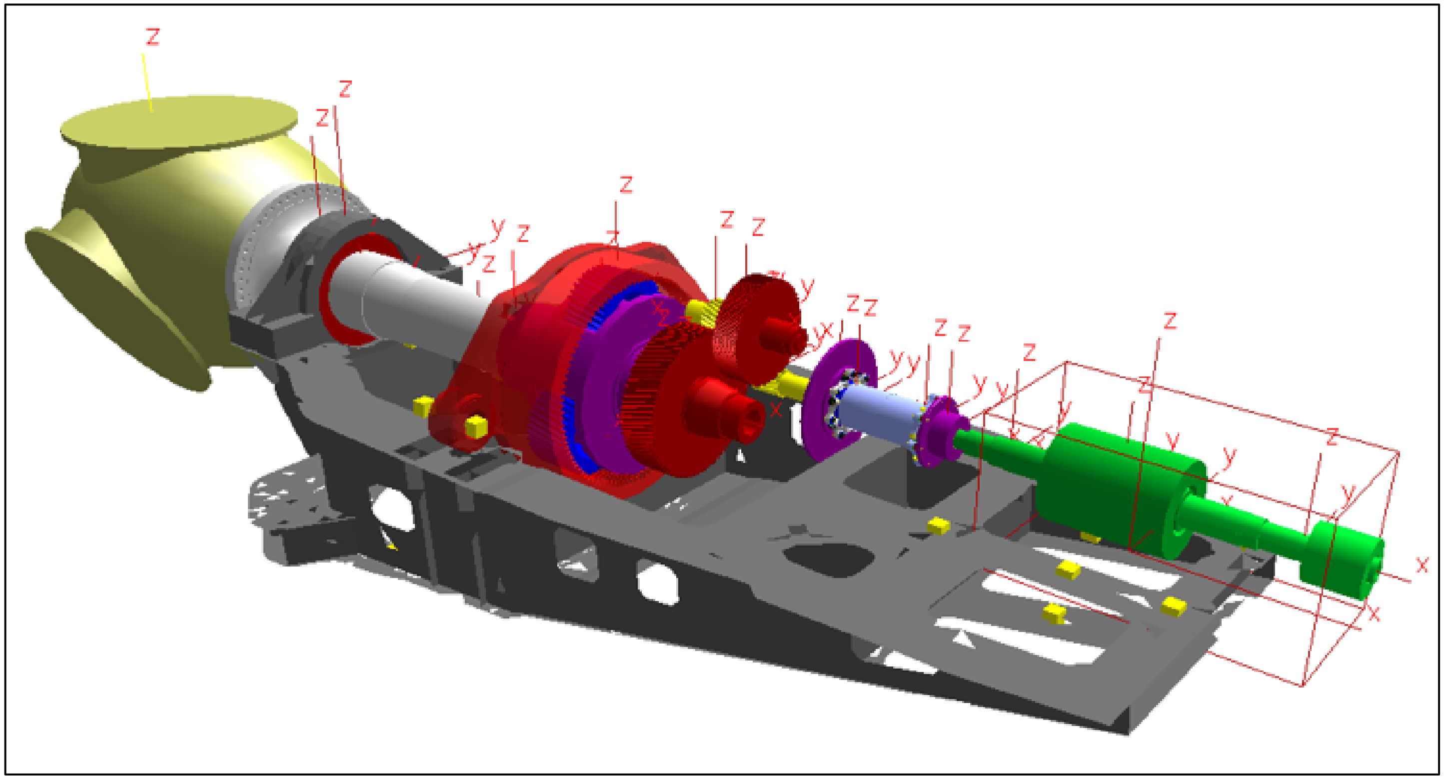
Wind Turbine – Rigid Multibody System Model

A typical wind turbine with 1500 kW output power as MBS-model with a mass discrete main frame and rotor blades



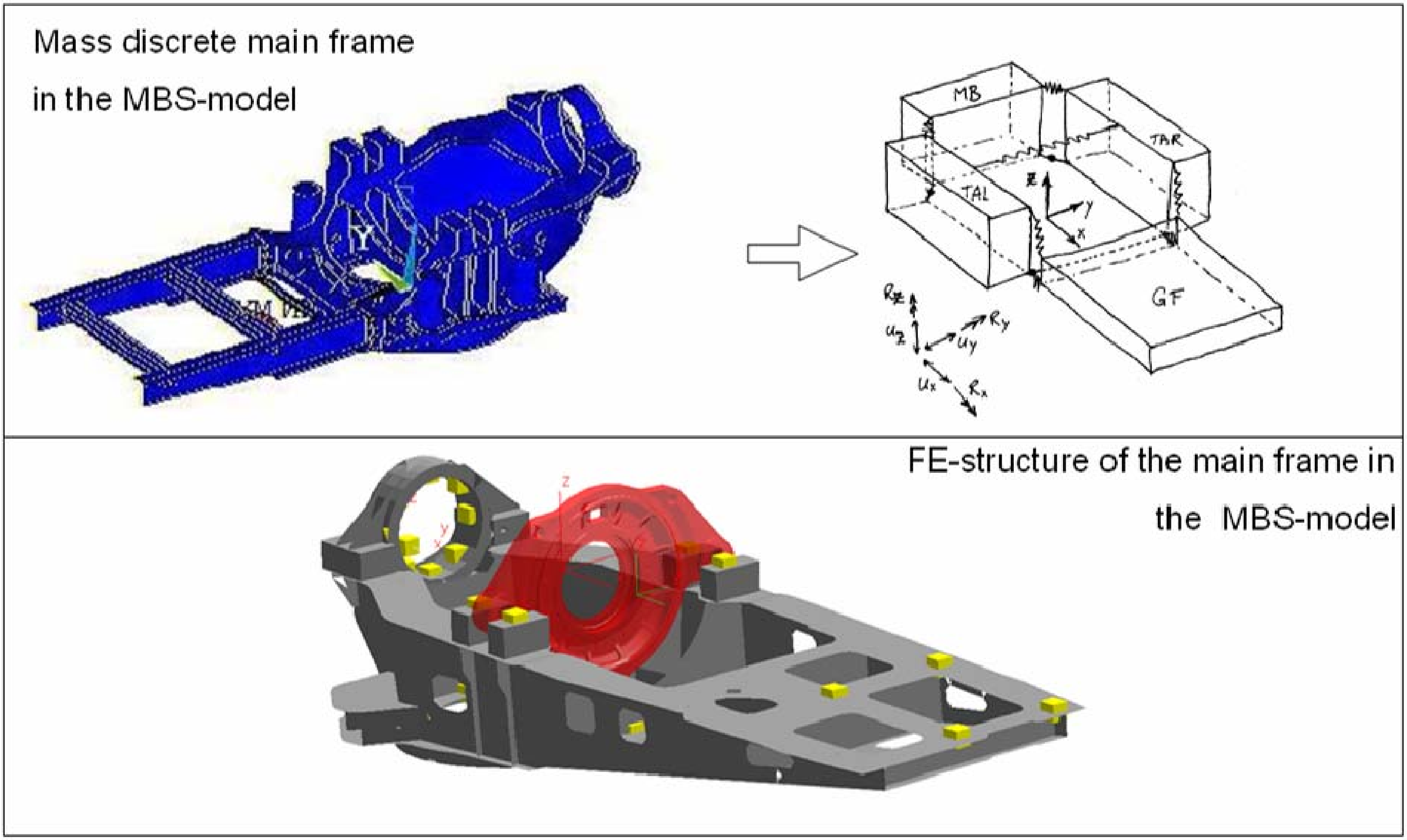
Wind Turbine – Flexible Multibody System Model

- The newest model generation is a combination of the mbs-method and the finite element method
- The relevant components of the real system are described by elastic bodies (e.g. the mainframe) with connections to the mbs-model



Wind Turbine – Flexible Multibody-System-Model

- Two different variants of modeling of elastic bodies in the mbs-software



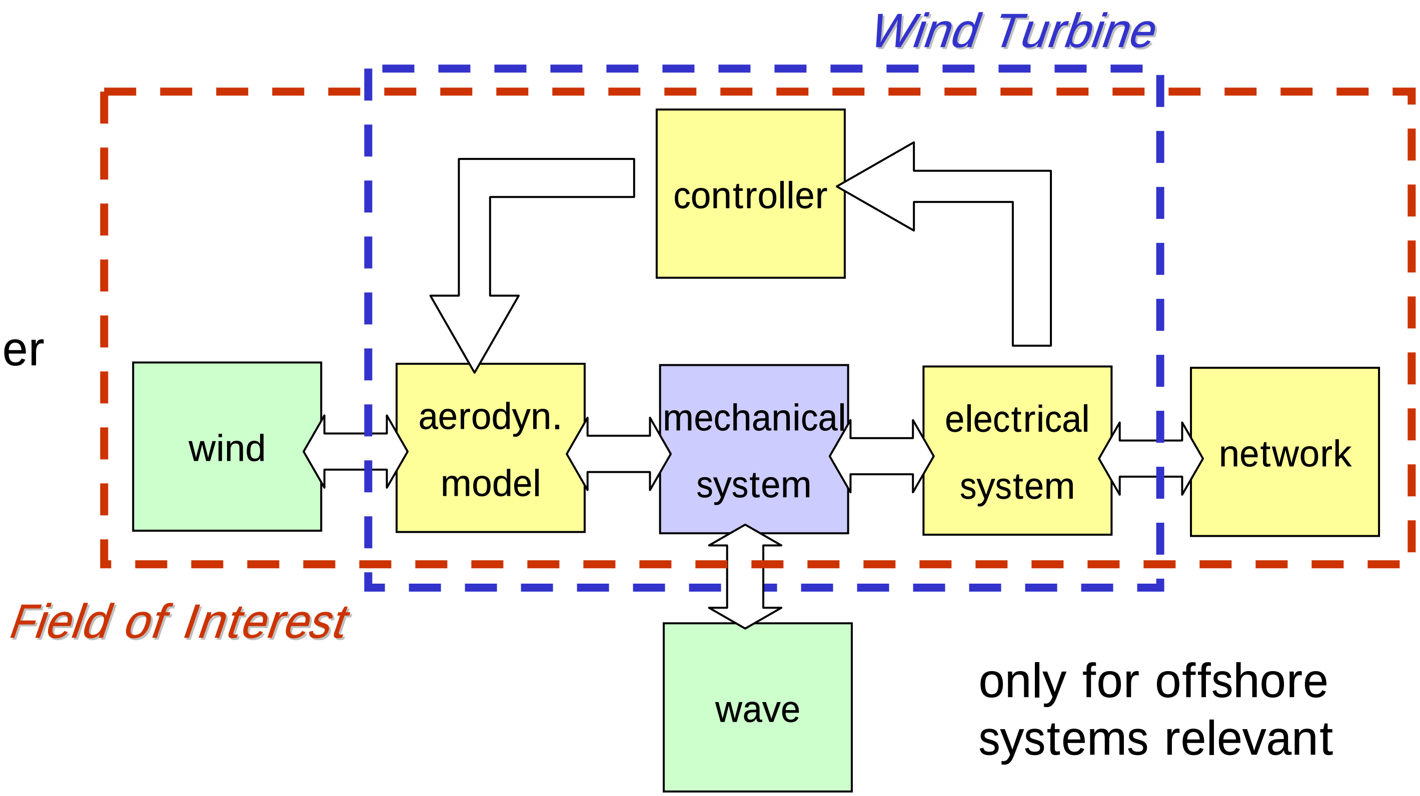
Necessary Complexity – Overview

Mechanical system consists of:

- Rotor, main shaft
- Gear unit
- Coupling, brake disk
- Generator

Controller consists of:

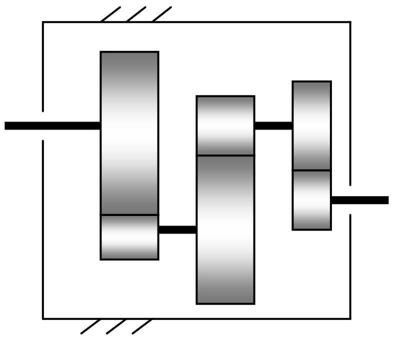
- Pitch controller
- Output power controller
- Speed controller
- Brake controller



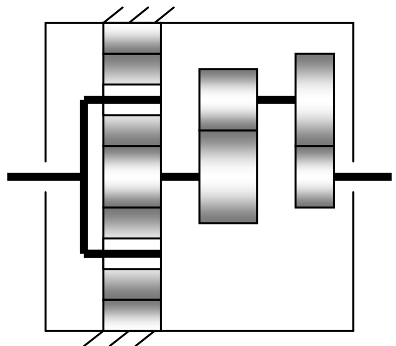
only for offshore systems relevant

Example Models – Overview

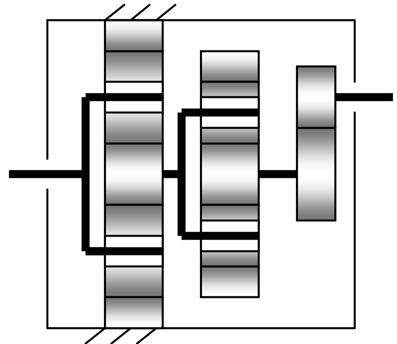
Different gear units, simulated at the Chair of Machine Elements in Dresden



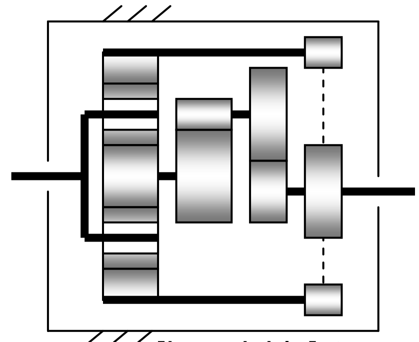
3-stage helical gear unit



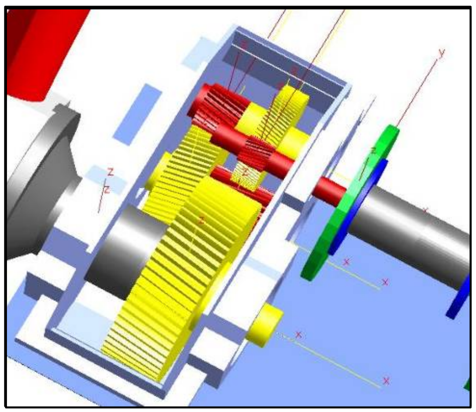
3-stage
planetary- / spur gear unit

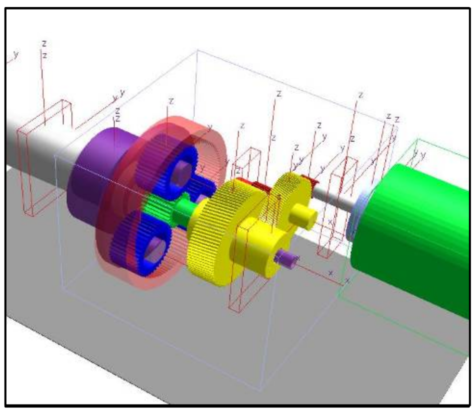


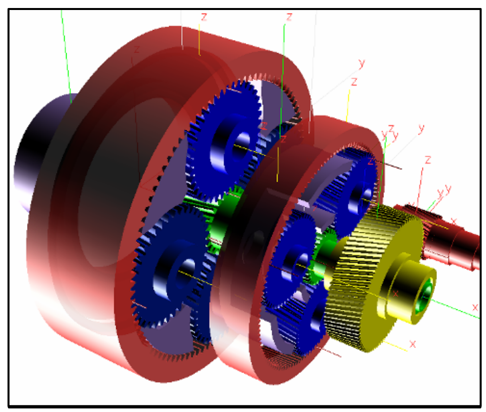
3-stage
planetary- / helical gear unit

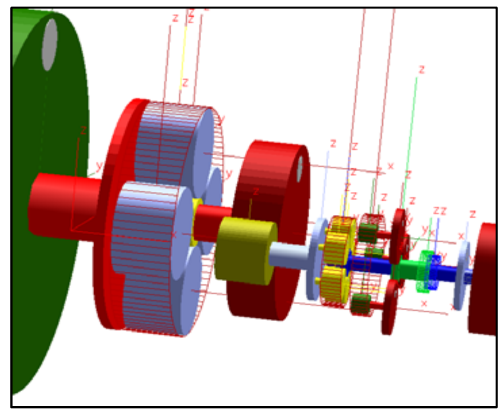


[i=variable] 3-stage
planetary- / helical gear unit





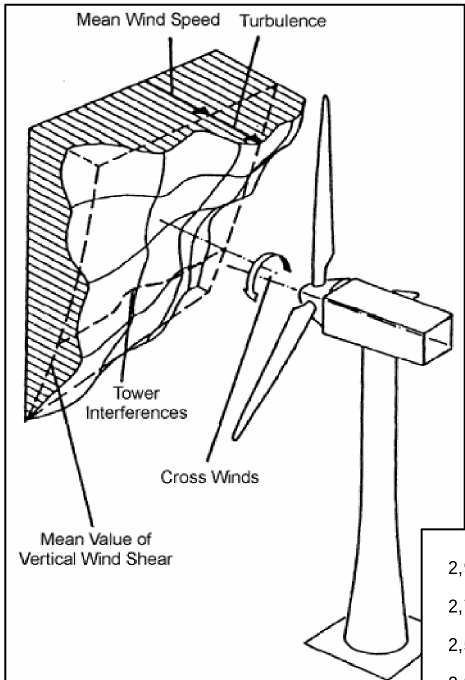




Example Models

Method A:

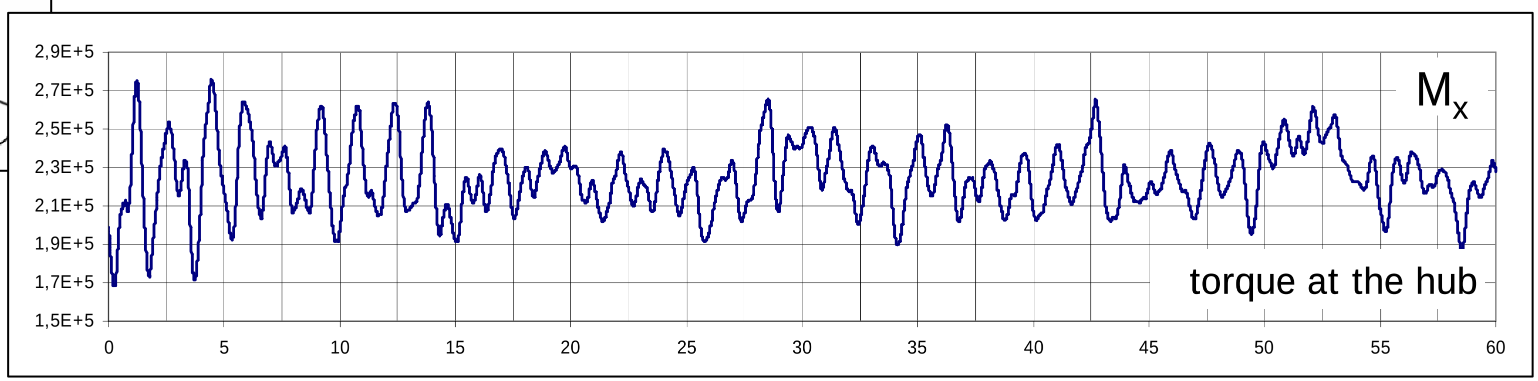
With a wind simulation software (Flex, Bladed, ...) the 3 torques and 3 forces at the rotor hub based on the 3d-windfield can be calculated



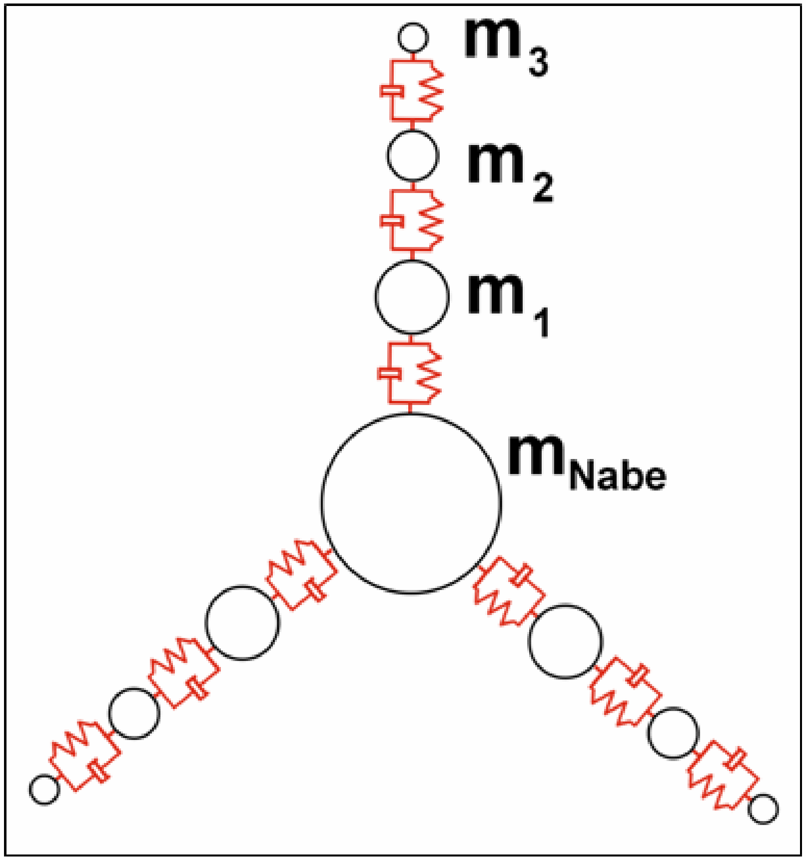
These are the input values for the mechanical drive train

Disadvantage:

There is no feedback between the aerodynamic and mechanical system

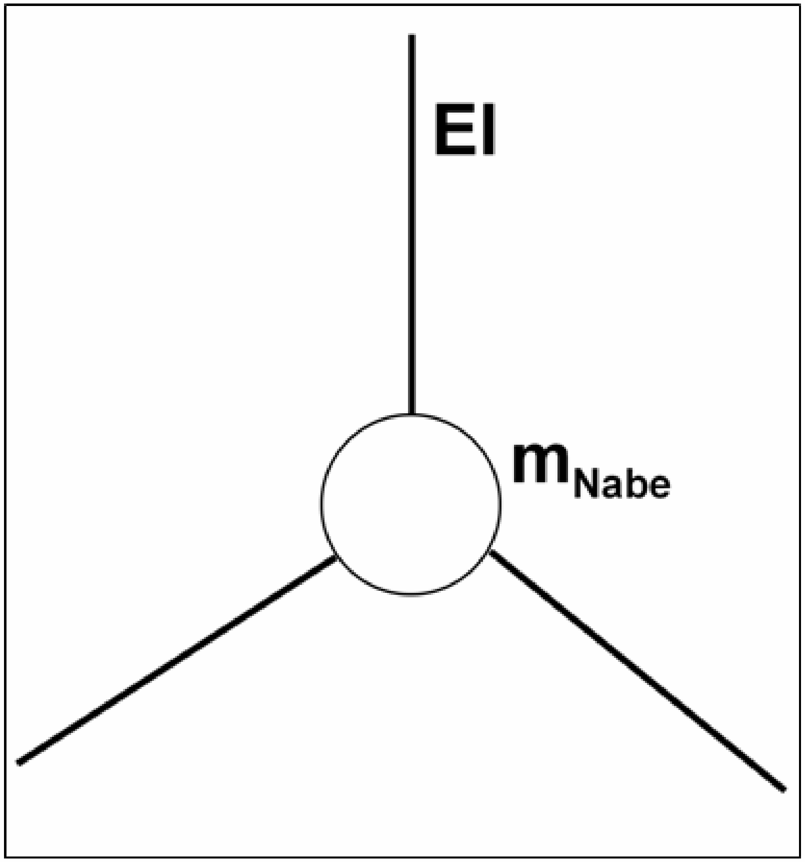


Example Models - Rotor



MBS-Model

- ✓ Discrete Rigid Bodies
- ✓ Stiffness Between The Bodies



FEM-Model

- ✓ Structure Of The Hub and Blades
- ✓ Beam-Elements For The Blades

Example Models - Rotor

The results of the frequency analysis for a single rotor model

Bending in rotor plane

Bending vertical to rotor plane

Vibration of higher order

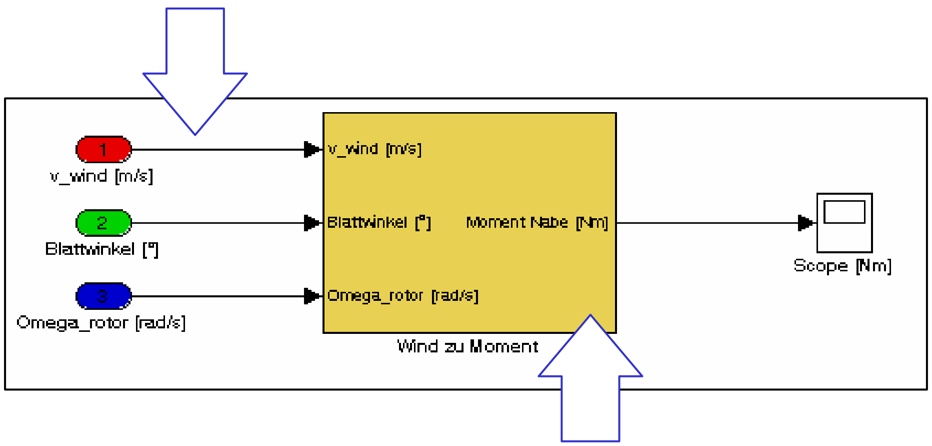
The figures show the most important natural frequencies of the single rotor model

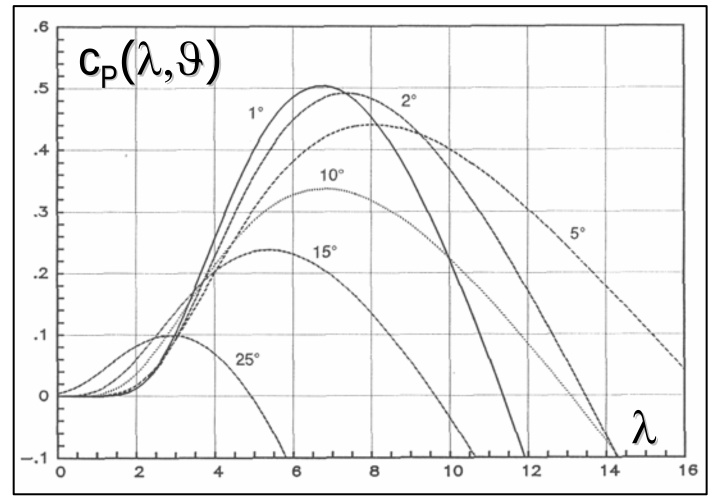
Example Models

Method B:

The torque and the force at the hub are calculated with the power equation at the rotor from the 1d-windfield and an analytic c_P-curve

wind speed v	[m/s]
pitch angle ϑ	[degree]
revolute speed rotor ω	[rad/s]





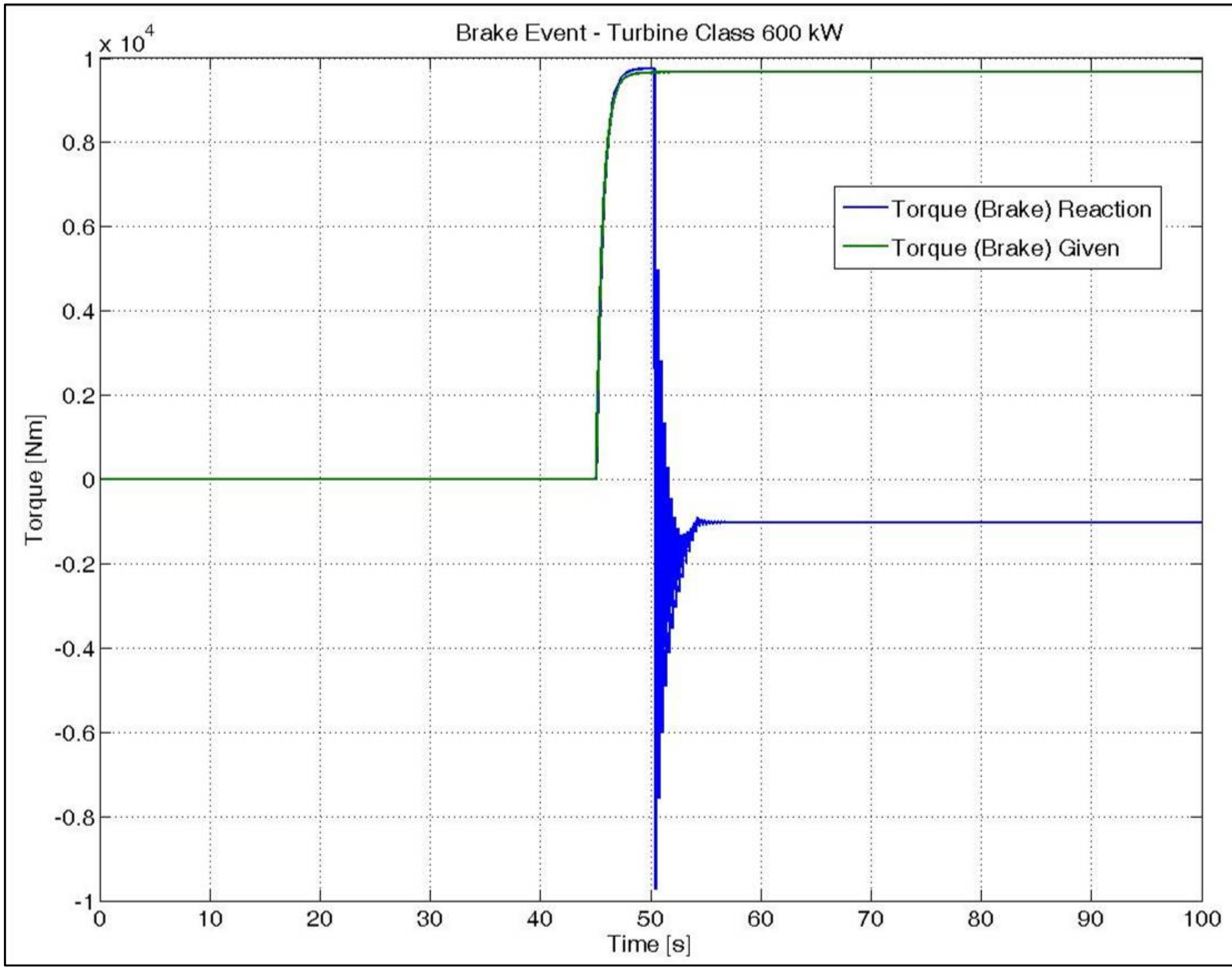
$$M_{Rotor} = \frac{P}{\omega} = \frac{\frac{\rho}{2} \cdot c_P(\lambda,\vartheta) \cdot A_R \cdot v^3}{\omega}$$

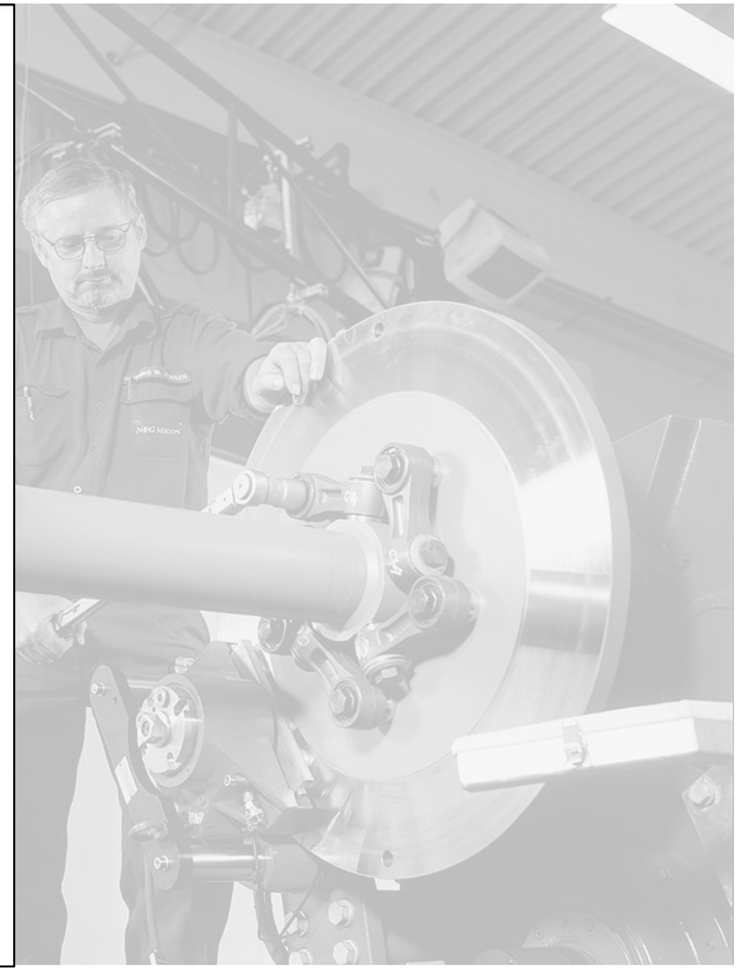
with

$$c_P(\lambda,\vartheta) = c_1 \cdot (c_2 - c_3 \cdot \vartheta - c_4 \cdot \vartheta^x - c_5) \cdot e^{-c_6(\lambda,\vartheta)}$$

Example Models – Brake Model

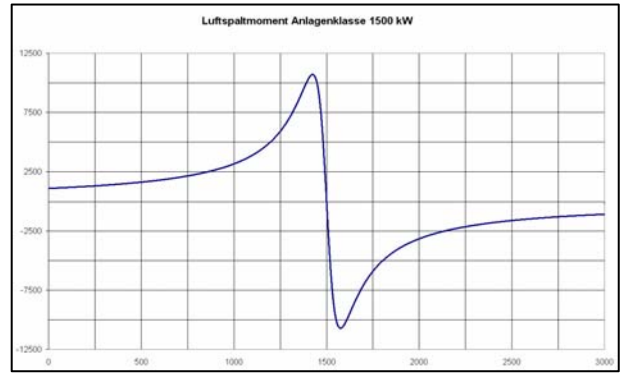
- The brake model bases on a special force element of the software Simpack with the option of static and sliding friction





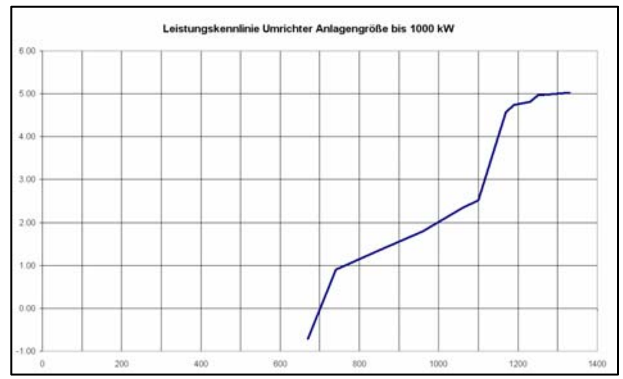
Example Models – Generator Model

- For the modeling of the generator there are 3 different methods available



Method A

The generator characteristic line of the air gap moment (“Kloss Equation”) M = f(s) (e.g. asynchronous generator)



Method B

Characteristic line of the power converter M = f(n)

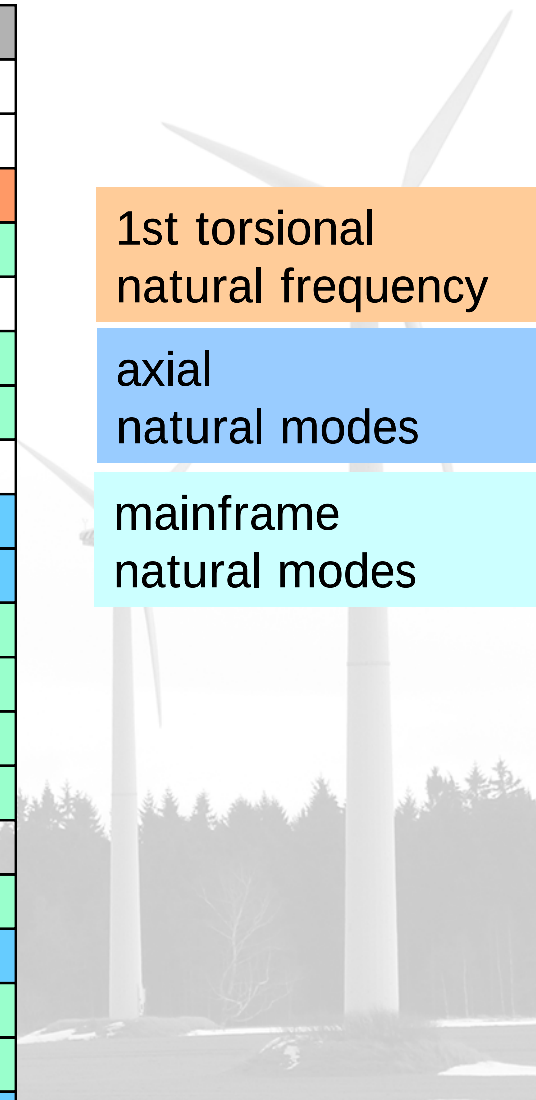
Method C

Completely description of the generator and converter characteristic in Matlab/Simulink

(e.g. synchronous generator)

General Results – Natural Frequencies

Nr.	MBS with m-frame [Hz]	Torsion and axial [Hz]	Torsion [Hz]
01/02	0.00	0.00	0.00
03/04	1.19	---	---
05/06	2.12	2.53	2.53
07/08	14.17	---	---
09/10	27.62	32.72	33.01
11/12	45.42	---	---
13/14	61.59	---	---
15/16	72.20	76.73	80.65
17/18	81.03	89.45	---
19/20	90.05	115.34	---
21/22	91.80	---	---
23/24	92.41	---	---
25/26	110.47	---	---
27/28	110.63	---	---
29/30	125.51	126.51	147.98
31/32	126.84	---	---
33/34	159.74	154.55	---
35/36	167.47	---	---
37/38	196.50	---	---
39/40	217.57	224.51	---



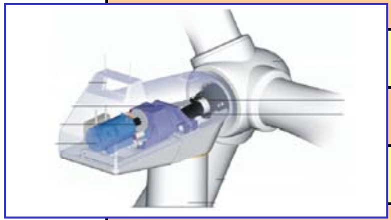
1st torsional natural frequency

axial natural modes

mainframe natural modes

General Results – Natural Frequencies

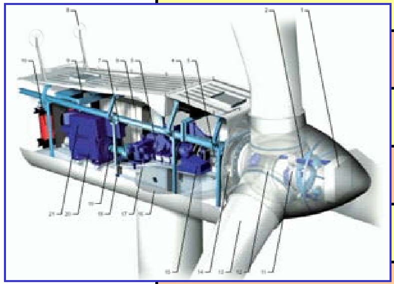
Natural Frequency Nr.	Turbine with Output smaller than 1000 kW
1	0,0000
2	7,3805
3	25,5619
4	296,4316
5	468,0630
6	593,2840
7	657,4992
8	1302,6689
9	2278,3430
10	2403,3762



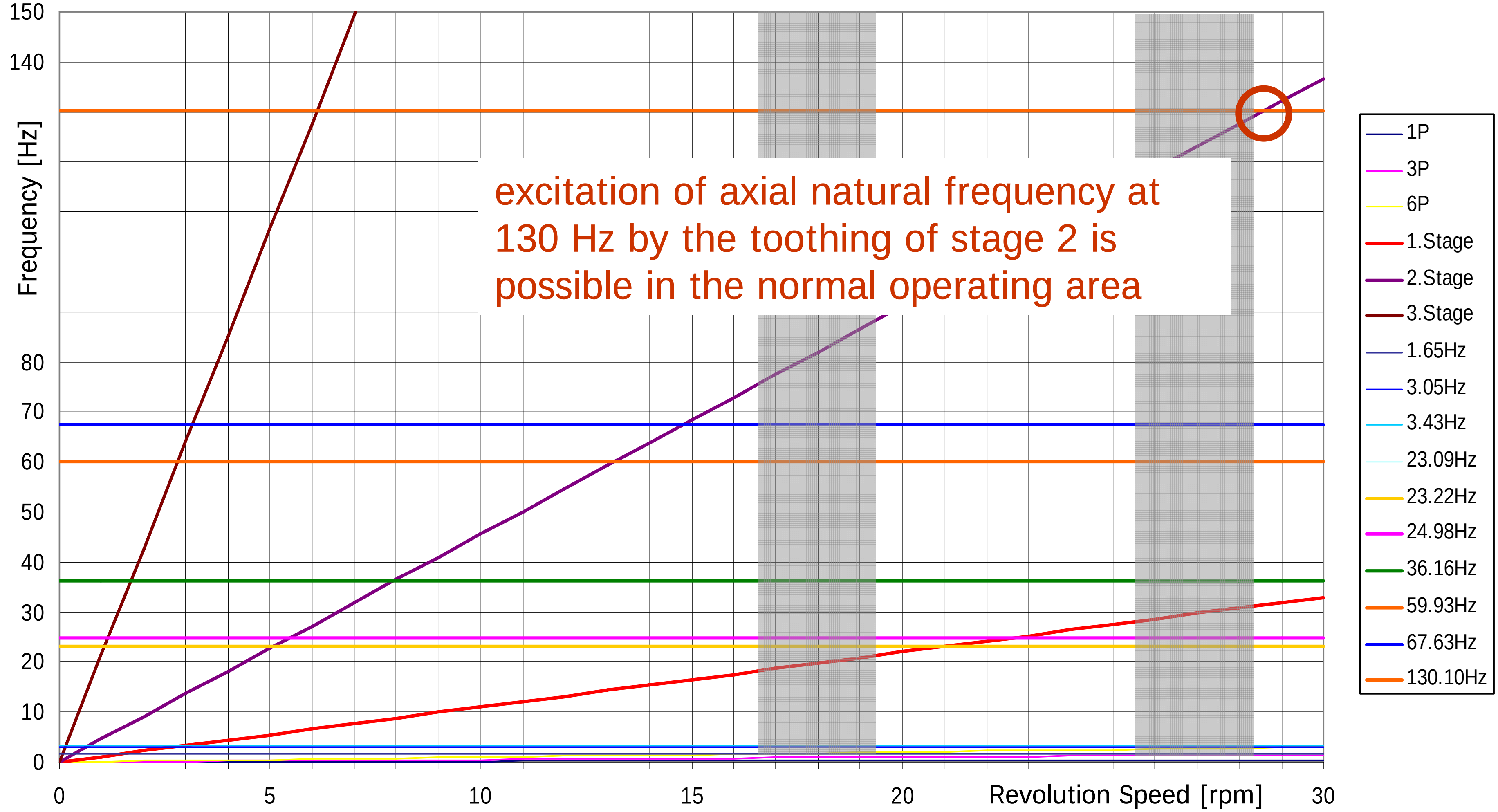
Comparison of the first 10 natural frequencies of a small and medium size turbine:

- ✓ Lowering of natural frequencies

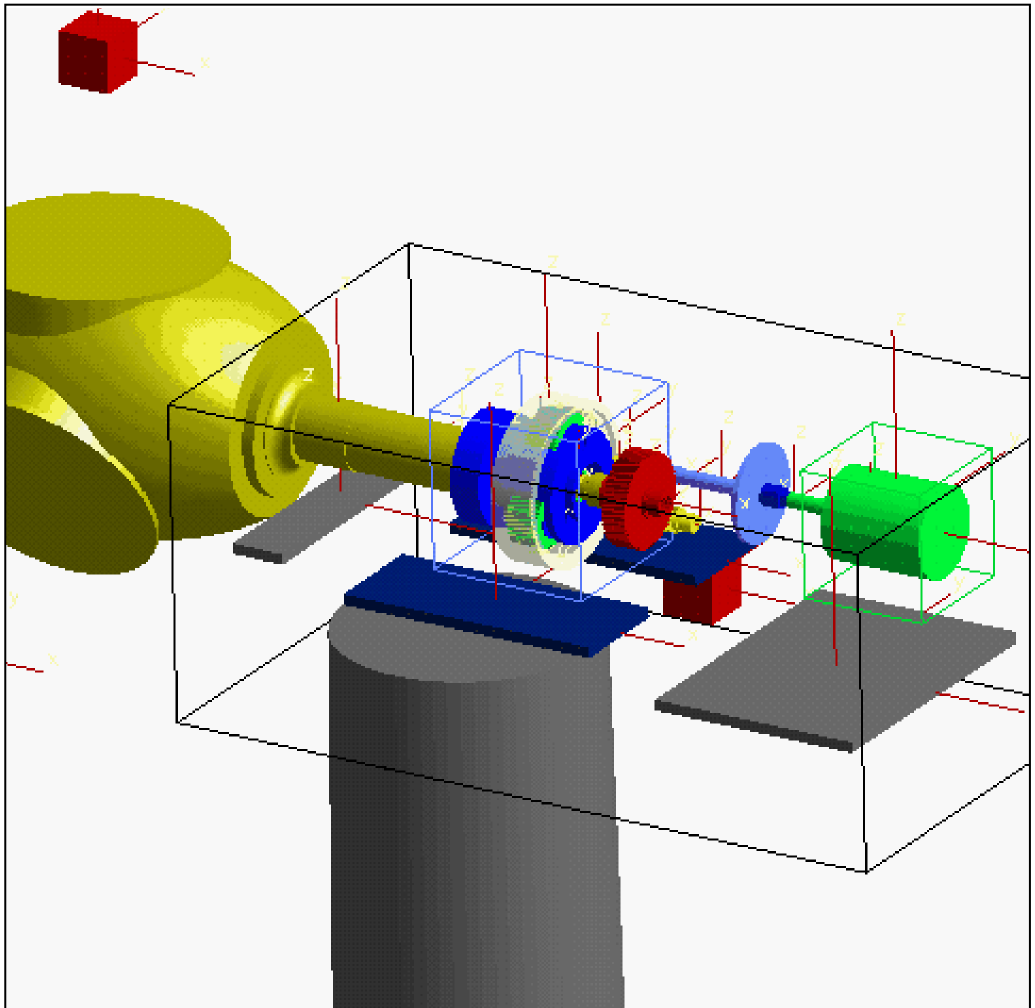
Natural Frequency Nr.	Turbine with Output larger 1 MW and smaller 3 MW
1	0,0000
2	3,0880
3	32,7192
4	80,2594
5	193,5722
6	222,5120
7	333,1371
8	343,9640
9	617,8328
10	970,8328



General Results – Campbell Diagram



General Results – Natural Modes (1)



natural modes of the drive train

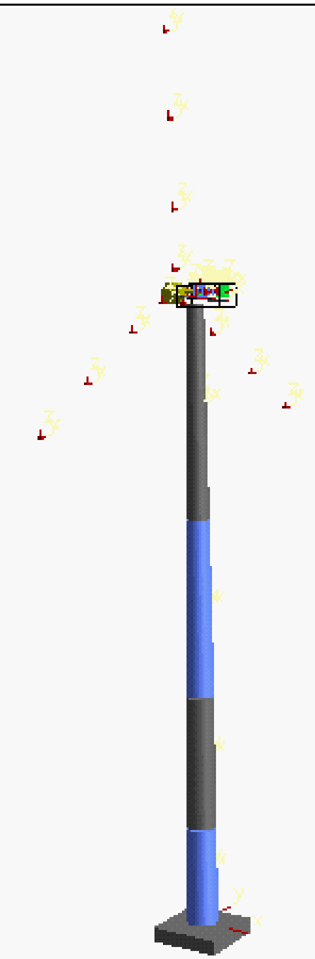
Wind Turbine Class: 1500 kW

(A) Bending Of The Mainframe At The Mainbearing [0.22 Hz]

(B) First Torsional Natural Frequency In The Mainshaft [7.56 Hz]

(C) Rotating Of The GearBox With Vertical Displacements At The Coupling [153.33 Hz]

General Results – Natural Modes (2)



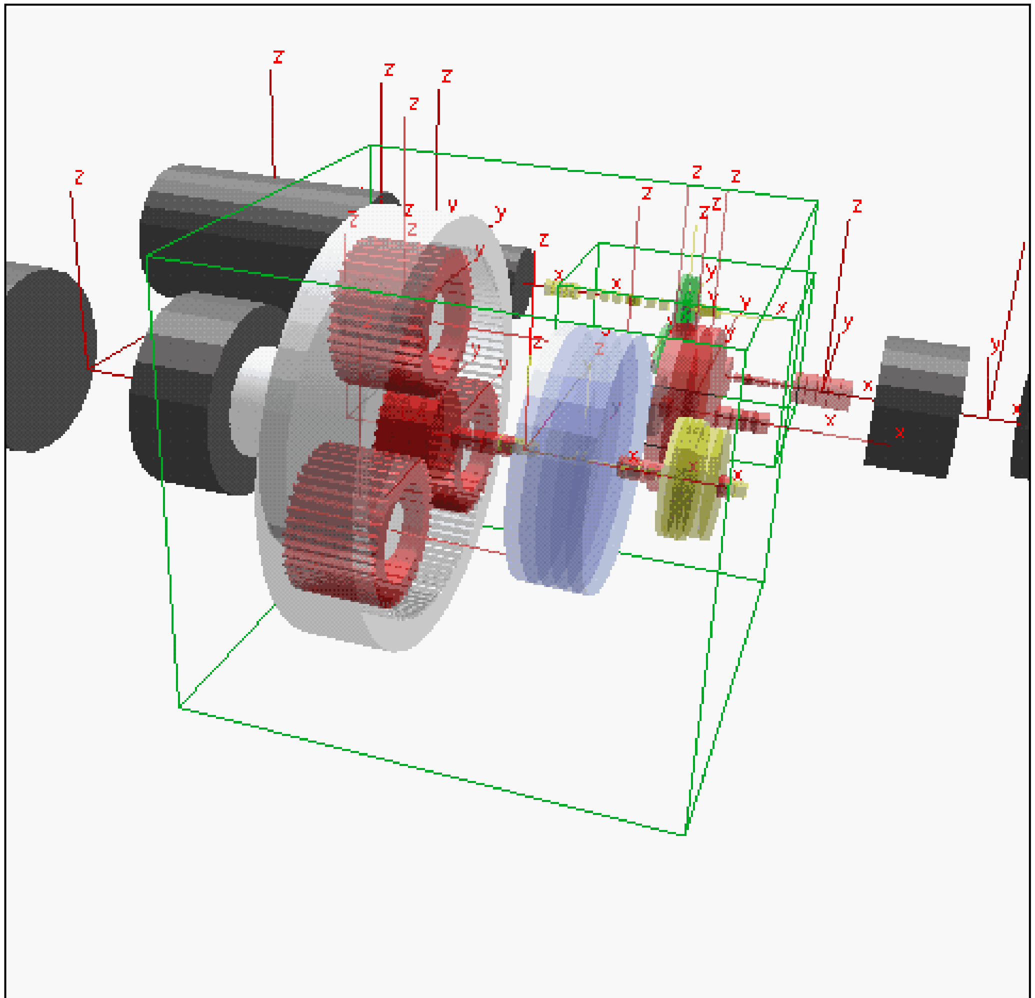
Natural Modes Of The Structure

Wind Turbine Class: 1500 kW

(D) Bending – 2. Natural Mode Of The Rotor [0.22 Hz]

(E) Bending – Natural Mode Of The Rotor And The Tower [3.19 Hz]

General Results – Natural Modes (3)



bending modes of the gear unit

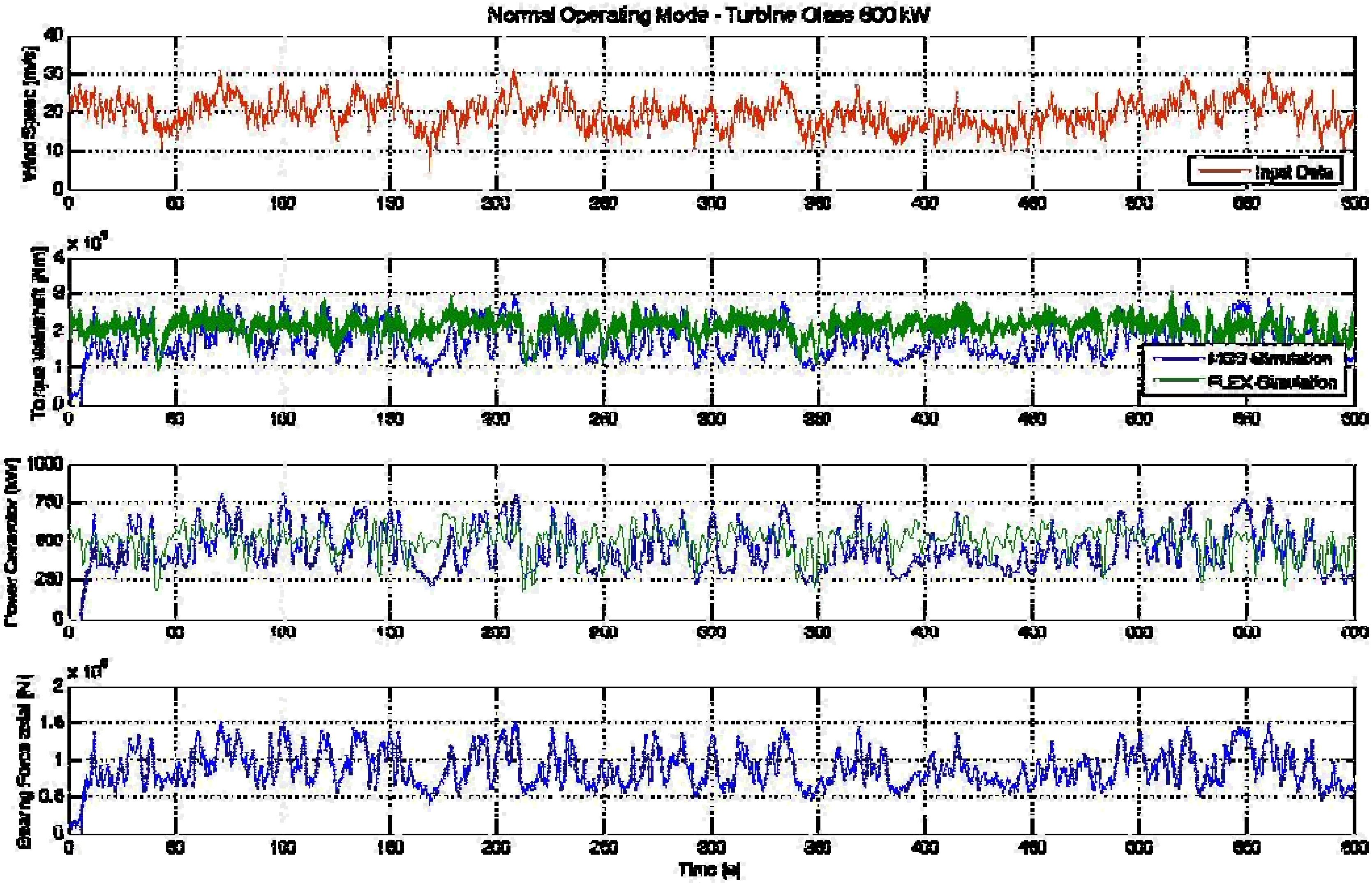
Wind Turbine Class: 1500 kW

(F) Bending – IMS Shaft [41.10 Hz]

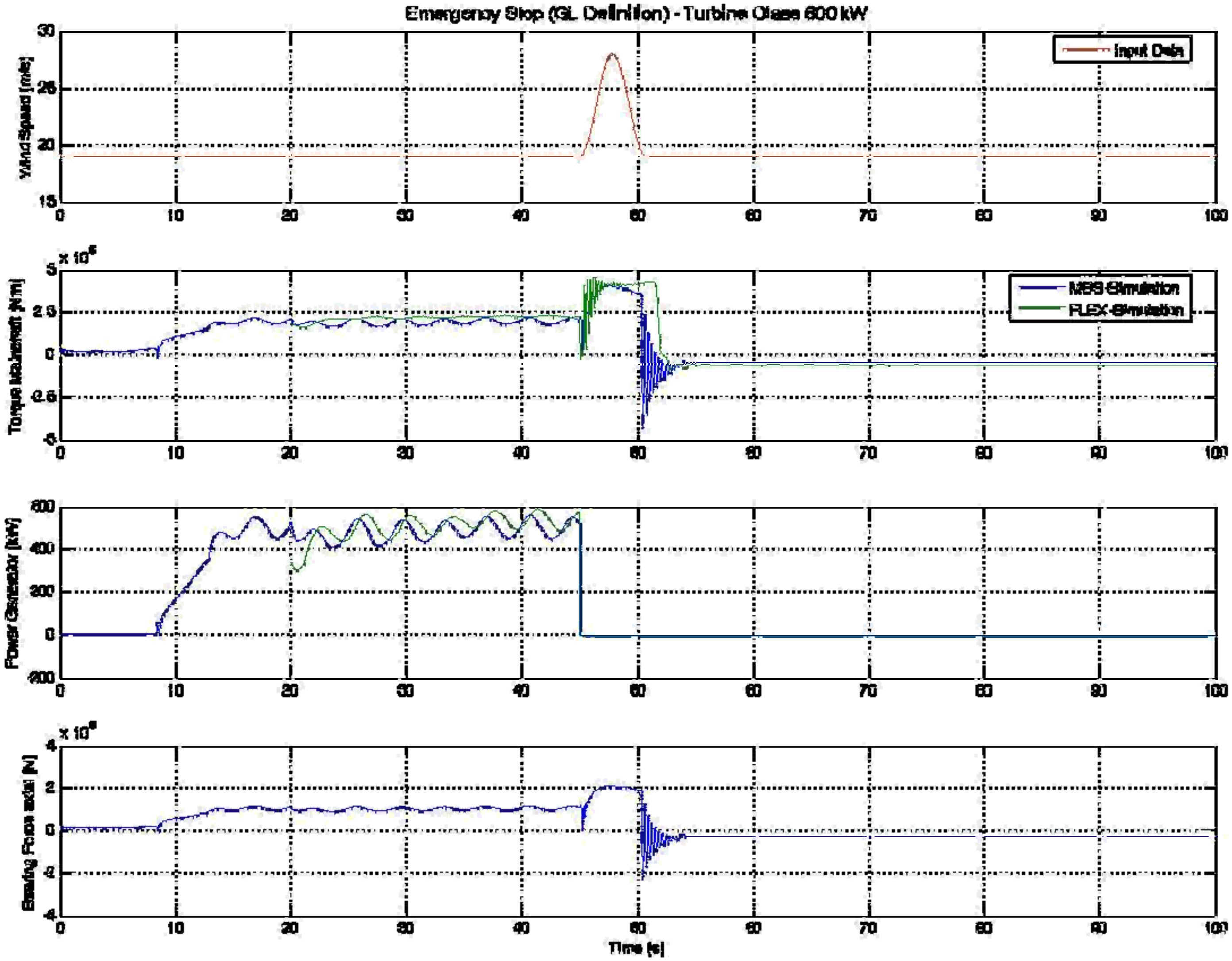
(G) Bending – Sunwheel Shaft With Bad Load Conditions In The Planetary Gear [58.88 Hz]

(H) Bending – Sunwheel Shaft With Bad Load Conditions In The Planetary Gear [367.33 Hz]

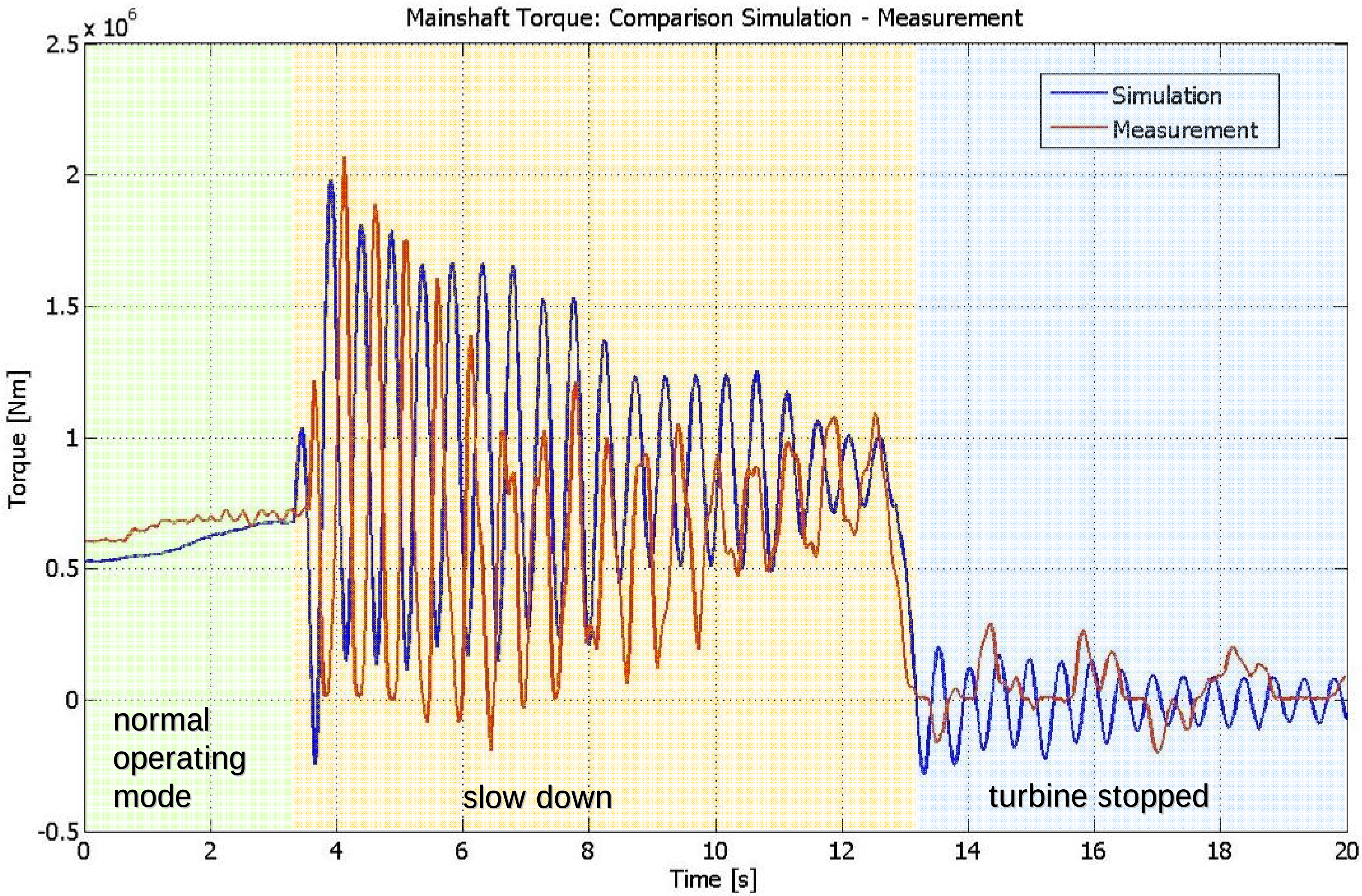
General Results – Load Case: Normal Operating



General Results – Load Case: Brake Event



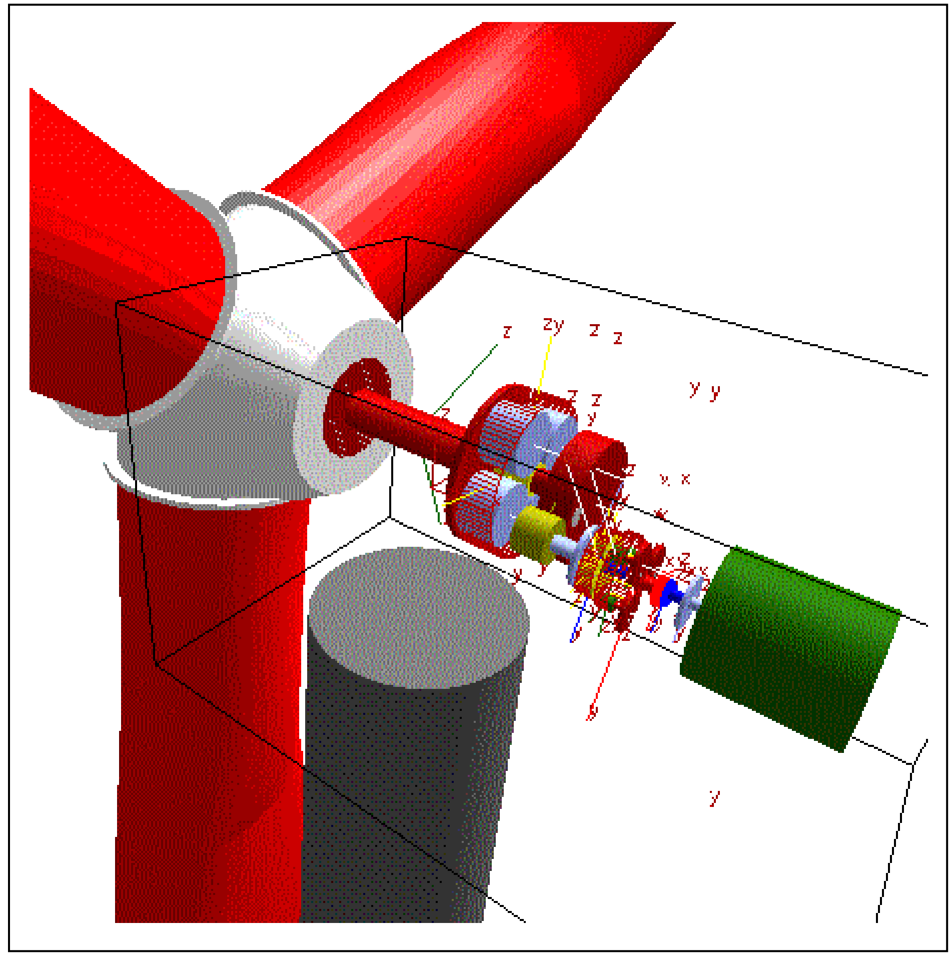
Result-Verification – Crowbar Event



simulation of a crowbar event in a wind turbine of the 1500 kW class.

1. blocking of generator
2. shut down the generator
3. emergency brake down

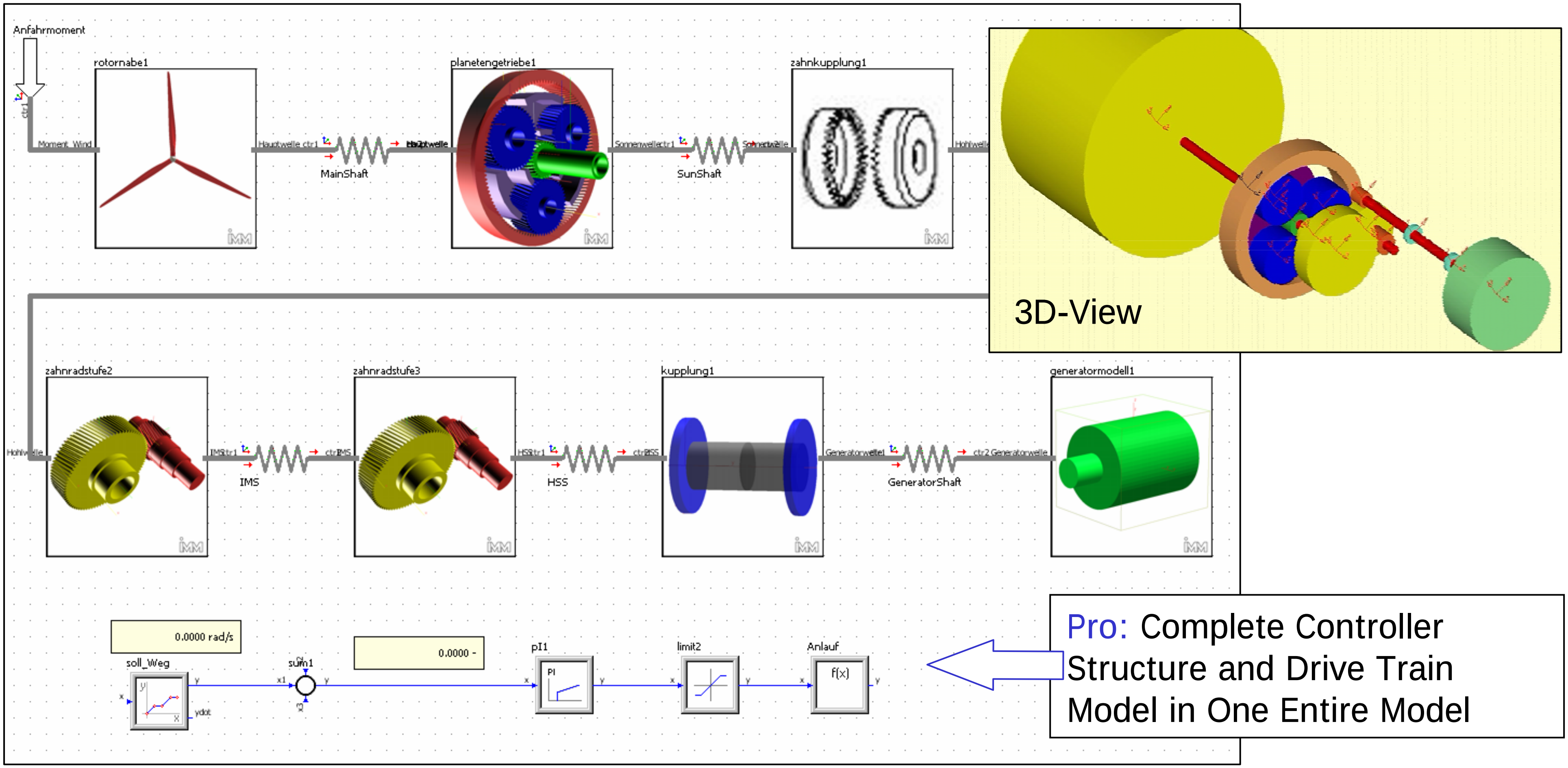
Normal Operating – Complete Turbine / Drive Train



Wind Turbine Class: 2.xx MW

Outlook – Structured Simulation Model

Structured Model of a Wind Turbine with 1500 kW Output Power:



Pro: Complete Controller Structure and Drive Train Model in One Entire Model

Summary and Future Prospects

- ✓ The Multi-Mega-Watt-Wind-Turbine is a Power Station and it has to have its reliability
- ✓ To build reliable Wind Turbines of the Multi-Megawatt-Size it is absolutely necessary:
  - to focus not only on Aerodynamics and Structural Dynamics
  - to have a very, very close look on the Mechanical and Electrical Specialities of Equipment of that size and the interdependencies with the Control System
- ✓ The special design of Wind Turbines (tower, rotor blades, rotatable nacelles) leads to a structure that is elastically in every respect
- ✓ Wind Load Simulation Software will not be able to show the effects of the dynamic loads in the drive train
- ✓ The Multibody-System-Simulation is an effective tool to analyze the oscillational behaviour of the drive train and (maybe in the near future) the complete Wind Turbine

Conclusion

The most important thing is that all experts of the

- Turbine Manufacturer
- OEM-Suppliers
- Institutes
- Research Centres
- and Universities

have to work in close cooperation to bring in their specific knowledge.

We all have the same problems, we shouldn´t try to event the wheel again.

Thank you for your Attention

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