NTNU – Trondheim
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NORTH WIND

Drivetrain structural flexibility in OpenFAST

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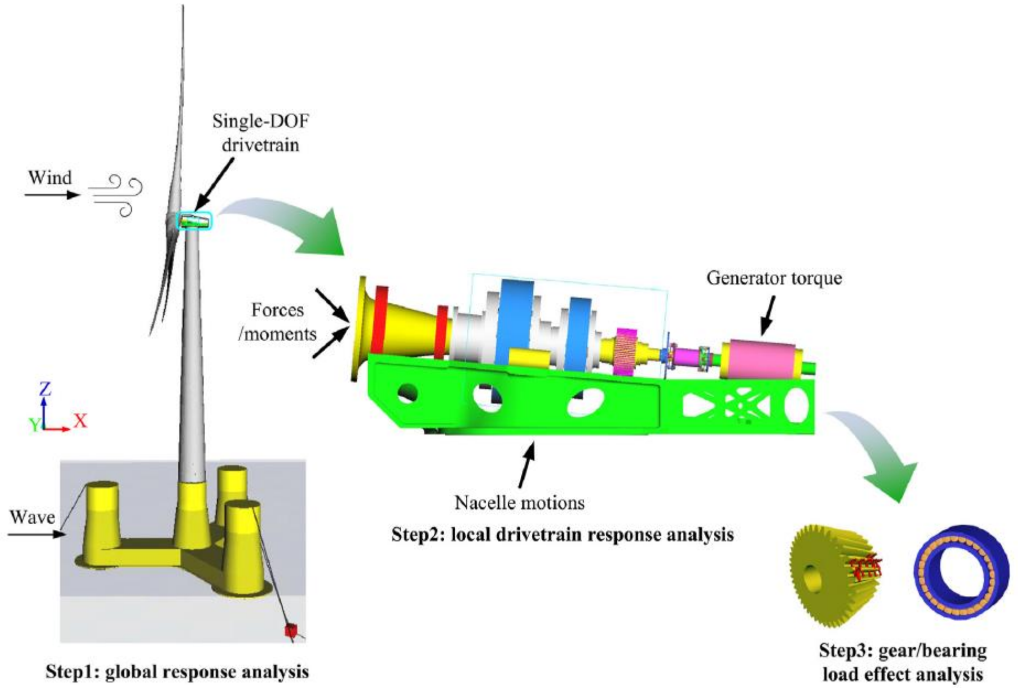
Agenda

- Introduction
  - Background
  - Motivation
- Methodology
  - OpenFAST
  - Base case
  - Implementation
- Preliminary results
- Future work

Background
Traditional analysis

- One-way coupled drivetrain model

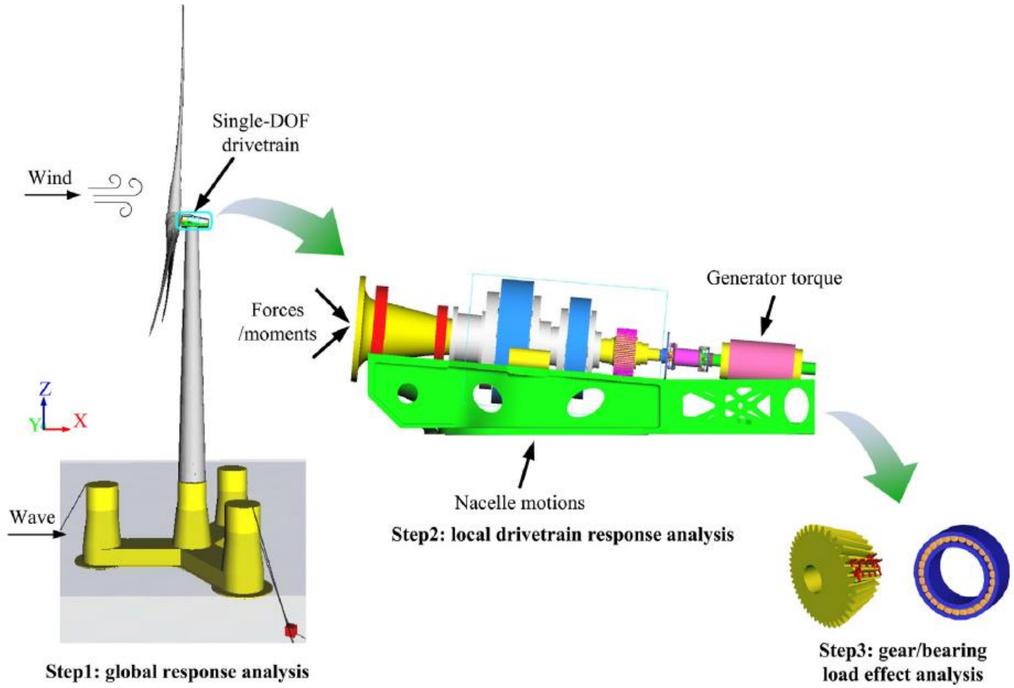


A comparative study of fully coupled and de-coupled methods on dynamic behaviour of floating wind turbine drivetrains, Wang et al., 2021

Background

Traditional analysis

- One-way coupled drivetrain model
- Drivetrain nat. frequencies > 2 Hz
- 10 MW DTU RWT - 12P = 1.92 Hz



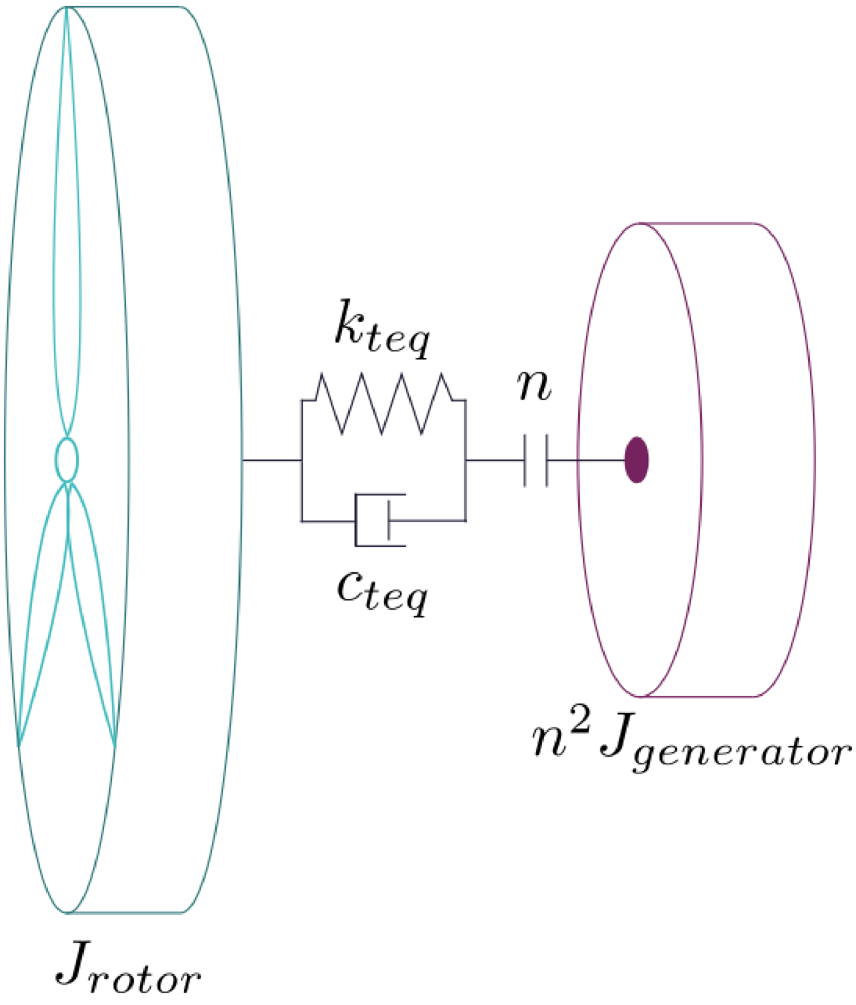
A comparative study of fully coupled and de-coupled methods on dynamic behaviour of floating wind turbine drivetrains, Wang et al., 2021

Background

Drivetrain in global analysis

- 1 DOF: Torsion
- Equivalent stiffness and damping

$$k_{teq} = \frac{k_{tr} n^2 k_{tg}}{k_{tr} + n^2 k_{tg}}$$



Motivation

Objective

Medium-fidelity model of the drivetrain in global wind turbine analysis

Motivation

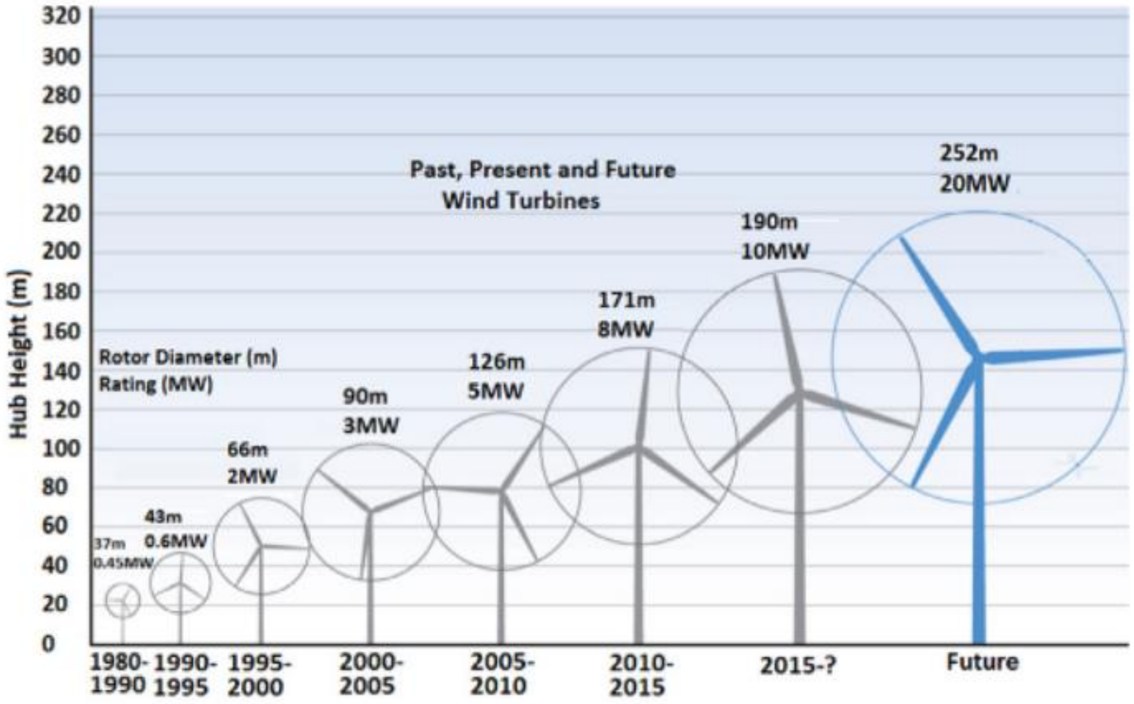
Objective

Medium-fidelity model of the drivetrain in global wind turbine analysis

Why?

Motivation
Structural flexibility of drivetrain

Larger turbines



4Coffshore. Offshore Turbine Database, 2016, Igwemezie et al., 2019

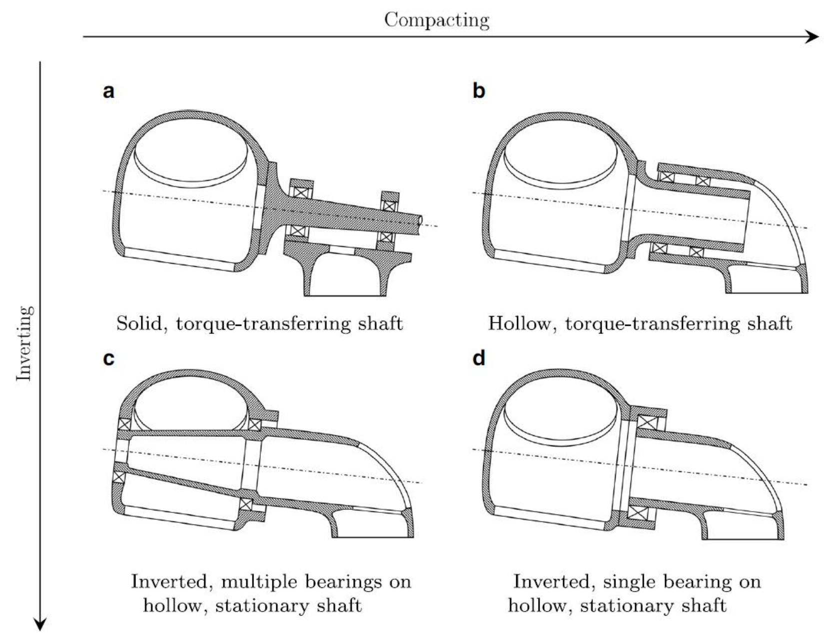
Motivation

Structural flexibility of drivetrain

Larger turbines

Drivetrain flexibility ↑

Drivetrain natural frequencies ↓

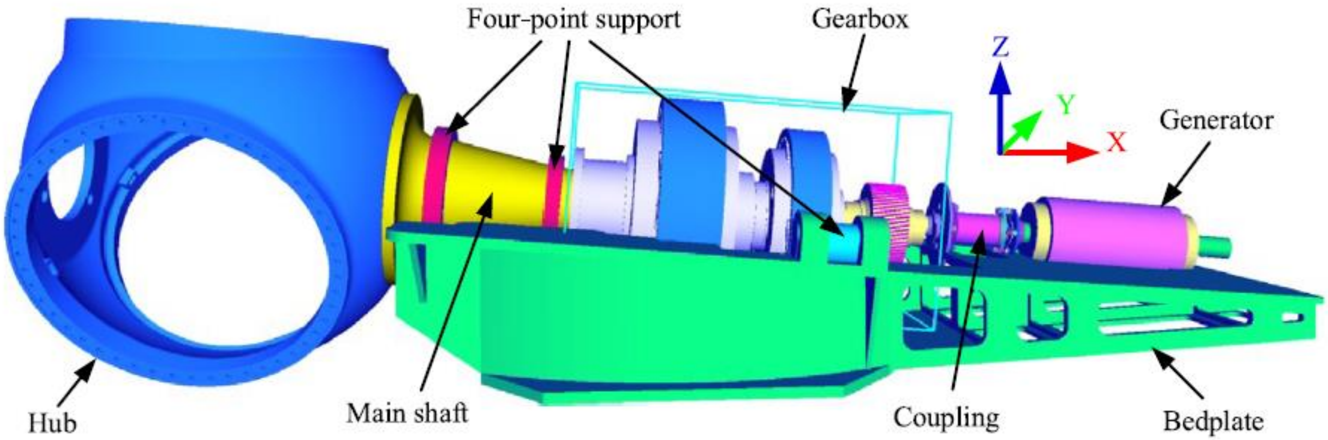


A comparative study of fully coupled and de-coupled methods on dynamic behaviour of floating wind turbine drivetrains, Wang et al., 2021
Drivetrains on floating offshore wind turbines: lessons learned over the last 10 years, Nejad et al., 2021,
Main bearings in large offshore wind turbines: development trends, design and analysis requirements, Torsvik et al., 2018

Motivation

Structural flexibility of drivetrain

- Case study:
  - Medium-speed drivetrain
  - Flexible shaft
  - Flexible bedplate

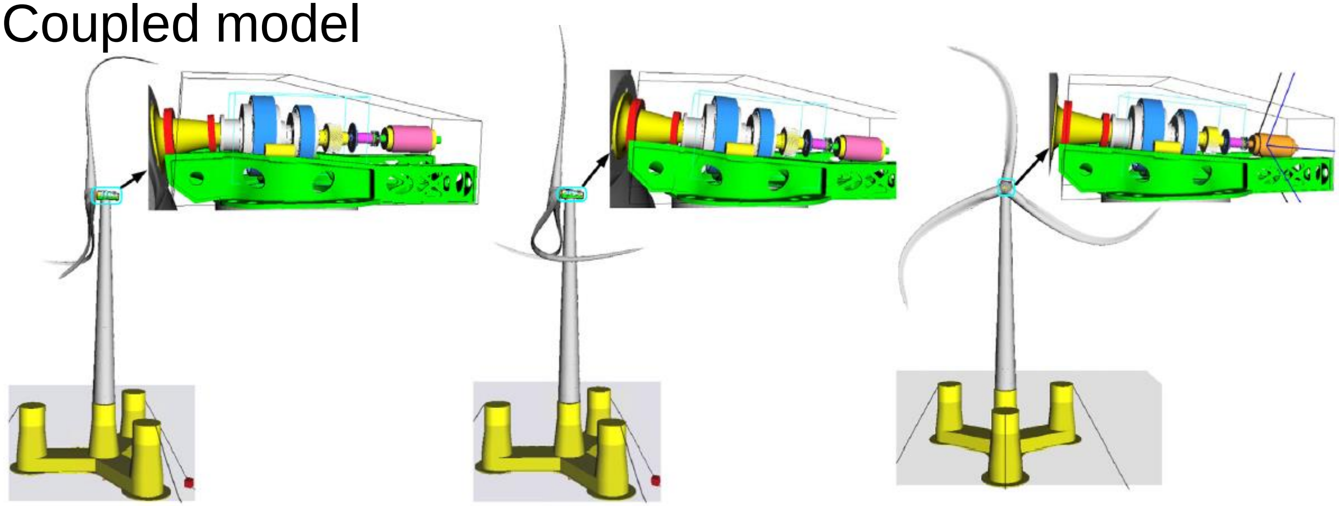


A comparative study of fully coupled and de-coupled methods on dynamic behaviour of floating wind turbine drivetrains, Wang et al., 2021

Motivation

Structural flexibility of drivetrain

- Case study:
  - Medium-speed drivetrain
  - Flexible shaft
  - Flexible bedplate
  - Coupled model



Mode1 (1.528Hz) Mode2 (1.532 Hz) Mode3 (1.884 Hz)

Fig. 7. The first three eigenmodes of the 10-MW fully coupled rotor-drivetrain-bedplate-tower model.

A comparative study of fully coupled and de-coupled methods on dynamic behaviour of floating wind turbine drivetrains, Wang et al., 2021

Motivation

Structural flexibility of drivetrain

- Case study:
  - Medium-speed drivetrain
  - Flexible shaft
  - Flexible bedplate
  - Coupled model

Non-torsional natural frequencies	<	First torsional natural frequency

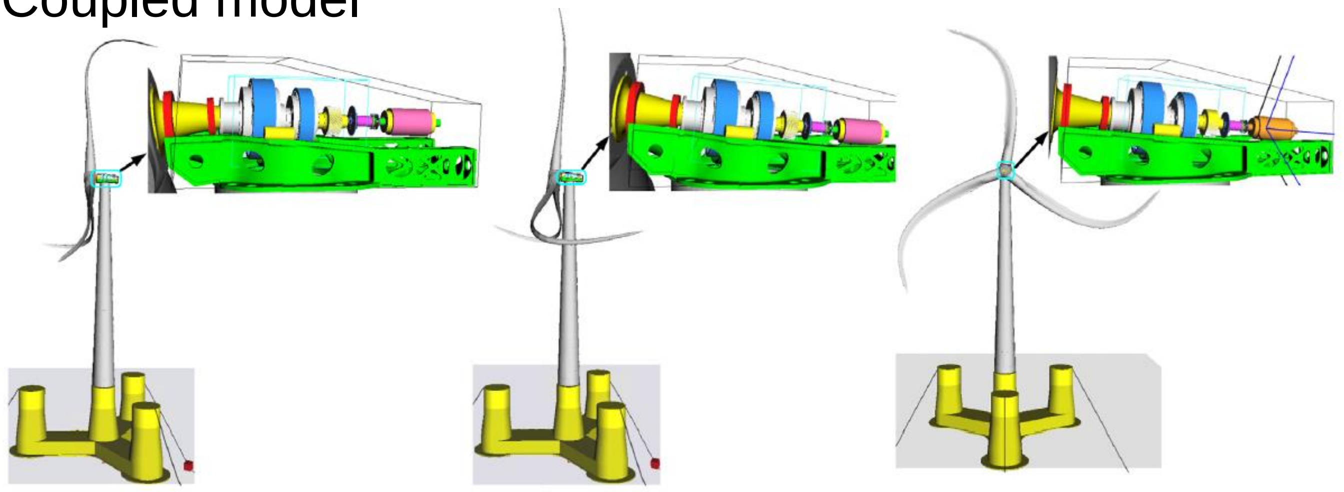


Fig. 7. The first three eigenmodes of the 10-MW fully coupled rotor-drivetrain-bedplate-tower model.

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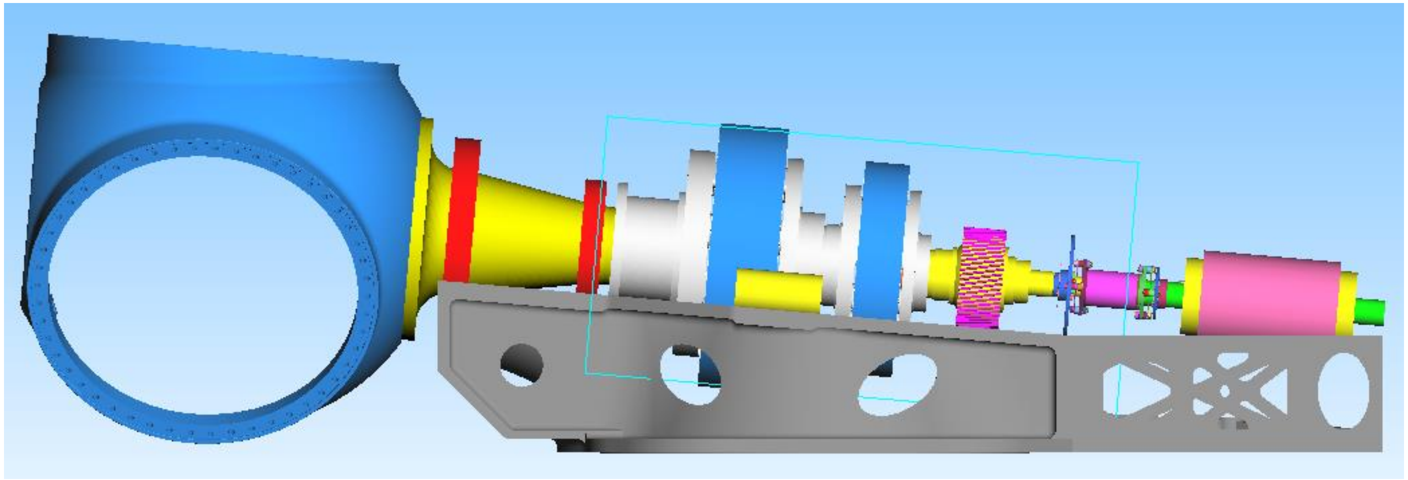
Motivation

Structural flexibility of drivetrain

Traditionally hub/rotor mass and inertia included either in:

- The local model
  - Neglect flexibility of the blades

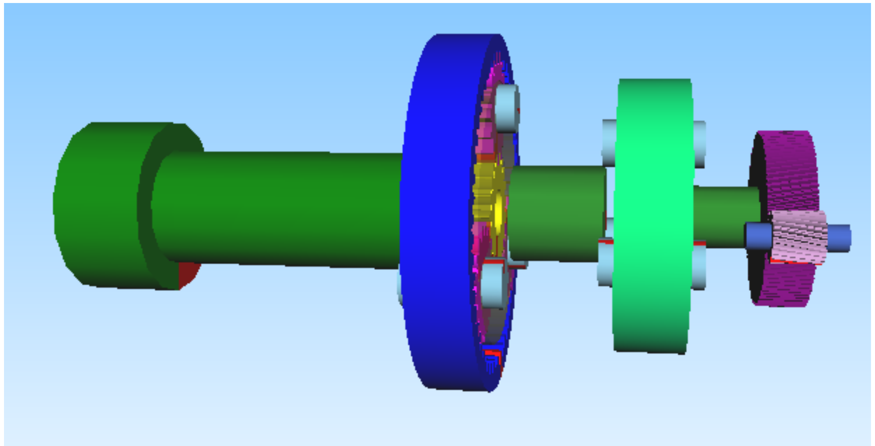


Motivation

Structural flexibility of drivetrain

Traditionally hub/rotor mass and inertia included either in:

- The local model
  - Neglect flexibility of the blades
- Or the global model
  - Wrong eigenfrequencies of the drivetrain model

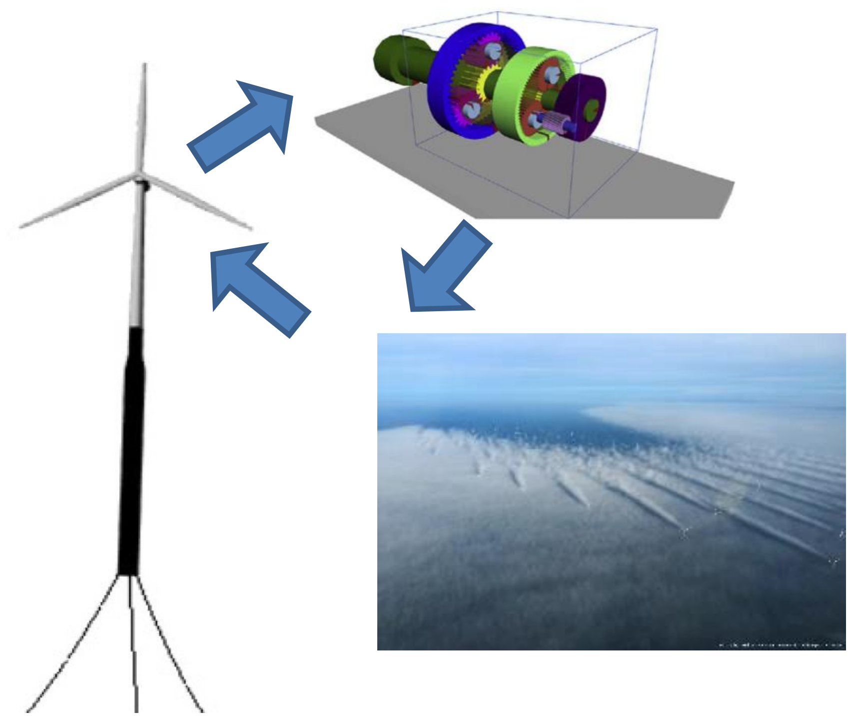


Motivation

Computational efficiency

Benefits of medium-fidelity drivetrain in global analysis:

- Reduced computational expenses
- Drivetrain response to global factors:
  - Farm level effects
  - Farm level control
  - Wind fields

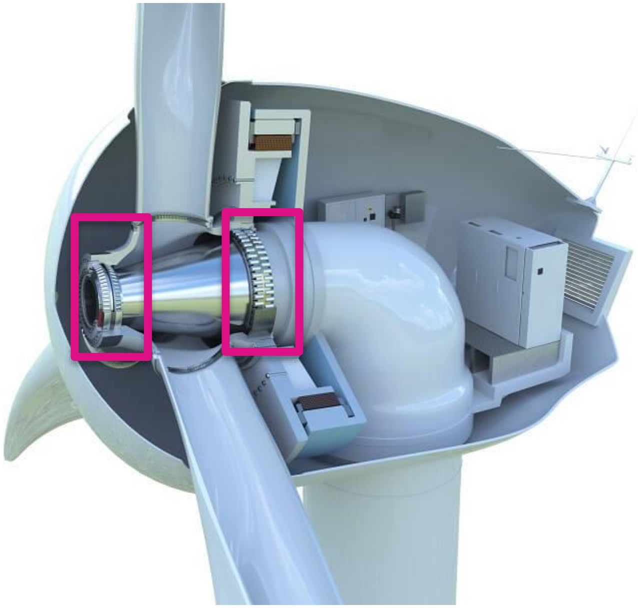


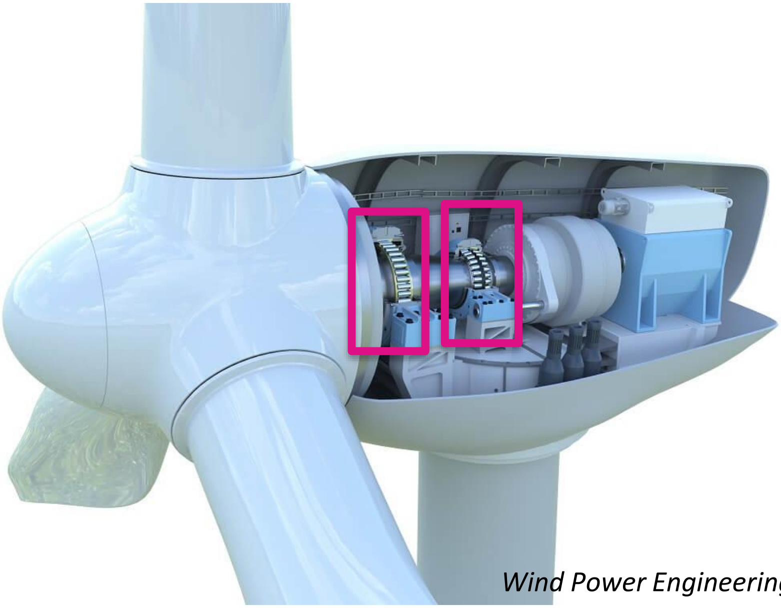
Motivation

Main bearings

- Transfer non-torque loads to bedplate and tower
- Difficult to replace
- High failure rate

Main bearing dynamics in three-point suspension drivetrains for wind turbines, Sethuraman et al. 2015
A review of wind turbine main bearings: design, operation, modelling, damage mechanisms and fault detection, Hart et al. 2019
Wind turbine drivetrain reliability collaborative workshop, Keller et al. 2016



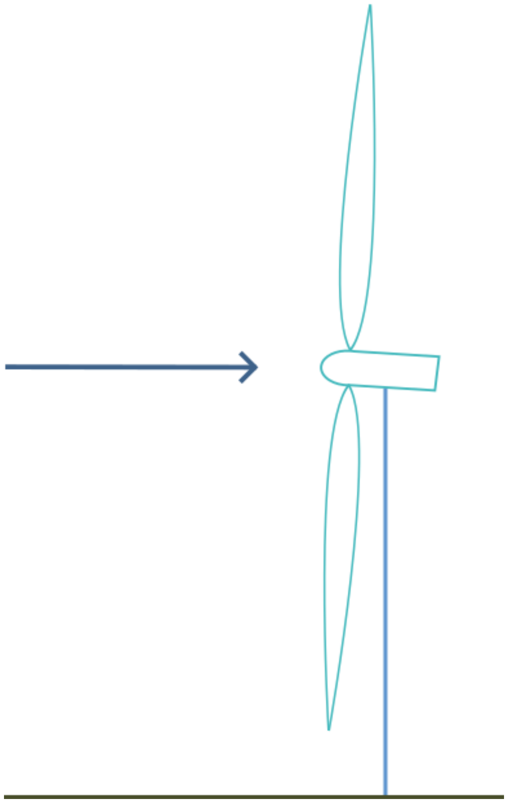


Motivation

Main bearing fatigue

Sensitive to

- Mean wind speed



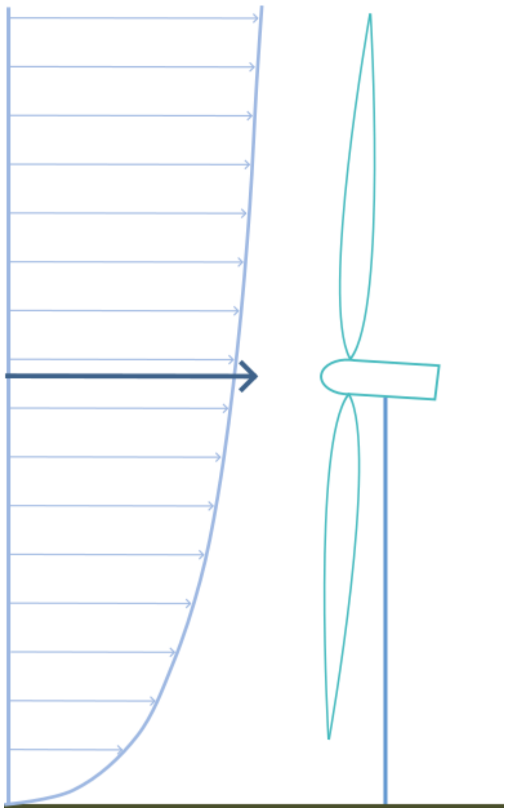
Influence of variability and uncertainty of wind and waves on fatigue damage of a floating wind turbine drivetrain, Wang et al., 2022,
Impacts of wind field characteristics and non-steady deterministic wind events on time varying main-bearing loads, Hart et al., 2022,
Drivetrains on floating offshore wind turbines: lessons learned over the last 10 years, Nejad et al., 2021,

Motivation

Main bearing fatigue

Sensitive to

- Mean wind speed
- Wind shear



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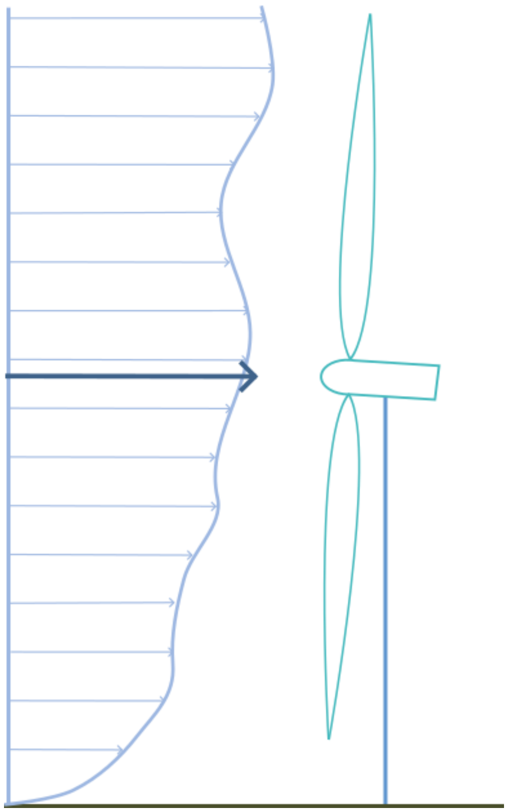
Motivation

Main bearing fatigue

Sensitive to

- Mean wind speed
- Wind shear
- Turbulence



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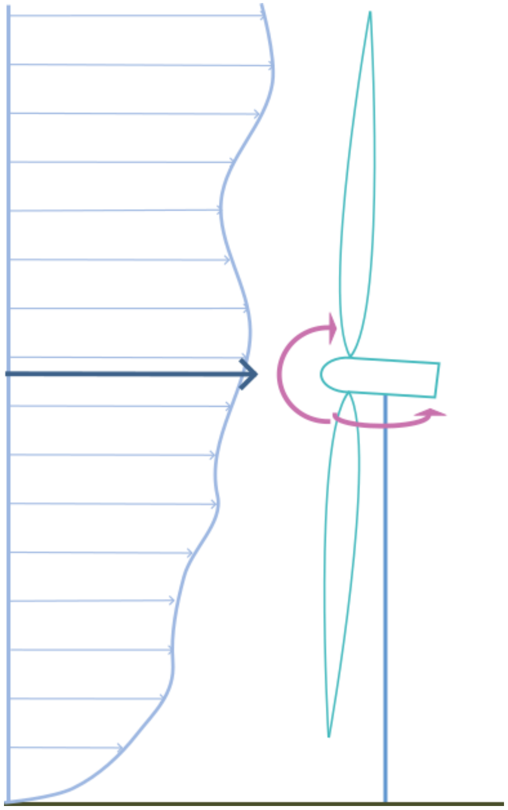
Motivation

Main bearing fatigue

Sensitive to

- Mean wind speed
- Wind shear
- Turbulence
- Tower top yaw and pitch moments



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Motivation

Main bearing fatigue

Sensitive to

- Mean wind speed
- Wind shear
- Turbulence
- Tower top yaw and pitch moments

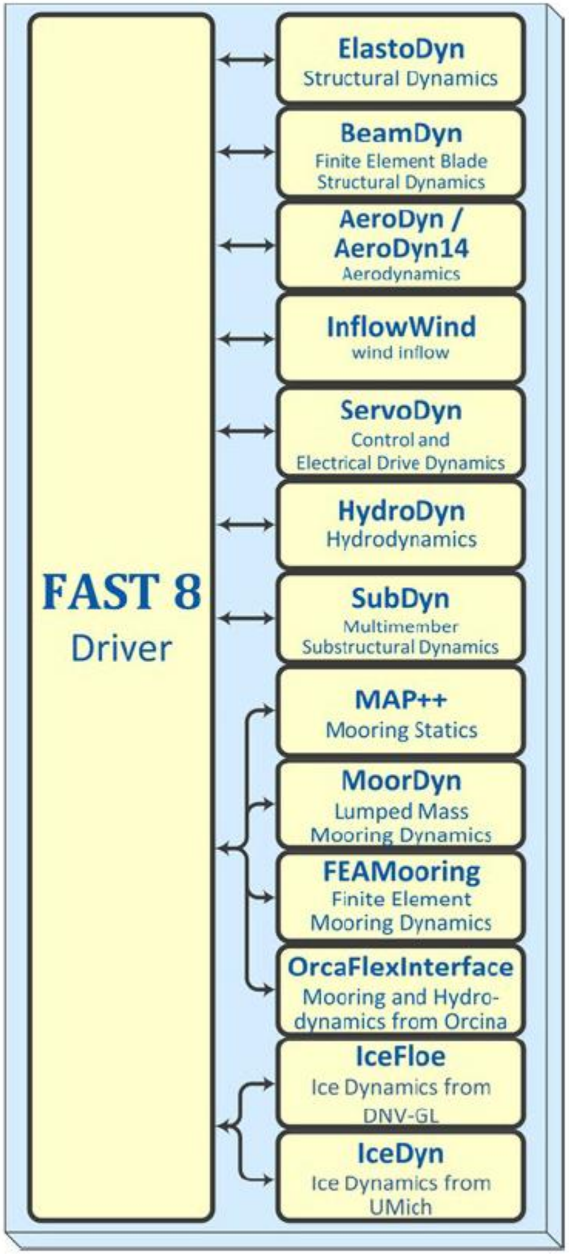
Influenced by atmospheric conditions, wind field models and wake effects

Wake meandering effects on floating wind turbines, Wise & Bachnyski, 2020
Response sensitivity of a semisubmersible floating offshore wind turbine to different wind spectral models, Putri et al., 2020,
Effects of atmospheric stability on the structural response of a 12 MW semisubmersible floating wind turbine, Rivera-Arreba, 2022,
Sensitivity of the dynamic response of a multimegawatt floating wind turbine to the choice of turbulence model, Nybø, 2022

Methodology

OpenFAST

- NREL’s wind turbine engineering tool for global analysis
- Open-source
- Modular framework



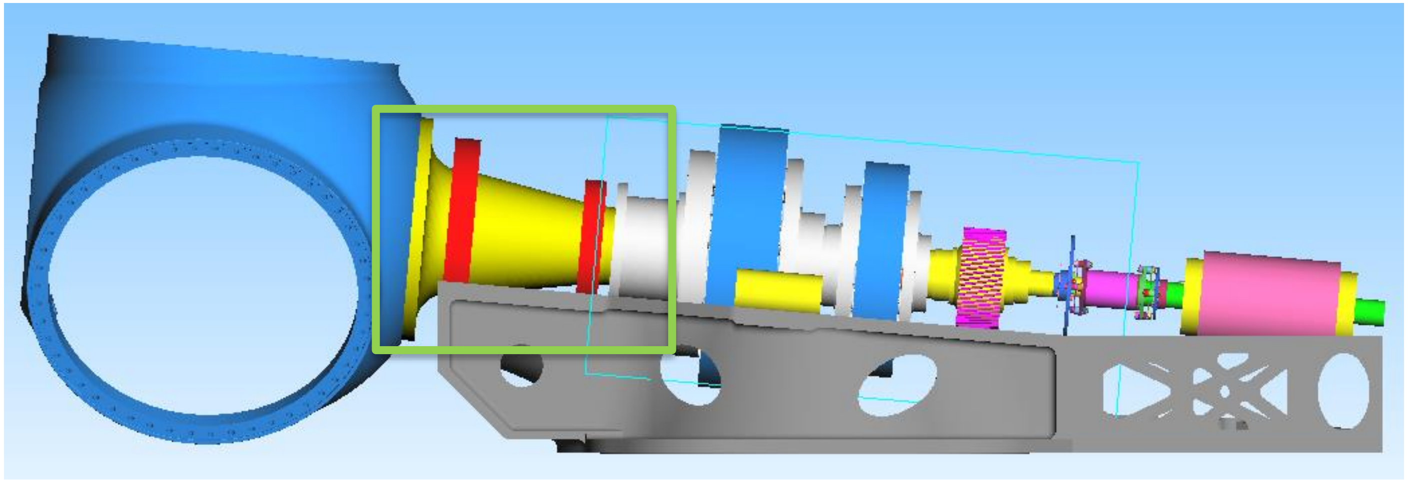
Jonkman, 2022

Methodology

OpenFAST

Add components to OpenFAST:

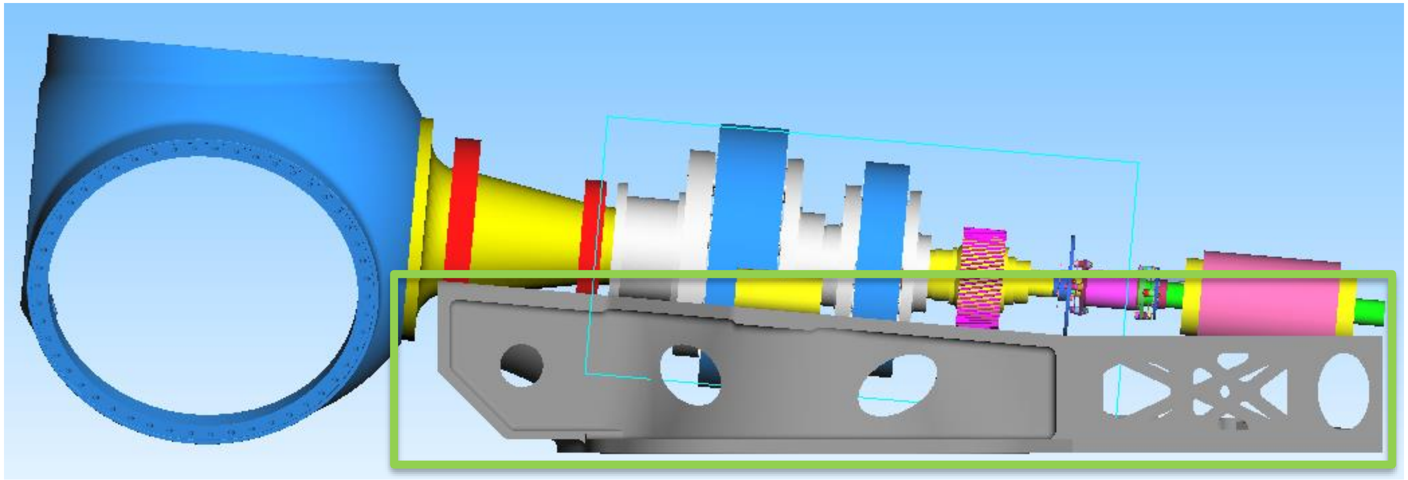
- Flexible shaft



Methodology
OpenFAST

Add components to OpenFAST:

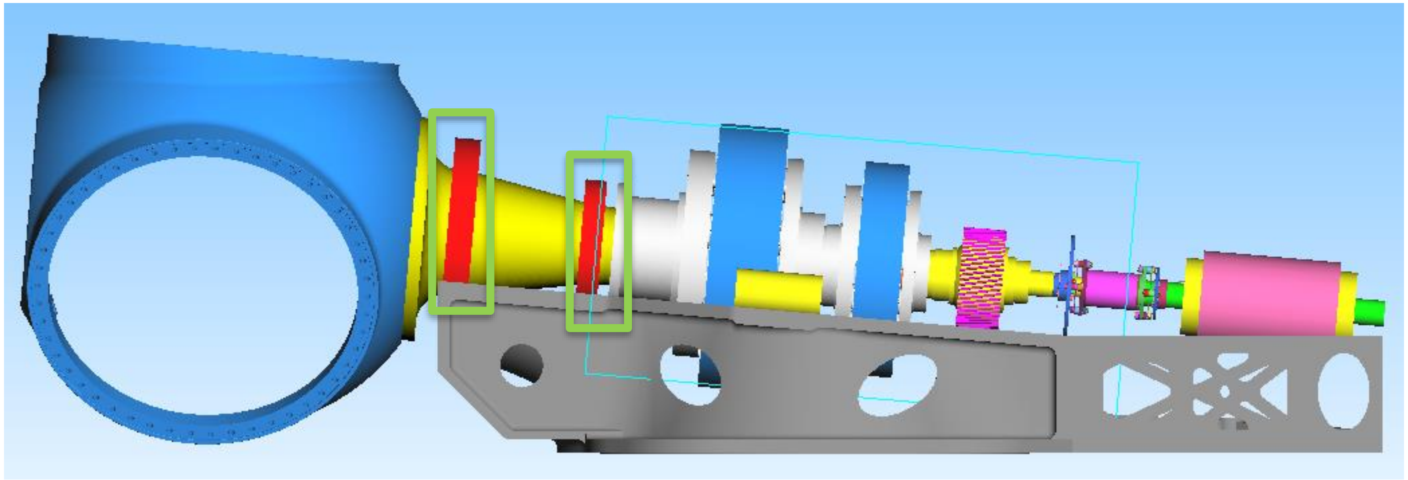
- Flexible shaft, bedplate



Methodology
OpenFAST

Add components to OpenFAST:

- Flexible shaft, bedplate and main bearings



Methodology
OpenFAST

Add components to OpenFAST:

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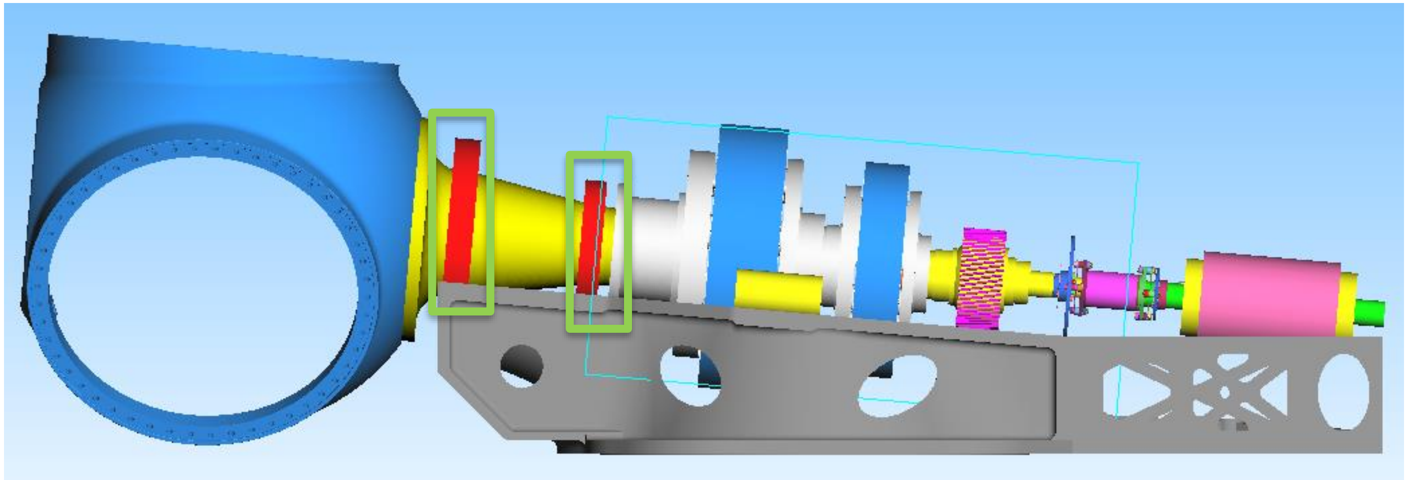


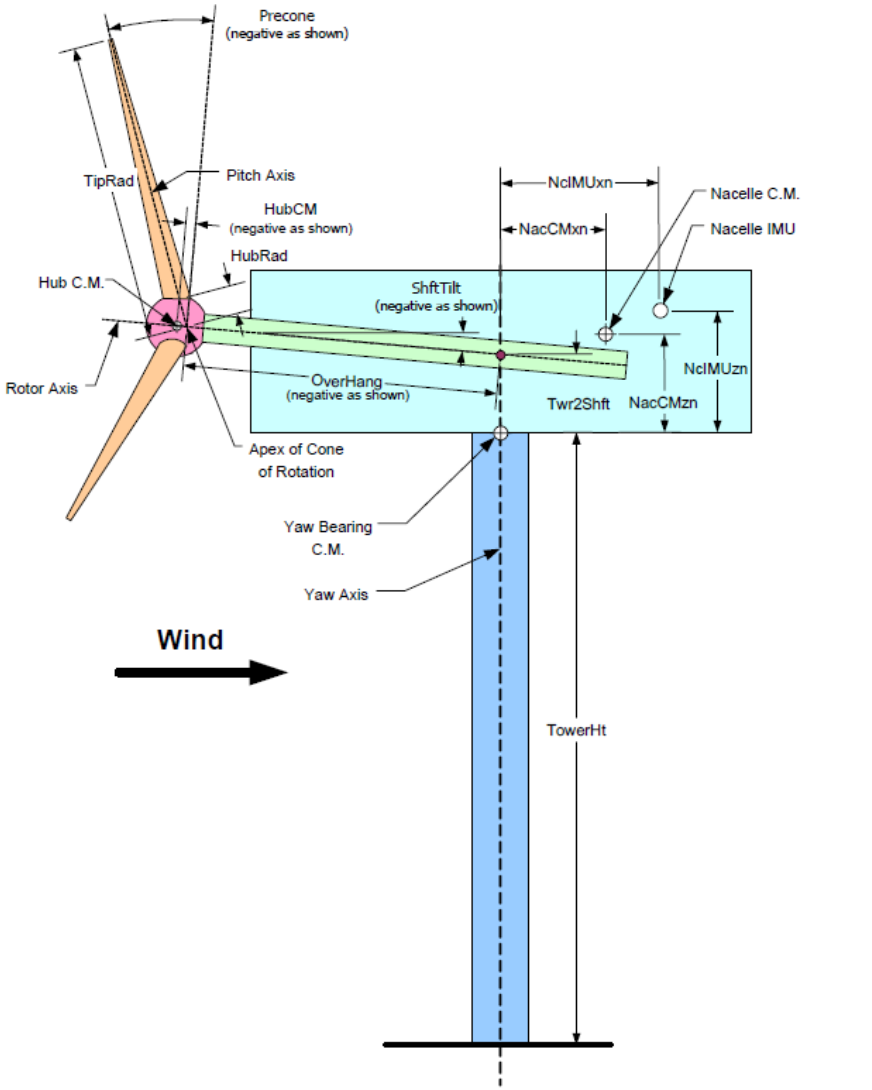
Target:

- Reliable main bearing loads from global analysis

Methodology

ElastoDyn module

- Current method
- Multi-body + modal representation
  - Modal:
    - Tower
    - Blades
  - Multi-body:
    - Platform
    - Nacelle
    - Drivetrain
    - Hub

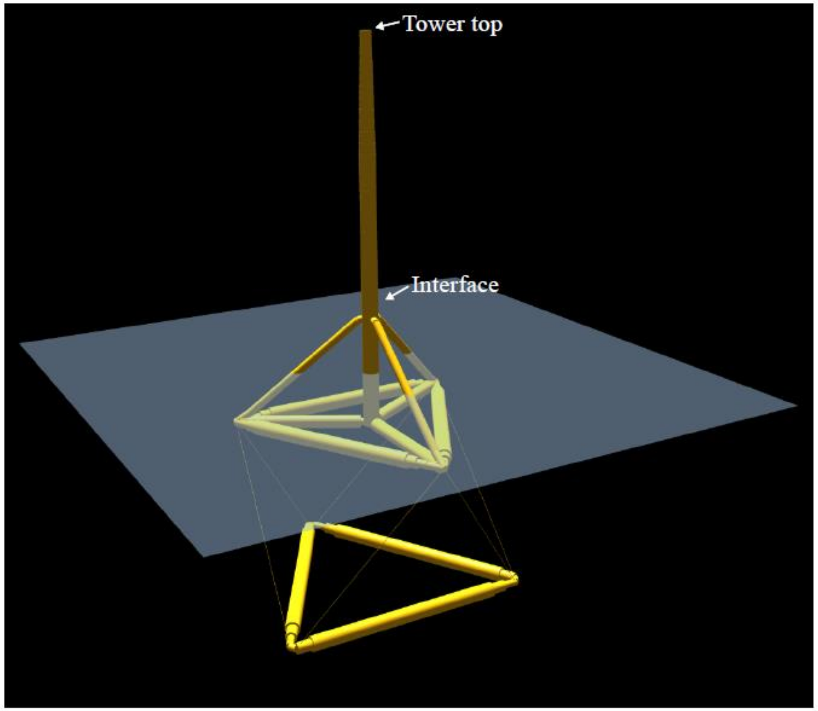


FAST User guide, 2005

Methodology

SubDyn module

- Linear frame FE model
  - Beam elements
  - Rigid links
  - Cantilever, pin, universal and ball joints
  - Cable elements
- Craig-Bampton dynamic system reduction
- Floating reference frame
- Substructure modelling
- Small angle assumption

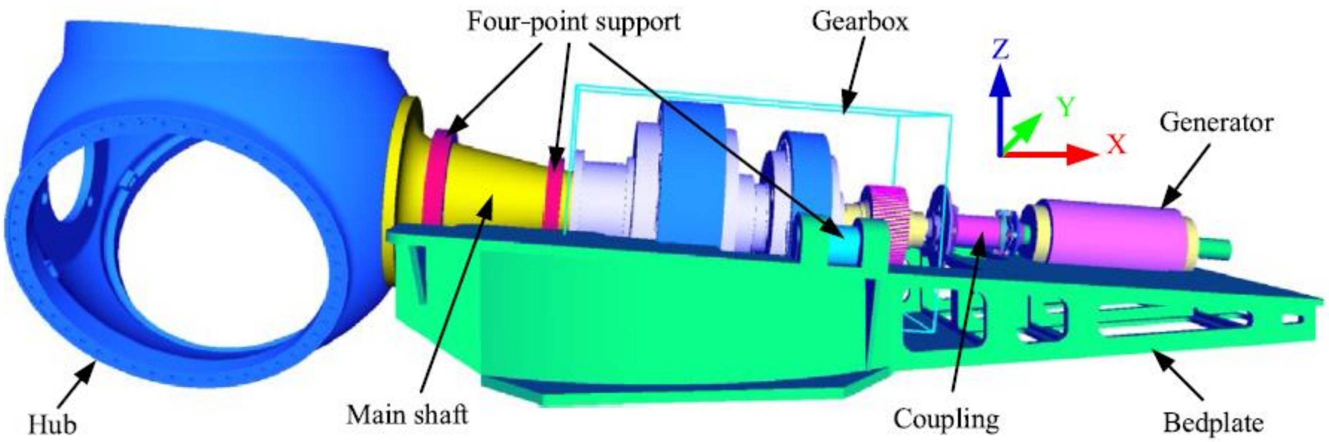


Modeling the TetraSpar Floating OffshoreWind Turbine Foundation as a Flexible Structure in OrcaFlex and OpenFAST, Thomsen et al., 2021

Methodology

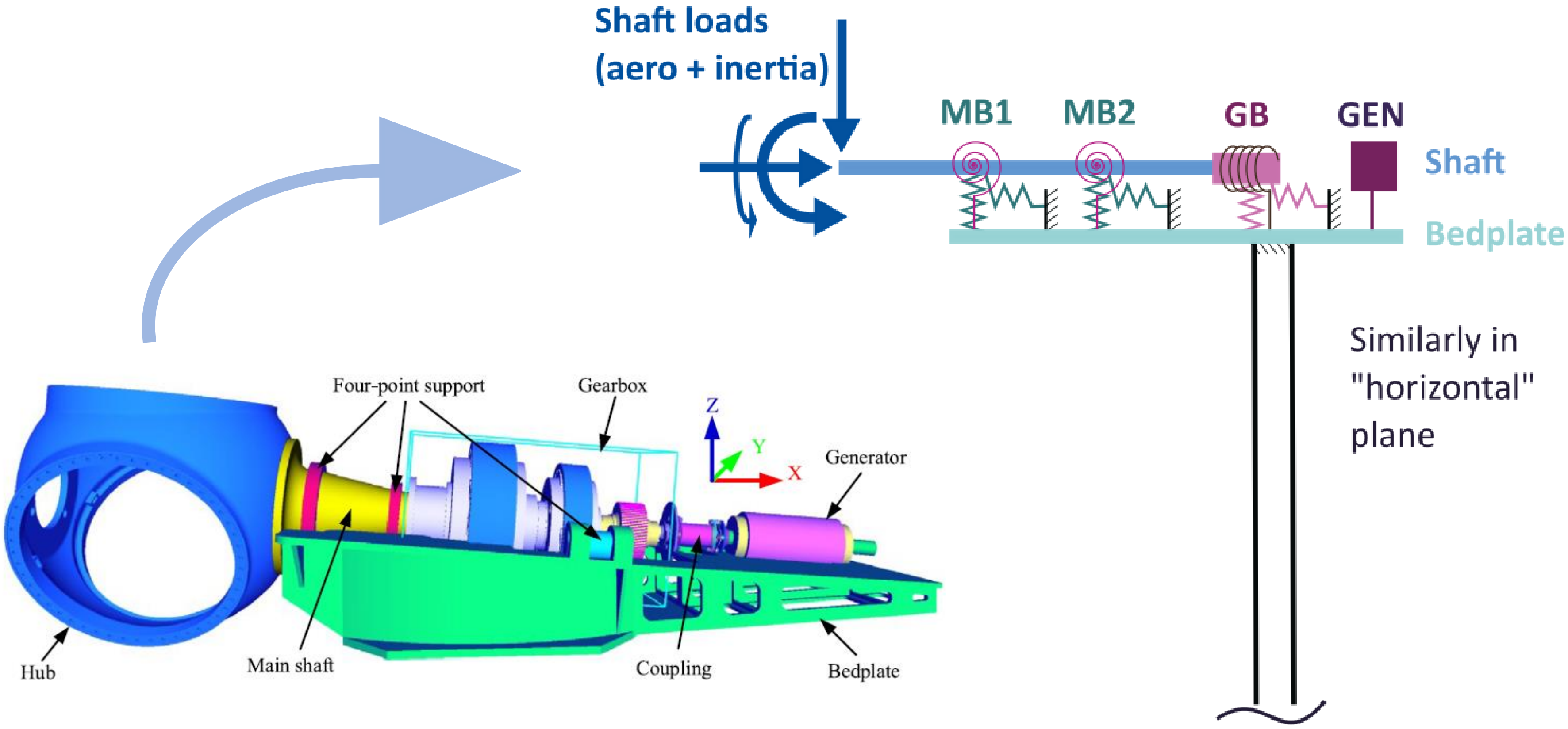
Base case

- DTU 10 MW RWT
- Medium-speed drivetrain
- Land-based turbine



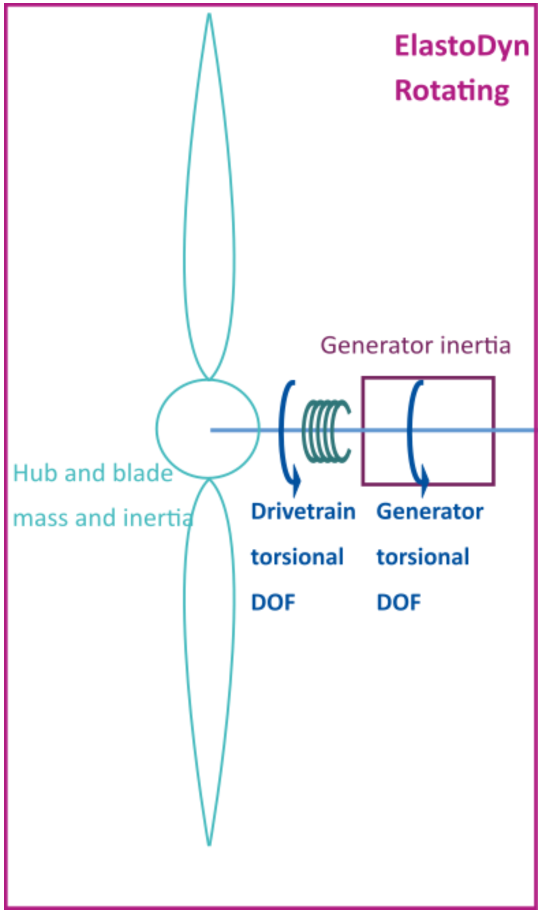
On design, modelling, and analysis of a 10-MWmedium-speed drivetrain for offshore wind turbines, Wang, 2019

Methodology
Simplified model



Methodology

Implementation in OpenFAST

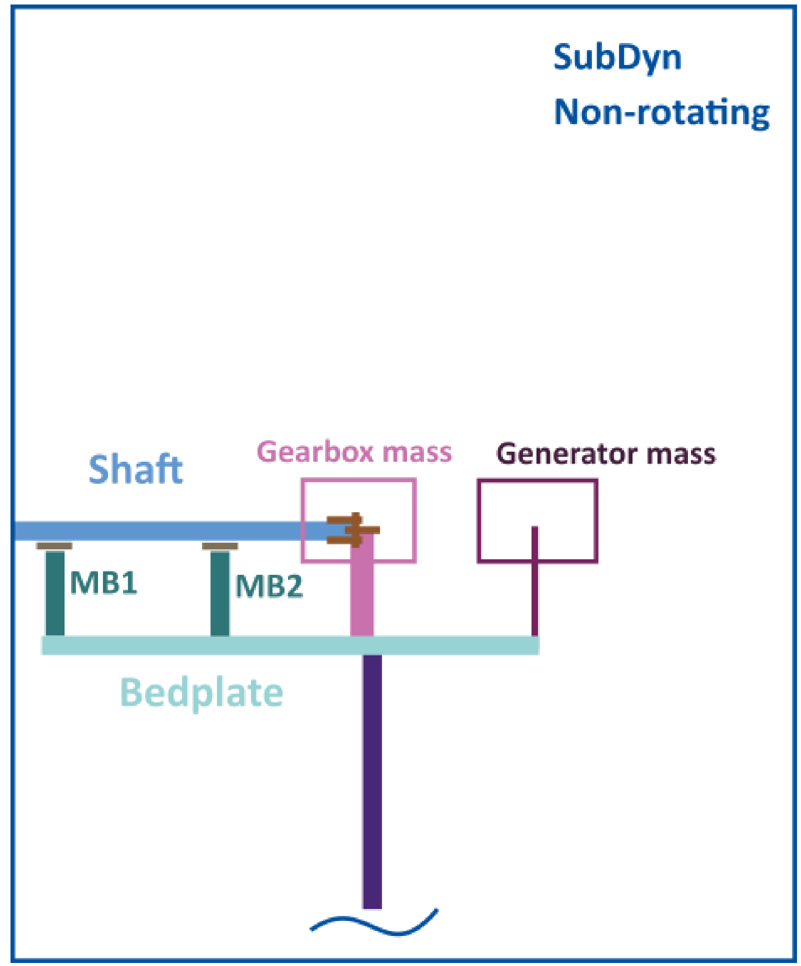


- ElastoDyn
  - Shaft (rotating)
  - Hub
  - Blades

Methodology

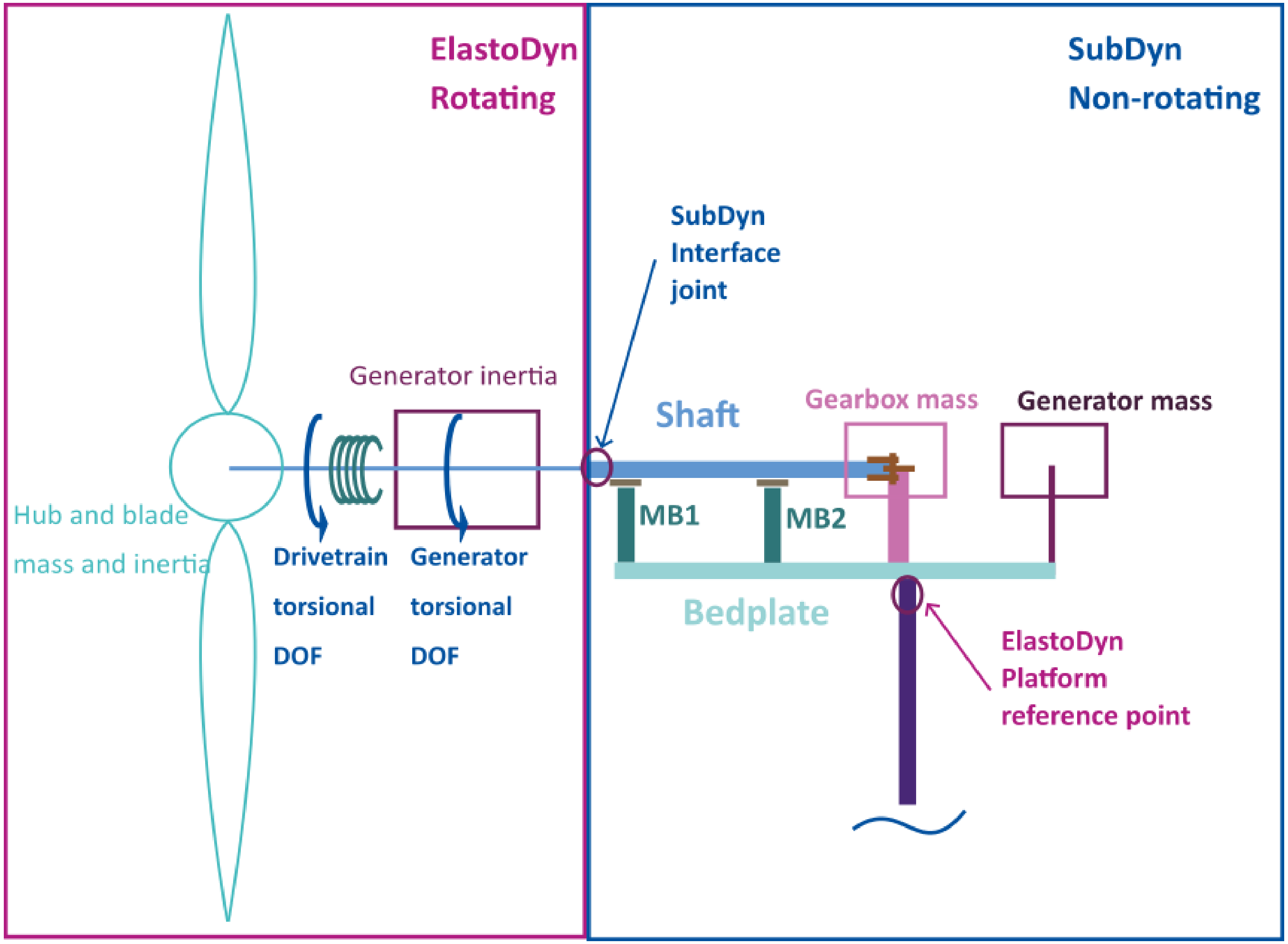
Implementation in OpenFAST

- SubDyn
  - Tower
  - Bedplate
  - Drivetrain
  - Shaft (non-rotating)



Methodology

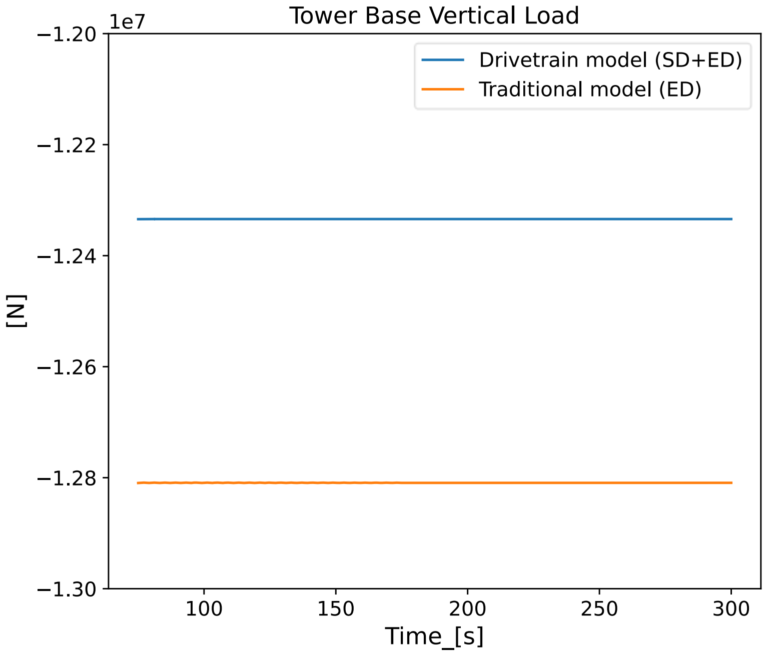
Implementation in OpenFAST

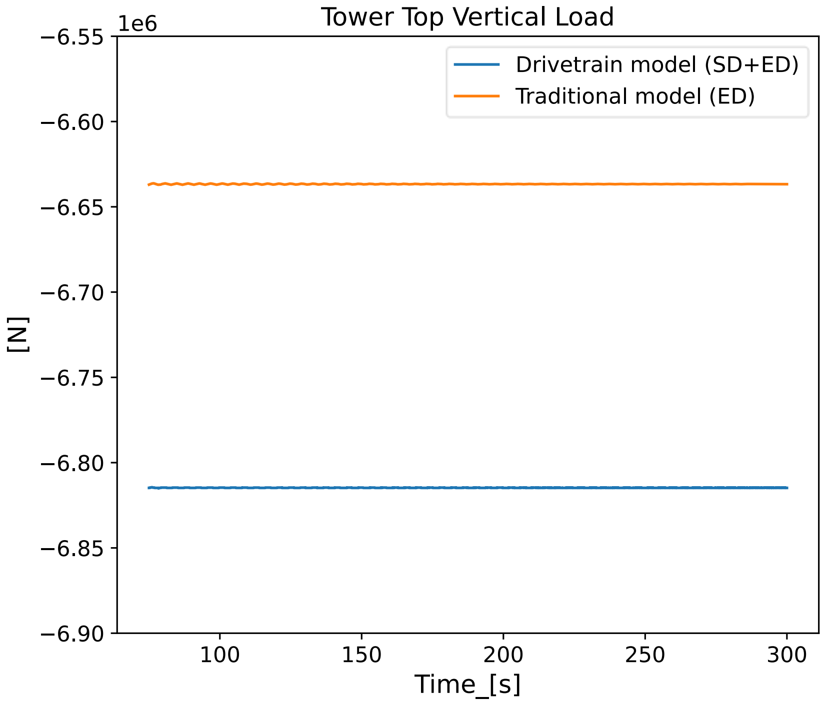


Preliminary results

Tower static loads

- Comparing traditional model (ED) and new model (SD+ED)



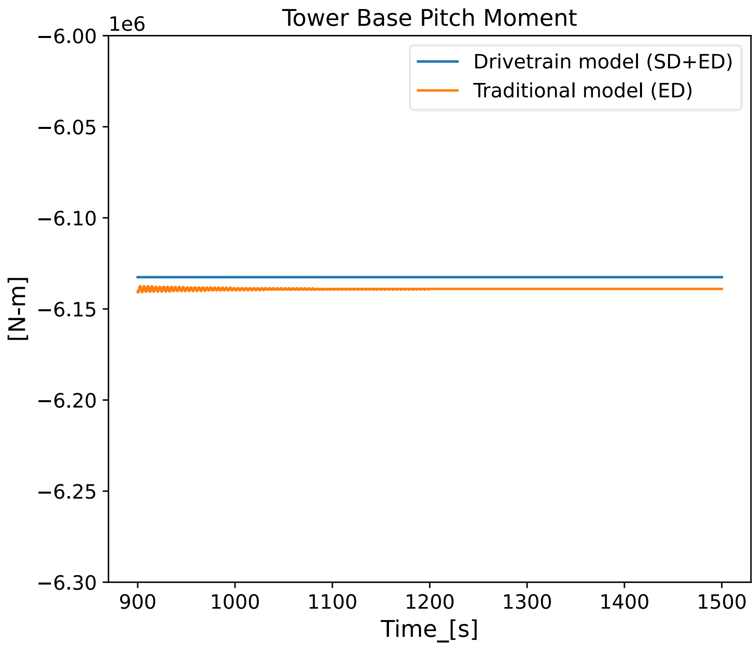


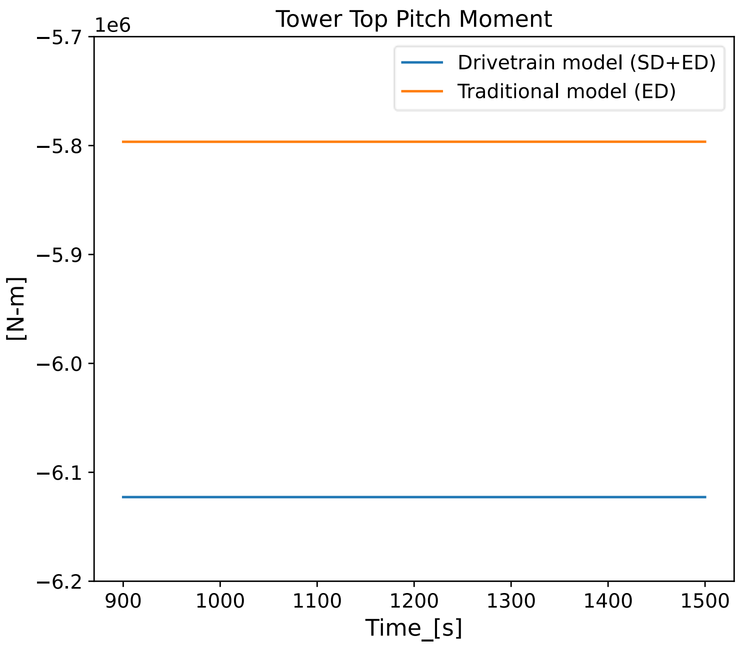
- SubDyn gravitational loads taken at member mid-section

Preliminary results

Tower static moments

- Comparing traditional model (ED) and new model (SD+ED)



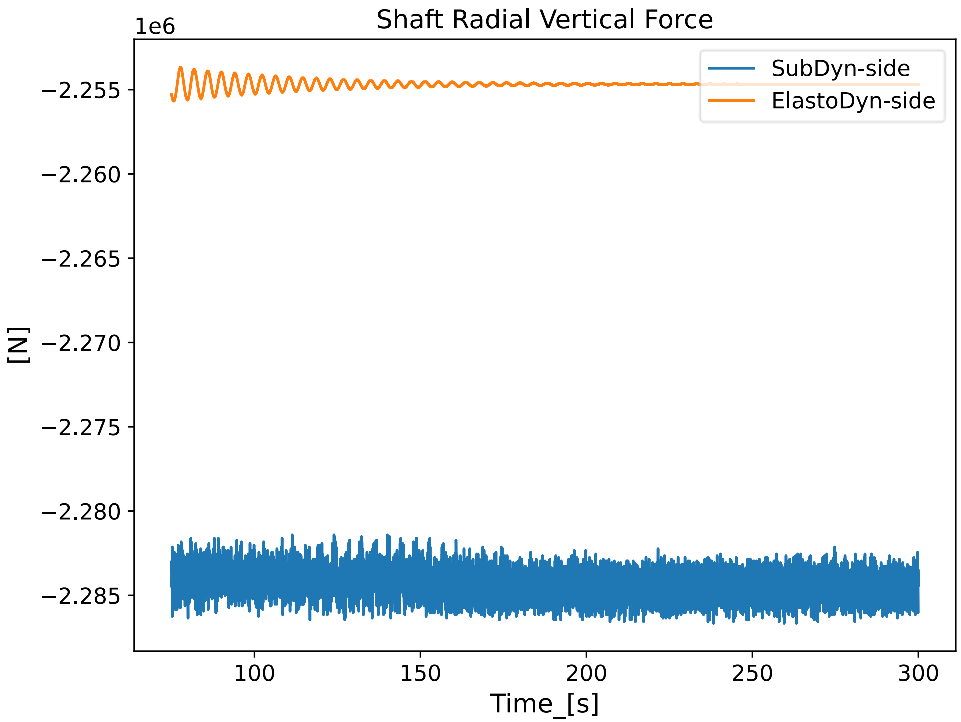


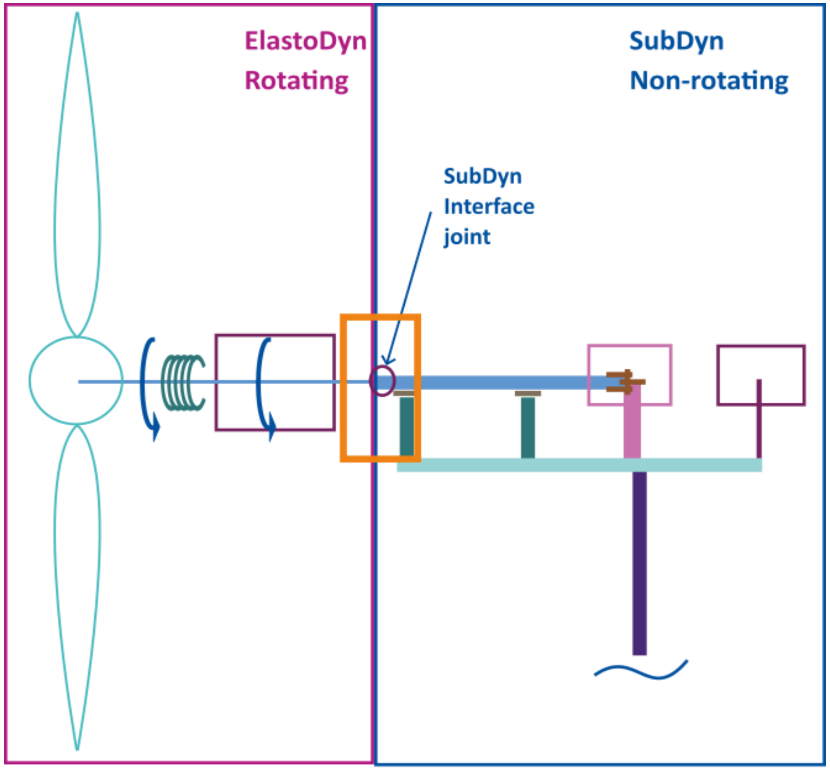
- ElastoDyn accounts for geometric nonlinearities

Preliminary results

Shaft static loads

- New model only (SD+ED)



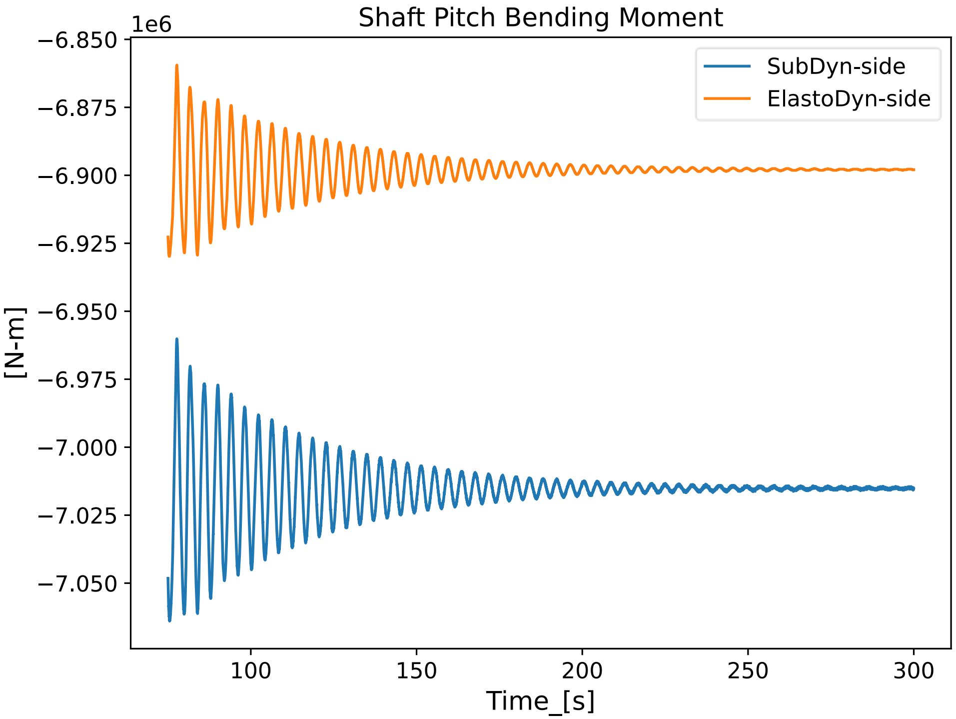


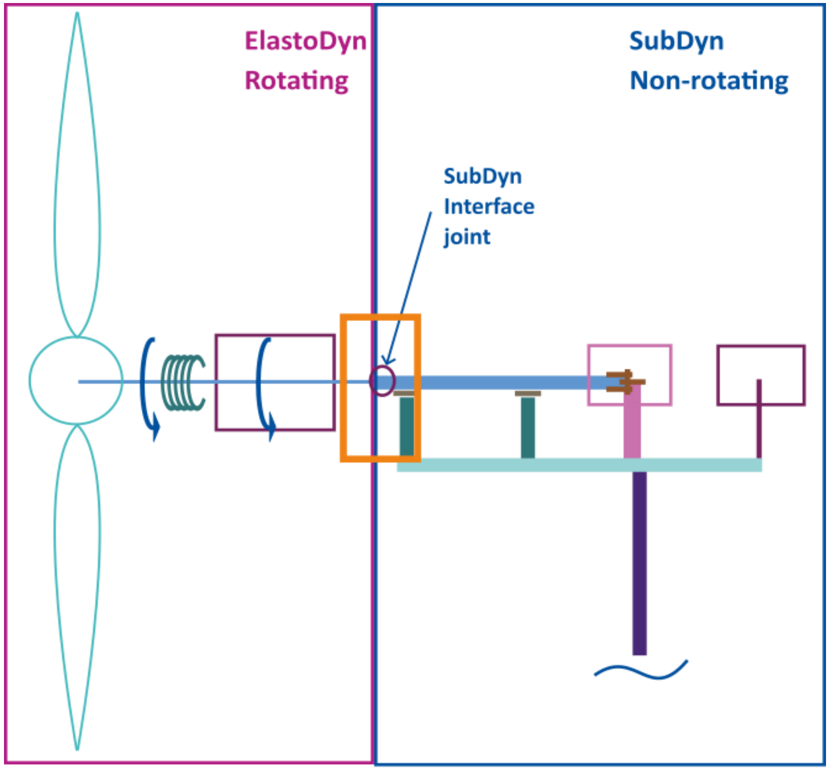
- Mean offset due to gravitational loads of member

Preliminary results

Shaft static loads

- New model only (SD+ED)





Preliminary results

Shaft static loads

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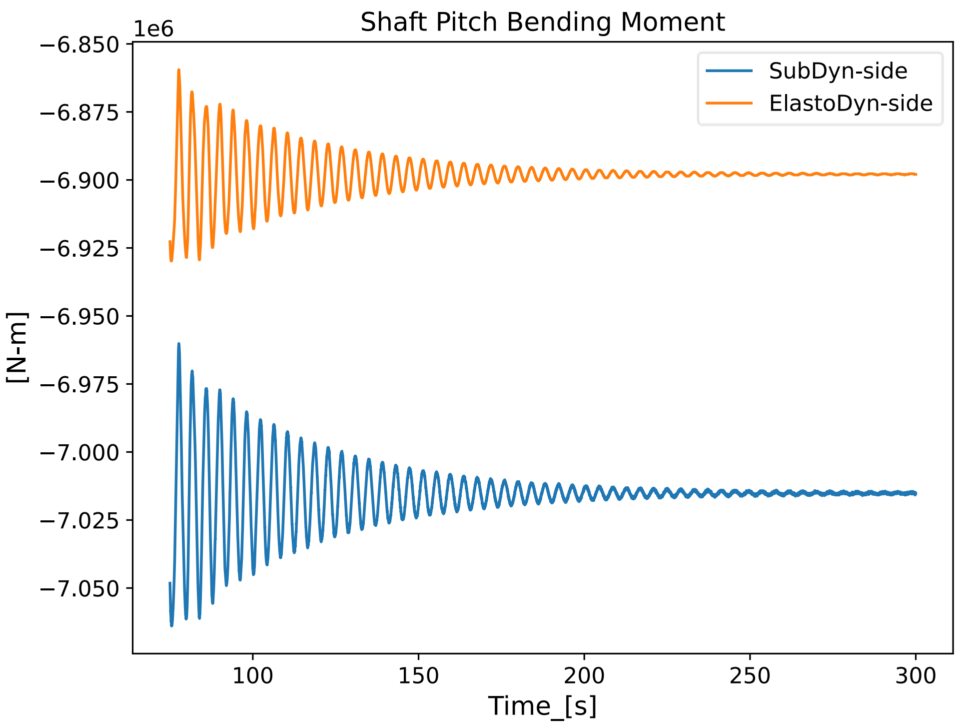
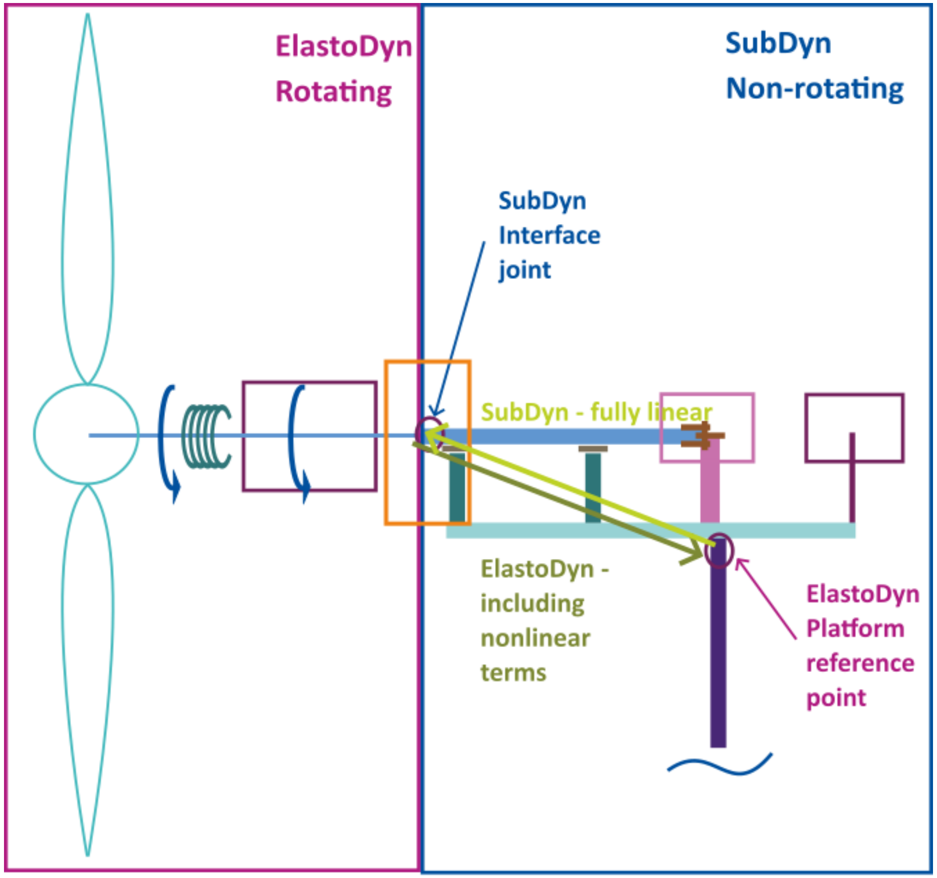
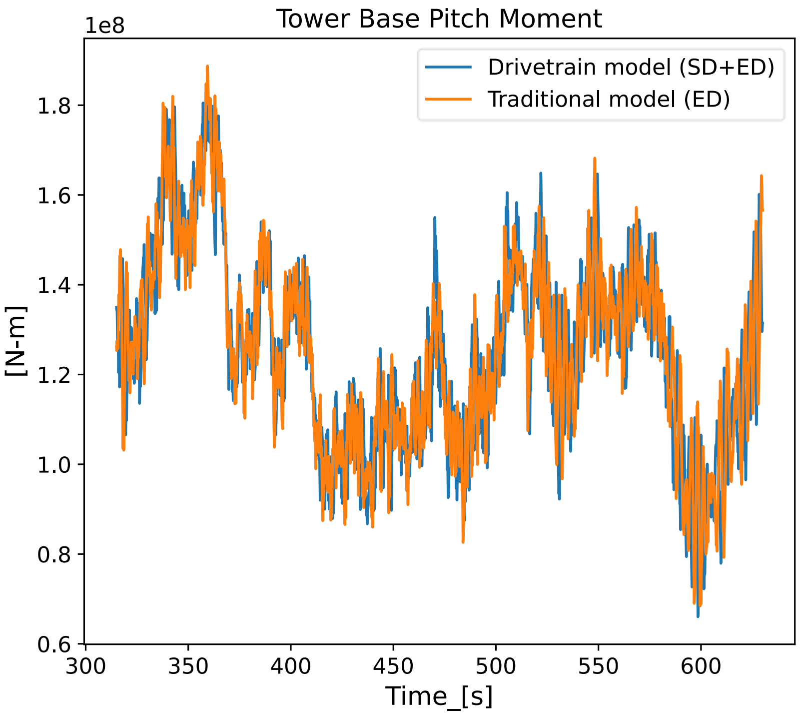


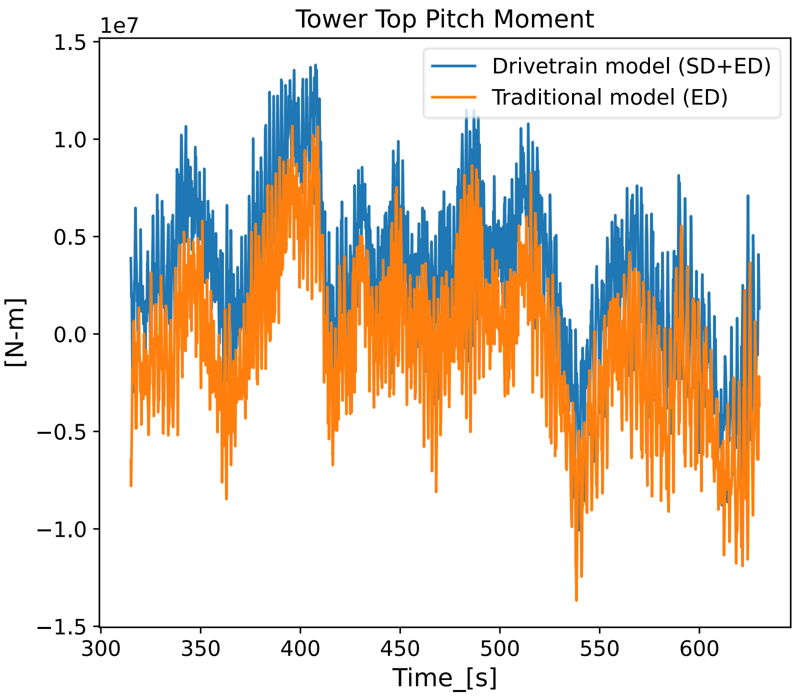


Preliminary results

Tower loads – turbulent wind

- Comparing traditional model (ED) and new model (SD+ED)

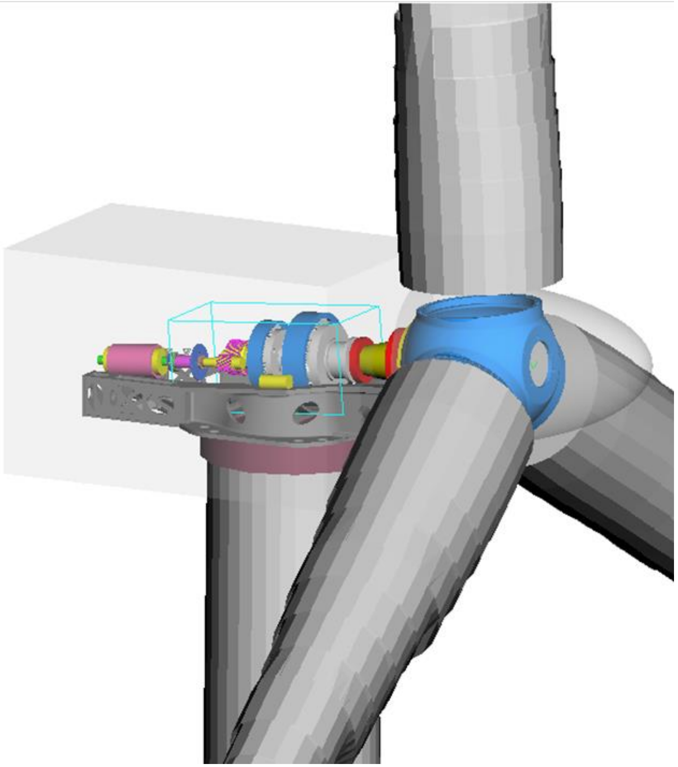




- Work in progress

Future work

- Verification against SIMPACK coupled model
  - Campbell-diagram/eigenvalue analysis
  - Time series simulation
    - Shaft deflection
    - Shaft and bearing loads



Jakob Gebel

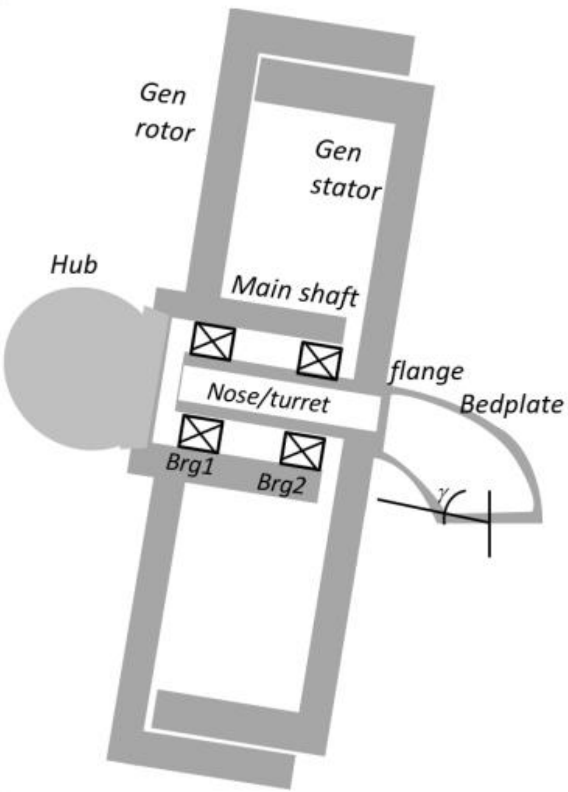
Future work

- Verification against SIMPACK coupled model
  - Campbell-diagram/eigenvalue analysis
  - Time series simulation
    - Shaft deflection
    - Shaft and bearing loads
- Bearing fatigue

$$D = \sum_i \frac{l_i}{L_i} = \frac{1}{10^6 C_{10}^p} \sum_i l_i P_i^p$$

Future work

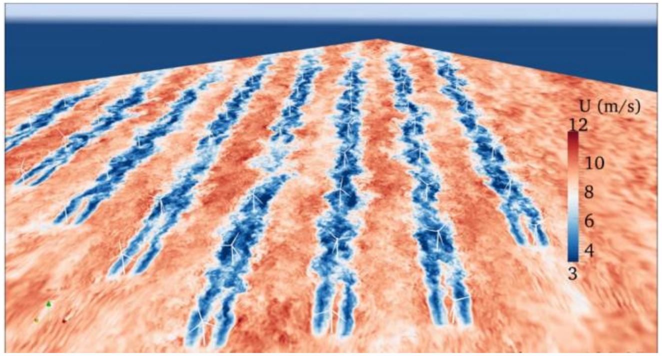
- Verification against SIMPACK coupled model
  - Campbell-diagram/eigenvalue analysis
  - Time series simulation
    - Shaft deflection
    - Shaft and bearing loads
- Bearing fatigue
- Implementation of IEA 15 MW direct drive with Umaine floating platform



Gaertner et al. 2020

Future work

- Verification against SIMPACK coupled model
  - Campbell-diagram/eigenvalue analysis
  - Time series simulation
    - Shaft deflection
    - Shaft and bearing loads
- Bearing fatigue
- Implementation of IEA 15 MW direct drive with Umaine floating platform
- Drivetrain sensitivity to
  - wind field models
  - wake effects



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Thank you!

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