University of Stuttgart
Stuttgart Wind Energy (SWE)
@ Institute of Aircraft Design

FlexDyn – A new OpenFAST Structural Dynamics Module for a General, User-Defined Wind Turbine Topology

Wind Energy Science Conference
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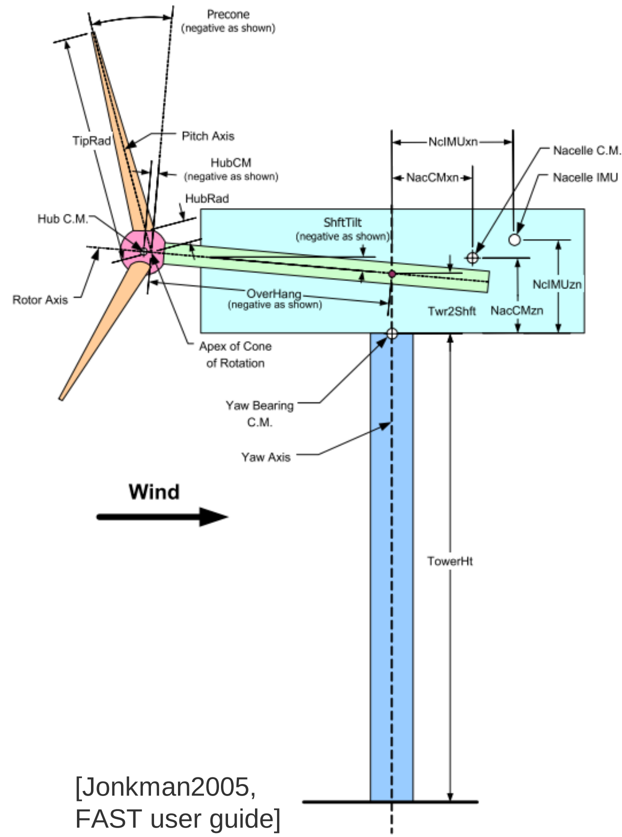
(University of Stuttgart)

Danai Skandali, Steffen Raach
(sowento GmbH)

Background: Aero-Hydro-Servo-Elastic Modeling

- Structural dynamics, aerodynamics, hydrodynamics, controls



[Jonkman2005, FAST user guide]

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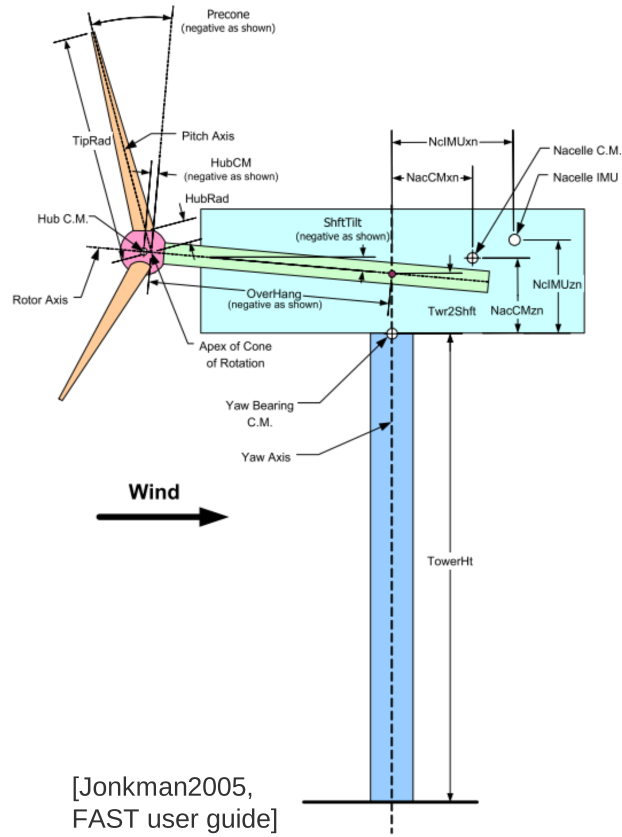
- Nonlinear time-domain
- Linearization



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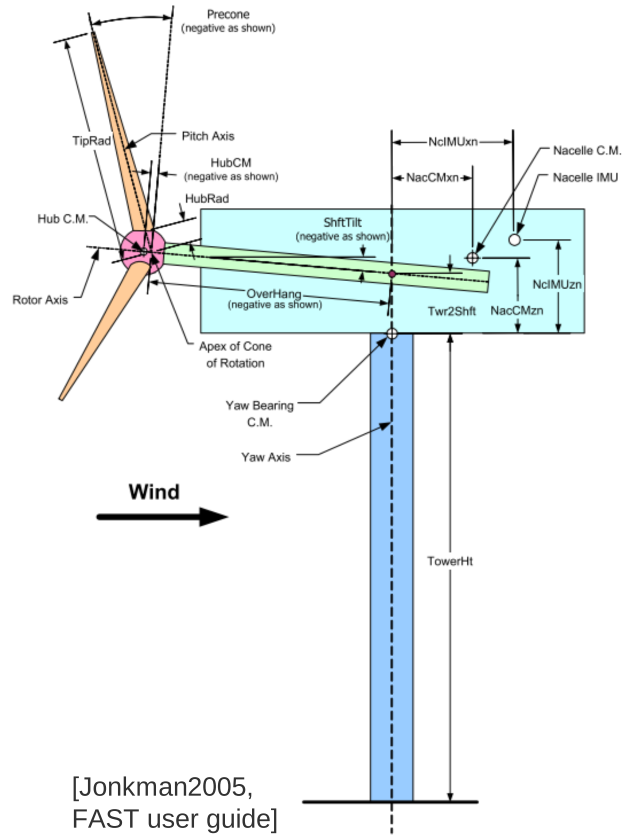

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- „Engineering“ model
- Blade-element momentum theory
- „Modal“ reduction of beams

- Nonlinear time-domain
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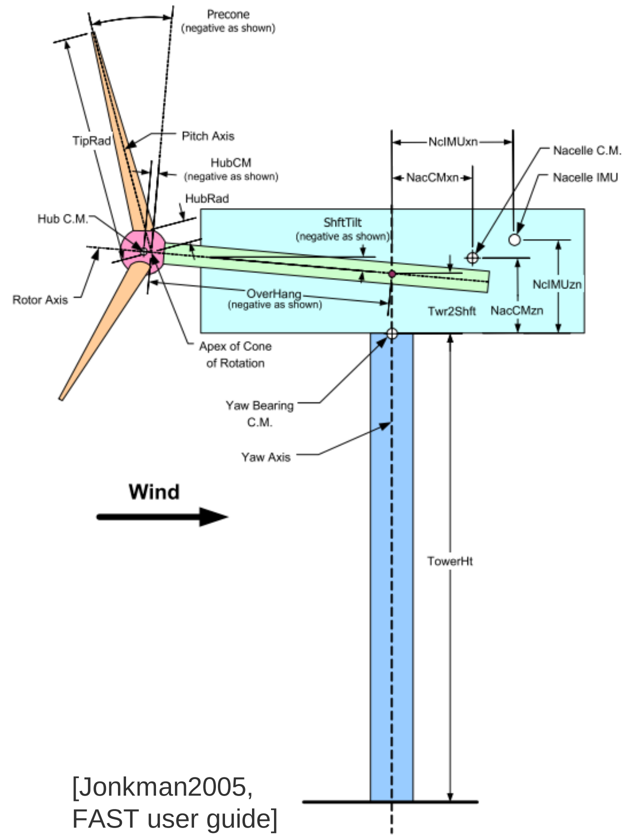
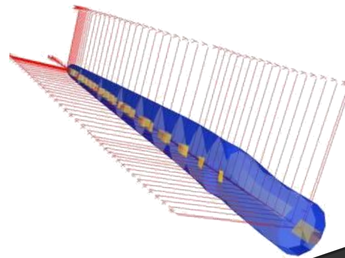


- Nonlinear time-domain
- Linearization

[Jonkman2005, FAST user guide]

- Two/three bladed
- Upwind/downwind
- Onshore/Offshore

Motivation: User-Defined Multibody System Topology



Automated Equations of Motion

User-defined fidelity level

Innovative designs

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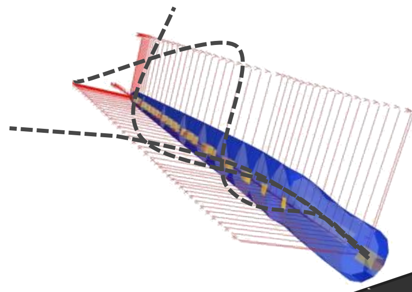

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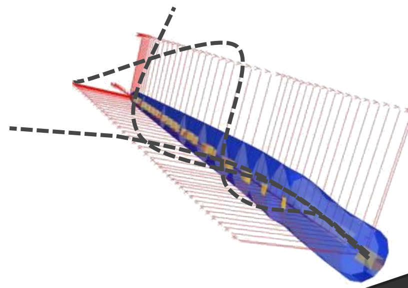

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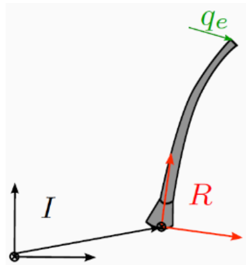
Methodology: Newton-Euler Formalism

1. Topology definition:
   - Reference frame position, angular velocity
   - Distributed mass, elasticity



Automated Equations of Motion

Schiehlen, W., & Eberhard, P. (2014). *Applied Dynamics* (1st ed.). https://doi.org/10.1007/978-3-319-07335-4

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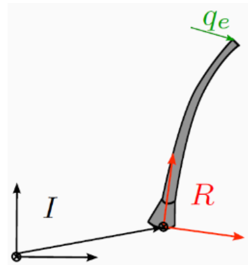
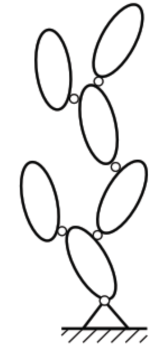
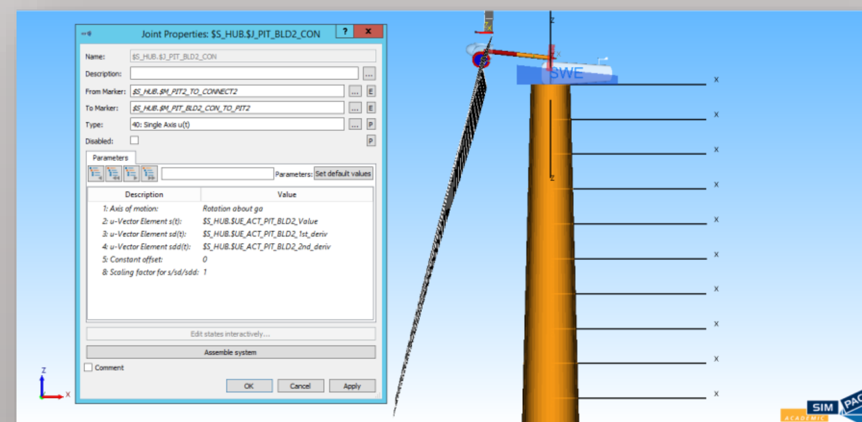




Automated Equations of Motion

Example from Simpack:



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Methodology: Newton-Euler Formalism

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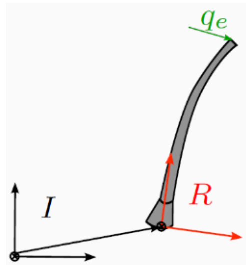
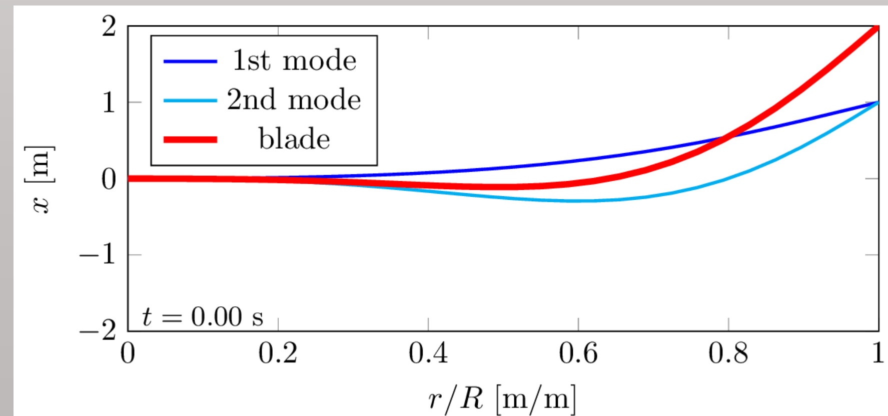


Automated Equations of Motion

Shape functions (by David Schlipf, WETI, HS Flensburg):



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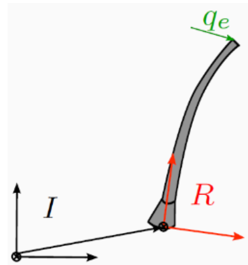

2. Newton-Euler Formalism

$$\underbrace{M\ddot{z}} + h_\omega = h_g + h_d + h_e + h_r$$

$$M\ddot{z} = \begin{bmatrix} m & & \text{sym.} \\ m\tilde{S}(c) & I & \\ C_t & C_r & M_e \end{bmatrix} \begin{bmatrix} {}^R a \\ {}^R \alpha \\ \ddot{q}_e \end{bmatrix}$$

body i

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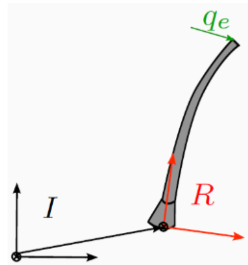

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Transformation

$$J = [J_{t,1}, J_{r,1}, J_{e,1}, \ldots, J_{t,p}, J_{r,p}, J_{e,p}]^T$$

3. Minimal coordinates

$$\overline{M}(q)\ddot{q} + \overline{h}_\omega(q,\dot{q}) = \overline{h}_g(q) + \overline{h}_d(q,\dot{q}) + \overline{h}_e(q_e)$$

Automated Equations of Motion

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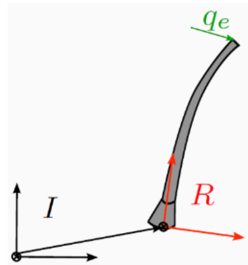

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$$q = \begin{bmatrix} x_p, & z_p, & \beta_p, & \varphi, & x_t, & \dots \end{bmatrix}^T$$

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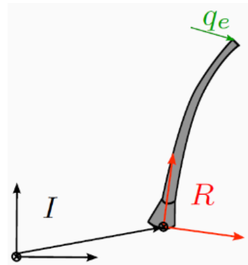

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Automated Equations of Motion

Result:
- ➢ Ordinary differential equation
- ➢ No constraint equations
- ➢ Combination of rigid + elastic bodies

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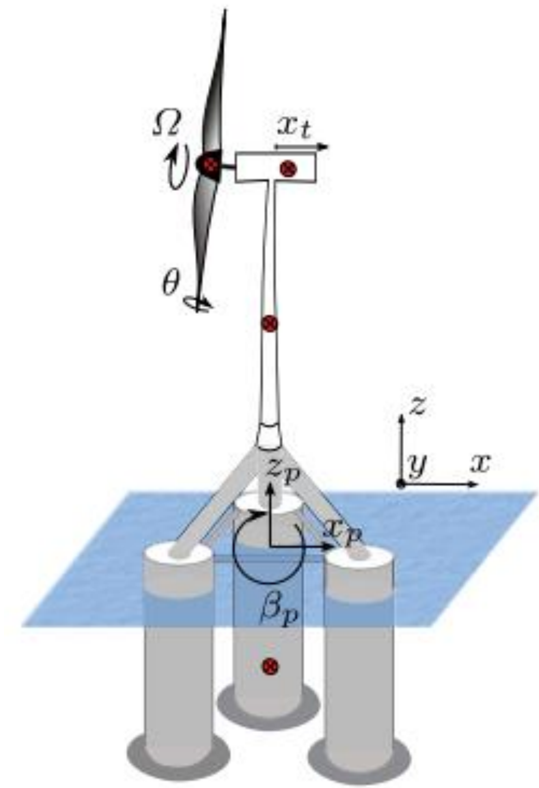
Methodology: Newton-Euler Formalism

Pre-existing in-house model SLOW:

- Purpose:
  - Low-order model (~5-10 DOFs)
  - Quick design load assessment (3600x real time)
  - Nonlinear & linear state-space
- Symbolic programming
- Matlab-based



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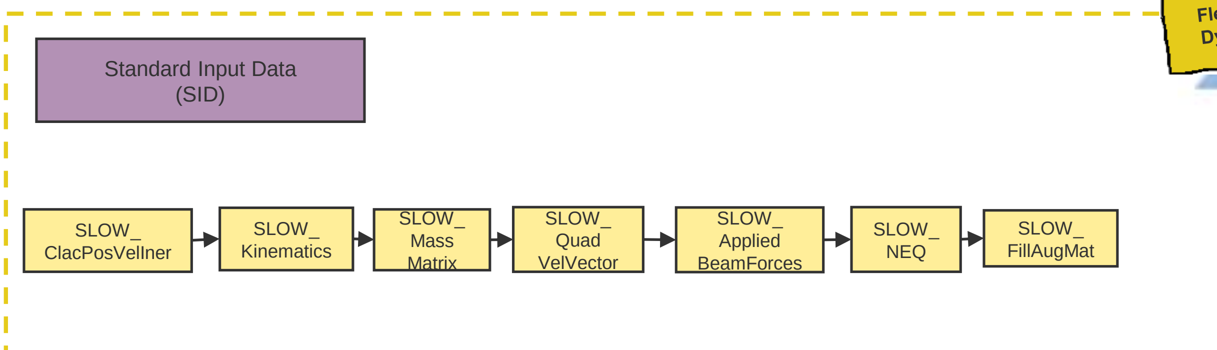

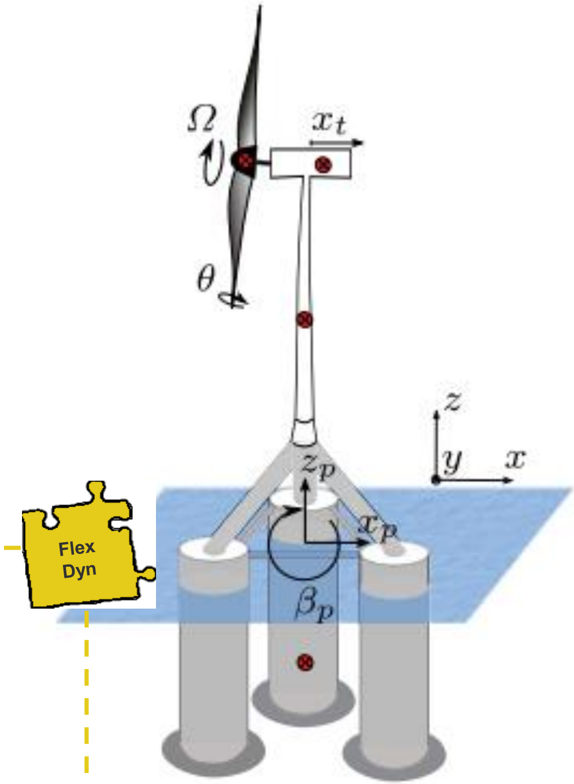

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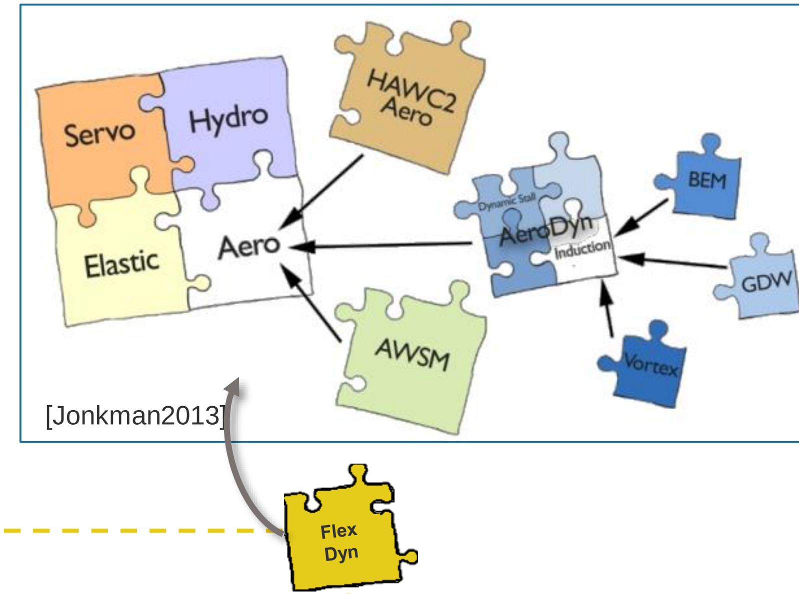
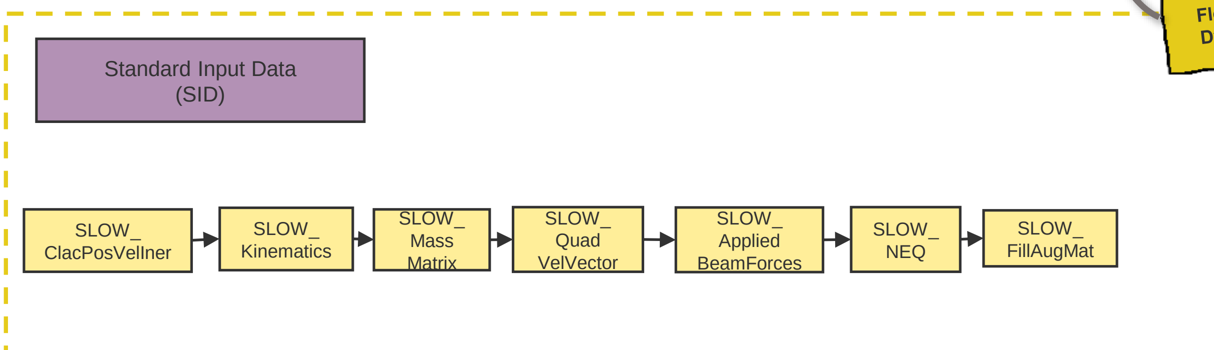


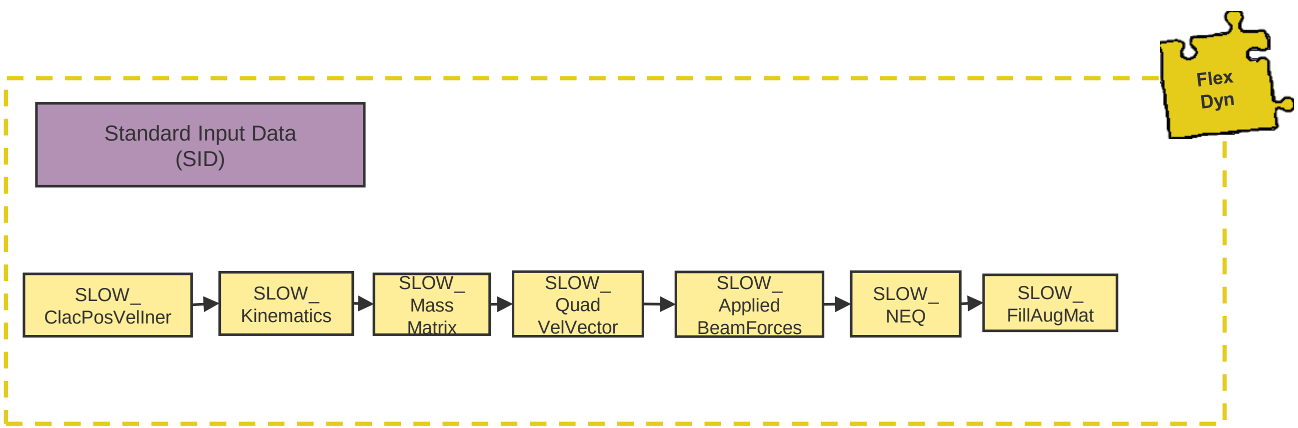
[Jonkman2013]



Use-Case: Blades with Torsion-DOF

Steps:

- User inputs:
  - Reference frame position, angular velocity
  - Distributed mass, elasticity



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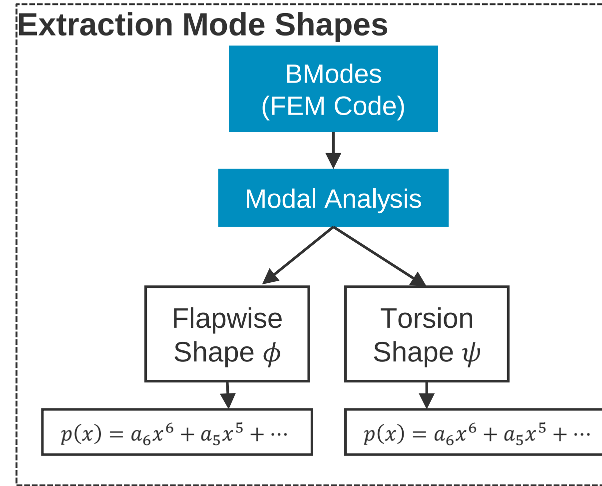
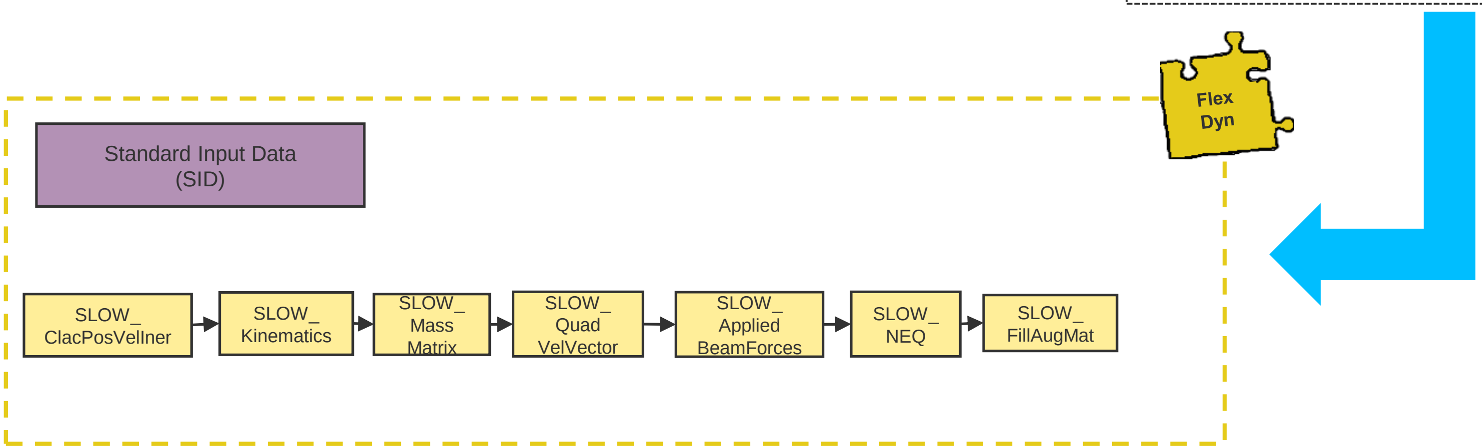
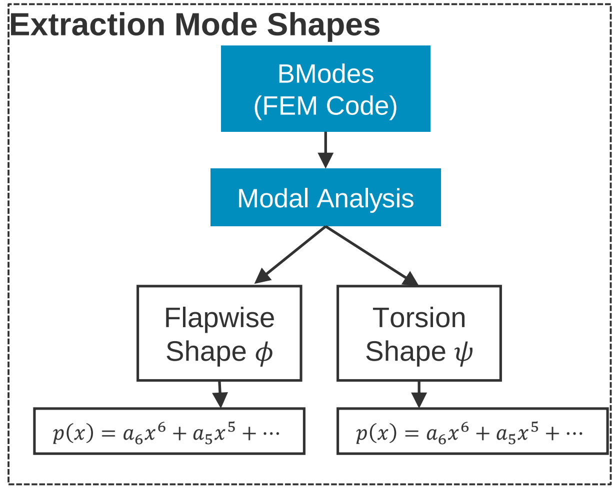


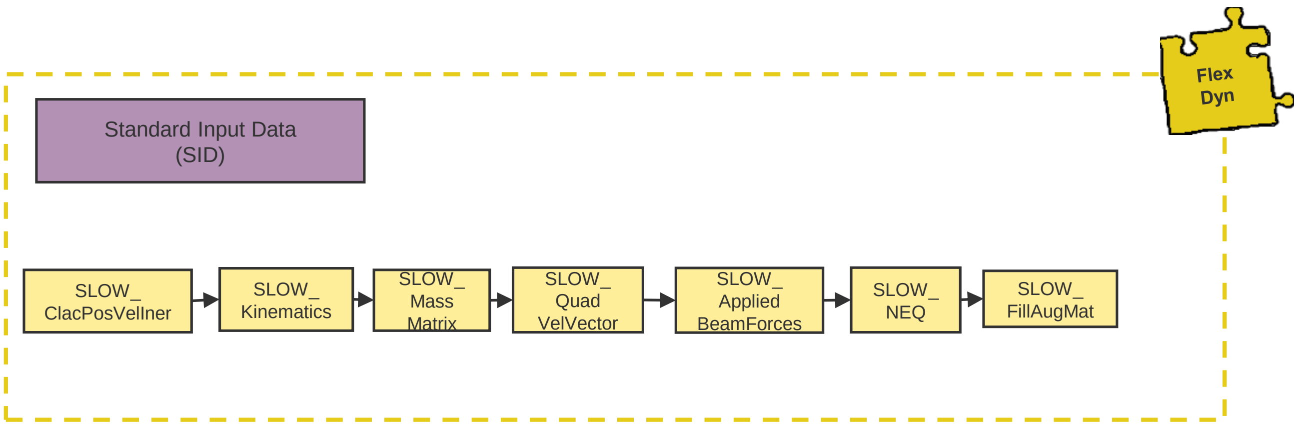


Use-Case: Blades with Torsion-DOF

Verification: FEM vs. Modal reduction

Model	Flapwise Frequency [Hz]	Error [%]
BModes	0.656	0.0
ElastoDyn	0.629	4.1
FlexDyn	0.620	5.5





Use-Case: Blades with Torsion-DOF

Steps:

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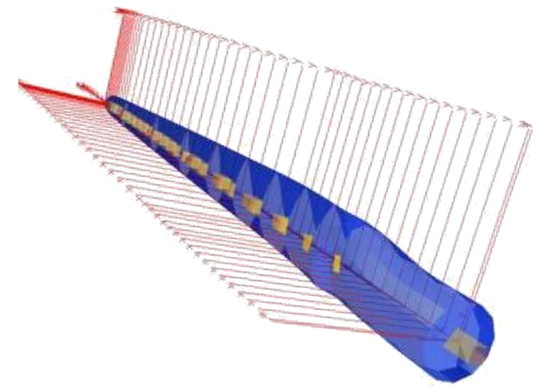
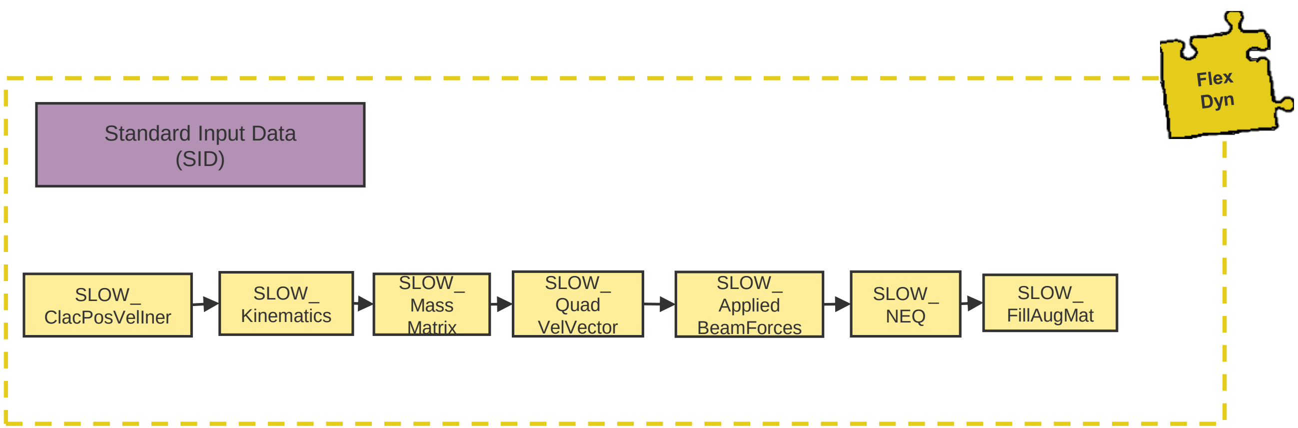
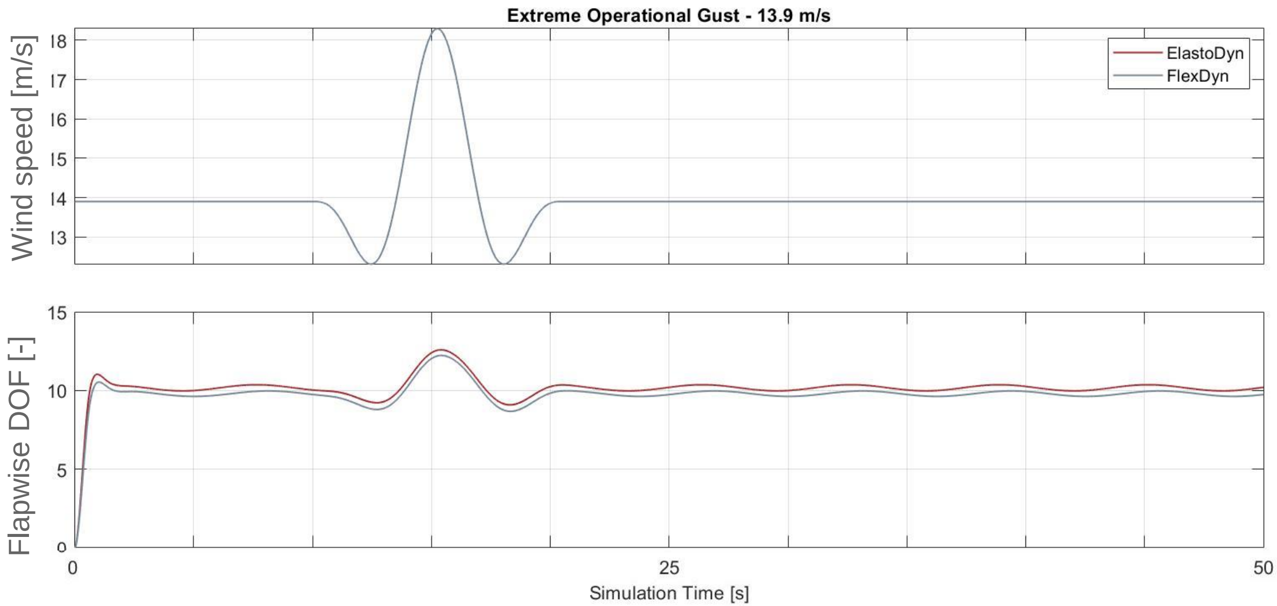
  - Shape functions
- AeroDyn: Generalized forces, kinematics





Verification ElastoDyn vs. FlexDyn

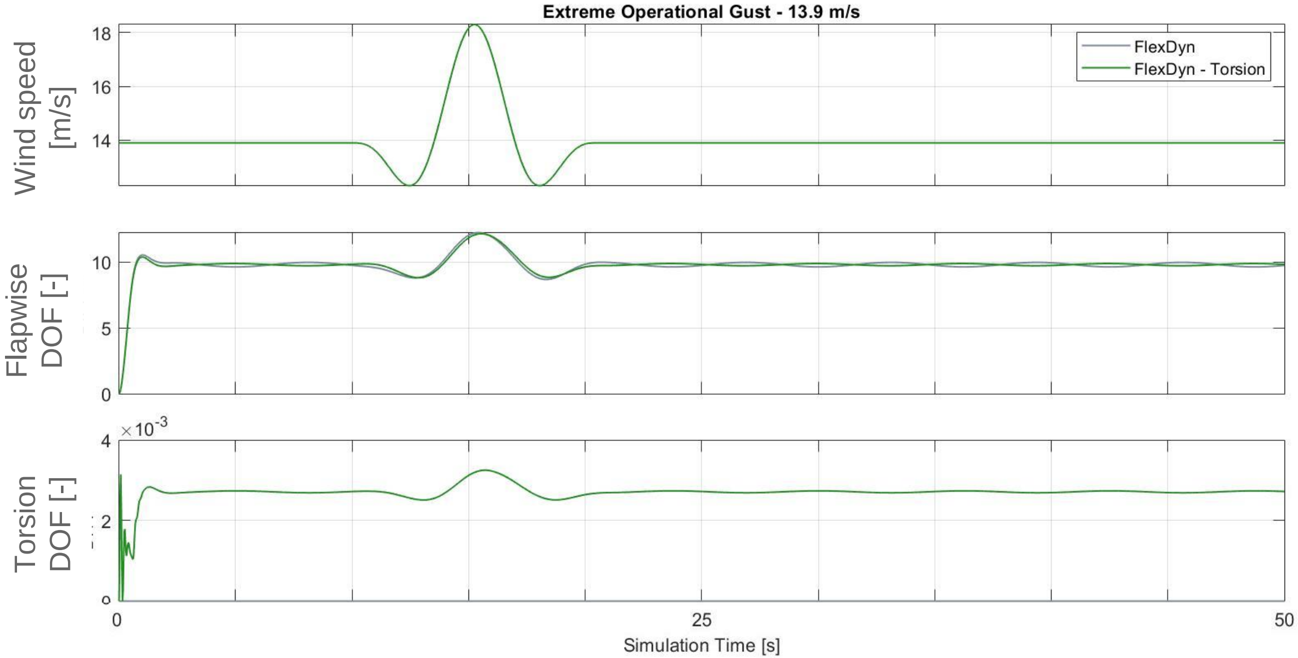
- Extreme Operating Gust:



➢ Good agreement of new FlexDyn with existing ElastoDyn

Comparison Blade Torsion FlexDyn

- Extreme Operating Gust:



➢ Successful implementation of blade torsion.

Summary & Conclusions

1. Newton-Euler formalism for Multibody Systems successfully implemented in OpenFAST framework
2. First verifications show good agreement with existing ElastoDyn
3. Added torsional degree of freedom with plausible results

- Next steps:
  - Verification
  - OpenFAST Modularization framework
  - Investigate potential to add FlexDyn into OpenFAST
  - Evaluate options for 3D shape functions
  - Incorporate Finite Element bodies into Multibody Equations

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Thank you!

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ZIM
Zentrales Innovationsprogramm Mittelstand

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