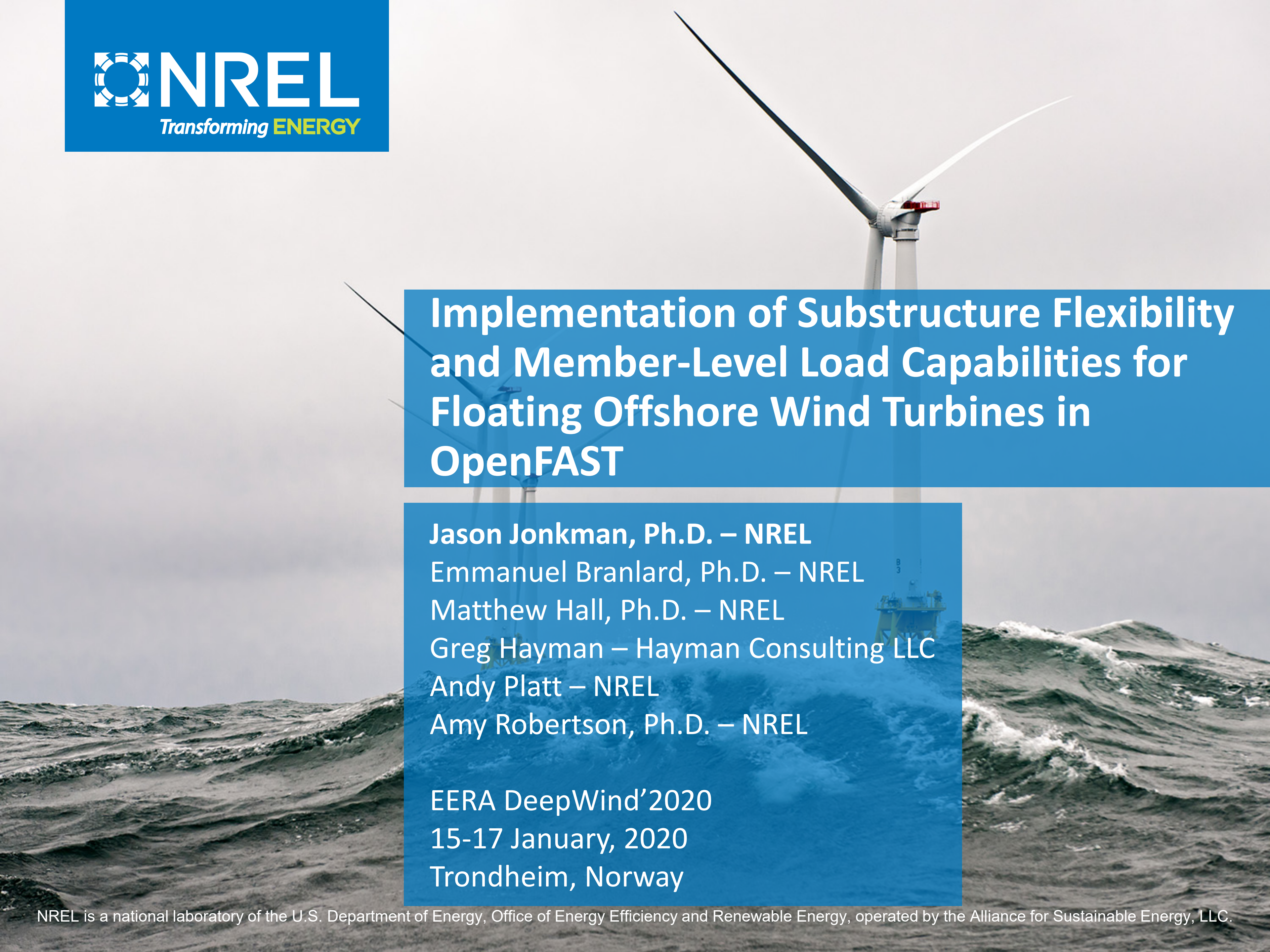

NREL
Transforming ENERGY

Implementation of Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST

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EERA DeepWind'2020
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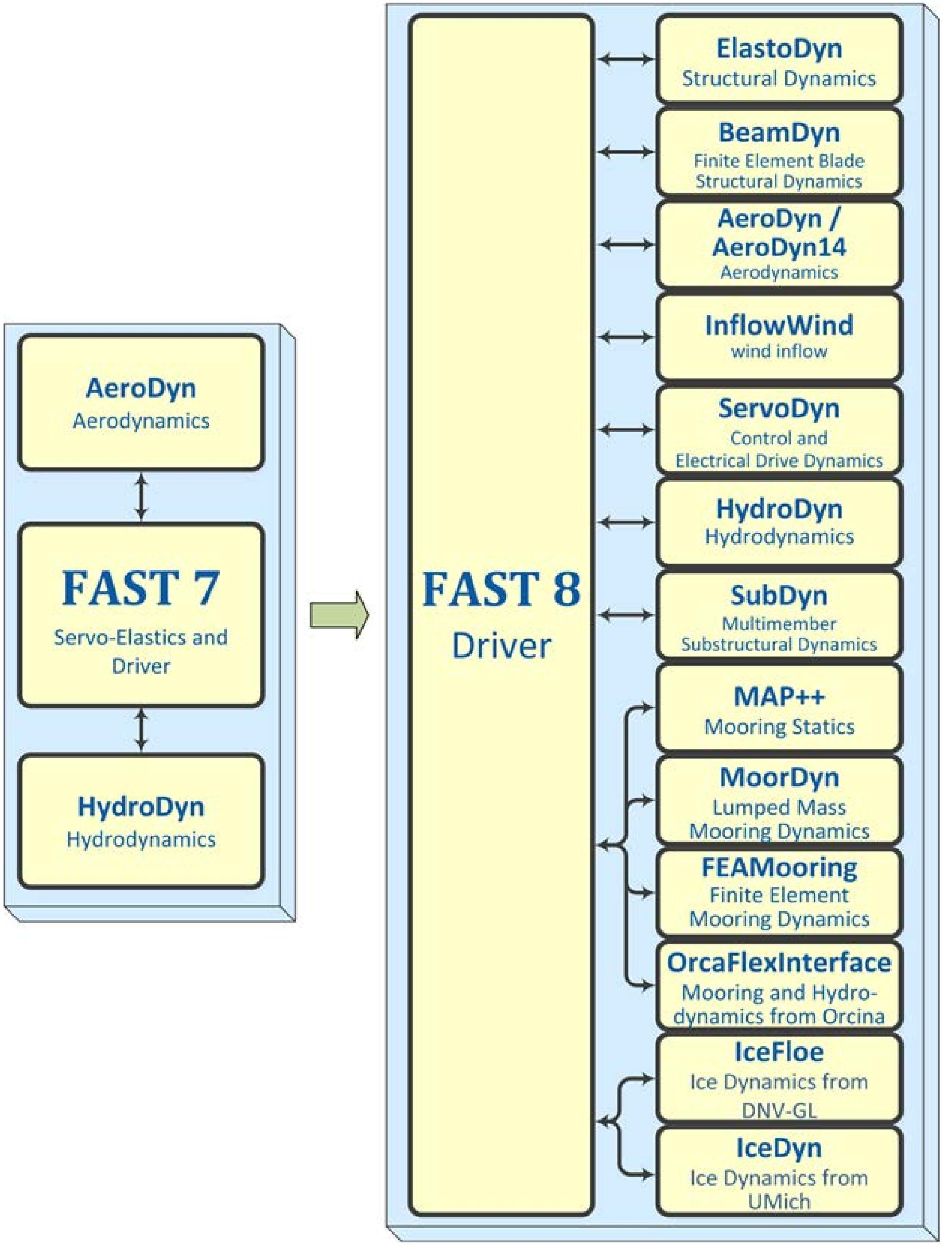
Trondheim, Norway

OpenFAST Overview

- **OpenFAST** is DOE / NREL's premier open-source wind turbine physics-based engineering tool
- **FAST** has undergone a major restructuring, with a new modularization framework (v8)
- Not only is the framework supporting expanded functionality, but it is facilitating the establishment of an open-source code-development community for physics-based engineering models (**OpenFAST**)



Prior Offshore Functionality

HydroDyn module – Hydrodynamics for fixed & floating substructures:

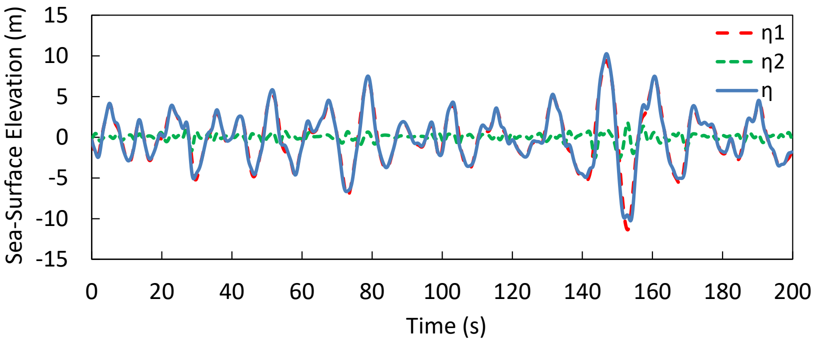
- Waves – 2nd order regular / irregular & directional spreading
- Sea currents
- Hydrodynamic loads – Hybrid combination of strip theory (Morison's eq.) & potential flow

SubDyn module – Fixed substructure structural dynamics:

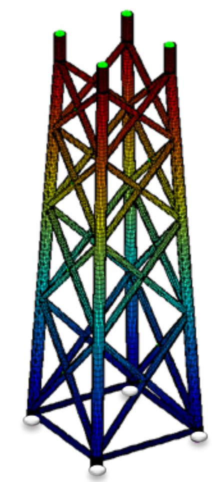
- Linear frame finite-element beam model
- Craig-Bampton dynamic system reduction
- Static-improvement method

MoorDyn & **MAP++** modules – Lumped mass mooring dynamics (MD) or analytical mooring quasi-statics (MAP):

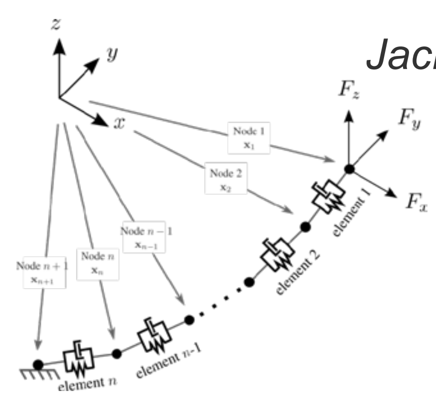
- Multi-segmented taut / catenary lines
- Clump weights & buoyancy tanks
- Elastic stretching & nonlinear geometric restoring
- Structural damping & hydro. drag (MD)
- Apparent weight of lines & added mass (MD)
- Seabed friction



Sea-Surface Elevation (η) from the Summing of 1st- (η_1) & 2nd- (η_2) Order Waves



Jacket Substructure



Lumped-Mass Mooring Dynamics

Objective & Approach

- *Objective*: Introduce substructure flexibility & member-level load calculations in **OpenFAST** to enable design & optimization of floating substructures—especially next-generation platforms that show promise to be streamlined, flexible, & cost-effective
- Prior work (IOWTC 2019):
  - Establish functional requirements
  - Identify modeling approaches that address functional requirements
  - Approach:
    - Meet modeling needs of most FOWT support structures (spar, semi, TLP)
    - Review existing FOWT prototypes & proposed concepts
    - Identify physics-based modeling needs
    - Only consider modeling approaches that maintain computational efficiency
- This work:
  - Mathematical details
  - Changes to **SubDyn**, **HydroDyn**, & **OpenFAST glue code**
- Future work:
  - Source-code implementation (nearing completion)
  - Verification & validation in collaboration w/ Stiesdal
  - Applications

SubDyn – New Element Types (In Addition to Beams)

- Pretensioned cable element:
  - Important for hanging ballast & stiffeners
- Rigid-link element:
  - Important for large-volume members & high natural frequencies
  - Direct elimination of linear multipoint constraints:
    – ODEs instead of DAEs
  - Eliminate 6 DOFs per element

$$\epsilon_0 = \frac{T_0}{EA}$$

$$\mathrm{K}_e = \frac{EA}{L_0}\begin{bmatrix} \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\ 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\ 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix} \qquad \mathrm{f}_e = EA\epsilon_0 \begin{Bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ -1 \end{Bmatrix}$$

Pretensioned Cable Element (Mass not Shown)

Full set

Reduced set

$$\mathrm{x} = \mathrm{T}\,\tilde{\mathrm{x}}$$

Reduction of global mass, stiffness & force

$$\widetilde{\mathrm{M}} = \mathrm{T}^{\mathrm{T}}\mathrm{M}\mathrm{T}, \quad \widetilde{\mathrm{K}} = \mathrm{T}^{\mathrm{T}}\mathrm{K}\mathrm{T}, \quad \widetilde{\mathrm{F}} = \mathrm{T}^{\mathrm{T}}\mathrm{F}$$

$$\mathrm{T}_c = \begin{bmatrix} \mathrm{I}_6 \\ \mathrm{A}_{12} \\ \vdots \\ \mathrm{A}_{1n} \end{bmatrix}, \quad \text{with } \mathrm{A}_{1j} = \begin{bmatrix} 1 & 0 & 0 & 0 & (z_j - z_1) & -(y_j - y_1) \\ 0 & 1 & 0 & -(z_j - z_1) & 0 & (x_j - x_1) \\ 0 & 0 & 1 & (y_j - y_1) & -(x_j - x_1) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Rigid-Link Element

SubDyn – New Rotational Joints (In Addition to Cantilevered)

- Introduced 3 new joint types:
  - Important for some floaters (e.g., TetraSpar & SpiderFloat)
  - Direct elimination of linear multipoint constraints:
    – ODEs instead of DAEs
  - Pin – Adds 1 DOF per beam @ joint (minus 1)
  - Universal – Adds 2 DOF per beam @ joint (minus 1)
  - Ball – Adds 3 DOF per beam @ joint (minus 1)

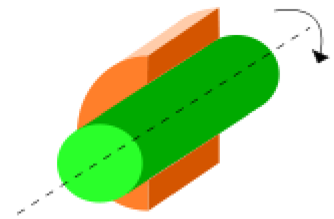
Full set

$$\mathrm{x} = \mathrm{T}\,\tilde{\mathrm{x}}$$

Reduced set

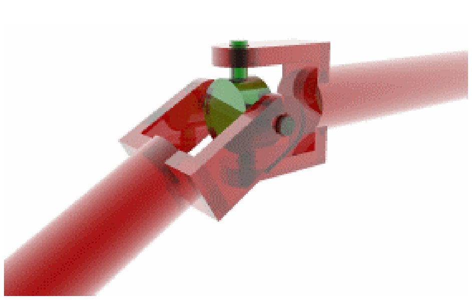
Reduction of global mass, stiffness & force

$$\tilde{\mathrm{M}} = \mathrm{T}^{\mathrm{T}}\mathrm{M}\mathrm{T}, \quad \tilde{\mathrm{K}} = \mathrm{T}^{\mathrm{T}}\mathrm{K}\mathrm{T}, \quad \tilde{\mathrm{F}} = \mathrm{T}^{\mathrm{T}}\mathrm{F}$$



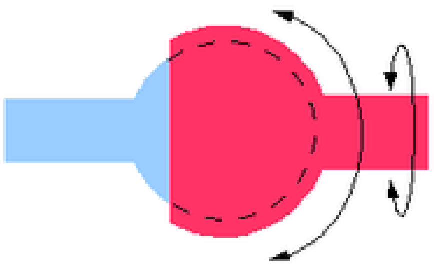
$$\mathrm{T}_c = \begin{bmatrix} \hat{\mathrm{p}}_1^T/n & \cdots & \hat{\mathrm{p}}_1^T/n \\ \hat{\mathrm{p}}_2^T/n & \cdots & \hat{\mathrm{p}}_2^T/n \\ \hat{\mathrm{p}}^t & & 0 \\ & \ddots & \\ 0 & & \hat{\mathrm{p}}^t \end{bmatrix}^{-1*}$$

Pin Joint



$$\mathrm{T}_c = \begin{bmatrix} \hat{\mathrm{z}}_{e_1}^T/n & \cdots & \hat{\mathrm{z}}_{e_n}^T/n \\ \hat{\mathrm{x}}_{e_1}^T & & 0 \\ \hat{\mathrm{y}}_{e_1}^T & & 0 \\ 0 & \ddots & 0 \\ 0 & & \hat{\mathrm{x}}_{e_n}^T \\ 0 & \cdots & \hat{\mathrm{y}}_{e_n}^T \end{bmatrix}^{-1*}$$

Universal Joint

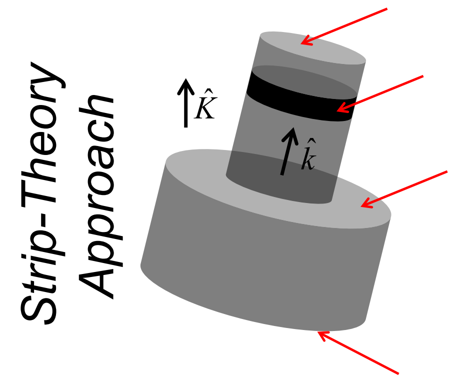


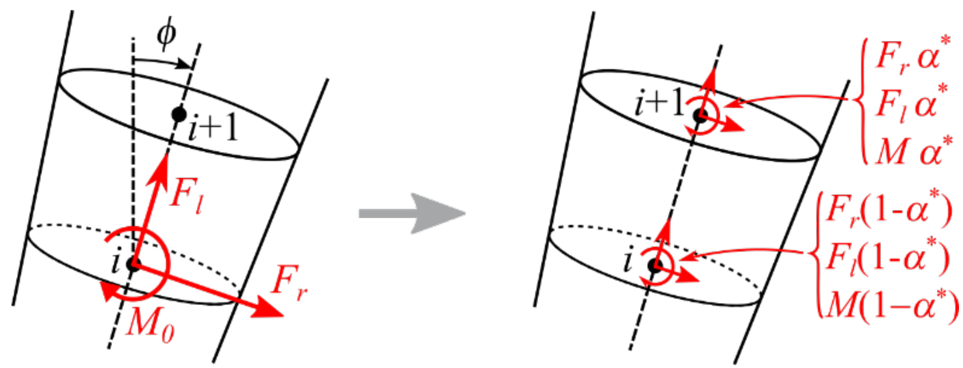
$$\mathrm{T}_c = \begin{bmatrix} \mathrm{I}_3 & & 0 \\ & \ddots & \\ 0 & & \mathrm{I}_3 \end{bmatrix}$$

Ball Joint

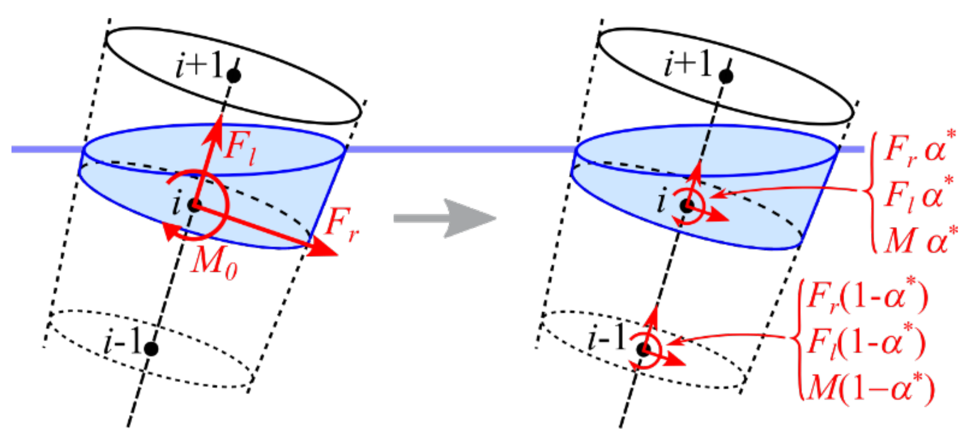
HydroDyn – Updated Member-Level Hydrostatics in Strip-Theory

- Important for slender structures @ member level
- Updated strip-theory buoyancy calculation:
  - Exact for cylindrical or tapered members
  - Based on integrated hydrostatic pressure on submerged surface area
  - Dependent on displacement & deflection
  - Forces distributed to analysis nodes, including smoothing to ensure forces don't "step" when crossing SWL





Loads on a Fully Submerged Element



Loads on a Partially Submerged Element

HydroDyn – Support for Multiple Potential Flow Bodies

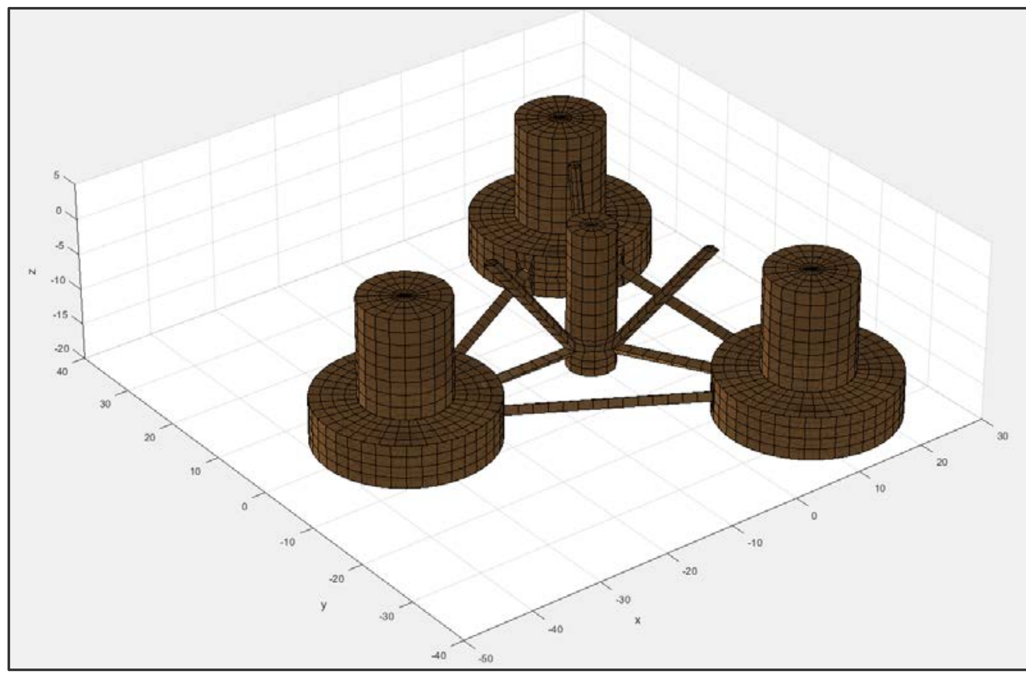
- Important for multiple large-volume bodies w/ radiation & diffraction
- Optional inclusion of hydrodynamic interaction:
  - “NBody” option in **WAMIT** or separate single bodies
- New “NBodyMod” switch:
  1) Full hydrodynamic interaction between bodies
  2) Separate bodies, each centered @ origin:
     – Offsets (phase shift) included in **HydroDyn**
  3) Separate bodies, each located @ correct offset in floater

$$\vec{F}^{Radiation}(t) = -\mathbf{A}^{\infty}\,\ddot{\vec{q}}(t) - \int_0^t \mathbf{K}(t-\tau)\,\dot{\vec{q}}(\tau)\,d\tau$$

$$\begin{bmatrix} \vec{F}_1^{Radiation}(t) \\ \vec{F}_2^{Radiation}(t) \\ \vdots \\ \vec{F}_N^{Radiation}(t) \end{bmatrix} = -\begin{bmatrix} \mathbf{A}_{11}^{\infty} & \mathbf{A}_{12}^{\infty} & \cdots & \mathbf{A}_{1N}^{\infty} \\ \mathbf{A}_{21}^{\infty} & \mathbf{A}_{22}^{\infty} & \cdots & \mathbf{A}_{2N}^{\infty} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{N1}^{\infty} & \mathbf{A}_{N2}^{\infty} & \cdots & \mathbf{A}_{NN}^{\infty} \end{bmatrix} \begin{bmatrix} \ddot{\vec{q}}_1(t) \\ \ddot{\vec{q}}_2(t) \\ \vdots \\ \ddot{\vec{q}}_N(t) \end{bmatrix} - \int_0^t \begin{bmatrix} \mathbf{K}_{11}(t-\tau) & \mathbf{K}_{12}(t-\tau) & \cdots & \mathbf{K}_{1N}(t-\tau) \\ \mathbf{K}_{21}(t-\tau) & \mathbf{K}_{22}(t-\tau) & \cdots & \mathbf{K}_{2N}(t-\tau) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{K}_{N1}(t-\tau) & \mathbf{K}_{N2}(t-\tau) & \cdots & \mathbf{K}_{NN}(t-\tau) \end{bmatrix} \begin{bmatrix} \dot{\vec{q}}_1(\tau) \\ \dot{\vec{q}}_2(\tau) \\ \vdots \\ \dot{\vec{q}}_N(\tau) \end{bmatrix} d\tau$$

or

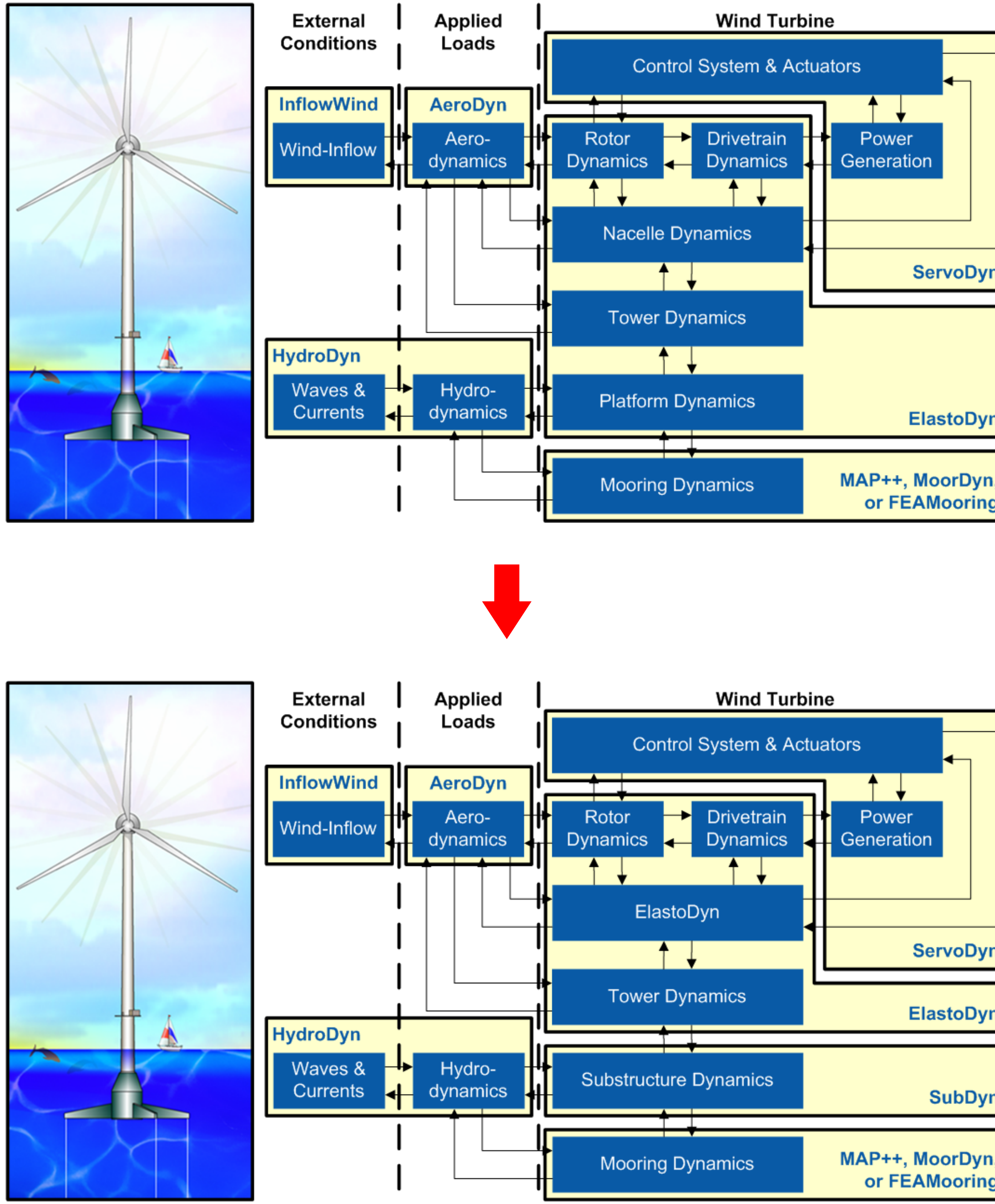
$$\begin{bmatrix} \vec{F}_1^{Radiation}(t) \\ \vec{F}_2^{Radiation}(t) \\ \vdots \\ \vec{F}_N^{Radiation}(t) \end{bmatrix} = -\begin{bmatrix} \mathbf{A}_{11}^{\infty} & 0 & \cdots & 0 \\ 0 & \mathbf{A}_{22}^{\infty} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{NN}^{\infty} \end{bmatrix} \begin{bmatrix} \ddot{\vec{q}}_1(t) \\ \ddot{\vec{q}}_2(t) \\ \vdots \\ \ddot{\vec{q}}_N(t) \end{bmatrix} - \int_0^t \begin{bmatrix} \mathbf{K}_{11}(t-\tau) & 0 & \cdots & 0 \\ 0 & \mathbf{K}_{22}(t-\tau) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{K}_{NN}(t-\tau) \end{bmatrix} \begin{bmatrix} \dot{\vec{q}}_1(\tau) \\ \dot{\vec{q}}_2(\tau) \\ \vdots \\ \dot{\vec{q}}_N(\tau) \end{bmatrix} d\tau$$



WAMIT Mesh of OC4-DeepCWind Semisubmersible

OpenFAST Glue Code – Updated Module-to-Module Coupling

- Allow **SubDyn** to be enabled for floating (in addition to fixed)
- Couple tower-substructure-hydrodynamic-mooring dynamics (**ElastoDyn – SubDyn – HydroDyn –** Mooring)



OpenFAST Glue Code – Updated Full-System Linearization

- **OpenFAST** primary used for nonlinear time-domain loads analysis (ultimate & fatigue)
- Linearization is about <u>*understanding*</u>:
  - Useful for eigenanalysis, controls design, stability analysis, gradients for optimization, & development of reduced-order models
- Prior focus:
  - Structuring source code to enable linearization
  - Developing general approach to linearizing mesh-mapping w/n module-to-module input-output coupling relationships, including rotations
  - Linearizing core (but not all) features of **InflowWind**, **ServoDyn**, **ElastoDyn**, **BeamDyn**, **AeroDyn**, **HydroDyn**, & **MAP++** modules & their coupling
  - Verifying implementation
- This work:
  - Expanding linearization of **HydroDyn** to strip-theory hydrostatics & state-space-based wave excitation & radiation for multiple bodies
  - Linearizing all features of **SubDyn**
  - Including linearized **ElastoDyn-SubDyn-HydroDyn-MAP++** coupling in the **OpenFAST glue code**

$$\dot{x} = X\left(x,z,u,t\right)$$

$$0 = Z\left(x,z,u,t\right) \quad with \left|\frac{\partial Z}{\partial z}\right| \neq 0$$

$$y = Y\left(x,z,u,t\right)$$

$$u = u\big|_{op} + \Delta u \quad etc.$$

$$\Delta\dot{x} = A\Delta x + B\Delta u$$

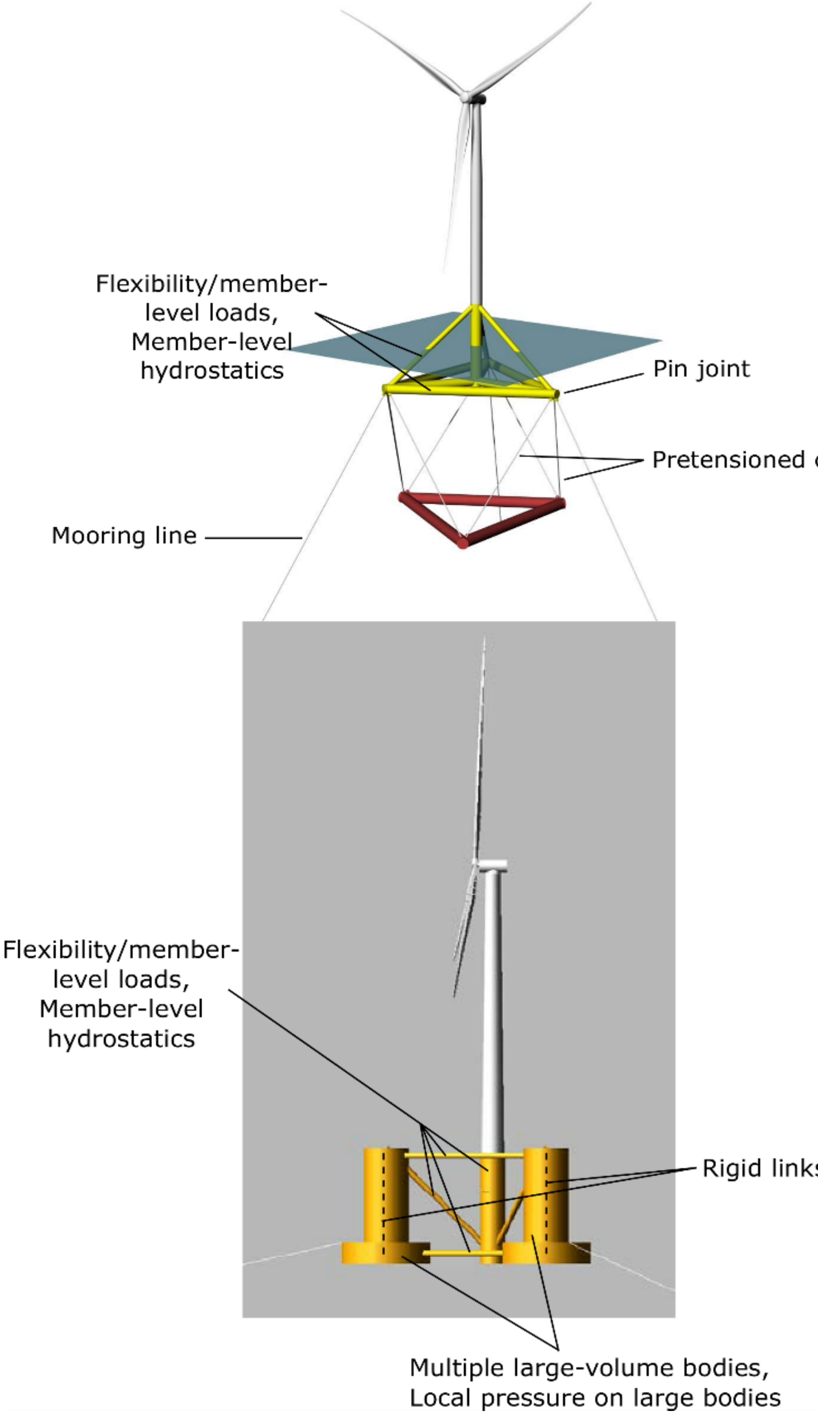
$$\Delta y = C\Delta x + D\Delta u$$

with

$$A = \left[\frac{\partial X}{\partial x} - \frac{\partial X}{\partial z}\left[\frac{\partial Z}{\partial z}\right]^{-1}\frac{\partial Z}{\partial x}\right]\Bigg|_{op} \quad etc.$$

Closing Summary

- Next generation FOWT likely to be more streamlined, flexible, & cost-effective
- Floating flexibility & member-level loads introduced into **OpenFAST**:
  - Substructure flexibility
  - Member-level loads
  - Pretensioned cables
  - Rigid links
  - Pin, universal, & ball joints
  - Distributed buoyancy on slender members
  - Multiple large-volume bodies
  - Time domain & linearization
- Coming soon: Verification, validation, & demonstration in collaboration w/ Stiesdal



Carpe Ventum!

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