Overview of Offshore Features of FAST – HydroDyn, SubDyn, & MAP

NREL Wind Turbine Modeling Workshop

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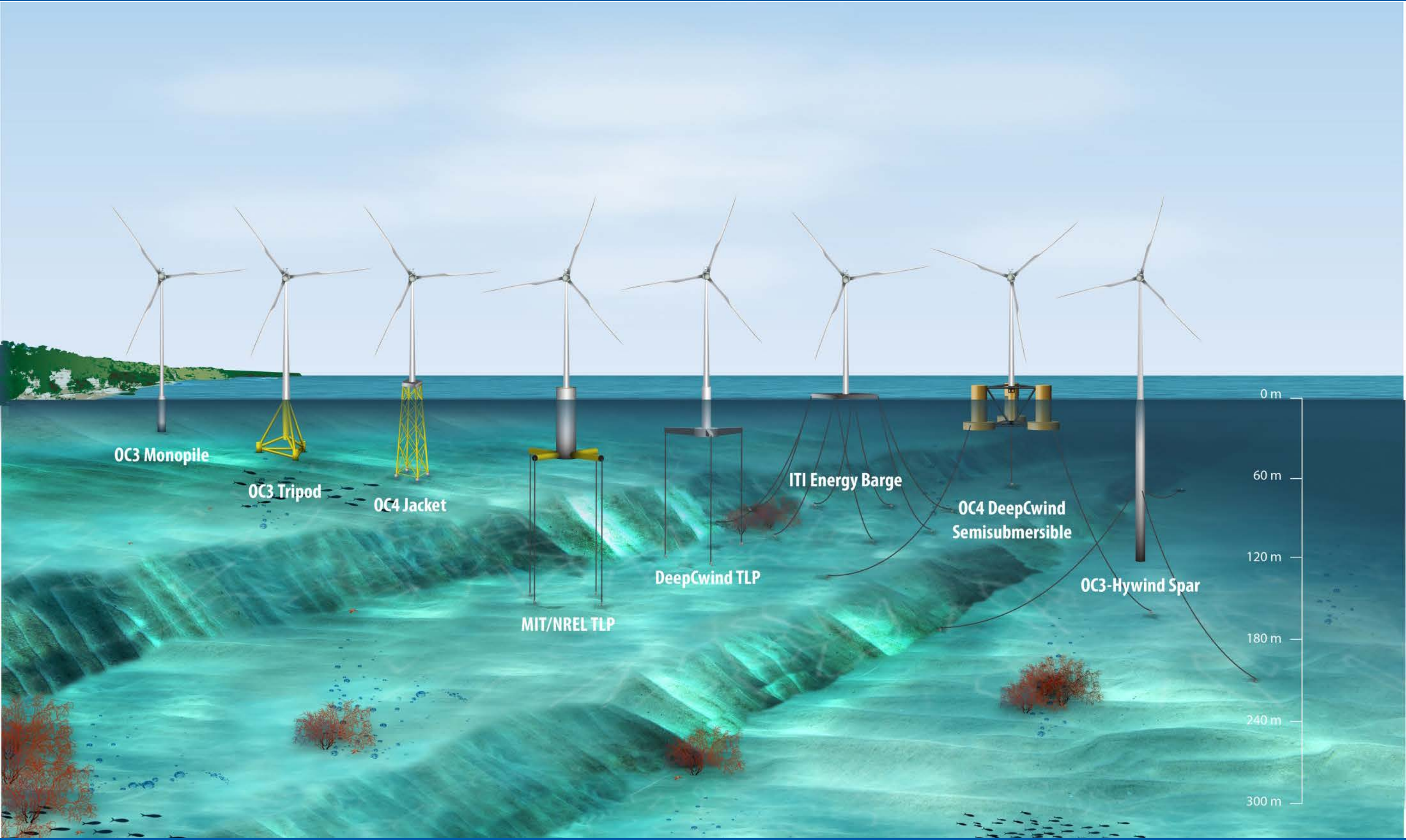
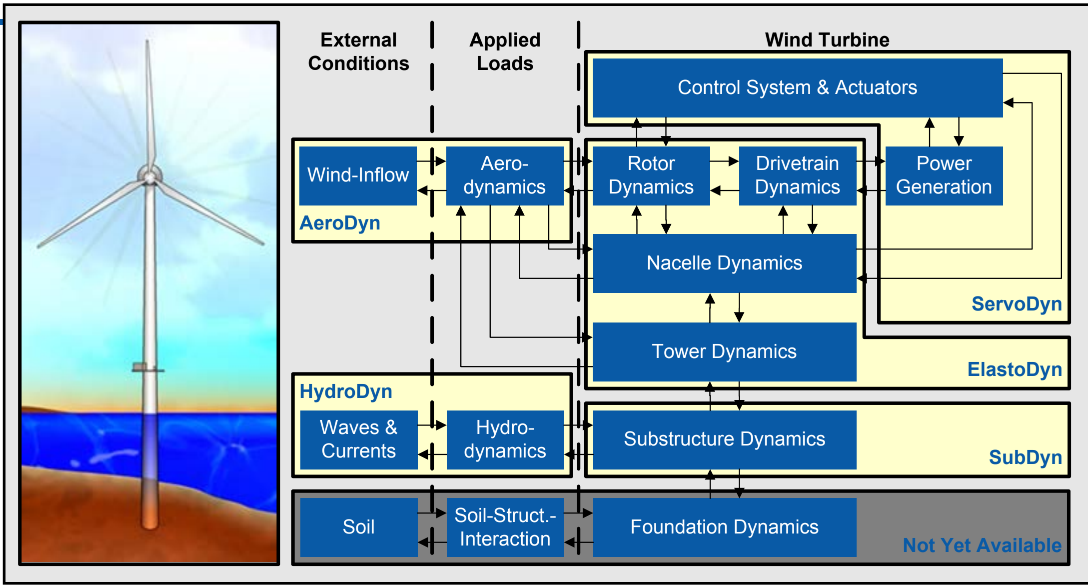
Introduction & Background

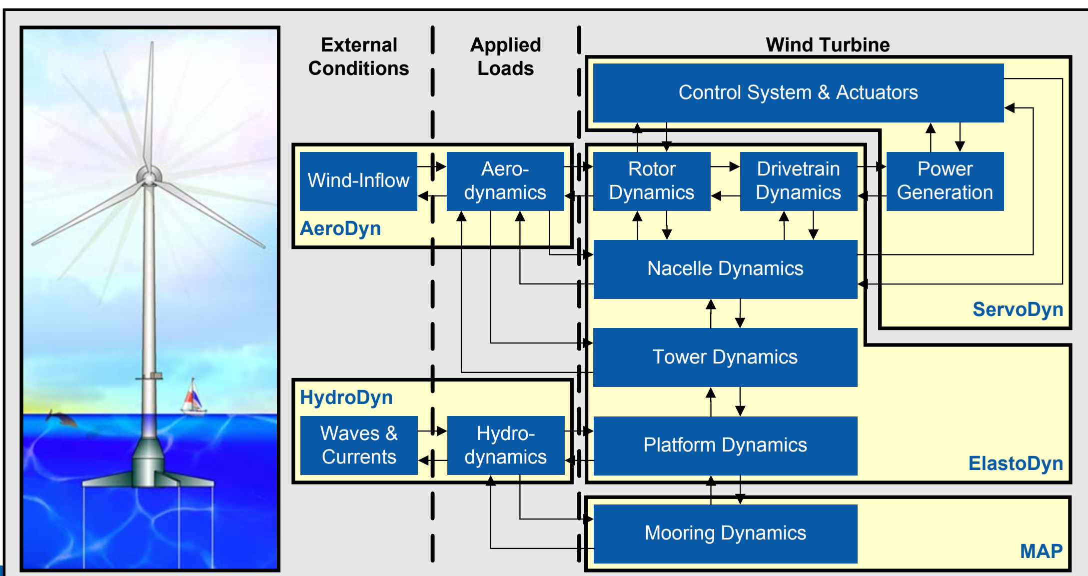
Support-Structure Types



Introduction & Background

Offshore Modules of FAST

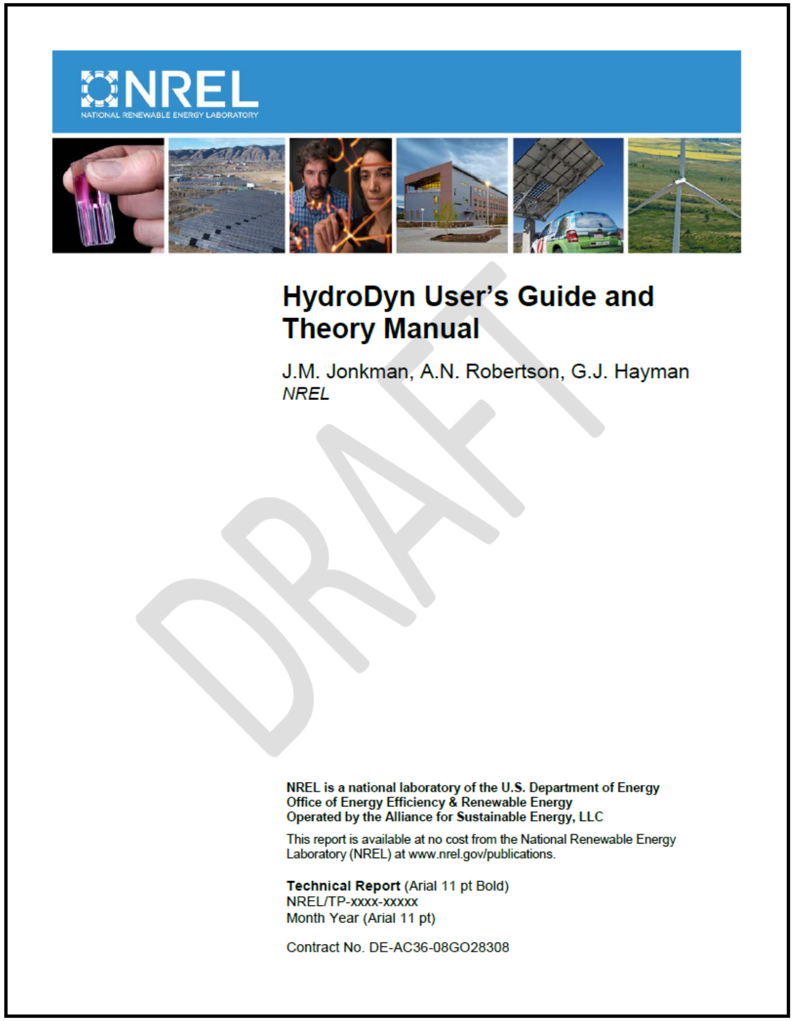




- **HydroDyn** – Offshore hydrodynamics for fixed-bottom & floating
- **SubDyn** – Fixed-bottom substructure structural dynamics
- **MAP** – Mooring quasi-statics
- Not presented:
  - **FEAMooring** – Mooring dynamics (under development)
  - **IceFloe** – Quasi-steady sea ice for fixed-bottom
  - **IceDyn** – Sea ice dynamics (under development)
  - **OrcaFlex-FAST** v7 coupling for mooring dynamics

HydroDyn
What Is It?

- Hydrodynamics module for offshore fixed-bottom & floating:
  - Used to be an undocumented part of **FAST**
  - Now split out as a callable module in the **FAST** framework with separate input files & source code
  - Also coupled to **SIMPACK** (original coupled to **MSC.ADAMS**)
- Latest version:
  - v2.01.01c-gjh (July 2014)
  - Newer in progress
- Documentation – HydroDyn User's Guide & Theory Manual (2014)
  - Theory section being updated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HydroDyn User's Guide and Theory Manual

J.M. Jonkman, A.N. Robertson, G.J. Hayman
NREL

DRAFT

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Contract No. DE-AC36-08GO28308

HydroDyn

Inputs, Outputs, States, & Parameters

Inputs:
- Substructure disp.
- Substructure vel.
- Substructure accel.

HydroDyn

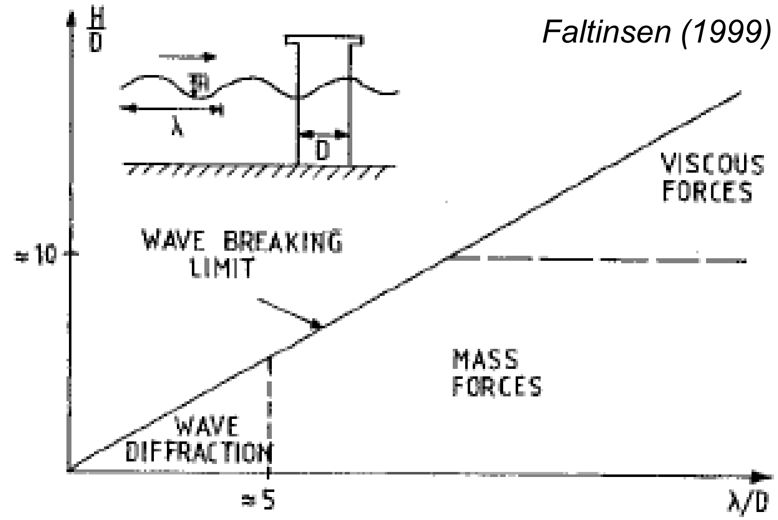
Continuous States:
- State-space-based radiation “memory”

Discrete States:
- Convolution-based radiation “memory”

Parameters:
- Geometry
- Hydrodynamic coefficients
- Undisturbed incident waves
- Water Density
- Gravity

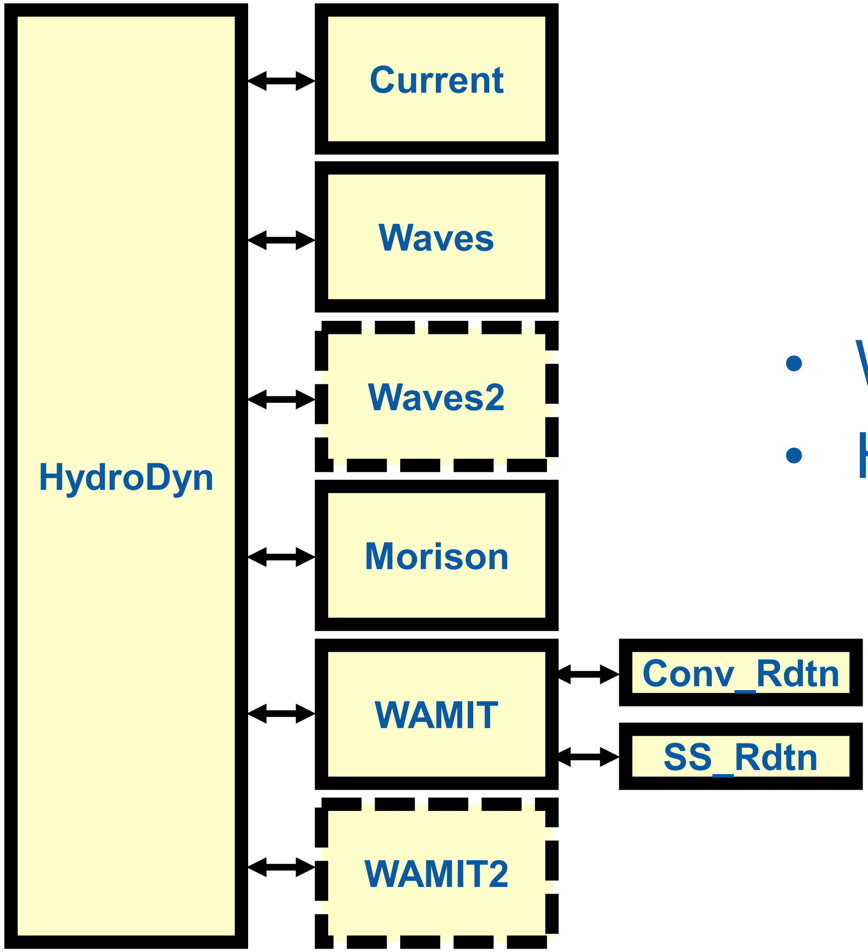
Outputs:
- Hydro. loads

HydroDyn
Submodel Options



Faltinsen (1999)

Relative Importance of Hydrodynamic Loads

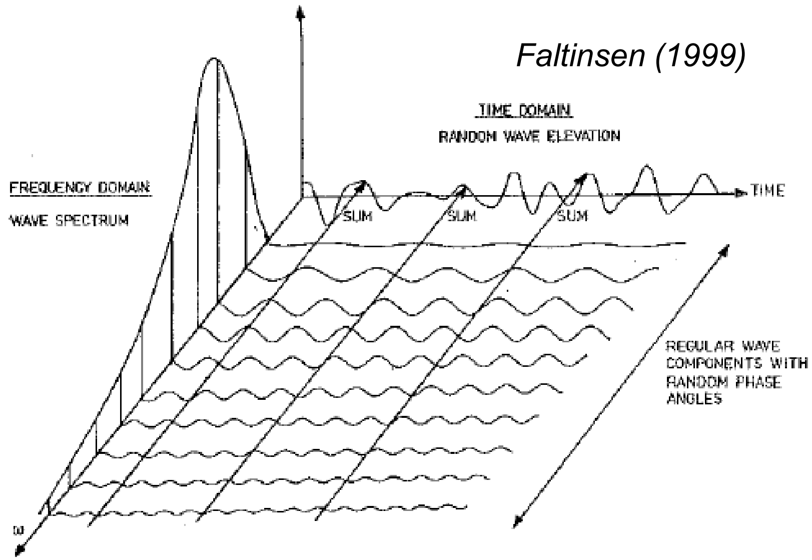


HydroDyn *Submodules*

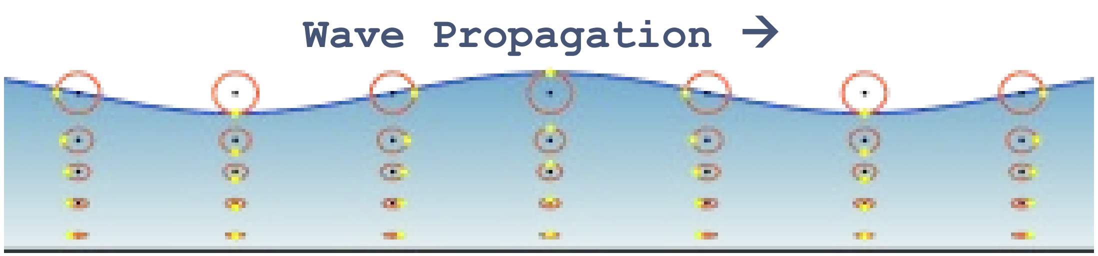
- Waves & Current
- Hydrodynamic loading:
  - Strip theory (Morison):
    - For “slender” members
    - Inertia, added mass, viscous, & buoyancy loads
  - Potential flow (**WAMIT**):
    - For “large” platforms
    - Radiation, diffraction, & buoyancy loads
  - Combination of these two

HydroDyn
Waves & Currents

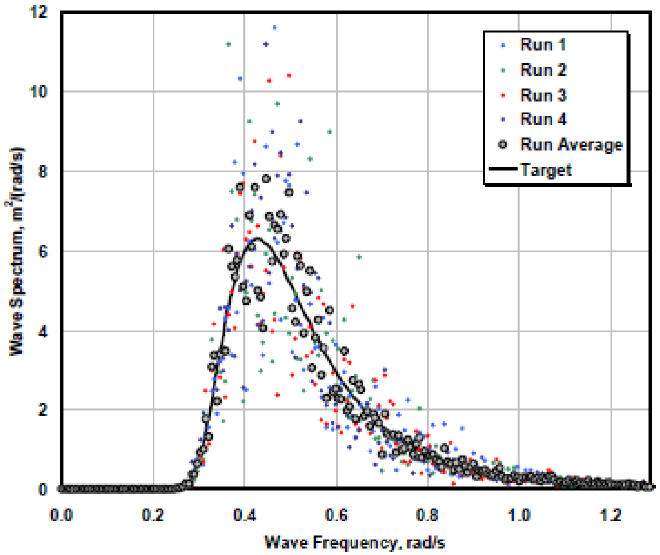
- Wave kinematics:
  - Linear (Airy) regular (periodic)
  - Linear (Airy) irregular (stochastic):
    - Pierson-Moskowitz, JONSWAP, white-noise, or user-defined spectrum
    - Optional randomly distributed amplitudes
    - Frequency-to-time-domain transforms implemented through FFT



Frequency-to-Time Domain Transform of Wave Elevation



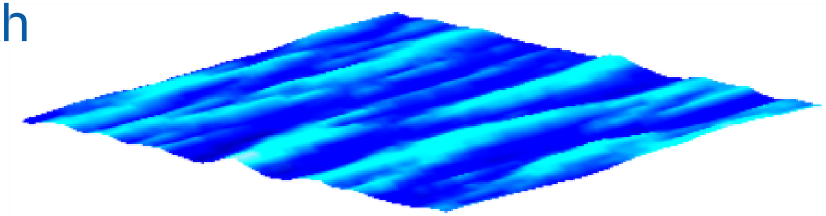
Orbital Wave Motion



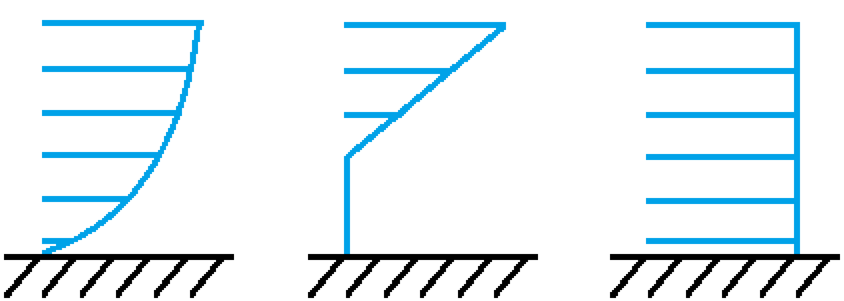
Wave Spectrum with Randomly Distributed Amplitudes

HydroDyn
Waves & Currents (cont)

- Wave kinematics (cont):
  - Arbitrary choice of wave direction with directional spreading implemented through an equal-energy method:
    - Uses a $COS()^{2S}$ spreading function
    - Requires $S(\omega,\beta) = S(\omega)D(\beta)$
  - 2nd-order terms (difference- & sum-frequency) coming soon
- Steady sea currents:
  - IEC-style sub-surface, near-surface, & depth-independent
  - Or user-defined
- Limitations:
  - No wave stretching*
  - No higher order theories
  - No time-varying current



Multi-Directional Sea State

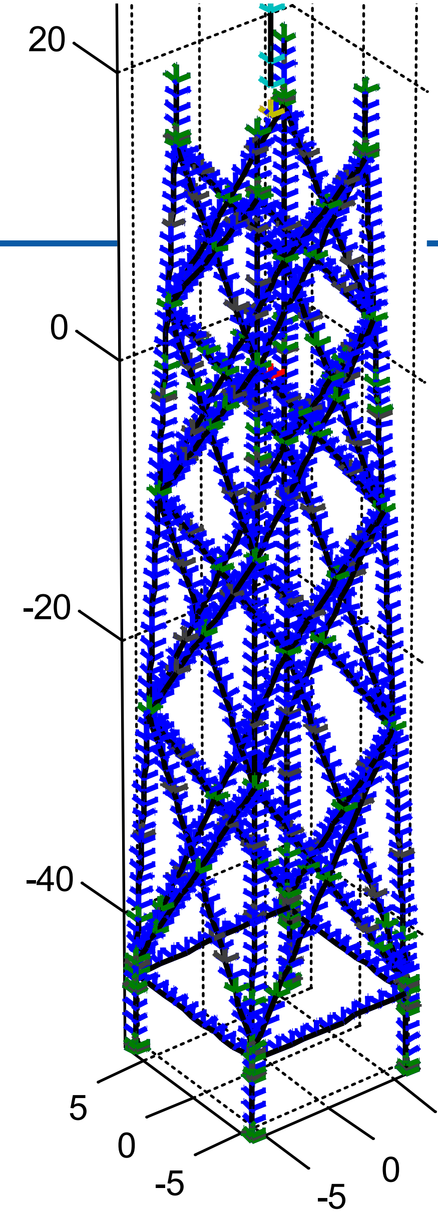


IEC Sea Currents

Available in* ***FAST* *v7, but not yet in v8*

HydroDyn
Strip Theory – Overview

- Features:
  - Multiple members with interconnections at joints
  - Inclined & tapered members
  - User-specified dynamic-pressure, added mass, & drag coefficients
  - Flooded & ballasted members
  - Marine growth
  - Rigid or flexible multi-member substructures
- Hydrodynamic loads:
  - Distributed inertia, added mass, & viscous drag (Morison)
  - Distributed axial loads on tapered members
  - Distributed static buoyancy
  - Concentrated loads at member ends
  - Derived directly from undisturbed wave & current kinematics @ undisplaced position
- Applicable to:
  - Fixed-bottom gravity base, monopile, tripod, or jacket substructures
  - Slender members (e.g., braces/spokes) of floating platforms

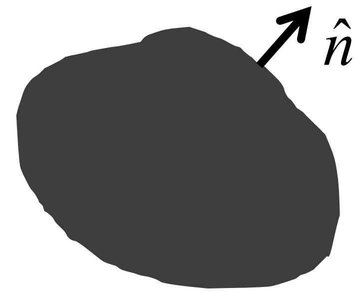


*OC4-Jacket Meshes – **HydroDyn** (Blue, Green, Red) & **SubDyn** (Gray)*

HydroDyn

Strip Theory – Loads on Small Bodies

$$\vec{F}_{Hydro} = \vec{F}_{Inertia} + \vec{F}_{AddedMass} + \vec{F}_{Drag} + \vec{F}_{Buoy}$$



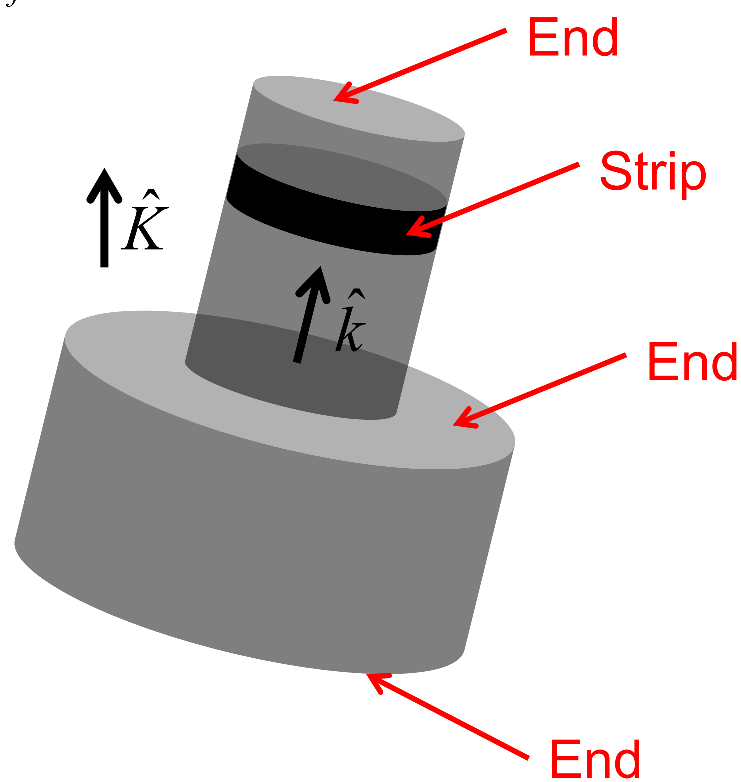
Froude-Kriloff　　Scattering

$$\vec{F}_{Inertia} = -\iint_A p_{dyn}\hat{n}dA + \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \vec{a}_f$$

$$\vec{F}_{AddedMass} = -\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \vec{a}_s$$

$$\vec{F}_{Drag} = \frac{1}{2} C_D \rho_f A_{ref} \left\| \vec{v}_{rel} \right\|_2 \vec{v}_{rel}$$

$$\vec{F}_{Buoy} = \iint_A \left(\rho_f g Z \right) \hat{n} dA$$



HydroDyn

Strip Theory – Loads on Member Strips

$$\vec{F}_{Hydro} = \vec{F}_{Inertia} + \vec{F}_{AddedMass} + \vec{F}_{Drag} + \vec{F}_{Buoy}$$

For a cylinder:
$C_P = 1$
$C_M = 1 + C_A$

Froude-Kriloff   Scattering

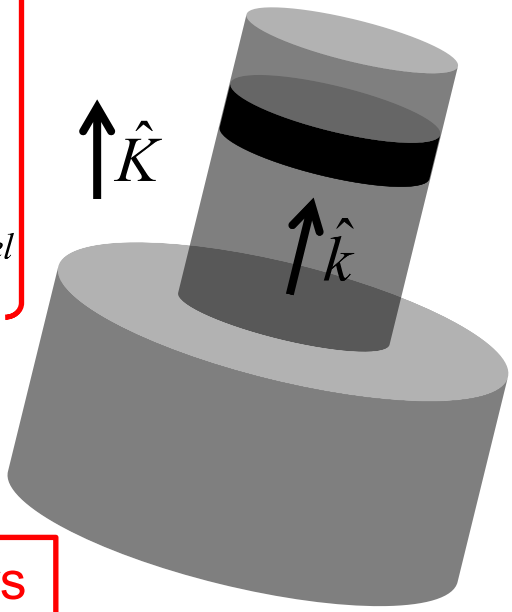
$$\frac{d\vec{F}_{Inertia}}{dz} = \left(C_P + C_A\right)\rho_f\left(\pi R^2\right)\left[I - \hat{k}\hat{k}^T\right]\vec{a}_f$$

$$\frac{d\vec{F}_{AddedMass}}{dz} = -C_A\rho_f\left(\pi R^2\right)\left[I - \hat{k}\hat{k}^T\right]\vec{a}_s$$

$$\frac{d\vec{F}_{Drag}}{dz} = \frac{1}{2}C_D\rho_f\left(2R\right)\left\|\left[I - \hat{k}\hat{k}^T\right]\vec{v}_{rel}\right\|_2\left[I - \hat{k}\hat{k}^T\right]\vec{v}_{rel}$$

Relative form of Morison's equation

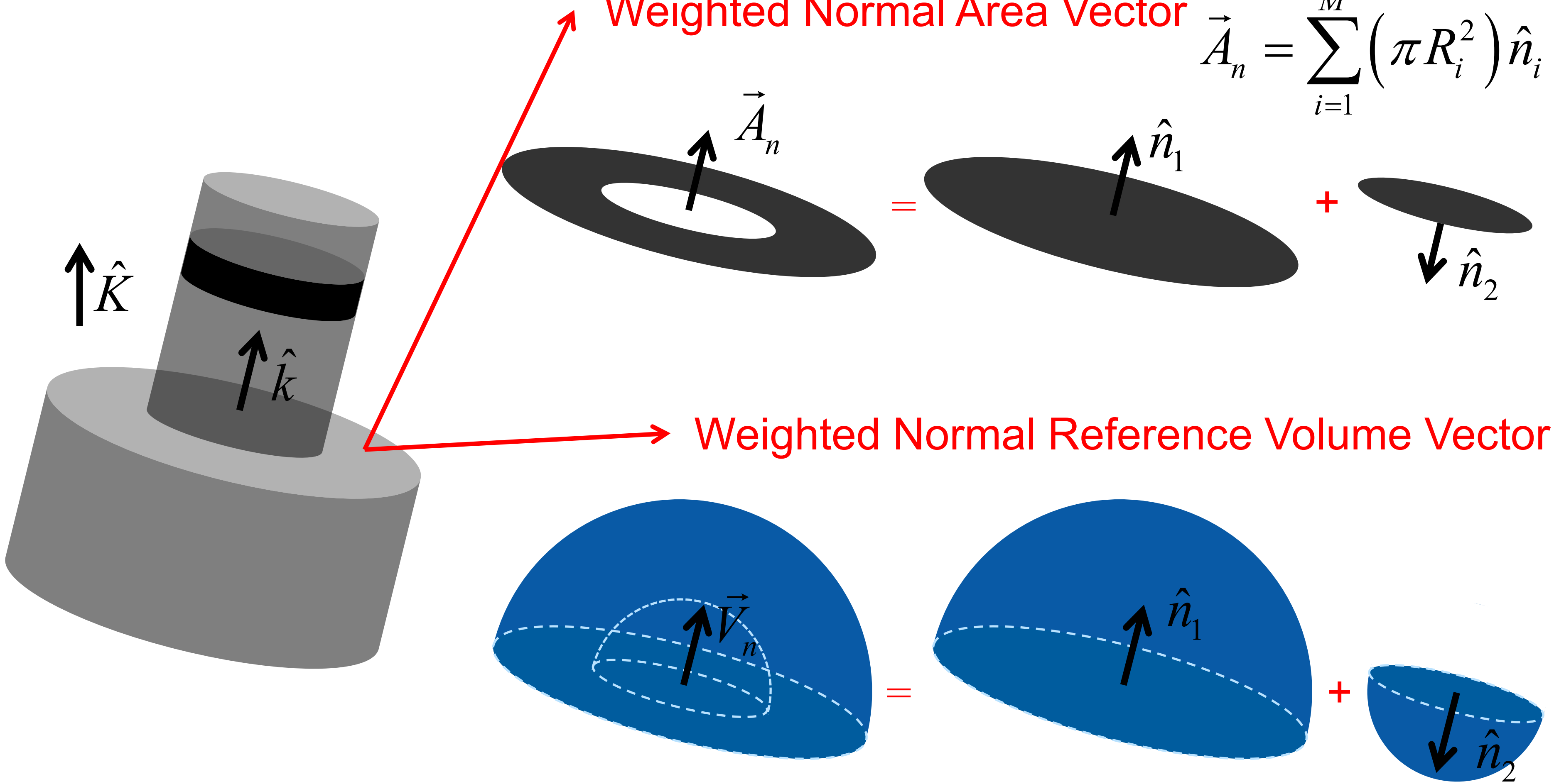
$$\frac{d\vec{F}_{Buoy}}{dz} = \rho_f g\left(\pi R^2\right)\left[\hat{i}\hat{i}^T + \hat{j}\hat{j}^T\right]\hat{K}$$



Axial terms added for tapered members

HydroDyn

Strip Theory – Loads on Member Ends



$$\vec{A}_n = \sum_{i=1}^{M} \left(\pi R_i^2 \right) \hat{n}_i$$

$$\vec{V}_n = \sum_{i=1}^{M} \left(\frac{2}{3} \pi R_i^3 \right) \hat{n}_i$$

HydroDyn

Strip Theory – Loads on Member Ends (cont)

$$\vec{F}_{Hydro} = \vec{F}_{Inertia} + \vec{F}_{AddedMass} + \vec{F}_{Drag} + \vec{F}_{Buoy}$$

Froude-Kriloff → $C_{P_{Ax}} p_{dyn} \vec{A}_n$ Scattering → $C_{A_{Ax}} \rho_f [\cdots] \vec{a}_f$

$$\vec{F}_{Inertia} = -C_{P_{Ax}} p_{dyn} \vec{A}_n + C_{A_{Ax}} \rho_f \left[\frac{\vec{V}_n \vec{V}_n^T}{\sqrt{\left(\vec{V}_n^T \vec{V}_n\right)}} \right] \vec{a}_f$$

$$\vec{F}_{AddedMass} = -C_{A_{Ax}} \rho_f \left[\frac{\vec{V}_n \vec{V}_n^T}{\sqrt{\left(\vec{V}_n^T \vec{V}_n\right)}} \right] \vec{a}_s$$

$$\vec{F}_{Drag} = \frac{1}{2} C_{D_{Ax}} \rho_f \left[\frac{\vec{A}_n \left\| \vec{A}_n^T \vec{v}_{rel} \right\|_2 \vec{A}_n^T}{2\left(\vec{A}_n^T \vec{A}_n\right)} \right] \vec{v}_{rel}$$

$$\vec{F}_{Buoy} = \left(\rho_f g Z\right) \vec{A}_n$$

Weighted Normal Reference Volume Vector

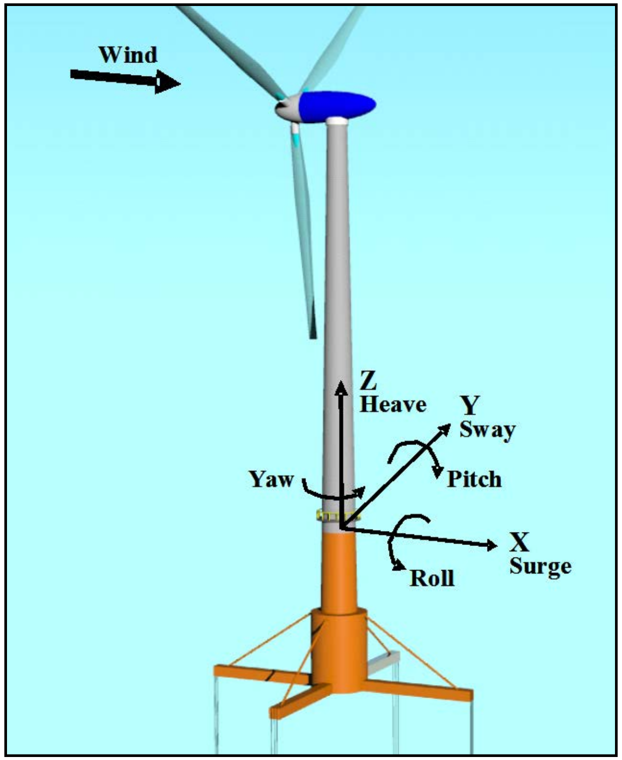
$$\vec{V}_n = \sum_{i=1}^{M} \left(\frac{2}{3} \pi R_i^3 \right) \hat{n}_i$$

Weighted Normal Area Vector

$$\vec{A}_n = \sum_{i=1}^{M} \left(\pi R_i^2 \right) \hat{n}_i$$

HydroDyn
Potential Flow – Overview

- For "large" platforms of arbitrary geometry
- Frequency-domain hydrodynamic coefficients imported from **WAMIT** (or equivalent) panel code:
  - $A_{ij}(\omega)$, $B_{ij}(\omega)$, C_{ij}, & $X_i(\omega,\beta)$
  - Internal frequency-to-time-domain conversion
  - Assumed rigid platform undergoing small motion $q << \lambda$
- Load components (sum of 3 separate terms):
  - Linear hydrostatic restoring
  - Linear diffraction (wave-excitation)
  - Linear radiation, incl. added mass & damping:
    - "Memory effect" accounted for by direct time-domain convolution or state-space (SS) form
  - Applied as 6-component (lumped) load
  - 2^{nd}-order terms (mean-drift, slow-drift, & sum-frequency) coming soon:
    - Both Newman's approximation & full QTF



Support Platform DOFs

HydroDyn

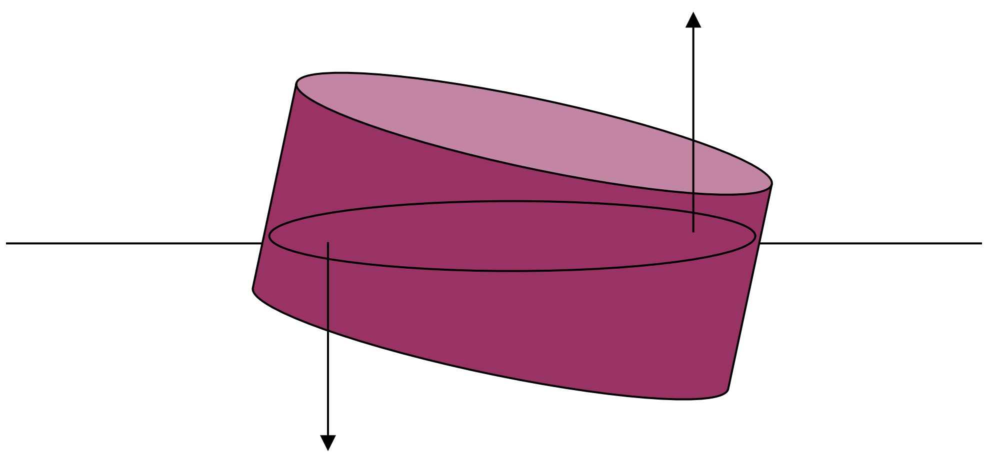
Potential Flow – Hydrostatics

- Quasi-static buoyancy loads from Archimedes' Principle:

$$F_i^{Hydrostatic} = \rho g V_0 \left(\delta_{i3} + y^{CB} \delta_{i4} - x^{CB} \delta_{i5} \right) - C_{ij}^{Hydrostatic} q_j$$

Static load from undisplaced volume (including CB offsets)

Change in load from platform displacement (including waterplane area & CB offsets)



HydroDyn
Potential Flow – Diffraction

- Diffraction loads are generated by incident waves impinging on the undisplaced platform

Wave component complex amplitude (including phase)

- Wave elevation: $$\eta\left(t\right) = \text{Re}\left\{ \sum_{n=1}^{N} A_n e^{j\omega_n t} \right\}$$

- Wave-excitation loads: $$F_i^{Diffraction}\left(t\right) = \text{Re}\left\{ \sum_{n=1}^{N} A_n X_i\left(\omega_n, \beta_n\right) e^{j\omega_n t} \right\}$$

Complex wave-excitation load (including phase) per unit wave amplitude

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HydroDyn
Potential Flow – Radiation

- Radiation loads are generated by waves radiating away from a moving platform, with no incident waves present:

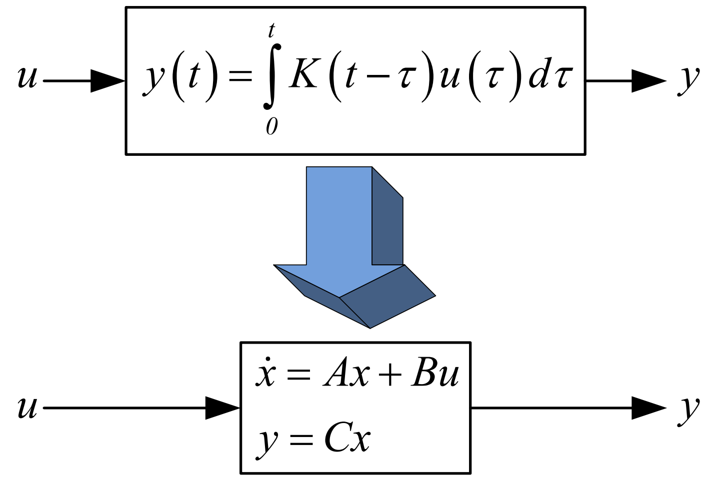
$$F_i^{Radiation} = -A_{ij}\ddot{q}_j - \int_0^t K_{ij}(t-\tau)\dot{q}_j(\tau)\,d\tau$$

Added mass

$$A_{ij} = \lim_{\omega\to\infty} A_{ij}(\omega)$$

Damping, including "memory effect"

$$K_{ij}(t) = \frac{2}{\pi}\int_0^\infty B_{ij}(\omega)\,COS(\omega t)\,d\omega$$



Reformulation of Radiation Convolution to Linear SS Form

- "Memory effect" accounted for by:
  - Direct time-domain (numerical) convolution
  - Linear state-space (SS) form:
    - SS matrices derived from **SS_Fitting** pre-processor using 4 system-ID approaches

HydroDyn

Features of FAST v8 Compared to v7

- All new features are being added to the new framework
- Until all features of v7 are included in v8, both will be supported

FAST Features	v7.02	v8.08
• Linear regular or irregular waves	✓	✓
• White-noise waves		✓
• Wave directional spreading		✓
• Wave stretching	✓	
• Externally generated wave data	✓	
• Sea current	✓	✓
• Strip theory for central member	✓	✓
• Strip theory for multiple intersecting members		✓
• Distributed static buoyancy		✓
• Concentrated loads on member ends		✓
• Support for inclined and tapered members		✓
• Support for flooded and ballasted members		✓
• Support for marine growth		✓
• First-order potential flow (from WAMIT)	✓	✓
• Radiation "memory effect" captured through time-domain convolution	✓	✓
• Radiation "memory effect" captured through linear state-space form		✓
• Quasi-steady and dynamic surface-ice loading		✓

HydroDyn
Modeling Guidance

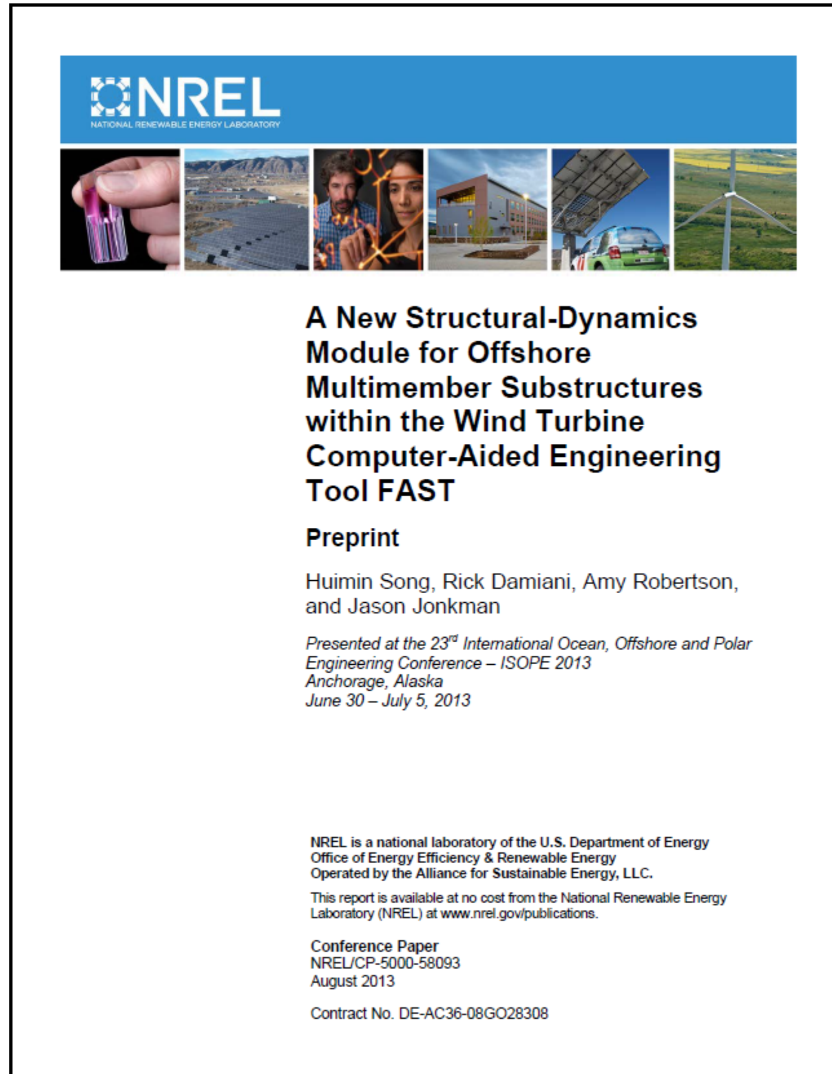
- Change `WaveSeed` between simulations to produce different instances of wave time history for the same conditions
- Strip-theory discretization:
  - Define geometry in water by joints & members
  - Subdivide members using `MDivSize`
  - Resolution may decrease with depth:
    - 0.5 m near free surface
    - 1.0 m in intermediate depth
    - 2.0 m below 50-m depth
- Strip-theory hydrodynamic coefficients:
  - Derive from tables based on Re & KC
  - Cylinders are assumed, but coefficients may include shape corrections
- Use platform additional stiffness & damping to:
  - Model a linearized mooring system
  - Augment strip-theory members with linear hydrostatic restoring
  - “Tune” **HydroDyn** to match known damping, e.g. from free-decay tests

HydroDyn
Modeling Guidance (cont)

- Fixed-bottom substructures:
  - Use strip theory
  - Members embedded into seabed must have a joint located below water depth to avoid having **HydroDyn** apply static pressure loads at bottom
  - Gravity-based foundations should have lowest joint at seabed
  - Use `MSL2SWL` to model changes in water depth due to tides/surges
- Floating platforms:
  - Use potential-flow theory, strip theory, or a hybrid model
  - Ensure undisplaced condition has platform-heave DOF in equilibrium:
    - $\rho g V_0 - m_{Total} g - T_{Mooring} = 0$
  - In addition to `BlPitch` & `RotSpeed` in **ElastoDyn**, set proper IC for `PtfmSurge` & `PtfmPitch`
  - For strip-theory solutions, specify 6x6 linear hydrostatic restoring matrix through `AddCLin`
  - For potential-flow solutions, **WAMIT** (or equivalent) solution should:
    - Contain a large range of frequencies (0-5 rad/s)
    - Neglect influence of platform mass center in hydrostatic stiffness

SubDyn
What Is It?

- Structural-dynamics module for multi-member fixed-bottom substructures:
  - Linear frame finite-element (FE) beam model with Craig-Bampton (C-B) reduction
  - New to **FAST** v8
- Latest version:
  - v1.01.00a-rrd (July 2014)
  - Newer in progress
- Documentation:
  - User – ReadMe (2014)
  - Theory – Song et al (ISOPE 2013)
  - SubDyn User's Guide & Theory Manual coming soon



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A New Structural-Dynamics Module for Offshore Multimember Substructures within the Wind Turbine Computer-Aided Engineering Tool FAST

Preprint

Huimin Song, Rick Damiani, Amy Robertson, and Jason Jonkman

Presented at the 23rd International Ocean, Offshore and Polar Engineering Conference – ISOPE 2013
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Conference Paper
NREL/CP-5000-58093
August 2013

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SubDyn
Inputs, Outputs, States, & Parameters

Inputs:
- Hydrodynamic loads
- TP* displacements
- TP* velocities
- TP* accelerations

SubDyn

Continuous States:
- Displacements
- Velocities

Parameters:
- Geometry
- Mass/inertia
- Stiffness coefficients
- Damping coefficients
- Gravity

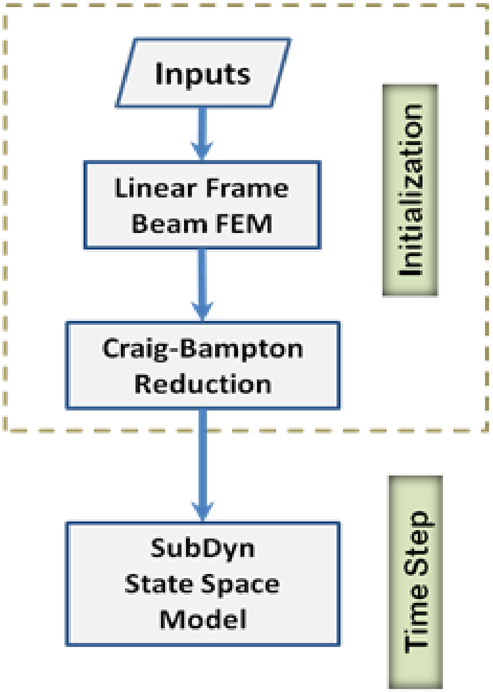
Outputs:
- Displacements
- Velocities
- Accelerations
- Reaction loads

**TP = Transition piece*

SubDyn
Theory Basis

- Linear frame finite-element beam model:
  - Euler-Bernoulli or Timoshenko beam elements
  - Constant or tapered cross-sections
- C-B dynamic linear system reduction:
  - DOFs reduced from 10^3 to 10^1
  - Physical DOFs at boundaries + modal coordinates
  - Discard high-frequency content in the system dynamics
- Static-Improvement Method – All modes not considered by the C-B reduction are treated quasi-statically
- Degree of fixity – Clamped/Clamped
- Time integrator - RK4, AB4, ABM4, AM2

Damiani et al (OMAE 2013) showed that support-structure nonlinearities are mainly associated with mono-tower dynamics

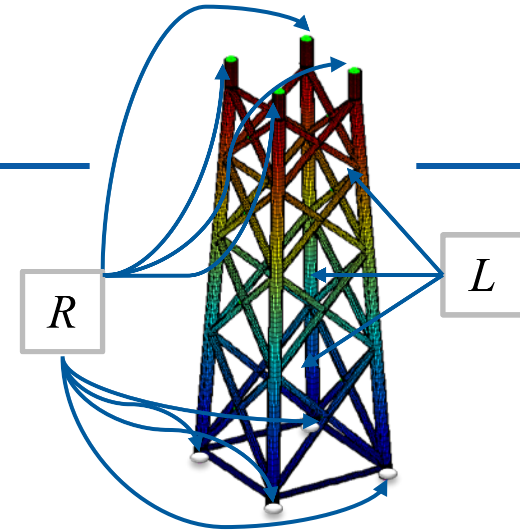


SubDyn *Flow Chart*

SubDyn

Craig-Bampton Fundamentals

$$\begin{bmatrix} M_{RR} & M_{RL} \\ M_{LR} & M_{LL} \end{bmatrix} \begin{Bmatrix} \ddot{U}_R \\ \ddot{U}_L \end{Bmatrix} + \begin{bmatrix} C_{RR} & C_{RL} \\ C_{LR} & C_{LL} \end{bmatrix} \begin{Bmatrix} \dot{U}_R \\ \dot{U}_L \end{Bmatrix} + \begin{bmatrix} K_{RR} & K_{RL} \\ K_{LR} & K_{LL} \end{bmatrix} \begin{Bmatrix} U_R \\ U_L \end{Bmatrix} = \begin{Bmatrix} F_R + F_{Rg} \\ F_L + F_{Lg} \end{Bmatrix}$$



Restrained (R) & Interior (L) DOFs

- Separate boundary & internal DOFs
- Retain just *m* internal generalized (modal) DOFs
- Assume negligible cross damping

$$\begin{bmatrix} M_{BB} & M_{Bm} \\ M_{mB} & I \end{bmatrix} \begin{Bmatrix} \ddot{U}_R \\ \ddot{q}_m \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\zeta\Omega_m \end{bmatrix} \begin{Bmatrix} \dot{U}_R \\ \dot{q}_m \end{Bmatrix} + \begin{bmatrix} K_{BB} & 0 \\ 0 & \Omega_m^2 \end{bmatrix} \begin{Bmatrix} U_R \\ q_m \end{Bmatrix} = \begin{Bmatrix} \left(F_R + F_{Rg}\right) + \Phi_R^T \left(F_L + F_{Lg}\right) \\ \Phi_m^T \left(F_L + F_{Lg}\right) \end{Bmatrix}$$

- Remove restrained node DOFs
- Condense interface nodes:
  - 6 TP DOFs (input from **ElastoDyn**)

$$\begin{Bmatrix} U_R \\ U_L \end{Bmatrix} = \begin{bmatrix} I & 0 \\ \Phi_R & \Phi_m \end{bmatrix} \begin{Bmatrix} U_R \\ q_m \end{Bmatrix}$$

$$K_{LL}\Phi_m = \omega^2 M_{LL}\Phi_m$$

$$\Phi_R = -K_{LL}^{-1}K_{LR}$$

Craig-Bampton Reduction

$$\begin{bmatrix} \tilde{M}_{BB} & \tilde{M}_{Bm} \\ \tilde{M}_{mB} & I \end{bmatrix} \begin{Bmatrix} \ddot{U}_{TP} \\ \ddot{q}_m \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\zeta\Omega_m \end{bmatrix} \begin{Bmatrix} \dot{U}_{TP} \\ \dot{q}_m \end{Bmatrix} + \begin{bmatrix} \tilde{K}_{BB} & 0 \\ 0 & \Omega_m^2 \end{bmatrix} \begin{Bmatrix} U_{TP} \\ q_m \end{Bmatrix} = \begin{Bmatrix} \tilde{F}_{TP} \\ \tilde{F}_m \end{Bmatrix}$$

SubDyn
Modeling Guidance

- Geometry/discretization:
  - Define complete substructure geometry by joints & members
  - Subdivide members using `NDiv`
    - Tapered members should have `NDiv` > 1
  - Resolution may decrease with depth:
    - < 5 m near free surface
    - < 10 m in intermediate depth
    - < 20 m below 50-m depth
- Integration method & time step:
  - `IntMethod` = 3 – ABM4
  - `SDdeltaT` = 1/(10*highest frequency in Hz of retained C-B modes or of physical modes when coupled to **FAST**)

SubDyn
Modeling Guidance (cont)

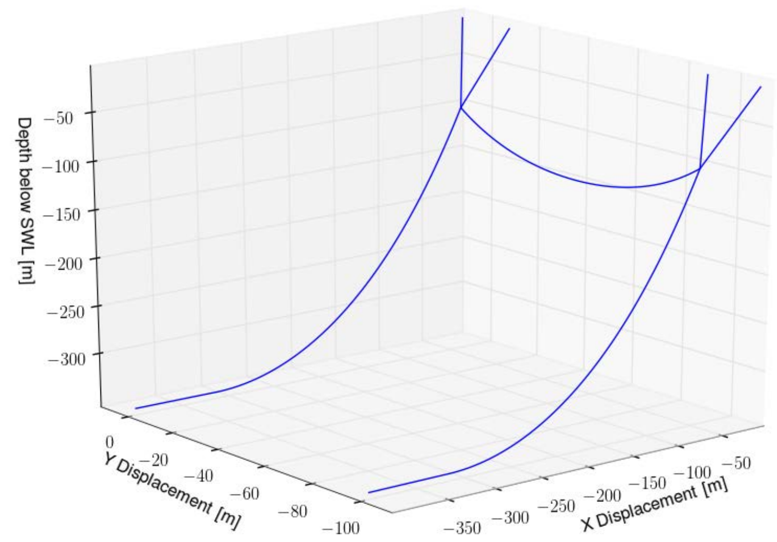
- C-B reduction (`CBMod` = True):
  - Retain all physical modes up to 2-3 Hz (or all C-B modes up to 10 Hz)
  - `SttcSolve` = True – Employ the static-improvement method
  - Stiff substructures may not need any C-B modes
- Coupling to **FAST**:
  - Enable all 6 platform DOFs in **ElastoDyn** to couple loads & displacements between tower & substructure
  - `PtfmYIner` > 0 – Avoid ÷ 0 problem in **ElastoDyn** when nacelle-yaw is enabled (use tower-yaw inertia not already accounted for)
  - Tower mode shapes in **ElastoDyn** depend on substructure mass/stiffness – Recompute with change to substructure (**BModes**)
  - Minimize platform-heave motion to mitigate numerical problems:
    - Add 1% damping to platform-heave DOF (`AddBLin` in **HydroDyn**)
    - Set initial platform-heave displacement (`PtfmHeave` in **ElastoDyn**) to its natural static-equilibrium position

MAP

What Is It?

- **M**ooring **A**nalysis **P**rogram:
  - Quasi-static module for multi-segmented mooring systems (MSQS)
  - New to **FAST** v8 – Replaces prior mooring model included in **HydroDyn**
- Mixed-language:
  - Source code in C++
  - Python-binding for standalone driver
  - Coupled to **FAST** (Fortran)
- Latest version:
  - v0.87.01a-mdm (October 2013)
- Documentation – Instructional & Theory Guide to the Mooring Analysis Program (2013)
- Rewrite in progress

MOORING
ANALYSIS PROGRAM



Example Multi-Segmented Mooring System Analyzed by ***MAP***

MAP

Inputs, Outputs, States, & Parameters

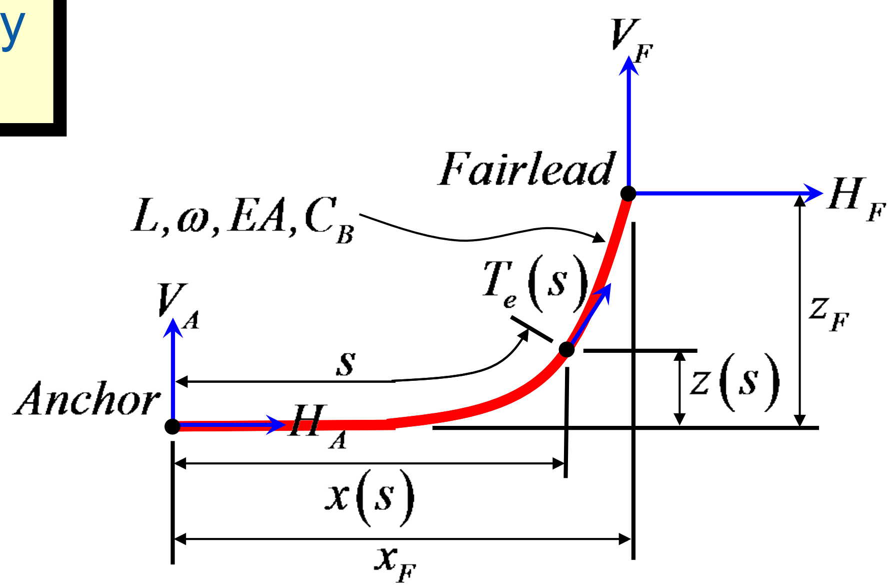
MAP

Inputs:
- Platform disp.

Constraint States:
- Line tensions
- Joint locations

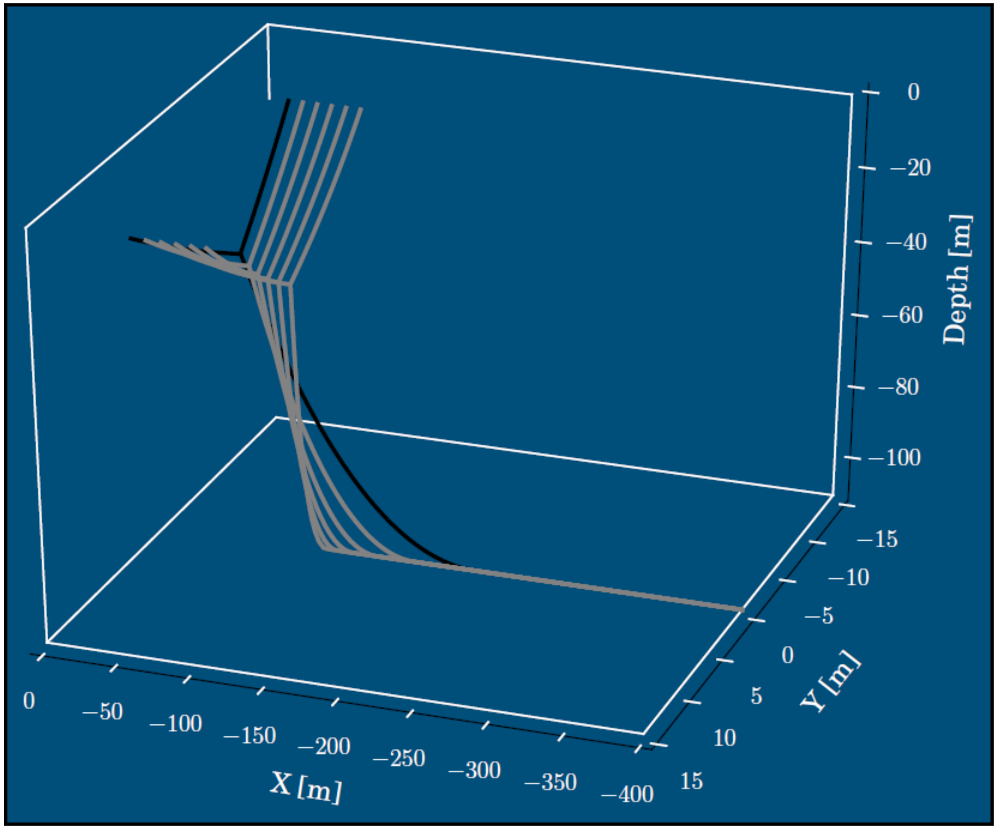
Parameters:
- Line properties
- Line connectivity
- Gravity

Outputs:
- Line tensions
- Line disp.



MAP
Features

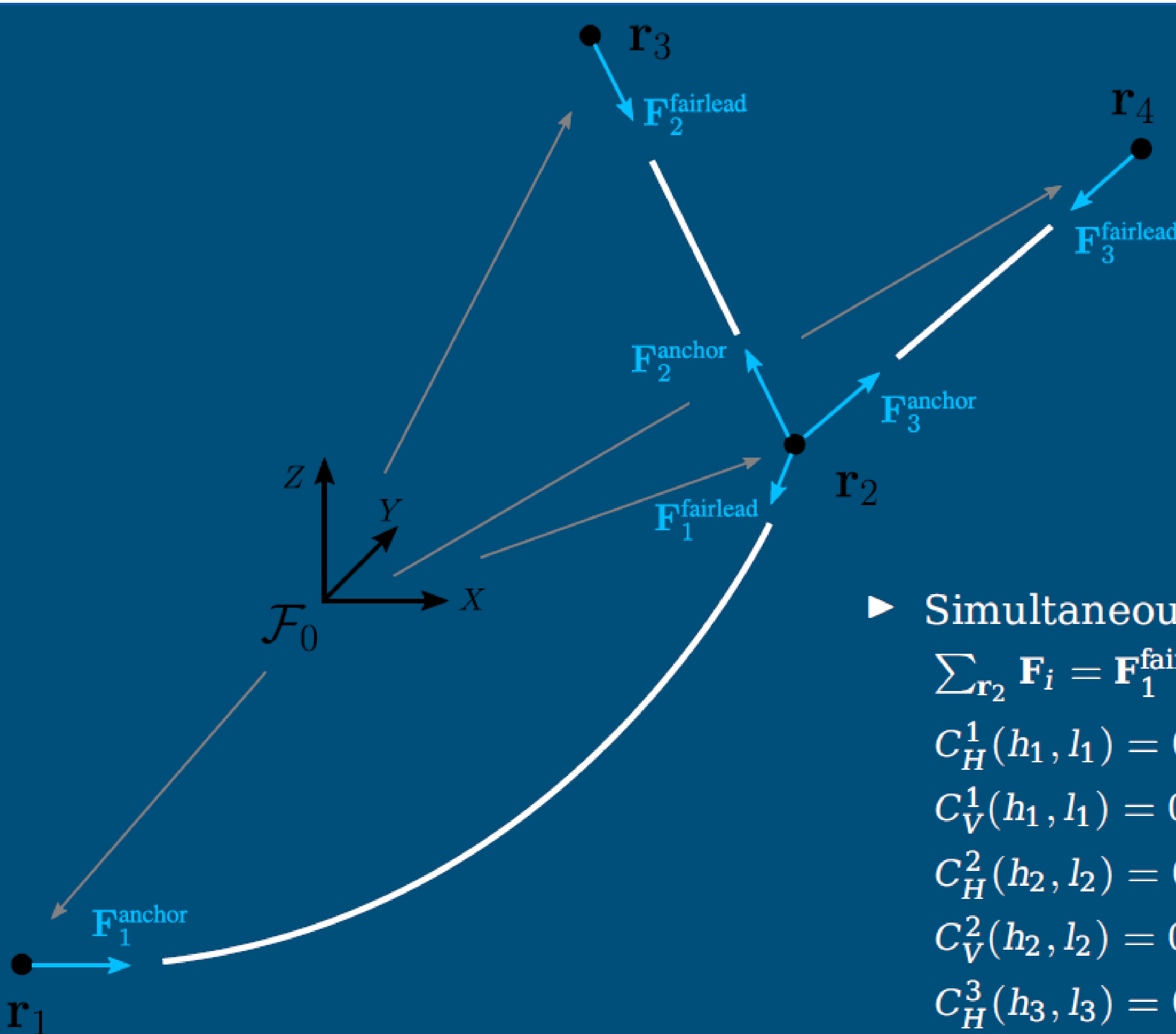
- Accounts for:
  - Multi-segmented array of taut or catenary lines
  - Apparent weight of line in fluid
  - Elastic stretching
  - Seabed friction
  - Clump weights & buoyancy tanks
  - Nonlinear geometric restoring
- Neglects:
  - Axial & transverse waves
  - Inertia, damping, bending, & 3D shape of lines
  - Hydrodynamic loads



Mooring Behavior with Platform-Surge Variation

MAP

Solution Strategy (by Example)



- Simultaneously solve

$$\sum_{\mathbf{r}_2} \mathbf{F}_i = \mathbf{F}_1^{\text{fairlead}} + \mathbf{F}_2^{\text{anchor}} + \mathbf{F}_3^{\text{anchor}} = 0$$

$$C_H^1(h_1, l_1) = 0$$

$$C_V^1(h_1, l_1) = 0$$

$$C_H^2(h_2, l_2) = 0$$

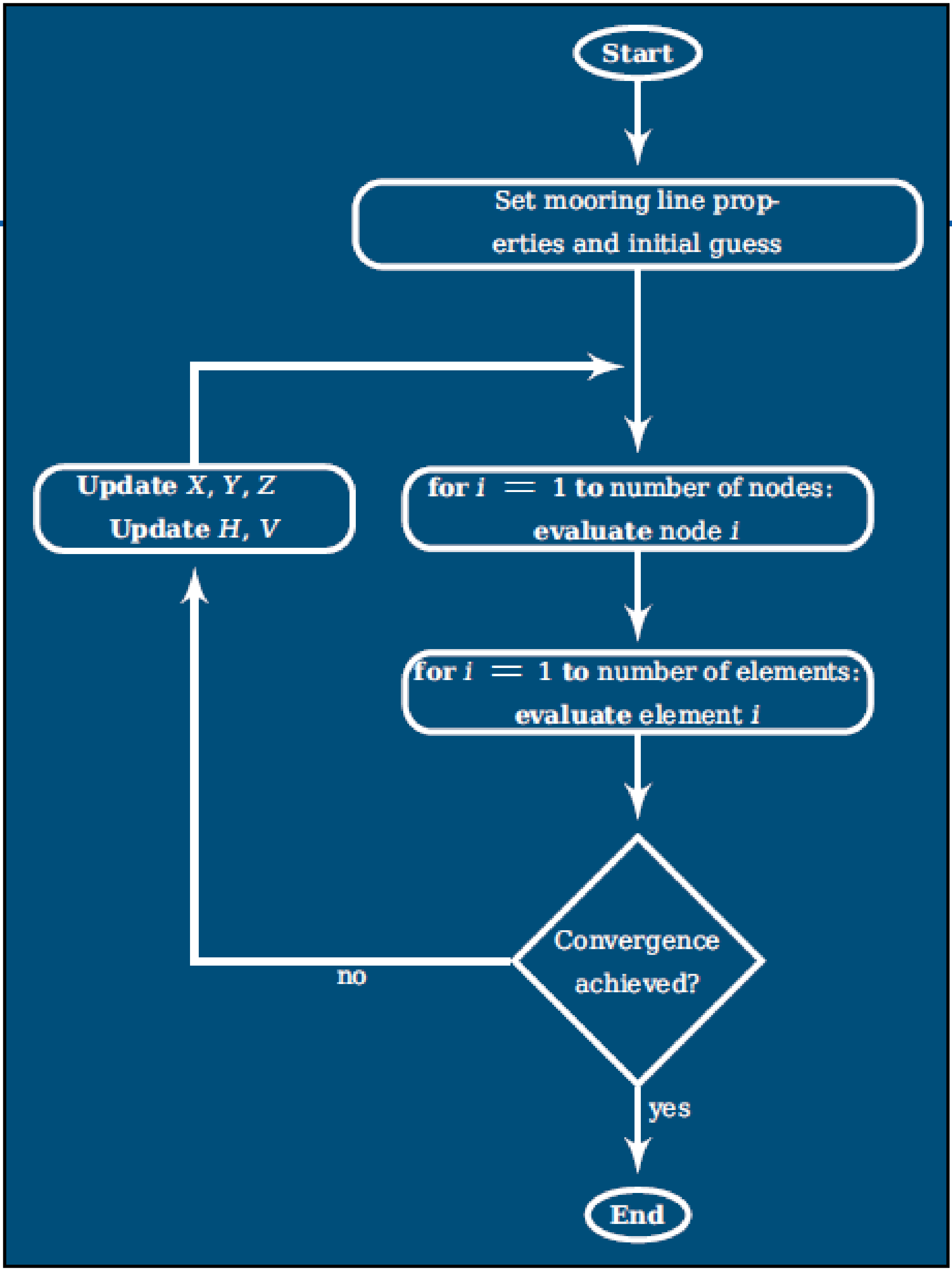
$$C_V^2(h_2, l_2) = 0$$

$$C_H^3(h_3, l_3) = 0$$

$$C_V^3(h_3, l_3) = 0$$

MAP
Solution Strategy

- Simultaneously solves nonlinear catenary & force-balance equations:
  - Unlike traditional nested loops
- Jacobian computed analytically:
  - No finite-differencing
- Numerical solution via **P**ortable **E**xtensible **T**oolkit for **S**cientific **c**omputation (**PETSc**)



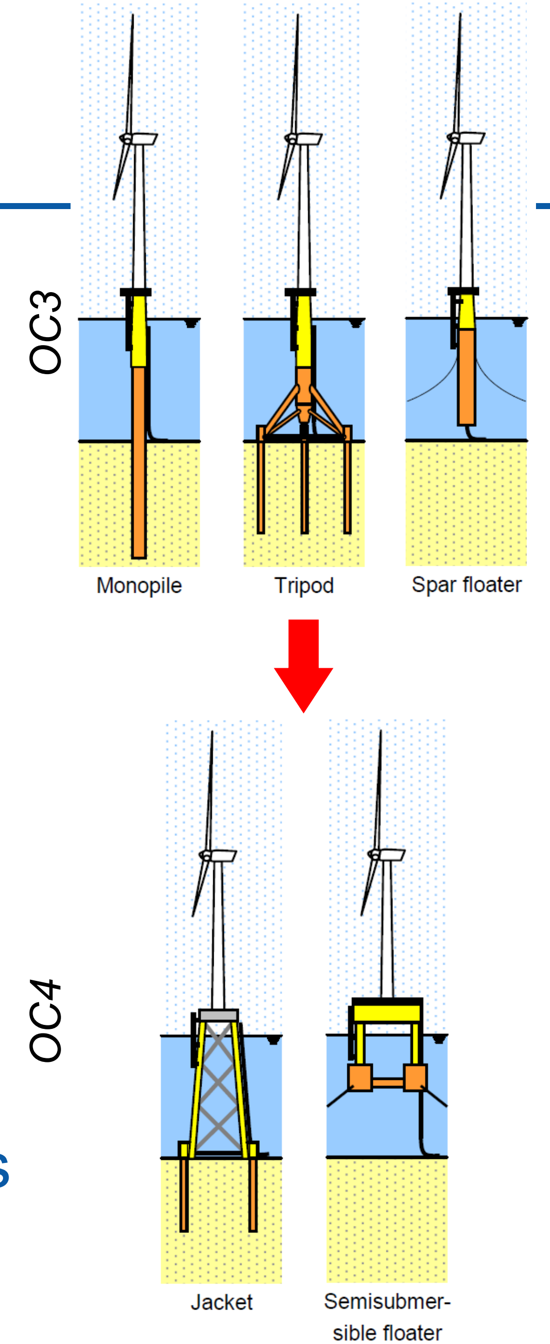
***MAP** Solution Strategy*

MAP
Modeling Guidance

- Geometry/discretization:
  - Define mooring system by nodes & lines
  - Nodes can be of 1 of 3 `Type`s:
    - `Fix` – Anchor
    - `Connect` – Line-to-line interconnection
    - `Vessel` – Fairlead
  - No need to subdivide lines because solution is analytical
  - Use `OMIT_CONTACT` flag to avoid modeling seabed
  - Use `REPEAT` option for creating multiple identical lines (rotated about platform)
- Initial guess are identified by # preceding a value, e.g.:
  - Location of `Connect` nodes
  - Reactions at anchors (`Fix` nodes) & fairleads (`Vessel` nodes)
- **PETSc** solver options:
  - Many options; difficult to set
  - Use defaults wherever possible

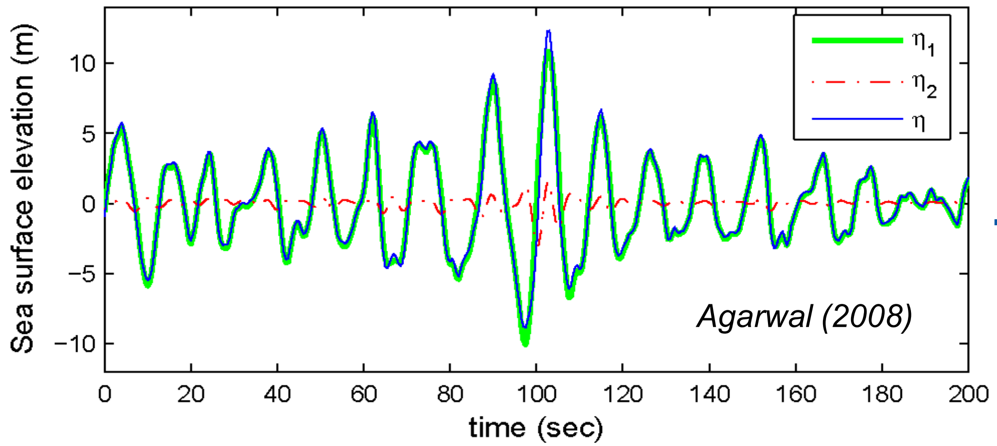
Recent Work

- Converted **HydroDyn** to new **FAST** framework (for v8) with separate input file & source code
- Added linear SS-based radiation formulation alternative to convolution within **HydroDyn**
- Added multi-member strip theory to **HydroDyn**
- Added wave directional spreading to **HydroDyn**
- Introduced **SubDyn** & **MAP**
- Verified **FAST** for offshore support structures under IEA Wind Task 23 (OC3) & 30 (OC4)

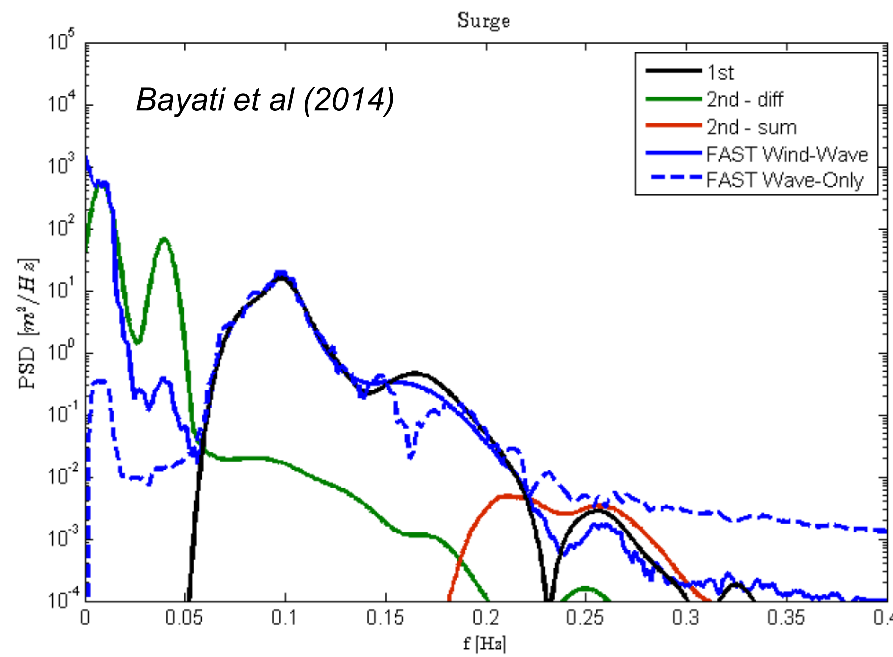


Current & Planned Work

- Complete addition of 2nd-order hydrodynamic effects:
  - Add 2nd-order (difference- & sum-frequency) irregular wave kinematics (with UT-Austin)
  - Add mean-drift, slow-drift, & sum-frequency hydrodynamic loads for floaters (with IST-Portugal):
    - Both Newman's approximation & full QTF
- Complete **SubDyn** User's Guide & Theory Manual
- Complete rewrite or **MAP**



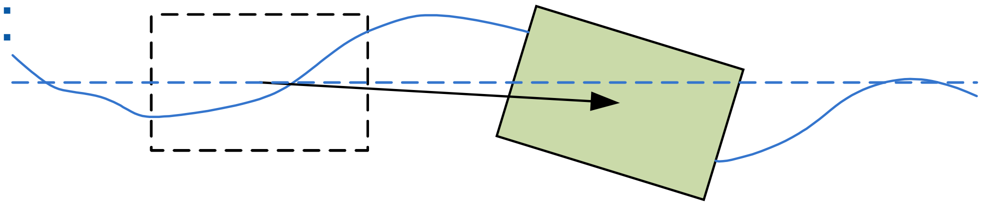
Sea-Surface Elevation (η) from the Summing of 1st- (η_1) & 2nd- (η_2) Order Waves



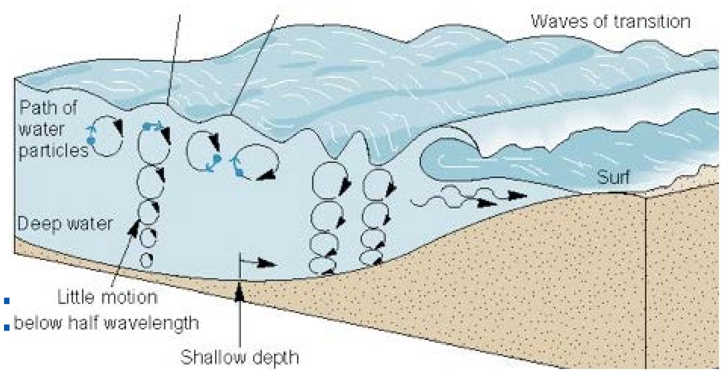
*Surge Response PSD Comparing **WAMIT** & **FAST** w/ V_0 = 9 m/s, H_s = 7 m, T_p = 10 s*

Current & Planned Work (cont)

- Support interface of **FAST** to:
  - **FEAMooring** for mooring dynamics (with TAMU)
  - **IceDyn** for ice dynamics (with UMich)
  - Nonlinear fluid-impulse theory (**FIT**) module (with MIT)
  - **SACS** for fixed-bottom code checks (with Bentley)
- Add ability to import wave time history:
  - Construct hydrodynamics around known wave elevation
  - Prescribe full wave kinematics (e.g. for higher order theories)
- Develop dynamic mooring capability in **MAP**



Sea-Surface Interaction With a Platform Experiencing Large Displacement



Wave Propagation from Deep to Shallow

Current & Planned Work (cont)

- Calibrate & validate floating functionality through:
  - DeepCwind – 1:50 scale of 5-MW atop spar buoy, TLP, & semisubmersible
  - SWAY – 1:6.5 scale of 5-MW downwind turbine atop a TLS
  - WindFloat – Vestas V80 2-MW atop a PPI semisubmersible
  - Hywind – Siemens 2.3-MW atop Statoil spar buoy

DeepCwind TLP

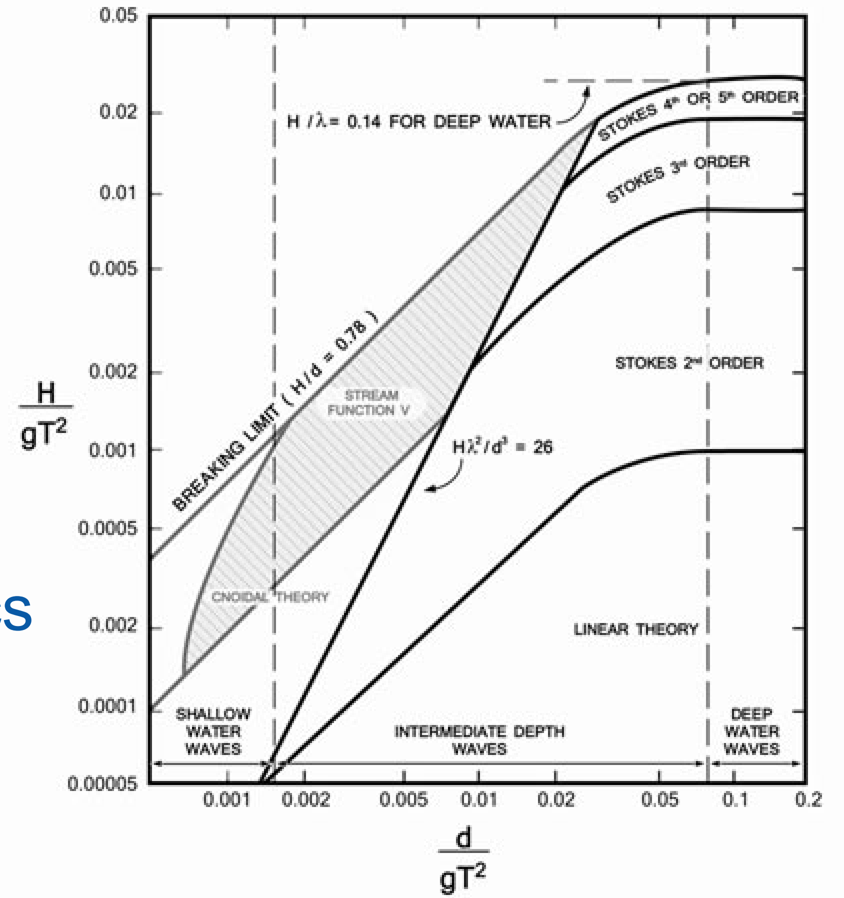
SWAY

WindFloat

Hywind

Future Opportunities

- Calculate overlap of intersecting members at joints
- Add wave stretching
- Add nonlinear regular wave kinematics for fixed-bottom
- Add breaking wave-impact loads for fixed-bottom
- Add floating platform hydro-elastics
- Add pressure mapping for floaters
- Implement joint flexibility in **SubDyn**
- Redevelop **OrcaFlex** interface for **FAST** v8



Applicability of Different Wave Theories

Questions?

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