Application of a Tightly-Coupled CFD/6-DOF Solver For Simulating Offshore Wind–Turbine Platforms

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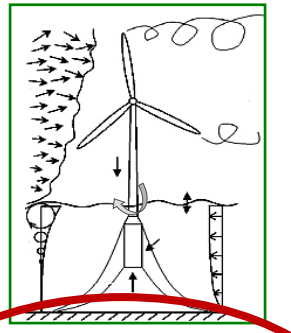


MESOSCALE, WEATHER

*ATMOSPHERIC BOUNDARY LAYER TURBULENT WINDS

WAKE TURBULENCE BLADE-WAKE-ATMOSPHERE

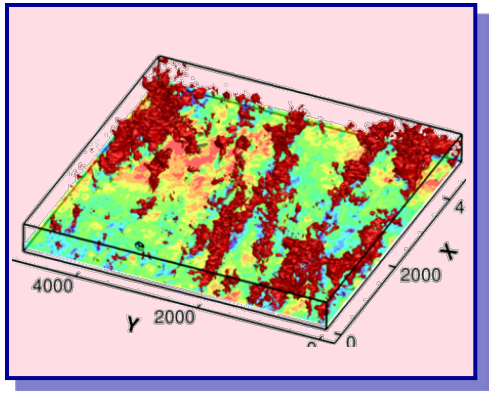
*PLATFORM-WAVE HYDRODYNAMICS and 6-DOF MOTIONS

*BLADE AERODYNAMICS, SPACE-TIME LOADINGS

WAKE-TURBINE INTERACTIONS (wind plant)

*BLADE AND *TOWER ELASTIC DEFORMATION

*Shaft Torque, *Drivetrain Loadings

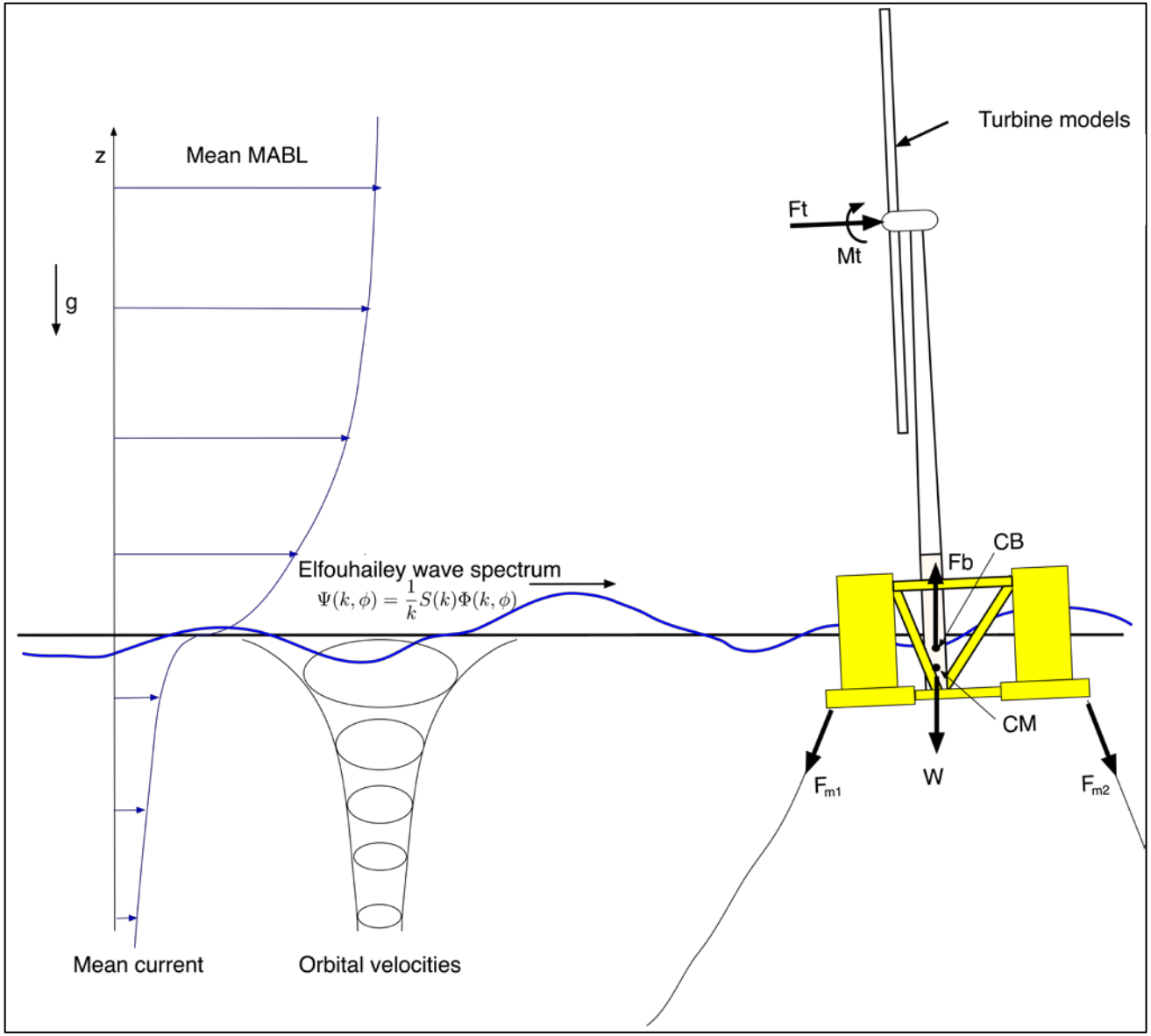


CYBER WIND FACILITY

- highly resolved 4-D cyber data
- coupled atmospheric turbulence-blade loadings-shaft torque data
- coupled wave structure – platform motion – turbine loadings data
- experiment design, test-bed, turbine design, controls concepts and testing
- advanced correlations for BEM and other design tools using look-up tables.

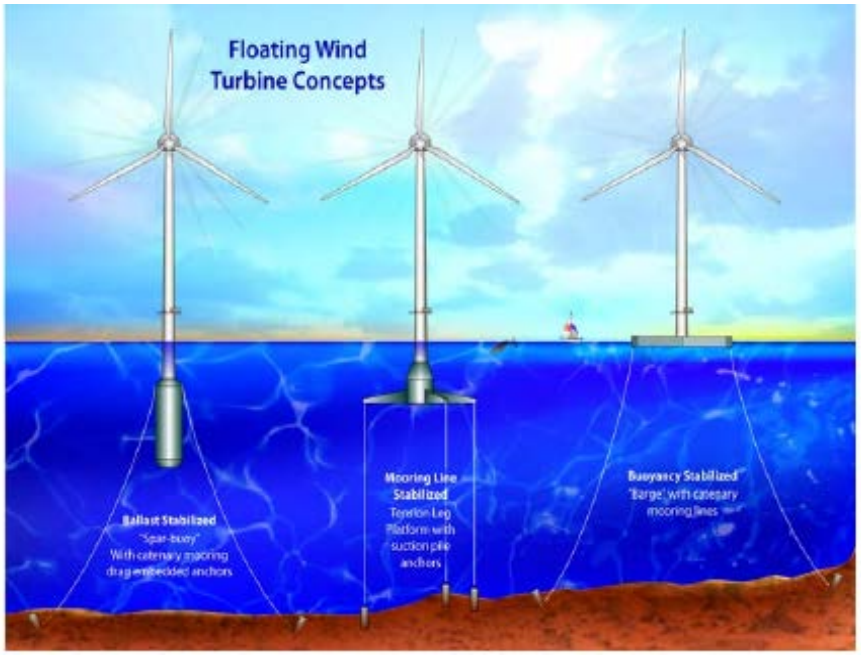
*sensors, controllers, diagnostics

Hydrodynamic Module Overview



Motivation

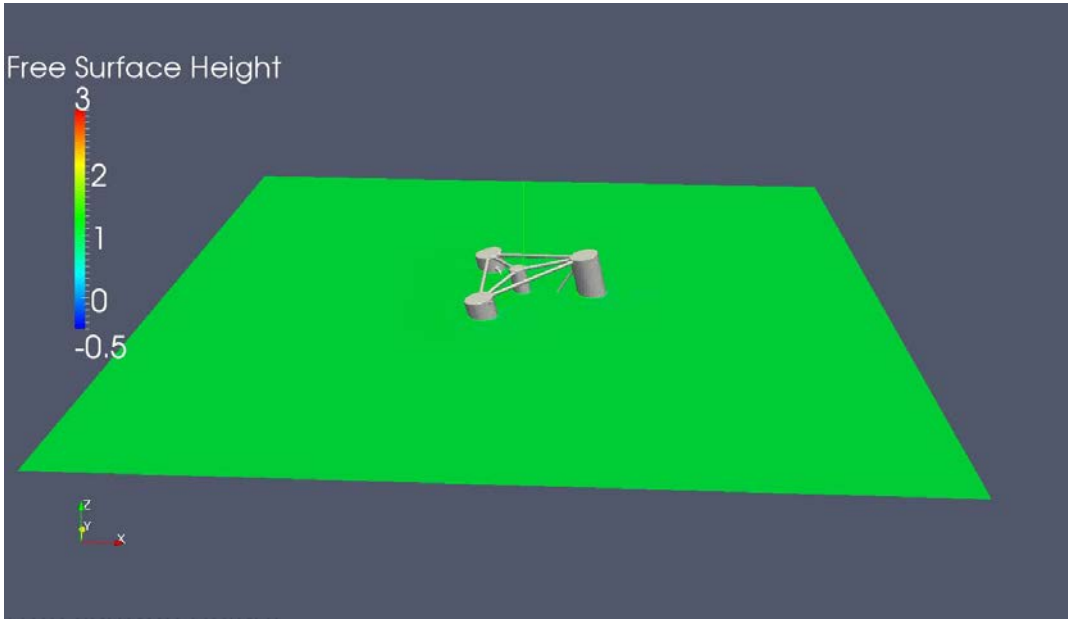
- Floating platform based offshore wind turbine
  - Current fixed-bottom type tower is limited to 20 meters
  - Floating platform type offshore wind turbine an be used even at 200 meters
- Platform dynamics influence:
  - Wind turbine performance
  - Structural integrity/lifetime
- Need for high fidelity multiphase model
  - Current state-of-the-art: reduced order models
- Applications
  - Cyber Wind Facility
  - Develop reduced order model coefficients for designers (i.e., cyber wave basin experiments)
  - Testing of mooring systems



(Butterfield et al., 2005)

Objectives

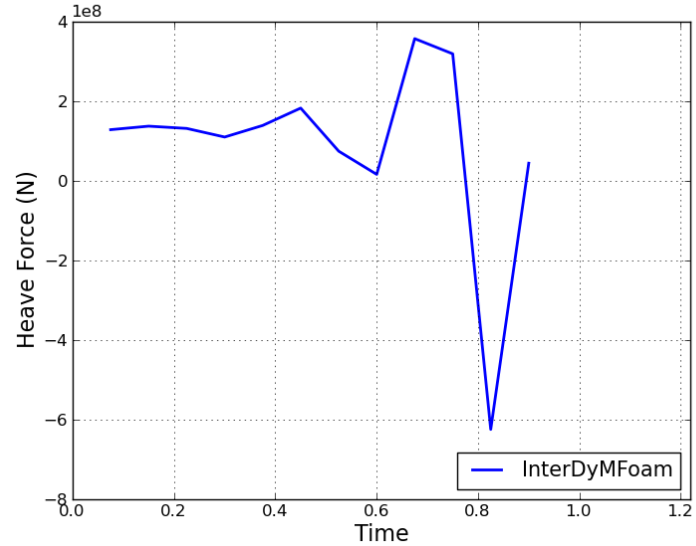
- Develop a Tightly-Coupled CFD/6-DOF (Degree Of Freedom) solver for simulating offshore platforms
- Validate against benchmark experimental data
- Simulate with floating semi-submersible platform (OC4 Phase II)
- Implement wind turbine model for accurate turbine loading

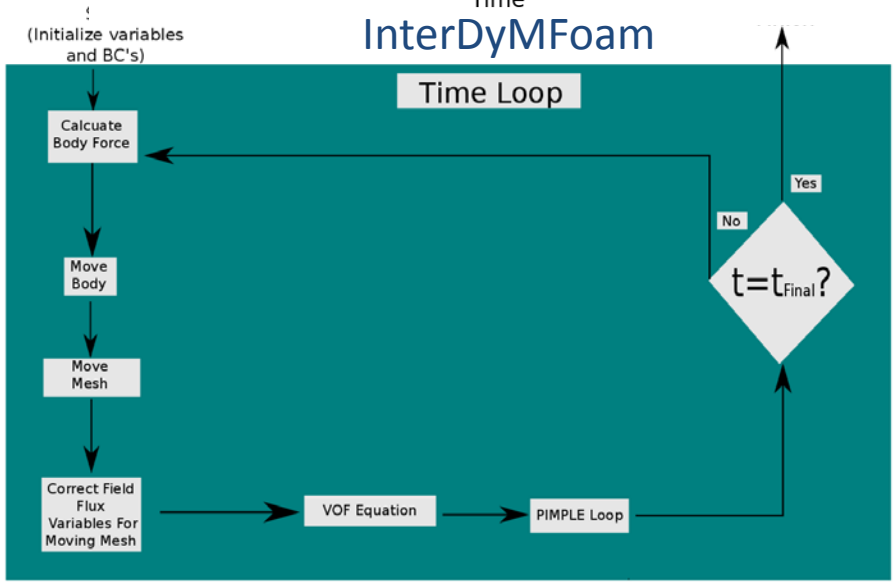


Simulation of Offshore Platform in Rolling Motion

Artificial Added Mass Instability in OpenFOAM

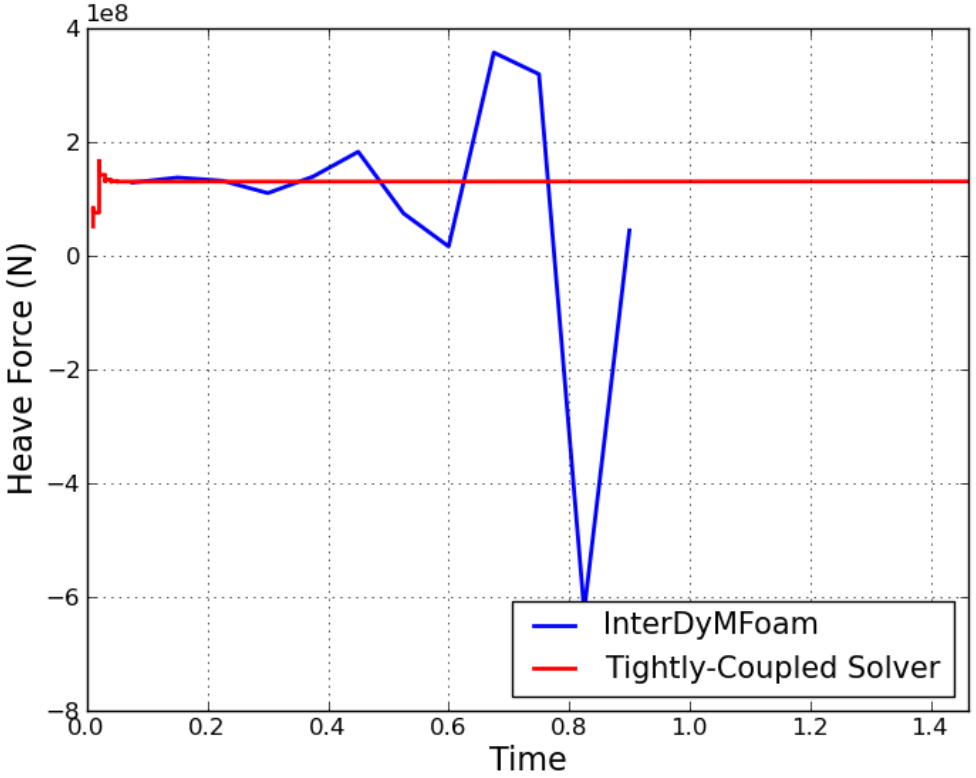
- InterDyMFoam uses a partitioned approach to CFD/6-DOF
  - Combines two specifically designed codes
- Loosely coupled scheme
  - One solution of 6DOF and fluid field per time step
- Creates error in each time step
  - Error may be damped in "weak" fluid-structure interaction
- Error largely affected by:
  - Time steps





Tightly-Coupled CFD/6-DOF

- Started with interDyMFoam
  - 6-DOF
  - Dynamic Mesh Motion
  - Multiphase - Volume of Fluid (VOF)
  - Loosely-coupled
  - Sequentially staggered CFD/6-DOF
- Tight-coupling required for stability
  - Implement a sub iteration loop
  - Dynamic coupled solution relaxation (Aitken's method)
- Currently implemented in OpenFOAM



Highlights of Tightly-Coupled Solver Changes

- Introduction of Convergence criteria for sub iteration loop

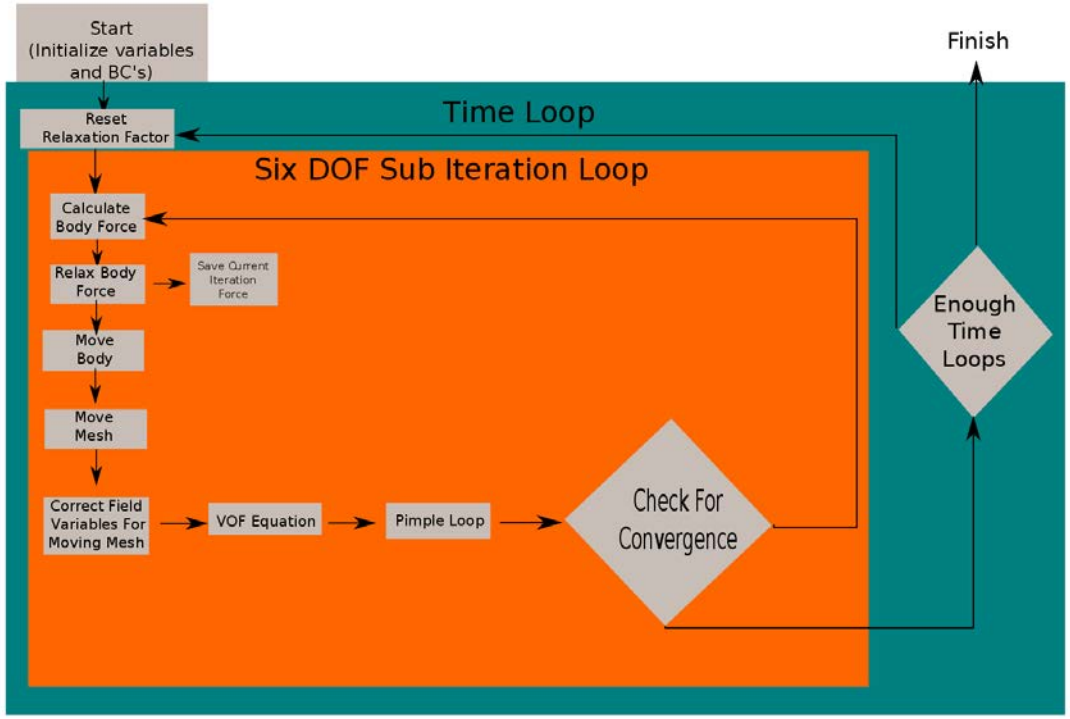
$$C = \frac{\left|\overrightarrow{F_i} - \overrightarrow{F_{i-1}}\right|}{mg}$$

- Dynamic relaxation for faster convergence

$$\overrightarrow{F_i^*} = \omega_i\left(\overrightarrow{F_i} - \overrightarrow{F_{i-1}}\right) + \overrightarrow{F_{i-1}}$$

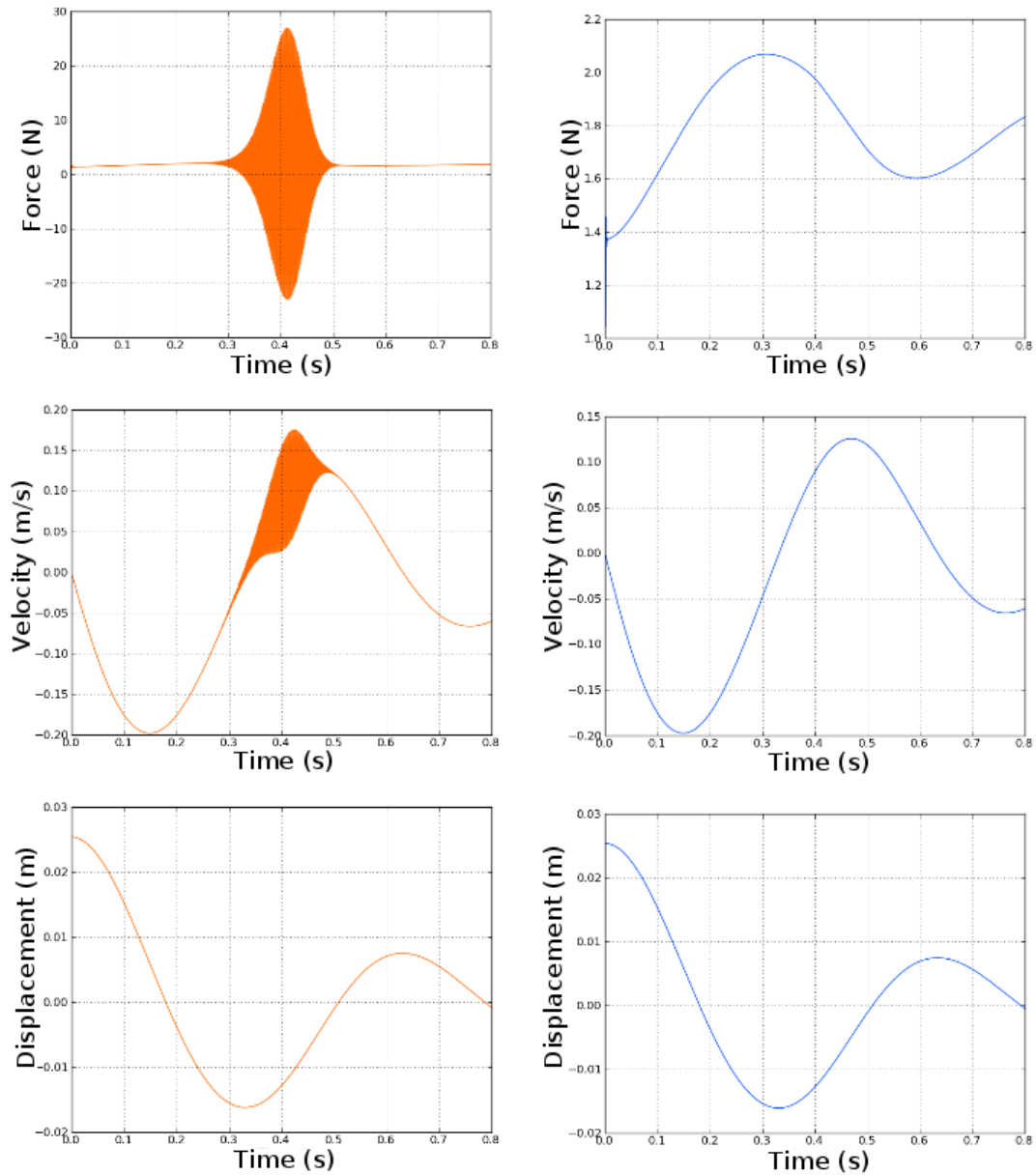
$$\omega_i = \omega_{i-1}\frac{(r_{i-1} \cdot (r_i - r_{i-1}))}{|r_i - r_{i-1}|^2}$$

Where: $r_i = \overrightarrow{F_i} - \overrightarrow{F_{i-1}}$



Artificial Added Mass Instability in OpenFOAM

InterDyMFoam

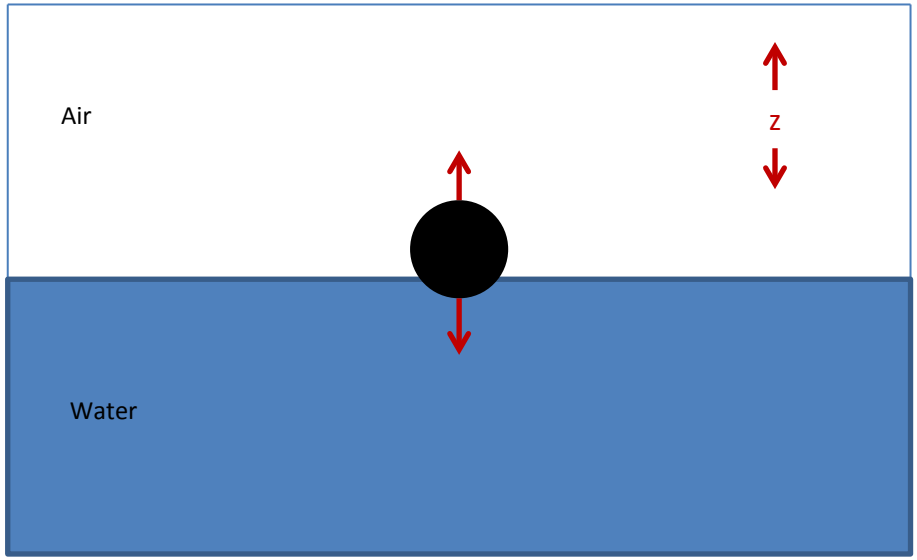


Tightly-Coupled Solver

Code Development/Validation

- 2D heaving cylinder
- Prescribed heaving motion
  - Vugts 1976
  - Contento 1997

- Free heave decay
  - Ito 1977
  - Maskell – Ursell 1970

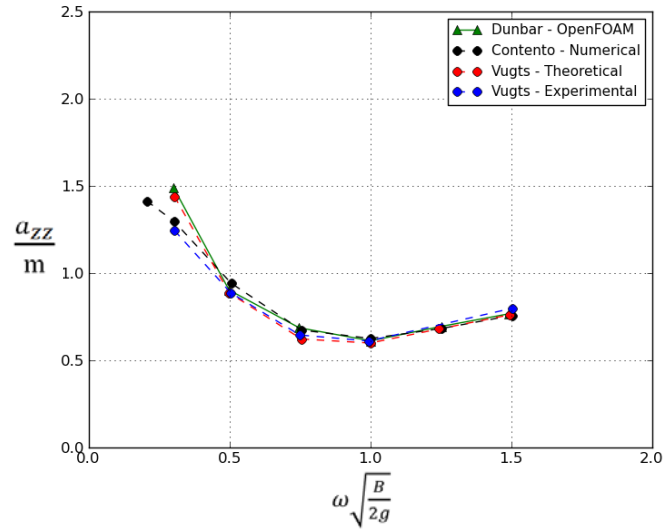


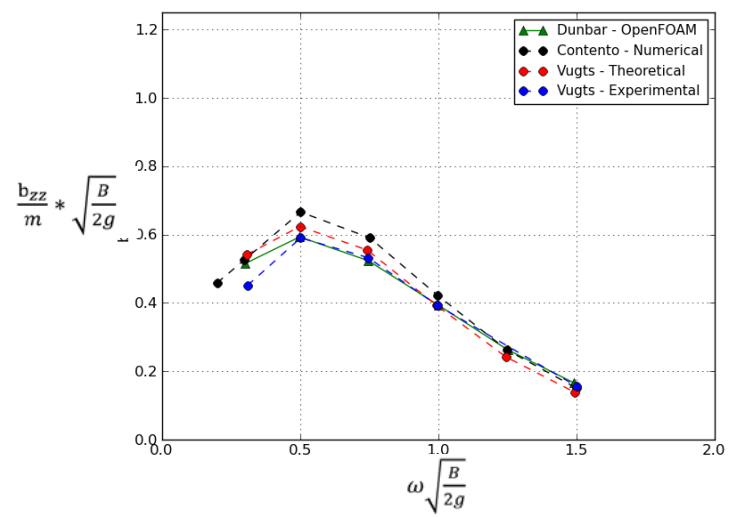
Validation

Prescribed Heave Case:

- OpenFOAM used to compute added mass and damping coefficients

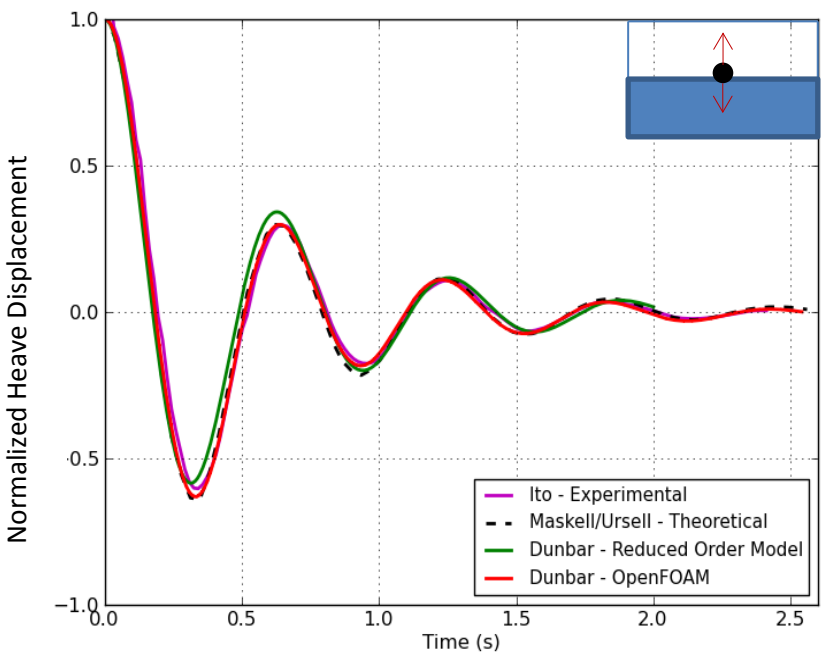
$$(m + a_{zz}) * \ddot{Z} + b_{zz} * \dot{Z} + c_{zz} * Z = F_z$$





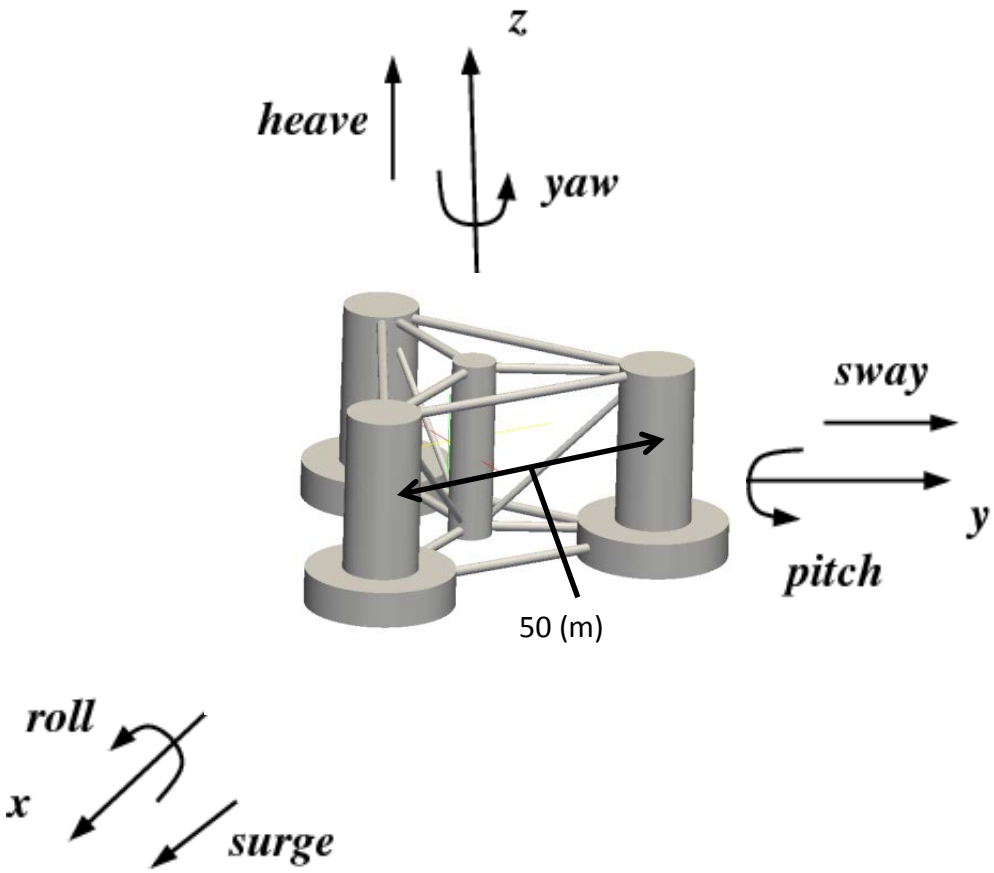
Free Heave Case:

- Excellent comparison with theoretical and experimental data



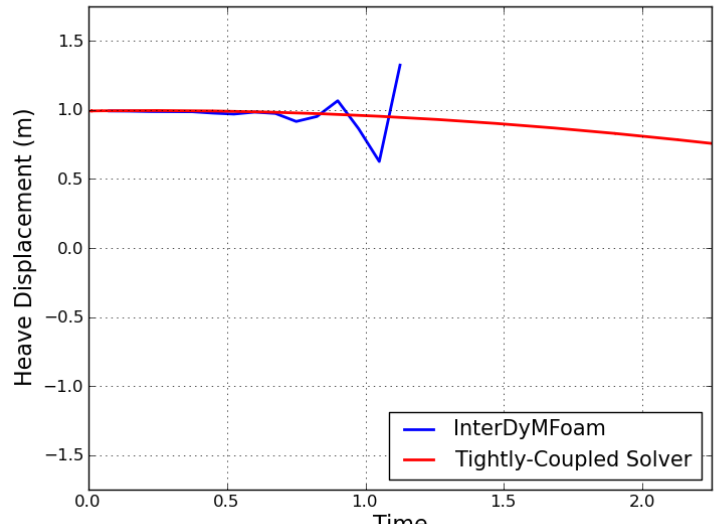
OC4 Phase II Semisubmersible Platform

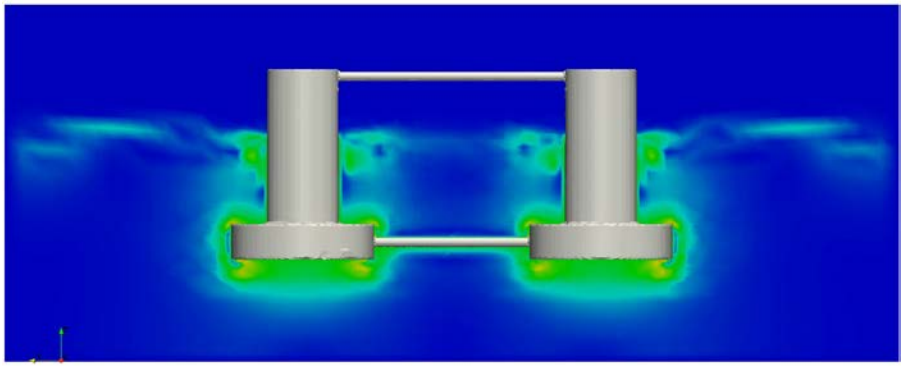
- Offshore Code Comparison Collaboration Continuation (OC4)
  - Organized to create and compare computational tools for offshore wind turbines and support structures
- Platform designed for the DeepCwind project
- Computations designed to simulate the dynamics of the platform at full scale:
  - Free decay
  - Normal operation conditions
  - Extreme conditions
- Participants primarily use reduced order models

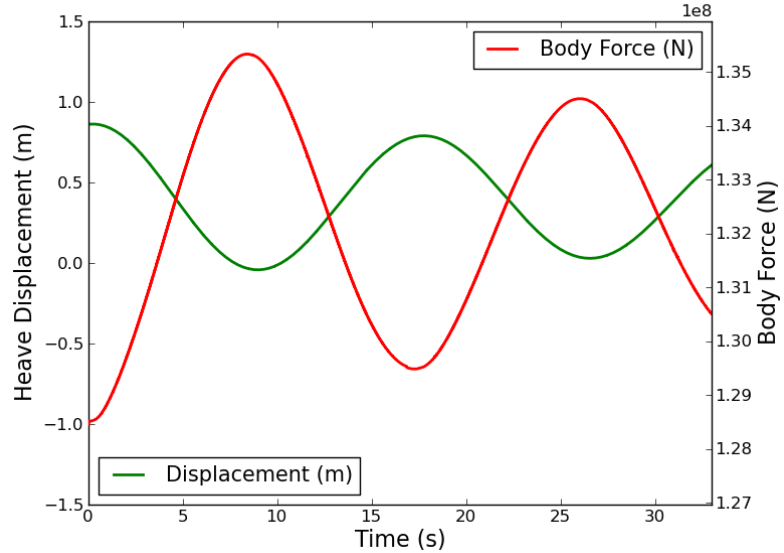


Semisubmersible Free Heave Decay

- Increased stability of solver
  - InterDyMFoam is unstable
  - Tightly-Coupled solver is stable







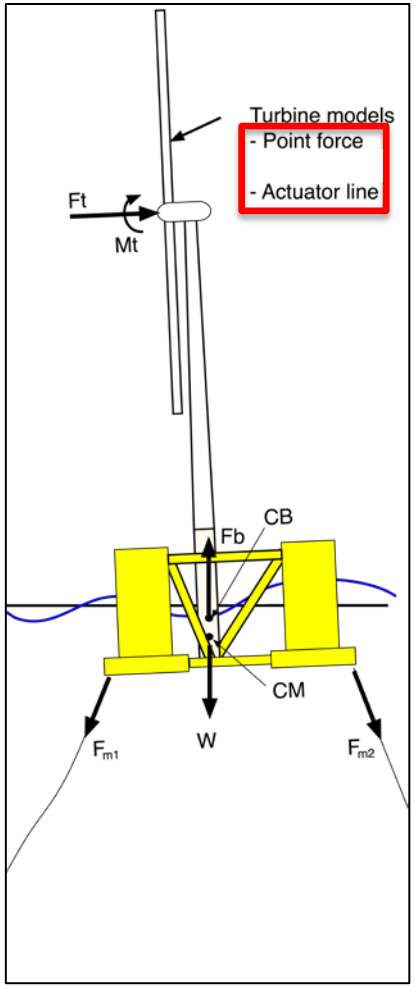
Wind Turbine Models in Tightly-Coupled CFD/6-DOF

Wind turbine model choices:

- Point Force
  - Preliminary Model
  - Constant Force applied at hub height
- Actuator Line Method (ALM)
  - ALM provided by NREL SOWFA 2012
  - In OpenFOAM, ALM is implemented as a source term in the momentum equation

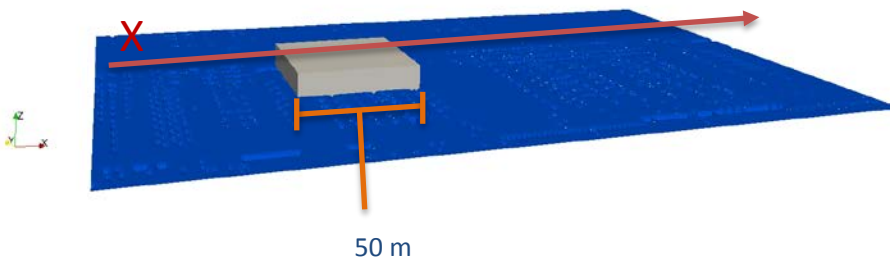
$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{u} - \nabla \cdot \tau_{Turb} + \vec{F}_{ALM}$$

  - Uses lookup tables to update blade loadings each time step
- Adding forces to 6-DOF solver
  - Calculate forces and moments from model
  - Couple platform motion to wind turbine
- Currently implemented in OpenFOAM



Constant Point Force Application

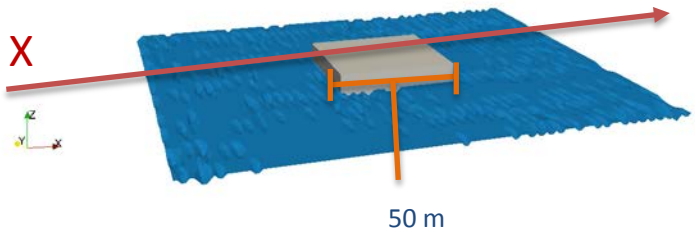
- Applied averaged thrust load to box barge
  - Force applied at hub height (100 m)
  - Constant load of 275KN
  - Applied in the surge direction (x)
- Free motion
  - No mooring line or restraining force applied



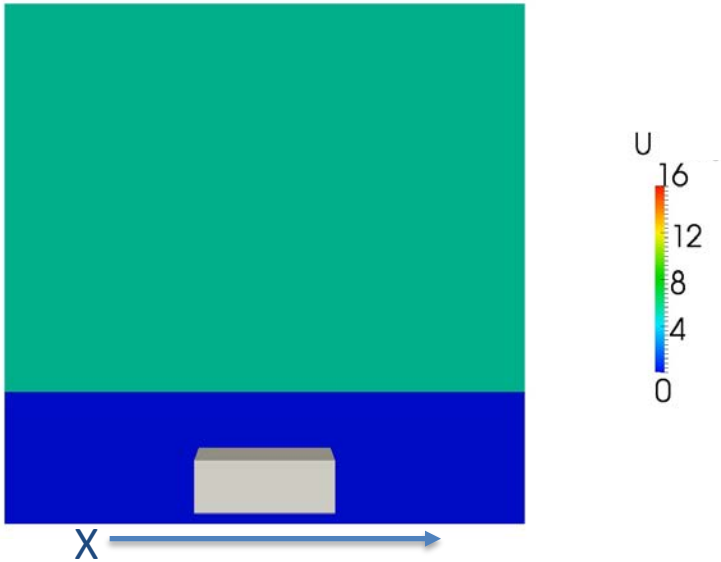
Translation of box barge

Actuator Line Method

- Specified wind inflow above water line
  - Inflow velocity 10 m/s in the surge direction (x) at specified height above free surface
  - Wind turbine blades - NREL 5MW
  - Tower Height of 100M
- Free Motion
  - No mooring line or restraining force applied
- More computationally expensive



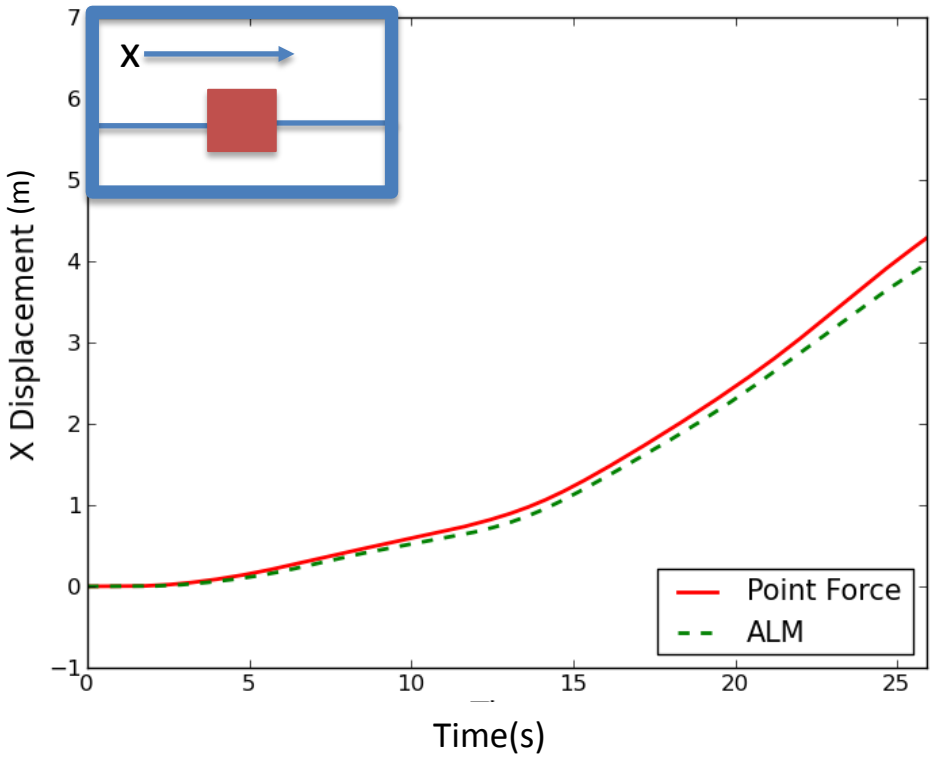
Translation of Box Barge Visualizing Blade Force



Velocity Magnitude Visualizing Blade Force

Comparison of Methods

- Deviation of cases small
  - Little platform motion



- ALM will be important for large platform motion
  - AOA changes

Conclusion

- Tightly-Coupled CFD/6DOF developed and validated
- Solver used to simulate heaving wind turbine platform
- ALM model added to incorporate blade aerodynamics

Future Work

- For accurate ALM simulations:
  - Realistic wind
- For comparison with other models
  - Semisubmersible and tower
  - Mooring line model
  - Wave spectrum model