Development of coupling module between BHawC aeroelastic software and OrcaFlex for coupled dynamic analysis of floating wind turbines

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- Modelization of floating wind turbines
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  - Control
  - Aerodynamics
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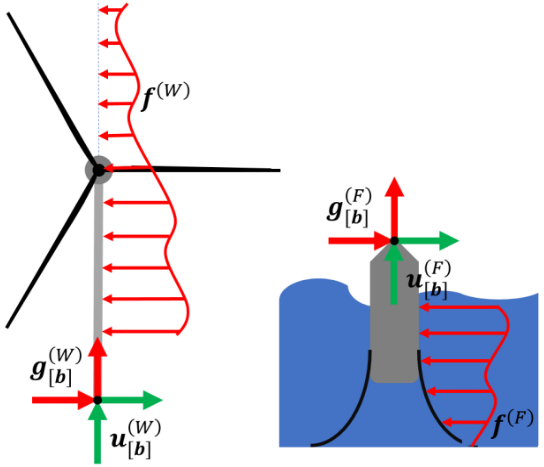
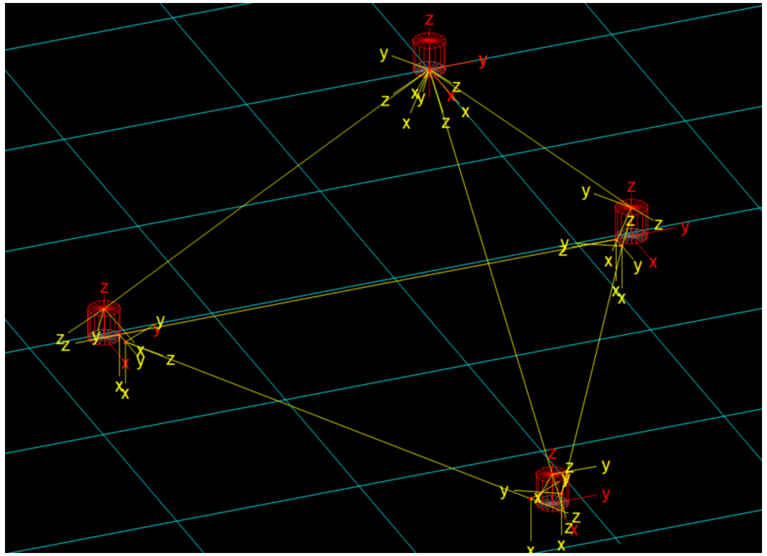
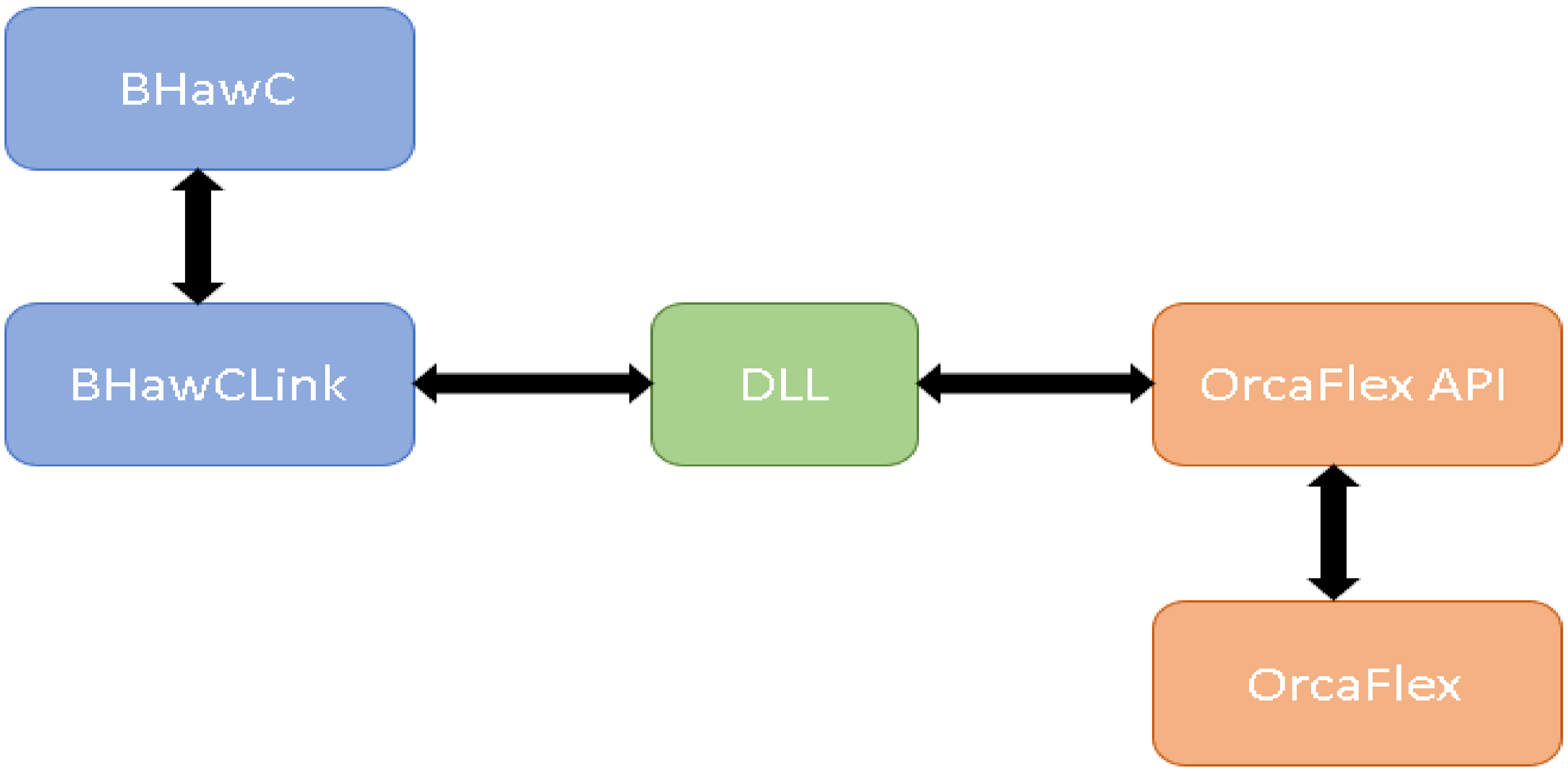
  - BHawC: non-linear aeroelastic tool for dynamic analysis of wind turbines
  - OrcaFlex: dynamic analysis tool for offshore marine systems





Coupling methodology



'Decoupled' equation of motion for substructure (S):

$$\boldsymbol{M}^{(S)}(\boldsymbol{u}^{(S)})\ddot{\boldsymbol{u}}^{(S)} + \boldsymbol{p}^{(S)}(\dot{\boldsymbol{u}}^{(S)}, \boldsymbol{u}^{(S)}) = \boldsymbol{f}^{(S)}(\dot{\boldsymbol{u}}^{(S)}, \boldsymbol{u}^{(S)}) + \boldsymbol{g}^{(S)}$$

Introduce compatibility, and Lagrange multipliers for interface load:

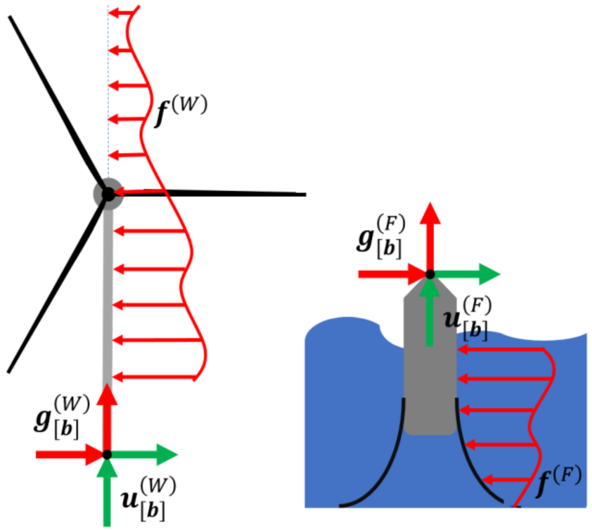
$$\boldsymbol{u}_b^{(W)} - \boldsymbol{u}_b^{(F)} = \boldsymbol{B}^{(W)}\boldsymbol{u}^{(W)} + \boldsymbol{B}^{(F)}\boldsymbol{u}^{(F)} = \boldsymbol{0}; \qquad \boldsymbol{g}^{(S)} = \boldsymbol{B}^{(s)^T}\boldsymbol{\lambda}$$

Generalized alpha time integration of the wind turbine DOF is performed according to:

$$\Delta\boldsymbol{u}_n^{(W)} = -\hat{\boldsymbol{S}}^{(W)^{-1}}\left(\boldsymbol{r}_n^{(W)} + \boldsymbol{B}^{(W)^T}\left((\boldsymbol{1}-\alpha_f)\,\boldsymbol{S}_{int}^F\right)^{-1}\boldsymbol{B}^{(F)}\Delta\hat{\boldsymbol{u}}^{(F)}\right)$$

$$\hat{\boldsymbol{S}}^{(W)} = \boldsymbol{S}^{(W)} + \boldsymbol{B}^{(W)^T}\left(\boldsymbol{S}_{int}^F\right)^{-1}\boldsymbol{B}^{(W)}$$

$$\boldsymbol{S}_{int}^F = \boldsymbol{B}^{(F)}\boldsymbol{S}^{(F)^{-1}}\boldsymbol{B}^{(F)^T}$$



Mathematical background

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Condensing Foundation DOF onto 6 equivalent interface DOF

$$\boldsymbol{M}_{eqv}^{(\boldsymbol{F})}(\boldsymbol{u}^{(\boldsymbol{F})})\ddot{u}_{int}^{(F)} + \boldsymbol{p}_{\text{eqv}}^{(F)}(\dot{\boldsymbol{u}}^{(\boldsymbol{F})}, \boldsymbol{u}^{(\boldsymbol{F})}) + \boldsymbol{B}^{\boldsymbol{T}}\boldsymbol{\lambda} = \boldsymbol{f}_{\text{eqv}}^{(F)}(\dot{\boldsymbol{u}}^{(\boldsymbol{F})}, \boldsymbol{u}^{(\boldsymbol{F})})$$

$$\boldsymbol{S}_{int}^{F} = \boldsymbol{B}^{(F)}\boldsymbol{S}^{(F)^{-1}}\boldsymbol{B}^{(F)^{T}} \approx \boldsymbol{S}_{eqv}^{F}$$

Advantages of this approach:

- Allows for limited data exchange
- Linearised per timestep: accurate for slow floater dynamics

Challenges:

- Linearization of trussframe structures

Data Exchanged during Newton Raphson iterations

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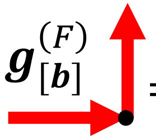
Matrix / Vector	Part modelled	Contribution
Mass ($\boldsymbol{M}_{\text{eqv}}^{(F)}$)	Floater	Mass Hydrodynamic added mass
	Mooring lines	Mass Hydrodynamic added mass
Stiffness ($\boldsymbol{K}_{t,\text{eqv}}^{(F)}$)	Floater	Hydrostatic stiffness Structural stiffness
	Mooring lines	Mooring stiffness Hydrostatic stiffness
Damping ($\boldsymbol{C}_{t,\text{eqv}}^{(F)}$)	Floater	Linear & Quadratic damping Hydrodynamic drag Structural damping Radiation damping
Load ($\boldsymbol{g}_{1}^{(W)}$)	Floater	Excitation loads Weight Hydrostatic stiffness Radiation damping Hydrodynamic drag Structural stiffness Structural damping Linear & Quadratic damping
	Mooring lines	Weight Hydrodynamic drag Mooring stiffness

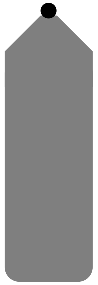
Data Exchanged during Newton Raphson iterations

- Load vector $\boldsymbol{g}_1^{(W)}$
  - FASTExtractAddedMassAndLoad OrcaFlex-API function;
  - Contains the frequency dependent added mass contribution.



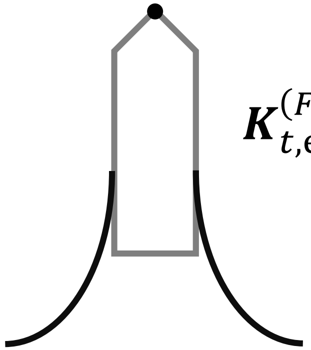
$$\boldsymbol{g}_{[b]}^{(F)} = \left[\boldsymbol{p}^{(F)} + \widetilde{\boldsymbol{f}^{(F)}(\omega)} \right]$$

- Mass matrix $\boldsymbol{M}_{\text{eqv}}^{(F)}$
  - FASTExtractAddedMassAndLoad OrcaFlex-API function;
  - Only contains the frequency independent added mass.



$$\boldsymbol{M}_{\text{eqv}}^{(F)} = \left[\boldsymbol{M}^{(F)} + \widetilde{\boldsymbol{M}^{(F)}}(\omega_{inf}) \right]$$

- Stiffness matrix $\boldsymbol{K}_{t,\text{eqv}}^{(F)}$
  - $\boldsymbol{K}_{t,\text{eqv}}^{(F)} = \boldsymbol{K}_{mooring} + \boldsymbol{K}_{vessel}$;
  - $\boldsymbol{K}_{mooring}$ evaluated in shadow stiffness model;
  - $\boldsymbol{K}_{vessel}$ directly read in OrcaFlex model.

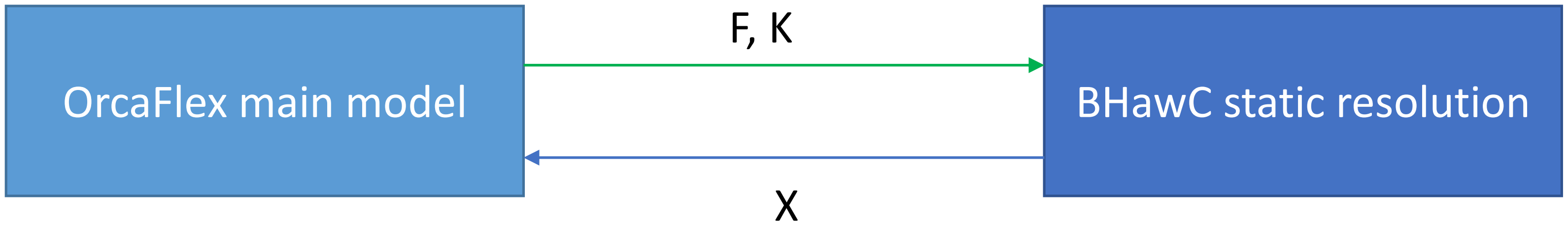


$\boldsymbol{K}_{t,\text{eqv}}^{(F)}$

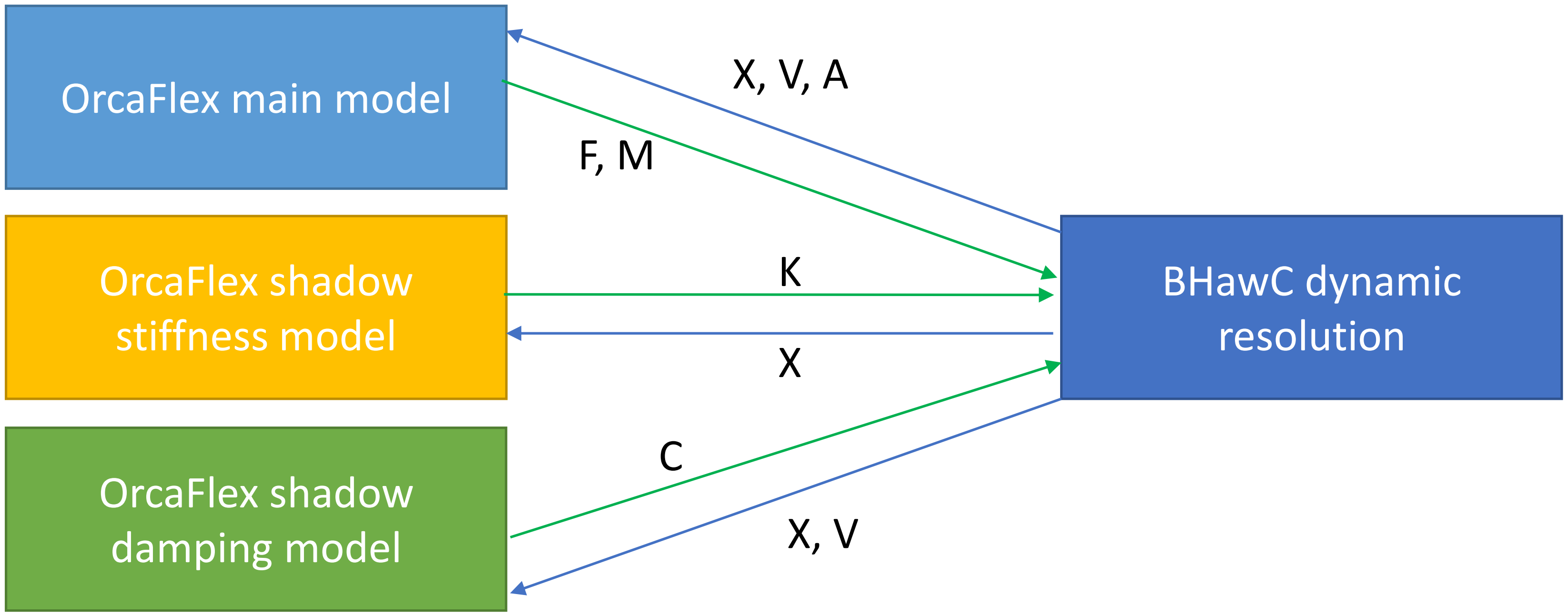
- Damping matrix $\boldsymbol{C}_{t,\text{eqv}}^{(F)}$
  - $C_{ii}(t) = \frac{f_i(t)-f_i(t-\Delta t)}{\dot{x}_i(t)-\dot{x}_i(t-\Delta t)}$;
  - $f_i(t)$ evaluated in a shadow damping model.

Data Exchanged during Newton Raphson iterations

- Static phase (ramping gravitational, internal and steady wind loads)



- Dynamic phase (ramping wave, current and vessel motion during initialization)



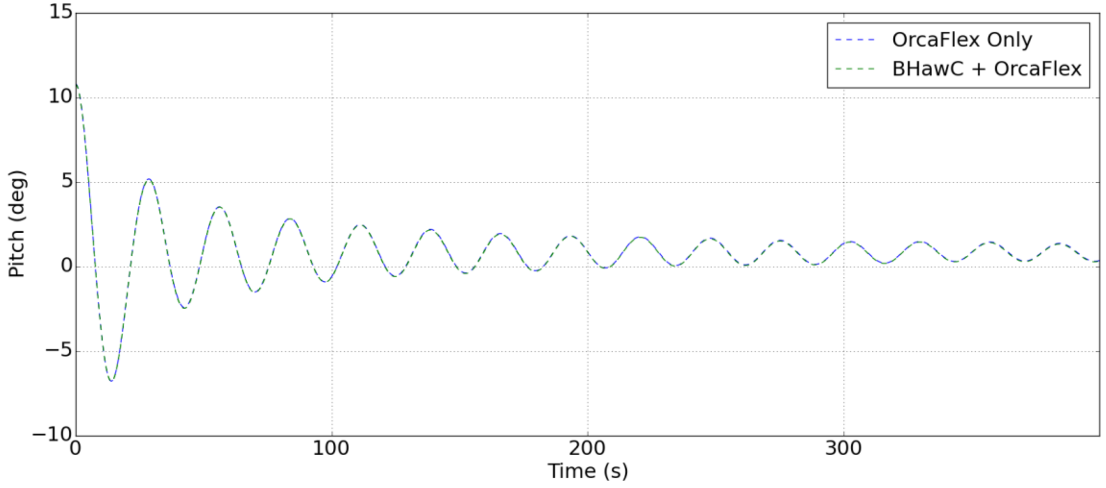
Data Exchanged during Newton Raphson iterations

- Shadow models
  - Shadow damping model
    - Environment:
      - Wave, current and wind are deactivated;
      - Excitation loads neglected;
    - OrcaFlex elements:
      - Mass, added mass and buoyancy neglected.
      - Damping contributions are kept.
  - Shadow stiffness model
    - Interface position imposed
    - System static equilibrium solved by OrcaFlex
    - The stiffness matrix at that position is then calculated by OrcaFlex.

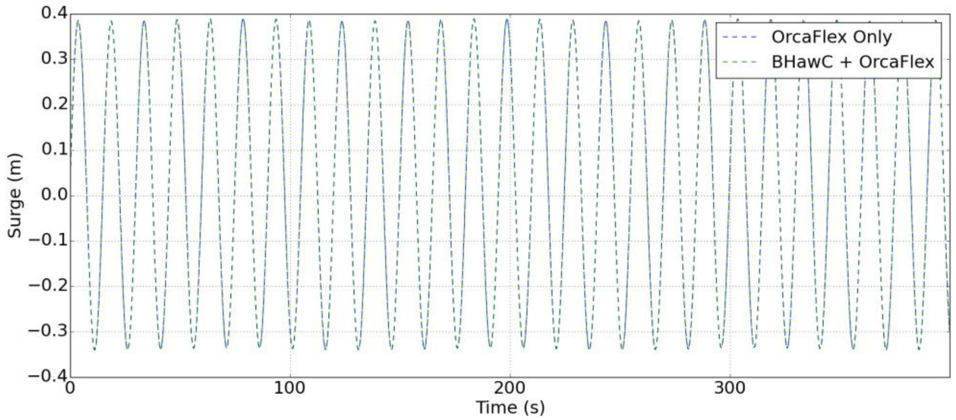
Verification

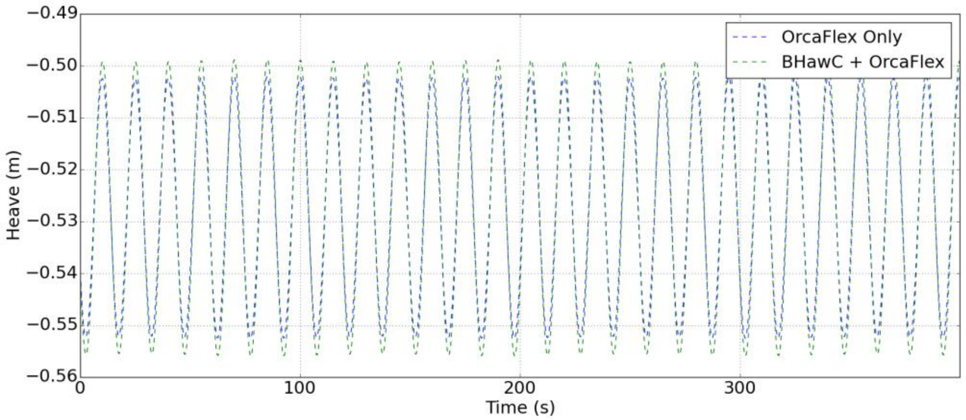
- Static equilibrium test with and without wind;
- Decay tests with and without wind;
- Regular and irregular waves with and without wind simulations.

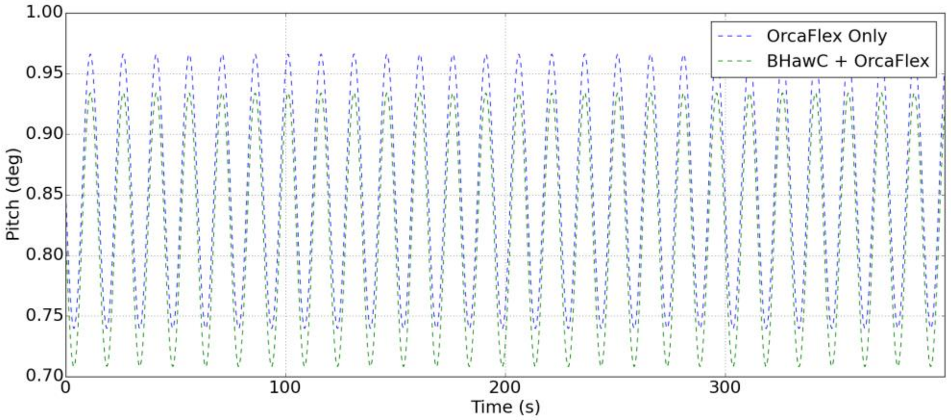
DOF	Eigen Period (s)		Difference (%)
	BHawC + OrcaFlex	OrcaFlex only	
Surge	112,5 s	111,4 s	1.0%
Sway	112,9 s	112,6 s	0.3%
Heave	17,6 s	17,5 s	0.6%
Roll	27,8 s	27,6 s	0.7%
Pitch	27,5 s	27,6 s	-0.4%
Yaw	80,1 s	80,8 s	-0.9%



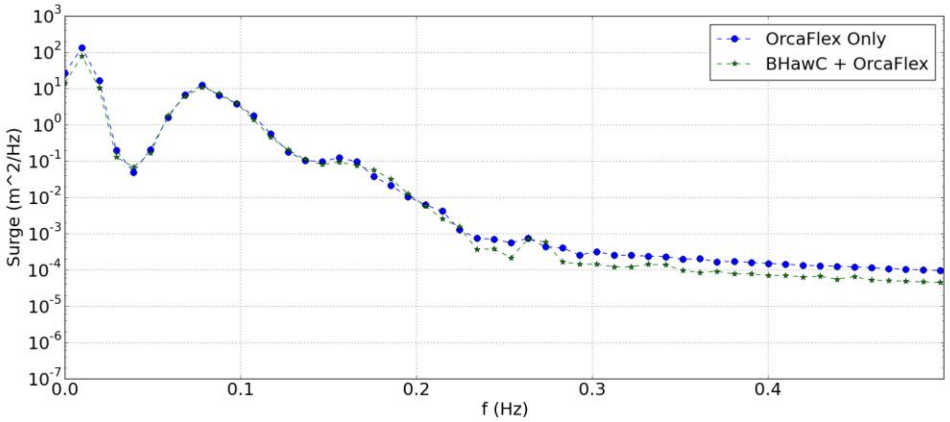
Verification

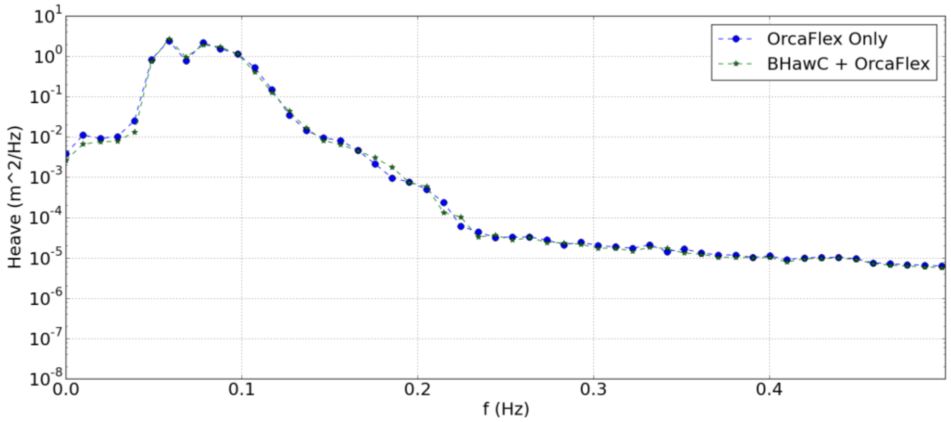


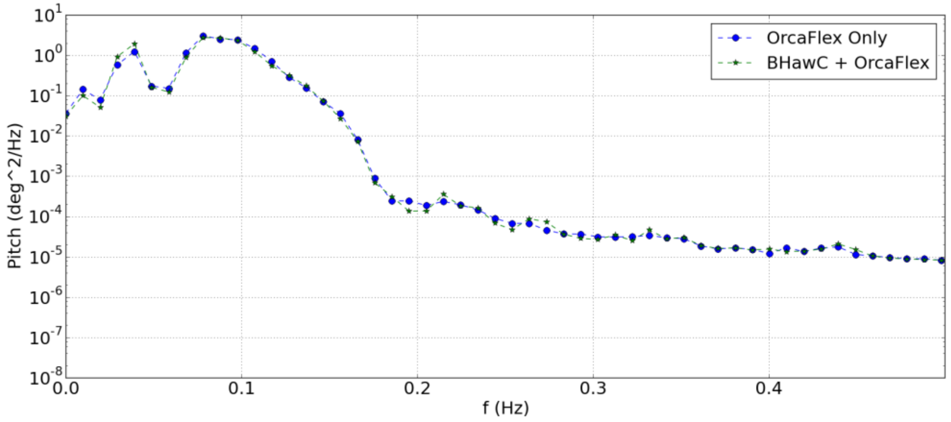




Verification







Conclusion

- Large range of floaters and mooring system
- Flexibility offered by OrcaFlex and coupling methodology
- Verifications on rigid floater showed a very good agreement
- Verifications on flexible floater still on going but showed a very good agreement

- Further developments:
  - Simulation CPU time for complex model
  - Different timestep for each domain
  - Improve convergence of flexible floaters models
  - Modal analysis

Difference between Fast-OrcaFlex and BHawC-OrcaFlex

Fast-OrcaFlex	BHawC-OrcaFlex
Rigid floater only	Rigid and Flexible floater
Total floater mass defined in FAST	Floater can be defined into separated elements in OrcaFlex
Wind turbine modelization and interface motion calculation done in FAST	Wind turbine modelization and interface motion calculation done in BHawC
Load vector and Mass matrix exchanged at each time step	Load vector, Mass, Damping and Stiffness matrix exchanged at each time step
	Iterations are done in BhawC using stiffness and damping matrices
Position, Velocity and Acceleration imposed in OrcaFlex at each time step	Position, Velocity and Acceleration imposed in OrcaFlex at each time step