FULLY COUPLED HYDROELASTIC ANALYSIS OF FLOATING WIND PLATFORMS

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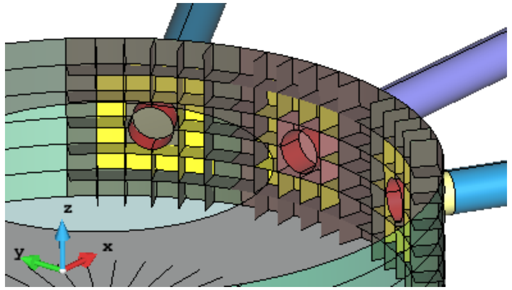
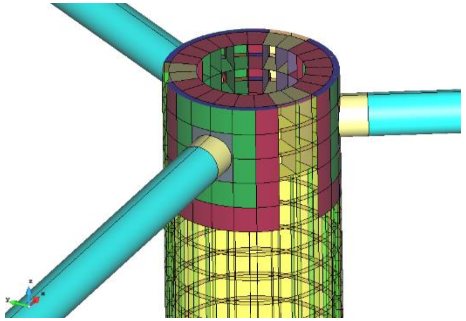
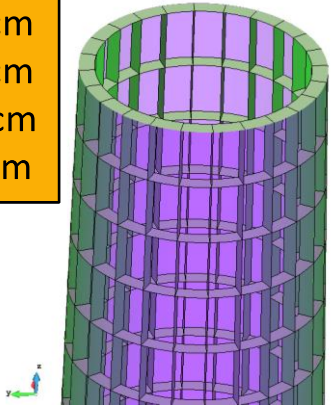
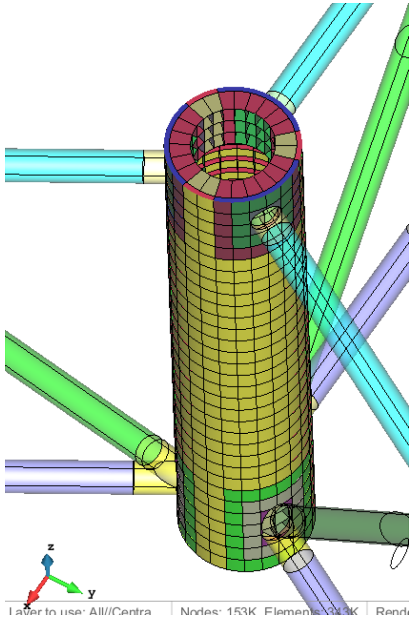
CIMNE–DeepCwind: Structural details

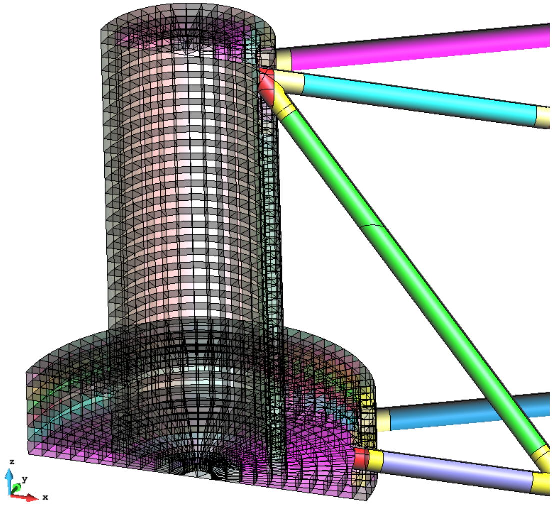
Steel thickness:
Bracing…………..1.75cm
Heave plates……… 3cm
Columns……………..2cm
Central column……2cm
Tower……………..1.35cm

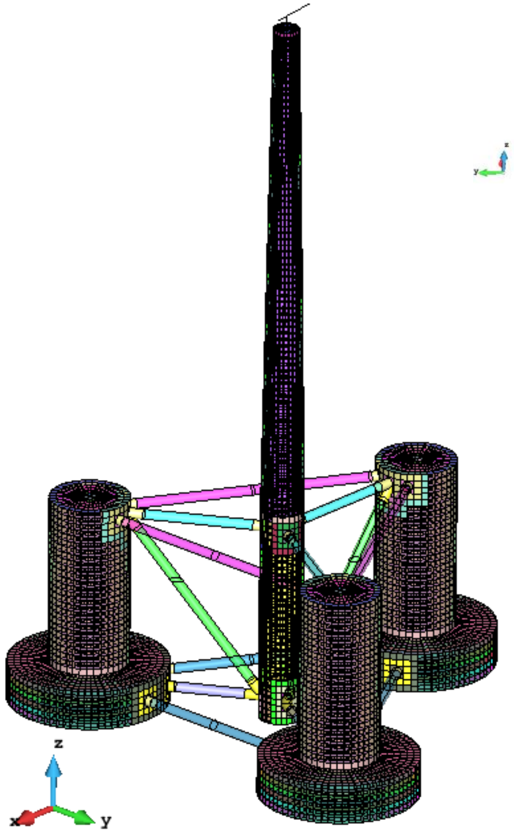


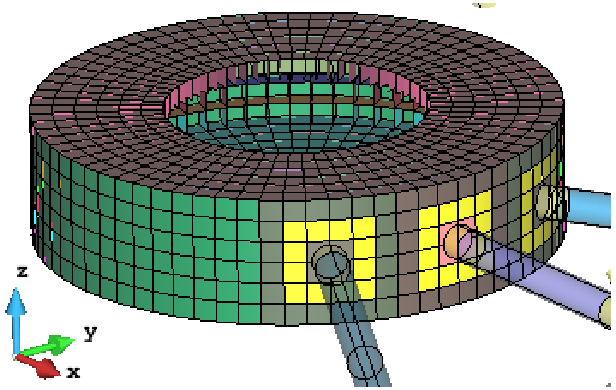






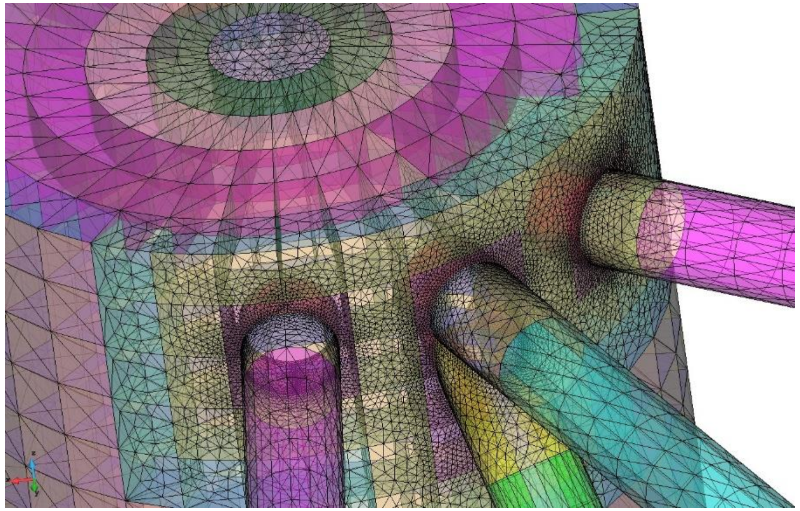






CIMNE – DeepCwind:

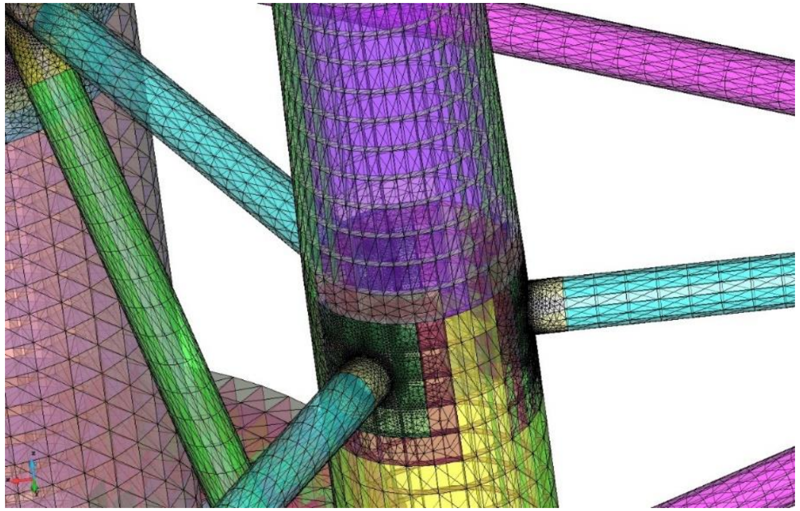
	Unit	OC4-DeepCwind	CIMNE-DeepCwind
Mass (with ballast)	kg	14,072,718	14,077,353
Downwind distance of CM	m	0.00	0.00
Lateral distance of CM	m	0.00	0.00
Vertical distance of CM	m	-9.888	-11.057
Roll inertia about CM	$kg\cdot m^2$	$12{,}581\cdot 10^6$	$11{,}206\cdot 10^6$
Pitch inertia about CM	$kg\cdot m^2$	$12{,}567\cdot 10^6$	$11{,}140\cdot 10^6$
Yaw inertia about CM	$kg\cdot m^2$	$12{,}290\cdot 10^6$	$11{,}302\cdot 10^6$
Ballast mass	kg	$9.6208\cdot 10^6$	$8.5062\cdot 10^6$



Natural periods:

	NREL-DeepCwind	CIMNE DeepCwind
Surge	107.52 s	112.2 s
Sway	113.63 s	112.025 s
Heave	17.24 s	16.72 s
Roll	27.03 s	23.3 s
Pitch	27.02 s	23.275 s
Yaw	83.33 s	78.13 s

Finite Element Particulars:
380,999 FEs
171,025 Nodes
1,026,150 DOFs
Min. FE size: 2cm
Max. FE size: 1m



MODAL MATRIX REDUCTION (MMR)

Structural dynamics…………………… $\bar{\bar{\boldsymbol{M}}}\ddot{\boldsymbol{u}}(t) + \bar{\bar{\boldsymbol{C}}}\dot{\boldsymbol{u}}(t) + \bar{\bar{\boldsymbol{K}}}\boldsymbol{u}(t) = \boldsymbol{f}(t) = \boldsymbol{f}_D(t) + \boldsymbol{f}_S$ **Structural FEM solver**

Structural displacements …. … $\boldsymbol{u}(t) = \boldsymbol{u}_D(t) + \boldsymbol{u}_S$

Finite element system……………. $\begin{cases} \bar{\bar{\boldsymbol{M}}}\ddot{\boldsymbol{u}}_D(t) + \bar{\bar{\boldsymbol{C}}}\dot{\boldsymbol{u}}_D(t) + \bar{\bar{\boldsymbol{K}}}\boldsymbol{u}_D(t) = \boldsymbol{f}_D(t) \\ \bar{\bar{\boldsymbol{K}}}\boldsymbol{u}_S = \boldsymbol{f}_S \end{cases}$

Eigenvalue problem………………… $\left(\bar{\bar{\boldsymbol{M}}}^{-1}\bar{\bar{\boldsymbol{K}}}\right)\boldsymbol{a} = \Omega^2\boldsymbol{a}$

Modal basis solution……………… $\boldsymbol{u}_D(t) = \sum_{i=1}^{N_{DOF}} \boldsymbol{q}_i(t)\,\boldsymbol{a}_i$

MMR approximation……………. $\boldsymbol{u}_{MMR}(t) = \sum_{i=1}^{N_m} q_i(t)\,\boldsymbol{a}_i \approx \boldsymbol{u}_D(t)$ $\quad N_m \sim O(10^2 - 10^3) \ll N_{DOF} \sim O(10^6)$

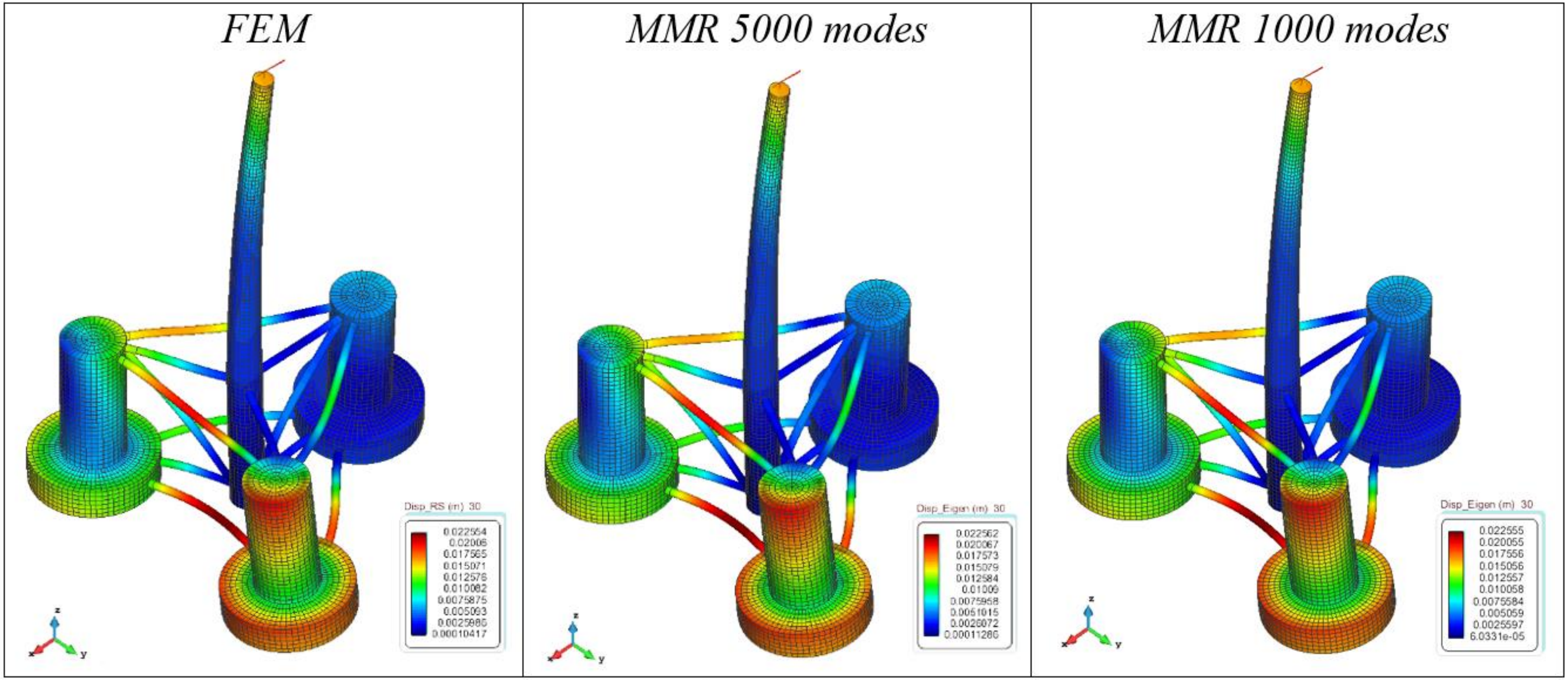
High fidelity approximation **Large reduction of DOFs**

MMR system………………………… $\ddot{q}_i(t) + c_i\dot{q}_i(t) + \Omega_i^2 q_i(t) = \boldsymbol{f}_D(t)\cdot\boldsymbol{a}_i \quad i = 1,2,\dots,N_m \quad c_i = \begin{cases} \alpha_M + \alpha_K\Omega_i^2 & Rayleigh \\ 2\eta\Omega_i & Modal\ damping \end{cases}$

Structural MMR solver **Fast computation**

Energy convergence criterion……… $\frac{E_{FEM}^D - E_{MMR}^D}{E_{FEM}^D} < \epsilon \begin{cases} E_{FEM}^D(t) = \boldsymbol{u}_D^T\bar{\bar{\boldsymbol{K}}}\boldsymbol{u}_D \\ E_{MMR}^D(t) = \boldsymbol{u}_{MMR}^T\bar{\bar{\boldsymbol{K}}}\boldsymbol{u}_{MMR} = \sum_{i=1}^{i=N_m}\frac{1}{2}\Omega_i^2 q_i^2 \end{cases}$

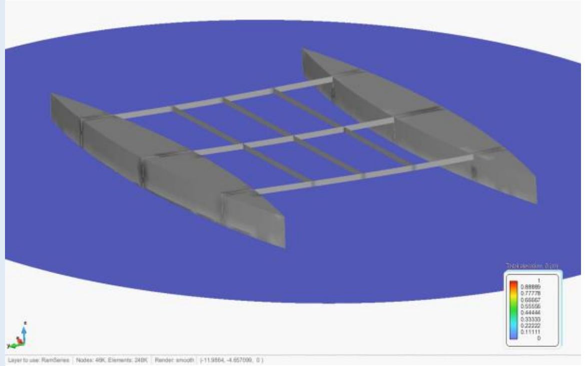
HYDROSTATIC EQUILIBRIUM

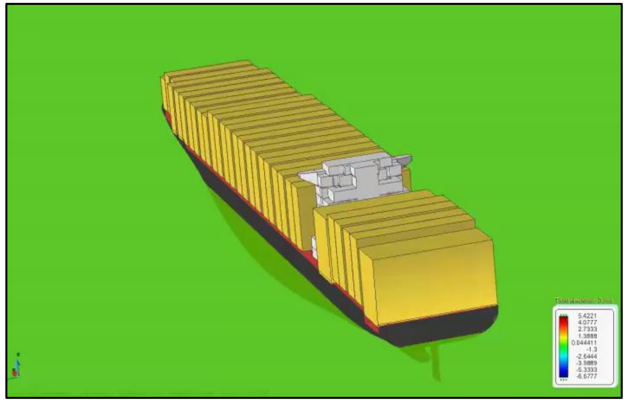


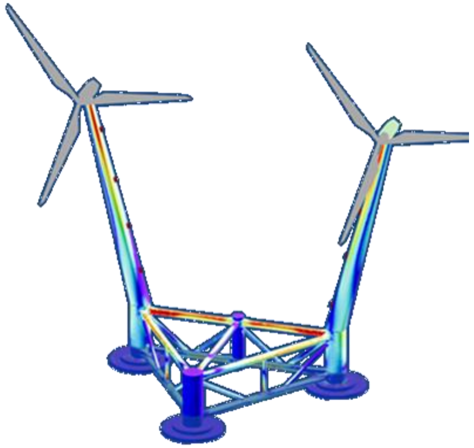
SEAFEM®: https://www.compassis.com/en/tdyn/seakeeping-tdyn-seafem/

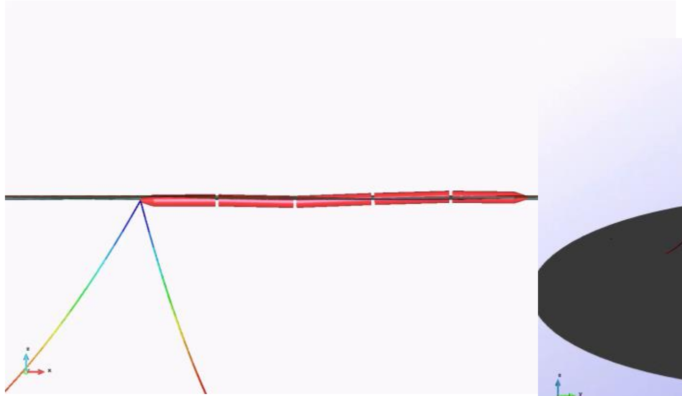
SeaFEM suite of tools:

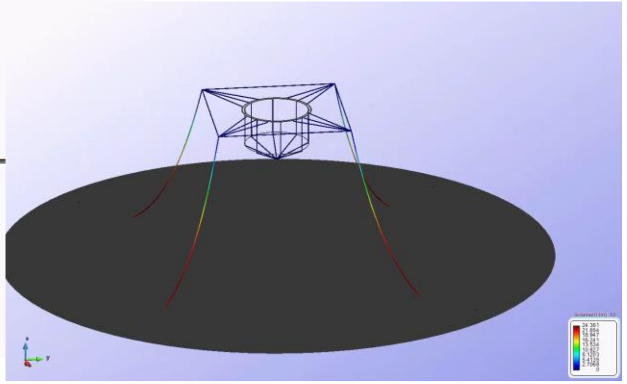
- **Wave diffraction-radiation**
  - 2nd order Time-domain solver
  - Based on FEM
- **Mooring solver**
  - Springs
  - Elastic catenary
  - Dynamic FEM
  - Multi-segment lines
- **Rigid Body Solver**
  - Multibody systems
  - Body links
  - Morison elements
- **Structural solver**
  - Full FEM: $\overline{\overline{\boldsymbol{M}}}$ & $\overline{\overline{\boldsymbol{K}}}$
  - MMR: modal base $\boldsymbol{a}_i(\boldsymbol{x})$
- **Wind turbine solver**
  - OpenFAST coupling

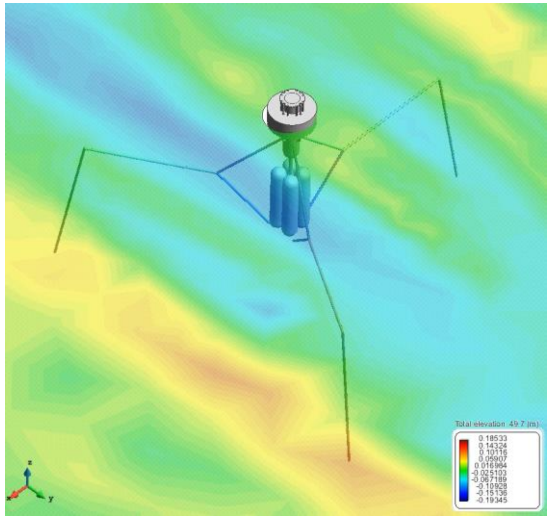






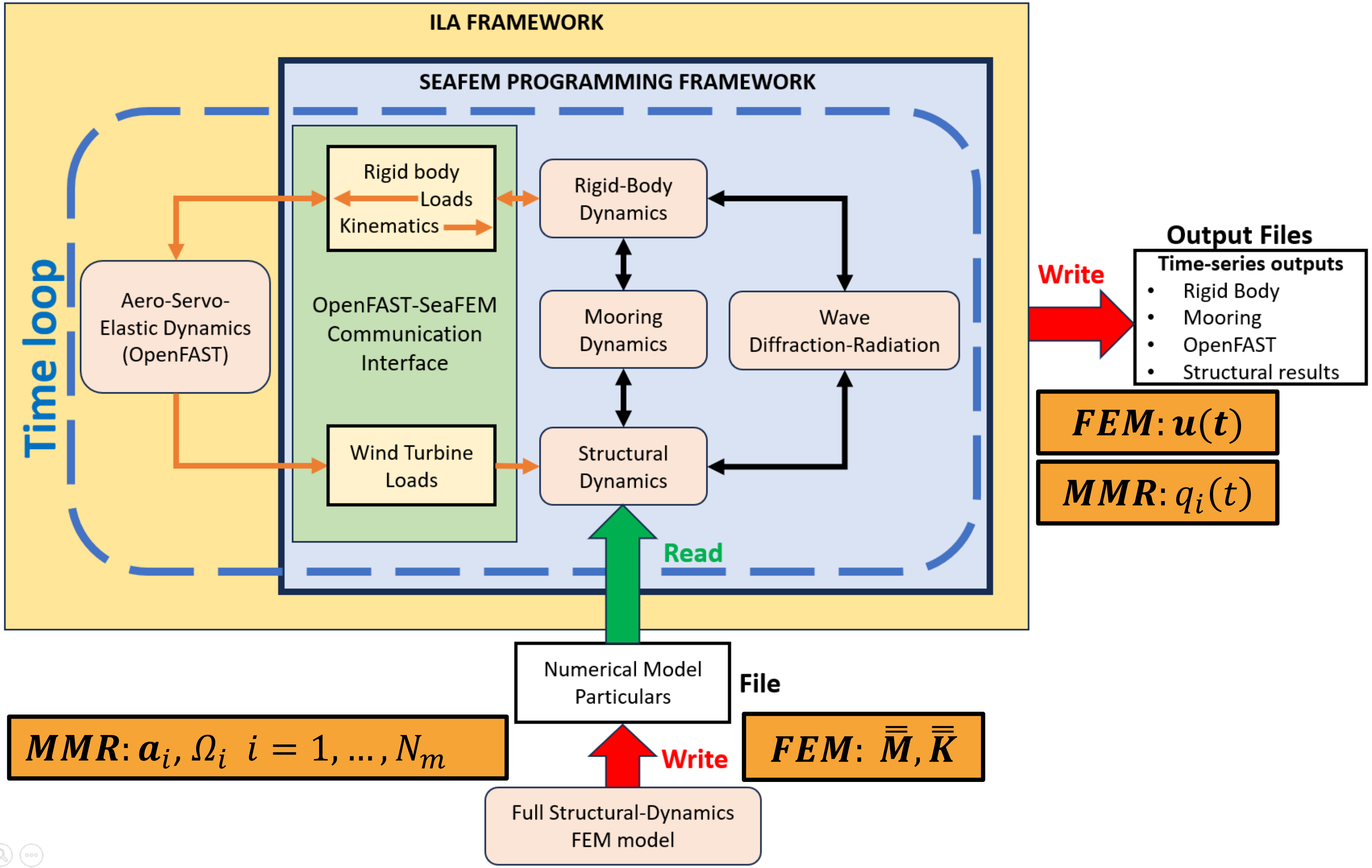






ILA FRAMEWORK

1-way/2-ways coupling

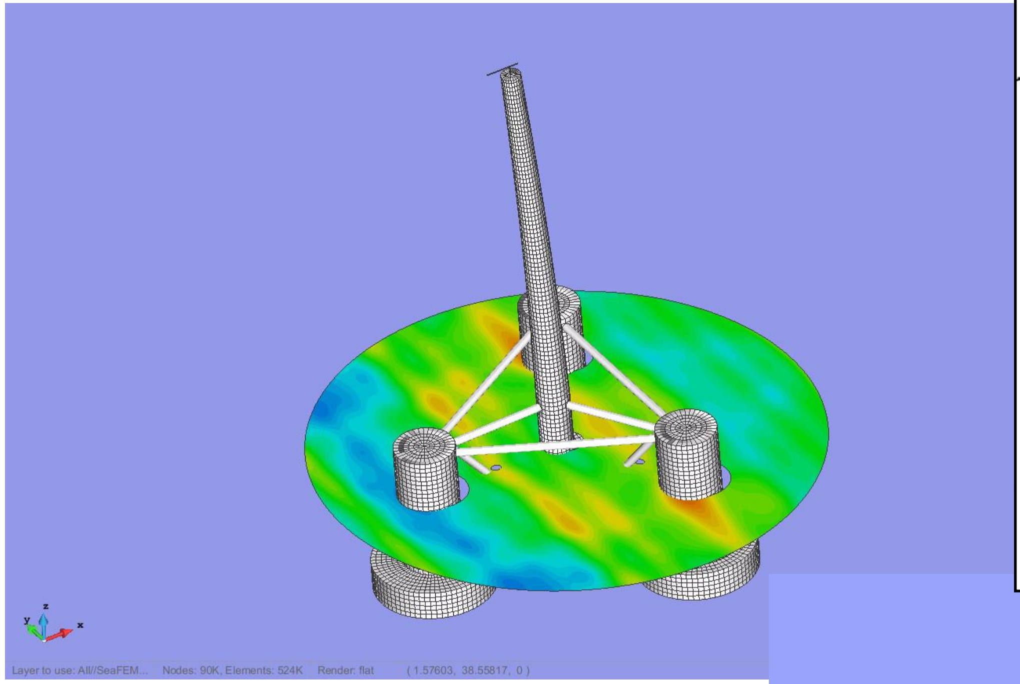


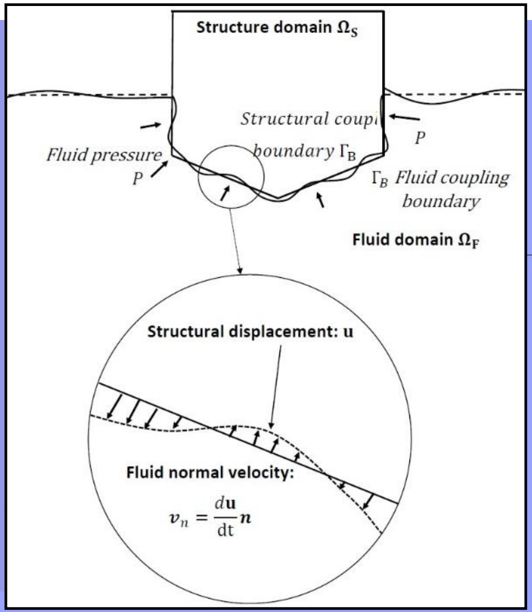
Advantages:

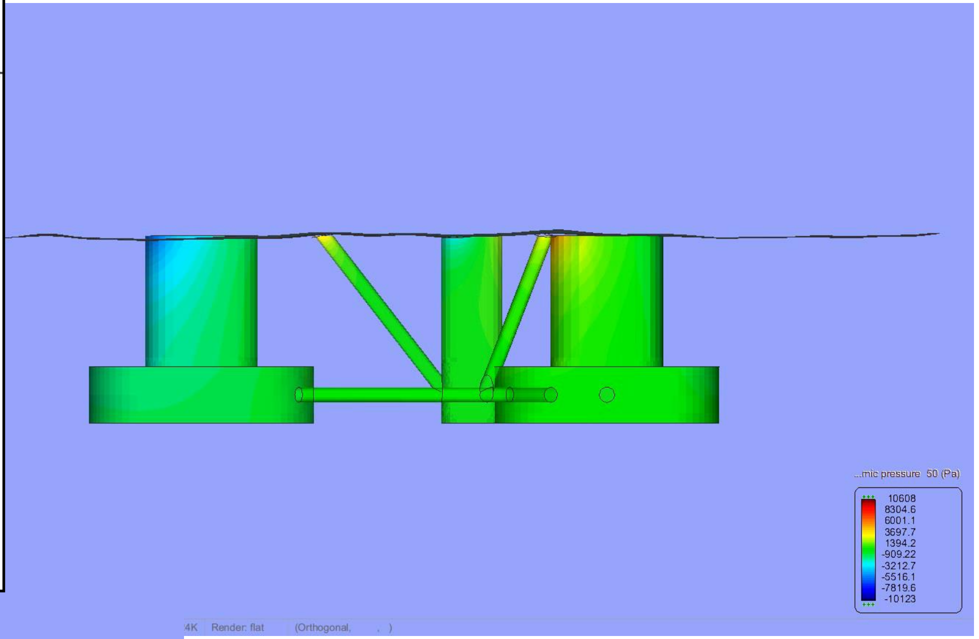
- All computed simultaneously in the time-domain (on the fly).
- Fast communication among solver (happens at RAM memory level)
- No need to write/read files from different softwares.
- Structural stresses can be reconstructed offline (afterwards) on demand.

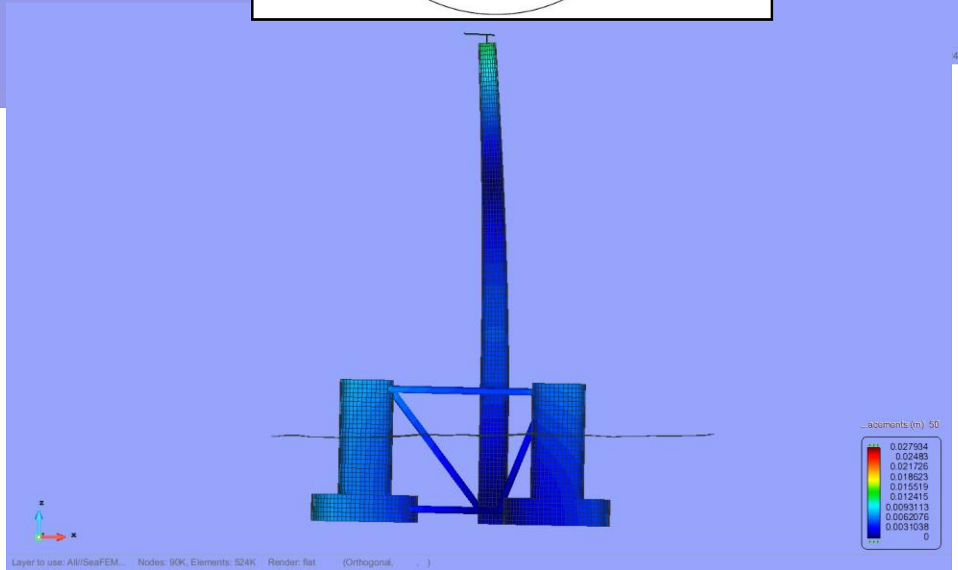
HYDROELASTIC SOLVER COUPLING

Wave diffraction-radiation (FEM) – Structural (FEM) coupling



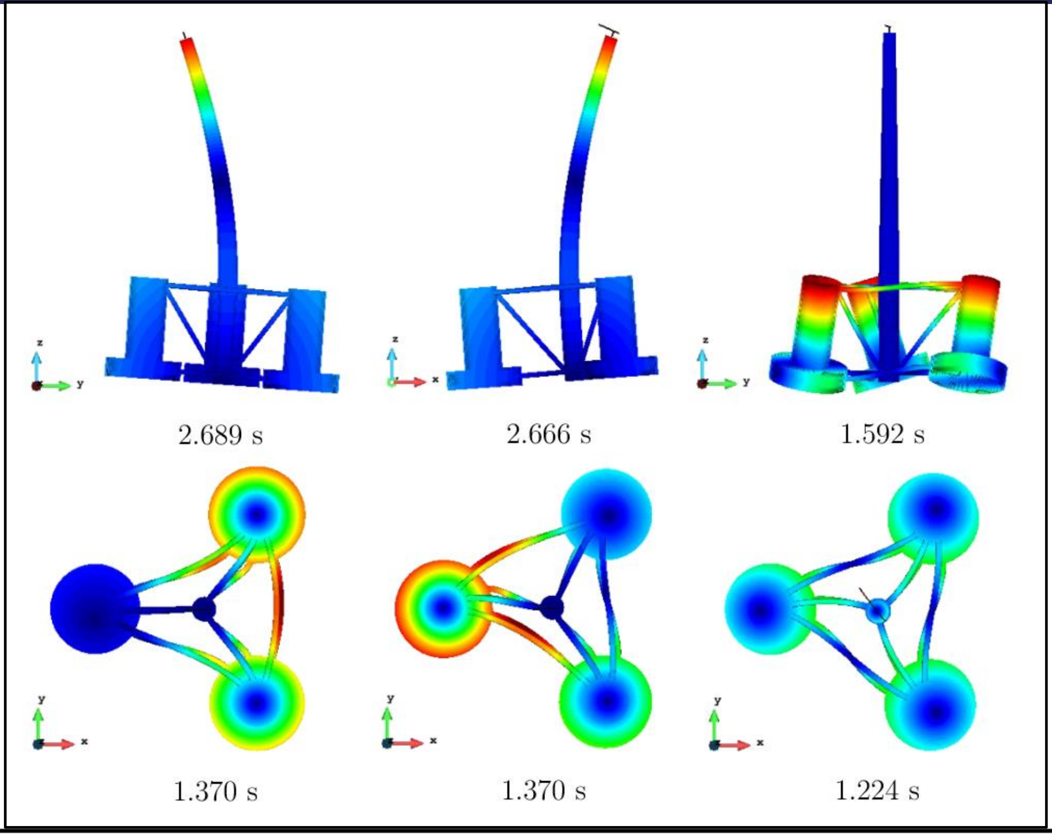




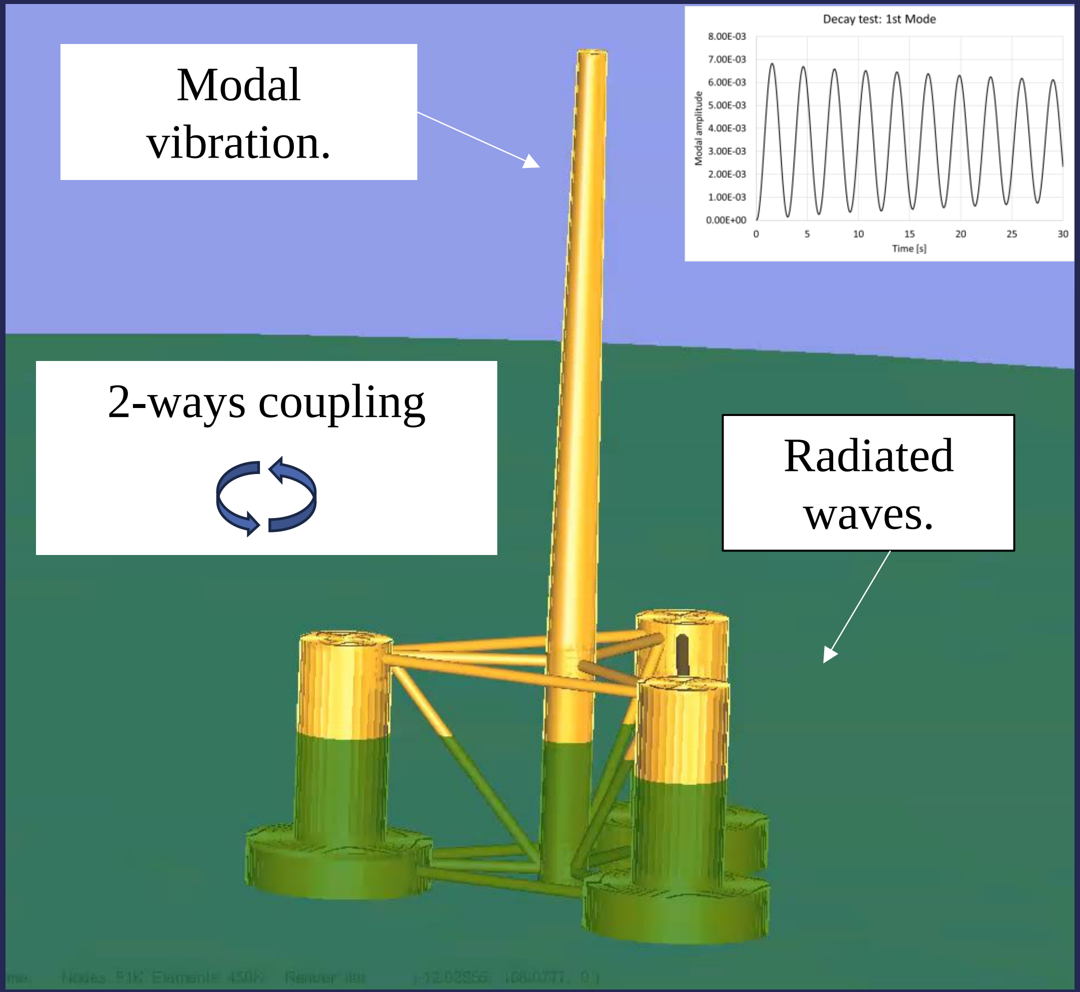


CIMNE

MODAL DECAY TEST



	1st Mode	2nd Mode	3rd Mode
Dry period [s]	2.689	2.666	1.592
Wet period [s]	3.055	3.033	1.769
Wave radiation damping [%]	0.462	0.456	0.968



Modal decay test.

MODAL RESPONSE AMPLITUDE OPERATORS (MRAOS)

QS: quasistatic $(\bar{\bar{M}}\ddot{u}_D(t) + \bar{\bar{C}}\dot{u}_D(t) + \bar{\bar{K}}u_D(t) = f_D(t))$

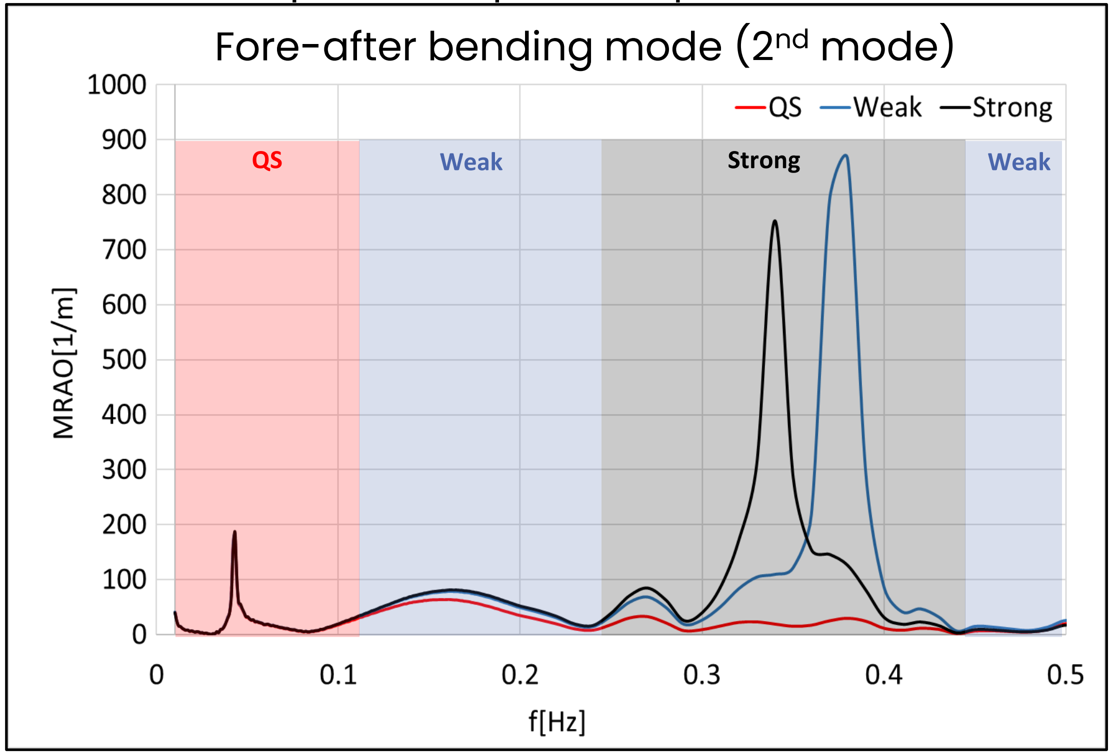
Weak: dynamic & 1-way coupling

Strong: dynamic & 2-ways coupling

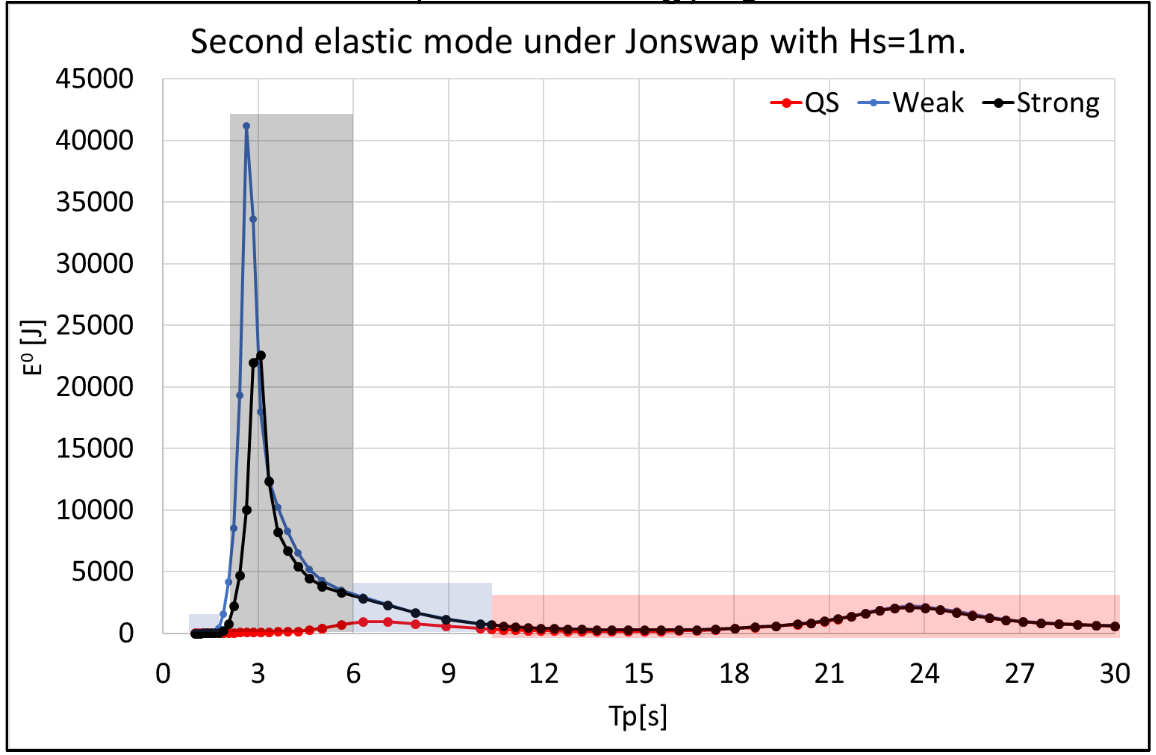
Spectral modal energy $S_m(\omega) = \Omega_m^2\, S_w(\omega)\, MRAOs(\omega)^2$

Zero order moment: $E_m^0 = \int_0^\infty S_m(\omega)d\omega$

Modal Response amplitude Operators (MRAOs)



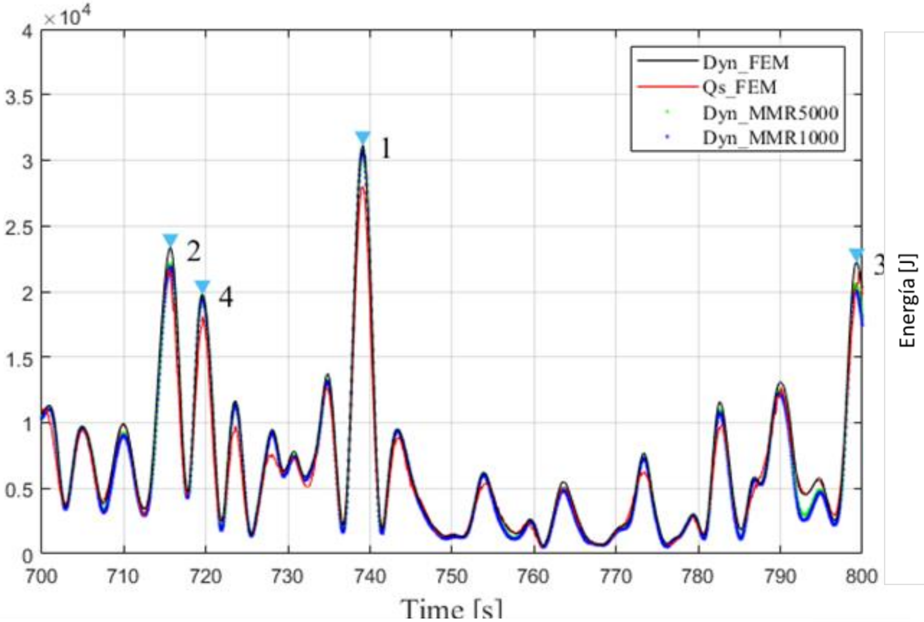
Spectral energy E_2^0

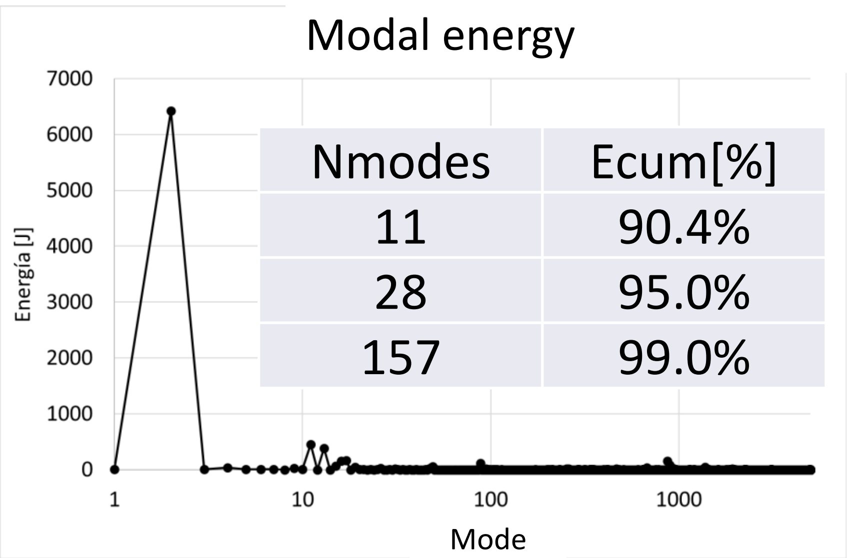


CIMNE

DLC 1.6 ANALYSIS

DLC	1.6 Production design
Site location	Morro Bay (California)
Depth	200m
System condition	Intact
Wind	Speed: 14.8 m/s (hub height)
	Normal turbulence
Waves	Severe
	Spectrum: Jonwap
	Hs=6m
	T=14 s
	Direction: 0º
	Spreading: Unidirectional





Nmodes	Ecum[%]
11	90.4%
28	95.0%
157	99.0%

Analysis type	Dynamic FEM	Dynamic		Quasistatic	
		MMR 5000	MMR 1000	MMR 5000	MMR 1000
Peak 1	100%	99.07%	98.74%	88.19%	87.87%
Peak 2	100%	95.05%	93.87%	86.26%	85.10%
Peak 3	100%	92.31%	89.93%	84.90%	82.52%
Peak 4	100%	99.16%	98.83%	85.97%	85.63%

	Modo	E [J]	E[%]	CumE[%]
1	2	6421	71.8%	71.8%
2	11	448	5.0%	76.8%
3	13	379	4.2%	81.1%
4	17	161	1.8%	82.8%
5	865	155	1.7%	84.6%
6	16	154	1.7%	86.3%
7	88	118	1.3%	87.6%
8	894	88	1.0%	88.6%
9	15	63	0.7%	89.3%
10	49	52	0.6%	89.9%
11	1376	42	0.5%	90.4%

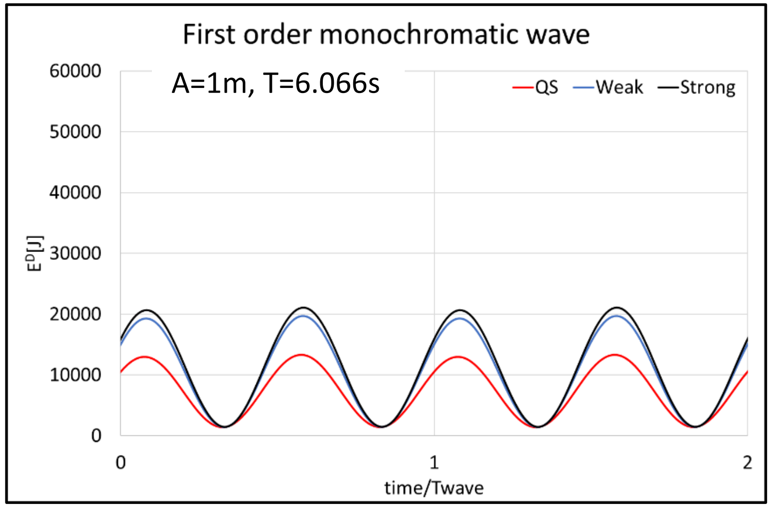
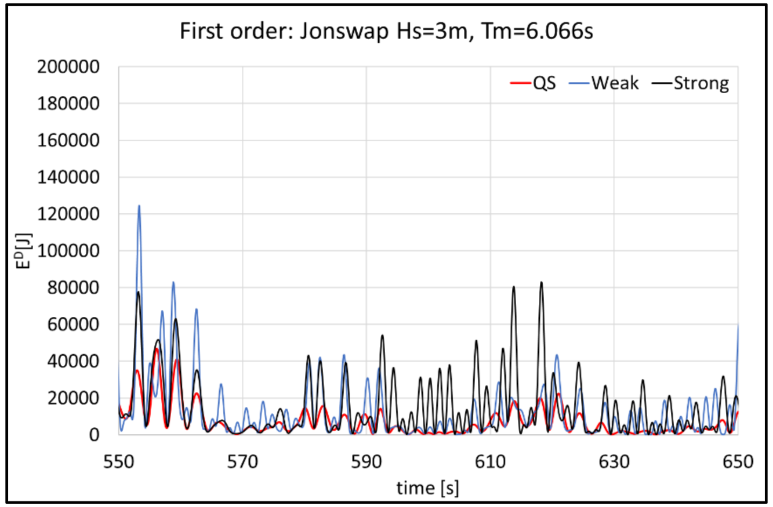
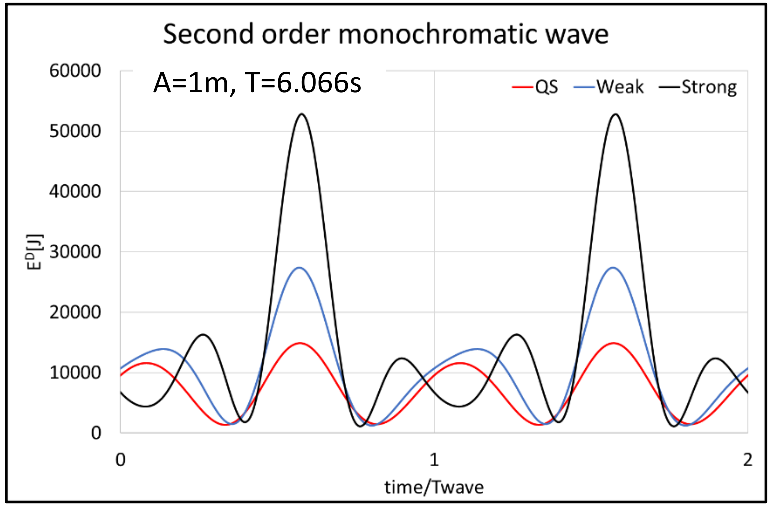
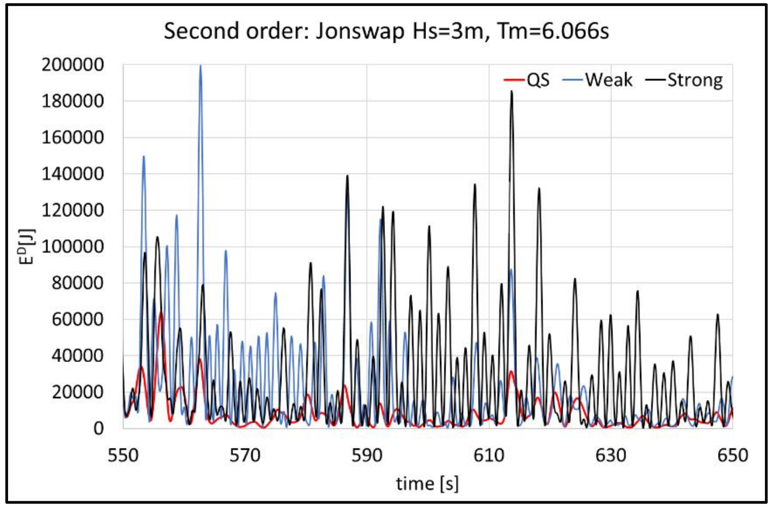
OpenMP with 4 threads.
CPU: AMD Ryzen Threadripper 3970X 3.70GHz.

Computational time / simulation time

Solver		Hydroelastic coupling	
		1-way (weak)	2-ways (strong)
Rigid Body+Dynamic Mooring (FEM):		0.66 s/s	1.03 s/s
Wave diffraction-radiation		0.87 s/s	1.37 s/s
Structural	FEM	**4.6** s/s	**50** s/s
	MMR5000	**0.47** s/s	5.1 s/s
	MMR1000	**0.10** s/s	**1.1** s/s

Structural solver:
- 1-way coupling: 1 solve per time step.
- 2-ways coupling: 1 solver per iteration (12 iterations per time step)

SECOND-ORDER WAVE RESONANCE

Twave=2Tmodal	Regular wave	Irregular waves
First-order waves		
Second-order waves		

OFFLINE ANALYSES BASED ON MRAOS

Computational resources:

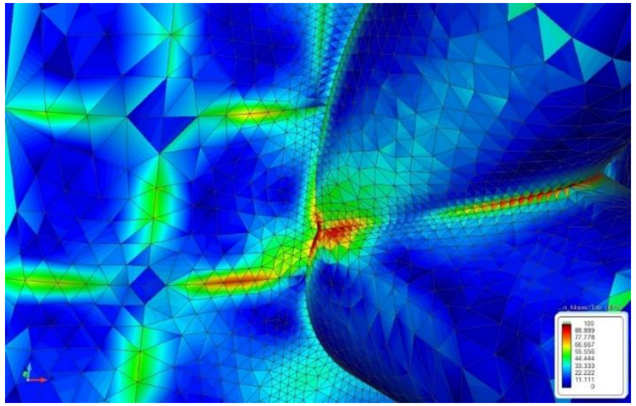
- Number of Workstations: **1**
- RAM memory: **512Gb**
- CPU unit: AMD Ryzen Threadripper PRO 5995WX **64-Cores** 2.70 GHz

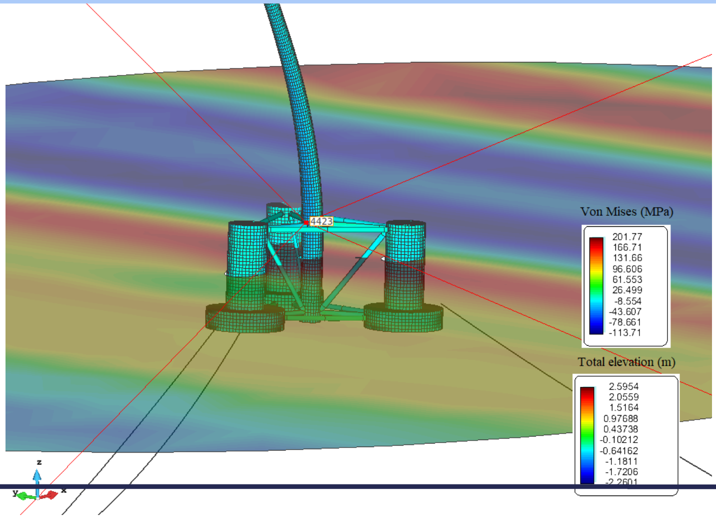
Step 1: Modal analysis (5000 modes): 16h

- FEM model: **1,026,150 DOFs**
- RAM required: **150 Gb**
- Parallel execution: **64 cores**

Step 2:Modal Response Amplitude Operators (MRAOS): 22h

- **72** time-domain **simulations** with white-noise spectrum
- **36** wave **directions** x **177 frequencies** x 5000 modes = **31,860,000 MRAOs**
- Files size: **576 Mb**





OFFLINE FATIGUE ANALYSIS: computational time…. 1.1h

- Number of **loadcases**: **1000** (Tm, Hs, wave direction).
- Simulation **time** per loadcase: **3h**
- **Time-step: 0.1s.**
- **Number of hotspots**: **1000** FE
- Computational times breakdown:
  - Read structural/material/mesh data at hotspots….0.03s
  - Read modal basis at hotspots…………………………….....26s
  - Compute modal amplitudes time series……………...700s
  - Compute at FE hotspots…………………………………3263s
    - Nodal displacements……………………….. 1140s
    - Stresses tensor………………………………... 568s
    - Von Misses stresses……………………….. 1150s
    - Fatigue damage (Rainflow counting)…... 406s

OFFLINE STRESS ANALYSIS: computational time….1.26h

- Number of **loadcases**: **1000** (Tm, Hs, wave direction).
- Simulation **time** per loadcase: **3h**
- **Time-step: 0.1s.**
- **Number of time-steps** per loadcase: **200** (structural energy peaks)
- Computational times breakdown:
  - Read structural/material/mesh data at hotspots….0.016s
  - Read modal basis at hotspots…………………………….....20s
  - Compute modal amplitudes time series……………...232s
  - Compute at all FEs………………………………………….4288s
    - Nodal displacements……………………….. 1407s
    - Stresses tensor………………………………...1039s
    - Von Misses stresses……………………….. 1842s

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