Structural assessment of vessels by dynamic hydroelastic analysis based on modal matrix reduction

Antonio José Lorente López (ETSINO-UPCT), Julio García Espinosa (ETSIN-UPM), José Enrique Gutiérrez Romero (ETSINO-UPCT), Borja Serván Camas (CIMNE), Pablo Romero Tello (ETSINO-UPCT)

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EXCELENCIA SEVERO OCHOA

OBJECTIVES OF THIS WORK

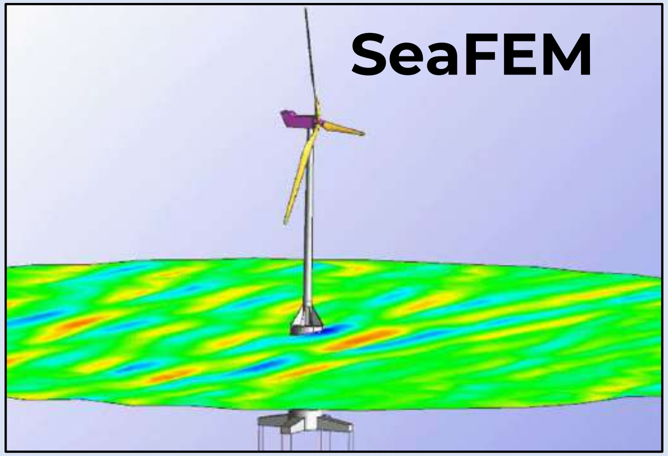
1. Showcasing the complexity of the hydroelastic problem
2. Introducing our proposed model to address the issue.
3. Advantages of the reduced-order model based on modal matrix reduction.
4. Demonstration of capabilities with a case study.
5. Analyzing the results obtained to focus on future work.

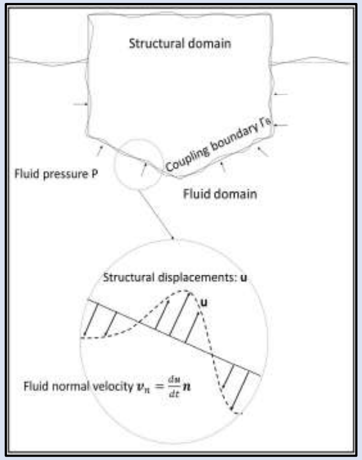
OUTLINE

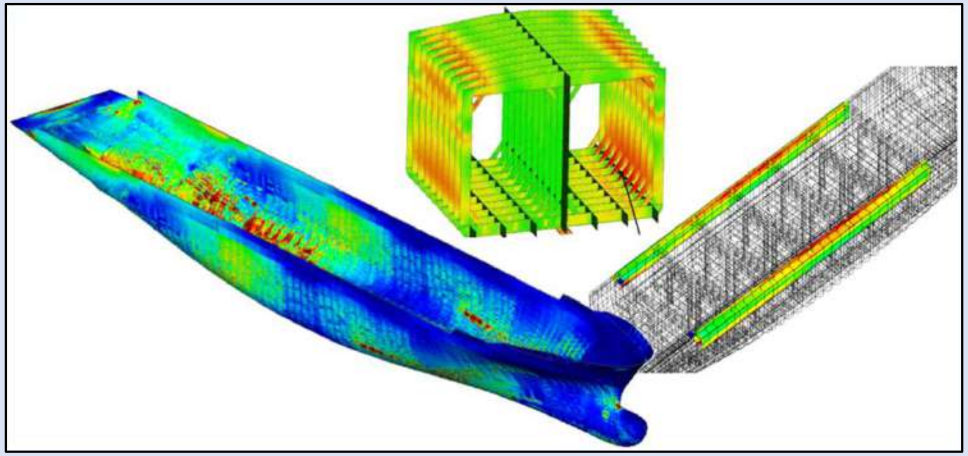
63º Congreso Internacional de Ingeniería Naval e Industria Marítima

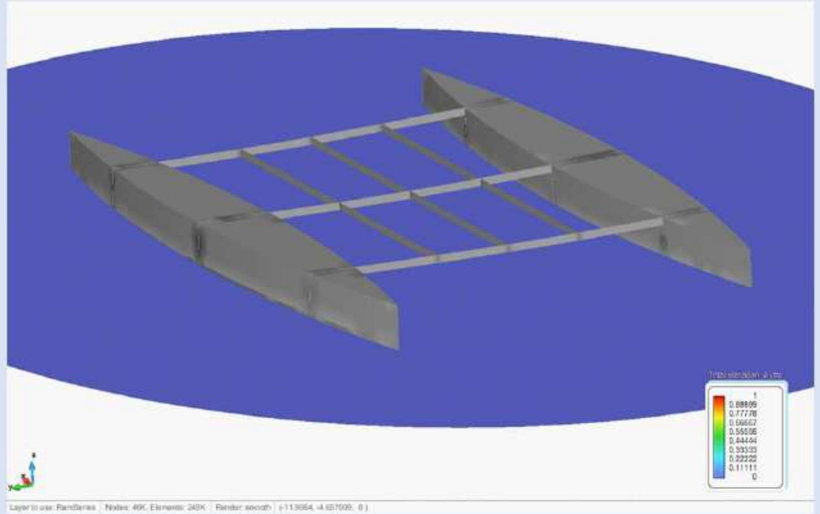
Hydroelasticity

Seakeeping hydrodynamics | **Coupling** | **Structural FEM**









Some 90% of computational time can be taken by solving the structural dynamics!!

Servan-Camas et al. Fully 3D ship hydroelasticity: Monolithic versus partitioned strategies for tight coupling. Marine Structures 80 (2021) 103098

COMPLEXITY AND CHALLENGES OF THE COMPUTATIONAL MODEL

- **Coupling** among hydrodynamics and structural dynamics.
- Requires **time-domain** dynamic analysis.
- **Long computational times** (not suitable for digital twin applications).
- **Bottle neck:** dynamic structural analysis.

STRUCTURAL REDUCED ORDER MODEL (ROM)

- **Objective:** drastically reduce CPU times for dynamic structural analysis.
- **Purpose:** To be used for: digital twin, during structural design, and fatigue damage assessment.
- **ROM:** Projecting onto the modal base: Modal Matrix Reduction (MMR)

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = 0 \equiv \left\{\boldsymbol{u}(t) = \boldsymbol{a}\,\mathrm{e}^{i\omega t}\right\} \equiv \left(\mathbf{M}^{-1}\mathbf{K}\right)\mathbf{a} = \omega^2\mathbf{a}$$

$$\boldsymbol{u}(\boldsymbol{x}, t) = \sum_{i=1}^{m} q_{\mathrm{i}}(t) \cdot \boldsymbol{a}_{\mathrm{i}}(\boldsymbol{x}) \equiv \mathbf{u} = \mathbf{A}\mathbf{q}$$

$$\ddot{q}_i + 2\xi\omega_i\dot{q}_i + \omega_i^2 q_i = \frac{\boldsymbol{a}_{\mathrm{i}}(\boldsymbol{x})}{m_i}\mathbf{f}(x, t)$$

García-Espinosa, J.; Serván-Camas, B.; Calpe-Linares, M. High Fidelity Hydroelastic Analysis Using Modal Matrix Reduction. J. Mar. Sci. Eng. 2023, 11, 1168. https://doi.org/10.3390/jmse11061168

ADVANTAGES OF STRUCTURAL REDUCED ORDER MODEL (ROM)

1. Modal base is **orthogonal**: $\mathbf{M\ddot{u}} + \mathbf{C}\dot{\boldsymbol{u}} + \mathbf{Ku}$=F(t) $\ddot{q}_i + 2\xi\omega_i\dot{q}_i + \omega_i^2 q_i = \frac{\mathbf{a_i}}{m_i}\mathbf{f}(t)$

Highly reduce the cost of solving the structural system of equations.

2. Neglect low energy modes: $\boldsymbol{u}(\boldsymbol{x},t) = \sum_{i=1}^{m} q_\mathrm{i}(t)\cdot\boldsymbol{a}_\mathrm{i}(\boldsymbol{x})$

Drastic reduction of degrees of freedom m<<N (O(100)-O(1000)).

Drastic reduction of computational cost (O(100)-O(1000)).

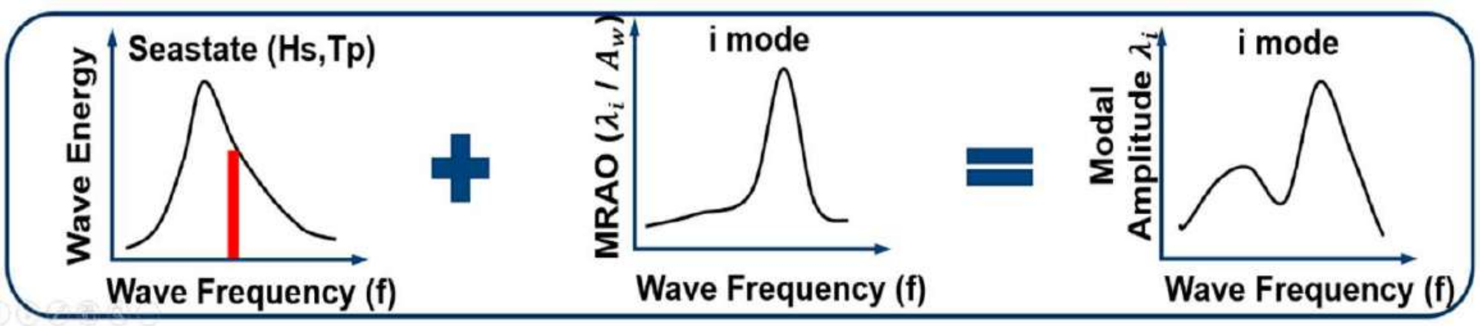
3. If external loads F(t) are **linear** (mooring, linear waves, …), then compute Modal Response Amplitude Operators (MRAOs).

3.1 Offline **MRAOs** for single wind and wave loads.

3.2 **Fast** reconstruction of dynamic analysis under irregular loads.

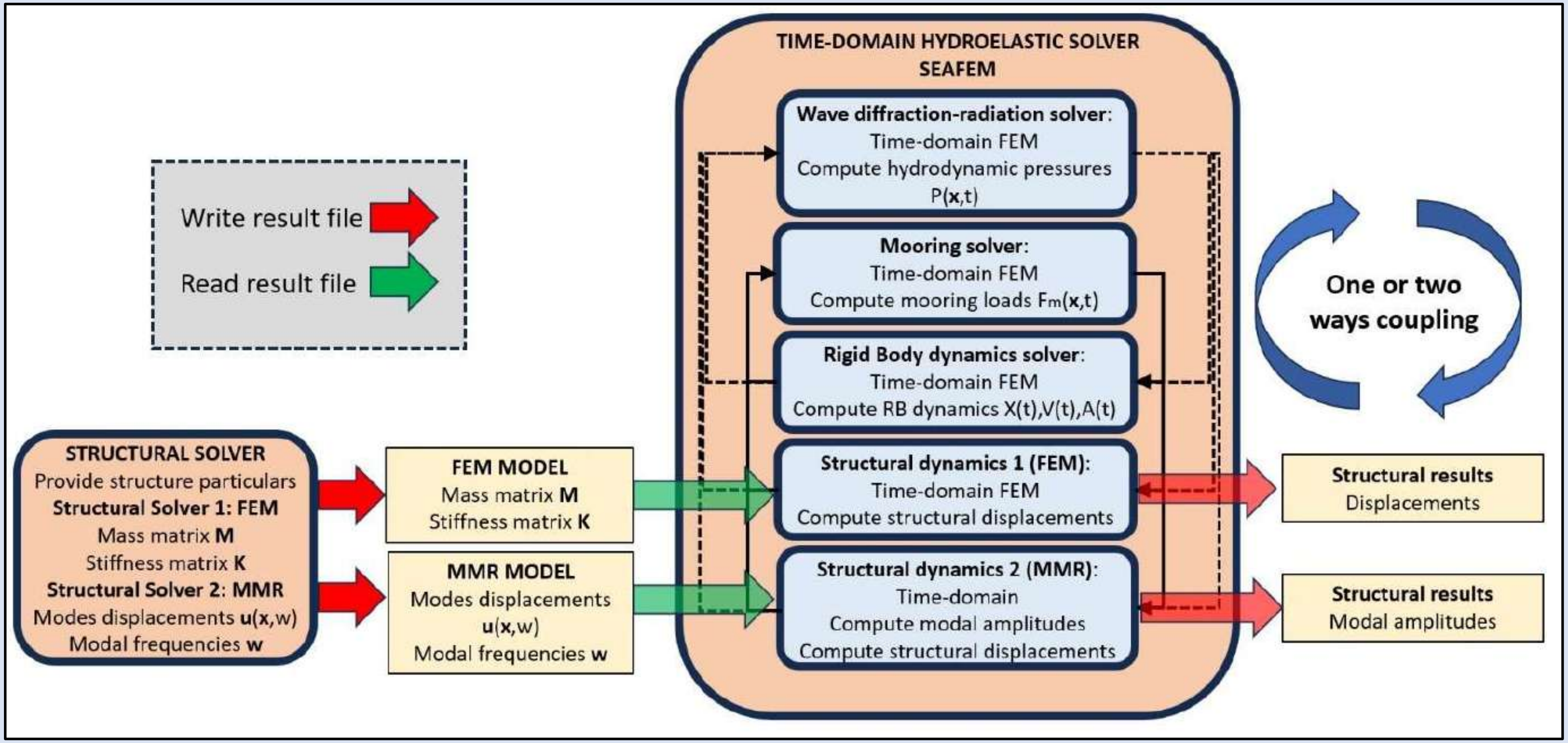
3.3 Allows to **compute a large number of loadcases**: fatigue damage assessment, structural design optimization.

3.4 Use in operational conditions: **digital twin**



TIME-DOMAIN HYDROELASTIC MODEL

FEM coupled analysis: Extract the FE mass **M** and stiffness **K** matrices
MMR analysis: Extract the structural **eigenmodes** and modal **frequencies**

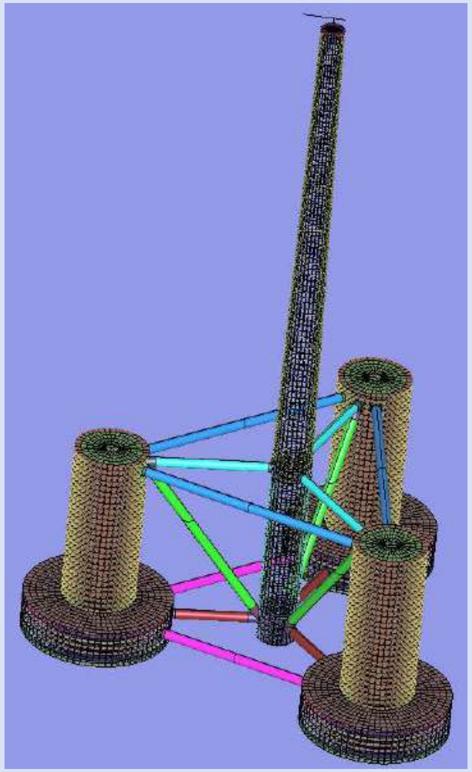
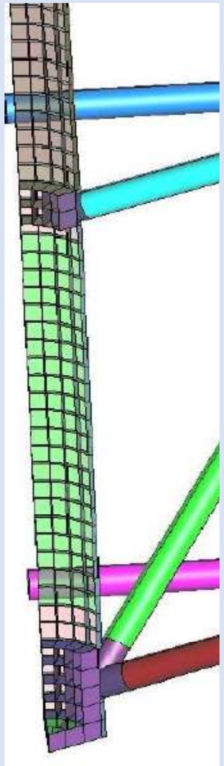
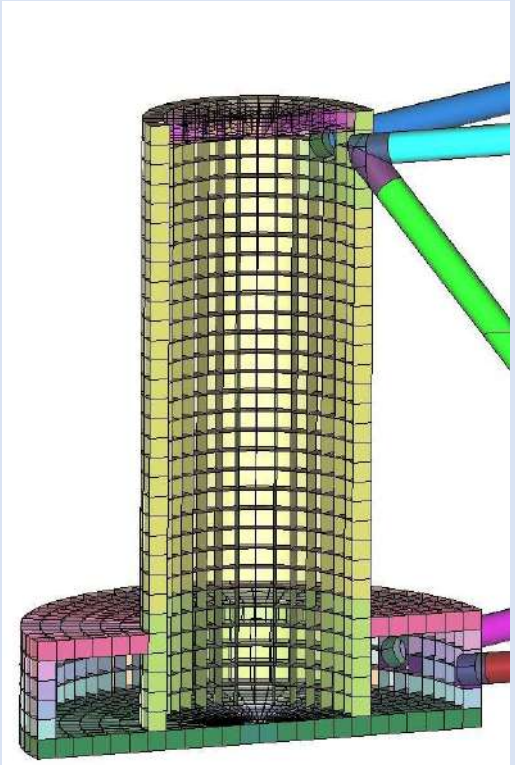
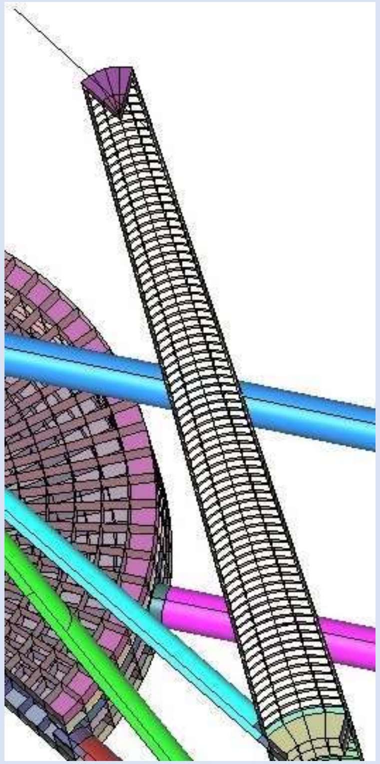
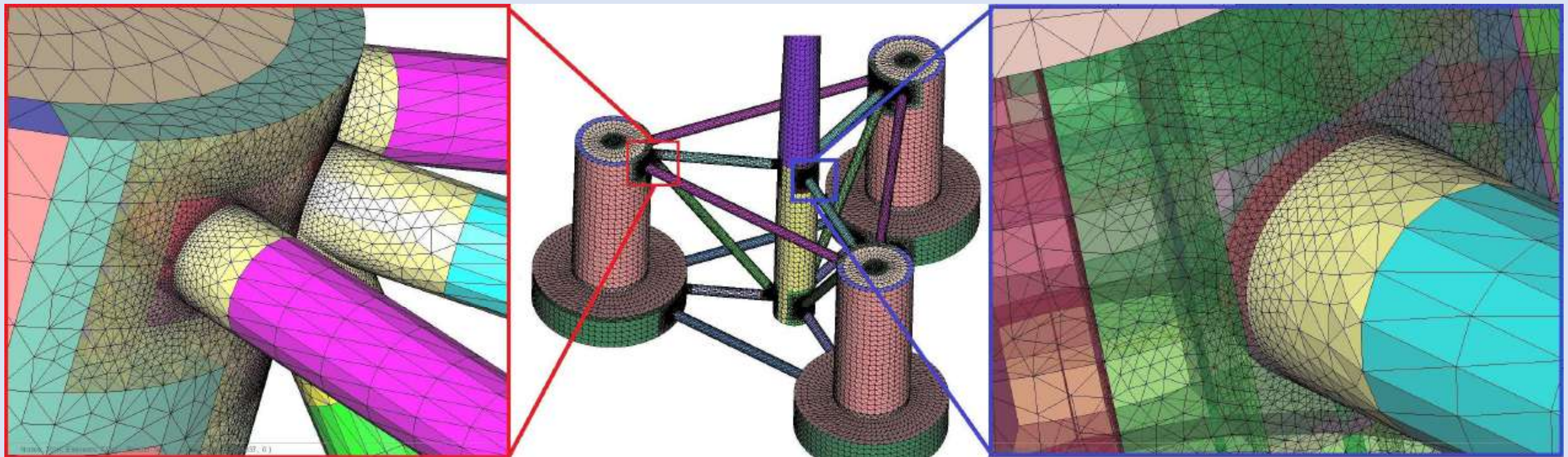


The time-domain hydroelastic simulation provides, as result:

- FEM coupling: the time history of the structural displacements and energy
- MMR coupling: the time history of modal amplitudes and energy.

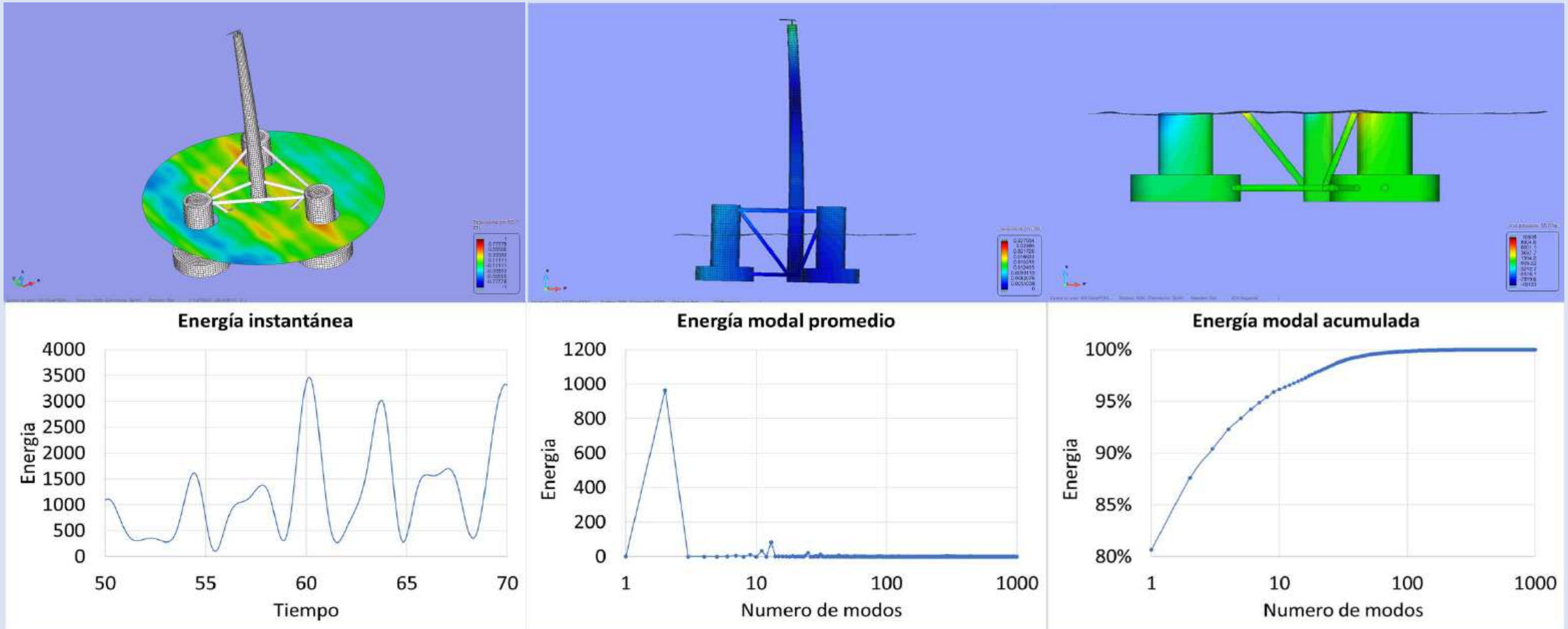
SHOWCASE: DEEPCWIND

Structural design for DeepCWind platform, and structural FEM mesh used.

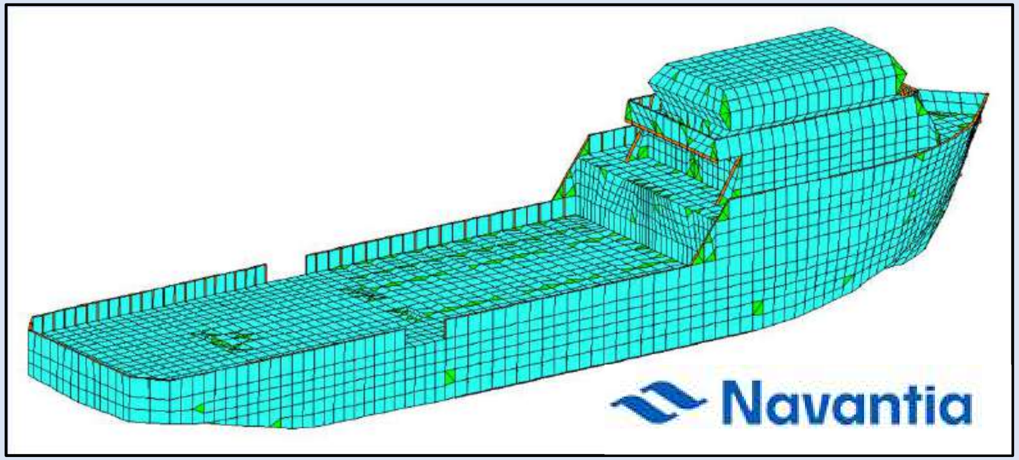
SHOWCASE: DEEPCWIND

Dynamic case: irregular wave loads: Jonswap (Hs=1m, Tm=5s)



Hydroelastic response of DeepCWind platform.

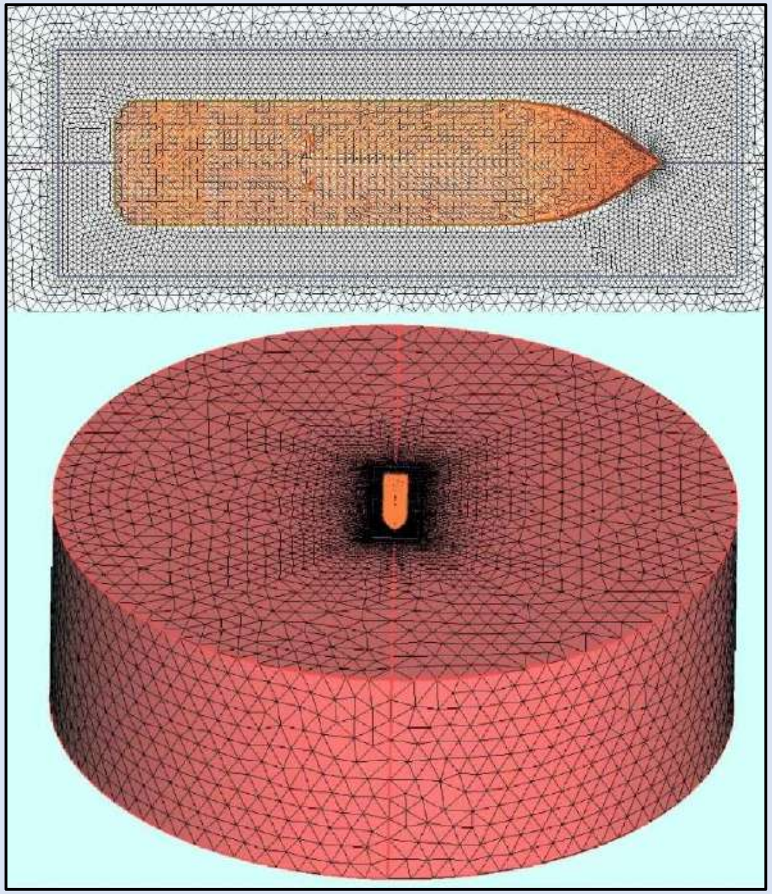
CASE STUDY – Model description



Structural FEM mesh

Ship particulars

Displacement	1153 t
Overall length	50.292 m
Overall beam	11.03 m
Draft	3.06 m
Number of FE	19130
Number of nodes	9036
Number of degrees of freedom	54216

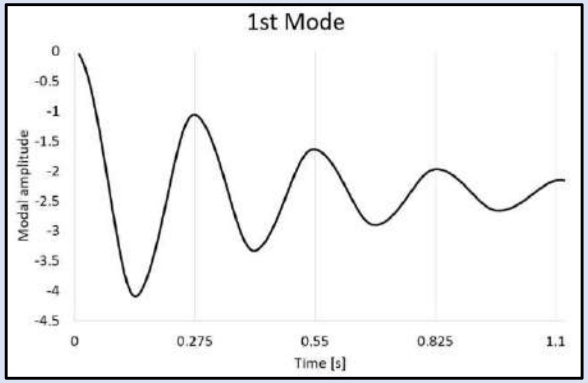


Seakeeping hydrodynamics mesh

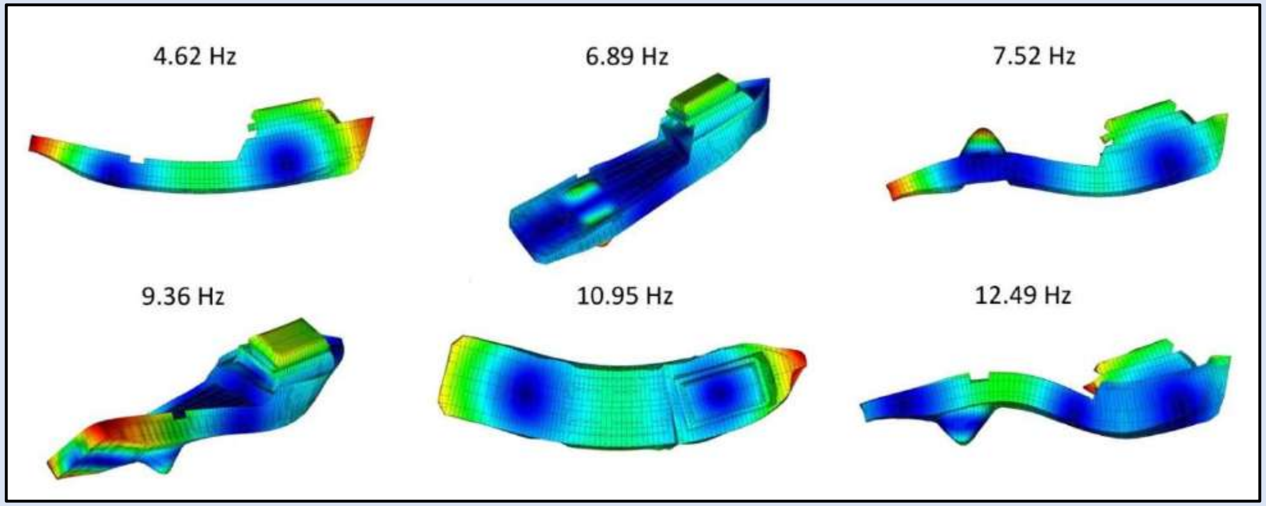
CASE STUDY – Modal Analysis

Modal analysis with the model free and dry, for the first 1000 modes.

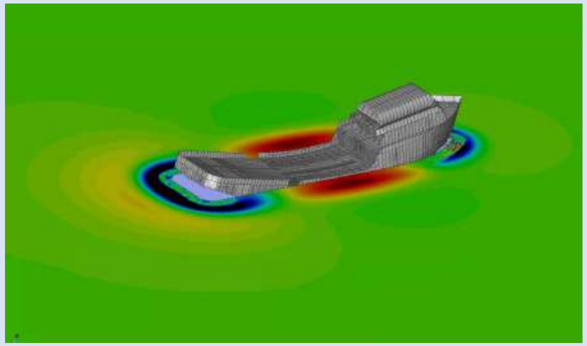
If water is considered, structural displacement radiates waves and hydrostatic pressures changes.



First mode extinction test



First 6 modes

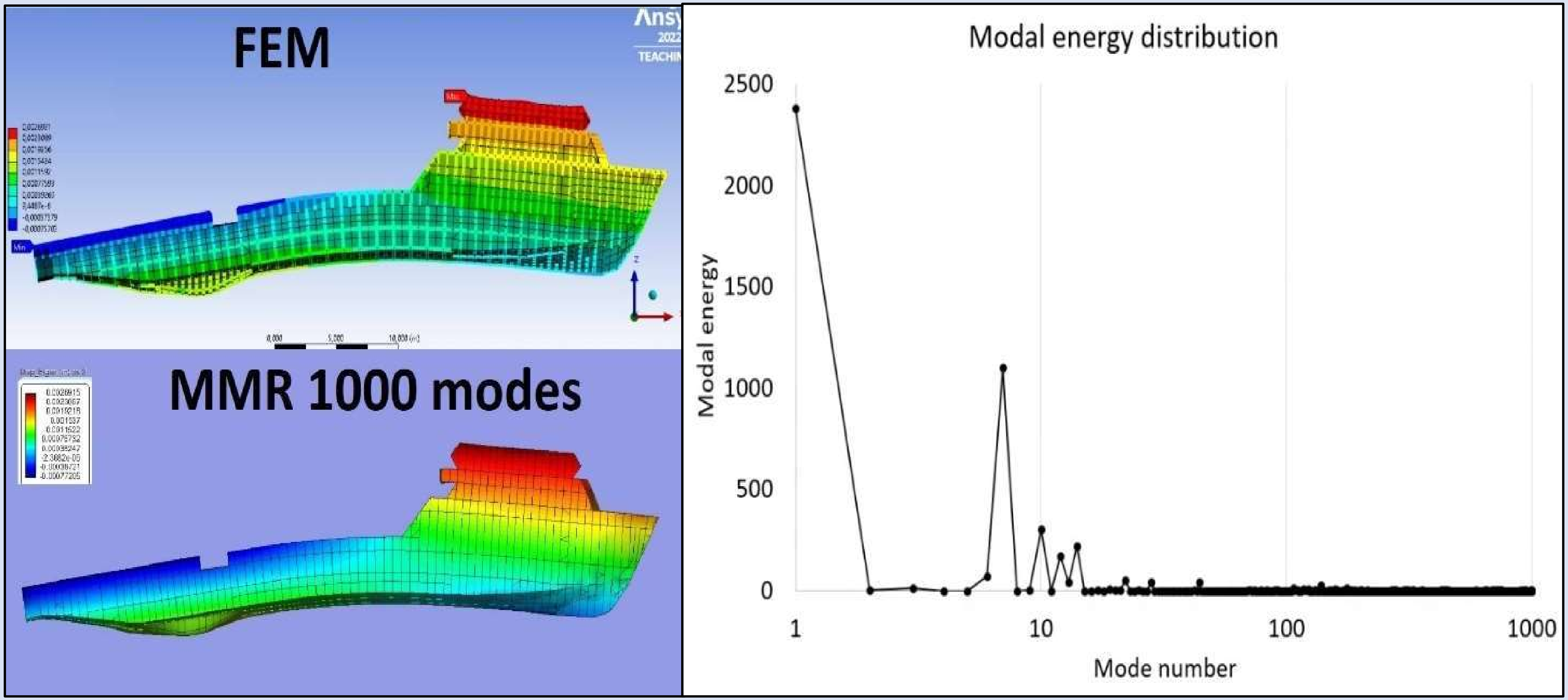


Dry vs wet modal frequencies

Mode	1st Mode	2nd Mode	3rd Mode	4th Mode	5th Mode	6th Mode
Dry freq.	4.62 Hz	6.891 Hz	7.52 Hz	9.36 Hz	10.95 Hz	12.48 Hz
Wet freq.	3.64 Hz	6.37 Hz	6.29 Hz	8.24 Hz	10.00 Hz	9.71 Hz
Dry period	0.216 s	0.145 s	0.133 s	0.107 s	0.091 s	0.080 s
Wet period	0.275 s	0.157 s	0.159 s	0.121 s	0.100 s	0.103 s

CASE STUDY – Hydrostatic Equilibrium

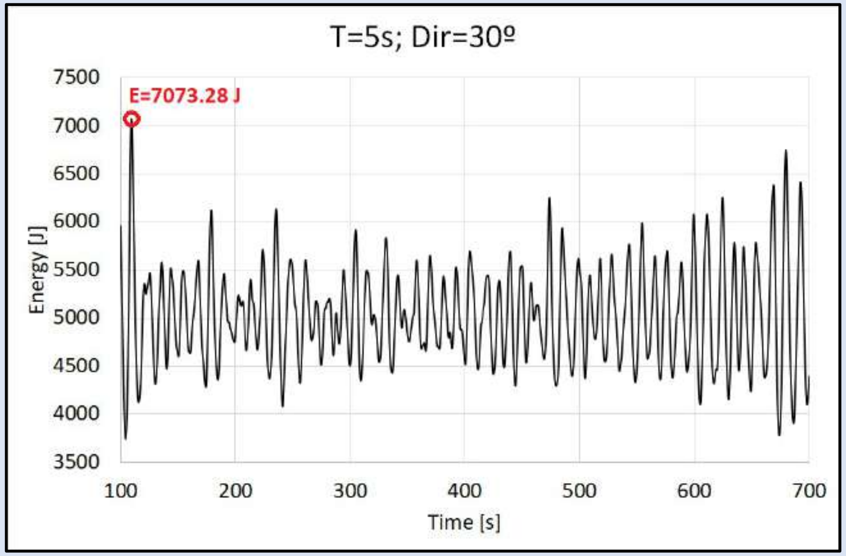
Static analysis under the hydrostatic pressure and self-weight loads.
MMR approximation recovers **96.3%** of the total energy.



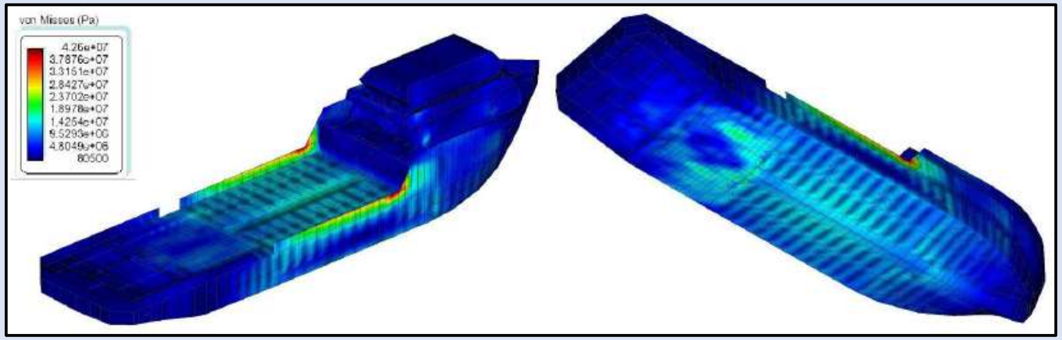
CASE STUDY – Navigation at 10kn

Test matrix

Forward speed: V	10 kn						
Wave height: Hs	1 m						
Wave Periods: T	3s	**5s**	7s	9s	11s	13s	15s
Wave directions	0º	**30º**	60º	90º	120º	150º	180º



Instantaneous structural energy.



Instantaneous stresses at most energetic instant.

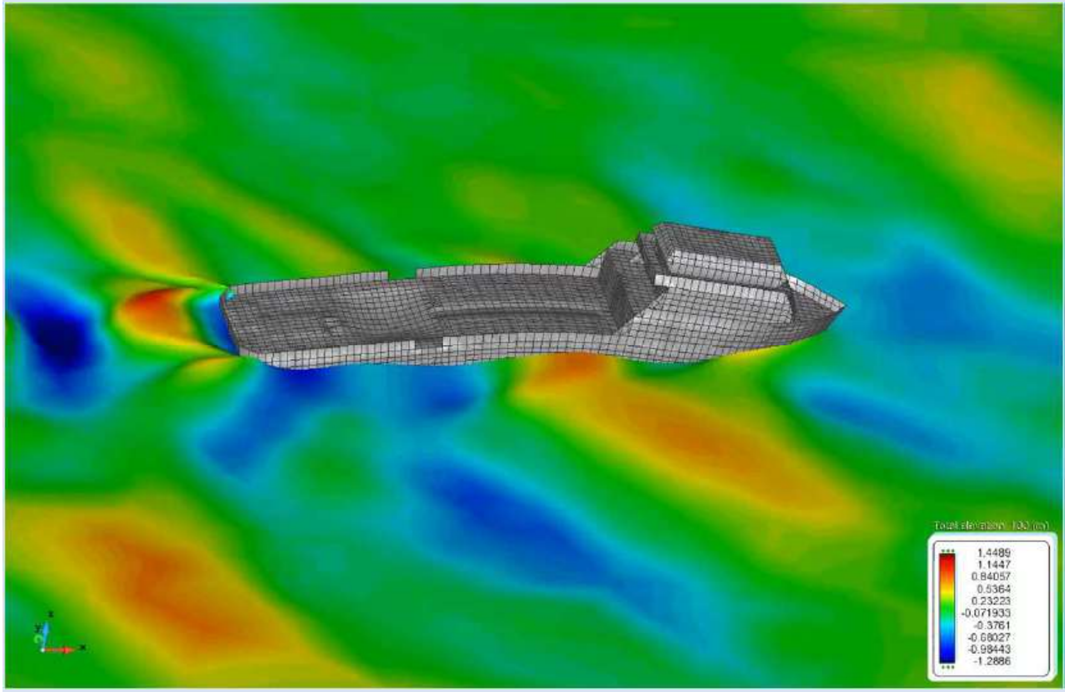
With only ten modes, some 95% of the energy is recovered. And only the first mode contains 42.83% of the energy.

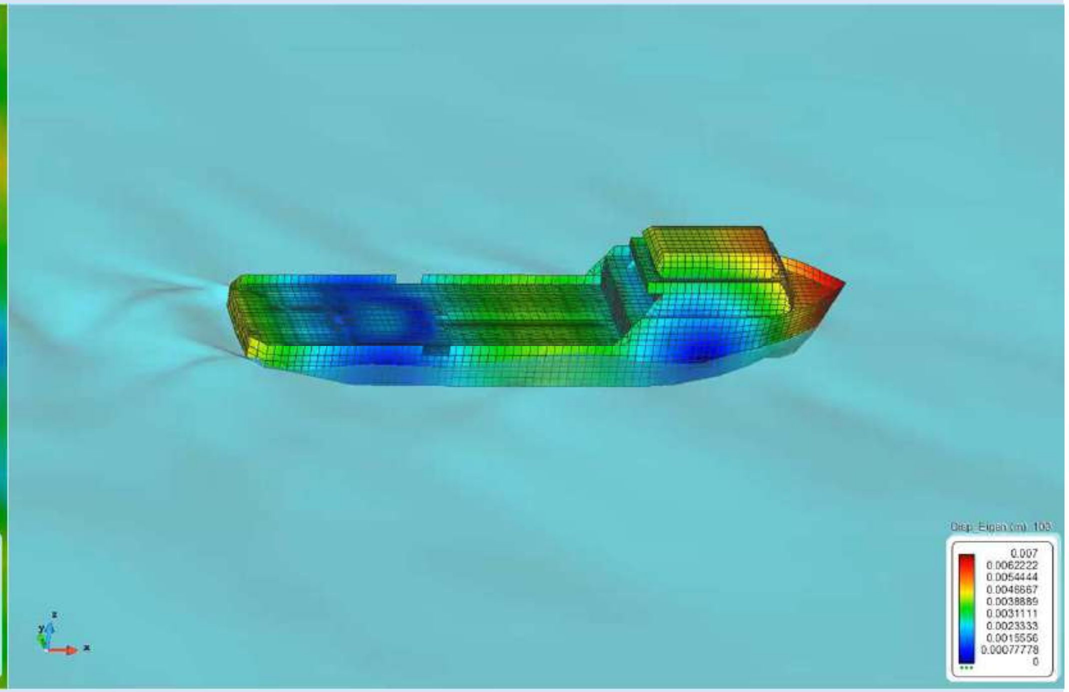
Energy analysis.

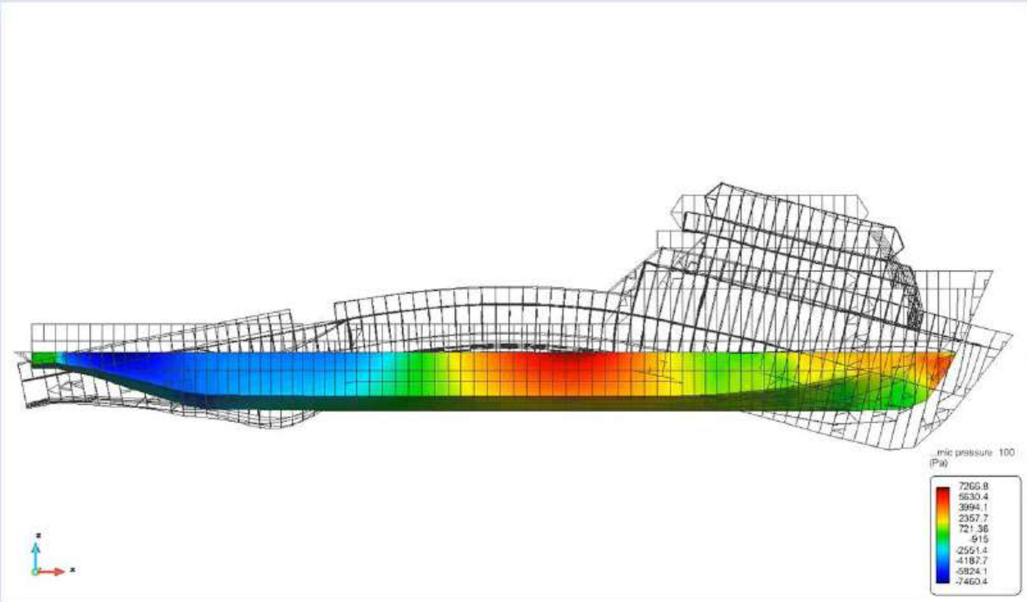
	Mode number	Modal E	Cumulative E
1	1	42.83%	42.83%
2	3	37.23%	80.06%
3	6	9.08%	89.14%
4	9	1.92%	91.06%
5	8	1.09%	92.14%
6	23	1.07%	93.21%
7	38	0.93%	94.14%
8	103	0.33%	94.48%
9	16	0.24%	94.72%
10	128	0.23%	94.95%

CASE STUDY – Navigation at 10kn

Hs=1m, T=5s, 30º wave heading







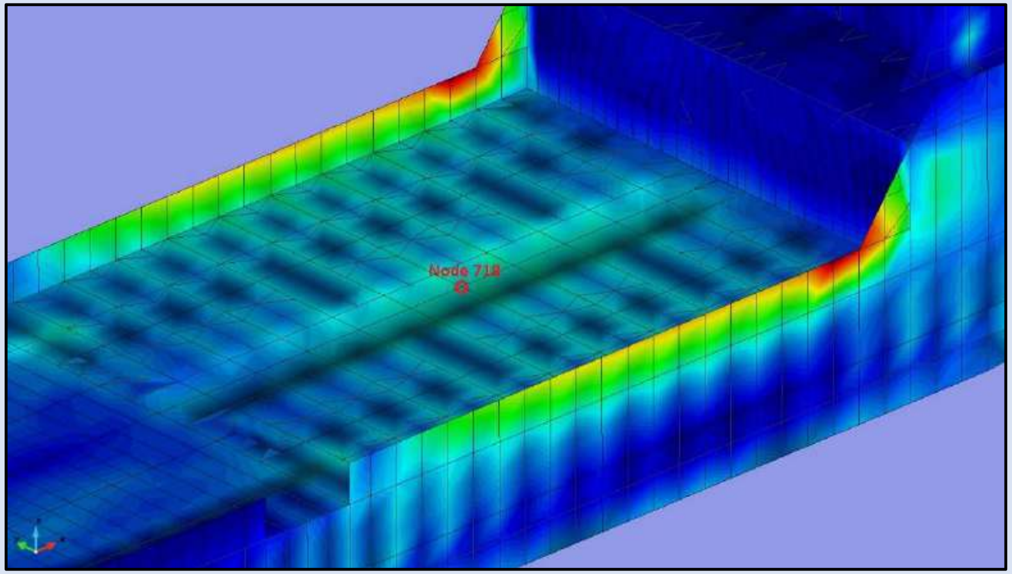
CASE STUDY – Fatigue Analysis

The hydroelastic analysis provide the **instantaneous modal amplitude** for each mode considered and every time step.

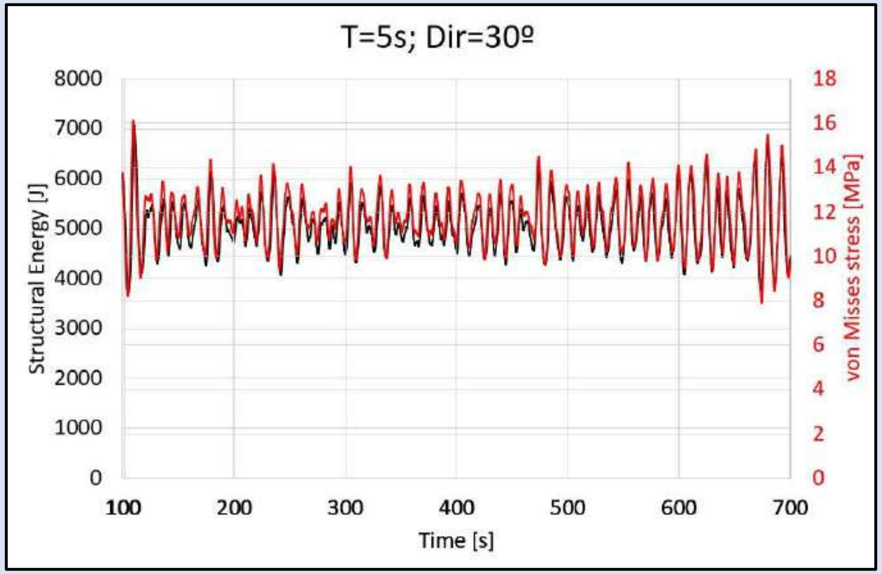
Given a hot spot of the structure, the stress tensor can be easily obtained just by **linear combination of the modal stresses** at that point.

Using the **rain-flow counting** algorithm in the time evolution of the stresses at the hot spot, the cycle counting and stress levels are obtained.

Using the **SN curve** of the material, the fatigue damage for the operational condition is obtained.



Von Misses stresses distribution and hot spot location



Instantaneous stresses at hot spot and structural energy

CASE STUDY – Fatigue Analysis

The instantaneous stresses time history is what is needed to perform the fatigue analysis.
The wave direction is considered relative to the ship course, and to be equally probable.
The average damage is obtained by weighting the damage for each direction.

Annual fatigue damage [0-1]		T					
		3s	5s	7s	9s	11s	13s
Hs	1m	1.13E-08	1.10E-07	7.60E-09	1.67E-09	9.41E-11	3.32E-11
	2m	1.38E-06	1.35E-05	8.94E-07	2.11E-07	1.21E-08	4.24E-09
	3m	2.33E-05	2.11E-04	1.51E-05	3.55E-06	2.07E-07	7.22E-08
	4m	1.59E-04	8.72E-04	1.03E-04	2.55E-05	1.53E-06	5.38E-07
	5m	7.30E-04	3.09E-03	4.35E-04	1.18E-04	7.23E-06	2.54E-06
	6m	2.24E-03	8.53E-03	1.45E-03	3.99E-04	2.56E-05	9.12E-06
	7m	5.63E-03	1.83E-02	3.46E-03	9.94E-04	7.42E-05	2.63E-05
	8m	1.16E-02	3.51E-02	7.06E-03	2.10E-03	1.83E-04	6.59E-05

Seastate annual probability

Mean Annual fatigue damage [0-1]		T						
		3s	5s	7s	9s	11s	13s	
Hs	1m	1.85E-10	2.90E-08	1.42E-09	1.07E-10	1.64E-12	2.76E-14	3.08E-08
	2m	0	4.86E-07	9.24E-08	2.27E-08	6.00E-10	3.02E-11	6.01E-07
	3m	0	4.43E-08	2.29E-07	2.05E-07	4.58E-09	3.37E-10	4.84E-07
	4m	0	0	2.16E-08	3.25E-07	2.44E-08	5.92E-10	3.72E-07
	5m	0	0	0	1.12E-07	7.17E-08	4.68E-09	1.89E-07
	6m	0	0	0	0	6.46E-08	7.66E-09	7.23E-08
	7m	0	0	0	0	3.49E-08	1.24E-08	4.72E-08
	8m	0	0	0	0	2.93E-08	9.36E-08	1.23E-07
		1.85E-10	5.59E-07	3.45E-07	6.66E-07	2.30E-07	1.19E-07	1.92E-06

CONCLUSIONS

- A novel strategy for simulating hydroelastic, based on the direct simulation in the time-domain of the seakeeping hydrodynamics problem coupled with the structural problem, is presented:
    - Allows one-way and two-ways coupled hydroelastic simulations.
    - Hydroelastic problem solved under the same programming framework, reducing overheads from communication/data exchange among different software.
    - Drastic reduction of CPU time by using MMR instead of solving the full FEM.
    - Drastic reduction of outputs by using MMR (only modal amplitudes are recorded for the whole simulation).
    - Capabilities to compute modal RAOs (MRAOs).

- Applied to analyse the structural response of a ship under specific operational conditions and to demonstrate the capabilities of the present methodology.

- Once the MRAOS are obtained for the previous conditions, any irregular seastate can be accurately represented.

- Long modal realizations for any operational conditions can be performed very fast with no need of performing more numerical hydroelastic simulations in the time-domain

ACKNOWLEDGEMENTS

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The structural FEM model has been taken from MAESTRO and provided by Navantia for the execution of the present study case.

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63° Congreso Internacional de Ingeniería Naval e Industria Marítima

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THANKS FOR YOUR ATTENTION

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