Accelerated fully coupled hydro-elastic analysis of ships based on modal matrix reduction

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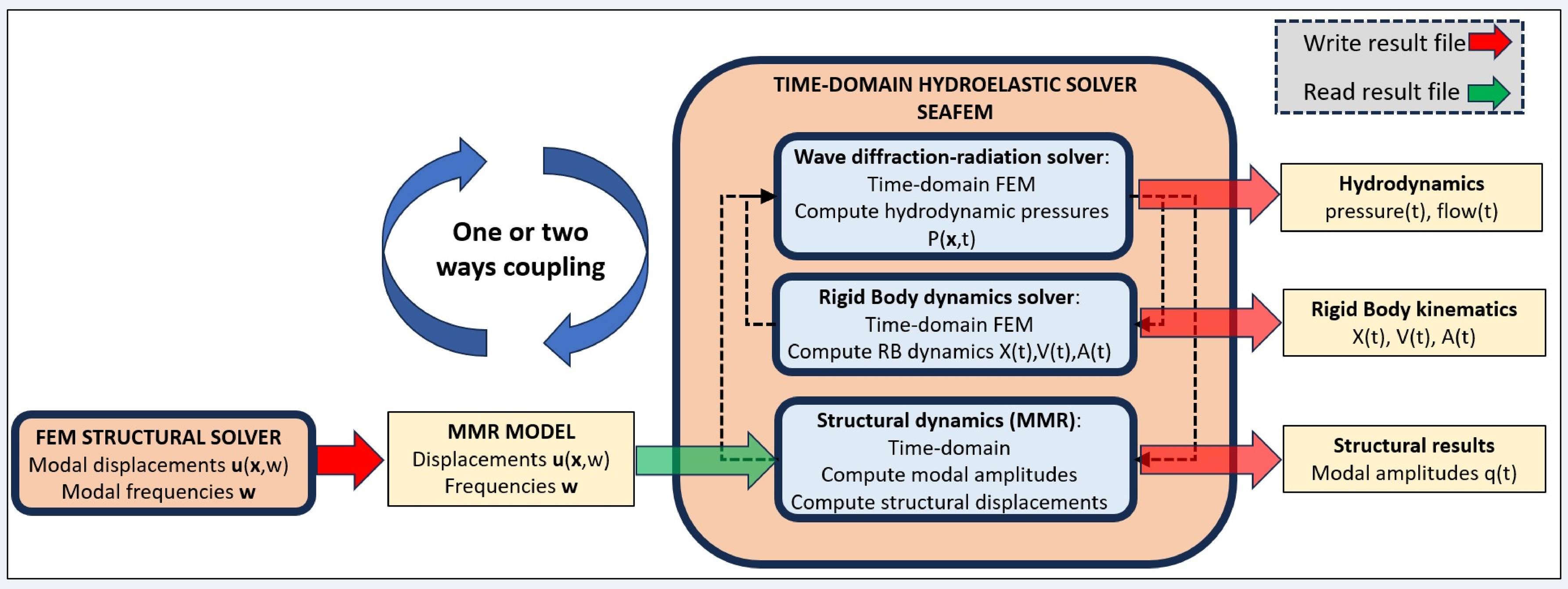
1. MOTIVATION AND BACKGROUND

Hydro-elastic effects such as springing, whipping and racking can significantly increase hull stresses and fatigue damage. However, **fully coupled time-domain hydro-elastic simulations** remain computationally prohibitive for practical ship design due to the high cost of the structural solver.

Objective: Develop an **efficient two-way coupled hydro-elastic framework** capable of capturing resonance effects with **full-length detailed structural models**, while drastically reducing computational cost.

2. COMPUTATIONAL FRAMEWORK



3. MODAL MATRIX REDUCTION (MMR)

- Structural displacement expressed as modal superposition:

$$\boldsymbol{U}_D(t) = \sum_{i=1}^{N_{DOF}} q_i(t)\,\boldsymbol{D}_i$$

- Modal truncation based on energy criterion:

$$\Omega_{N_m} \geq 4 \cdot \omega_{max}$$

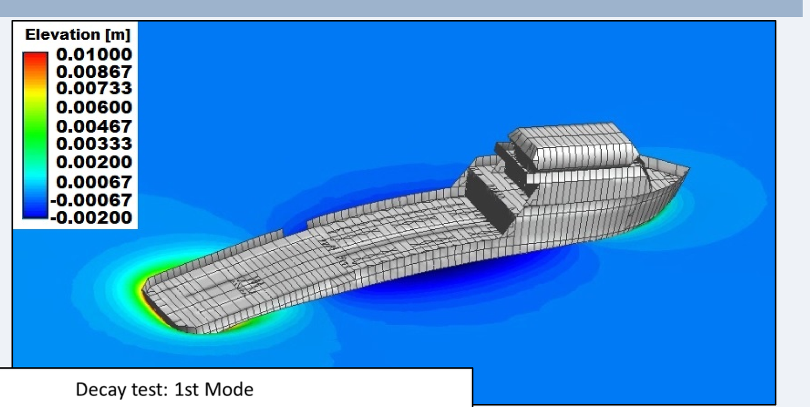
Hybrid Strategy
- Low-frequency modes: **strong two-way coupling**
- High-frequency modes: **quasi-static / weak coupling**
- Residual FEM correction restores local accuracy

Two orders of magnitude reduction in DOFs without loss of fidelity.

4. CASE STUDY

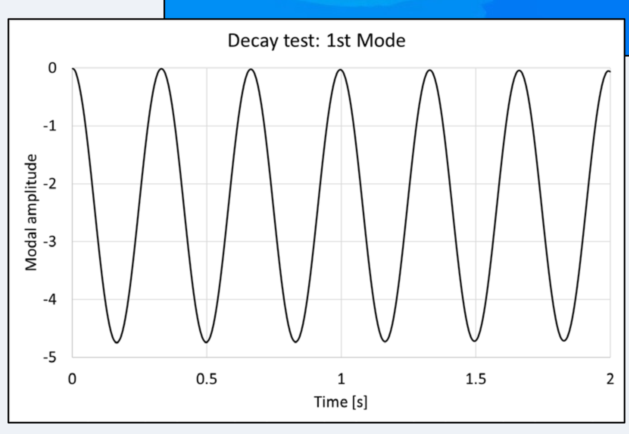
Ship Model:

- Full-length 3D FEM (shell + beam)
- **235,116 DOFs**
- Forward speed: **10kN**
- Transom Stern configuration



Modal Properties:

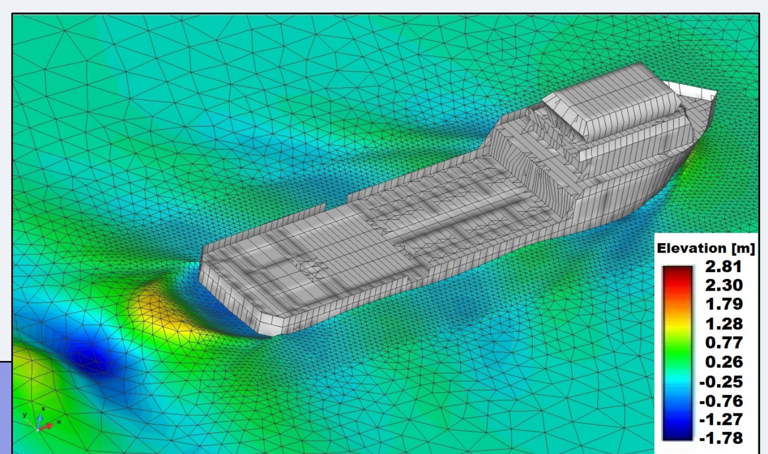
- 10,000 elastic modes
- Significant **wet-dry frequency shift** for lower modes
- Radiation damping obtained via extinction tests

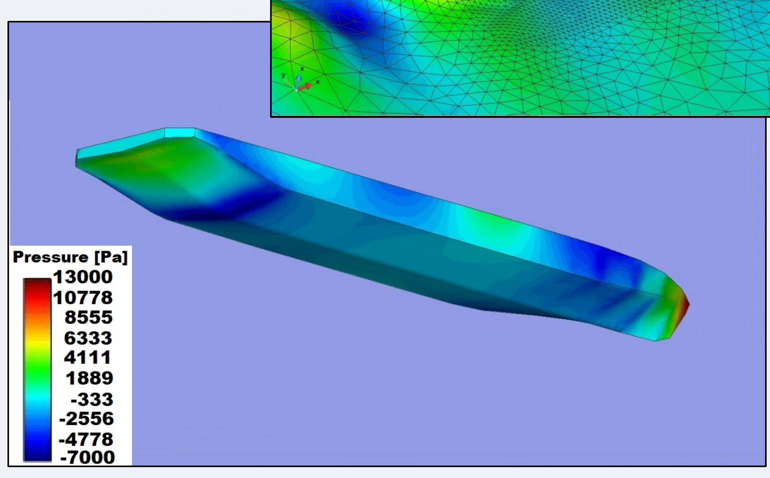


	1st Mode	2nd Mode	3rd Mode	4th Mode	5th Mode	6th Mode
Dry period [s]	0.220	0.154	0.144	0.112	0.093	0.085
Wet period [s]	0.332	0.171	0.188	0.136	0.104	0.120
Wave radiation damping [%]	0.063	0.124	0.232	0.370	0.377	0.730

5. SEAKEEPING & HYDRODYNAMICS

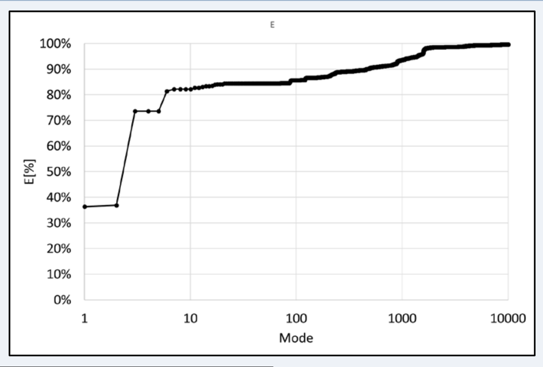
- **Time-domain FEM diffraction–radiation solver**
- Forward speed included via **double-body linearization**
- **Transom stern modeling**:
  - Flow detachment enforced
  - Zero pressure on dry transom surface

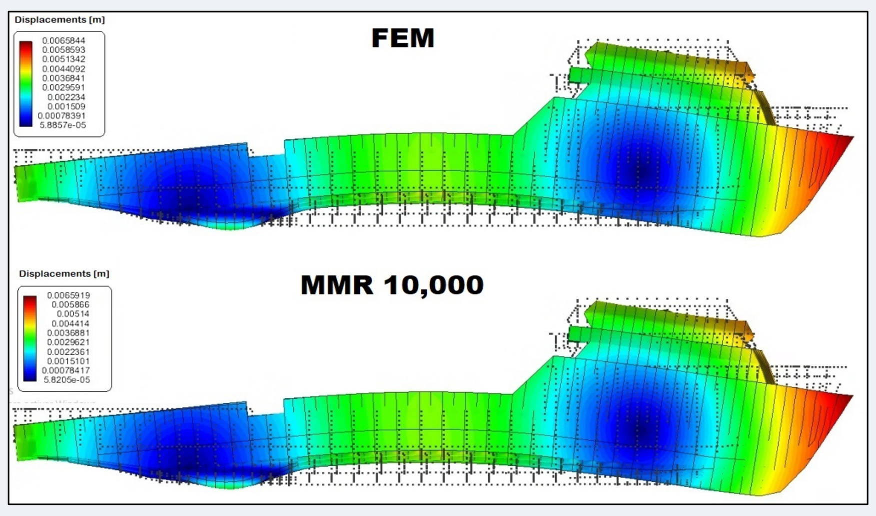


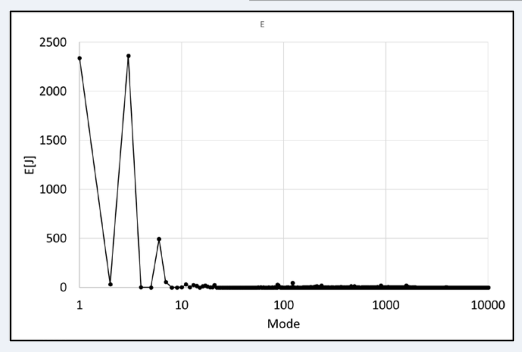


6. HYDROSTATIC VALIDATION

- ROM vs FOM under hydrostatic loading
- **99.7% elastic energy recovered** using 10,000 modes
- Excellent agreement in displacement fields



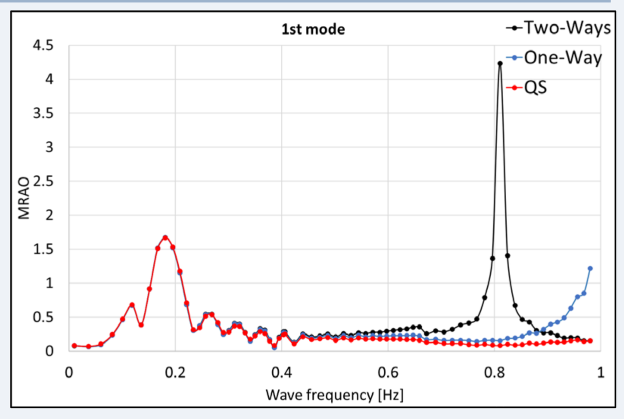


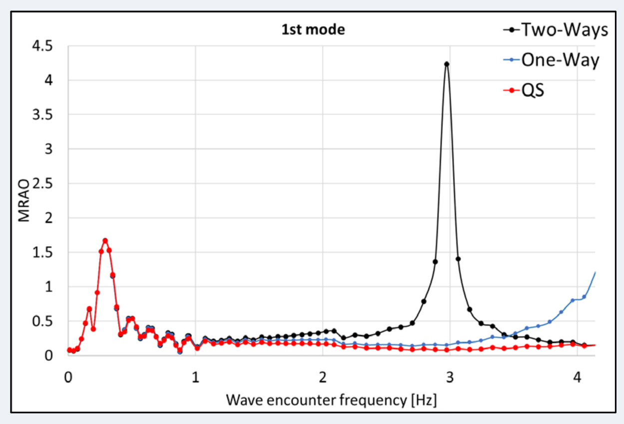


7. MODAL RAOs & RESONANCE EFFECTS

MRAOs) computed & Comparision of:
- Quasi - static
- Weak coupling
- Strong coupling

Key Results:
- **Weak quasi-static approaches fail near resonance**
- Strong coupling captures:
  - Frequency shift
  - Radiation damping
  - Resonant amplification

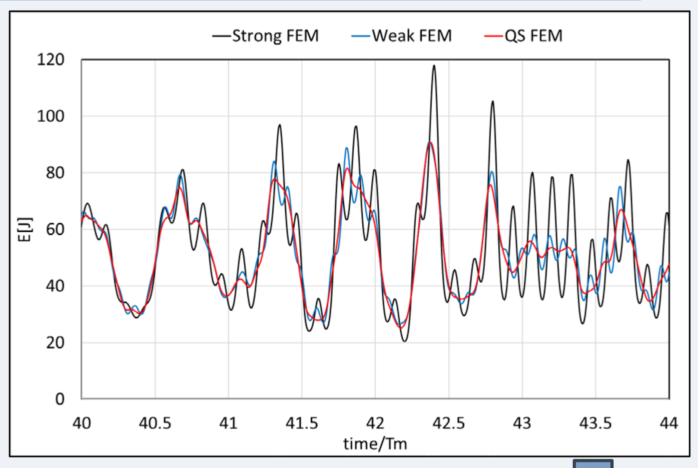


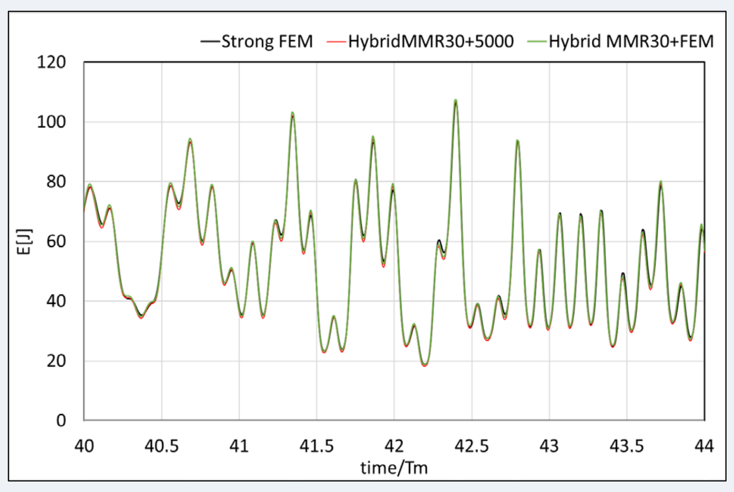


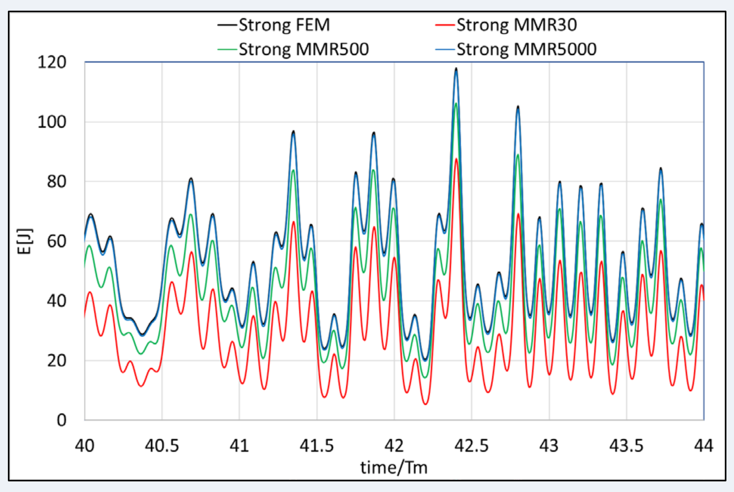
8. IRREGULAR WAVES – HYDROELASTIC RESPONSE

- JONSWAP spectrum
- Encounter frequencies overlap 1st bending mode
- Strong coupling required

Results:
- ROM converges to FOM as modal basis increases
- Hybrid ROM–FOM matches strong FOM response
- Dynamic elastic energy accurately recovered







9. COMPUTATIONAL PERFORMANCE

Speed-up

- **Hybrid-FOM**: up to 8x
- **Hybrid-ROM**: up to 125x
- **Refined mesh**: up to 300x

Computational times in second per second of simulation

	Type of Coupling	Model order	Solver	Computational time
Structural solver – Refined mesh (943,470 DOFs)	Quasi-static	ROM	MMR5000	0.93 s/s
	Quasi-static	FOM	FEM	47.91 s/s
	Weak	ROM	MMR5000	0.94 s/s
	Weak	FOM	FEM	47.79 s/s
	Strong	ROM	MMR5000	26.96 s/s
	Strong	FOM	FEM	398.87 s/s
	Hybrid	ROM	MMR30-5000	1.34 s/s
	Hybrid	FOM	MMR30+FEM	48.63 s/s
Rigid body solver				0.03 s/s

- **Structural solver dominates total cost**
- **MMR dramatically reduces runtime**

10. CONCLUSIONS

- Fully coupled hydroelastic analysis is **essential** near resonance
- Hybrid ROM – FOM:
  - Preserves local stress accuracy
  - Enables near-real-time hydroelastic simulations
- MMR enables accurate ROMs with enormous DOF reduction
- Framework suitable for:
  - **Design loops**
  - **Fatigue assessment**
  - **Digital Twin applications**

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