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Hydrodynamic analysis of a Semisubmersible Floating Wind Turbine. Numerical validation of a second order coupled analysis

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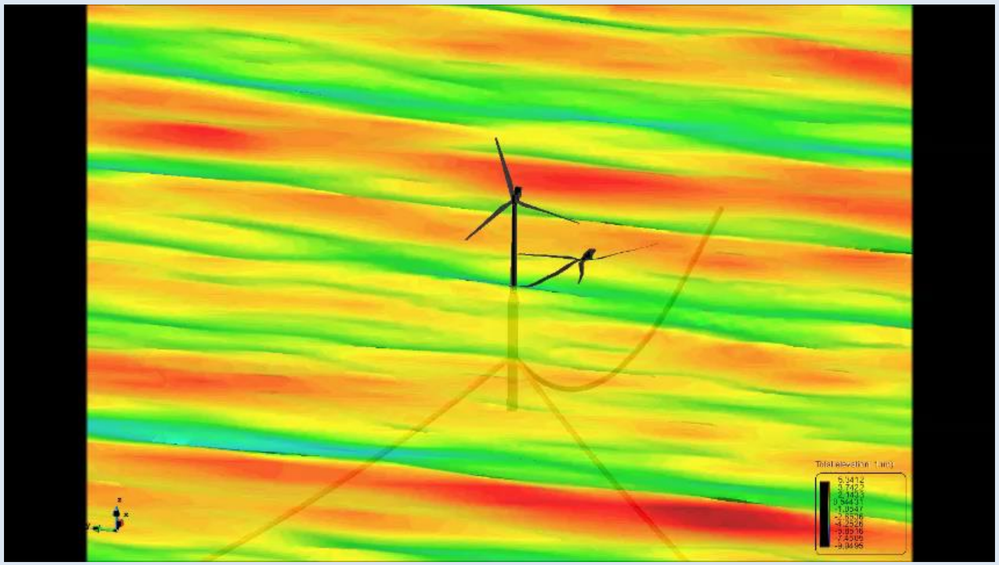
OUTLINE

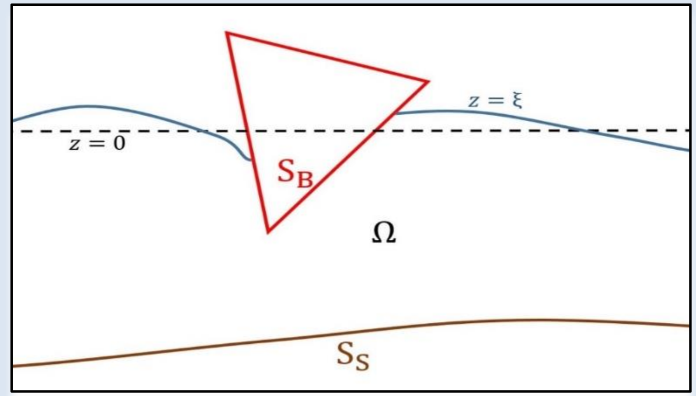
- ✓ Introduction
  - ✓ Hydrodynamics governing equations
  - ✓ Numerical model
  - ✓ Mooring models
  - ✓ Coupling Seakeeping and Mooring
- ✓ Validation
  - ✓ HiPRWind model description
  - ✓ Experimental setup
  - ✓ Numerical setup
  - ✓ Model calibration
  - ✓ Analysis on bichromatic waves
  - ✓ Analysis on irregular waves
- ✓ Summary and Conclusions
- ✓ Acknowledgements

INTRODUCTION

HYDRODYNAMICS GOVERNING EQUATIONS

✓ Governing equations based on incompressible and irrotational flow





$\Delta\varphi = 0$	$in\ \Omega,$
$\frac{\partial\xi}{\partial t} + \frac{\partial\varphi}{\partial x}\frac{\partial\xi}{\partial x} + \frac{\partial\varphi}{\partial y}\frac{\partial\xi}{\partial y} - \frac{\partial\varphi}{\partial z} = 0$	$on\ z = \xi$
$\frac{\partial\varphi}{\partial t} + \frac{1}{2}\nabla\varphi\cdot\nabla\varphi + \frac{P_{fs}}{\rho} + g\xi = 0$	$on\ z = \xi$
$\boldsymbol{v}_p\cdot\boldsymbol{n}_p + \boldsymbol{v}_\varphi\cdot\boldsymbol{n}_p = 0$	$on\ P \in S_B$
$P_p = -\rho\frac{\partial\varphi}{\partial t} - \frac{1}{2}\rho\nabla\varphi\cdot\nabla\varphi - \rho g z_p$	

φ: velocity potential $\boldsymbol{v}_\varphi = \nabla\varphi$

ξ : Free Surface elevation

HYDRODYNAMICS GOVERNING EQUATIONS

- ✓ Taylor series expansion carried out to free surface boundary condition around z=0 to approximate the condition on $z = \xi$.
- ✓ Taylor series expansion carried out to body boundary condition around $\mathrm{S}_{\mathrm{B}}^{0}$ to approximate the condition on S_{B}.
- ✓ Perturbed solution:

Velocity potential: $\varphi = \epsilon^1\varphi^1 + \epsilon^2\varphi^2 + \epsilon^3\varphi^3 + \cdots$

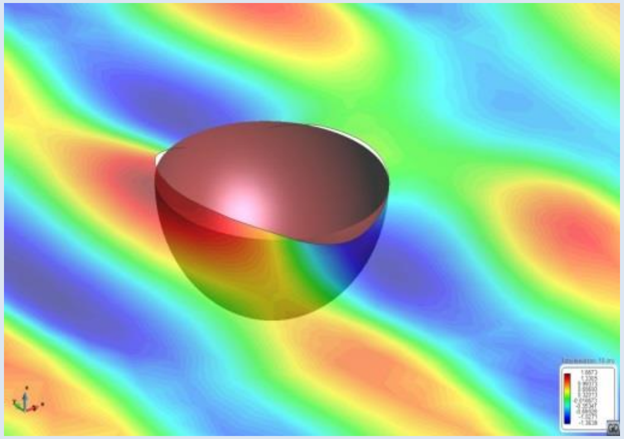
Free surface elevation: $\xi = \epsilon^1\xi^1 + \epsilon^2\xi^2 + \epsilon^3\xi^3 + \cdots$

Body position: $\boldsymbol{X} = \epsilon^1\boldsymbol{X}^1 + \epsilon^2\boldsymbol{X}^2 + \epsilon^3\boldsymbol{X}^3$ ...

Body velocity: $\boldsymbol{V} = \epsilon^1\boldsymbol{V}^1 + \epsilon^2\boldsymbol{V}^2 + \epsilon^3\boldsymbol{V}^3$ ...

- ✓ Decomposition solution: total =incident + diff-rad

$\varphi^{\mathrm{i}} = \psi^{\mathrm{i}} + \phi^{\mathrm{i}}; \ \xi^{i} = \zeta^{\mathrm{i}} + \eta^{\mathrm{i}}$



HYDRODYNAMICS GOVERNING EQUATIONS

- ✓ Up to second-order wave diffraction-radiation problem
  - ✓ Governing equations (summing up first and second order equations):

$\Delta\phi^{1+2} = 0$	in Ω,
$\frac{\partial\eta^{1+2}}{\partial t} - \frac{\partial\phi^{1+2}}{\partial z} = -S^1$	on z=0,
$\frac{\partial\phi^{1+2}}{\partial t} + \frac{P_{fs}}{\rho} + g\eta^{1+2} = -R^1$	on z=0,
$v_\phi^{1+2} \cdot n_p^0 + v_\phi^1 \cdot n_p^1 = -\left(v_p^1 + v_\psi^1\right) \cdot n_p^1 - \left(v_p^{1+2} + v_\psi^{1+2} + r_p^1 \cdot \left(\nabla v_\phi^1 + \nabla v_\psi^1\right)\right) \cdot n_p^0$	on $P \in S_B^0$
$R^1 = \eta^1 \frac{\partial}{\partial z}\left(\frac{\partial\phi^1}{\partial t}\right) + \zeta^1 \frac{\partial}{\partial z}\left(\frac{\partial\phi^1}{\partial t}\right) + \eta^1 \frac{\partial}{\partial z}\left(\frac{\partial\psi^1}{\partial t}\right) + \frac{1}{2}\nabla\phi^1 \cdot \nabla\phi^1 + \nabla\psi^1 \cdot \nabla\phi^1$	
$S^1 = \frac{\partial\phi^1}{\partial x}\frac{\partial\eta^1}{\partial x} + \frac{\partial\phi^1}{\partial y}\frac{\partial\eta^1}{\partial y} + \frac{\partial\phi^1}{\partial x}\frac{\partial\zeta^1}{\partial x} + \frac{\partial\phi^1}{\partial y}\frac{\partial\zeta^1}{\partial y} + \frac{\partial\psi^1}{\partial x}\frac{\partial\eta^1}{\partial x} + \frac{\partial\psi^1}{\partial y}\frac{\partial\eta^1}{\partial y}$	

NUMERICAL MODEL

- ✓ Wave diffraction-radiation solver:
  - ✓ Potential flow equation(Laplace): solved by FEM
  - ✓ Free surface boundary condition:
    - ✓ Combined kinematic and dynamic conditions:

$$\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial z} + \frac{\partial}{\partial t}\left(\frac{P_{fs}}{\rho}\right) + \{Q^1\} = 0$$

    - ✓ Fourth order compact Padé scheme:

$$\frac{\phi^{n+1} - 2\phi^n + \phi^{n-1}}{\Delta t^2} = -g\phi_z^n - \frac{1}{12}g(\phi_z^{n+1} + 10\phi_z^n + \phi_z^{n-1})$$
$$-\frac{P_{fs}^{n+1} - P_{fs}^{n-1}}{\rho 2\Delta t} - \left\{\frac{1}{12}\left((Q^1)^{n+1} + 10(Q^1)^n + (Q^1)^{n-1}\right)\right\}$$

    - ✓ Absorption condition: $P_{fs}(\boldsymbol{x},t) = \kappa(\boldsymbol{x})\rho\frac{\partial \phi}{\partial z}$
    - ✓ Radiation condition: $(\phi_{\boldsymbol{n}}^R)^{n+1} = -\frac{\phi^{n-1} - \phi^n}{c\Delta t}$
- ✓ Body dynamics solver

$$\bar{\bar{\mathbf{M}}}\,\mathbf{X}_{tt} + \bar{\bar{\mathbf{K}}}\,\mathbf{X} = \mathbf{F}$$

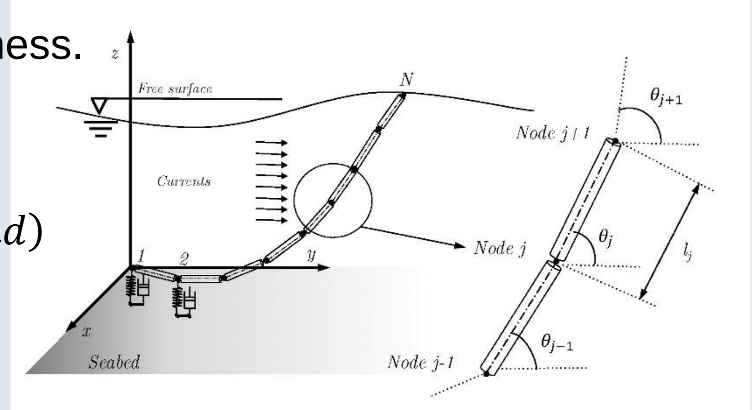
Temporal integrator: Newmark's scheme

MOORING MODELS

- ✓ Elastic catenary: quasistatic model including stiffness
  - ✓ Reference: *Jonkman, J.M. Dynamic modelling and loads analysis of an offshore floating wind turbine, Technical report NREL/TP-500-41958; November 2007*
- ✓ Dynamic cable
  - ✓ Mathematical model:
    - ✓ Cable with negligible bending and torsional stiffness.

$$(\rho_w C_m A_0 + \rho_0)\frac{\partial^2 r_l}{\partial t^2} = \frac{\partial}{\partial l}\left(EA_0 + \frac{e}{e+1}\frac{\partial r_l}{\partial l}\right) + \mathrm{f}(t)(1+e)$$

$$\frac{\partial^2 r_l}{\partial t^2} = 0, \text{at } l = 0(anchor), \frac{\partial^2 r_l}{\partial t^2} = \ddot{r_b}, \text{at } l = L(fairlead)$$



  - ✓ Numerical model:
    - ✓ Solved using FEM:
    - ✓ Includes Morison Forces
    - ✓ Reference: *Gutiérrez-Romero, J.E., Serván-Camas, B., García-Espinosa, J. and Zamora-Parra, B. Non-linear dynamic analysis of the response of moored floating structures. Marine Structures 2016; 49:116-137*.

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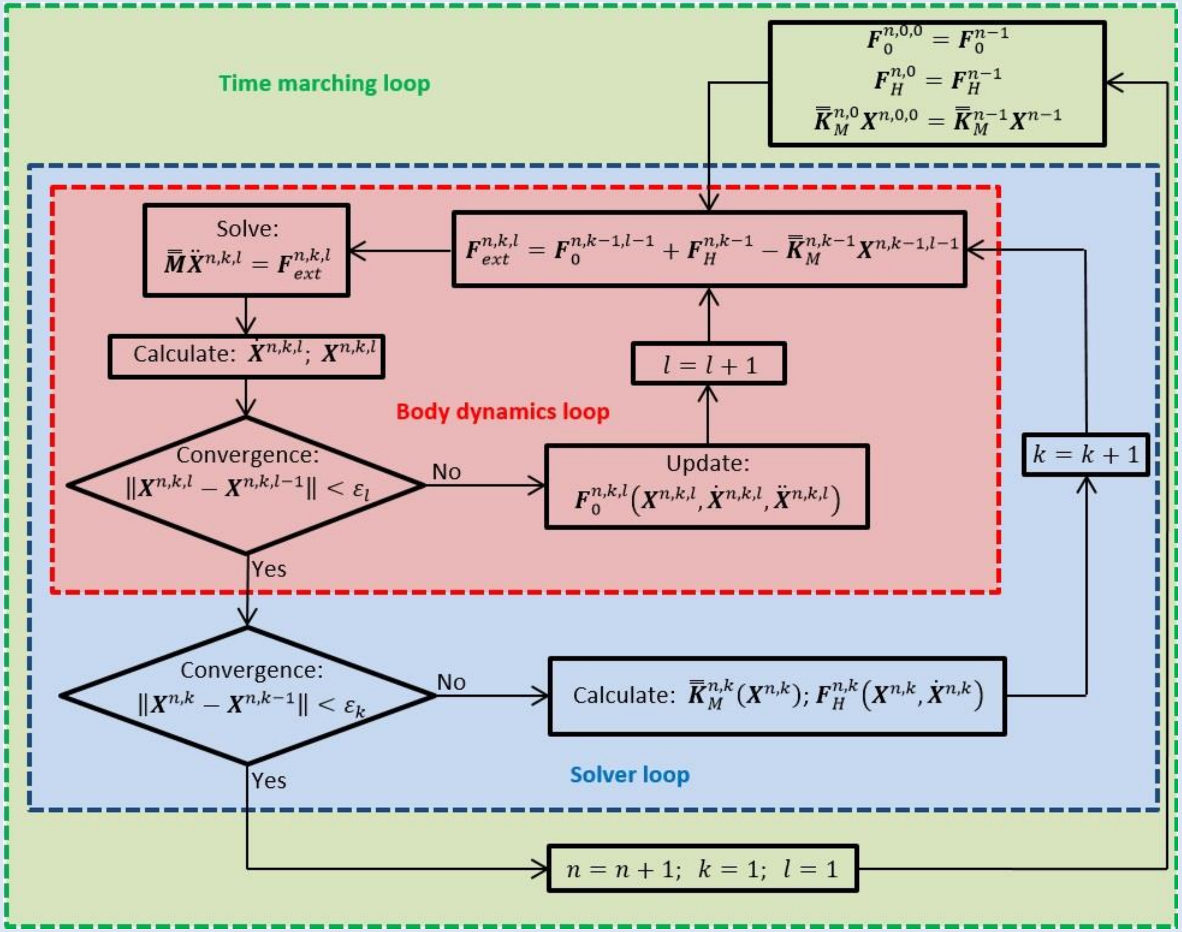
COUPLING SEEKEPING AND MOORING

- ✓ Embedded loops algorithm
- ✓ Three loops:
  - ✓ Time loop
  - ✓ Solver loop

  Solve diffraction-radiation.
  - ✓ Body dynamics loop
  - ✓ Solve body movements
- ✓ Mooring solver:
  - ✓ Non-linear
  - ✓ Jacobian matrix is updated within the Solver loop
  - ✓ Linear within the body dynamics loop.

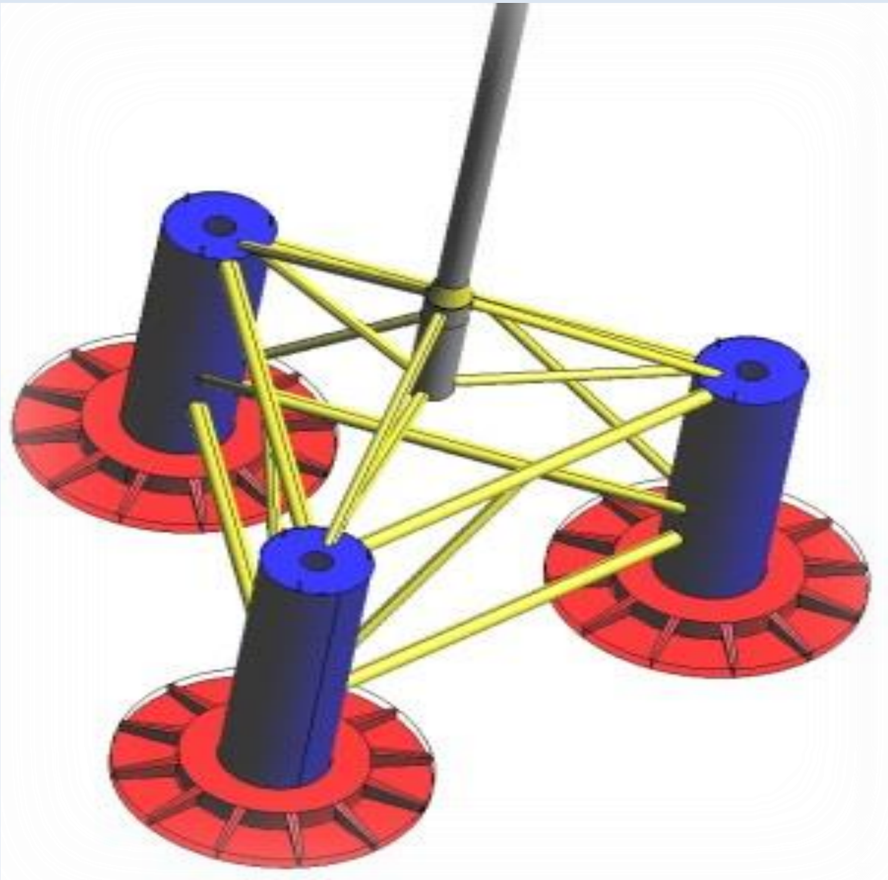


VALIDATION

HIPRWIND MODEL DESCRIPTION

✓ HiPRWind main particulars:

Depth	100 m
Operation design draft	15.5 m
Distance from column center to platform center	35 m
Column diameter	7 m
Heave plates diameter	20 m
Mass	2332 T
XG	0 m
YG	0 m
ZG	-4.46 m
Radii (pitch)	22.38 m



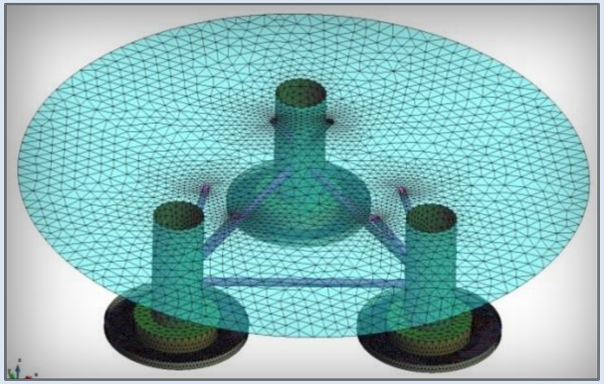
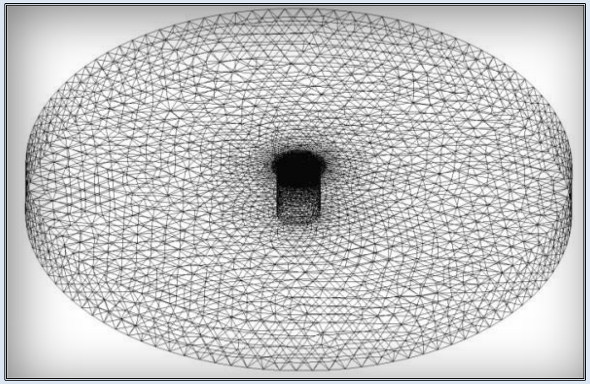
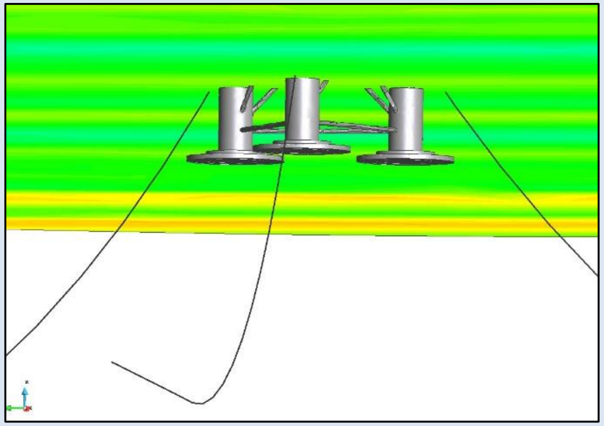
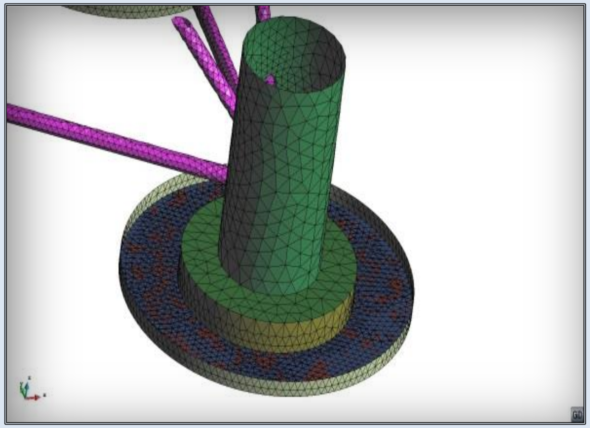
EXPERIMENTAL SETUP

✓ Facility particulars

Facility (model basin)	Ecole centrale de Nantes	Full scale
Model scale	19.8	-
Distance from wave generator to model	15.10 m	-
Distance from beach to model	29.45 m	-
Wave range	1.35s-4.5 s (2.84m-26.34m)	6s-20 s (56.3m520m)
Mooring line stiffness	51 N/m	20 KN/m
Mooring line pretension	70.85 N	550 KN

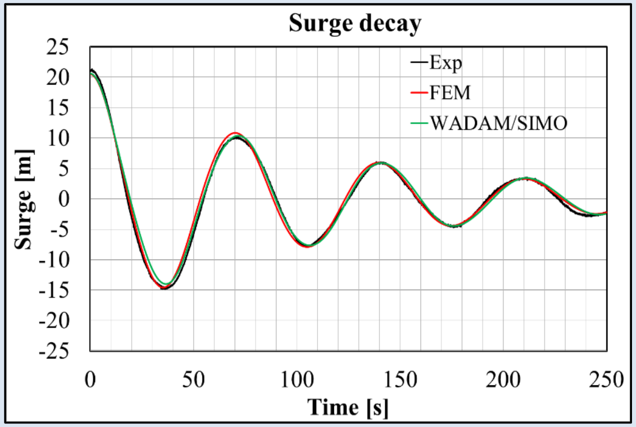
NUMERICAL SETUP

- ✓ Model geometry and mesh:
  - ✓ *Number of tetrahedral elements:* 567363
  - ✓ *Number of triangular elements:* 51398

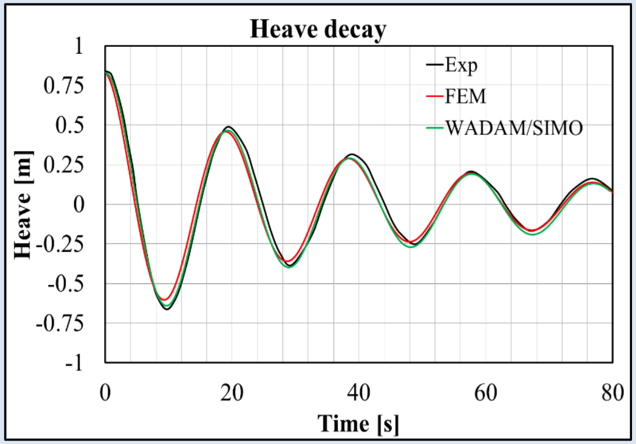





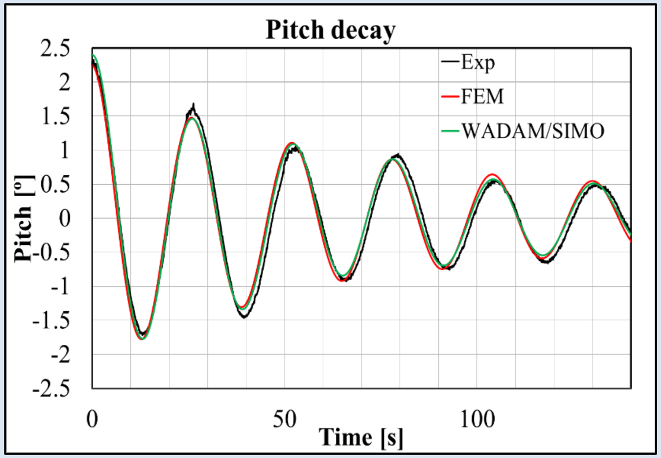
MODEL CALIBRATION

✓ Decay tests using elastic lines:



		FEM	WADAM/SIMO
Applied at CG	**Surge linear damping: B_{11}[KN/(m/s)]**	75	70
	Heave added mass: A_{33} [t]	1200	1000
	Heave linear damping: B_{33}[KN/(m/s)]	1100	110
Applied at the center of each heave plate base	**Heave linear damping: B_{33}[KN/(m/s)]**	76	50
	Heave quadratic damping: B_{33}^2[KN/(m/s)^2]	805	600





Natural periods		
Surge	**Heave**	**Pitch**
70s	19s	26s

ANALYSIS ON BICHROMATIC WAVES

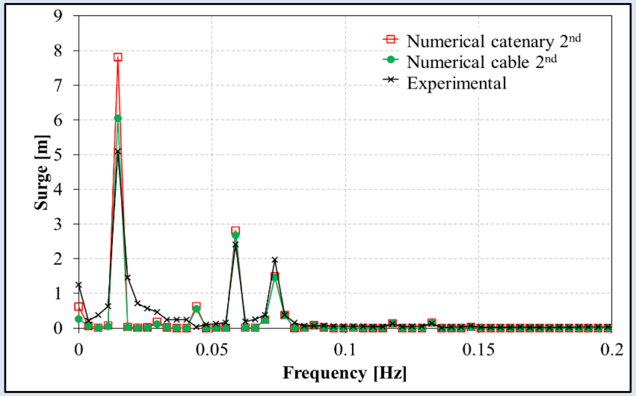
✓ Bichromatic test matrix

Case	Incident wave 1		Incident wave 2		Freq. difference		Freq. Sum	
	H_1 [m]	f_1 [Hz]	H_2 [m]	f_2 [Hz]	$f_2 - f_1$ [Hz]	T_{diff} [s]	$f_1 + f_2$ [Hz]	T_{sum} [s]
1	5.63	0.0582	4.32	0.0735	0.0153	65.4	0.1318	7.59
2	5.27	0.0667	3.54	0.0813	0.0146	68.3	0.1480	6.76
3	2.80	0.1053	1.62	0.1220	0.0167	59.9	0.2272	4.40
4	2.13	0.1205	1.27	0.1351	0.0147	68.2	0.2556	3.91
5	1.88	0.1300	1.14	0.1429	0.0128	78.0	0.2729	3.66
6	1.50	0.1449	0.92	0.1587	0.0138	72.4	0.3037	3.29
7	1.67	0.1370	1.02	0.1515	0.0145	68.8	0.2885	3.47
8	1.35	0.1515	0.84	0.1667	0.0152	66.0	0.3182	3.14
9	1.22	0.1613	0.77	0.1754	0.0141	70.7	0.3367	2.97
10	1.11	0.1667	0.70	0.1818	0.0152	66.0	0.3485	2.87
11	2.83	0.0909	2.10	0.1053	0.0144	69.7	0.1962	5.10
12	3.37	0.0833	2.44	0.0997	0.0163	61.2	0.1830	5.46
13	4.59	0.0714	3.16	0.0850	0.0135	73.8	0.1564	6.39
14	5.64	0.0526	5.16	0.0672	0.0145	68.9	0.1198	8.35
15	2.82	0.0526	5.16	0.0672	0.0145	68.9	0.1198	8.35
16	3.44	0.0476	6.03	0.0625	0.0149	67.2	0.1101	9.08

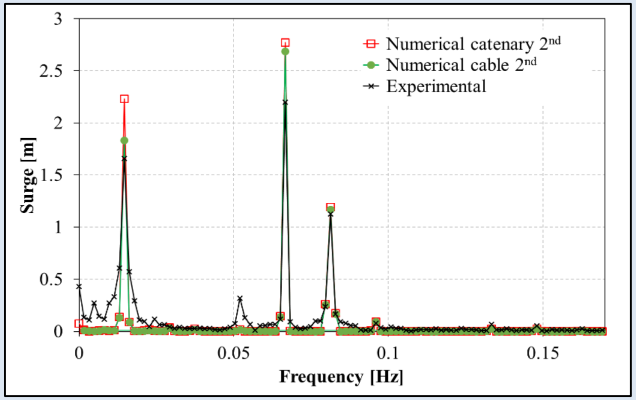
ANALYSIS ON BICHROMATIC WAVES

✓ Bichromatic test results

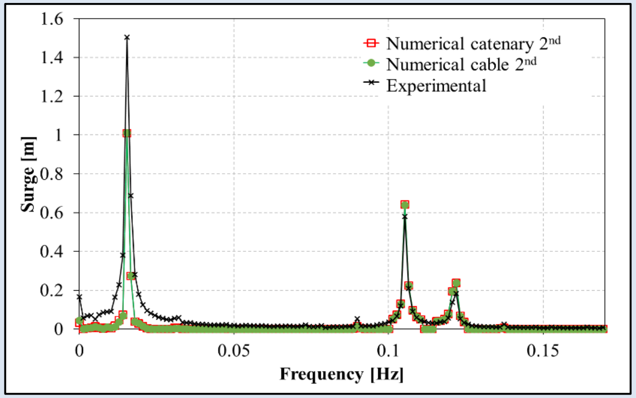
Case 1



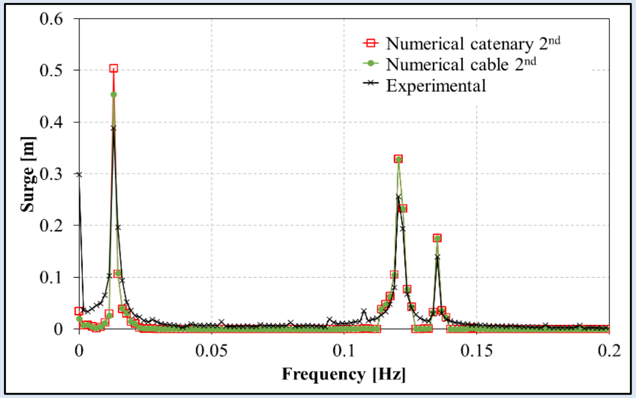
Case 2



Case 3



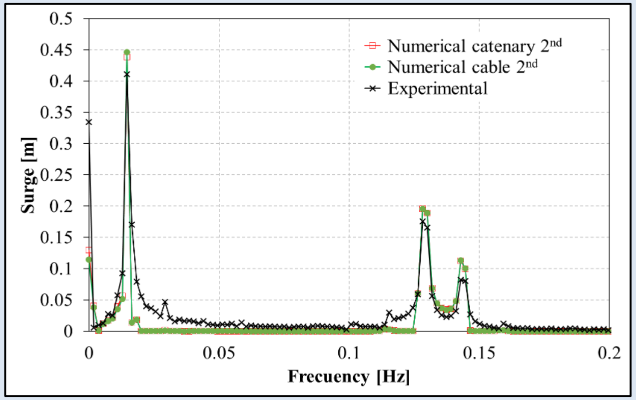
Case 4



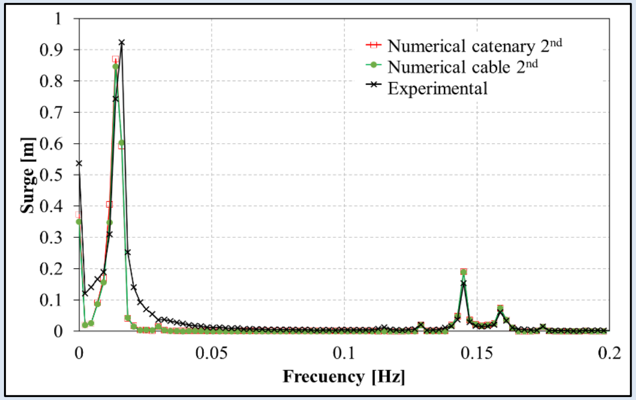
ANALYSIS ON BICHROMATIC WAVES

✓ Bichromatic test results

Case 5



Case 6



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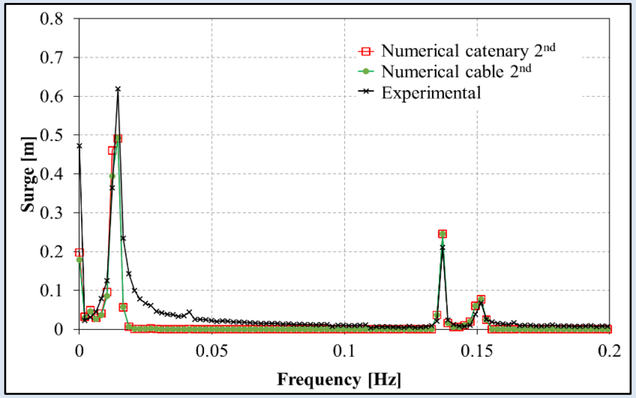
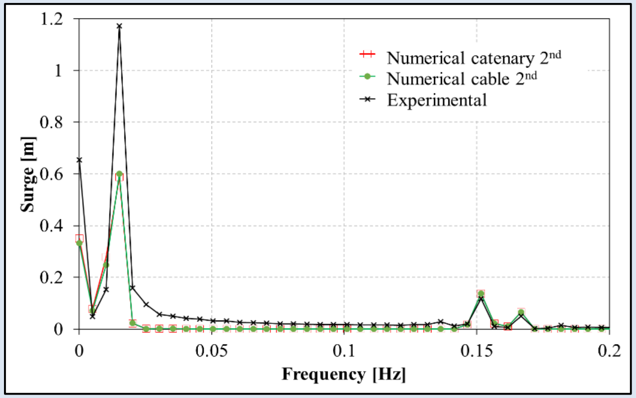


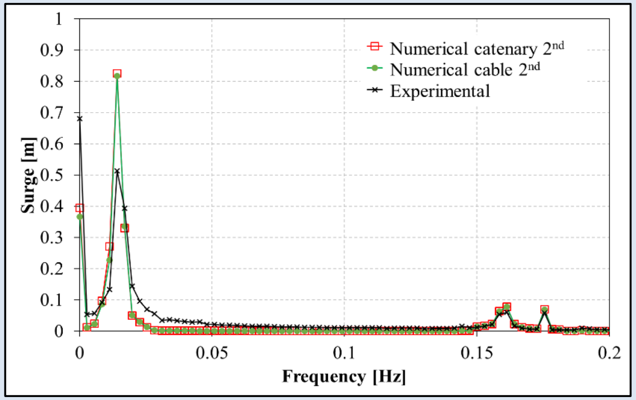
Case 8



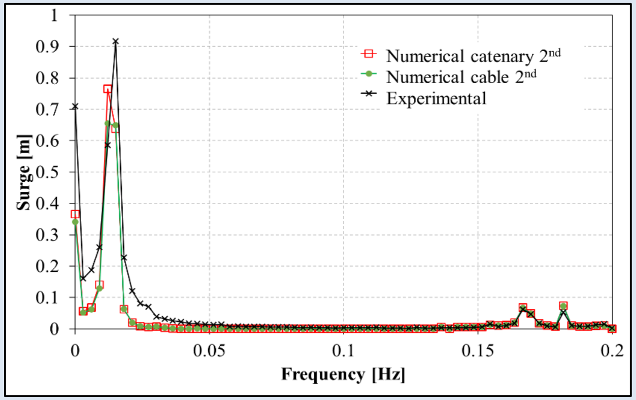
ANALYSIS ON BICHROMATIC WAVES

✓ Bichromatic test results

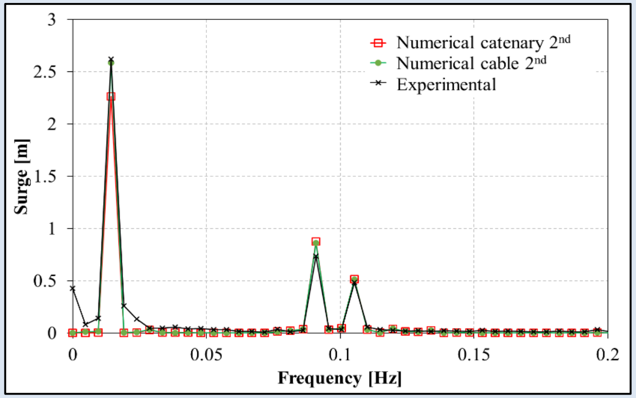
Case 9



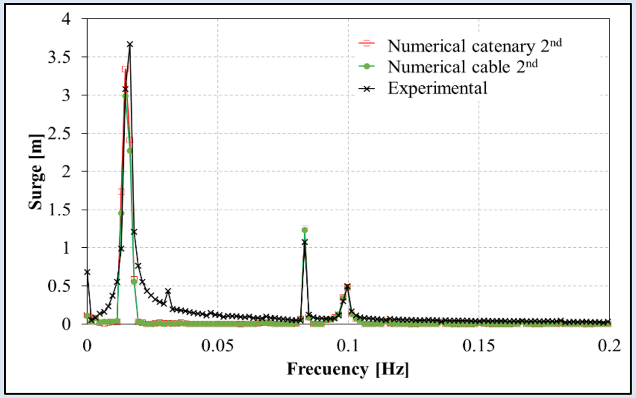
Case 10



Case 11



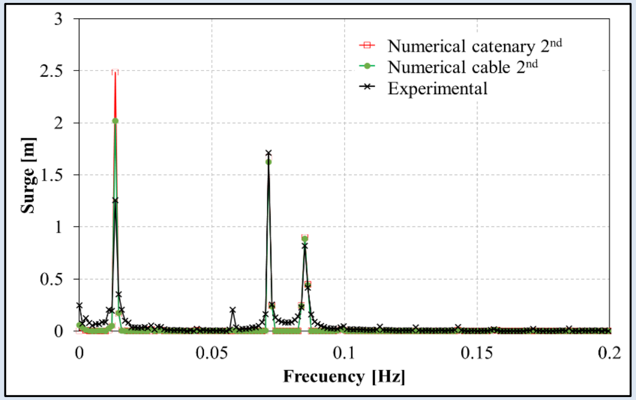
Case 12



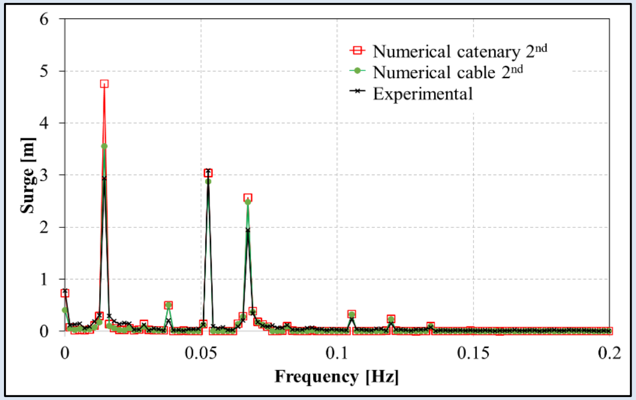
ANALYSIS ON BICHROMATIC WAVES

✓ Bichromatic test results

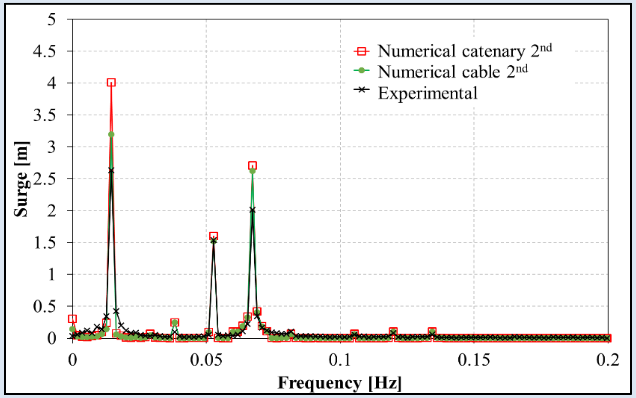
Case 13



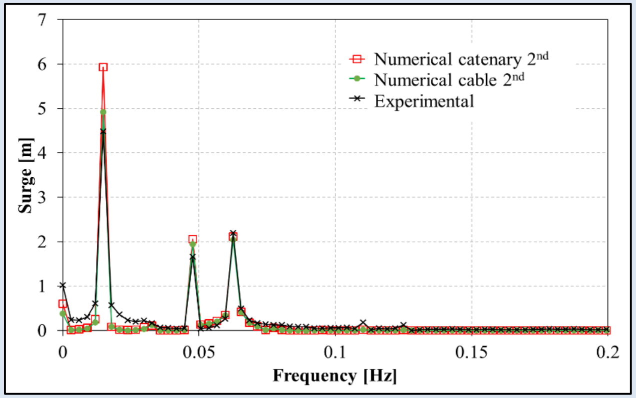
Case 14



Case 15

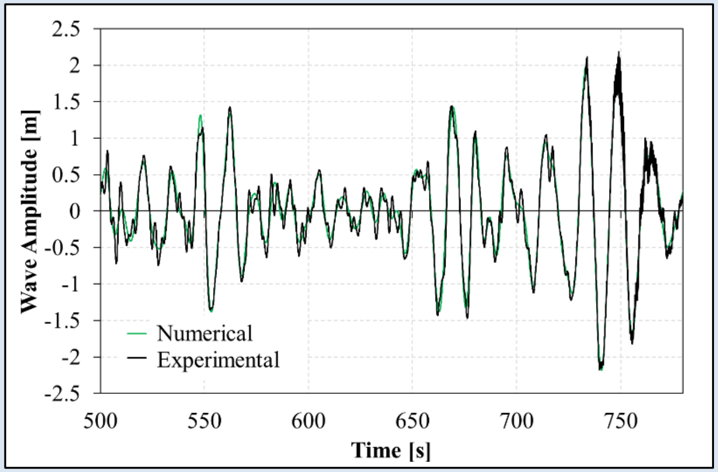


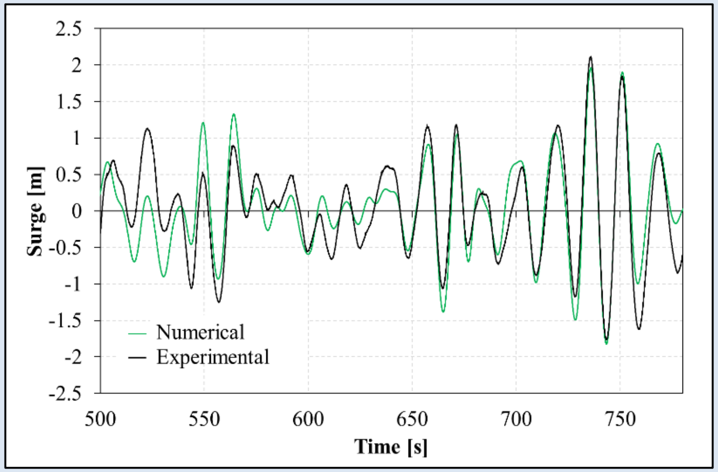
Case 16

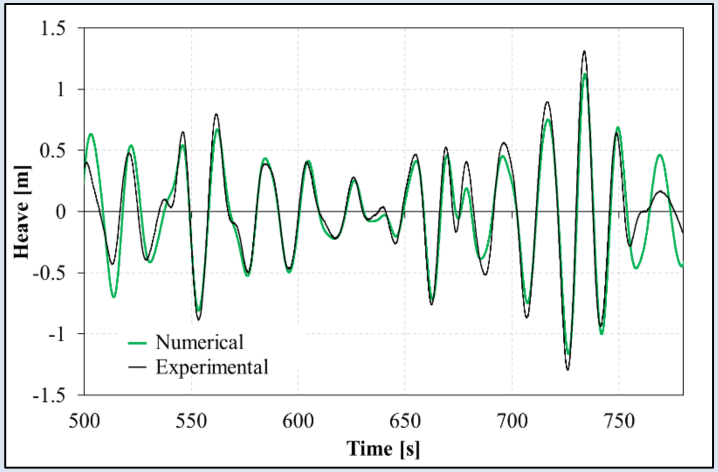


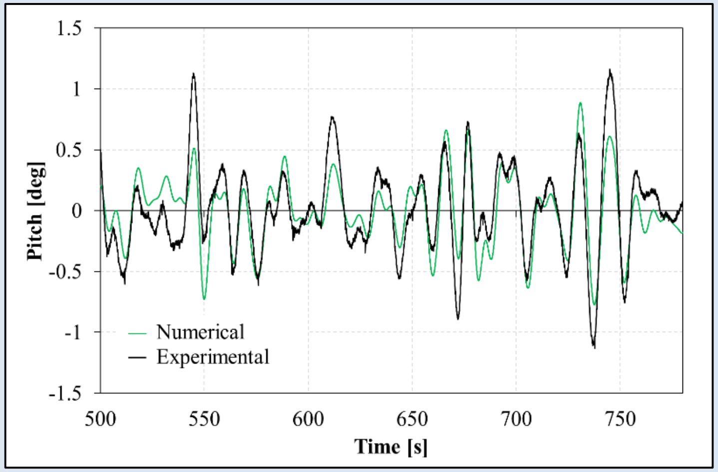
ANALYSIS ON BICHROMATIC WAVES

✓ Irregular test 1: H_s=2.5m, T_P=16s



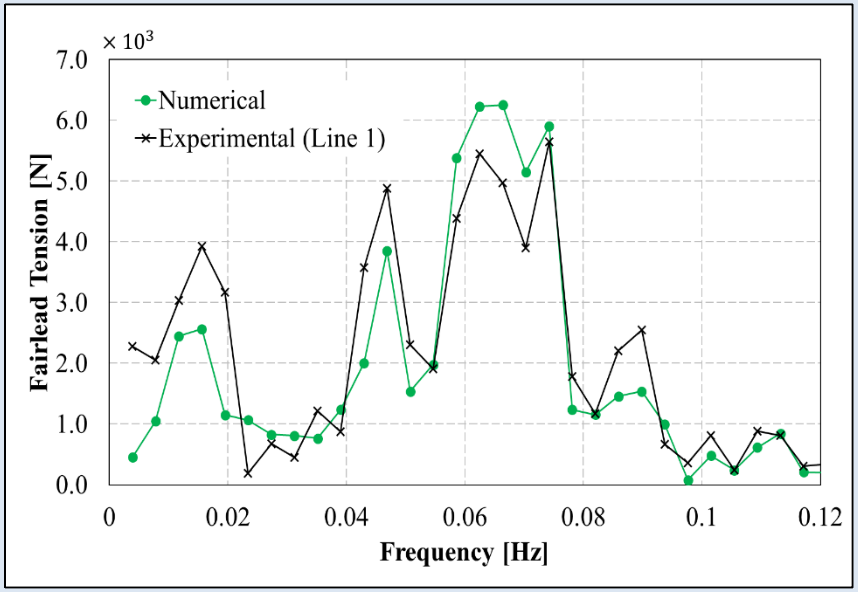


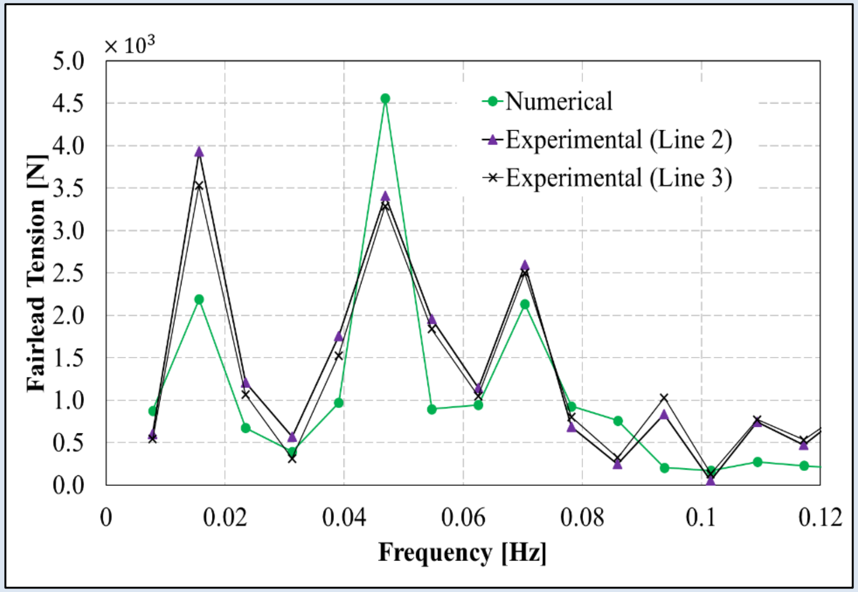




ANALYSIS ON BICHROMATIC WAVES

✓ Irregular test 1: H_s=2.5m, T_P=16s





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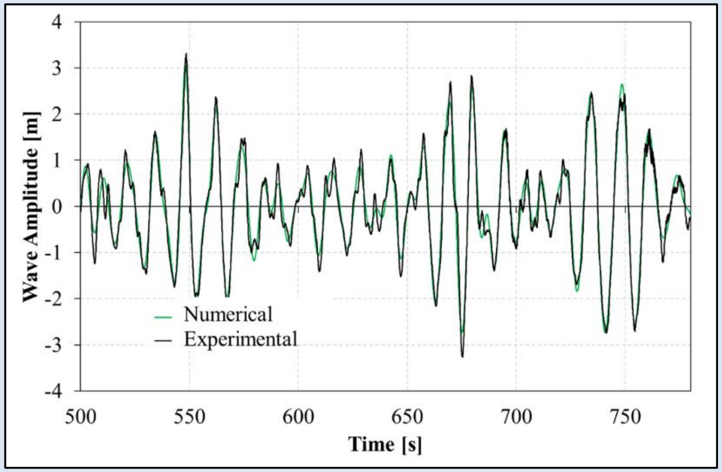
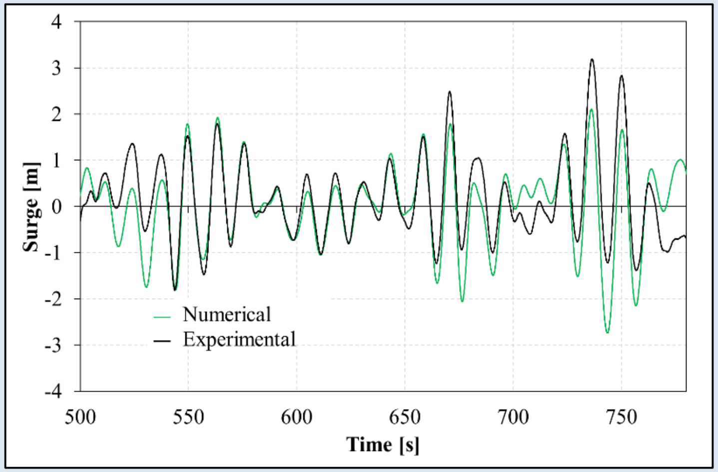
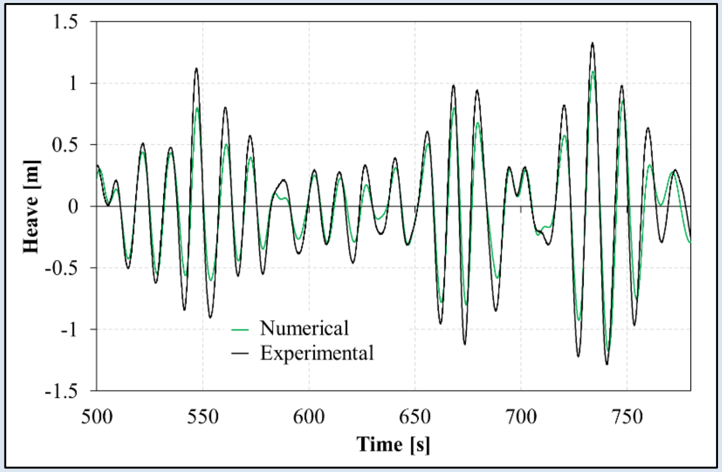
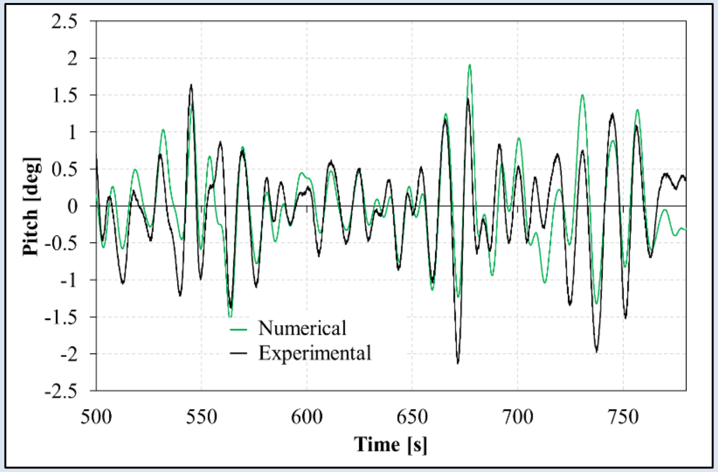
ANALYSIS ON BICHROMATIC WAVES

✓ Irregular test 2: H_s=4.0m, T_P=13s



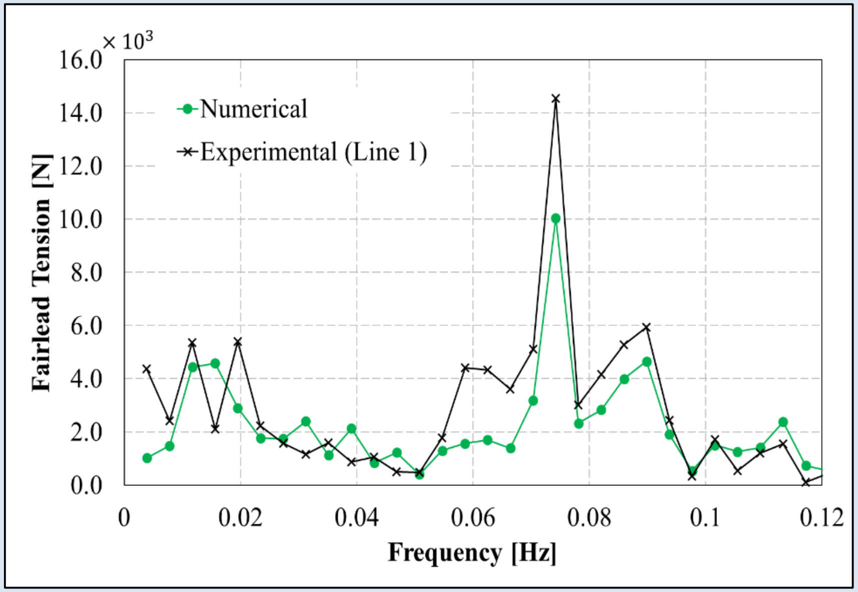


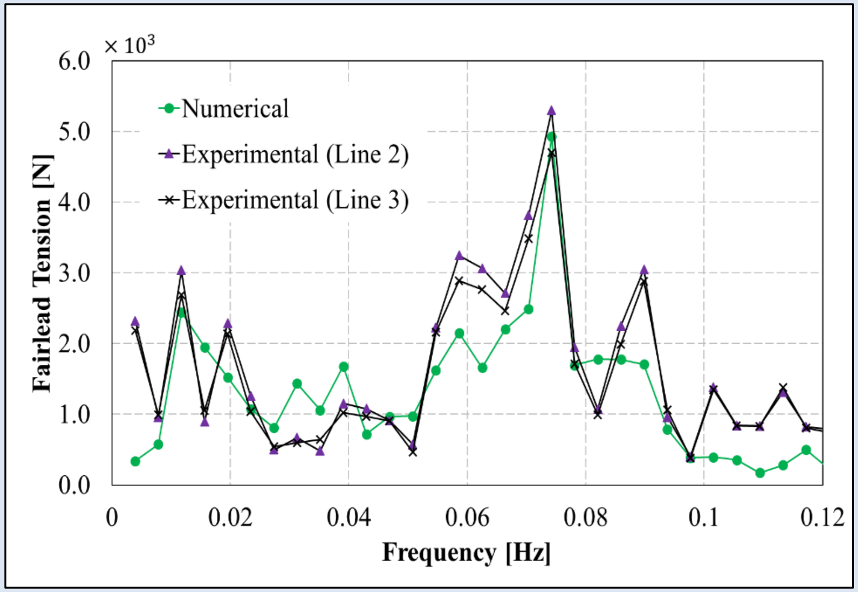




ANALYSIS ON BICHROMATIC WAVES

✓ Irregular test 1: H_s=4.0m, T_P=13s





SUMMARY AND CONCLUSIONS

- ✓ A time-domain up to second-order wave diffraction-radiation solver based on FEM has been presented.
- ✓ Two mooring models have been coupled with the diff-rad solver.
- ✓ The proposed methodology has been validated against experiments carried out for the HiPRWind semi-submersible platform.
- ✓ Test in bichromatic waves:
  - ✓ No large differences between the elastic catenary and dynamic cable model.
  - ✓ Fair agreement between numerical and experimental (better in the higher frequency range).
- ✓ Test in bichromatic waves:
  - ✓ Good movements phase agreement.
  - ✓ Some movement deviation, mostly in the low frequency.
  - ✓ Numerical mooring loads follow the trend of the experimental measurements.

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