PO. 201

Dynamic Response Prediction of Floating Offshore Wind Turbine System using Fully Nonlinear Model

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Objectives

Floating Offshore Wind Turbine System (FOWTS) is made of light materials compared to conventional offshore structures, which results in large motion under wind and wave load. Therefore, the nonlinearity of the mooring stiffness and the dynamic interaction between wind turbine, floater and mooring system have to be considered when dynamic response analysis of FOTWS is performed.

Existing studies[1][2] on the dynamic motion of FOWTS are based on some simplifications, such as ignoring the dynamic interaction, assuming hydrostatic restoring force and linear mooring system, which may cause some errors.

The University of Tokyo has been developing a fully nonlinear FEM for the dynamic response prediction of FOWTS[3]. In this study, non-hydrostatic restoring force model was applied and verified through comparison with hydrostatic model and water tank experiment. Then the effect of heave plates was investigated with this updated model. Finally, based on this model, nonlinear mooring system considering full dynamic coupling was modeled and their effects compared to linear mooring system were simulated.

Nonlinear FEM model

The equation of motion can be written as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

where

$$\mathbf{M} = \begin{bmatrix} \mathbf{M_T} & 0 & 0 \\ 0 & \mathbf{M_F} & 0 \\ 0 & 0 & \mathbf{M_M} \end{bmatrix}, \mathbf{C} = \begin{bmatrix} \mathbf{C_{TT}} & \mathbf{C_{TF}} & 0 \\ \mathbf{C_{FT}} & \mathbf{C_{FF}} & \mathbf{C_{FM}} \\ 0 & \mathbf{C_{MF}} & \mathbf{C_{MM}} \end{bmatrix}, \mathbf{K} = \begin{bmatrix} \mathbf{K_{TT}} & \mathbf{K_{TF}} & 0 \\ \mathbf{K_{FT}} & \mathbf{K_{FF}} & \mathbf{K_{FM}} \\ 0 & \mathbf{K_{MF}} & \mathbf{K_{MM}} \end{bmatrix}, \mathbf{x} = \begin{Bmatrix} \mathbf{x_T} \\ \mathbf{x_F} \\ \mathbf{x_M} \end{Bmatrix}$$

The subscripts refer to Turbine, Floater and Mooring system respectively. External force includes: Gravitational force, Buoyancy force, Hydrodynamic force, Restoring force, Seabed contact force and Aerodynamic force.

- Hydrodynamic force on cylinder members is modeled using Morison's equation modified by Sarpkaya & Isaacson[4]. This force consists of added inertia force, Froude-Krylov force and drag force.

$$\mathbf{f_H} = \mathbf{f_{HM}} + \mathbf{f_{HW}} + \mathbf{f_{HD}}$$

$$\mathbf{f_{HM}} = -M_a\ddot{\mathbf{x}} \qquad \text{where } M_a = \rho_w (C_M - 1) A$$

$$\mathbf{f_{HW}} = \rho_w C_M A \dot{\mathbf{u}}$$

$$\mathbf{f_{HD}} = \frac{1}{2}\rho_w C_D A \{\mathbf{u} - \dot{\mathbf{x}}\} \left|\{\mathbf{u} - \dot{\mathbf{x}}\}\right|$$

C_D, C_M are functions of Keulegan-Carpenter number.

- Hydrodynamic force on column base consists of added inertia force and damping force.

$$\mathbf{f_H} = \mathbf{f_{HM}} + \mathbf{f_{HD}}$$

$$\mathbf{f_{HM}} = -M_a\ddot{\mathbf{x}} \qquad \text{where } M_a = \rho_w (C_M - 1) V$$

$$\mathbf{f_{HD}} = \mathbf{C_{ED}}\dot{\mathbf{x}}$$

where V is a half sphere volume of water proposed in Haslum's model[5]. Damping ratio is 15% following Srinivasan's model[6]

- Restoring force:

Non-hydrostatic restoring force

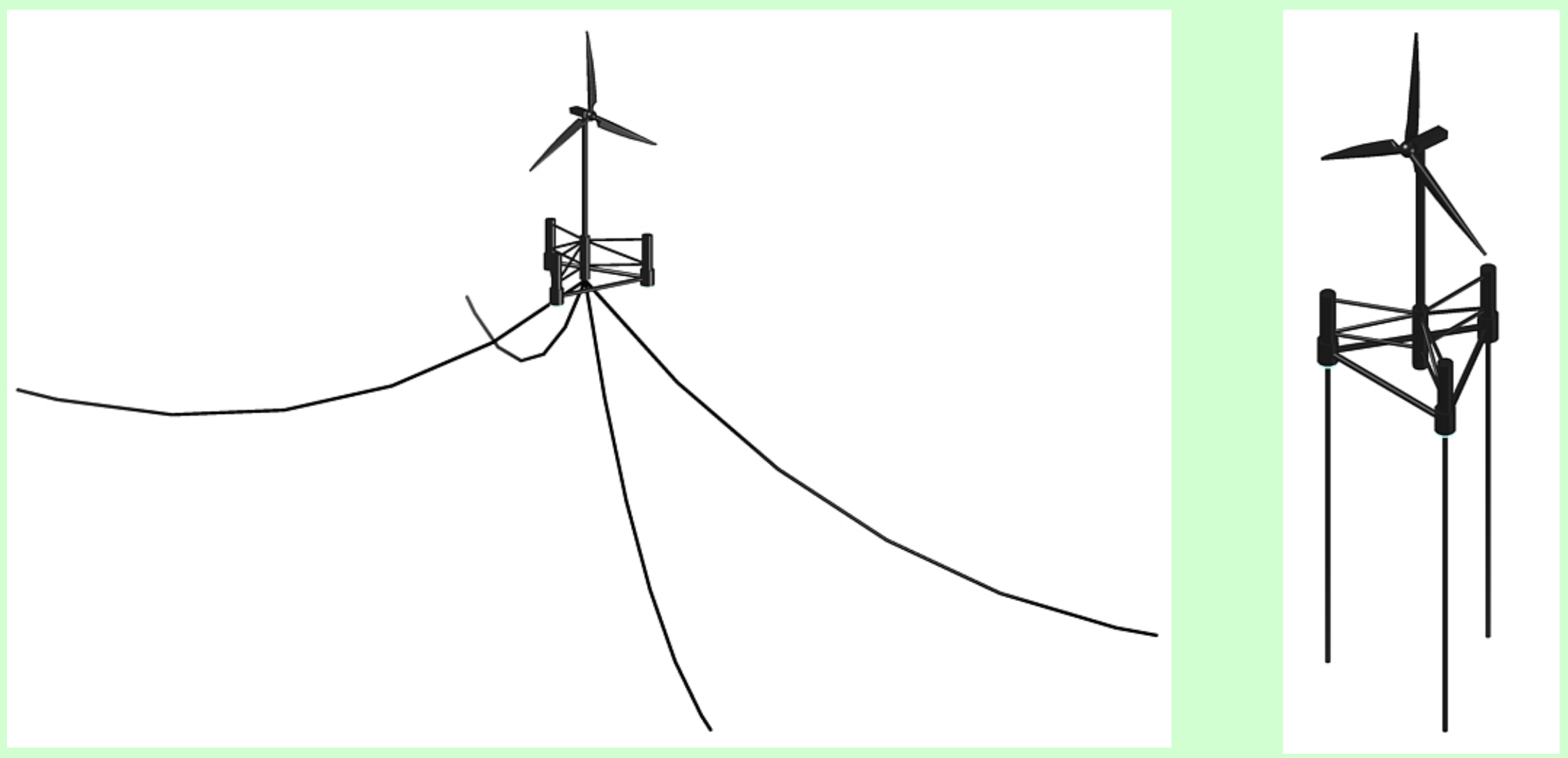
$$\mathbf{f_R}\big|_{\mathbf{NHM}} = \mathbf{K_R}(\mathbf{x} - \boldsymbol{\eta})$$

where η is the wave height.

- Seabed contact force for nonlinear catenary mooring consists of frictional and normal force acting only on elements in contact with the sea bed. According to Ju et al[7], it is expressed using penalty constant *k*, frictional coefficient μ and relative displacement in tangential and normal directions

$$\{\mathbf{f_c}\} = \begin{Bmatrix} \mathbf{f_t} \\ \mathbf{f_n} \end{Bmatrix} = k \begin{bmatrix} \mu^2 & \mu \\ \mu & 1 \end{bmatrix} \begin{Bmatrix} \mathbf{U} \\ \mathbf{V} \end{Bmatrix}$$

- Aerodynamic force is modeled using Quasi-steady theory, Blade element theory and Momentum theory considering blade tip loss, hub loss and tower shadow. However, wind is not considered in this study.



Catenary (left) and Tension Legged (right) mooring system

Total Lagrangian formulation with Newmark-β method is used to solve the full elastic structure. Rayleigh damping is considered with damping ratio of 0.5%

Modeling of the FOWTS

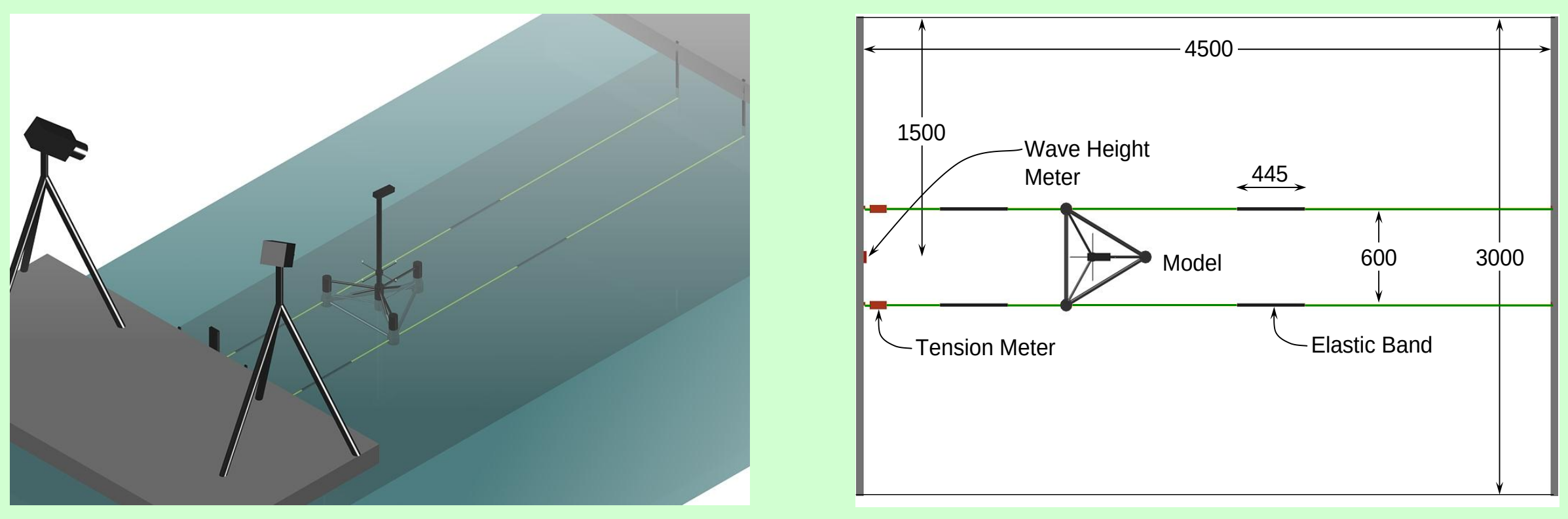
Component	Description		No. of Elements	Type
Wind Turbine	Tower		13	Beam
Floater			109	Beam
Mooring System	Experimental Setup	Elastic	4	Spring
		Kevlar	24	Truss
	Catenary Mooring		30 / line	Truss
	Tension Leg Mooring		10 / tether	Pre-stressed Beam

Specification

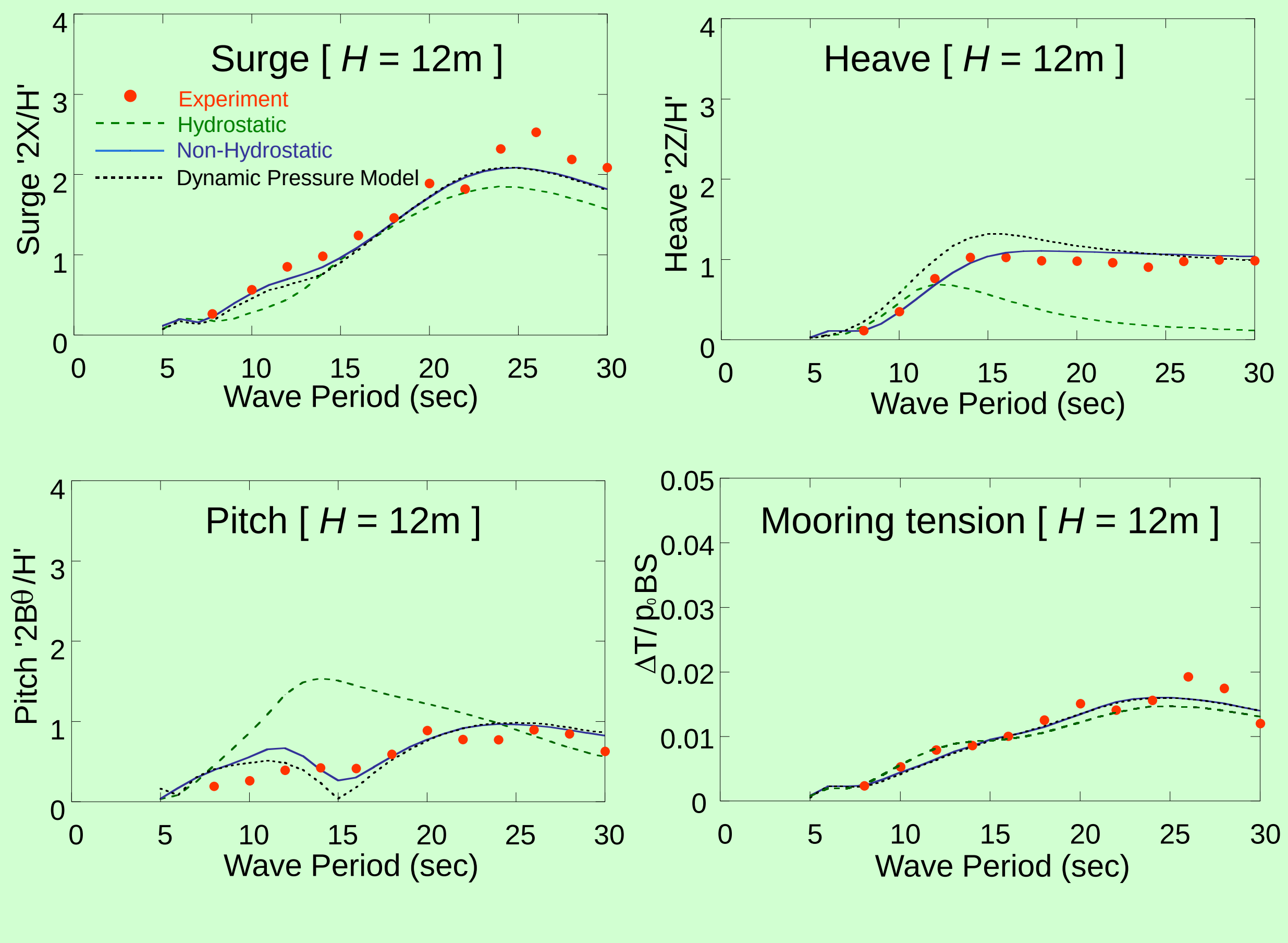
Floater span	60m
Tower height	70m
Sea depth	150m
Catenary chain length	660m
Total pretension of TLP tendons	6870kN

Verification of the nonlinear model

A water tank experiment was conducted to verify the FEM model. The scale was 1:100 following Froude similitude. Four horizontal mooring lines connected to elastic bands were used. Waves corresponding to 4m (rated state) and 12m (extreme state) were generated and the response of the floater was observed.



Experimental setup

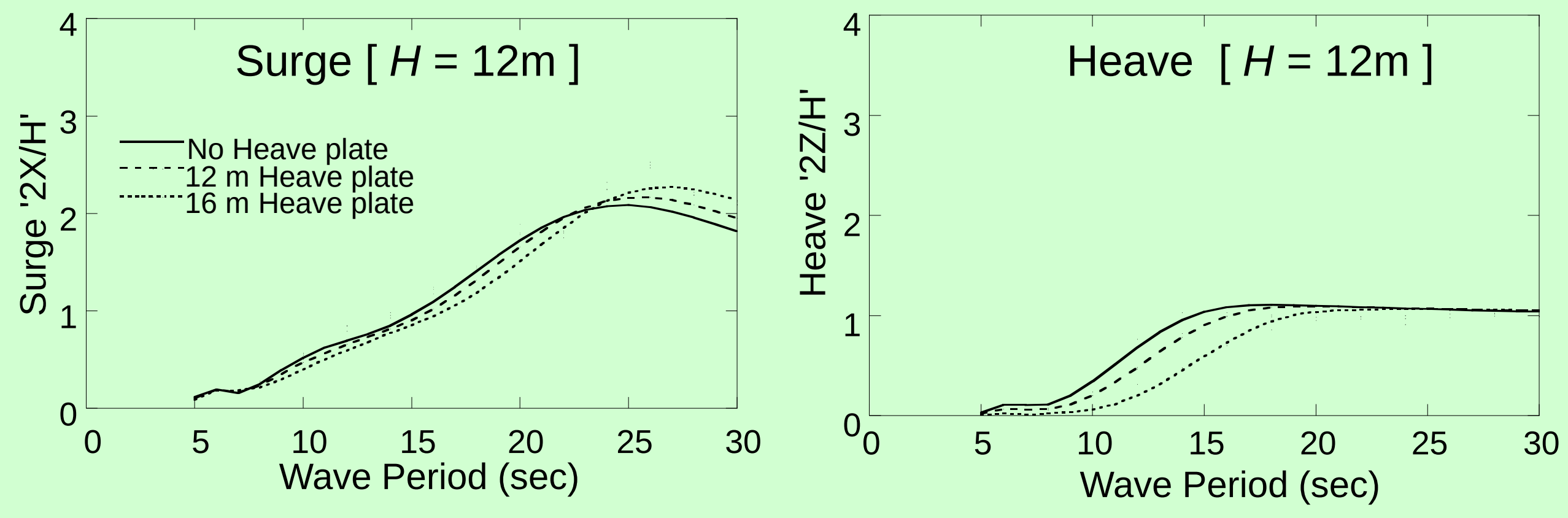


Response of the floater to regular waves (no wind)

- Non-hydrostatic model agreed well with the experiment for the surge, heave, pitch and the mooring line tension. Hydrostatic model underestimates the heave response due to underestimation of vertical restoring force.
- These results verify the hydrodynamic force and response evaluation in the developed model. Similar results were seen for the 4m case as well.

Effect of heave plates and nonlinear mooring

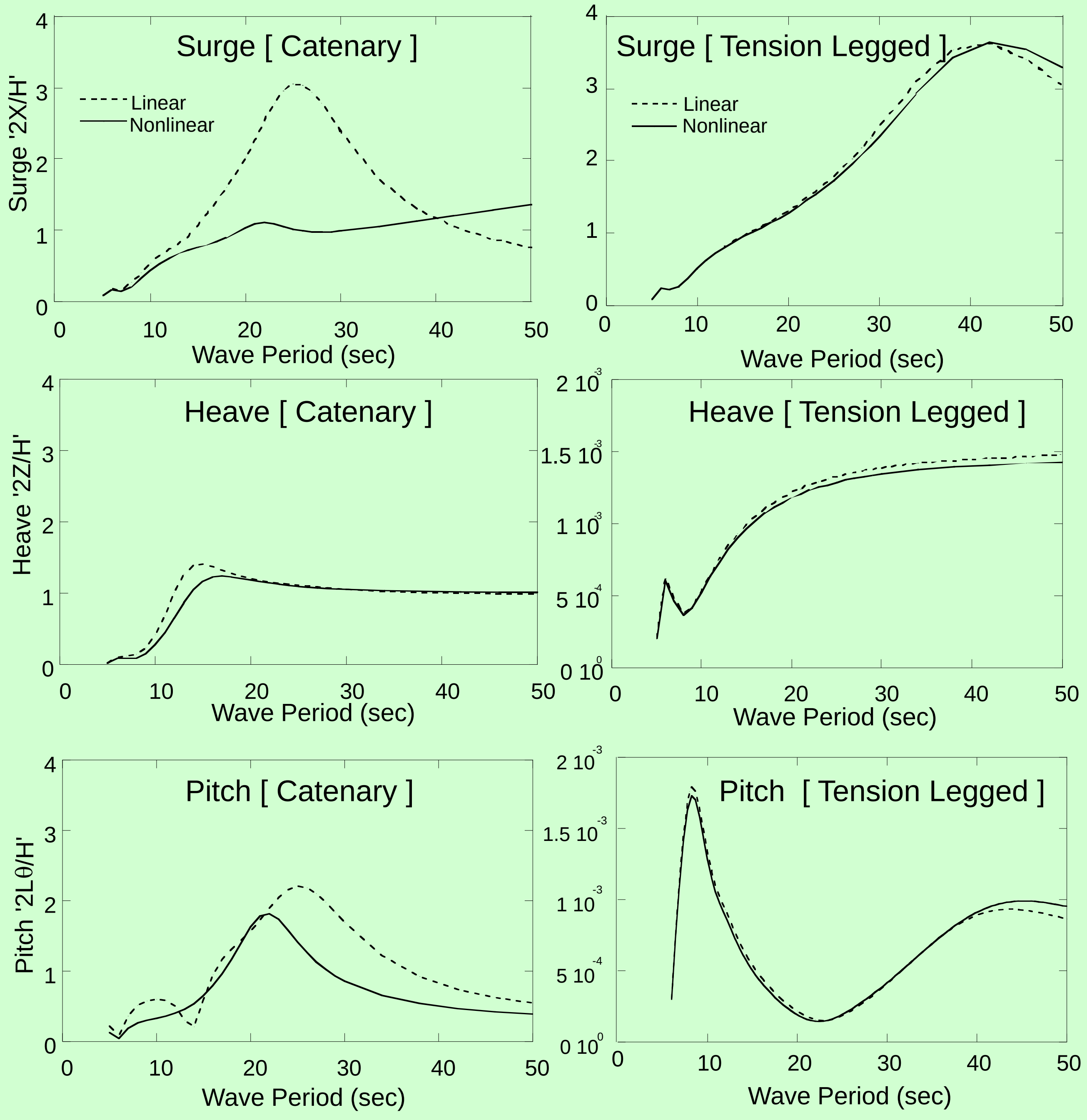
The experimental model was tested without (D=8m) and with heave plates (D=12m,16m).



Response with different sized heave plates (no wind)

- Heave plates reduced the heave response by up to more than 50% between 5-20 second wave period range. This is due to the shift of the resonance peak to longer period caused by the increased added mass.

FOWTS with nonlinear catenary and tension legged mooring were modeled using the FEM and their response to regular waves with no wind was simulated. The results were compared with linear mooring assuming restoring force proportional to the displacement.



Floater response for linear and non-linear mooring [*H* = 4m]

- For the catenary mooring, the linear model overestimated the surge response. This is due to the large dynamic component in the mooring force.
- For the tension legged mooring, both models showed similar results. This is due to the strong initial tension of the tendons resulting in relatively small nonlinearity.

Conclusions

- A fully coupled nonlinear FEM was developed to predict the dynamic response of FOWTS and it was verified through water tank experiment.
- Heave plates reduced the heave response by shifting the resonance peak to longer period.
- Simulation results showed small nonlinearity in tension legged mooring. However, the linear model overestimated the surge for catenary mooring due to the large dynamic component in the mooring force.

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