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Dynamic Analysis of Floating Offshore Wind Turbine System Considering Combined Hydrodynamic Loadings

Takeshi IHIHARA, Ken KAGAYA, Yuka KIKUCHI
Department of Civil Engineering, School of Engineering, The University of Tokyo

Introduction

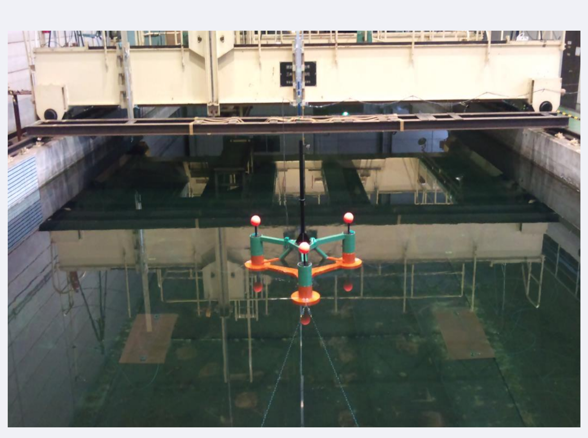
Fukushima Floating Offshore Wind Farm Demonstration Project has started in 2013. The nonlinear effect of hydrodynamic force and elastic motions are significant for dynamic analysis of Floating Offshore Wind Turbine System due to the slender members.

A nonlinear finite element model has been developed considering coupling between wind turbine, floater and mooring[1],[2] and used in this study to investigate the following issues.

1) Prediction of floater response in heave direction considering wave nonlinearity effect and comparison of it with that by conventional linear model.
2) Clarification of the mechanism of low-frequency motion (oscillatory) for semi-sub floater.
3) Estimation of the interaction of wave and current and comparison of the prediction by nonlinear model with that by superposing of wave and current response.

Water tank experiment

Water tank experiment was conducted to verify the FEM model. The scale was 1:50 following Froude similitude. The model was semi-sub floater used at Fukushima project and the wind turbine was simplified by a distributed mass. Water tank had 55m long and 8m wide. Water depth was set to 2.5m. Four catenary moorings were attached to keep the position and used to reproduce major motions in surge, heave and pitch.



Natural periods of floater
(Real scales in parentheses)

	Natural period
Surge	7.6 sec (53.7sec)
Heave	2.4 sec(17.0sec)
Pitch	3.0 sec(21.2sec)

Numerical model

In this study, nonlinear finite element scheme was used. The nonlinear damping model was introduced for drag force in vertical direction.

■ The equation of motion can be written as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F_R\}+\{F_E\}+\{F_G\}+\{F_W\}$$

F_R is restoring force, F_E is hydrodynamic force, F_G is gravitational force and F_W is aerodynamic force.

■ Hydrodynamic forces are estimated as a combination of Froude-Krilov force F_{EM}, diffraction force F_{EW} and drag force F_{ED}.

$$\{F_E\}=\{F_{EM}\}+\{F_{EW}\}+\{F_{ED}\}$$

$$F_{EM}=\rho_w A\dot{u} \qquad F_{EW}=\left(C_M-1\right)\rho_w V\left(\dot{u}-\ddot{x}\right)$$

$$F_{ED}=0.5\rho_w C_D A\left\{u-\dot{X}\right\}\left|\left\{u-\dot{X}\right\}\right|$$

Drag and inertia coefficients C_D, C_M were identified with test and C_D of mooring was obtained from DNV[4].

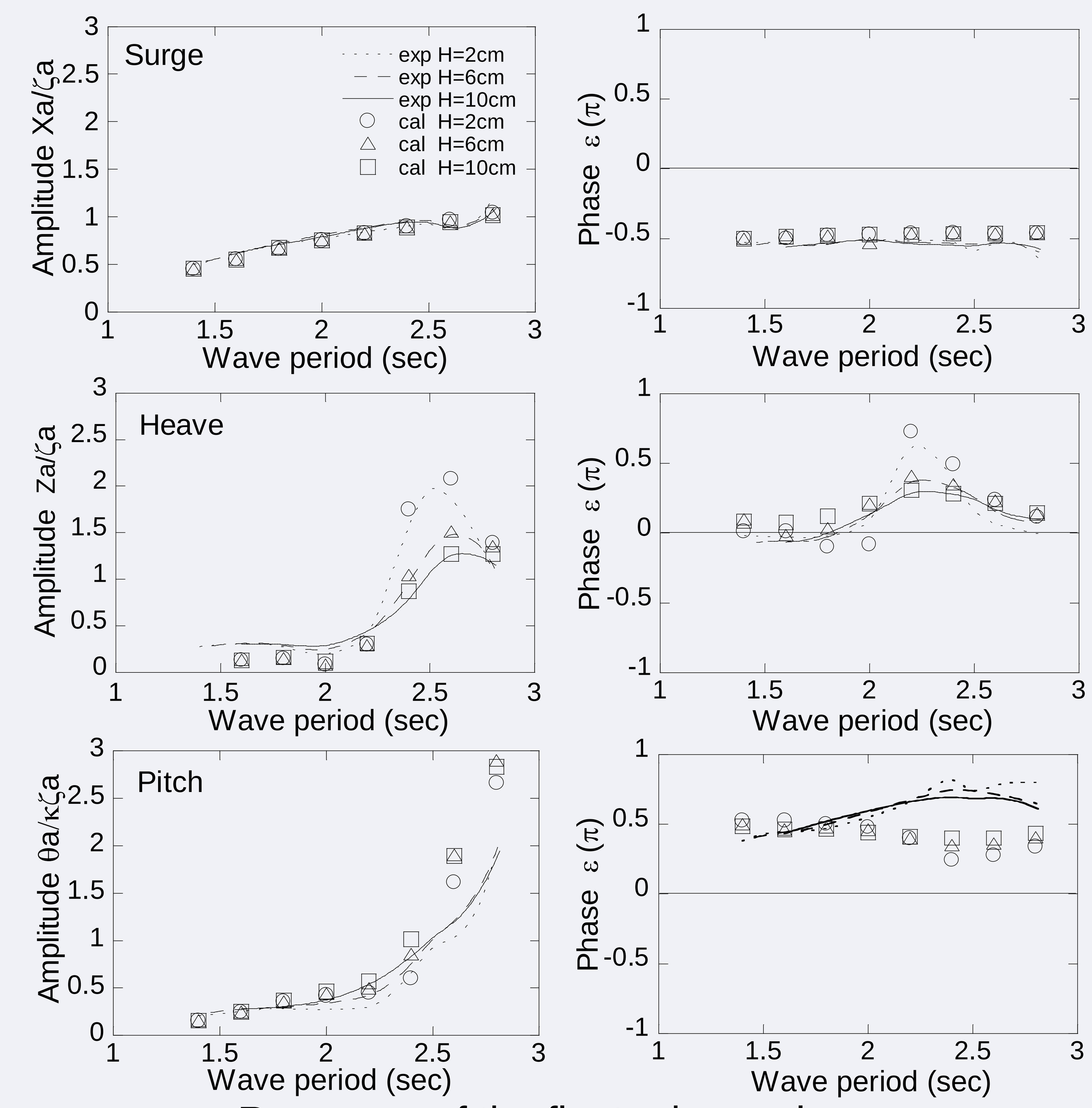
Drag and inertia force coefficients, C_D and C_M

		C_D	C_M
Floater	Horizontal	1.5	2.2
	Vertical	2.0	3.0
Mooring		1.3[4]	2.2

In this study, a linear damping ratio, 15 %[3] was used for comparison with the nonlinear model.

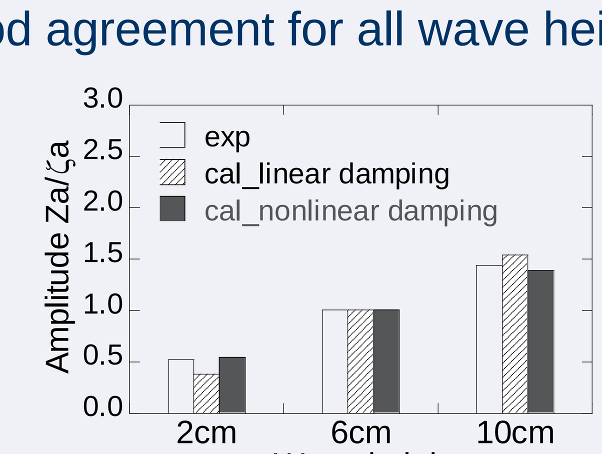
Nonlinear damping effect

Surge, heave and pitch motions were predicted by nonlinear model in regular waves. Predictions agree well with experiments. Wave nonlinearity effect was reproduced at resonant region in heave. The model underestimated heave before resonance period and overestimated pitch around natural period.



Response of the floater in regular waves

The comparison of heave motions measured and predicted by linear and nonlinear damping model was conducted with different wave heights. Linear model underestimated the experiment in 2cm and overestimated in 10cm of wave height. Nonlinear model shows good agreement for all wave heights.

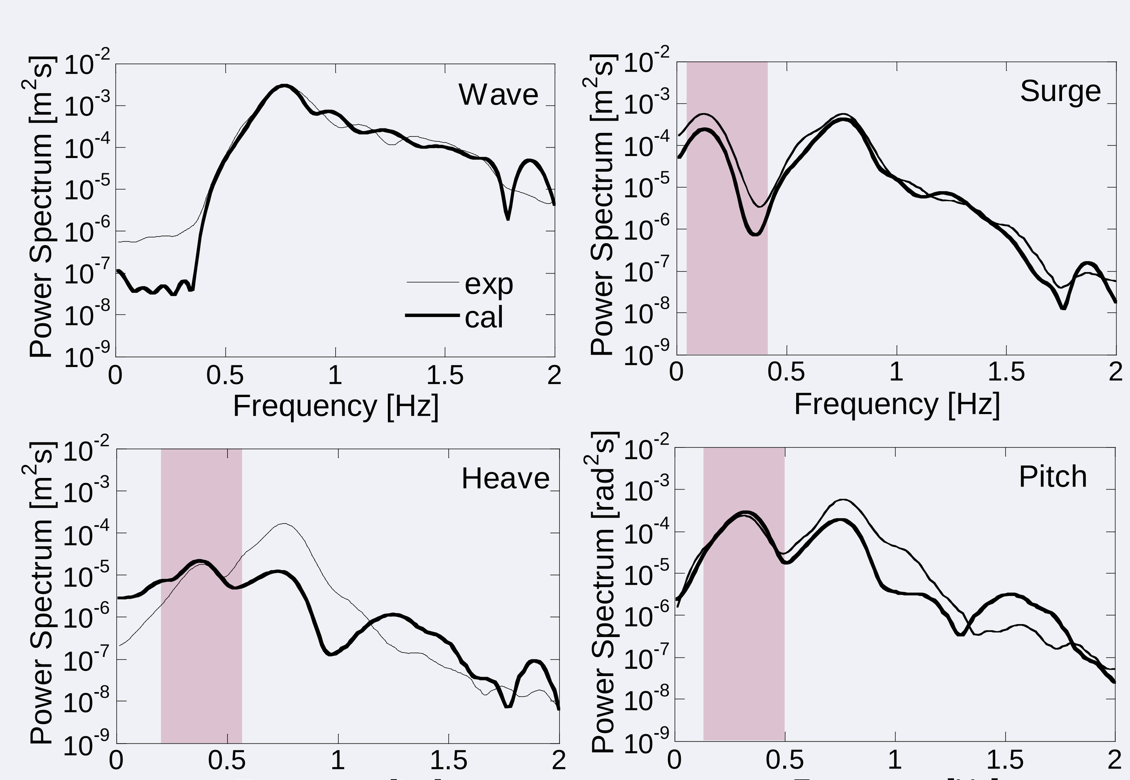


Comparison of heave responses measured and predicted by linear and nonlinear damping model

Low-frequency motion

To investigate the low-frequency motion, experiment and prediction were performed in irregular waves.

The low-frequency motions were observed in the frequencies according to the floater natural periods especially in surge and pitch. However, low-frequency energy is not significant in wave spectrum. This means that forces were excited by nonlinearity of drag force. The prediction underestimated heave response in high frequencies, which agreed with the prediction underestimated heave response before resonant region in regular waves.



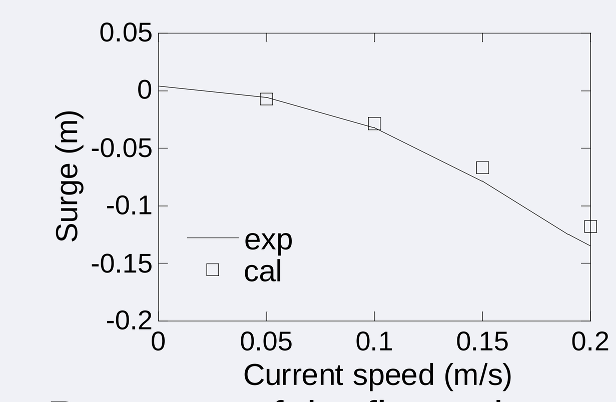
Response of the floater in irregular waves
(Significant wave height: 10cm, Peak wave period: 1.41s)

Interaction of wave and current

Conventionally, combined loading of wave and current is estimated by superposing of wave and current response, assuming no interaction. This study investigated the interaction between wave and current by comparing predictions by linear superposition model and nonlinear model with experiments.

■ Analysis in current only

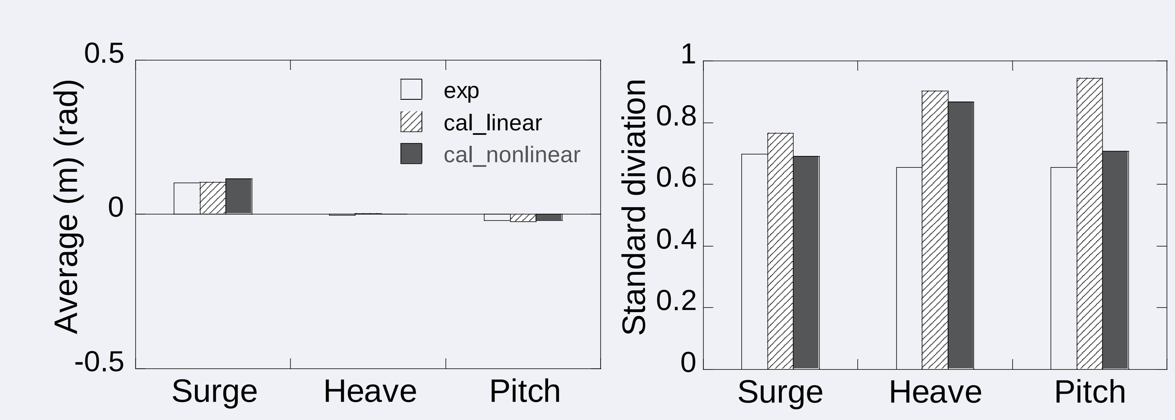
In current, mean displacement of floater motion was observed in surge. Predictions showed good agreement with experiments for all current speeds.



Response of the floater in current

■ Analysis in wave and current

To investigate the interaction between wave and current, experiment and prediction were performed in wave and current. Responses predicted by linear superposition and nonlinear model were compared with experiments. For mean displacement, predictions by linear and nonlinear model agreed well with experiments. For variance of displacement, predictions by linear model overestimated experiments and those by nonlinear model agreed well for surge and pitch. Heave response was still overestimated by nonlinear model. That means hydrodynamic damping decreased due to the current effect.



Comparison of prediction by linear and nonlinear model
(Current speed:0.2m/s Wave height:60mm Wave period:2.8s)

Conclusions

Dynamic analysis of floating offshore wind turbine system has been improved by introducing nonlinear damping model. By employing the model, low-frequency motion and interaction of wave and current has been investigated. Conclusions are summarized as follows.

1) By introducing nonlinear damping model, the amplitude-dependency of heave response was reproduced and prediction accuracy was improved.
2) The low-frequency motion is erected since irregular waves excite the low-frequency loadings through the drag force.
3) The interaction of wave and current leads to reduce hydrodynamic damping. Nonlinear analysis predict well experiment, while linear superposition model overestimated the variance of displacement.

References

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