

Numerical prediction of hydrodynamic coefficients for
a semi-sub platform by using large eddy simulation
with volume of fluid method and Richardson
extrapolation

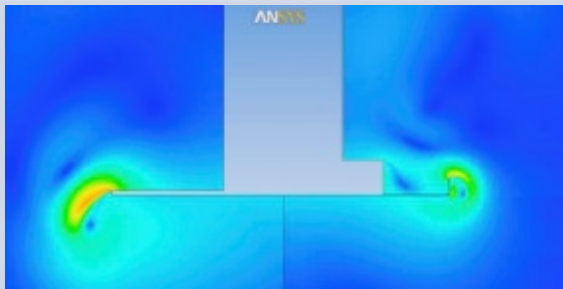
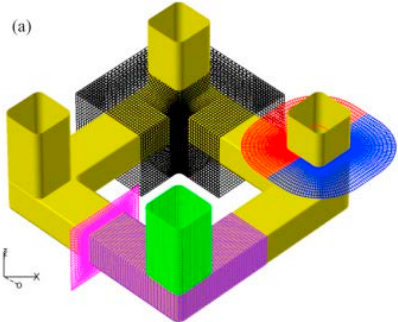
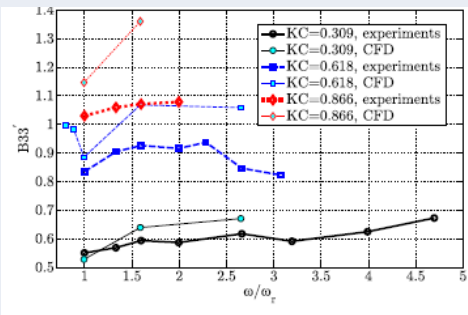
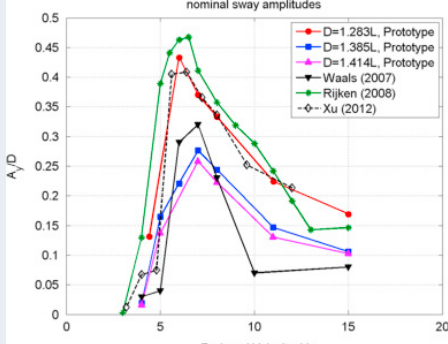
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2019/01/17

Hydrodynamic coefficients (Ca & Cd)

<p>Target structures</p> <ol style="list-style-type: none"> 1. Heave Plate 2. Floater 	<p>L.Tao,2004; Lpoez-Pavon, 2015 (CFD) (Shear Stress Transport (SST) model)</p> 	<p>Chia-Rong Chen, 2016(CFD) (No free water surface)</p> 
<p>Accuracy</p>		

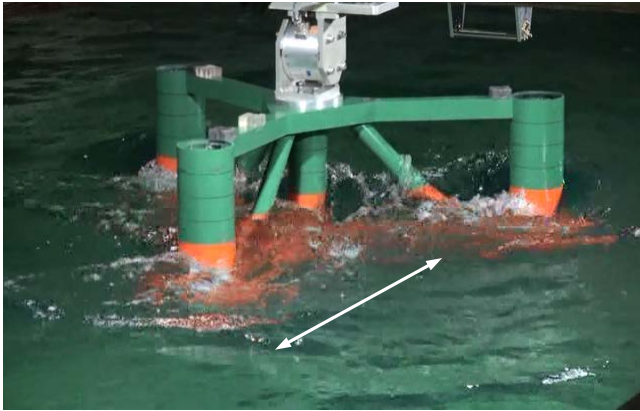
C_a : Added mass coefficient; C_d : Viscous drag coefficient

Keulegan-Carpenter (KC) number: $KC = \frac{2\pi A}{D}$ (A: amplitude of motion; D: diameter of typical component)

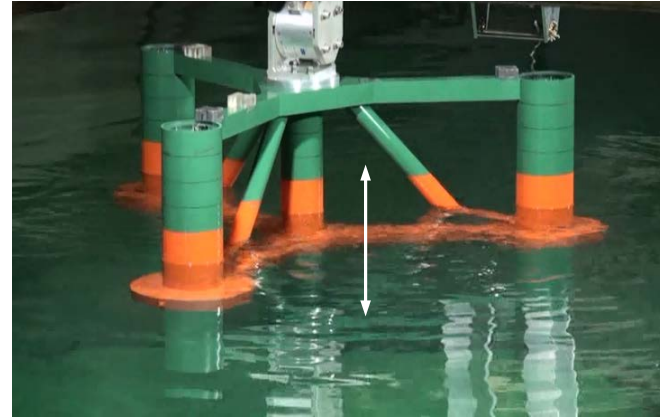
- The effects of **free water surface** and of **KC number** on hydrodynamic coefficients of a semi-sub model predicted should be systematically investigated by **LES with VOF**.
- **Accuracy** of predicted hydrodynamic coefficients by CFD should be improved.

1. To improve accuracy of the predicted hydrodynamic coefficients by Richardson extrapolation method.
2. To study the effect of KC number and frequency on the hydrodynamic coefficients.
3. To investigate the importance of the free water surface on evaluation of hydrodynamic coefficients by LES with VOF.

□ Forced vibration tests in the horizontal and vertical directions



Horizontally forced oscillation



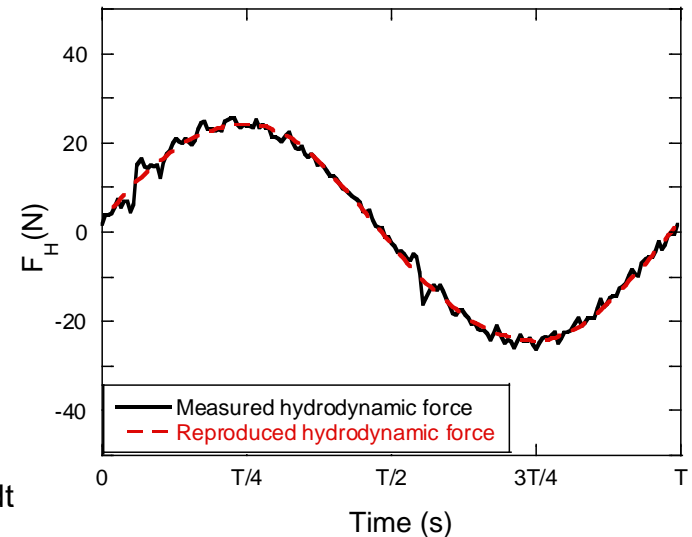
Vertically forced oscillation

- KC number $KC = \frac{V_{max}}{D_i f} = \frac{\omega a}{D_i f} = \frac{2\pi a}{D_i}$
- Definition of hydrodynamic coefficients C_a and C_d

$$F_H(t) = F(t) - F_b - F_l(t) - F_k(t) \quad F_H(t) = -C_a M \ddot{x}(t) - 0.5 C_d \rho_w A |\dot{x}(t)| \dot{x}(t)$$

$$C_a = \frac{\int_0^T F_H(t) \sin(\omega t) dt}{\rho_w \nabla a \omega^2 \int_0^T \sin^2(\omega t) dt} = \frac{1}{\pi \omega a \rho_w \nabla} \int_0^T F_H(t) \sin(\omega t) dt$$

$$C_d = -\frac{\int_0^T F_H(t) \cos(\omega t) dt}{\frac{1}{2} \rho_w A (\omega a)^2 \int_0^T |\cos(\omega t)| (\cos(\omega t)) \cos^2(\omega t) dt} = -\frac{3}{4 \rho_w A \omega a^2} \int_0^T F_H(t) \cos(\omega t) dt$$



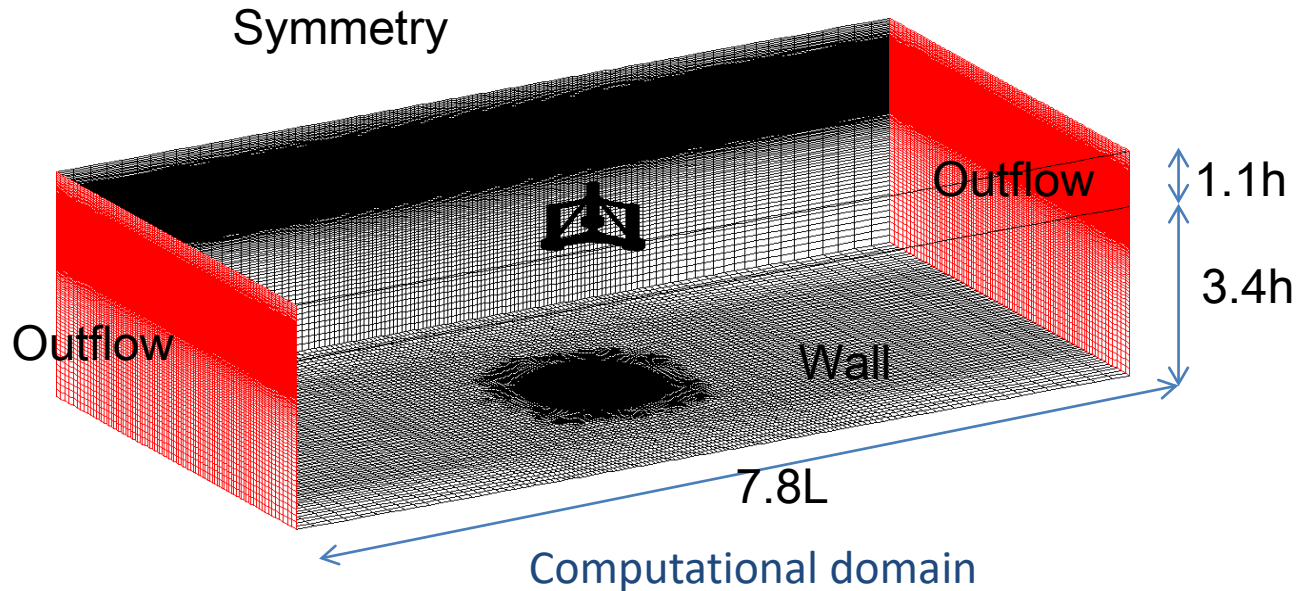
□ Governing equation

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

$$\rho \frac{\partial \tilde{u}_i}{\partial t} + \rho \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} = - \frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \right] - \frac{\partial \tau_{ij}}{\partial x_j}$$

□ Continuity equation for the volume fraction of water

$$\frac{1}{\rho_w} \left[\frac{\partial}{\partial t} (\alpha_w \rho_w) + \nabla \cdot (\alpha_w \rho_w \vec{v}_w) \right] = 0$$



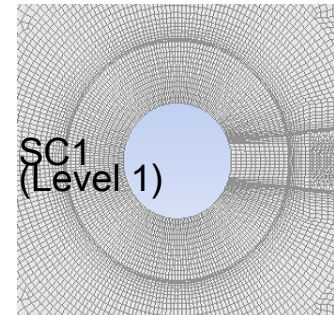
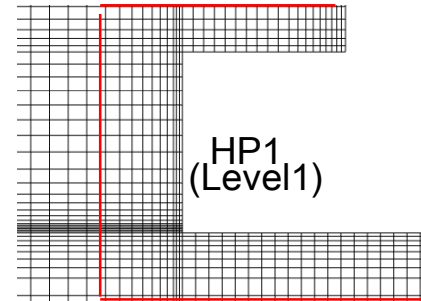
S.N.Zhang, T.Ishihara : Numerical study of hydrodynamic coefficients of multiple heave plates by large eddy simulations with volume of fluid method, Ocean Engineering, Vol.163, pp.583-598, 2018.

Grid refinement

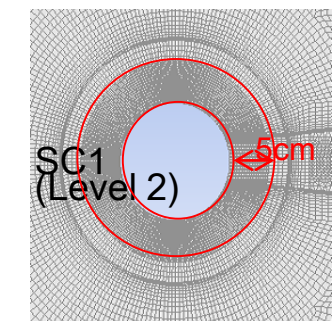
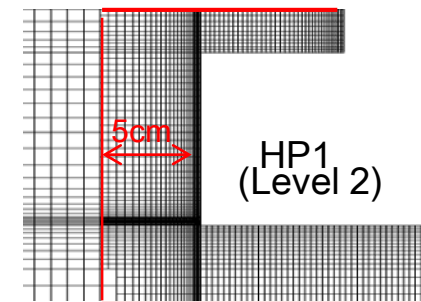
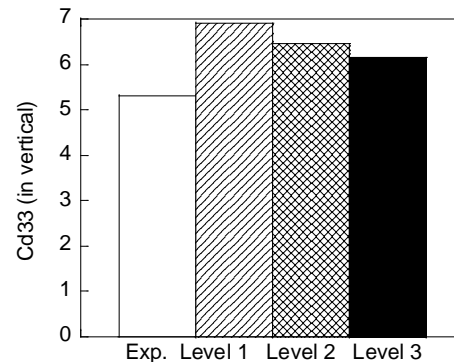
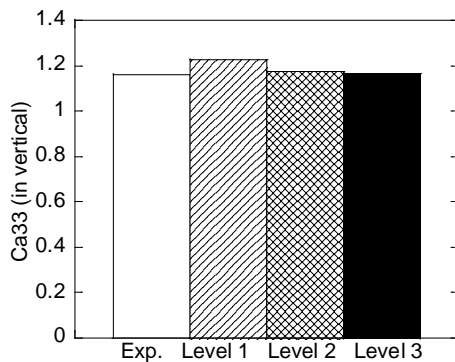
In the vertical : Refined area in a region of 5cm near Hp, Hp-C, Pntn

In the horizontal : Refined area in a region of 5cm near SC, CC

Grid level	1	2	3
Grid size	$h_1 = 8mm$	$h_2 = 4mm$	$h_3 = 2mm$
Grid number	13.7 million	18.8 million	63.8 million



Predicted Ca & Cd by refined grids



- The accuracy of predicted Cd by using grid refinement is not enough.

Richardson Extrapolation Method

7

Richardson Extrapolation Method

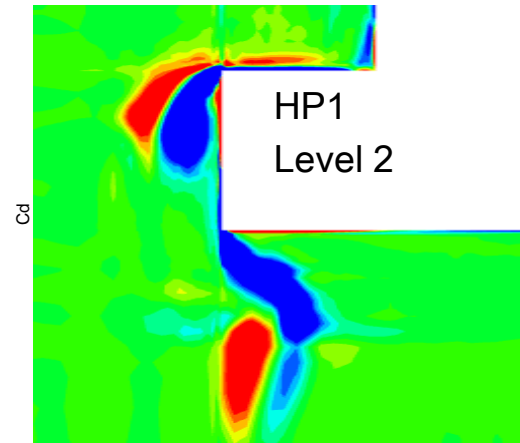
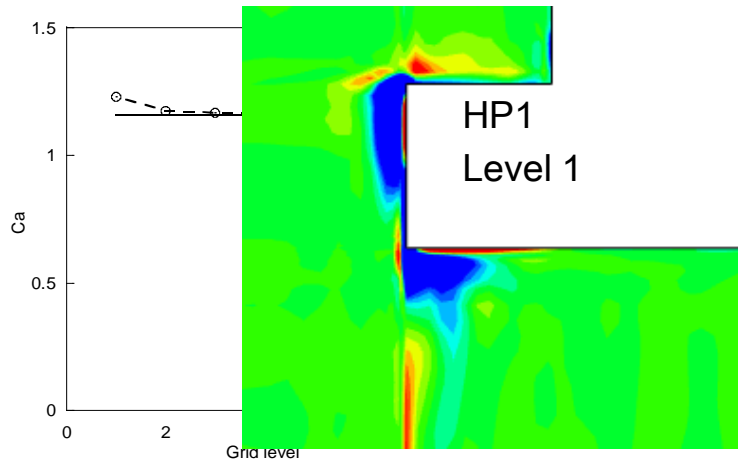
The exact solution $\Phi = \phi_h + \varepsilon_h = \phi_{h_i} + \alpha h_i^p + H$

where $p = \frac{\log((\phi_{h_2} - \phi_{h_1}) / (\phi_{h_3} - \phi_{h_2}))}{\log \lambda}$, $\alpha = \frac{\phi_{h_3} - \phi_{h_2}}{h_3^p (\lambda^p - 1)} = \frac{\phi_{h_2} - \phi_{h_1}}{h_2^p (\lambda^p - 1)}$, $\lambda = h_1 / h_2 = h_2 / h_3$

$p = 0.47$



$$\Phi = \phi_h + \varepsilon_h = \phi_{h_2} + \frac{\phi_{h_2} - \phi_{h_1}}{(\lambda^p - 1)}$$

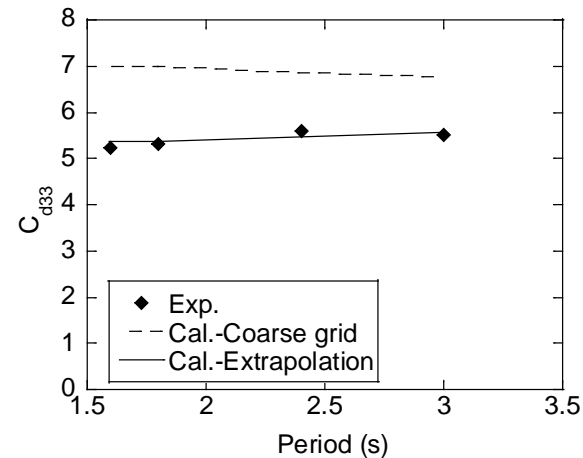
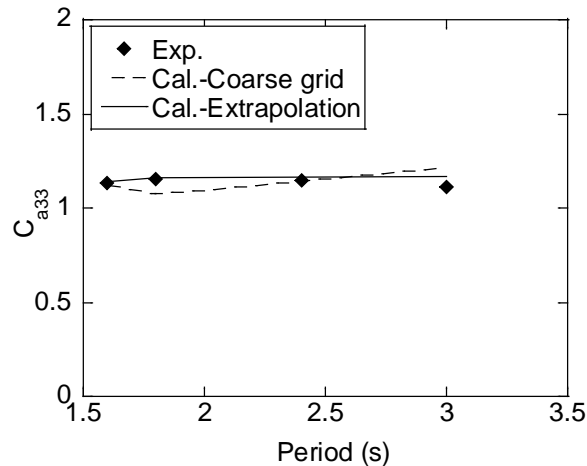
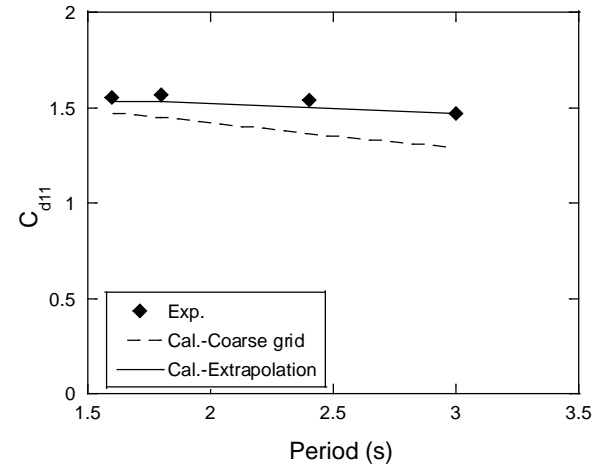
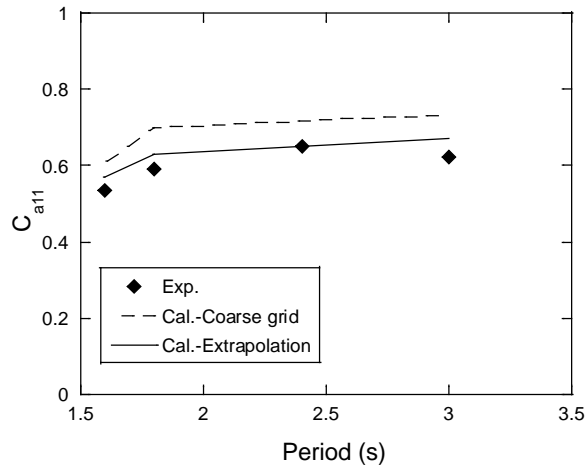


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Fine grid is required to accurately simulate the vortex shedding.

- Richardson Extrapolation Method on the finest grid is applied and **validated**.

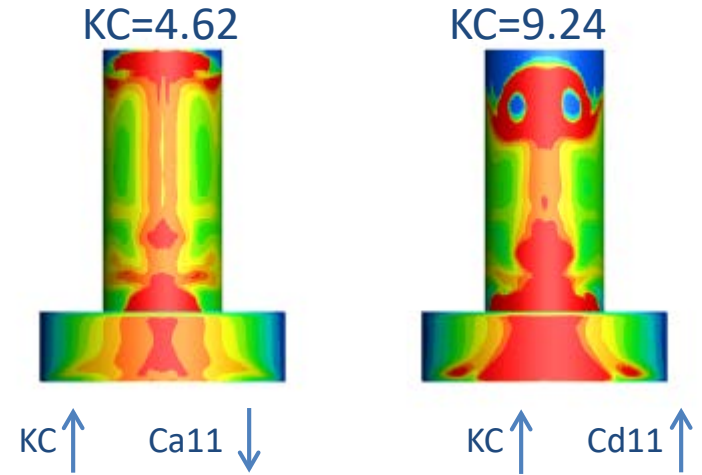
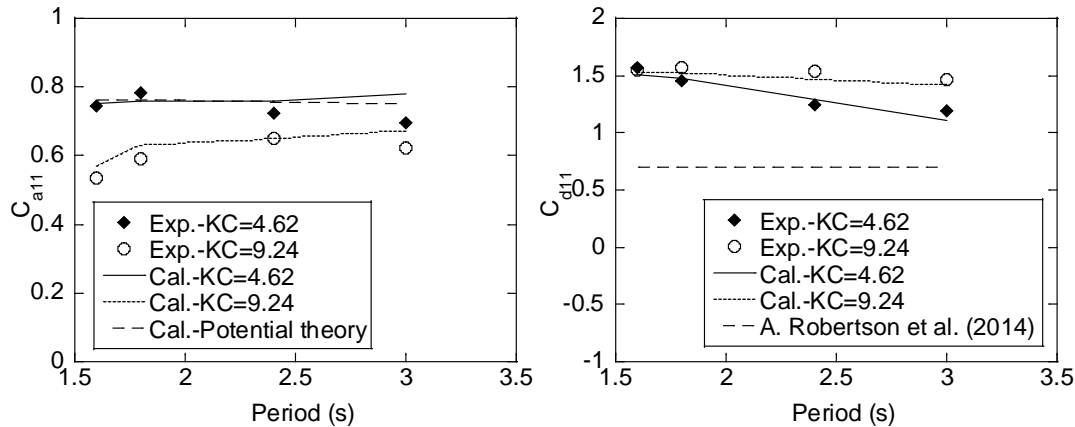
Effect of grid refinement



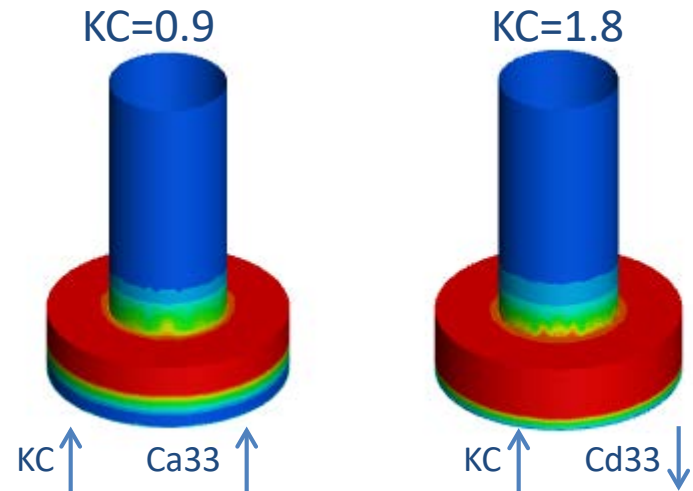
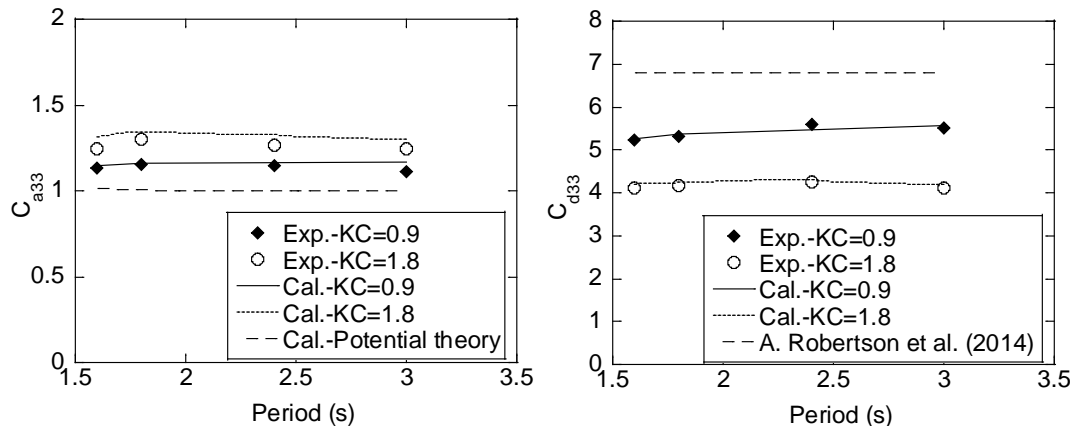
- The predicted hydrodynamic coefficients by using LES with VOF method agree well with the experimental data when Richardson extrapolation is performed.

Effect of KC number and wave frequency

□ In the horizontal direction



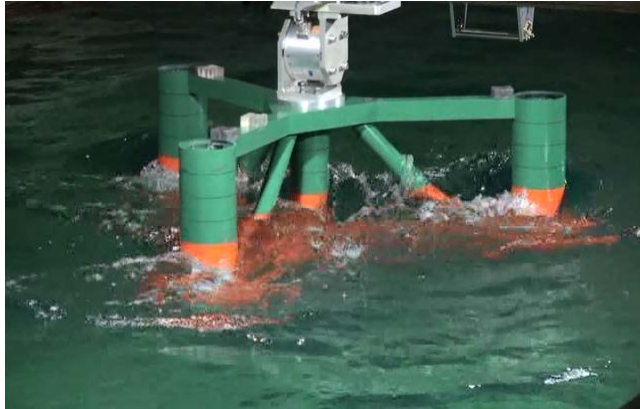
□ In the vertical direction



- Potential theory and database have limited accuracy for Ca and Cd, while **LES model with VOF** can **accurately predict** the Ca and Cd for different KC numbers and wave frequencies.

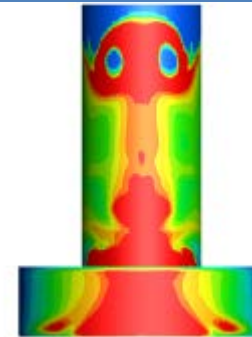
Effect of free water surface

□ In the horizontal direction

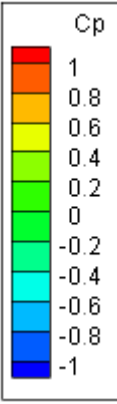


With free water surface

W/O free water surface

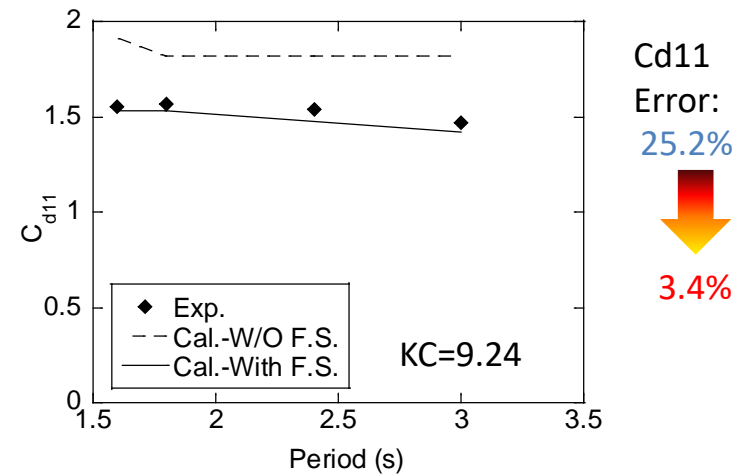
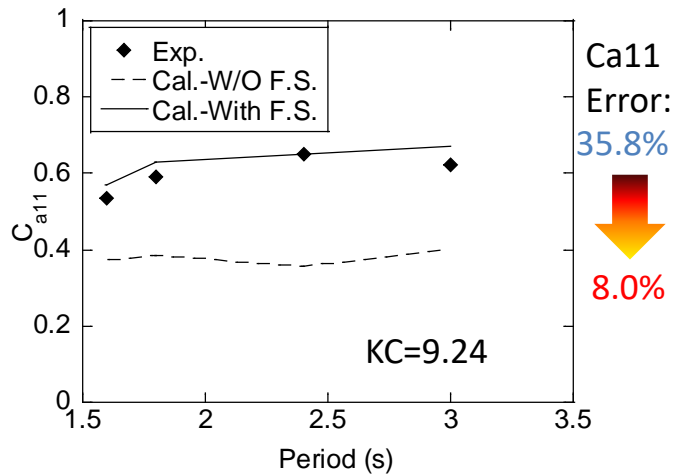


SWL



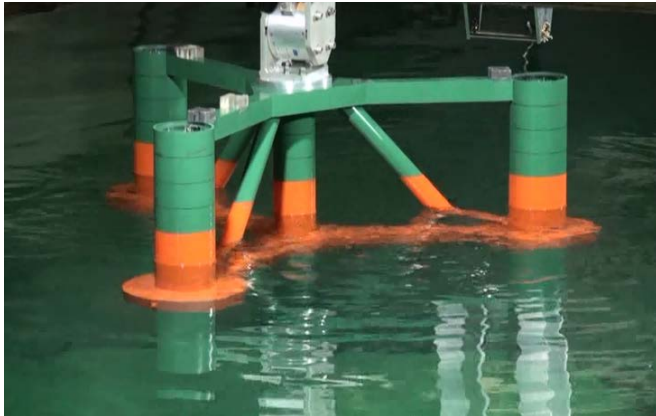
KC=9.24

KC=9.24

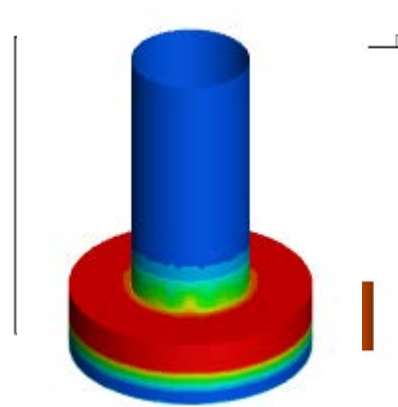


- The free water surface should be included to accurately predict hydrodynamic coefficients in the horizontal direction and can be captured by using LES with VOF.

□ In the vertical direction

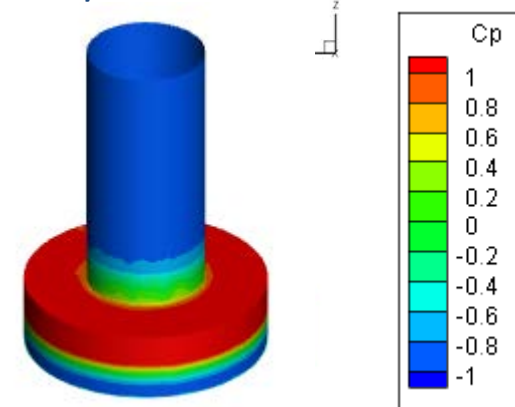


With free water surface

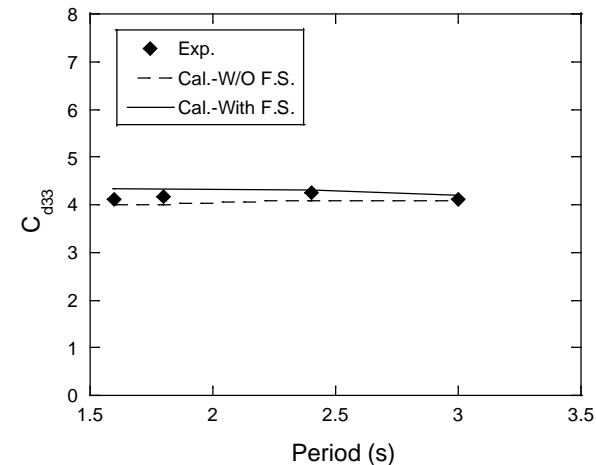
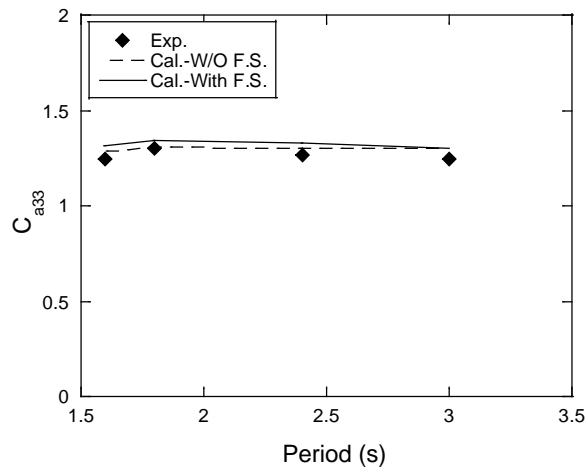


KC=1.8

W/O free water surface



KC=1.8



- The predicted C_a and C_d with and without free surface in the vertical direction coincide well with those from the water tank test, because the free surface has a limited effect on C_a and C_d in the vertical direction for the deep draft model.

See the poster No.37

The predicted dynamic responses in different wave heights by proposed model show good agreement with those from the water tank tests.

Prediction of dynamic response of a semi-submersible floating offshore wind turbine by KC dependent hydrodynamic coefficients

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Introduction

Added mass and drag coefficients are two critical parameters for accurate prediction of hydrodynamic loadings. For the dynamic response analysis of floating offshore wind turbine (FOWT), the added mass coefficient is mainly calculated by the boundary element method (BEM) and drag coefficient is used as a constant value as mentioned in the previous studies [1], [2]. This implies that the KC number dependency of hydrodynamic coefficients is neglected.

In this study, a model is developed to estimate hydrodynamic coefficients for a semi-submersible FOWT from added mass and drag coefficients of each element, considering interaction between elements, KC number and frequent dependencies. The proposed model is validated by the hydrodynamic coefficients and dynamic responses from water tank tests.

Water tank test

The motion and mooring tension is investigated by water tank test based on a down scale 2MW semi-submersible FOWT located in Fukushima. The Froude scaling law is used based on a linear scale factor $\lambda=30$, and all parameter presented in this study are given in down scale unless otherwise noted. The model is positioned on the water by 4 catenary mooring lines (13.3m) anchored on bottom of water tank at a depth of 2.5 m as Fig.1 shows below. The origin of coordinate locates at the centerline of center column on the water surface plane and reference point for motion is defined as gravity center.

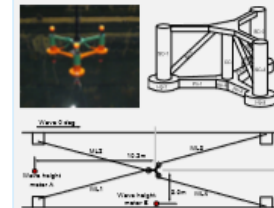


Fig.1 Configuration of the water tank test

Hydrodynamic coefficients

Distributed hydrodynamic coefficients are difficult to be determined for complex structure because they varies with several factors, such as interaction between components, KC number and frequency. To understand hydrodynamic coefficients of each component in semi-submersible FOWT, a formula is proposed to calculate the coefficients with consideration of these factors.

Formula for distributed hydrodynamic coefficients

The formula is proposed as

$$C_{ij}^k(\beta, KC, \eta) = C_{ij}^k(KC, \eta) \times \beta_i^k(\beta) \times \beta_j^k(\beta) \times \beta_k^k(KC) \times \beta_k^k(\eta, KC)$$

$$C_{ij}^k(\beta, KC, \eta) = C_{ij}^k(KC, \eta) \times \beta_i^k(\beta) \times \beta_j^k(\beta) \times \beta_k^k(KC) \times \beta_k^k(\eta, KC)$$

where i means each component in the floater; superscript k indicates direction of hydrodynamic coefficients, which can be in normal and tangential direction. Function β presents relationship of the coefficients with interaction effect (β), KC number (KC) and frequency (η).

Normalized frequency η is defined as wave frequency to typical wave frequency

$$\eta = \frac{\omega}{\omega_{typical}}$$

where $\omega_{typical}$ equals 0.63 rad/s (10s) in full scale.

A series horizontal and vertical forced oscillation were conducted by CFD [1] to study hydrodynamic coefficients of the same platform at various KC number and frequencies. Ca and Cd of each component by CFD at specified KC_0 and η_0 is used in this study.

Interaction correction factor
 The interaction correction factor [1] is defined as ratio between hydrodynamic coefficients of each component and referenced component at KC_0 and η_0 .

$$\beta_i^k(\beta) = \frac{C_{ij}^k(KC, \eta)}{C_{ij}^k(KC_0, \eta_0)} \quad \beta_j^k(\beta) = \frac{C_{ij}^k(KC, \eta)}{C_{ij}^k(KC_0, \eta_0)}$$

KC number dependency of hydrodynamic coefficients
 Ca and Cd of floater vary with KC number related with amplitude of motion. To present relationship between KC number and hydrodynamic coefficients, KC number correction factor $\beta_k^k(KC)$ is introduced, which is the ratio between coefficient of isolated cylinder in a range of KC number and coefficient of this cylinder in specified KC_0 and η_0 . Ca and Cd of isolated cylinder as Fig.2 from experiment in previous studies is used for calculation.

$$\beta_k^k(KC) = \frac{C_{ij}^k(KC, \eta)}{C_{ij}^k(KC_0, \eta_0)} \quad \beta_k^k(KC) = \frac{C_{ij}^k(KC, \eta)}{C_{ij}^k(KC_0, \eta_0)}$$

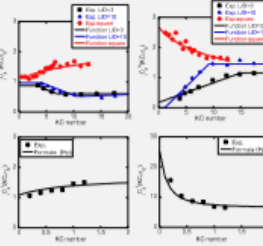


Fig.2 Relationship between KC number and hydrodynamic coefficients

In Fig.2, the experimental data is fitted as function of KC number shown as solid line. Upper two figures present variation of hydrodynamic coefficients for isolated circular cylinder with different aspect ratio and square cylinder. Other two figures shows Ca and Cd of heave plates in varied KC number.

Frequency dependency of hydrodynamic coefficients
 Frequency is one of important factor which affect hydrodynamic coefficients and dynamic response of floater [2]. To present effect of frequency, frequency correction factor $\beta_k^k(\eta, KC)$ is introduced to account frequency dependency of hydrodynamic coefficients in a range of KC number.

$$\beta_k^k(\eta, KC) = \frac{C_{ij}^k(\eta, KC)}{C_{ij}^k(KC_0, \eta_0)} \quad \beta_k^k(\eta, KC) = \frac{C_{ij}^k(\eta, KC)}{C_{ij}^k(KC_0, \eta_0)}$$

It is assumed that frequency correction factor for each component is same as the factor of global model. The factor $\beta_k^k(\eta, KC)$ can be considered as a constant value aspect factor coefficient in surge direction, which show large variation with KC number as below formulas

$$\beta_k^k(\eta, KC) = 1$$

$$\beta_k^k(\eta, KC) = \begin{cases} 1.19 - \frac{0.6}{\eta} \tan^{-1} \left(\frac{2.7}{\eta} - 3.8 \right) & KC \leq 4.62 \\ \text{Linear Interpolation} & 4.62 < KC \leq 9.26 \\ 1 & KC \geq 9.26 \end{cases}$$

$$\beta_k^k(\eta, KC) = 1$$

$$\beta_k^k(\eta, KC) = 1$$

Validation

Validation by global hydrodynamic coefficients
 From the proposed hydrodynamic coefficients model, Ca and Cd of each component can be calculated and integrated to be global hydrodynamic coefficients of the model [2]. Global hydrodynamic coefficients by proposed formula is validated by the coefficients from forced oscillation test as below. The effect of frequency on Cd in surge direction is obviously as the Fig.3.

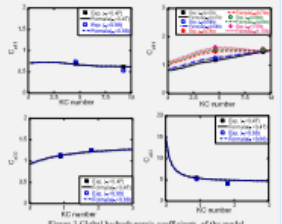


Fig.3 Global hydrodynamic coefficients of the model

Dynamic response of the platform

The calculated added mass and drag coefficients are used for dynamic response prediction of the model. Other loads such as diffraction force and radiation damping is obtained by BEM. To study effect of KC number on dynamic response of FOWT, Cd of cylinders without consideration of KC number dependency in OCA project is applied for comparison. From the result, KC number dependency of Cd is necessary especially in period range near natural period of motion. The response calculated by proposed model shows good agreement with experimental result.

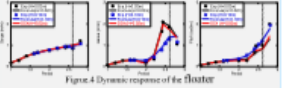


Fig.4 Dynamic response of the floater

Conclusion

In this study, a model is proposed to estimate global hydrodynamic coefficients for a semi-submersible FOWT, considering interaction between elements, KC number and frequent dependencies.

1. The predicted global coefficients for a semi-submersible FOWT from added mass and drag coefficients of each element by proposed model show good agreement with those obtained from the water tank tests.
2. The predicted dynamic responses in different wave heights by proposed global hydrodynamic coefficients agree well with those from the experiments.

This research is carried out as a part of the Fukushima floating offshore wind farm demonstration project funded by the Ministry of Economy, Trade and Industry.

Reference

[1] Pan, J. and Ishihara, T. "Numerical prediction of hydrodynamic coefficients for a semi-sub platform by using large eddy simulation with method of fluid method and Richardson extrapolation method" EERA DeepWind2019 conference
 [2] Ishihara, T and Zhang, S.N. "Prediction of dynamic response of semi-submersible floating offshore wind turbine using augmented Morison's equation with frequency dependent hydrodynamic coefficients." Renewable Energy 131 (2019): 1186-1207.

1. The grid refinement can improve accuracy by capturing the vortex shedding near the model and the predicted drag coefficients by Richardson extrapolation method show good agreement with those from the water tank test.
2. LES model with VOF can accurately predict the KC number effect on the hydrodynamic coefficients in the horizontal and vertical directions, while potential theory and database have limited accuracy.
3. The hydrodynamic coefficients in the horizontal direction by LES with VOF show good agreement with the experimental data, while those predicted by LES without the free surface show significant differences.

Thank you for your attention!

This research is carried out as a part of the Fukushima floating offshore wind farm demonstration project funded by Ministry of Economy, Trade and Industry.

