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

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Introduction

The added mass and drag coefficients are two critical parameters for accurate prediction of hydrodynamic forces on the floaters. For the dynamic response analysis of floating offshore wind turbine (FOWT), the added mass coefficient is usually calculated by using the boundary element method (BEM) and the drag coefficient is used as a constant value as mentioned in the references [1] and [2]. It implies that the effect of KC number on the hydrodynamic coefficients is neglected in the previous studies.

In this study, a model is developed to estimate global hydrodynamic coefficients for a semisubmersible FOWT from the added mass and drag coefficients for each element, considering effects of interaction of elements, KC number and wave frequency in the hydrodynamic coefficients. The proposed model is validated by the global hydrodynamic coefficients and dynamic responses obtained from the water tank tests.

Water tank tests

The motions and mooring tensions for a 2MW semisubmersible FOWT located at Fukushima offshore site are investigated by the water tank tests. The Froude scaling law is used and the scale factor is 1:50. The model is positioned by 4 catenary mooring lines of 10.3 m anchored on the bottom of water tank at a depth of 2.5 m as shown in Fig.1. The origin of coordinate locates at the centerline of center column of floater on the water surface and the reference point for the floater motions is defined at the gravity center. The global hydrodynamic coefficients are measured by the forced oscillation test using the same model
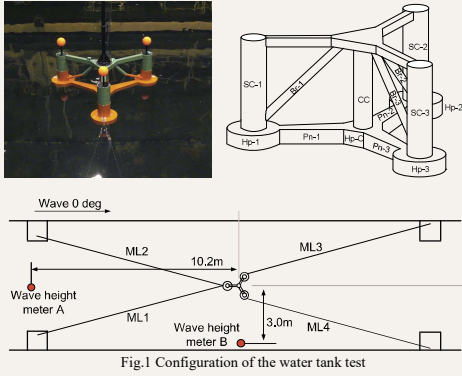

Fig.1 Configuration of the water tank test

Hydrodynamic coefficients

The hydrodynamic coefficients are different for each floater because they are affected by interaction of elements, KC number and frequency of wave. A model is proposed to calculate hydrodynamic coefficients for a semisubmersible FOWT from those for each element considering these factors.

❑ **Hydrodynamic coefficients of each element**

The hydrodynamic coefficients of each element can be expressed as a function of interaction of elements (β), KC number (KC) and normalized frequency of wave (η)

$$_iC_a^k(\beta, KC, \eta) = {}_iC_a^k(KC_0, \eta_0) \times {}_i\gamma_a^k(\beta) \times {}_i\gamma_a^k(KC) \times {}_i\gamma_a^k(\eta|KC)$$

$$_iC_d^k(\beta, KC, \eta) = {}_iC_d^k(KC_0, \eta_0) \times {}_i\gamma_d^k(\beta) \times {}_i\gamma_d^k(KC) \times {}_i\gamma_d^k(\eta|KC)$$

where i denotes the number of element for a floater; k indicates the normal and tangential directions for an element, γ presents correction factors. ${}_iC_a^k(KC_0, \eta_0)$ and ${}_iC_d^k(KC_0, \eta_0)$ are the added mass and drag coefficients at a specified KC_0 and η_0. The normalized frequency η is defined as a ratio of wave frequency to a typical wave frequency $\omega_{typical}$, which is 0.628 Hz for a typical wave period of 10s in full scale.

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

The hydrodynamic coefficients of the floater shown in Fig.1 are investigated by using the horizontal and vertical forced oscillations with CFD [1] for various KC number and frequency of wave. C_a and C_d for each element at a specified KC_0 and η_0 shown in Ref. [1] are used to model C_a and C_d for different KC and η in this study.

❑ **Interaction correction factor**

The interaction correction factor for each element is defined in [1] as a ratio of hydrodynamic coefficient between each element and the referenced one at KC_0 and η_0:

$$_i\gamma_a^k(\beta) = \frac{{}_iC_a^k(KC_0, \eta_0)}{{}_rC_a^k(KC_0, \eta_0)}, \qquad _i\gamma_a^k(\beta) = \frac{{}_iC_d^k(KC_0, \eta_0)}{{}_rC_d^k(KC_0, \eta_0)}$$

❑ **KC number correction factor**

C_a and C_d for each element vary with KC number related to the amplitude of floater motion. The KC number correction factor, ${}_i\gamma^k(KC)$, is defined as a ratio of the hydrodynamic coefficients of element to those at a specified KC_0 and η_0. The predicted and measured C_a and C_d for a square, cylinders with different aspect ratios and a heave plate are compared as shown in Fig.2 and are used for calculation of C_a and C_d of a whole floater.

$$_i\gamma_a^k(KC) = \frac{{}_iC_a^k(KC, \eta_0)}{{}_iC_a^k(KC_0, \eta_0)}, \qquad _i\gamma_d^k(KC) = \frac{{}_iC_d^k(KC, \eta_0)}{{}_iC_d^k(KC_0, \eta_0)}$$
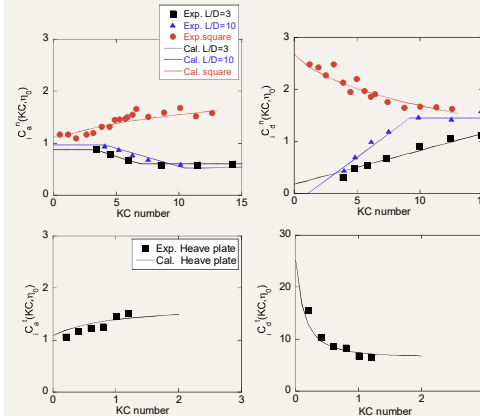

Figure.2 Variation of hydrodynamic coefficients with KC number

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

❑ **Frequency correction factor**

The frequency of wave is an important factor which affects hydrodynamic coefficients and dynamic responses of floater as shown in [2]. The frequency correction factor, ${}_i\gamma(\eta|KC)$, is introduced to account the effect of wave frequency on the hydrodynamic coefficients for each element at a KC number.

$$_i\gamma_a^k(\eta|KC) = \frac{C_a^k(KC, \eta)}{C_a^k(KC, \eta_0)}, \qquad _i\gamma_d^k(\eta|KC) = \frac{C_d^k(KC, \eta)}{C_d^k(KC, \eta_0)}$$

It is noticed that the frequency correction factors for each component is the same as that for the whole floater as shown in [2]. This factor can also be assumed as a constant value except for the drag coefficient in the surge direction, which is expressed as a function of KC number:

$$_i\gamma_a^n(\eta|KC) = 1$$

$$_i\gamma_d^n(\eta|KC) = \begin{cases} 1.19 - \frac{0.6}{\pi}\tan^{-1}\left(\frac{2.7}{\eta} - 3,8\right) & KC \leq 4.62 \\ Linear\ Interpolation & 4,62 < KC < 9,26 \\ 1 & KC \geq 9.26 \end{cases}$$

$$_i\gamma_a^t(\eta|KC) = 1$$

$$_i\gamma_d^t(\eta|KC) = 1$$

Validation

❑ **Global hydrodynamic coefficients**

The formulas shown in Ref. [2] are used to calculate the global hydrodynamic coefficients from the proposed hydrodynamic coefficients for each element. Predicted global hydrodynamic coefficients by the proposed model are compared with those obtained from the forced oscillation tests. The effect of wave frequency on C_d in the surge direction is significant as shown in Fig.3.
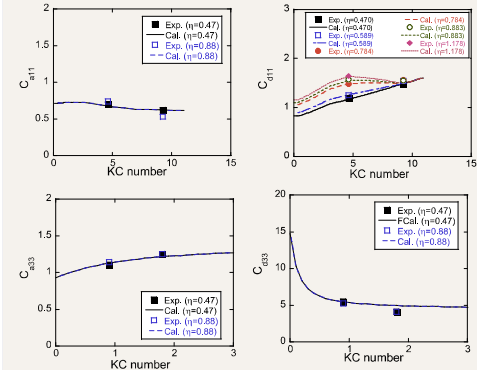

Figure.3 Variation of global hydrodynamic coefficients with KC number

❑ **Dynamic responses**

The added mass and drag coefficients calculated by the proposed model as well as the diffraction force and radiation damping obtained by BEM are used to predict the dynamic responses of the floater. Cd of cylinders without consideration of KC number dependency as shown in OC4 project is also used to investigate the effect of KC number on the dynamic responses of FOWT. From Fig. 4, The effect of KC number dependency of Cd appears at the periods near the natural period of motion in the heave direction. The predicted RAOs by the proposed model show good agreement with those from the water tank tests.
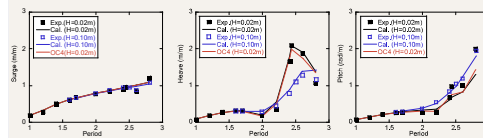

Figrue.4 Dynamic responses in the surge, heave and pitch directions

Conclusion

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

1. The predicted global coefficients 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.

Reference

[1] Pan, J. and Ishihara, T., "Numerical prediction of hydrodynamic coefficients for a semi-sub platform by using large eddy simulation with volume of fluid method and Richardson extrapolation method" EERA DeepWind'2019 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.