A Study on Numerical Simulation of Wave Energy Converter Considering Nonlinear Wave Interaction Using BEM

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Marine renewable energy is an important future energy source. For wave energy, a point absorber with an oscillating body is a well-known type of wave energy converter and its features are relatively simpler system and lower cost than other types of wave energy converters. Reactive control concept is important to achieve larger energy income, but large motion of the float by reactive control is matter. The understanding of the device's behavior is important for the design but the large motion of the float is difficult to predict by the numerical simulation. The numerical simulation of the point absorber's behavior is often based on the so-called "linear theory". Linear problems are easy to analyze with BEM software like WAMIT, but nonlinear problems with the large motion of the float are difficult to analyze. CFD or FEM techniques will predict the nonlinear problems, but those techniques need the huge computer resources. In this study, the authors tried to simulate the large motion of the float using BEM and a fluid parameter table look-up technique is used. In the fluid parameter table look-up technique, several cases of the float's position are considered and fluid parameters for each case are calculated by BEM software. The calculated fluid parameters are kept in a memory and the time domain simulation program uses the parameters correspond to the position of the float. Using that technique, the numerical simulations of wave energy converters with cylinder shape float and tapered shape floats are demonstrated.

Keyword: Wave energy converter, Wave interaction, Reactive control, Time domain simulation

1. INTRODUCTION

Marine renewable energy is an important future energy source. There has been many research projects and commercialization challenge but there are still many problems to be solved. For wave energy, a point absorber with an oscillating body is a well-known type of wave energy converter and it is considered that the system will be simpler than other types of wave energy converters and the cost will be lower[1)]. This type devices may be most studied and tested by researchers and many types of control strategies from resistive control to model predictive control are suggested[2,3,4)], and the important basic understanding may be that the large motion is need to achieve the large energy income.

Reactive control is a basic concept to achieve larger energy income by enlarging the motion of the float based on the resonant phenomena, but large motion of the float by reactive control causes many problems. The difficulty of the numerical simulation is focused in this study. The understanding of the device's behavior is important for the design but the large motion of the float is difficult to predict by the numerical simulation, of course, the analytical analysis is much more difficult. The numerical simulation of the point absorber's behavior is often based on the so-called "linear theory". Linear theory is based on the small motion assumption and it is widely used for the ocean engineering with the reliability. Linear problems are easy to analyze with BEM software like WAMIT. The nonlinear problems with the large motion of the

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float, which are outside of the linear theory, are difficult to analyze and CFD or FEM techniques will be suitable to analyze the nonlinear problems, but those techniques need the huge computer resources. In this study, the authors tried to simulate the large motion of the float with BEM and some small techniques. To prepare the simulation, several cases of the float's position are considered and fluids parameters for each case are calculated by BEM software. The calculated fluids parameters are kept in a memory table and the time domain simulation program uses the parameters correspond to the position of the float.

If considering only the heave motion, the motion of the float (one body) is described by Eq.1 based on the linear theory. In Eq.1, M is the float's mass, m_ω is the added mass, N_ω is the wave damping coefficient, C_ω is the restoring coefficient, X_ω is the wave excitation force coefficient, H_w is the wave elevation, F_{PTO} is the control force (load by the generator and thrust by the motor) from the power take off (PTO) system, z is the vertical position of the float and the dot means that it is the time differential value. ω means the parameters are depends on the wave frequency ω [rad/s] (=$2\pi / T$, T: wave period [s]). Although there are some techniques those convert the parameters and equations to the frequency independent forms, those techniques were not used in this study because it makes the parameter preparation complex. The control force of reactive control is described by Eq.2. In Eq.2, D_{PTO} and C_{PTO} are the control parameters those should be tuned for the resonance.

$$(M + m_\omega)\ddot{z}_{float}(t) + N_\omega \dot{z}_{float}(t) + C_\omega z_{float}(t) = X_\omega H_w(t) + F_{PTO}(t) \quad (1)$$

$$F_{PTO}(t) = -D_{PTO}\dot{z}_{float}(t) - C_{PTO} z_{float}(t) \quad (2)$$

To simulate the nonlinear behavior, the fluid parameters were prepared considering the position of the float and the simulation program runs referring the parameter table. Similar concepts may have been tried by many researchers, and this study presents just only our trials.

Figure 1: Example of the wave energy converter by Ocean Power Technologies[6].

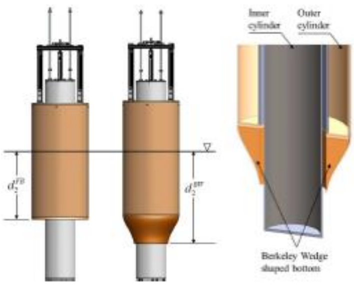


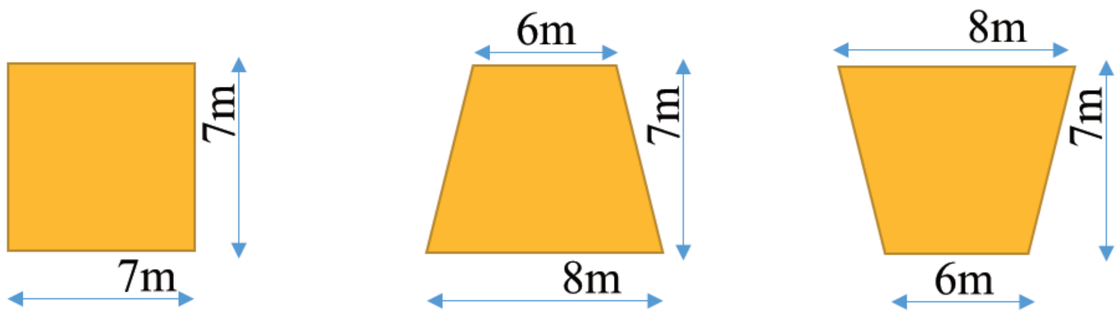
Figure 2: Example of the cylinder shape float by NREL[7].

2. FLOAT SHAPES AND PARAMETERS

(1) Float shapes

The disc shape floats had been used widely for the wave energy converter (Fig .1), but recently the cylinder shape floats are increasing for the purpose of using reactive control. Employing the cylinder type floats will be possible to avoid (or reduce) the effects of the position changing and it enables the larger movement and the larger energy achievement. The most unwelcome case is that the float fries out, and it must cause the reduction of the energy income and it matters rather than the difficulty of the simulation. Fig. 2 shows an example of the cylinder shaper float by NREL[7]. They also discussed the effect of the floater bottom shape, but the effect was ignored in this study because the effect was not computed by WAMIT.

In this study, three types of floats were tested based on those cylinder float concepts (Fig. 3). One is the just cylinder shape float, and the other two floats are tapered cylinder shaped (Up-tapered float and down-tapered float). Since approximately 7m-sized floats had been seen much in the many projects, the sizes of the floats in this study were set based on 7m-length. To simplify the float, the through hole for the spar part was ignored. From the comparison of these floats' behaviors, we want to find the nonlinear effects and its influence on the energy income.



a) Cylinder float b) Up-tapered float c) Down-tapered float

Figure 3: Side-view of the cylinder shape float and two tapered shape floats those were studied in this paper.

(2) Fluid parameters

Fluid parameters were computed by the Boundary Element Methods (BEM) code WAMIT. When using WAMIT, the position of the float and water level is important and often it is same as the equilibrium position. We assumed that the equilibrium position is the vertical center of the float and calculated the fluids parameters at the equilibrium position and several different positions.

The fluid parameters were computed as a following procedure. The seven positions were considered to compute the parameters. Here, the "position" equals the "water level". The seven positions were the equilibrium position (E: z = 0m), three upper position (U1: z = 1m, U2: z = 2m, U3: z = 3m) and three lower position (L1: z = -1m, L2: z = -2m, L3: z = -3m). In Fig.4, those positions for the cylinder shape float are illustrated. The computed coefficients were shown in Fig. 5, 6, 7 and 8, and those parameters were computed for wave periods, but the restoring coefficient is constant for wave periods. By the same procedure, the fluid parameters of the up-tapered shape float and down-tapered shape float were computed and those were shown in Fig. 10, 11, 12, 13, 15, 16, 17 and 18. The figures show the variations of the parameters because of the shapes.

To simplify the parameters, one regular wave condition with wave period T=7s was studied in this study. For T=7s, the parameters were picked up and these are shown in the figures. The parameters, especially damping coefficient, were varied by the position, and there were larger changes in the parameters of the tapered shape floats than those of the cylinder shape float (See Fig. 9, 14 and 19).

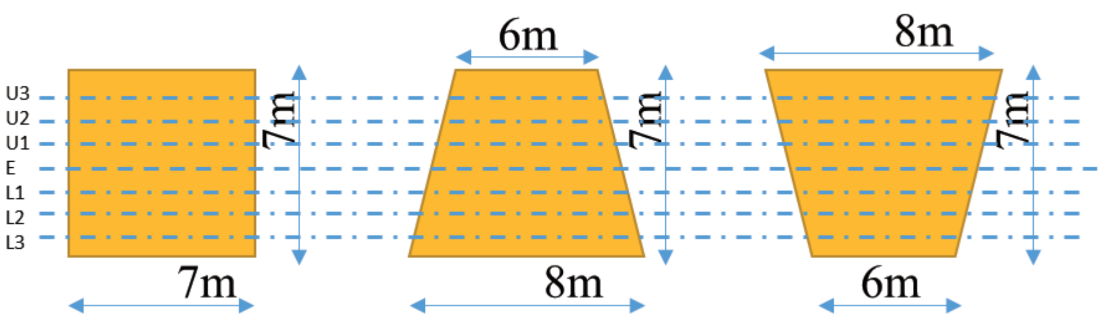


Figure 4: Image view of the seven vertical position for the cylinder shape float.

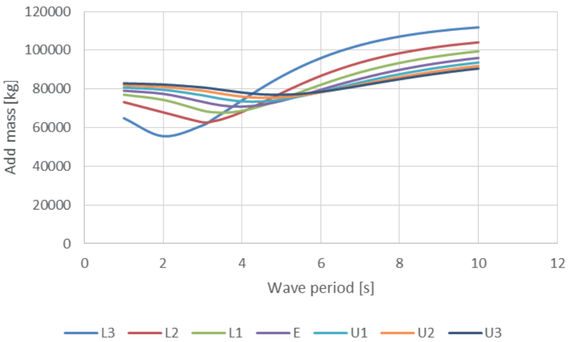


Figure 5: Computed add mass of the cylinder shape float with the seven positions.

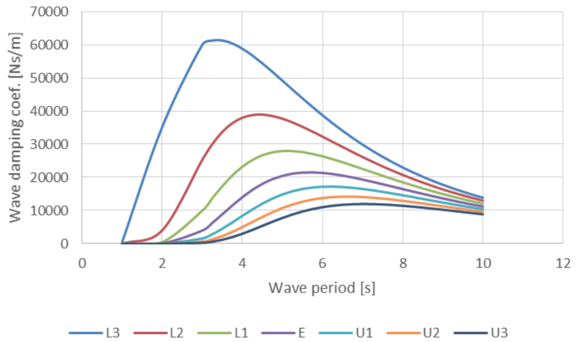


Figure 6: Computed wave damping coefficient of the cylinder shape float with the seven positions.

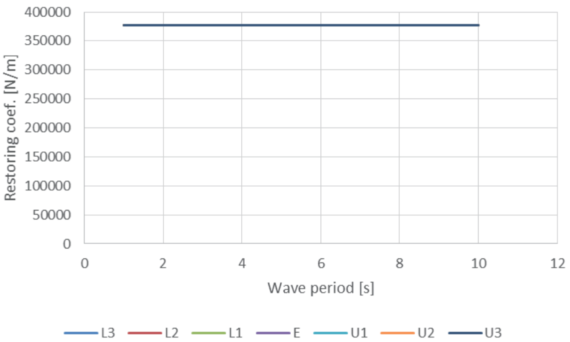


Figure 7: Computed wave restoring coefficient of the cylinder shape float with the seven positions.

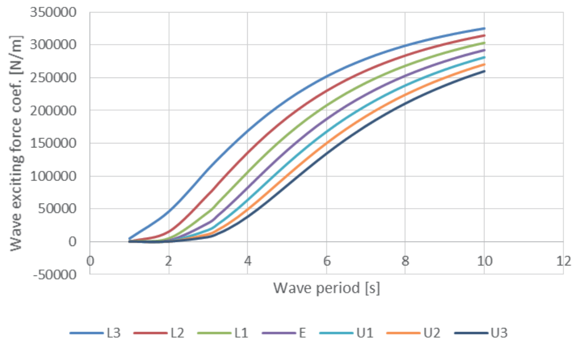


Figure 8: Computed wave exciting force coefficient of the cylinder shape float with the seven positions.

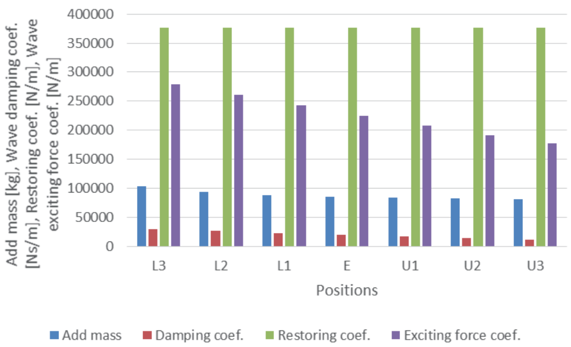


Figure 9: Values at wave period T=7s of the computed coefficients of the cylinder shape float with the seven positions

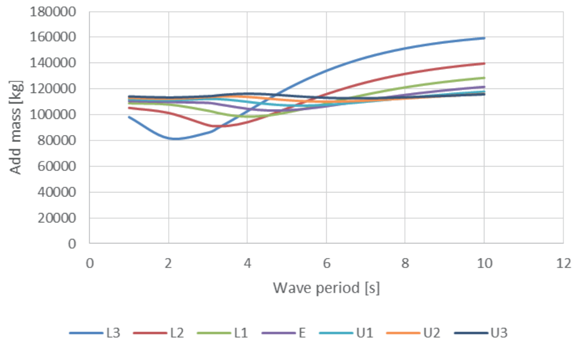


Figure 10: Computed add mass of the up-tapered shape float with the seven positions.

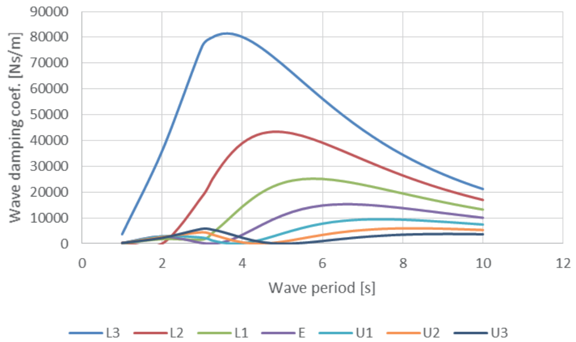


Figure 11: Computed wave damping coefficient of the up-tapered shape float with the seven positions.

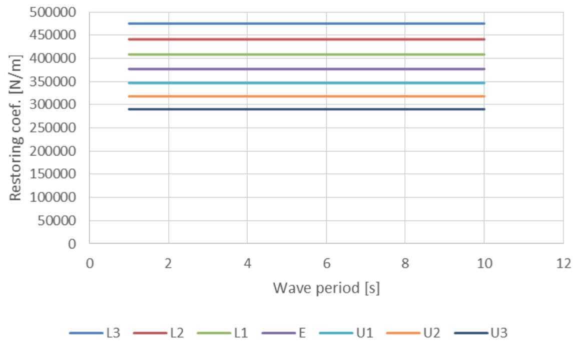


Figure 12: Computed wave restoring coefficient of the up-tapered shape float with the seven positions.

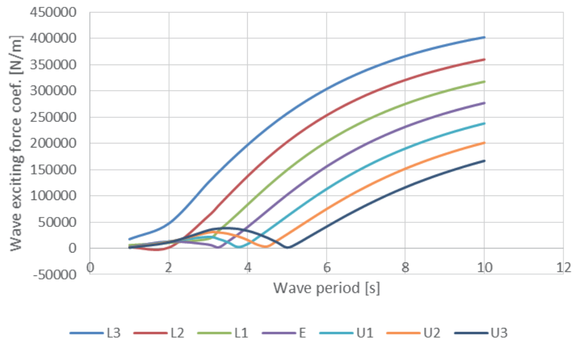


Figure 13: Computed wave exciting force coefficient of the up-tapered shape float with the seven positions.

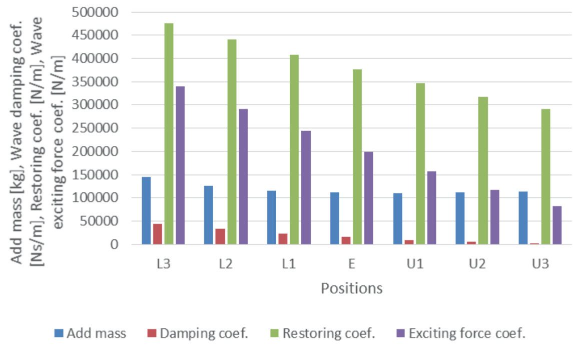


Figure 14: Values at wave period T=7s of the computed coefficients of the up-tapered shape float with the seven positions

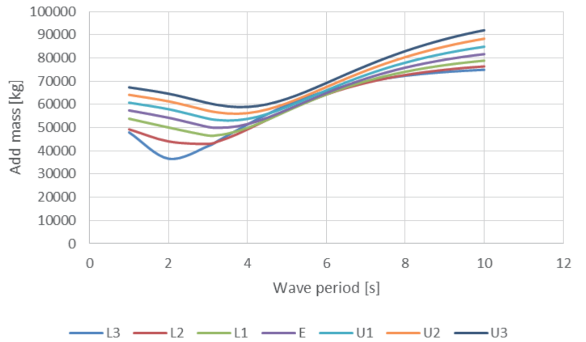


Figure 15: Computed add mass of the down-tapered shape float with the seven positions.

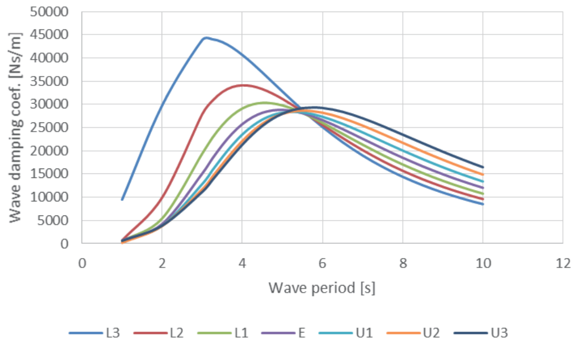


Figure 16: Computed wave damping coefficient of the down-tapered shape float with the seven positions.

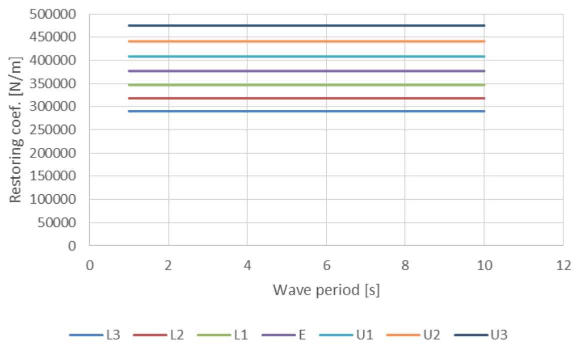


Figure 17: Computed wave restoring coefficient of the down-tapered shape float with the seven positions.

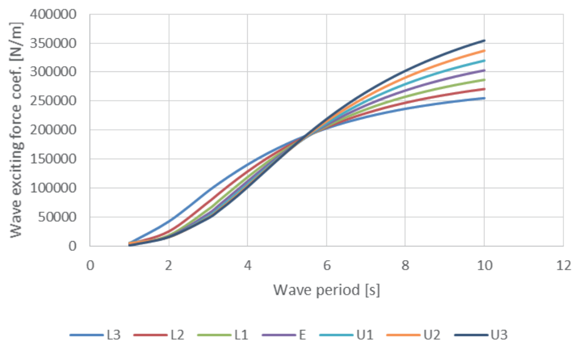


Figure 18: Computed wave exciting force coefficient of the down-tapered shape float with the seven positions.

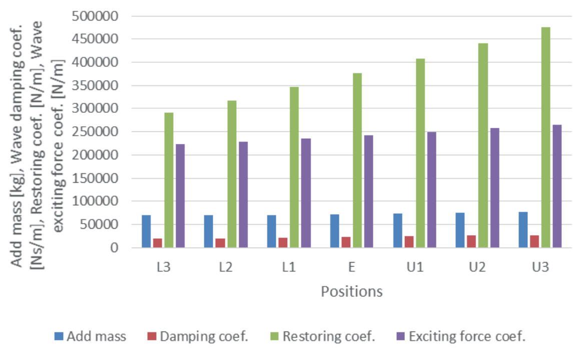


Figure 19: Values at wave period T=7s of the computed coefficients of the down-tapered shape float with the seven positions

(3) Control parameters

The control parameters in Eq.2 for reactive control were prepared based on the conditions of the cylinder shape float. The additional conditions are: (a) Based on linear theory (equilibrium position), (b) The wave is the regular wave (sine wave) with wave period T=7s and wave height H=1m, (c) The displacement must be smaller than 3m.

The tested parameters were found by the frequency analysis. When D_{PTO} = 22kNs/m, C_{PTO} = -200kN/m, the float's displacement will be less than 3m, and then the average output power is guessed to be 81kW. Those values will be change by the nonlinear behaviors.

3. NUMERICAL SIMULATIONS

(1) Fluid parameter table look-up

As mentioned above, the time domain simulation in this study uses the fluid parameters referring the obtained seven position data table with the linear interpolation. Initially, the relative position between the water elevation and float elevation is calculated. Then, the modified fluid parameters in the equation are given. These are described as follows.

$$r(t) = z_{float}(t) - H_w(t) \tag{3}$$

$$(M + m_\omega(r(t)))\ddot{z}_{float}(t) + N_\omega(r(t))\dot{z}_{float}(t) + C_\omega(r(t))z_{float}(t) = X_\omega(r(t))H_w(t) + F_{PTO}(t) \tag{4}$$

(2) Time domain simulation

We performed the time-domain simulations by using the Newmark-β method, which is an implicit method, so that we could use a relatively large time step in the calculations. But the time step of the time-domain simulations in this study was 0.01s, which may be sufficiently small. The time-domain simulation was programmed as MATLAB scripts.

By the Newmark-β method, the velocity and displacement at time step $t + \Delta t$ are described by the values at time step t as:

$$\dot{z}(t+\Delta t) = \dot{z}(t) + \Delta t \cdot [\gamma \cdot \bar{\ddot{z}} + (1-\gamma)\cdot \ddot{z}(t)] \tag{5}$$

$$z(t+\Delta t) = z(t) + \Delta t \cdot \dot{z}(t) + \Delta t^2 \{(0.5-\beta)\cdot \ddot{z}(t) + \beta \cdot \ddot{z}(t+\Delta t)\} \tag{6}$$

where $\bar{\ddot{z}}$ is an assumed acceleration at $t + \Delta t$. β and γ are coefficients, and the values of β = 1/4 and γ = 1/2 were used. When those values are used, it is also called the average acceleration method and the solutions are stable against any value of Δt. First, we give the assumed acceleration of the float, which is initially given as the same value of the acceleration at the former time step t, and then calculate the velocity and displacement at $t + \Delta t$ by Eq. 5 and Eq. 6, and also the acceleration at $t + \Delta t$ based by the motion equation. Until satisfying the following condition, the modification of the assumed acceleration and re-calculation of the velocity and displacement are repeated.

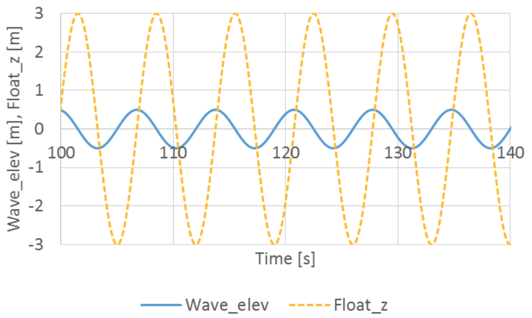
$$\left|\bar{\ddot{z}} - \ddot{z}(t+\Delta t)\right| \le \varepsilon \tag{7}$$

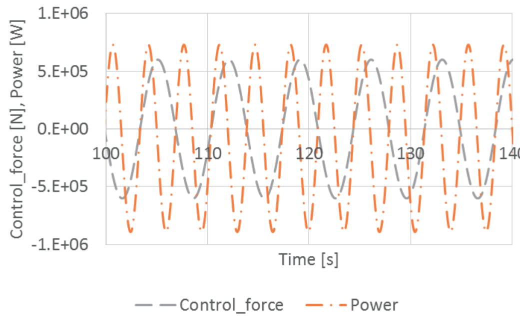
where ε is a constant for the convergence test.

4. SIMULATION RESULTS

(1) Results of the four cases

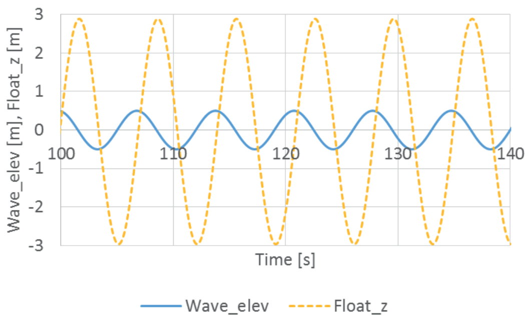
First, we show the results of the four cases: (1) Linear simulation of the cylinder shape float (General "linear theory" based simulation), (2) Nonlinear simulation of the cylinder shape float, (3) Nonlinear simulation of the up-tapered shape float and (4) Nonlinear simulation of the down-tapered shape float.

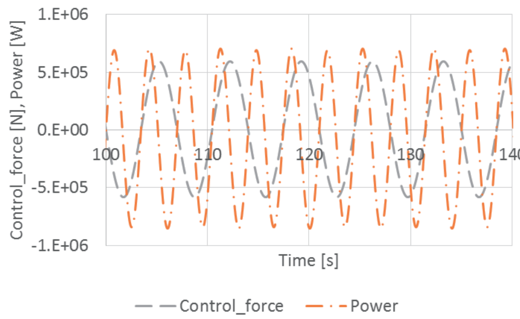




(a) Float’s movement (b) Control force and power

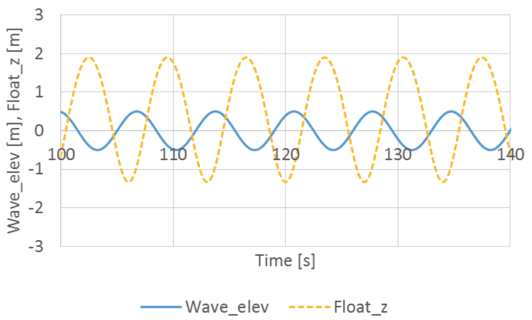
Figure 20: Linear simulation of the cylinder shape float.

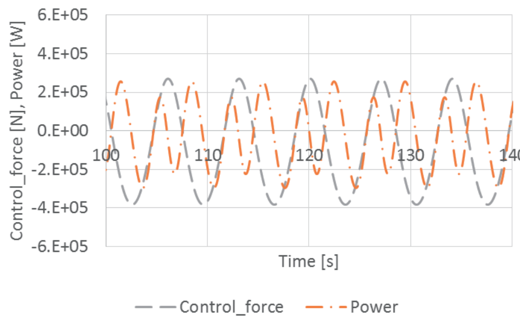




(a) Float’s movement (b) Control force and power

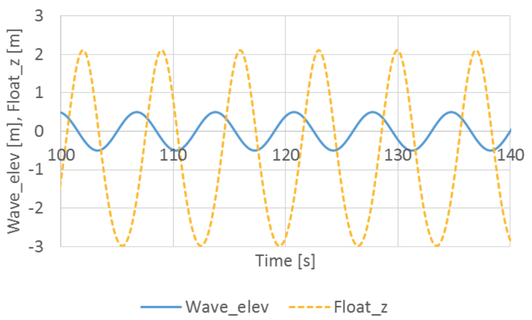
Figure 21: Nonlinear simulation of the cylinder shape float.

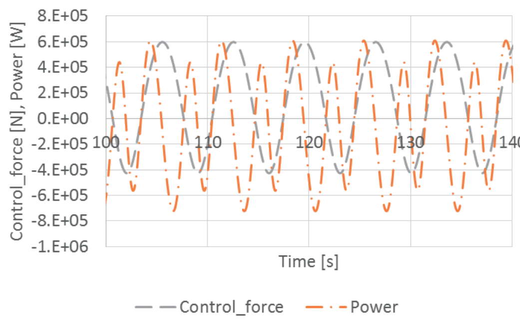




(a) Float’s movement (b) Control force and power

Figure 22: Nonlinear simulation of the up-tapered shape float.





(a) Float’s movement (b) Control force and power

Figure 23: Nonlinear simulation of the down-tapered shape float.

Table 1: z_{max}, r_{max}, r_{min} and P_{ave}.

Cases	z_{max} [m]	r_{max} [m]	r_{min} [m]	P_{ave} [kW]
(1)	3.00	3.04	-3.04	80.63
(2)	2.89	2.99	-3.06	76.75
(3)	1.91	2.32	-1.75	23.81
(4)	2.10	2.33	-3.24	58.48

Fig. 20, 21, 22 and 23 show the movements of the floats, control forces and power. Table 1 shows the maximum float's displacement z_{max}, the maximum relative position between the water elevation and float elevation r_{max}, the minimum of it r_{min}, and the averaged first-conversion power P_{ave}. The values of z_{max}, r_{max} and r_{min} indicate that the movements of the floats were within the expected movements and within the float's vertical size, and the computed results will be reasonable (It does not mean that the results are real, and it must be confirmed by comparing with the experiments).

(2) Discussions

Firstly, looking the result of the linear simulation of the cylinder shape float, the maximum displacement was 3m and the averaged power was approximate 81kW. Those were agreed with the expected values by the frequency analysis and those results may be some confirmations of the simulation program in this study.

Secondary, comparing the linear simulation and nonlinear simulation of the cylinder shape float, the differences of the movement and the averaged power were very small. This results may support the concept of the cylinder shape for avoiding the nonlinear effects. At the same time, it may be confirmed that the general linear simulation method is available within the float's vertical size.

Thirdly, the movement of the up-tapered shape float was smaller than other cases and the averaged power was much smaller than other cases. Those might be caused by the change of the wave exciting force coefficient for the position. Especially, the decrease of the coefficient from the lower position to the upper position was notable, because the wave exciting force is proportional to the vertical projected area of the float, and the cancellation of the force of the upper part and lower part is caused.

Fourthly, the movement and the averaged power of the down-tapered shape float was smaller than those of the cylinder shape float. For the down-tapered shape float, the change of the wave exciting force coefficient by the positions were small. But the change of the wave damping coefficient was notable and the increase of the coefficient from the lower position to the upper position might cause the slow-down of the float's movement.

The comparison of the three floats indicates that the change of the float's shape will be hard to lead the achieved power. But the control strategy was not optimized for each case in this study, and the result would be changed if the suitable control strategy would be used.

5. CONCLUSION

In this study, the pseudo nonlinear simulations with the table look-up of the fluid parameters for the three different shape floats were demonstrated. The fluid parameters for the floats were prepared by computing with WAMIT for the seven vertical position and those indicated the variations of the parameters. The results of the pseudo nonlinear simulations showed that (1) the linear simulation method does not matter for the cylinder shape float within the float size-order motion and (2) the up-tapered shape float and down-tapered shape float does not lead the increase of the achieved power and the change of the float shape needs more careful thought.

Since there was no comparison nor discussion with the experimental data in this study, the reliability and accuracy of the simulations were unknown. The experimental data will be essential, and the simulation data by many methods including CFD will be required to discuss the nonlinear simulation as further work.

ACKNOWLEDGMENT

The authors thank for the New Energy and Industrial Technology Development Organization (NEDO) supporting the ocean energy development projects.

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