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Numerical Modelling of Double Slit Caisson Breakwater Integrated Oscillating Water Column Wave Energy Converter with Modal Superposition Method

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Abstract

Oscillating water column wave energy converter is a power generation device in which ocean waves excite the oscillation of the water surface in an air chamber, which generates fluctuations in air pressure and rotate air turbine generator(s). The oscillation of the fluid in the air chamber is a fluid oscillation phenomenon with a natural period, similar to fluid oscillation in a container such as sloshing. Previous research has shown that for an oscillating water column with a single air chamber submerged in water, the oscillation characteristics can be modeled as a one-degree-of-freedom oscillation system that takes only a single oscillation mode into account. However, a double-slit breakwater integrated oscillating water column wave energy converter using two water columns of the breakwater separated by slit walls, has been verified to have two resonance periods. In this study, the free oscillating motion of the oscillating water column wave energy converter using the double-slit breakwater is modeled by modal superposition method including the first-order and second-order modes of vertical motion of the two water surfaces. The result from the simulation is similar to the result of the free vibration experiment.

Keywords

Fluid Oscillation, Wave Energy, Oscillating Water Column, Modal Analysis

1. Introduction

Oscillating water column wave energy converter is a wave power generation system that is more robust and reliable than other wave power devices because there are no moving parts in the water column and flow direction to the moving device has fixed single axis to the turbine. This system consists of a primary conversion part that converts wave energy into air energy by an air chamber and a secondary conversion unit that converts air energy into electrical energy by turbine generator(s) as presented in Figure 1. This study focuses on the oscillation characteristics of this primary conversion part. It is the part that pushes and pulls the air by exciting the vertical reciprocating movement of the water surface in the air chamber from incoming waves.

The conversion efficiency from wave energy to air energy in the primary conversion part is highly frequency-dependent. In general, for short-period, high-frequency waves, almost no vertical movement of the water surface occurs inside the air chamber, resulting in a significant decrease in efficiency. On the other hand, it is known that the efficiency is higher under incoming wave period coincides with the resonance period of the vertical motion of the water surface.

Even the primary converter has the oscillating characteristics described qualitatively above, quantitative evaluation of the output performance is indispensable in actual design. In the early research works in the 1970s and 1980s, model scale experiments in the wave basin using scaled models were often used to evaluate the vibration characteristics of primary transducers in order to evaluate the output performance at the development stage. After those days and until recent, with improvements in computer computing power, non-viscous or viscous numerical fluid dynamics analysis has been used. However, numerical simulation of wave energy converter, which is intrinsically an unsteady phenomenon, requires a time marching analysis resulting in huge computational costs. Furthermore, the state of the vertical oscillation of the water surface and the efficiency of the wave-to-air flow conversion depend on the fluctuating frequency of the input wave and the pressure of the air turbine that converts the output air flow into mechanical power. Therefore, a large number of calculation cases are needed if a designer requires optimization of the design.

In view of the above situation, simplified calculation methods, such as so-called 1D models, which allow faster simulation and parametric investigations than any experiments or numerical hydrodynamic analyses. Regarding oscillating water column systems, a mechanical analogical model as shown in Figure 2 which has been proposed as a 1D model for the primary conversion part.

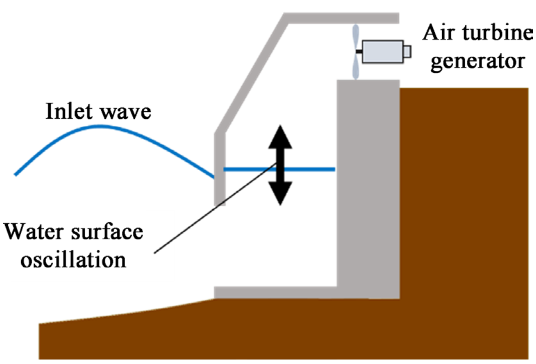

Figure 1. Principle of oscillating water column wave energy converter.

Although it involves the spatial distribution of the water level in the air chamber water surface in the primary conversion section, the air flow rate depends only the spacial average velocity of the water level which is obvious from the continuity equation. Therefore, using this model, if the response of the displacement x, representative of the average water level in the water column section modelled as mass m, is determined, air flow rate from pushed and pulled by the water surface can be calculated. Çelik1 *et al.* [1] identified the parameters in this type of mechanical model by free decay oscillation experiments in the water tank and also varidated the model using regular wave excited experiments.

As described above, the oscillating water column primary conversion part is basically using 1 degree of freedom oscillation phenomenon. However, some proposals have been made for an oscillating water column with two resonance periods in previous researches [2] [3]. A method of installing an oscillating water column wave power generator on a double-slit breakwater (**Figure 3**) is one of those concepts. In this method, a double slit caisson breakwater with two front and back water columns is used as part of primary conversion part. Kihara *et al.* [2] clarified secondary resonance period of oscillating water column is realized using this type of breakwater as a primary conversion part which results in wider operating wave period range of the wave energy converter. However none of these oscillating water column wave power generators with two resonance periods have been quantitatively modelled in a simple method which can be classified as a so-called 1D model, as shown in **Figure 2**.

This paper aims to model an oscillating water column with these two resonance

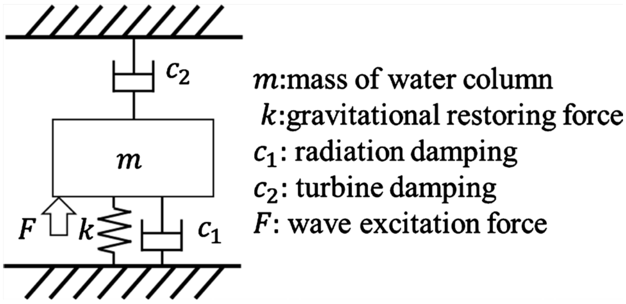

Figure 2. Mechanical analogic model of oscillating water column wave energy converter.

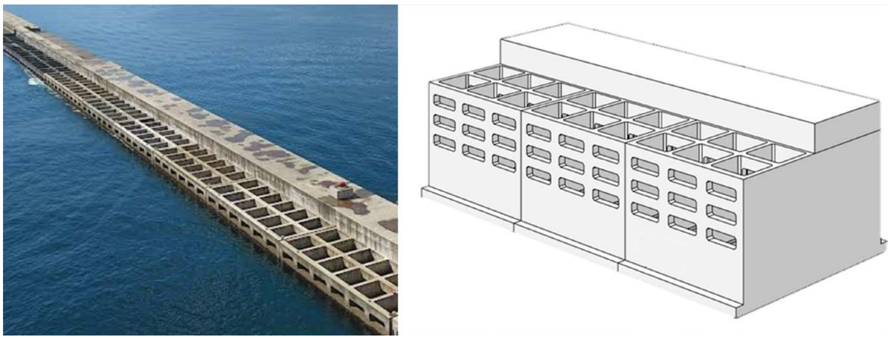

Figure 3. Double slit caisson breakwater (left: photo taken at Kamaishi bay breakwater [5] right: perspective view including underwater structures).

periods with low computational cost, which currently could only be predicted numerically by computational fluid dynamics analysis without experiment which enables more practical design studies such as wave-to-wire simulation, which has been established for conventional oscillating water columns [4], and or the prediction of overall system characteristics, such as power fluctuations or optimisation of turbine control in power take off systems.

In this study, a model of an oscillating water column wave power generator installed on a double-slit breakwater is built and the characteristics of two resonance periods with two water columns are measured by a free decay oscillation test. Then a simplified model expressing the vibration characteristics using the mode superposition method is proposed and verified with the experimental result.

2. Free Decay Oscillation Experiment

2.1. Experimental Setup

In this study, tank experiments were conducted on a scaled model of a slit breakwater shown in Figure 4 and Figure 5, on which two square column-shaped

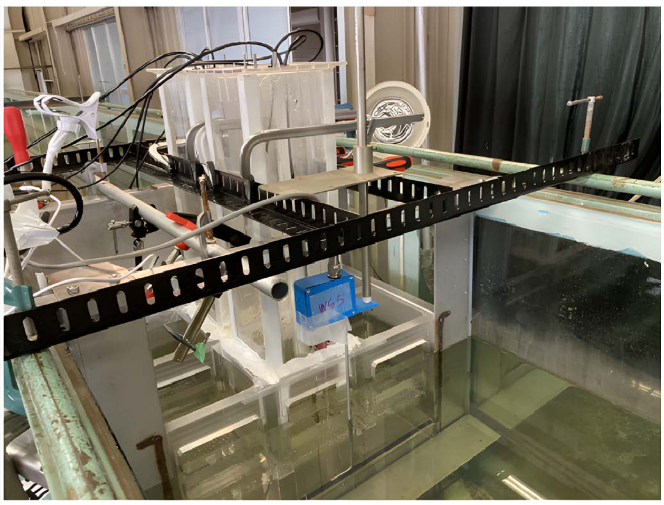

Figure 4. Photograph of experimental setup.

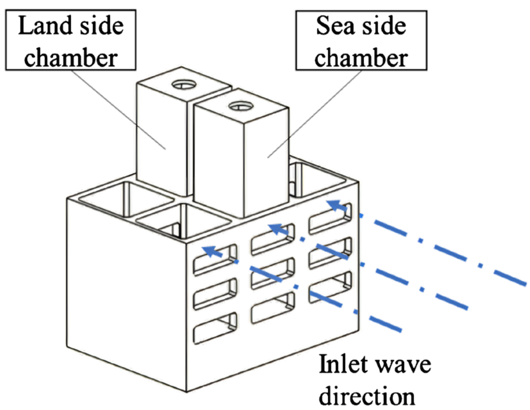

Figure 5. Perspective view of the model and assumed wave direction during power generation operation.

primary conversion parts (air chambers) on the land side and sea side are installed. The model consists of an acrylic slit caisson model with a width of 600 mm, depth of 430 mm, with three columns and two rows as shown in **Figure 5**. The dimensions of one square of the water chamber are 170 mm wide (perpendicular to the waves) and 180 mm wide (in the direction facing the waves), which are 1/25 scale dimensions of the breakwater installed at Kamaishi Bay shown in **Figure 3**. Two 150 mm × 150 mm air chambers on the landward and seaward sides, have a hole at the top of each chamber with 1/20 the size of the cross-sectional area of the chamber cross sectional area. A total of four water level gauges are mounted on the wall of each air chamber, one at the front and rear. The air chamber are installed and fixed so that they are aligned in a straight line in parallel to the wave, one on the seaward side and one on the landward side as shown in **Figure 5**. The average water level of each of the two wave gauges was treated as the seaward side and the landward side in order to determine the water level fluctuations as presented in **Figure 6**. To eliminate the effect of sloshing, where the water surface oscillates without the mean water level rising, and to obtain the mean water level variation, the mean water level of each of the two wave gauges was treated as the mean vertical displacement of each of the chambers.

2.2. Experimental Result

The time series of data from free decay oscillations after raising the landside water level to 18 cm is shown in **Figure 7**. At 0 s in **Figure 7**, the water level starts fall down as can be seen from the figure, the water level of the land-side air chamber, indicated by the blue line, decreases from the maximum point at 0 s, while the water level of the sea-side air chamber, indicated by the orange line, rises at the same time. After that, it can be seen that the water levels of the two

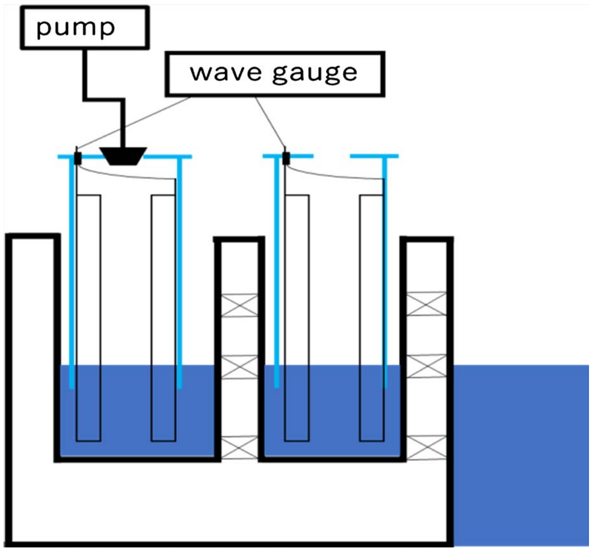

Figure 6. Wave gauge mounting position and suction pump set-up for raising the water surface.

amphibious chambers both oscillate and gradually decay. In the mode decomposition described below and the numerical modelling described in the next section, the data from 0.75 s, when the water level on the landward side first drops below 0 cm, were used as experimental data (Figure 8).

The time history data shown in Figure 8 clearly contains several frequency components. As it is difficult to model this multi-frequency signal as they are, mode decomposition process is applied to these data so that modal superposition method in the latter part can be applied. The empirical mode decomposition method using the "vmd" function in MATLAB R2020a was used for the mode decomposition. The detailed theory for this mode decomposition method is explained in [6]. The results of the mode decomposition for the 4 seconds of data from 0.75 to 4.75 s shown in Figure 8 are shown in Figure 9 and Figure 10. As can be seen from the figures, there are two dominant decaying signals: a first-order mode in-phase on the land and sea sides (black line) and a second-order mode in-phase on the land and sea sides (yellow line). The frequency of each mode was 3.81 Hz for the first-order mode and 8.43 Hz for the second-order mode. Third-order or higher component was also present, but no clear decay was observed compared to the first- and second-order modes.

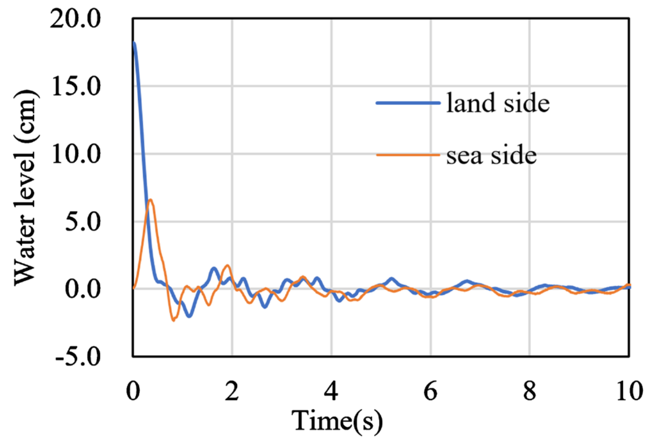

Figure 7. Free decay oscillation result.

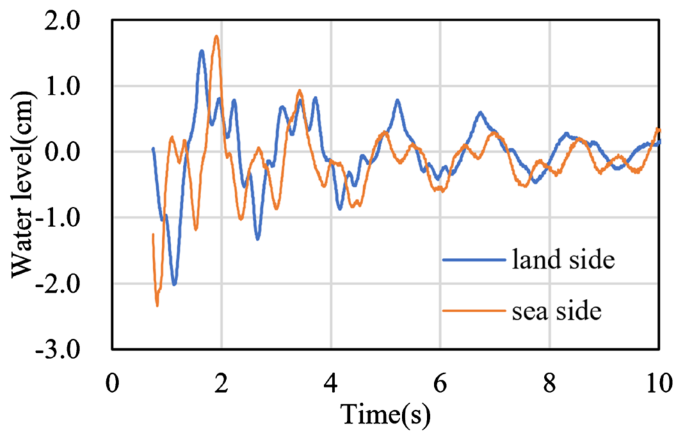

Figure 8. Free decay oscillation result cropped for data analysis.

3. Two Degree of Freedom Modal Superposition Modelling of Oscillation Characteristics

In this research, the oscillating motion of water column presented in the previous section is represented by a numerical model using the modal superposition method. And a time history analysis of the model is executed to demonstrate the applicability of the model. Section 3.1 describes the model and section 3.2 presents the results of verification and comparison of the numerical model with experimental results.

3.1. Model Description

The modal superposition method represents the vibration in real space as a superposition of multiple vibration states (mode coordinates) representative of the

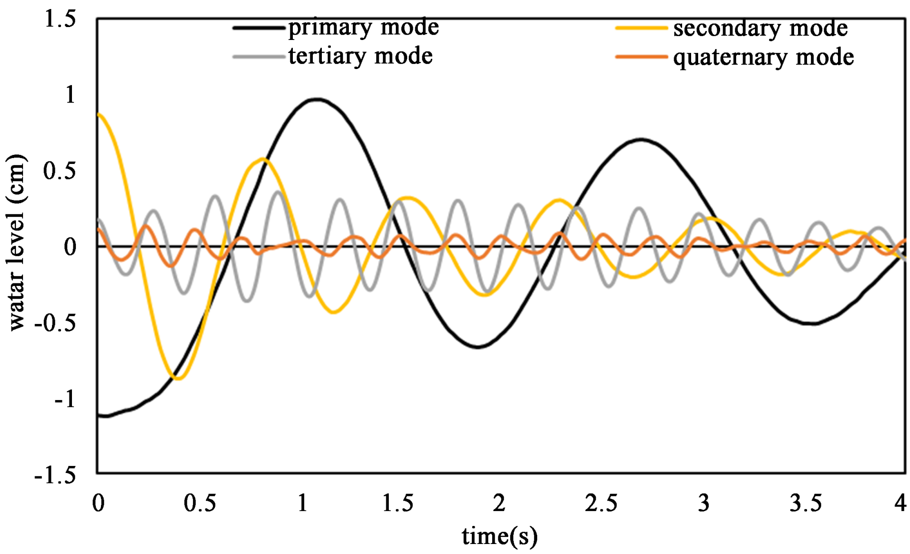

Figure 9. Land side modal decomposed time series data.

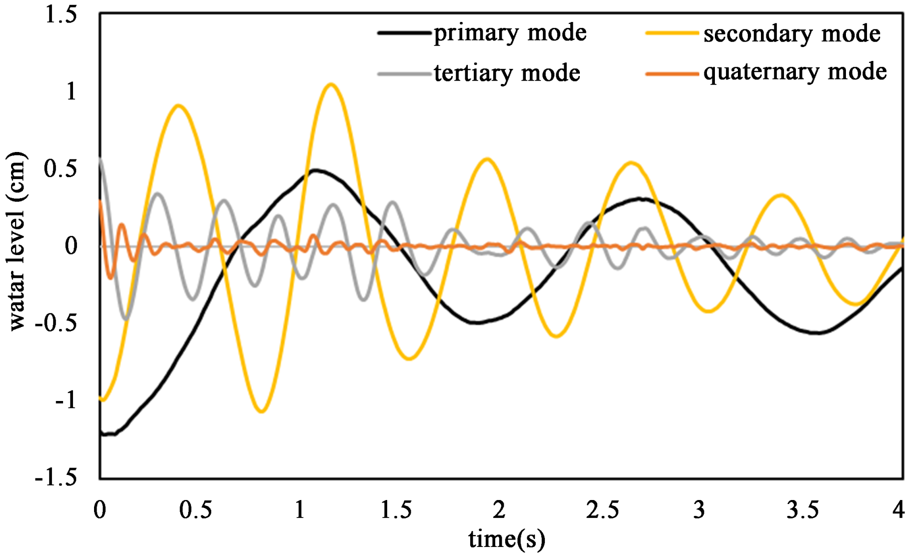

Figure 10. Sea side modal decomposed time series data.

mode shape. As the oscillation of the double slit breakwater integrated oscillating water column has two dominant natural frequency and respective modal state, the equations of motion for the first- and second-order modes respectively are shown in the following equations, assuming that each mode is a linearly damped vibration. As indicated in the previous section, the first-order mode is one in which the seaside and landside water columns oscillate in phase with each other, while the second-order mode is one in which the seaside and landside water columns oscillate in opposite phase. The suffix 1 and 2 correspond to the components of the first-order and second-order modes respectively.

$$\ddot{x}_1^* + 2\zeta_1^* \omega_1 \dot{x}_1^* + \omega_1^2 x_1^* = 0 \quad (1)$$

$$\ddot{x}_2^* + 2\zeta_2^* \omega_2 \dot{x}_2^* + \omega_2^2 x_2^* = 0 \quad (2)$$

The variables x_1^*, x_2^* in the equation of motion are the modal coordinates of the primary and secondary modes, which can be converted to the real space displacements x_1 (water level on land side) and x_2 (water level on sea side) as in Equation (4) by multiplying modal transformation matrix $\boldsymbol{T}$. In this study, the landside water level is x_1 and the seaside water level is x_2. Consequentrly, the modal amplitude of the landward water level is set to 1.

$$\boldsymbol{T} = \begin{bmatrix} 1 & 1 \\ A_{12}/A_{11} & A_{22}/A_{21} \end{bmatrix} \quad (3)$$

$$\boldsymbol{T} \begin{bmatrix} x_1^* \\ x_2^* \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (4)$$

The basic equations of the modal superposition model are Equations (1) and (2) with linear damping, but the comparison with the model resulted in too fast decay of oscillation compared to the experimental results (the results of this linear simulation is not shown in this abstract). Therefore, a model with a square proportional non-linear damping term as shown in the following Equation (5) and (6) is used in the latter of this abstract. c_1^* and c_2^* are the modal damping coefficients.

$$\ddot{x}_1^* + 2c_1^* \dot{x}_1^* \left|\dot{x}_1^*\right| + \omega_1^2 x_1^* = 0 \quad (5)$$

$$\ddot{x}_2^* + 2c_2^* \dot{x}_2^* \left|\dot{x}_2^*\right| + \omega_2^2 x_2^* = 0 \quad (6)$$

The six parameters in Equations (5) and (6), the amplitude ratios A_{12}/A_{11} and A_{22}/A_{21} the mode damping coefficients c_1^* and c_2^*, and the natural angular frequencies ω_1 and ω_2 must to be determined. ω_1, ω_2 are identified theoretically from the mode decomposition results in previous section. A_{12}/A_{11} and A_{22}/A_{21} are also determined by averaging amplitude ratio of sea side and land side water level. c_1^*, c_2^*, are tuned to match the decomposition results of each mode. The coefficients for each of the mode superposition models are shown in **Table 1**.

In order to solve the equation of motion, Equations (1) and (2) are implemented in MATLAB Simulink R2020a. At each calculation time step, each water column level x_1 and x_2 are using calculated from Equations (3) and (4) also implemented in Simulink program. As initial conditions, x_1^*, x_2^* and first order differentiated value of them are needed. In this work, those values are determined from the measured value presented in Figure 8.

3.2. Simulation Results

Comparisons of seaside and landside air chambers' water levels between the experiment and the simulation are shown in Figure 11 and Figure 12. A comparison of the first and secondary landside modal displacement is shown in Figure 13. From Figure 11 and Figure 12, it can be seen that the amplitude and decaying trends of the water level for both the land side air chamber and the sea side air chamber shows good agreement between experiment and simulation. As

Table 1. Parameters of the modal superposition model.

Primary mode amplitude ratio	A_{12}/A_{11}	0.689
Secondary amplitude ratio	A_{22}/A_{21}	−2.014
Primary mode angular frequency (rad/s)	ω_1	3.81
Secondary mode angular frequency (rad/s)	ω_2	8.43
Primary mode modal damping factor(1/m)	c_1	0.586
Primary mode modal damping factor(1/m)	c_2	0.547

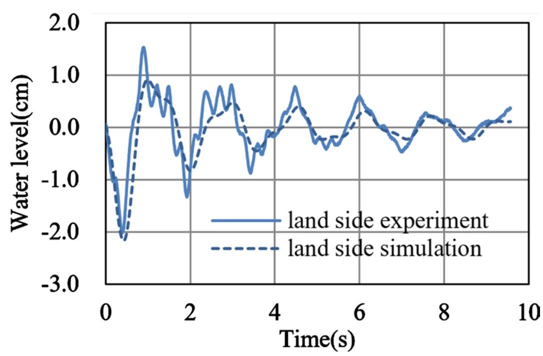

Figure 11. Land side air chamber water level time series.

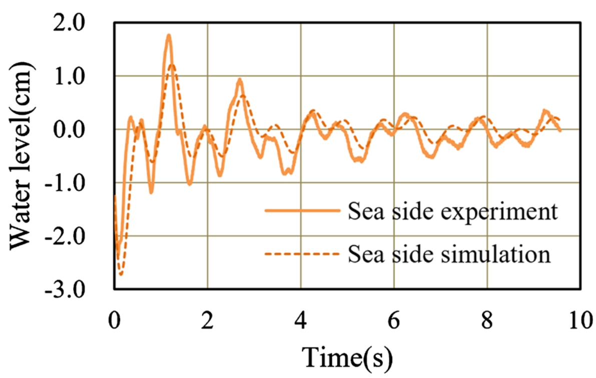

Figure 12. Sea side air chamber water level time series.

the model is limited up to second-order oscillation components, the simulation results do not show any high-frequency oscillation components. This characteristic can be clearly observed between 0 and 4 seconds in Figure 11.

A comparison of the time series for the different modes on which time series in Figure 11 and Figure 12 are based is shown in Figure 13. In Figure 13, "primary simulation" is the time history for mode coordinate x_1^* and the "secondary simulation" is the time history for mode coordinate x_2^*. The experimental values in Figure 13 are identical to the time series of the primary and secondary modes shown in Figure 9. The figures show that the primary mode has a large difference at the first wave, but after that the waveforms agrees well, while the secondary mode shows constant agreement of amplitude and decay characteristics between simulation and experiment.

Finally, the amplitude spectra from the experiment and the simulation are shown in Figure 14. The amplitudes of the peaks of the primary and secondary modes and the widths of the width of the peaks on both sea and land sides shows a good agreement. The experimental data have a higher frequency peaks above 2 Hz, which is not observed in the simulation model. 2 Hz in this model scale corresponds to 0.4 Hz on the real scale considering Froude similarity, and waves below 0.4 Hz, or 2.5 s period, are too high frequency in natural ocean waves.

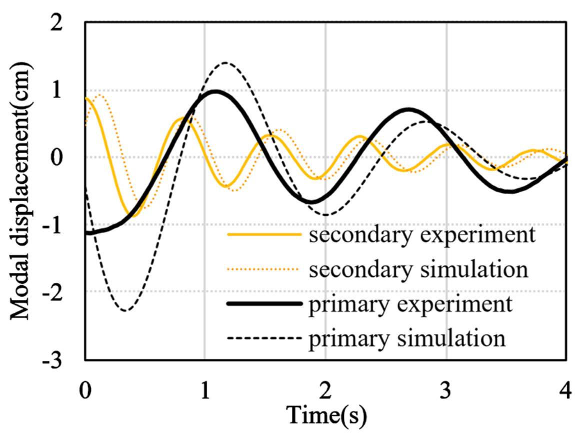

Figure 13. Decay oscillation time series of each oscillation mode.

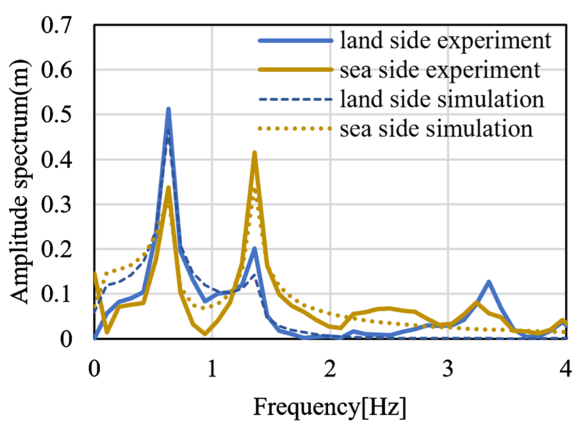

Figure 14. Amplitude spectrum.

Therefore, as an wave energy converter simulation model, the model proposed in this study which reproduces the characteristics up to the second-order vibration mode is considered to be useful in predicting the output energy.

4. Conclusion and Future Work

This study aimed to develop a dynamic modelling of an oscillating water column wave power generator using a double slit breakwater. The results of a free oscillation experiment using a water tank experimental model were analysed using variational mode decomposition. As a result, a time series data is decomposed into multiple vibration components and the identification of two dominant natural oscillation modes and frequencies. Simulations were carried out using a two-degree-of-freedom modal superposition method which parameters were determined from the experiment. The simulation results of the model reproduced waveforms similar to those of the free vibration experiments. In the future, the efficiency of the primary converter will be evaluated by simulations that also consider the excitation force due to waves. This modal decomposition and modal superposition analysis approach can be applied not only to the double-slit type, but also to other oscillating water column systems with multi resonance modes, for example [7]. In addition, the present method was limited in terms of modelling and experimental conditions. In the future, it will be necessary to evaluate the influence of the higher-order modes ignored this time in the model, to add more modes if necessary, and to study the conditions under which the waves strike as an excitation force from outside.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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