Apparatus and Theory of a Submerged Point Absorber using Oscillating Water Column

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***Abstract*—We present a submerged point absorber using oscillating water column (SPA-OWC) that converts ocean wave energy into electric energy. The SPA-OWC comprises a hollow pipe with a power take off system and uses a heave motion of the water inside. Therefore, it has the lightweight and simple structure which would be helpful to reduce production and maintenance costs. The goal of the research described in this paper is to explain the operation principle of the SPA-OWC and to prove the its potential through showing its performance via linear wave theory. A model dynamics based on Newton's law applied to the SPA-OWC will be derived and then simulations of the SPA-OWC with different submerged depths will be carried out with an analysis of the results.**

I. Introduction

Wave energy converters (WECs) have been receiving great attention in a renewable energy field because the hydrokinetic energy is more persistent and spatially concentrated compared to wind and solar energy [1]-[3]. In spite of advantages of WECs, it is still undeveloped and commercialization is still some away off. One of the major issues of WECs is survivability. In order to harness a lot of the wave power, the WECs should be installed in the ocean with high wave energy density. Hence, the WECs must be able to withstand the extreme harshness of the sea environment and also should be activated under this condition. For solving these challenges, several types of WECs were developed to be completely submerged since the submerged types of WECs in general are less vulnerable in storms. Besides, by the low-pass filtering effect, submerged WECs are only affected by the low frequency of the waves and are easier to resonate with the peak frequency of the ocean. A representative example of fully submerged WECs is an Archimedes Wave Swing (AWS) [4], [5]. It is a completely submerged offshore WEC activated by the fluctuations of pressure caused by the surface waves. Basically, the AWS is an air-filled cylindrical steel chamber whose lid, called the floater, is a heaving body while the bottom part is fixed. However, it requires a pneumatic maintenance device to prevent the waterlogging into the silo, an additional spring to cancel the hydraulic spring coefficient having negative sign, and a durable foundation to withstand the hydraulic pressure acting vertically downward on the lid. Accordingly, this system is heavy, huge, and complex.

In this paper, we introduce a submerged point absorber using oscillating water column (SPA-OWC). The operation principle of our system is similar to the previous AWS system.

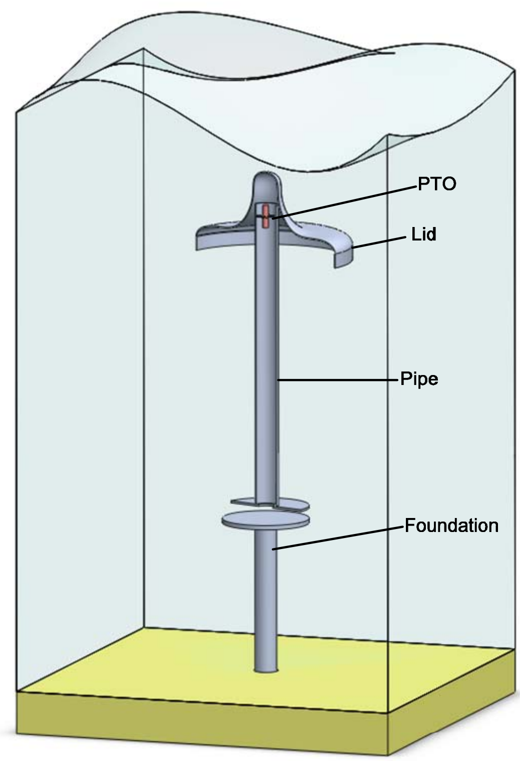

Fig. 1. Schematic figure of the SPA-OWC.

But unlike the AWS system, it has no moving parts but uses only the movement of the seawater inside the body. Also, it does not require an additional spring since the hydraulic spring coefficient of the system has positive sign. Further, it has the high volumetric efficiency which makes the system more survivable and reliable.

II. Concept of SPA-OWC

A. Description of SPA-OWC

The SPA-OWC consists of a lid, a pipe, a foundation, and a power take off system (PTO). The lid is a hollow cylindrical chamber having open bottom and closed top. The pipe is a hollow cylindrical chamber with open ends. The foundation is a component to fix the device on the seabed. Each part is relatively fixed and arranged as shown in Fig. 1. The lid is placed on the top of the device, the pipe is arranged under

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the lid, and both are fixed at the top of the foundation. Since we only introduce the concept of device, it may be not appropriate to define a specific type of PTO. However, it may be recommended that a Wells turbine is used as the PTO, which is generally introduced and used in an oscillating water column wave energy converter (OWC-WEC) [6]-[8]. This turbine is located near the top-end of the pipe.

B. Operation Principle of SPA-OWC

The SPA-OWC is fully submerged under the sea water surface. Since this device structure is open to the sea, most of the inside is filled with water and free movement of the water is allowed between the body inside and the outer space. However, the upper parts of the lid and pipe are filled with air and its pressure is equivalent to the external water pressure in the static state.

When wave crest passes over the device, hydraulic pressures under the bottoms of the lid and the pipe increase which are generally called excitation forces. These pressures have different magnitudes because water molecules undergo a circular motion which decreases exponentially with depth via linear wave theory (LWT) [9], [10]. Accordingly, the increment of the pressure acting on the lid is higher than its acting on the bottom of the pipe via LWT. Consequently, the water level of the pipe is falling as the wave crest coming. When wave trough passes, the hydraulic pressures decrease and the water level of the pipe moves up. As two processes repeat, the water filling in the pipe has reciprocating heave motions.

In addition, By the assumption of incompressible air in the lid and the flow conservation law, the displacement and the velocity of the water in the pipe are amplified with a magnitude which is proportional to the area ratio between the pipe and the lid. That is why Wells turbine can be used.

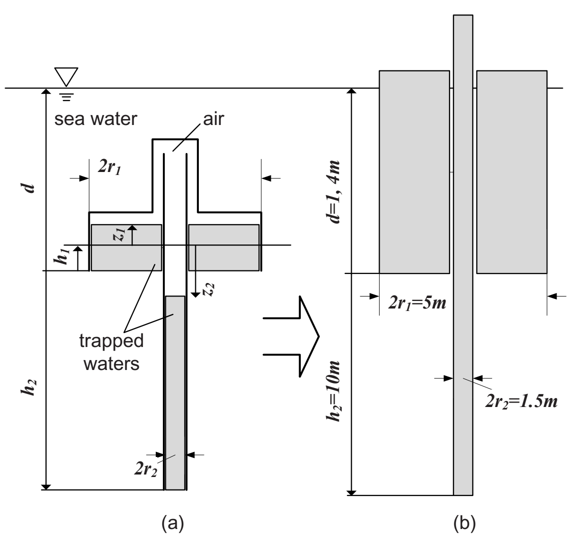


Fig. 2. Diagram of the SPA-OWC: (a) outline of SPA-OWC including parameters; (b) AQWA modelling with the simulation size.

III. Modelling

A. Equations of Motion

Unlike previous point absorbers using a rigid buoy, the SPA-OWC uses the direct motion of the sea water vibration. Therefore, analyzing the motion of the water vibration is needed. The sea water filling in the device is mainly divided into two parts, water in the lid and water in the pipe. It is assumed that both can only move in the vertical direction, then it is possible to define water levels as z_1 and z_2 from the mean levels in the static state, which represent the behaviors of the waters in the lid and pipe, respectively. A diagram of the system is shown in Fig 2(a). Dynamics of two water levels based on Newton's law are expressed as follows [11], [12]:

$$\{m_{add1} + \rho S_1(h_1 - z_1)\}\ddot{z}_1 - \rho S_1 \dot{z}_1^2 = F_{e1} - F_{r1} - \rho g S_1 z_1 + P S_1 - b_1 \dot{z}_1, \quad (1)$$

$$\{m_{add2} + \rho S_2(h_1 + h_2 - z_2)\}\ddot{z}_2 - \rho S_2 \dot{z}_2^2 = F_{e2} - F_{r2} - \rho g S_2 z_2 + P S_2 - b_2 \dot{z}_2 + F_{gen}, \quad (2)$$

where ρ, g, and P denote the sea water density, the gravity acceleration, and the internal air pressure, respectively. S_1 and S_2 are surface areas of the lid and the pipe, respectively. h_1 and h_2 are heights from the bottom of the lid to the internal mean water level and the bottom of the pipe, respectively. F_{e1} and F_{e2} are the excitation forces exerted on the bottoms of the lid and the pipe. m_{add1} and m_{add2}, and F_{r1} and F_{r2} are the added masses and radiation damping forces exerted on the bottoms of the lid and the pipe, respectively, which are responsible for generating the radiated wave. b_i is the drag coefficient which can be obtained experimentally, so it will be ignored in left sections.

The excitation forces and the radiation forces can be described by

$$F_{ei} = \int_{-\infty}^{\infty} f_{ei}(t-\tau)\eta(\tau)d\tau, \quad for\ i = 1, 2, \quad (3)$$

$$F_{ri} = \int_{0}^{\infty} f_{ri}(t-\tau)\dot{z}_i d\tau, \quad for\ i = 1, 2, \quad (4)$$

where $\eta(\tau)$ denotes the incident wave height. f_{ei} and f_{ri} are the impulse response functions of excitation and radiation, respectively.

F_{gen} is the force applied by the generator. For better numerical calculation of extracted power, it is assumed that F_{gen} is modelled as follows:

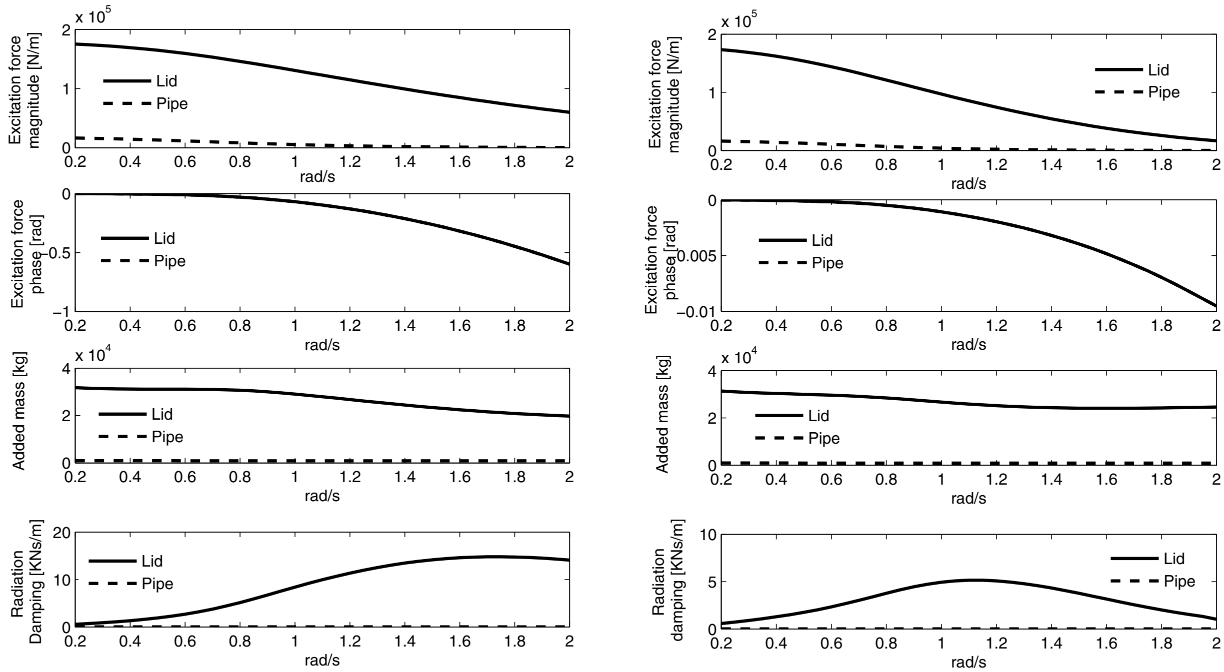
$$F_{gen} = -\beta \dot{z}_2, \quad (5)$$

where β is the damping coefficient due to the generator.

Moreover, from the assumption of incompressible gas in the lid and conservation law, a following relation can be obtained:

$$S_1 z_1 + S_2 z_2 = const. \quad (6)$$

From the behaviors of the SPA-OWC which has reciprocating heave motion, it can be expected to behave like a mass-damper-spring system. From substituting (6) into (1) and



(a)

(b)

Fig. 3. Simulation results using AQWA: (a) SPA-OWC submerged at $d = 1[m]$; (b) SPA-OWC submerged at $d = 4[m]$.

then combining with (2) with ignoring nonlinear terms, one dynamic equation of z_2 is obtained as follows:

$$M\ddot{z}_2 + \beta\dot{z}_2 + kz_2 = F_e - F_r, \tag{7}$$

where

$$\begin{aligned} M &= \rho S_2(s_{21}h_1 + h_1 + h_2) + s_{21}^2 m_{add1} + m_{add2}, \\ K &= (1 + s_{21})\rho g S_2, \\ F_e &= \int_{-\infty}^{\infty} -\{s_{21}f_{e1}(t-\tau) - f_{e2}(t-\tau)\}\eta(\tau)d\tau, \\ F_r &= \int_{0}^{\infty} \{s_{21}^2 f_{r1}(t-\tau) + f_{r2}(t-\tau)\}\dot{z}_2(\tau)d\tau. \end{aligned}$$

Taking the Fourier transform of (7) gives

$$\begin{aligned} [-M\omega^2 + j\omega\{\beta + s_{21}^2\mathcal{F}_{r1}(\omega) + \mathcal{F}_{r2}(\omega)\} + K]Z_2(\omega) \\ = -\{s_{21}\mathcal{F}_{e1}(\omega) - \mathcal{F}_{e2}(\omega)\}A(\omega), \end{aligned} \tag{8}$$

where $Z_2(\omega)$ and $A(\omega)$ are the Fourier transforms of $z_2(t)$ and $\eta(t)$, respectively. $\mathcal{F}_{e1}(\omega)$, $\mathcal{F}_{e2}(\omega)$, $\mathcal{F}_{r1}(\omega)$, and $\mathcal{F}_{r2}(\omega)$ denote the Fourier transforms of f_{e1}, f_{e2}, f_{r1}, and f_{r2}, respectively. This expression can be written as

$$Z_2(\omega) = \mathcal{H}(\omega)A(\omega), \tag{9}$$

with

$$\mathcal{H}(\omega) = \frac{\mathcal{F}_{e2}(\omega) - s_{21}\mathcal{F}_{e1}(\omega)}{K - M\omega^2 + j\omega\{\beta + s_{21}^2\mathcal{F}_{r1}(\omega) + \mathcal{F}_{r2}(\omega)\}}. \tag{10}$$

Here, $\mathcal{H}(\omega)$ is the transfer function from the wave amplitude $A(\omega)$ to the water level of the pipe $Z_2(\omega)$. The transfer function contains information about the resonance frequency, which occurs when:

$$\omega = \sqrt{\frac{K}{M}}. \tag{11}$$

B. Frequency Domain Response using AQWA

In order to implement the SPA-OWC defined in the previous section, the hydrodynamic response must be determined. The required hydrodynamic functions are the excitation, the radiation, and the added mass in the frequency domain. In general, to obtain these functions, offshore structural design and analysis engineering softwares are used such as AQWA which is a boundary element method code based on the principle of LWT, so the frequency-domain response has the assumptions of incompressible, irrotational, and inviscid flow [13]. However, this tool has the constraint that only provides the solution of the rigid body floating on the water surface. Unlike general point absorbers, the SPA-OWC is oscillating under the sea water surface. Therefore, it is impossible to analyze the SPA-OWC using AQWA directly. In order to overcome this constraint, we assume that the two rigid bodies are submerged as deep as bottoms of the lid and the pipe, respectively. The floating bodies replacing the waters in the lid and pipe have shapes as a thick disk and a cylinder, respectively. Both are exposed over the sea water surface as figured in Fig. 2(b). The geometric parameters of two bodies are shown in Fig. 2(b) with 30 $[m]$ water depth . When the SPA-OWC geometry is imported into a frequency-domain hydrodynamic code, the mesh should be sized to meet these requirements because the mesh determines the frequency range response the code solves for. The size of mesh was set to the defeaturing tolerance of $0.4[m]$ and the max element size of $0.8[m]$. The frequency range was set to 0.2 $[rad/s]$ to 2 $[rad/s]$ with the interval of 0.05 $[rad/s]$. To analyze the effect of submerged depth, the simulation of SPA-OWC was carried out with different submerged depths as 1 $[m]$ and 4 $[m]$. The excitation forces, radiation forces, and added masses of the SPA-OWC with different submerged depths are shown in Fig. 3. In all graphs, a solid line and a dashed line are results for $d = 1$ $[m]$ and $d = 4$ $[m]$, respectively. From substituting the added mass into (11), it can be confirmed that the resonance frequency of the SPA-OWC with given parameters is about $\omega = 1$ $[rad/s]$ which is a same result with different submerged depths. It is thought that this can be drawn since both added masses are almost the same as seen in Figs. 3.

IV. Power Absorption with a JONSWAP Spectrum

The average power extraction from the SPA-OWC taken over the time interval [0, t] is given by,

$$p_{gen}(t) = \frac{1}{t}\int_0^t \beta \dot{z}_2^2 dt. \quad (12)$$

Its Fourier transform with a constant wave angular velocity ω is given as

$$P_{gen}(\omega) = \frac{\beta\omega^2}{2}|Z_2(\omega)|^2. \quad (13)$$

By normalizing the generated power with a wave amplitude $A(\omega)$, it is possible to derive an auxiliary absorber power $P_{aux}(\omega)$ which is given by

$$P_{aux}(\omega) = \frac{\beta\omega^2}{2}\left|\frac{Z_2(\omega)}{A(\omega)}\right|^2 = \frac{\beta\omega^2}{2}\left|\mathcal{H}(\omega)\right|^2. \quad (14)$$

The extracted power spectrum $S_{gen}(\omega)$ from substituting the irregular wave spectrum can be expressed as follows:

$$S_{gen}(\omega) = P_{aux}(\omega)\cdot S_\zeta(\omega). \quad (15)$$

Here, $S_\zeta(\omega)$ is the irregular wave spectrum. When $S_\zeta(\omega)$ is in the case of JONSWAP spectrum [14], it is given as

$$S_\zeta(\omega) = \frac{5}{16}H_{1/3}^2\omega_p^4\omega^{-5}\exp[-1.25(\omega_p/\omega)^4]\gamma^B, \quad (16)$$

where

$$\omega_p = \frac{2\pi}{T_p}, \quad (17)$$

$$B = \exp[\frac{-(\omega-\omega_p)^2}{2\sigma^2\omega_p}]. \quad (18)$$

Here, $H_{1/3}$ and T_p denote the significant wave height and the peak period, respectively. σ is 0.07 when $\omega \le \omega_p$ or is 0.09 when $\omega > \omega_p$. γ is 3.3. Finally, the average extracted power can be calculated as follows:

$$\bar{P}_{gen} = \int_0^\infty S_{gen}(\omega)d\omega. \quad (19)$$

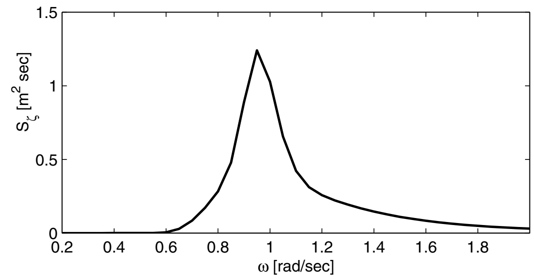


Fig. 4. JONSWAP spectrum with peak frequency $\omega_p = 1[rad/s]$.

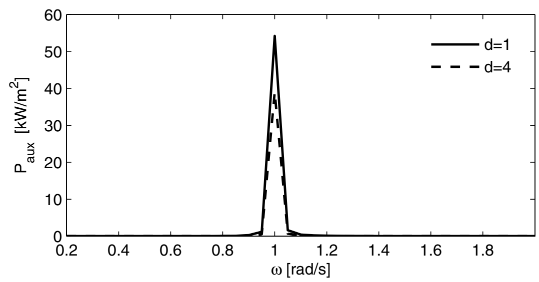


Fig. 5. Auxiliary power.

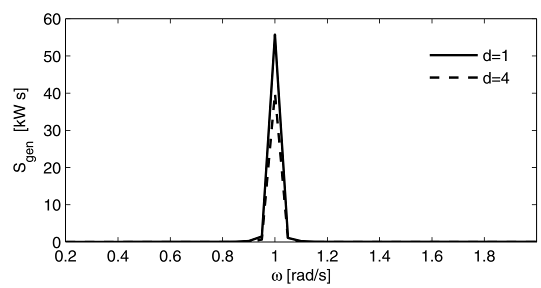


Fig. 6. Extracted power spectrum.

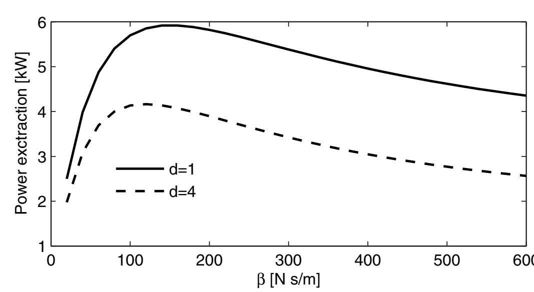


Fig. 7. Extracted power versus damping coefficient with JONSWAP spectrum having $H_{1/3} = 2[m]$ and $\omega_p = 1[rad/s]$.

Using the results obtained in the previous subsection, The power extraction from the SPA-OWC can be obtained. It is assumed that installation ocean environment follows a JONSWAP spectrum with peak frequency $\omega_p = 1$ $[rad/s]$ and the significant wave height $H_{1/3} = 2$ $[m]$ as shown in Fig. 4. The peak frequency is chosen to coincide with the resonance frequency of the SPA-OWC. By substituting hydrodynamic functions into (14), auxiliary powers with the different submerged depths can be obtained and are figured in Fig. 5, when the result for $d = 1[m]$ has the damping coefficient as $160[Ns/m]$ and for $d = 4[m]$ has the damping coefficient as $120[Ns/m]$. Both have the peak values at the resonance frequency $1[rad/s]$ and values are $5919[W/m^2]$ and $4165[W/m^2]$. From Figs. 4 and 5, the extracted power spectrum S_{gen} can be obtained which is shown in Fig. 6. Since the peak frequency of the JONSWAP spectrum was deliberately set to the resonance frequency, S_{gen} also has the peak value at the resonance frequency and values are $55.72[kWs]$ and $40.05[kWs]$. Finally, by integrating S_{gen} in the frequency domain, the extracted power can be achieved. Since its result is affected by the damping coefficient β, the calculation of the extracted power versus damping coefficient should be carried out and is shown in Fig. 7. The maximum extracted powers at $d = 1$ and 4 $[m]$ are about 5.9 $[kW]$ and 4.1 $[kW]$ with $\beta = 160$ $[Ns/m]$ and $\beta = 120$ $[Ns/m]$, respectively. When considering only the effect of excitation force, the extracted power at $d = 4$ $[m]$ should be less than 0.54 times of that at $d = 1$ $[m]$. However, only an 0.7 fold decrease was observed. It may be thought that the effect by reduction of radiation force increases the extracted power.

V. Conclusion

In this paper, a submerged point absorber using oscillating water column (SPA-OWC) was presented. Compared to floating point absorbers, the SPA-OWC is able to adjust its submergence depth. Accordingly, it can be applied even under the very harsh ocean environment. Furthermore, since it does not use mechanical moving parts, it has a light weight and simple structure. We analyzed its operation principle via LWT, carried out the simulation using AQWA, and analyzed its performance. The result from the simulation remains to be verified by experimental work. Future work will be focused on experimental setups and further simulations of the many parameters involved in the design and physical behavior. Although these presented the concept and simulation of the SPA-OWC look in the abstract, this work is only expected to serve as a starting point toward a future real device.

Acknowledgment

This work was supported by the New & Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning(20103020070070) grant funded by the Korea government Ministry of Knowledge Economy.

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