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Original Paper

Hydraulic Model Test of a Floating Wave Energy Converter with a Cross-flow Turbine

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Abstract

Almost 70% of the earth is covered by the ocean. Extracting the power available in the ocean using a wave energy converter has been seen to be eco-friendly and renewable. This study focuses on developing a method for analyzing a wave energy device that uses a cross-flow turbine. The motion of the ocean wave causes an internal bi-directional flow of water and the cross-flow turbine is able to rotate in one direction. This device is considered of double-hull structure, and because of this structure, sea water does not come into contact with theturbine. Due to this, the problem of befouling on the turbine is avoided. This study shows specific relationship for wave length and several motions.

Keywords: Ocean energy, Floating wave energy converter(WEC), Cross-flow turbine, Power take-off system(PTO), Double-hull structure, Hydraulic model test.

1. Introduction

Interest in renewable energy sources such as solar energy, hydropower, ocean energy, geothermal energy etc. have been increasing in the last decade. Countries with access to oceans can harness the ocean energy such as wave energy or tidal energy [1, 2, 3, 4]. Wave energy is usually harnessed using a wave energy convertor and these convertors have diverse methods of energy conversion [5]. Different devices can be classified by their operational methods [6,7].

With the numerous methods for wave energy conversion, McCormick and Stigter [8, 9] have suggested some basic concepts for a wave energy converter with the ability to use power take-off (PTO) system.

This study was carried out on a floating type double-hull device which uses the oscillating motion of the waves to pitch up and down and drives the internal water through a cross flow turbine. The main advantage of this device is the use of fresh water within the structure which prevents bio-fouling of the turbine [10]. It is possible to install this device offshore where more wave energy is available than at the coastal regions [11, 12]. In addition, the internal structure allows the cross-flow turbine to rotate in a single direction even in a bi-directional flow [10, 13, 14]. The turbine design and optimization was carried out by Choi et al [15] and the dimensions of the turbine used in this study are shown in Fig.1.

This study aims on finding optimum wave states for device operation for sea trials. For the sea trials, finding the parameters such as wave length, water depth, wave period and wave height for optimum performance is important as device performance can vary significantly in different wave states. A study done by Choi et al [16] focuses on the importance of wave states especially with water depth, using directly driven turbine for WEC. The hydraulic model tests are carried out on a scaled down model of the device in a wave tank in Korea Maritime and Ocean University.

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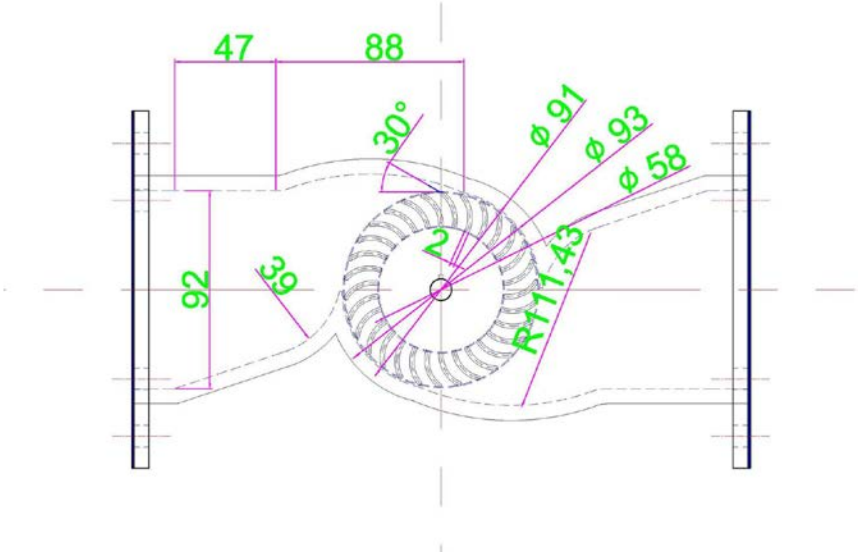

Fig. 1 Side view of the nozzle and cross-flow turbine with dimensions in millimetre (mm) [16]

2. Experimental procedure

The experiments were carried out in a 7.3 m long, 1 m wide and 1.8 m deep wave tank. The wave tank has a piston type wave maker which is controlled via a computer that can generate unidirectional waves with a maximum height of 0.3 m. Since the wave-maker is not provided with systems to absorb the reflected waves, dissipation is performed by wave absorber installed behind the device. Fig. 2 shows top and right side elevation view of the hydraulic model test within the wave tank and location of test model.

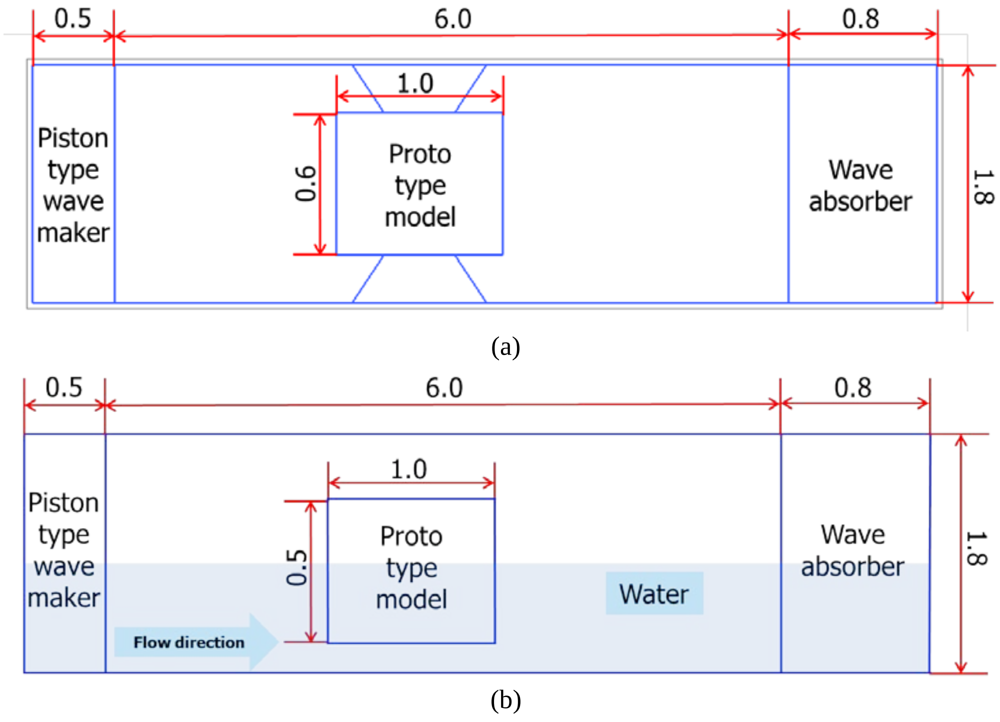

Fig. 2 Plan (a) and right side elevation (b) view of the wave energy converter and location of test device in the wave tank. Units are in metre (m).

Several sensors are used to monitor the performance characteristics for WEC and measure the wave characteristics. An Ultrasonic sensor (Ultralab® ULS Advanced) with a measurement range from 200 mm to 1200 mm and resolution of ±0.36 mm is installed 1. 5m front of the WEC to measure the wave height. To measure the pitch and heaving motion of the WEC, a 6 axis gyro sensor (CruizCore® XA330) with a resolution of ±0.05 º is mounted on to the top of the device. Fig. 3 shows the experimental setup of WEC and location of the sensors. Data from the sensors were recorded into a data logger.

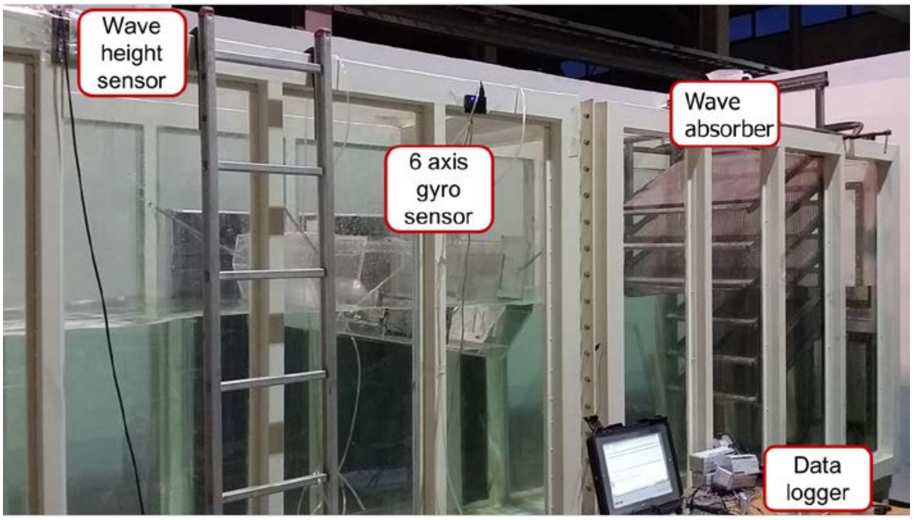

Fig. 3 Overall view of experimental setup

The acrylic model of the WEC device with the cross-flow turbine is shown in Fig.4. The WEC device is a 1/6th scale model that was 1m long and 0.6 m wide. The outer and inner diameter of the turbine in the device was 91 mm and 60 mm respectively. There were a total of 24 blades used in the turbine and is shown in Fig. 5.

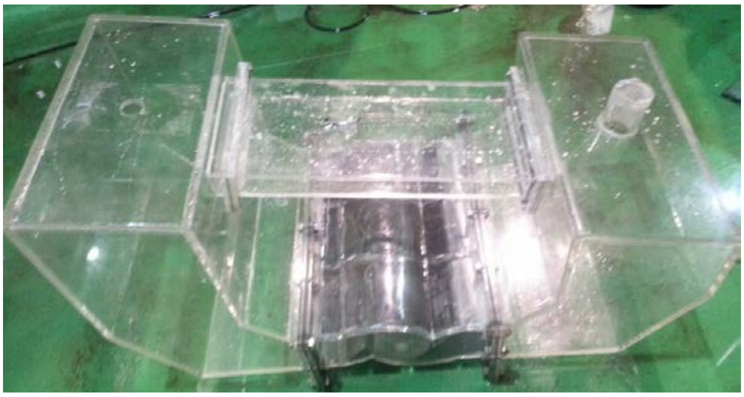

Fig. 4 Small scale acrylic model of WEC

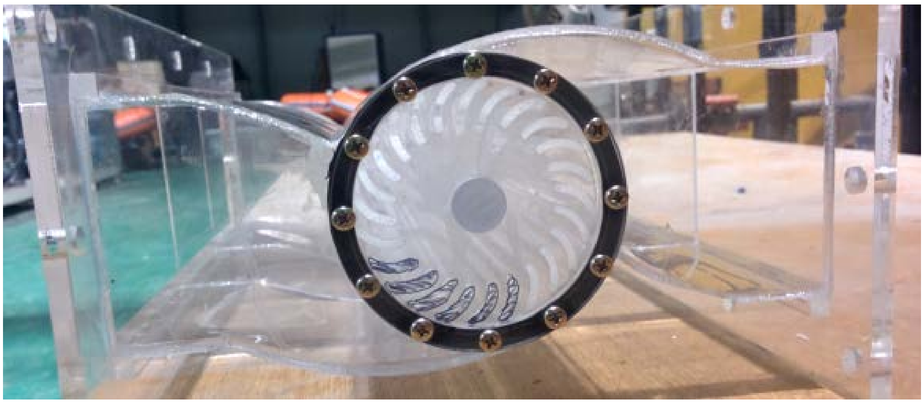

Fig. 5 Acrylic nozzle section and cross-flow turbine with 24 blades

All tests are performed in a water depth of 1m and monochromatic waves were generated in order to determine the general operating range of the device. The monochromatic waves were generated and measured for 1 minute. The model was initially tested in 42 different sets of wave states (7 different wave lengths and 6 different heights) in order to analyze its motion characteristics and turbine response. These wavelengths and heights are listed in Table 1.Then from the data set obtained; a few values of wave length and wave height were selected for further tests of the device in detail.

Table 1 Wave length and wave height of tested wave states

Wave state	1	2	3	4	5	6	7
Wave length, λ [m]	1.4	1.7	2.0	2.3	2.6	3.0	3.3
Waveheight, Hs [m]	0.01	0.04	0.07	0.1	0.13	0.16	

The wave length of the wave primarily depends on the period and height as given by relation in equation 1[5].

$$\lambda = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi H_w}{\lambda}\right) \tag{1}$$

Where, "g" is acceleration due to gravity, "T" is the wave period and "H_w" is the water depth.

3. Result

One of objectives of the test was to determine the dependency of the device on the wave height and wave length. In order to evaluate this, an analysis of the performance of the model was done for various wave lengths. These tests were carried out in regular waves with no load condition.

Fig. 6 shows the results of the test which shows the various wave lengths (λ) tested at different wave heights (H_s) and the turbine speed (N) obtained in those conditions. The speed of the turbine was seen to vary proportionally to the wave length; the increment in wave length produced corresponding increment in values of turbine speed. The maximum value of turbine speed was 83 RPM at a wave height of 0.07 m and wave length of 2.6 m. At the largest wave length of 3.3m, the highest speed of the turbine obtained was 38 RPM at a wave height of 0.13 m.

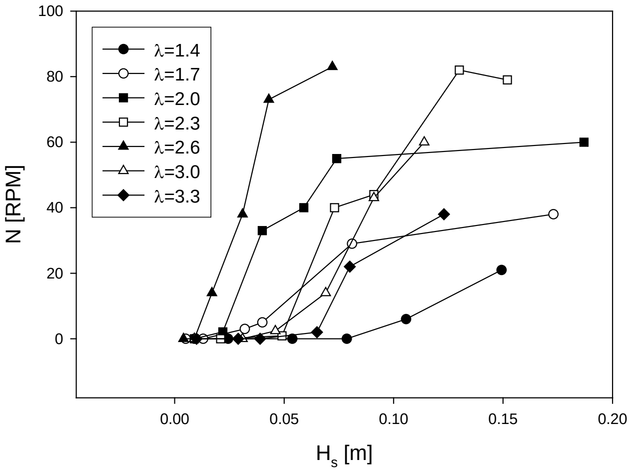

Fig. 6 Plot of speed of the turbine versus wave height for different values of wave length.

The left graph in Fig.7 shows the WEC pitching and heaving amplitude versus time at a wave length of 1.4 m and wave height of 0.08 m. The graph on the right in Fig.7 shows the plot of WEC's pitching and heaving amplitude versus time at wave length 2.6m and wave height of 0.07m. In Fig. 7 (left), the range of pitching degree is 9.5 º but the heaving amplitude is significantly lower than the pitching amplitude. At this condition, the rotational speed of the turbine was 0 RPM. On the other hand, in Fig.7 (right) the range of pitching amplitude was 22.5 º and the heaving amplitude is also similar. But, the rotational speed of the turbine obtained at this condition was 83 RPM.

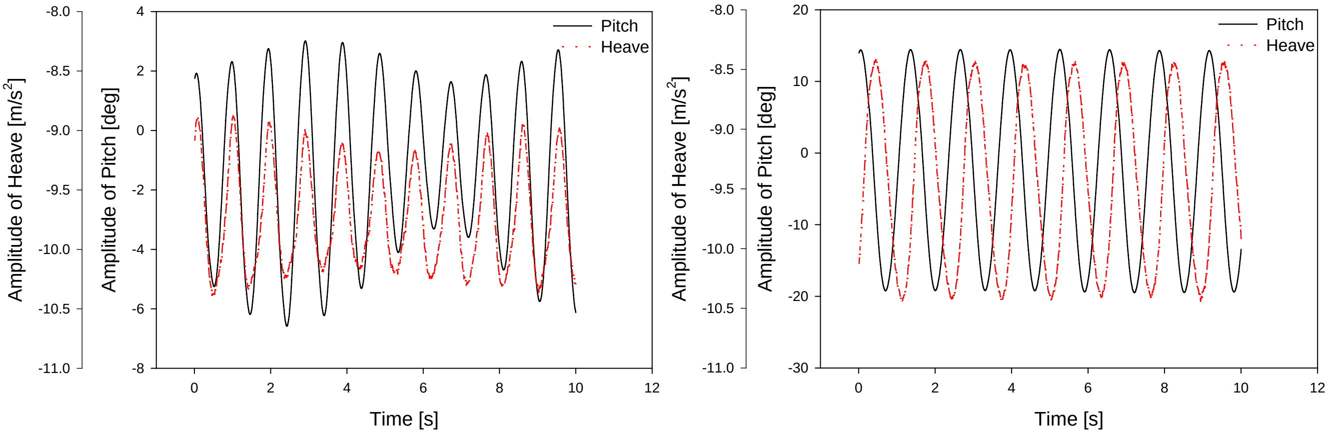

Fig. 7 Plot of pitching amplitude and heaving amplitude of device versus time at a wave height (H_s) = 0.08m and wave length (λ) =1.4m and the turbine speed (N) = 0 RPM (left) and at H_s=0.07m, λ =2.6m and N=83 RPM (right)

The pitch of the WEC is the rotation of the device about an axis through its center of gravity at certain range of angle. While the heaving motion of the WEC is the vertical movement of the device along an axis perpendicular to the axis through the center of gravity. A floating system will have either a natural heaving period or a natural pitching period or both if the float is unconstrained. The wave energy conversion is at a maximum when one or more of the natural frequencies resonate with either the highest energy wave in a wind generated sea. As this device has been designed to resonate with the natural pitching frequency; the heaving frequency produced in the system is seen as disturbance to the internal water flow and decrease the conversion efficiency [17]. Thus, having higher amplitude of pitching in the device means more energy conversion can occur while higher amplitude of heaving results in a larger reduction in energy conversion.

Fig. 8 shows the graphs comparing the pitching (left) and heaving (right) amplitudes of the device at wave lengths (λ) of 2.3 m and 2.6 m. When compared, the graphs show that the pitching amplitude of the device at a wave length of 2.6 m is higher than 2.3 m. The speed of the turbine obtained was also higher; 83 RPM at a wave length of 2.6m compared to 40 RPM at a wavelength of 2.3m. From Fig. 8 (right), the heaving amplitude is similar for both wave lengths although it is slightly higher at λ=2.6m. In a similar manner, the pitching amplitude at λ=2.6m is higher. From these graphs, even though the disturbance generated by the heaving motion was high the speed of the turbine obtained was high.

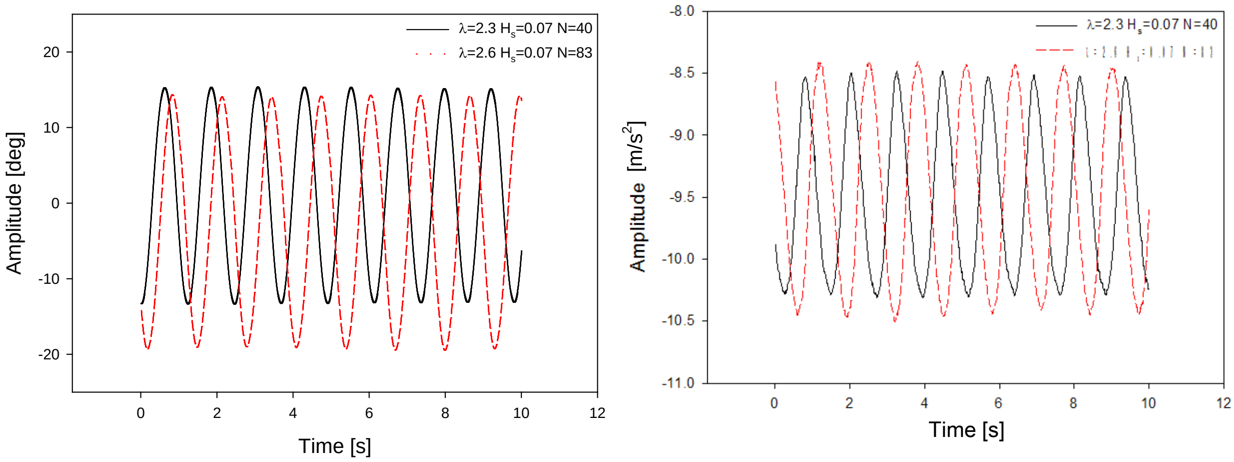

Fig. 8 Comparison of pitching amplitude (left) and heaving amplitude (right) plotted versus time for wave lengths of 2.3 m and 2.6 m

From these results, it is seen that the optimal wave length for this device is 2.6m. Equation 1 is used to calculate the different water depths and wave periods of the optimum wave length.

Fig. 11 shows the plot of time period versus various values of water depth for at a wave length, 2.6 m.

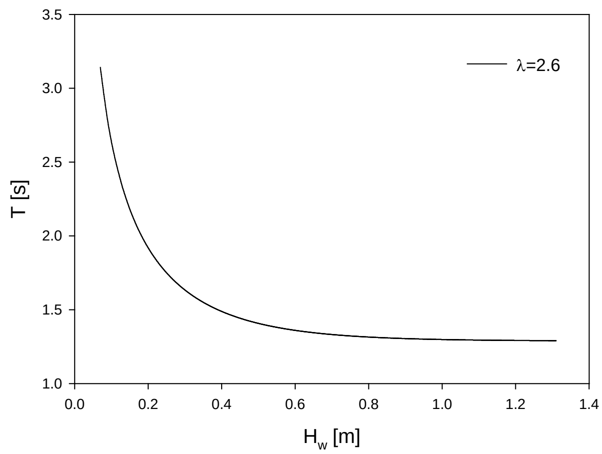

Fig. 11 Calculation for water depth and wave period

The wave climate near the coast of Korea Maritime and Ocean University was surveyed using a wave height sensor. Table 2 shows the summary data obtained during the survey.

Table 2 In-situ sea state distribution data near Korea Maritime and Ocean University

Wave state		1	2	3	4	5
Site	Water depth, H_w[m]	10	9	8	7	6
	Wave period, T [s]	7	6	5	4	3

Using the scale factor and results from the wave experiments, the optimum lengths of a full scale device was calculated according to different deployment site conditions and presented in Table 3. For example, for a site specified as 10m deep and a 7 second wave period, the optimal length of the WEC device is 23.1m. Similarly, at a depth of 6m and a wave period of 3 seconds, the device length calculated is 5.3m. This method can be used to calculate the device length for a specific site.

However, this study did not take into account the mooring system on the full scale device. This will be considered in future studies.

Table 3 Optimum length of WEC device for operation at different wave conditions

Wave state		Water depth, H_w[m]				
		10	9	8	7	6
Wave period, T [s]	7	23.1	22.2	21.2	20.2	19.0
	6	18.6	18.1	17.4	16.6	15.7
	5	14.1	13.8	13.4	13.0	12.4
	4	9.5	9.4	9.3	9.2	8.9
	3	5.6	5.4	5.4	5.4	5.3

4. Conclusion

A wave energy convertor that uses the pitching motion of the waves for energy conversion is tested in wave tank. Under no load conditions, the test was carried out under different wave lengths and wave heights. Using the turbine rotational speed as a basis for performance, a wave of 2.6m was found to be the optimum for operation.

Using the experiment results and site data obtained near the university, different device lengths were calculated according different specified wave conditions. This type of calculation can be used to calculate the device length for different deployment sites. In future studies, the effect of the mooring system will be accounted for.

Acknowledgments

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Nomenclature

H_s	Wave height [m]	T	Wave period [s]
N	Revolution per minute [RPM]	H_w	Water depth [m]
λ	Wave length [m]		

References

[1] International Energy Agency, 2010, Energy technology perspectives 2010: scenarios and strategies to 2050. OECD/IEA 2010.
[2] Ingram, D.M., Villate, J.L., Abonnel, C. and Johnstone, C., 2008, "The Development of Protocols for Equitable Testing and Evaluation in Ocean Energy-A Three-Year Strategy," International Journal of Fluid Machinery and Systems, Vol. 1, No. 1, pp.33-37.
[3] Nik, W. B. W., Muzathik, A. M., Samo, K. B. and Ibrahim, M. Z., 2009, "A Review of Ocean Wave Power Extraction; the primary interface," International Journal of Fluid Machinery and Systems, Vol. 2, No. 2, pp.156-164.
[4] Kim, J.H., Heo, M.W., Cha, K.H., Kim, K.Y., Tac, S.W., Cho, Y., Hwang, J.C. and Collins, M., 2012, "Effect of Intake Vortex Occurance on the Performance of an Axial Hydraulic Turbine in Sihwa-Lake Tidal Power Plant, Korea," International Journal of Fluid Machinery and Systems, Vol. 5, No. 4, pp.174-179.
[5] Choi, Y. D. and Lee, Y. H., 2007, "Summery of Wave Power and Present condition of Research and development," The Korean Solar Energy Society, Vol.6, No.1, pp. 17-24.
[6] Falcao, A. F. O., 2010, "Wave energy utilization: A review of the technologies," Renewable and Sustainable Energy Reviews Vol.14, pp. 899-918.
[7] Brooke, J., 2003, "Wave energy conversion," Oxford: Elsevier Science Ltd, Vol. 6.
[8] McCormick, M.E., 2007, "Ocean wave energy conversion," 1st edition, New York: Dover Publications.
[9] Stigter, C., 1966, "The performance of U Tanks as a passive anti-rolling device," The Royal Institute of Naval Architects, ISP-13 (144), pp. 249-275.
[10] Kim, B.H., Wata, J., Zullah, M.A., Ahmed, M.R. and Lee, Y.H., 2015, "Numerical and experimental studies on the PTO system of a novel floating wave energy converter," Renewable Energy, Vol. 72, pp. 111-121.
[11] Korde, U.A., 1999, "On providing a reaction for efficient wave energy absorption by floating devices," Ocean Research, Vol. 21, No. 5, pp. 235-248.
[12] Twidell, J. and Weir A.D., 2006, "Renewable energy resources," 2nd edition, New York: Taylor and Francis
[13] Faizal, M., Ahmed, M.R. and Lee, Y.H., 2014, "A design outline for floating point absorber wave energy converter," Hindawi, 1-18.
[14] Kim, B.H., Wata J., Zullah M.A. and Lee, Y.H., 2013, "Performance Study on Floating Wave Energy Converter Model by Experimental and CFD Methods," European Wave and Tidal Energy Conference Series 2013, pp. 1-9.
[15] Choi, Y.D., Kim, C.G., Kim, Y.T., Song, J.I. and Lee, Y.H., 2010, "A performance study on a direct drive hydro turbine for wave energy converter," Journal of Mechanical Science and Technology, vol.24, pp. 1-10.
[16] Choi, Y.D., Kim, C.G. and Lee, Y.H., 2009, "Effect of wave conditions on the performance and internal flow of a direct drive turbine," Journal of Mechanical Science and Technology, vol.23, pp. 1693-1701.
[17] Nuno, F., and Joao, P., 2012, "Numerical Modelling of a Wave Energy Converter based on U-Shaped Interior Oscillating Water Column," Ocean Research, pp. 1-14.