The Design of Physical Model and Preparation of Experimental Study on Articulated Tower – Ocean Wave Energy Converter (AT-OWEC)

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Abstract: A new concept has been proposed to contribute in the development of national ocean renewable energy program by the adoption of articulated tower structure for harvesting the ocean wave energy. Therefore the new concept is designated as the articulated tower for ocean wave energy converter, abbreviated as AT-OWEC. In the meantime, the establishment of AT-OWEC has come to the stage of the initial physical modelling and preparation of experimental study. This is commenced by the design of AT-OWEC main structure physical model by referring to the full scale structure, involving the rules of geometrical, kinematical and dynamical similarities. Next is the design of instrumentation for motion data measurement and acquisition, including necessary calibrations. This is followed by the plan of experimental work at the hydrodynamics laboratory and the expected data to be gathered. Discussion will then be concluded by putting forward results of numerical modelling on AT-OWEC dynamic behaviours prepared for comparison with future experimental data.

1 INTRODUCTION

The Director of Various New Energy and Renewable Energy (VNERE), Ministry of Energy and Mineral Resources (MoEMR), Republic of Indonesia describes the current condition of national energy fulfillment in Indonesia eventually is still dominated by the fossil energy (Direktur AEBET, 2013). This comprises of oil 46.77%, coal 23.91% and natural gas 24.29%, therefore in total the proportion is as much as 94.97%. The rest is supplied by new and renewable energy (NRE), which contribute only in the order of 5.03%. This condition is recognized by various parties as a matter of great concern, especially given the declining national oil reserves. Although Budiman et al. (Budiman, et al., 2014) is still advising to increase the utilization of national natural gas and coal potentials, efforts should be directed towards the development of NRE.

The Director of VNERE (Direktur AEBET, 2013) underlines that according to the Presidential Regulation No. 5 of 2006 on National Energy Policy the NRE development program has become a national priority. In the presidential decree, it has been declared that by 2025 the energy composition should bring down the contribution of petroleum to 20%, increasing natural gas to 30%, increasing coal to 33%, and increasing NRE 17%. The current NRE variability in Indonesia already includes globally developed types, including geothermal, microhydro, and biomass. By 2025 the national NRE variability will be pushed further, namely geothermal 5%, biomass 5%, liquid coal 2%, and other NRE up to 5%. Other NRE types here include nuclear, solar, wind, and others. Included in other components of NRE is of course ocean energy.

Ocean energy is not quite developed and operated globally, especially in Indonesia. The main obstacle to the limited development of ocean energy, according to Srikanth (Srikanth, 2014), is that technology is not yet mature and stable, the cost is

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still relatively high and far from economies of scale, only in certain locations and often non-mobile, etc. Considering this, efforts are being made at various universities and research institutions to develop a relatively low cost ocean energy conversion technology.

To meet the aforementioned challenges, early in 2017 a fundamental research on ocean energy conversion has been initiated at the Laboratory of Ocean Structure Hydrodynamics (Lab. OSH), Department of Ocean Engineering (DOE), Faculty of Marine Technology (FMT), Surabaya Institute of Technology (ITS), Surabaya, Indonesia. As described by Djatmiko et al. (Djatmiko, et al., 2017) the research was established by the adoption of the well known articulated tower (AT) platform technology to be implemented as an ocean wave energy converter (OWEC) system. Therefore the new concept is designated as the articulated tower for ocean wave energy converter, or shortly referred to as AT-OWEC.

2 THE CONCEPT OF AT-OWEC SYSTEM

Detail description on the concept development of AT-OWEC system has been put forward by Djatmiko et al. (2017). In principle the system adopts the AT platform technology widely used in offshore oil and gas industry since early 1970s as the primary dynamic structure. The common AT design is preserved with high stability to assure the safety and effective operation of offshore oil and gas activities (Chakrabarti & Cotter, 1980; Halvacioglu & Incecik, 1988; Bar-Avi & Benaroya, 1996; Chakrabarti, 2001; Murtejo, et. al., 2005; Atkins, 2017). However for the current AT-OWEC design, AT as the main component is designed to be unstable by configuring the buoyancy chamber in such a way the center of gravity is located well above the structure. Like so it could be expected AT to endure relatively larger motion when excited by the wave action. Further, the motion of the AT-OWEC main structure is restrained in 1-DOF rotational pitch mode by connecting the base of the supporting pole to a roller joint in the base template at seabed.

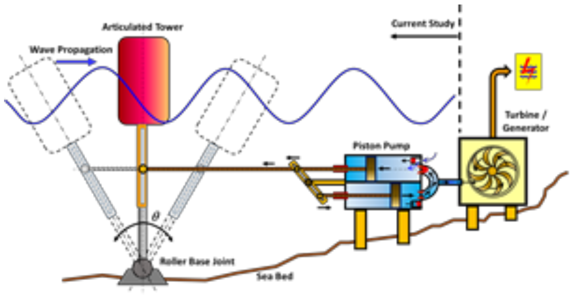

Figure 1: Schematic illustration of AT-OWEC system.

The large rotational pitch motion is then transformed into translational motion via an axis arm hinges connected to a double action piston pump (DAPP) with single pivot, following the idea from Choy *(Choy, 2012)*. The DAPP is designed with a single outlet, positioned in the water with an inlet on each tube, in the plane of pitch motion. The design of the axis arm hinges in such a way will be able to transform the rotational motion into translational motion of the shaft arm, and further the piston movement. Positive or negative rotational motion will induce the translational motion of each piston in a double tube in the opposite direction. That way the AT-OWEC rotational motion is positive and negative will still produce the water jets out of the pump. The water jet generated by the DAPP is directed drive a water turbine and further generate electrical power, as shown in Figure 1.

3 THE DESIGN OF AT-OWEC PHYSICAL MODEL

The design of full scale AT-OWEC has been established as explained in the research report (Djtamiko, et al., 2017). In this respect parametric study were carried out on circular and elliptical AT buoyancy chamber, each with 9 combinations of diameter *Dh* and height *Hh*. Hence overall there are 18 variations of AT-OWEC. For the purposes of discussions in this paper only one variation is selected, namely with *Dh* = 4.0 m and *Hh* = 5.5 m, fabricated with steel material of 15.0 mm in thickness. This structure is hypothetically to be operated at the sea water depth variations of 10.0 m, 15.0 m, and 20.0 m.

The design of the physical model should meet three similarity laws, namely: i) geometric similarity, ii) kinematic similarity, and iii) (hydro)-dynamic similarity (Djatmiko, 1987; Chakrabarti, 1998; Grinius, 2006; Chanson, 2008; Munson, et. al., 2013).

Further, the design also covers the material selection, as well as structural components or scantlings. Specifially the design of AT-OWEC main structure is depicted in Figure 2.

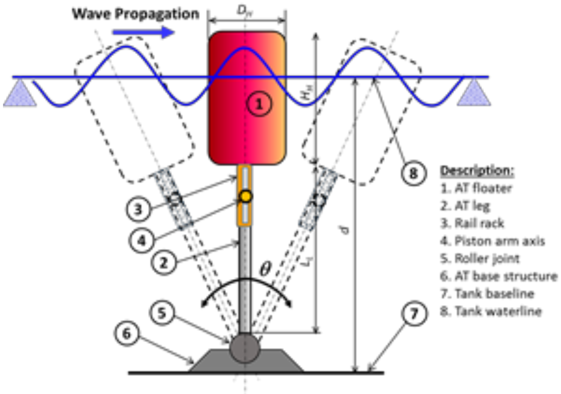

Figure 2: Basic configuration and components of AT-OWEC main structures.

In the design of AT-OWEC one primary consideration to be accounted for is the size of towing tank at Lab. OSH, which has a water depth d_b of 2.0 m. This water depth is then correlated to the case in the numerical study, where the system is to be operated at maximum water depth of 20.0 m. In this relation the scale factor of the model is then found to be 1 : 10 for the geometrical similarity, or λ = 10. Therefore, the model geometri will be made to have the size of $1/\lambda$ to the full scale. Furthermore, the extent of model's mass, mass moment of inertia for pitch motion, and the stiffness should comply with the dynamic similarity, and are governed by the scale of $1/\lambda^3$, $1/\lambda^5$, and $1/\lambda^4$ in relation the full scale.

For the kinematic similarity, the model should have a natural frequency comparable to the full scale. This is to be determined by the equivalency in the non-dimensional frequency ω' as given in the following equation:

$$\omega' = \frac{\omega}{\sqrt{g/L}} \qquad (1)$$

The variables in eq. (1) are, respectively, ω is the wave frequency, g is acceleration due to gravity, and L is length of the object. In the case of AT-OWEC L is equivalent to Dh.

Further the design taking also the stage of material selection to assure the model will meet the similarity lawas as described above. After some exploration it is then decided to select aluminum as the primary material for the buoyancy chamber. At this point the design of AT-OWEC physical model is concluded, as shown in Table 1, and ready for the construction.

Table 1: Data of AT-OWEC model main structure as function of water depth variations.

Diameter of buoyancy chamber Dh = 400.0 mm Height of buoyancy chamber Hh = 550.0 mm Aluminum plate thickness t = 4.0 mm					
Water Depth d (m)	Mass (kg)	Pitch Mass Moment of Inertia (kg.cm^2)	Pitch Stiffness (N.cm)	Pitch Natural Freq. (rad/sec)	Pitch Natural Period (sec)
1.0	11.02	5,111.8	20,873.0	2.021	3.11
1.5	11.02	13,188.7	33,635.0	1.597	3.93
2.0	11.02	25,237.9	45,366.0	1.341	4.68

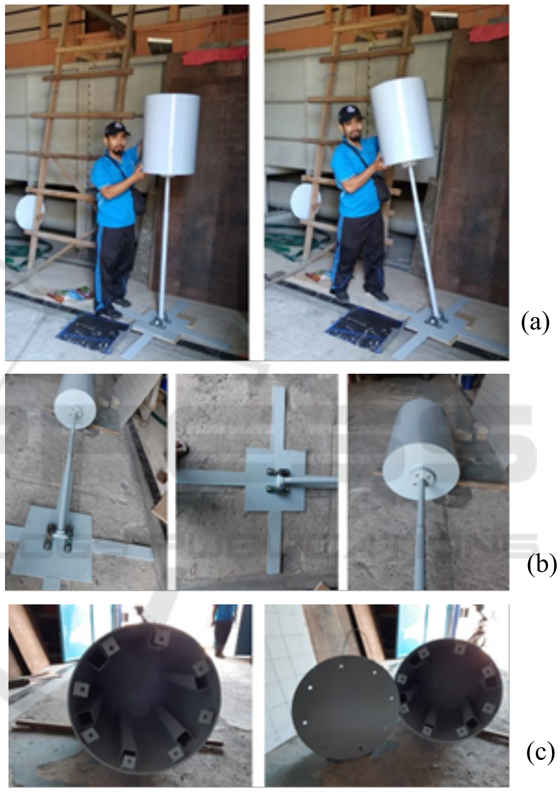

Figure 3: Physical model of AT-OWEC main structure.

The physical model has been constrcuted and its photos are displayed in Figure 3. In here, Figure 3a presents the AT-OWEC model in straight up and inclined positions, making use of the roller joint at the pole base. Model comprises three main components, i.e. cylindrical buoyancy chamber, supporting pole, and base template. Between the pole and cylinder, as revealed in Figure 3b, is furnished with bolted connector which could be released to take off the cylinder from the pole, and other cylinders of different sizes and configuration whenever available could then be fitted. Figure 3b also depicts the base template so designed to ease the installation of the structure on the towing tank base. At the center of the base template is located a roller joint as the rotational axis of the AT-OWEC. Figure 3c shows the internal space of the cylinder which is equipped with some vertical square tube which can be filled with solid counterweight to adjust the dynamical properties of the model. The upper part of the model equipped with the cover to assure the watertightness during the test is performed.

4 DESIGN AND ASSEMBLY OF TEST INSTRUMENTS

Experiments or test models are to be carried out primarily to measure the motion of the AT-OWEC structure when subjected to the excitation of regular wave loads in the towing tank. In this case the motion measuring instrumentation will be designed consisting of two types. First is the 3-axis accelero-gyro instrument or gyroscope, which functions to measure the model motion based on the acceleration of translational and rotational motions. The gyroscope instrument to be used is MPU 6050 GY87, capable of producing angle output formed by MPU 6050. In MPU 6050 there is an axis of orientation x, y and z, which will produce the respective angle of deviations. The magnitude of the angular deviation will be amplified and received by the Arduino UNO microcontroller and then be transferred to a laptop computer in digital quantities. The gyroscope sensor instrument, as in Figure 4 is placed at the top of the AT-OWEC cylinder cover.

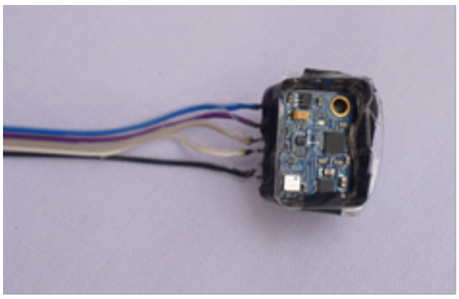

Figure 4: Gyroscope to measure the model pitch motion.

Secondly, as a checking instrument, visual tracer movements will be used in the form of target objects, namely two red plastic balls mounted with a support, and placed in two parallel upright positions at the top side of AT-OWEC floating cylinder, as can be seen in Figure 5. The target movement will be recorded by a video camera. Video recording can be downloaded by the appropriate software on a data processing computer, through digital image processing (DIP).

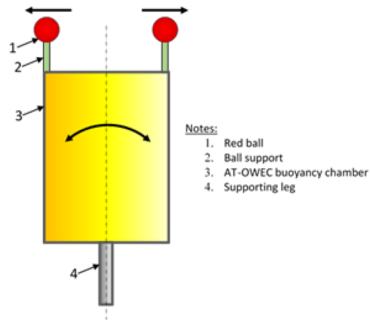

Figure 5: Positioning red balls as visual tracing target.

DIP is the processing of two-dimensional images by a computer device, which is the process of taking image attributes with input and output in the form of images. In this study DIP is used for the detection of objects in the video which is used to analyze the translational motion in x-direction or surge that occurs in the AT-OWEC model when afloats in the towing tank and is exposed to waves with a number of period variations. In the process of representation and modeling of an image, the quantity and character of the picture element (pixel) describe an object. Pixels are small units of dots that make up an image. Each pixel in the image stores the color information represented by the pixel. The number of pixels that make up an image depends on the resolution or density of the desired color. The DIP process here is done using a Logitech c270 webcam camera, as shown in Figure 6 which records video. Where from the video consists of many frames which are then processed using the help of visual basic c ++ software.

Figure 6: Digital camera and red ball visual tracing targets.

In addition to instrumentation for measuring the model structural motions, load cells are also made available in the test, as shown in Figure 7. These are utilized to measure the load acting on the pole of the structure.

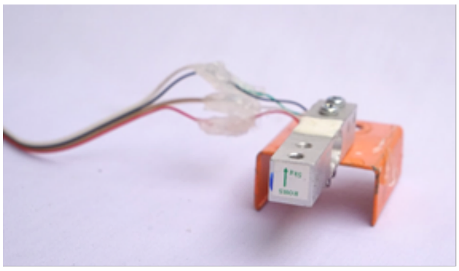

Figure 7: Load cell instrument to measure the load on AT-OWEC supporting pole.

The next instrument to be used in the test model are wave probes, which are devices to measure wave elevation. The wave probes used are three units over all, one is placed at a distance of about 3.0 m from the wave maker or wave generator, and the other two are positioned in the vicinity of the model. Thus, from the three wave probes, it can be checked if there is a significant change in the wave profile during one set of test is executed.

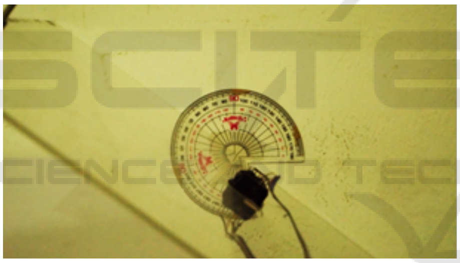

Figure 8: Calibration of gyroscope on swivel board with ruler arc.

Calibration on all measuring instruments were conducted to generate reference data to be inputted in the data acquisition system (DAS). Anytime the test is run and instruments measure the related variables to be transferred in the DAS, it will then be adjusted into the actual values of output data. An example of calibration is demonstarted for the case of gyroscope. As shown in Figure 8 it is performed with the aid of a swivel board equipped a ruler arc. The gyroscope is placed on the swivel board and then turned gradually from 0º up to 60º, at interval of 10º. The digital output of gyroscope is then correlated with the turning angle, as presented in Table 2. This is further used to plot a graphical correlation to derive the calibration equation as contained in Figure 9.

Table 2: Calibration data for gyroscope:

Anti-Clockwise		Clockwise	
Angle (deg)	Gyro Output (unit)	Angle (deg)	Gyro Output (unit)
-0º	-0.37	0º	0.60
-10º	-10.38	10º	10.20
-20º	-20.14	20º	20.42
-30º	-30.05	30º	30.75
-40º	-40.18	40º	40.44
-50º	-50.61	50º	50.05
-60º	-60.20	60º	60.30

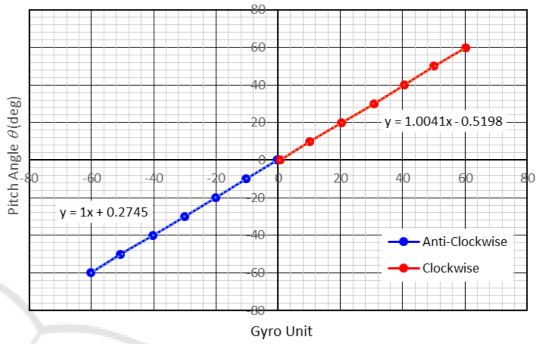

Figure 9: Calibration chart and equation for gyroscope.

5 DESIGN AND PREPARATION FA DATA ACQUISITION SYSTEM

Data acquisition system (DAS) is a series of measurement instruments, supporting instruments and collecting software and data recorders in a computer. In this study the DAS is arranged as shown in Figure 10. The first element is in the form of measurement instrumentation described in section 4, namely a gyroscope, a load cell and three wave probes.

The second element is a multi-channel amplifier, which functions to increase the voltage generated by the measuring instrument, which in this case is the load cell and wave probes. Voltage fluctuations that occur are derived from the help of resistors or capacitors that work on the instrument. For the purpose of transforming from voltage fluctuations into digital data, it is necessary to first calibrate related instruments. While the gyroscope does not require an amplifier. The third component is the micro-controller, which regulates signal fluctuations from direct measuring instruments and amplifiers.

From the micro-controller the electronic signal is transmitted to the micro-processor, as the fourth component. This equipment consists of digital circuits, registers, arithmetic logic processors, and sequential circuits. The role of microprocessors in the system is as a unit that controls the entire system work. Take instructions and data from memory, move data to and from memory, and send signals. Signal delivery from the microcomputer is done wirelessly through the help of Wi-Fi, as the fifth component. Finally the digital signal will be received by the computer as the sixth component.

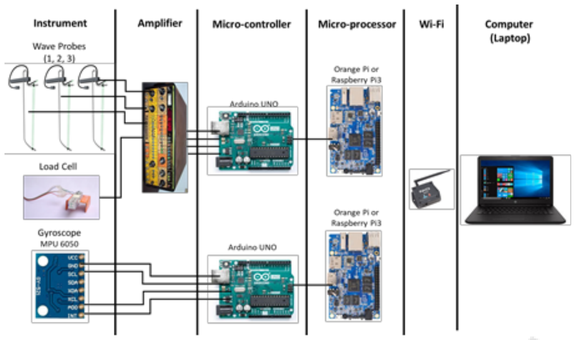

Figure 10: The general diagram of data acquisition system.

Inside the computer there is software that will pro-cess digital data coming from signal wave probes, gyro-scope, and visual tracer camera recordings. The raw digi-tal data from each of these equipment will be processed into real motion elevation data at any elapsed time, taking into account relevant calibration data.

6 PREPARATION OF HYDRODYNAMIC MODEL TESTING

Experimental study or hydrodynamic tests on the physical model of AT-OWEC will be carried out at the Lab. HBL, DOE - ITS, in a towing tank sized 50 m x 3 m x 2 m (LxBxd). This test tank is equipped with a wave generator of a flap type, which is driven by a hydraulic machine. Generated waves can be either regular or random. But in the present study regular waves only will be used.

Diagramatically the towing tank can be explained by referring to Figure 11. At the right end there is a small pool or pit, as a place to prepare the model before the test. Right on the lip of the small tank, a wave absorber is installed. At the left end of the pool is a hydraulic machine positioned to drive the wave generator. In this study the AT-OWEC model was installed at a position of about 25.0 m from the wave generator. Regular waves will propagate from the generator towards the wave absorber. With the absorber, there is a possibility to restraint the emergence of a reflected wave from the right side, which is likely to disrupt the generated wave profile.

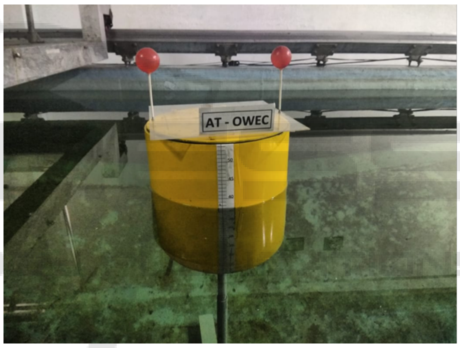

Figure 12: AT-OWEC model installed in the towing tank.

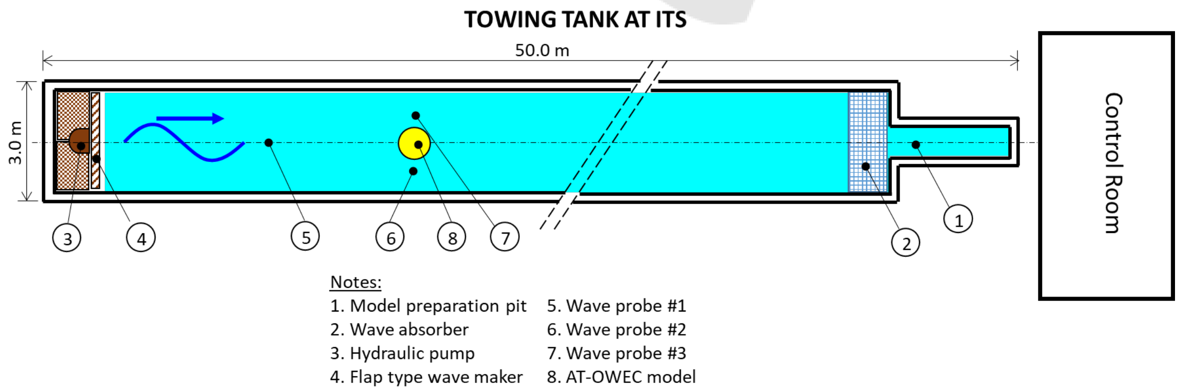

Figure 11: Towing tank and the positioning of AT-OWEC model.

The AT-OWEC model installed in the towing tank is as shown in Figure 12. Wave elevations will be detected by the first wave measuring instrument or wave probe (WP # 1) positioned in the center axis of the pull pool at a distance of 15.0 m from the plant.

With this position allows the measured waveform to show a profile that is not disturbed by the presence of objects in the water. Two other wave probes, namely WP # 2 and WP # 3 are placed on the transverse sides of the model at a distance of about 0.75 m. Both WPs will record wave patterns that may be deformed by the presence of the model.

The test will be carried out by generating waves, measuring 5.0 cm high or 2.5 cm amplitude. The wave period is varied from 1.0 sec to 8.0 sec, where between 1.0 and 5.0 sec the increase interval is 0.5 sec, while between 5.0 sec and 8.0 sec the increase interval is set to 1.0 sec. Data test recording will be carried out with a sample density or sampling rate of 10 Hz, or 10 samples per second. Thus it is believed that it will be able to provide a fairly smooth elevation curve.

7 NUMERICAL PREDICTION OF AT-OWEC MOTIONS

The beginning of this study has begun with numerical modeling of the main structural variants of AT-OWEC measuring the diameter and height of the buoyancy chamber, respectively, *Dh* = 4.0 m and *Hh* = 5.5 m, notionally to be operated in three variations of sea depth *d* of 10.0 m, 15.0 m and 20.0 m. At this stage the structure is assumed to be fabricated with steel material. The choice of this variant is done with consideration to get a system that has a larger movement. The main data of the variants reviewed, including mass, moment of inertia, mass of pitch movement, stiffness of pitch movement and natural frequency of pitch movement as a function of water depth *d* are as shown in Table 3. It is obvious when comparing the data in Table 3 and those in Table 1, although the units are different but the values of mass, mass moment of inertia, as well as stiffness are quite similar, i.e. in the order multiplication of $\lambda = 10$. The differences are also notable for the case of pitch natural frequencies and periods, due to the scaling as described in eq. (1).

Table 3: Data of full scale AT-OWEC main structure as function of water depth variations.

Diameter of buoyancy chamber *Dh* = 4.0 m Height of buoyancy chamber *Hh* = 5.5 m Aluminum plate thickness *t* = 15.0 mm					
Water Depth *d* (m)	Mass (ton)	Pitch Mass Moment of Inertia (ton.m^2)	Pitch Stiffness (MN.m)	Pitch Natural Freq. (rad/sec)	Pitch Natural Period (sec)
10.0	11.02	5,111.8	2,087.3	0.639	9.83
15.0	11.02	13,188.7	3,363.5	0.505	12.43
20.0	11.02	25,237.9	4,536.6	0.424	14.81

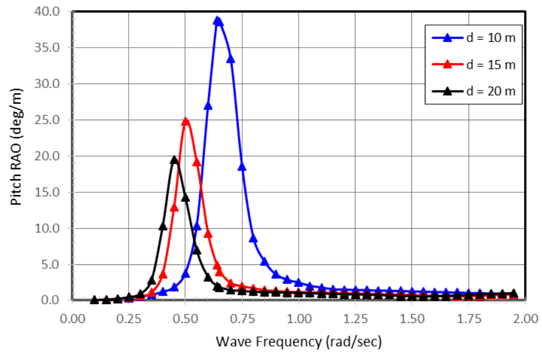

Figure 13: Results of numerical prediction on Pitch RAO of AT-OWEC sized Dh = 4.0 m and Hh = 5.5 m at three water depth variations.

Numerical modelling of AT-OWC pitch motion has been carried out using the software based on 3-D diffraction theory. Mathematical formulation of dynamic behaviour was developed with the implementation of pulsating-source theory distributed on the panels enclosing the buoyancy chamber, as described in the references (Murtejo, et. al., 2005; Atkins, 2017; Choy, 2012; Djatmiko et. at., 2017). With the input data of the structure in Table 3 the modelling is executed for variations in the regular wave frequency between 0.2 up to 2.0 rad / sec.

Output data from running the software in the form of AT-OWEC RAO pitch motion are as presented in Figure 13. It is interesting to observe this graph, where the largest response occurs when AT-OWEC is operated at a depth of *d* = 10.0 m, with the peak reaching around 38.0 deg/m. The area under the curve for this case is also quite large, thus indicating the capacity to absorb relatively large wave energy. When the operating depth rose to 15.0 m and 20.0 m apparently the motion intensity decreased, respectively, only reaching around 25.0 deg/m and 20.0 deg/m. As a consequence the area under the curve also decreases. This means that there will not be enough wave energy that will be absorbed. Especially if considering the occurrence of waves with large periods, above 12.0 seconds, the number of occurrences is relatively rare.

The numerical modelling results so presented are prepared for a comparative study with the results of the AT-OWEC model test, which will be implemented in the near future. In due course the results of the comparative study will be published in the appropriate dissemination forum or scientific journal.

8 CONCLUSIONS

This paper presents a stage in the development of AT-OWEC research, which involves the preparation of physical test models at the Laboratory of Ocean Structure Hydrodynamics, DOE - ITS. A number of important aspects that have been explained can further be summarized as follows:

- The AT-OWEC physical model measures 1 : 10 to the full scale, sized *Dh* = 400 mm and *Hh* = 550 mm, made of aluminum material, and has been designed to meet geometric, kinematic and dynamic similarities;
- The pitch motion measurement will be carried out utilizing the gyroscope as primary instrument, assisted by checking the target visual tracing recorded through a digital camera;
- Data acquisition system has been prepared with appropriate tools to produce outputs that take into account the appropriate calibration factors;

The results of numerical modelling of pitch motions have been prepared as data for comparative studies with the results of the test model, which will be implemented in the near future.

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