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Experimental Evaluation of IRWEC1, a Novel Offshore Wave Energy Converter

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ABSTRACT

This paper describes the innovative offshore point-absorber wave energy converter (WEC), IRWEC1, under development by the Hydrodynamics, Acoustics and Marine propulsion Group at Babol Noshirvani University of Technology. Totally enclosed in an outer shell, with no external moving parts, IRWEC1 is completely sealed which make it a robust and trustable system. Important motion for this WEC is the pitch motion, so, a pendulum is designed for transferring this motion to the PTO. In this paper, the WEC is evaluated for a wide range of waves in the wave tank. The wave characteristics are presented by which the system had appropriate pitch motion and acceptable extracted electrical energy.

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1. INTRODUCTION

Energies extracted from the ocean waves around the world are acknowledged as clean, natural, abundant and renewable. These renewable resources do not have any environmental pollution and will not lead to increase in the rate of global warming. Ocean waves have several advantages for using as a renewable energy production method; they are frequent, periodic, and predictable. Possibility of converting wave energy into usable energy has been an inspiration to many inventors and researchers [1]. By 1980, more than a thousand patents were registered in this area and since then the number has increased considerably [2].

In the leading countries, with respect to wave energy technologies, preliminary studies were developed for purpose of exploring wave energy resources. According to the literature, the majority of works are done with respect to the characteristic of a specified sea or region; on this basis in recent years, many seas around the world have been studied by researchers [3-7]. However, the Caspian Sea with having suitable energy level did not gain a lot of attentions. In the current article, the Caspian Sea is introduced briefly and wave energy potential near the coast of northern Iran is investigated.

In 2014, a comprehensive study was done by Alamian et al. [8] on the proper wave energy converters for extracting energy from the Caspian Sea waves. Their results indicated that a point absorber WEC with dominant oscillations in the pitch direction is the most suitable type of WEC for operating in the Caspian Sea. McCabe et al. in 2006, explored the development of PS Frog Mk 5 WEC made at Lancaster University [9]. This WEC consists of a large buoyant paddle with an integral ballasted 'handle' hanging below it. The waves act on the blade of the paddle and the ballast beneath provides the necessary reaction. When the WEC is pitching, power is extracted by partially resisting the sliding of a power-take-off mass, which moves in guides above sea level. It totally enclosed in a steel hull, with no external moving parts.

In the same year, Babarit et al. presented a new point absorber WEC, known as SEAREV [10]. SEAREV is a floating device enclosing a heavy horizontal axis wheel serving as an internal gravity reference. The center of gravity of the wheel being off-centered, this component

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behaves mechanically like pendulum. Two major advantages of this arrangement are that, firstly: all the moving parts are sheltered from the action of the sea inside a closed, waterproof shell; and secondly that the choice of a wheel working as a pendulum involves neither end stop nor any security system limiting the stroke. Later, Bracco et al. designed a 1:45 scaled WEC device, so called ISWEC, with rated power of 2.2 W and performed several tank tests with a simplified plain float to verify the actual prototype power capabilities [11]. ISWEC is a system using the gyroscopic reactions provided from a spinning flywheel to extract power. The flywheel works inside a sealed floating body in order to be protected from the outer environment and grant a reliable and durable operation.

The WEC, used in the current article, like the other three WECs mentioned above is placed in an outer shell for complete sealing. Its mechanical system consists of a pendulum and a power take-off (PTO) system. The working principles of this WEC are very close to the one explained for the SEAREV; however, the PTO which is used in this system is completely altered by applying a chain-and-gear system. The IRWEC1 and its PTO system are explained in detail in section 3.

In the recent years, the effects of different parameters on the WEC performance are studied to gain better efficiency. In 2011, Gomes et al, studied the wave energy conversion by fully-submerged bottom-hinged plates of finite width. In their work, a parametric study was made by varying the plate width and height [12]. In 2012, Flocard and Finningan optimized the power capture of a cylindrical bottom-hinged point absorber by modifying the inertia, which in practice was implemented by allowing some compartment of the device to be filled with water [13]. In 2013, Castellucci et al. presented a new method to increase the energy absorption during tides by designing and realizing a small-scale model of a point absorber equipped with a device that is able to adjust the length of the rope connected to the generator [14]. The adjustment is achieved by a screw that moves upwards in the presence of low tides and downwards in the presence of high tides.

In 2015, Bódai and Srinil considered a WEC concept which is created by linking a box barge to the mechanical reference by linear dampers [15]. They explicitly expressed the response to incident wave action in terms of power take-off as the solution of a linear frequency-domain model. In the same year, Davidson et al. developed a new modeling methodology, which combined the fidelity of CFD models with the computational attractiveness of BEM-type models [16]. They used this method to implement a linear parametric hydrodynamic study of an ocean wave energy converter identified from numerical wave tank experiments. In 2016, Silva et al. presented an optimization design procedure for wave energy converters (WECs) of the oscillating water column type [17]. They used Genetic Algorithm for the optimization process.

In the current paper, the parameter which is varied in order to gain better performance for WEC operation is pendulum weight; however the variation of this parameter is not in wide range; because, this is done for a specified purpose to obtain a defined power, which was set by the employer. For achieving this goal, in the current study an experimental wave tank is used to examine the performance of this WEC in a variety of sea conditions. For this purpose, first, waves generated by wave maker system are calibrated. Then, the WEC is placed in the wave tank and the data from WEC oscillation is analyzed and discussed. Then, the effect of the pendulum weight on the output power of the WEC is studied by increasing the pendulum weight. Finally, by considering converter performance in response to waves in the tank and by studying the data related to Caspian Sea waves, the appropriate scale is achieved to build a full scale model.

2. LABORATORY EQUIPMENT

For studying the designed WEC and according to the operating conditions and model scale assessment and calculations, a wave tank with dimensions of 11m length, 3m width, and 3m depth was designed and built in the Hydrodynamic, Acoustic and Marine Propulsion Laboratory of Babol Noshirvani University of Technology. The wave tank includes a wave maker system for generating different waves with desirable lengths and amplitudes and a wave damper for simulating seacoast. The wave damper decreases the reversing wave effects on the WEC motion. In Figure 1, the right and left side views of the wave tank are shown. As can be seen in these views, a passageway is made for accessing the WEC and its mooring system; also windows are situated for observation and video capturing.

Figure 2a shows the wave maker system which is controlled by an inverter device located outside of the wave tank. Designed wave maker system has 13 different arm lengths. This enables us 13 horizontal displacements of the wave maker plate, so called paddle, from 6 to 29 cm.

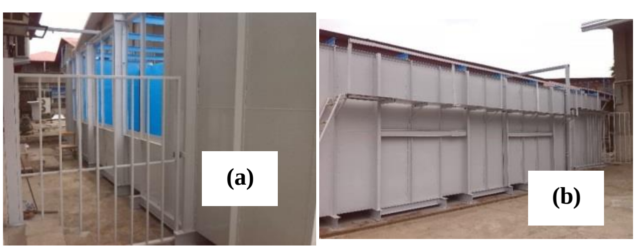

Figure 1. Wave tank, (a): Left side view, (b): Right side view

Table 1 shows displacement quantity of the paddle for each arm number. This system has a 5 kilowatts motor and a reduction gearbox; it provides revolutions variety of 10 to 150 rpm for wave maker system. The motor attached to wave maker system is displayed in Figure 2b.

Figure 3 shows a schematic view of the wave tank along with the WEC. In this figure, the location of the WEC in the wave tank and also the capturing system are shown. The Nikon's COOLPIX L830 camera is used to record the movement of WEC and wave fluctuations during the tests. The measurement of WEC and wave oscillations is done using image analysis software, so called Tracker. For measuring the characteristics of waves by the software, a buoy is placed at a distance of 2m before the WEC.

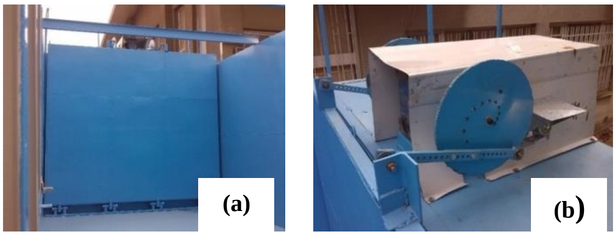

Figure 2. (a): the wave maker system, (b): motor and moving mechanism of the paddle

TABLE 1. The horizontal displacement of the wave maker plate (paddle) for each arm number

Arm number	The horizontal displacement of paddle (cm)	Arm number	The horizontal displacement of paddle (cm)
1	6	8	17
2	7	9	19
3	9	10	21
4	11	11	22
5	13	12	23
6	14	13	29
7	15		

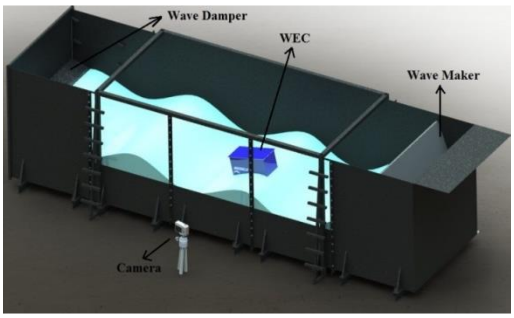

Figure 3. A schematic view of the wave tank along with the WEC

3. THE IRWEC1 INTRODUCTION

As also mentioned in the previous section, the sea which the WEC will be installed in is the Caspian Sea. Our previous studies indicate that a point absorber WEC with working principle like French SEAREV WEC is the most suitable type of WEC for operating in the Caspian Sea [8]. Thus, the initial concept of the IRWEC1 is based on SEAREV; however the PTO mechanism is entirely altered by applying a chain-and-gear system. This is the first stage for achieving an appropriate WEC for the characteristics of the Caspian Sea. The next stage will be the optimization of the geometry specifications and shape of the WEC, which are beyond the scope of this article and will be presented on the future work.

The length of IRWEC1 is 1.9m and its height and width are 1.6 and 1m, respectively. Weights of IRWEC1 and its pendulum are 832 and 174 kg, respectively. Its immersed volume is 0.832 m^3. The mechanical and electrical systems of this WEC are placed in an outer shell for complete sealing. Its mechanical system consists of a pendulum and a power take-off system. Important motion for the WEC is the pitch motion (rotation around axis, perpendicular to pendulum), so a pendulum is designed for converting this oscillation. In fact, WEC pitch oscillation causing the movement of the pendulum and this motion is transmitted to generator by power take-off system. The PTO consists of several gears for rectifying the reciprocating rotation at first stage and then converts them to an appropriate torque and angular velocity for transmitting it to generator. By generator rotation, electricity is produced. In Figure 4, the pendulum which is designed for the IRWEC1 and its outer shell are shown.

Main features and advantages of this WEC are presented in Table 2. As mentioned before in this section, the IRWEC1 includes two parts of mechanical and electrical systems. The mechanical part consists of a pendulum to absorb the wave oscillation and a chain-and-gear system to transfer the rotational motion to the electrical system. The electrical system includes a generator to convert the mechanical power to electricity. In the next section, these two parts are briefly described.

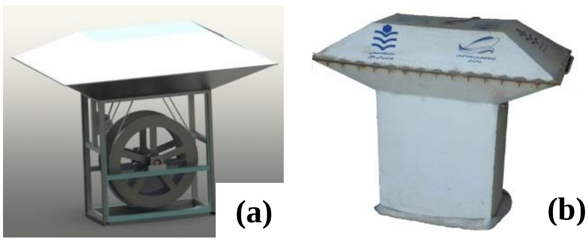

Figure 4.(a): The pendulum used for converting the pitch motion. (b): The outer shell of the IRWEC1

TABLE 2. Main features and advantages of IRWEC1

No.	Features	Advantages
1	Placing all the moving parts within the body	No direct contact with sea water Reducing maintenance costs
2	Having a large pendulum which its center of mass is different from the center of WEC	Ability to survive in confronting with sea rough waves
3	Having no external system and no attachment to seabed	Reduced maintenance and connection costs
4	In case of system failure, it can be dragged with a rope to the shore and repaired easily	Fixed systems haven't this capability
5	No need to advanced technology because it is floating in the sea	Reduced construction costs
6	The system is self-reference because of the pendulum. even a lonely holder cable is sufficient to keep the system in its place	Can reconcile itself with any sea waves or tides
7	The sea depth for installation of this WEC is about 50m.	The beach does not have any effect on it
8	This WEC is appropriate for short wavelengths and medium wave heights	Applying this WEC in the Caspian Sea which has these wave characteristics, is economical

3. 1. Mechanical System As explained before, the mechanical system has two parts including: the pendulum and the chain-and-gear system. It can be seen from Figure 5 that the pendulum consists of two parts. It has two sprocket wheels to transfer the torque to chain-and-gear system; also, there are several flywheels between these sprocket wheels in the sides to increase the WEC's momentum and thereby increment its extracted power. A schematic of chain-and-gear system is shown in Figure 5. In the bottom of this figure, the pendulum system is shown. The pendulum is connected to two gears which will transfer its torque to the gear box. The gearbox has the function of rectifying the reciprocating rotation of the pendulum. This gearbox is specified by a rectangle in the figure. In this system, there are two freewheeling gears which act on the opposite directions. After rectifying the rotation, there are reduction gears which increase the angular velocity of the rotation to reach the level which is appropriate for the generator. There is also an inertial wheel embedded in the last shaft to maintain the rotational speed and decrease the effect of end-stops in the pendulum system. Altough this system reduces the effects of end-stops but, it does not completely remove them, yet. This effect will cause to discontinuity on the extracted electricity from the generator. This is one of the disadvantages of these direct drive systems. It is needed to optimize the inertial wheel in order to make it more effective.

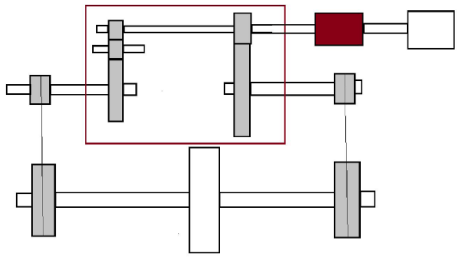

Figure 5. Schematic of chain-and-gear system

3. 2. Electrical System The electrical part of the IRWEC1consists of a brushless generator. The brushless generators are known for their durability, reliability, less losses, less weight and volume and high efficiency. The generator of IRWEC1 is completely designed and built in our Lab by the electrical team. The schematic of the generator and its segments are shown in Figure 6. In the Figure 6a, different segments of the generator are specified by numbers 1 to 8. In numerical order, they are rotating shaft, bearing, aluminum cap, rotating shell, permanent magnet, coil and core, bearing, and holder.

4. THE CASPIAN SEA

In this section, the Caspian Sea is introduced briefly. Then, the sea data, used in this study is described. Also, wave energy potential near the coast of northern Iran is investigated. Finally, based on observations, an optimal range of significant wave height and period for designing an efficient wave energy converter in these areas is suggested.

4. 1. The Caspian Sea Introduction The Caspian Sea is the largest lake on the Earth, a closed basin in the northern hemisphere of the Earth. It is situated where the South-Eastern Europe meets the Asia continent, between latitudes 47.13’N and 36.34’N and longitudes 46.43’E and 54.51’E. The Caspian Sea is bounded on the south by Iran, on the east and north-east by Turkmenistan and Kazakhstan, on the north-west and west by Russia, and on the west by Azerbaijan. Its coastline length is about 7,000km long which about 1,000km of it, belongs to Iran (from Astara to Atrak River).

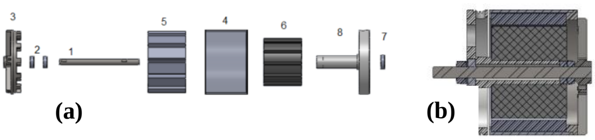

Figure 6. (a): Schematic of the IRWEC1’s generator. (b): Different segments of the generator

Although the Caspian Sea is a closed water basin, however, due to the large area and depth of the sea as well as different weather systems passing over it, most of the time it experiences the storms and elevated winds which subsequently results in storm waves. Northern part of the sea is very shallow, so that only 0.5 percent of the sea water exists in the northern quarter of the Sea. The sea depth increases from north to south and reaches about 900 to 1,000 meters in some regions. The Caspian Sea is not calm, and it is tempestuous most of the year due to the exposure to wind direction. In other words, it has high potential for wave energy conversion; however unfortunately, it has not been considered as energy source so far.

4. 2. The Caspian Sea Data The data used in this study, includes wave period, significant wave height and wave energy from 1999 to 2013 in the southern part of the Caspian Sea in the maritime border of Iran that is extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) server at six-hour intervals. The ECMWF is assimilation meteorological data project for predicting the wave and wind future state with respect to analyzing the long term measuring data and using the numerical modelling. The numerical models are applied based on the time evolution of the climate system from an initial state. The obtained data has been used in literature extensively and results produced based on these data has been validated against the experimental results of the installed buoys which are in excellent agreement [18-21].

Figure 7 shows time averaged wave energy per unit length of the wave front for wave period and significant wave height of the selected point near the city Babolsar. The design or selection of WECs should aim for maximum efficiency in terms of significant wave height (Hs) within the ranges of 0.5 to 1m and in terms of the wave period (Te) between 4 and 6s in the Babolsar, where 2.26 MWh (per unit length of wave front) can be utilized annually.

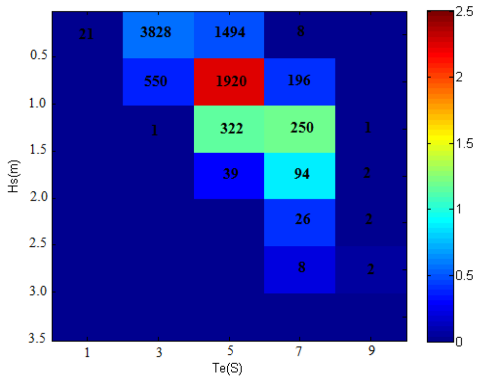

Figure 7. Combined scatter and energy diagrams of the annual energy corresponding to sea states in different ranges of Hs and Te for site near the Babolsar; the colour scale represents total annual energy per unit length of wave front, the bold numbers indicate the occurrence of sea states in number of hours per year.

Table 3 indicates wave characteristics of the Caspian Sea in the case of maximum extractable power and in the order of preference for selected site. Clearly, the design or selection of WECs should aim for maximum efficiency in priority 1.

5. RESULTS AND DISCUSSION

In this section, tests' results are reported and analyzed. The tests analysis includes two parts. The first is related to wave tank calibration. In the second part, the model is placed in the wave tank and several experimental studies are performed and analyzed. Finally, an appropriate scaling, according to oscillation type of the WEC, is obtained and presented in order to build full scale model for applying in the Caspian Sea.

5. 1. Wave Tank Calibration Wave calibration tests are performed in the first series of experiments. For exploration of incoming waves, paddle is tested for all possible scenarios. Experiments are executed for thirteen arm lengths; for smaller arms, the motor speed (ω) is changed from 10 to 70rpm and for larger arms, the motor speed is changed from 10 to 30rpm. To ensure the reliability of test results, tests are performed two times. The obtained results have acceptable accuracy (the average deviation is less than 0.5 cm and 0.05s, respectively, for the wave height and wave period parameters). Reported data are average data obtained from the results of two tests. Each arm has an individual horizontal displacement which generates waves with specific amplitude and wavelength. Characteristics of the waves, generated by the paddle in all cases are analyzed and measured. Then, results are sorted and categorized based on the wave height (H) and period (T).

5. 2. Experimental Test of IRWEC1 In the next step after wave tank calibration, surveying data which is obtained from IRWEC1 oscillations in different directions is discussed.

TABLE 3. The priorities of the wave characteristics of the Caspian Sea for selecting sites with maximum efficiency

Order of Preference	Wave period, Te (s)	Significant wave height, Hs (m)	Wave Energy (MWh)	Probability of Occurrence in Year (%)
1	4-6	0.5-1	2.26	21.9
2	6-8	1-1.5	1.19	2.9
3	4-6	1-1.5	1.16	3.7

The test conditions and data extraction are exactly the same as the ones explained for the wave calibration tests. As it is mentioned in the introduction section, experiments are accomplished for two different pendulum weights. WEC specifications are presented in section 3. For investigation of pendulum's weight on the performance of IRWEC1, about 30kg is added to pendulum which was first 174kg and tests are performed entirely for this case. It worth noted that for comprehensive study of the effects of pendulum's weight, a wider range should be chosen. However, in our case this was done to reach the power which was requested by the employer. WEC with illuminated lamps, which illustrate extracted power by the WEC, is shown in Figure 8.

As mentioned, the experiments are completed for 13 arm lengths. For arms smaller than arm's number 10, waves weren't strong enough for obtaining considerable pitch motion. Results for arm's numbers of 10 and 11 are shown in Figure 9.

It can be seen from Figure 9 that in all conditions, WEC maximum pitch motion is obtained when motor revolution was between 26 and 28rpm.

Figure 8. The WEC with lamps in the test system

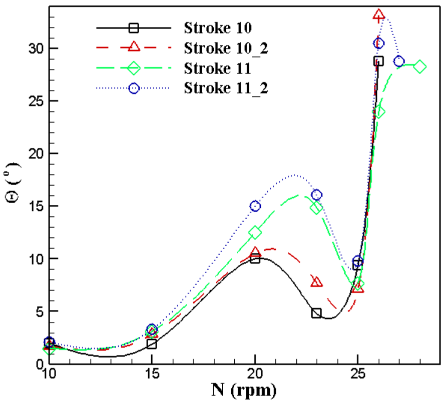

Figure 9. WEC experimental results for two different pendulum weights in arm's numbers (stroke) 10 and 11 (θ is pitch rotation angle and N is the angular velocity of the paddle's motor; the number 2 in the stroke number is for the second case with increased weight)

Also, it is clear that by augmenting pendulum weight, rotation amount will increase. Figure 10 presents experimental result for arm's numbers of 12 and 13.

As it is observed in Figure 10 that in all conditions, when motor revolution was between 25 and 28rpm, maximum WEC rotation in pitch direction is occurred. Increasing pendulum weight will boost rotation angle.

During the test, it is observed that when pitch angle (θ) was more than 20 degrees, a considerable power was generated and for angles more than 30 degrees, lamps were turned on. In the cases in which lamps were turned on, about 100 watts was extracted from the IRWEC1. However, it should also be kept in mind that these experiments were on their primary stage due to the great length of wire between model and lamps and use of inappropriate connections for wiring, electrical losses were considerable. In future tests, we seek to minimize these losses. For further investigation of IRWEC1's performance, pitch angles more than 20 degrees are selected. Table 4 presents the paddle and generated waves' properties for the heavier WEC.

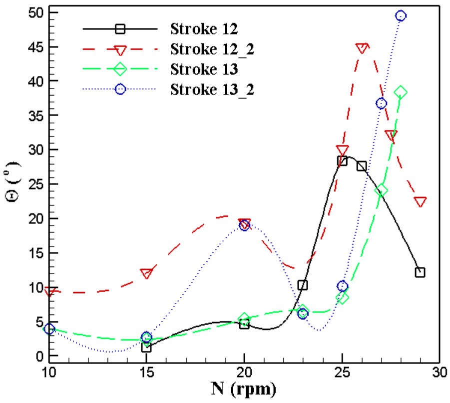

Figure 10. WEC experimental results for two different pendulum weights in arm's numbers (stroke) 12 and 13 (θ is pitch rotation angle and N is the angular velocity of the paddle's motor; the number 2 in the stroke number is for the second case with increased weight)

TABLE4. Paddle and generated waves' properties for the heavier WEC

Arm No.	ω (rpm)	H (cm)	T (s)	θ (°)
10	26	10.6	2.08	33.1
11	26	6	1.94	30.5
11	27	7	1.98	28.8
12	25	14	1.9	30.1
12	26	9.4	1.84	45
12	27.5	10	1.9	32.3
12	29	10.6	1.96	22.6
13	27	14.4	1.98	36.8
13	28	14.6	2.02	49.5

Based on Figure 7, as previously mentioned, first priority for designing a WEC in order to extract maximum annual power for the Caspian Sea waves is occurred in the period between 4 and 6s and significant wave height of 0.5 to 1m. In order to integrate the obtained results for actual sea conditions (i.e. practical situations), the model should be considered in real size (full scale). For this purpose, the Froude similarity between the full scale WEC and the prototype is performed. Accordingly, the following relationship between the wave height, period and power of prototype and full scale model can be derived:

$$\frac{H_2}{H_1} = \alpha_L \tag{1}$$

$$\frac{T_2}{T_1} = \alpha_L{}^{1/2} \tag{2}$$

$$\frac{P_2}{P_1} = \alpha_L{}^{3.5} \tag{3}$$

Here, H is wave height, T is wave period, P is wave power and αL is a dimension ratio of prototype and full scale model. By choosing αL equal to 8, Table 5 presents wave periods of the full scale model in appropriate pitch angles.

Table 5 shows that at the scale of 1:8 in all cases where the WEC pitch angle is more than 20 degree which means the WEC is operating at its maximum efficiency, sea wave period is between 4 and 6s. It also allocates itself the red area of the graph in Figure 7, which is equivalent to the priority 1 of the Caspian Sea. From this table, it can be concluded that on 1:8 scale, in most cases where the WEC pitch angle is more than 20 degree and the WEC is operating at its maximum efficiency, sea significant wave height is in the range of 0.5 to 1m. Thus, 1:8 scale will be the best scale for constructing the full scale model based on the current specifications of IRWEC1.

TABLE5. Tank and sea wave by selecting 1:8 scale

Arm No.	ω (rpm)	T_{tank} (s)	$T_{sea\ wave}$ (s)	H_{tank} (cm)	$H_{sea\ wave}$ (m)
10	26	2.08	5.88	10.6	0.85
11	26	1.94	5.49	6	0.48
11	27	1.98	5.6	7	0.56
12	25	1.9	5.37	14	1.12
12	26	1.84	5.2	9.4	0.75
12	27.5	1.9	5.37	10	0.8
12	29	1.96	5.54	10.6	0.85
13	27	1.98	5.6	14.4	1.15
13	28	2.02	5.71	14.6	1.17

This model, as already mentioned is a preliminary model and it is built with the idea of French model SEAREV. Results show that this model should be optimized for the Caspian Sea conditions. In our next step and future research, we will execute geometrical optimization for obtaining suitable pitch angle in periods between 4 and 6s and wave heights between 0.5 and 1m. Extracted power from prototype when system has suitable pitch angle is about 100 watts. Determining 1:8 scale and applying Equation (3), extractable power from the full scale model at sea will be about 145 kilowatts which is a considerable value.

6. CONCLUSIONS

In this article, IRWEC1, a novel WEC under development by the Hydrodynamics, Acoustics and Marine propulsion Group at Babol Noshirvani University of Technology is described and investigated. Generated waves were calibrated and surveyed by wave maker system at the first step. Then, having a calibrated wave tank, IRWEC1 is placed into it and the data from its oscillations in different directions is extracted, analyzed and discussed. The waves in which IRWEC1 has suitable pitch motions and acceptable extracted electrical energies are presented. Following, the pendulum weight is increased about 30kg and its effects on the WEC performance are studied. Based on the experimental test results, in the motor revolution between 26 to 28rpm, the WEC performance is in its best condition for all strokes. Also, it was shown that an increment in the pendulum weight has noticeable effect on the performance of the WEC. Moreover, according to diagrams and data obtained for WEC performance and annual energy diagram of the Caspian Sea, scale 1:8 is selected for making the full scale model of the IRWEC1. By selecting a scale of 1:8, extracted power from the full scale will be about 145 kilowatts.

7. ACKNOWLEDGMENTS

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Experimental Evaluation of IRWEC1, a Novel Offshore Wave Energy Converter

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چکیده

این مقاله به شرح سامانه بدیعIRWEC1 که یک سامانه مبدل انرژی امواج فراساحلی نوع جاذب نقطه‌ای می‌باشد، پرداخته است. این سامانه در آزمایشگاه تحقیقاتی هدرودینامیک، آکوستیک و پیش‌رانش دریایی دانشگاه صنعتی نوشیروانی بابل در حال توسعه می‌باشد. در سامانه IRWEC1، تمامی قسمت‌های متحرک آن در داخل یک پوسته خارجی قرار گرفته‌اند و این سامانه به طور کامل آب‌بند می‌باشد که این امر، آن را به یک سیستم مستحکم و قابل اطمینان مبدل کرده است. حرکتی که در این مبدل حائز اهمیت است، حرکت پیچ) چرخش حول محور عمود بر پاندول) می‌باشد که از پاندول‌های طراحی شده برای تبدیل این حرکت نوسانی و انتقال آن به سیستم انتقال قدرت استفاده شده است. در این مقاله، عملکرد سامانه مبدل انرژی موج IRWEC1 برای دامنه وسیعی از امواج در استخر موج، مورد ارزیابی قرار گرفته است و مشخصه‌های امواجی که در آنها سامانه، نوسان پیچ مناسب و همچنین انرژی الکتریکی خروجی قابل قبول داشت، ارائه شده است.

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