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New Pneumatic System for Tidal Energy Conversion

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Abstract

In this work, a new device for tidal energy conversion is presented. The main purpose of this research is to investigate the energy conversion of tidal energy into electrical one by building a small scale prototype using a pneumatic system representing the energy conversion device. The tidal energy conversion device consists of a concrete in cylindrical shape, a moving base that moves inside the concrete cylindrical body and two single acting pistons connected to a power turbine. The system specifications that mainly affect the amount of energy are the spring stiffness and hose diameter. It was found that there is a possibility to convert the tidal energy into electrical energy using the designed prototype. The maximum amount of electricity generated using the proposed prototype was about 5 Volts.

Keywords

Renewable Energy, Pneumatic, Power, Renewable, Tidal

1. Introduction

The renewable energies are free energy sources, such as wind, solar radiation, geothermal, and ocean energy. The energy in the seas and oceans can be classified into five main categories: wave energy, tidal energy, ocean thermal energy, ocean current energy, and salinity gradient energy [1]. Tidal and wave energies are stored in the ocean and can be extracted [2] [3] to contribute in reducing the total energy demand in the world due to the availability of water bodies. Recently the cost of ocean energy is very competitive due to improvements in the current technologies [3].

Wave energy is indirect form of solar energy since the wind produces waves [4]. However, the availability of wave energy is 90% which is 3 times more than solar irradiance and wind gusts occurrences which are approximated to be 20% and 30% respectively [3].

The power that can be extracted from the oceans on earth is around 1 TW. It corresponds to massive energy production which can compete with hydro and nuclear power production plants. Wave energy can be converted to electricity by several ways [3]. The first technique is oscillating water column [4] which is a mechanical interface that depend on the air-flux oscillations, it can be fixed or floating structures, for which the energy is extracted via air turbine [3] [4]. Second, oscillating floating or submerged bodies [4] use hydraulic interface which relies on water flux variation that can generate electricity using hydraulic turbine-generator system. Another oscillating body type relies on the moment generated by movement of multiple structures on the water body surface. A direct extraction is also possible by using linear generator. However, it is not recommended as wave energy conversion system [3]. Depth of the water body and the location is the criteria to select between the technologies available. Third, overtopping used with low-head hydraulic turbine, and the structure can be fixed or floating [4]. On other hand, tidal power has advantage over other types of ocean energy of being predictable [2]. Tidal energy stores potential and kinetic energies forms. Tidal barrages used to harness tidal potential energy and tidal current turbines used to extract the kinetic energy component in the tides. The gravitational force of the sun and the moon on earth in addition to the rotational motion of the moon and earth around each other, are the main reasons of the tidal energy. Tides energy is tides movement's energy dissipation which can be converted to useful energy through tidal stream turbine [5]. The energy that can be extracted by tidal turbines is much greater than wind turbines since the density of water is 800 times more than air [6].

Blunden *et al.* [7] reported that the classical analysis of wind turbines is similar to that for tidal turbines. If the flow is around wake region a correction must be required. Few number of tidal stream turbine design are published. However, they achieved experimental power factor of 0.4 compared with the modeled value 0.45 for their model. The number of inventions in tidal technology is stabilized, so improvements in the current technologies are crucial for reduction of the total energy demand.

The devices facilities that use tidal energy are usually of two types which are: marine barrages with turbines that use the advantage of the water level difference and marine turbines that use the marine currents kinetic energy produced by tides [8]. Design of tidal energy convertors has been a major concern during the last decade from environmental impact point of view. Many devices have been tested [5] but very little specific installations that obtain power directly from tidal currents are in operation.

The proposed device in this work has a great advantage over other tidal devices due to the fact that the turbine is not in direct contact with ocean water (saline) since the compressed air is running the turbine blades.

In this paper, a new device is designed to convert the tidal energy to electrical energy. The objective of this paper is to present the new design with some of basic formulations in energy production.

2. The Prototype of Pneumatic Tidal Energy Converter

The maximum height of the tidal level in Kuwait is 4.5 meters. In this work, a prototype tidal harvester with the total height of 1020 cm and the storage thank height of 410 cm is designed to obtain tidal power from the two pneumatic cylinders. The tank is made from steel sheet with 10 mm thickness which can withstand 400 MPa stresses. The maximum pressure acting on the base is calculated to be 45 kPa. The schematic diagram for the tidal energy harvester prototype is shown in Figure 1.

The concrete frame using 2 cylindrical shape woods was designed. First wood has a diameter of 330 mm which is placed into the other cylindrical shape wood with 430 mm. The concrete mixture will be placed between the 2 frames and that will give a cylindrical shape concrete with an inner diameter of 330 mm and outer diameter 43 mm. The concrete mixture is specifically used for a long life in the sea water. The concrete mixture was made of 25% sand, 10% cement, 45% small aggregate and 20% water. The main components of the device are: Housing of a turbine, Tank, Concrete body that will hold the cylinders with the tank, Valve, Cylinders, Springs, Motor, Turbine, Fan, and Pneumatic cylinders. The turbine used in this research is small wind turbine (see Figure 2) which is connected to a generator that produces electricity. The compressed air that will come from the cylinder will be directed to the blades of the turbine in order to run the turbine. The air speed that will allow the turbine to rotate should be measured so that the number and size of the cylinders that will be used can be determined.

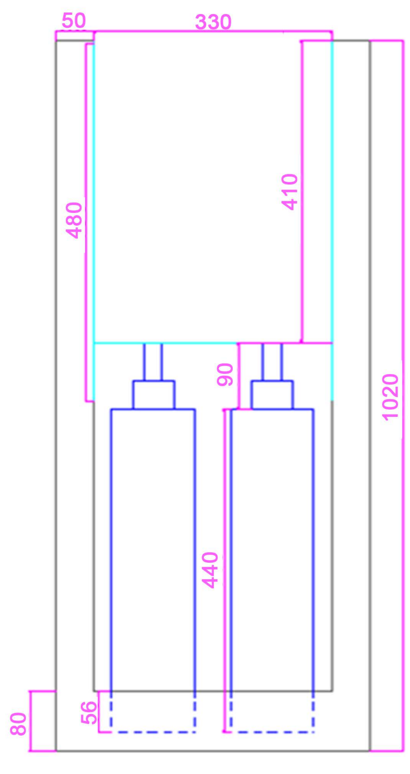

Figure 1. Schematic dimensions of the pneumatic tidal energy converter (dimensions in mm).

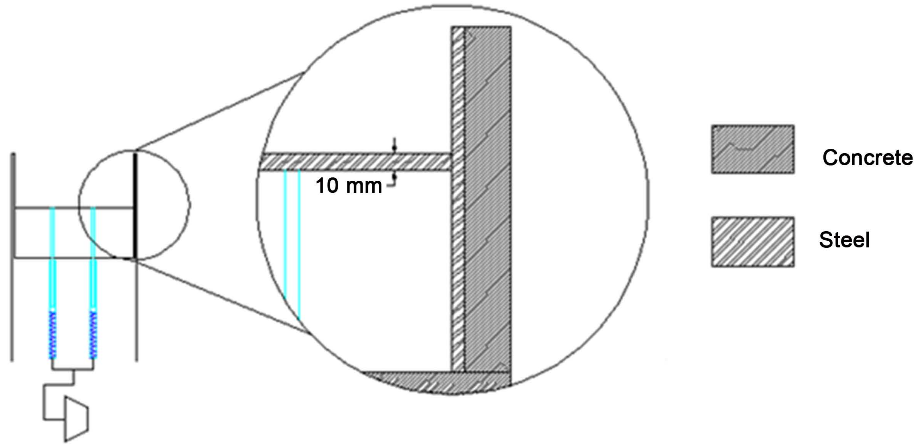

Figure 2. Dimension of the base thickness and the materials.

3. Mathematical Formulation

3.1. Base Thickness

Water properties and the conditions strongly affect the energy produced from tides [9]. When the waves of the sea enter the device form one side, this will create a force on one side of the base, which might unbalance the base and allow water to enter the bottom side of the device and might also affect the movement of the base. To avoid these problems a certain thickness should be designed to allow the wall of the tank to support the base and stop it from getting misaligned. If the wall of the tank is supporting the base, that means the misalignment doesn't have to cross more the half of the thickness. The thickness of the base is t and the radius of the base is designed to be 2.6 m. Water above the base will cause distributed load on the base. Knowing the magnitude of this external force of water , mg, where $m = \rho V$, and applying the summation of forces in the horizontal direction equals to zero and taking the moment at the center of the base equals to zero, we obtain the following equations:

F_{wall} is the force exerted by the wall on the base, hence we can write:

$$\sum F_x = Fw\cos\theta - F\ \text{wall} = 0 \tag{1}$$

$$\sum M = \left(Fw\sin\theta X\ r\,2/3\right) - \left(F\ \text{wall}\ X\ \frac{t}{2}\right) = 0 \tag{2}$$

where θ is the base misalignment angle as $\theta = \sin^{-1}\frac{t/2}{2.6}$

Using Equations (1) and (2), we obtain an Equation (3) from which the base thickness can be calculated using iteration procedure

$$\left[1.7Fw\sin\left(\sin^{-1}\frac{t/2}{2.6}\right)\right] - Fw\cos\left[\sin^{-1}\frac{\frac{t}{2}}{2.6}\right] = 0 \tag{3}$$

Substituting $F_w = 26745.2t\ N$, Equation (3) can be rewritten as

$$\left[\left[26745.2t\sin\left(\sin^{-1}\frac{t/2}{2.6}\right)X1.7\right]=26745.2t\cos\left[\sin^{-1}\frac{\frac{t}{2}}{2.6}\right]\right] \quad (4)$$

Using iteration technique, the thickness t of the base is obtained as $t = 0.01$ m.

3.2. Tank Size and Pressure

The maximum height of the tidal level in Kuwait is 4.5 meters. For this reason we chose the height of the device 4.5 m, to obtain maximum tidal power from the device. This height results in pressure of 45 kPa. The steel sheet with 10 mm thickness can withstand around 400 MPa, and that allows the device to be as big as it can be. Since the maximum pressure acting on the base is only 45 kPa, the diameter of the base can get up to 5.2 m maximum according to the standards of the steel sheets that come in maximum 5.2 m width.

3.3. Number of Cylinders Tank

In order to obtain the number of cylinders that are needed to obtain the tidal energy due to the tidal height, the total force acting on the base should be determined. The water volume above the base with 4.5 m can be obtained from $V\text{ water}=\left(\pi r^2\right)X$ the hight of the tank as $V=\left(\pi 2.6^2\right)\times 4.5=95.57\text{ m}^3$. The mass of the sea water of that volume is $m\text{ sea water}=1027\times 95.57=98150.39\text{ kg}$ hence the force of the water is $F\text{ sea water}=\text{mg}=962.85\text{ KN}$. We should also consider the force of the steel exerted due to the weight of the base in order to obtain the total force. The volume of the base is $V\text{ steel}=\left(\pi r^2\right)t=0.21\text{ m}^3$ and the mass of the base is $m\left(\text{base}\right)=7850\times 0.21=1667.12\text{ kg}$. Hence the force of the steel base is $F\text{ steel}=16.3\text{ KN}$.

The total force that will act on the cylinders is: $F_{\text{Total}}=F\text{ steel}+Fw=979.15\text{ kN}$.

The standard size of the pistons is the maximum diameter of air cylinder is 250 mm with length of 700 mm. In this work, the length has to be in the range of 4.3 - 4.5 m. The specifications of the air cylinder that is to help finding the number of cylinders we will use in the device. For 250 mm piston it can push up to 600 kPa, for 29.45 kN. Since the total force acting on the base is 979.15 kN, around 33 cylinders with maximum size according the tidal height are needed in the device.

3.4. Required Air Speed

The turbine used in this research is small wind turbine which is connected to a generator that produces electric while rotating. The compressed air that will come from the cylinder will be directed to the blades of the turbine in order to run the turbine. The air speed that will allow the turbine to rotate should be measured so that the number and size of the cylinders that will be used can be determined.

Air speed that comes from the compressor after leaving the cylinders is controlled by controlling the distance between the compressor and the turbine. Once the smoothest results are obtained the distance between the turbine and the compressor is marked and after that Air Speed Indicator (ASI) is used to measure the air speed of the compressor that needs to rotate the turbine. The recorded result of ASI was 36.45 m/s.

3.5. Spring Stiffness

The piston plus the rod mass is 2.5 kg which is 25 N. To fit the spring inside the cylinder, it should have 90 mm diameter and 300 mm length.

The stiffness of the spring can be obtained from the following equation

$$F = Kx \tag{5}$$

where F is the force, K is the spring stiffness and x is the spring elongation.

The piston and the rod weight will move the spring in a very small distance because the target of the spring is to move when the water weight is applied. In this case when the piston and the rod weight applies the spring will move maximum 40 mm (measured) along the cylinder. The stiffness of the spring is obtained as K = 613 N/m.

3.6. Water Tank Dimensions

The force that can move the spring from 300 mm long to 50 mm is needed to have the maximum volume of pressurized air from the piston cylinder. Using the stiffness of the spring, this force is obtained as 153 N.

In this research, 2 cylinders were needed to double the force needed, *i.e.*, 306 N for which the volume of water can be found equal to $0.032\ \text{m}^3$. Based on this volume, the radius and height of the water tank is found as shown in Table 1.

The chosen dimensions, diameter and height are 0.32 m and 0.4 m, respectively.

5. Results and Discussion

The concrete body that holds the cylinders within the tank was built, it was placed into wet conditions so that it can be saturated up to 28 - 30 days. After that the fiberglass sheet of the tank is placed with the moving base. Before placing the moving base, the rod on the piston is attached into the moving base then both placed into the device while the cylinder fits into its place in the concrete body. The base is checked by moving the piston up and down to check if it is going smoothly. The output air from the cylinder is connected from the forward position and the backward position direct to the turbine. The turbine will produce power that is measured in terms of voltmeter as shown in Table 2.

6. Conclusion

Tidal energy is a type of clean energy that may contribute as one of the main energy sources in the future. It produces energy from the tidal of the sea or ocean. In this work, a device basically consists of a tank with a moving base is designed to be filled with sea water during tidal changes. As long as the water fills the tank, the moving base will be forced to move downward to compress two pneumatic cylinders. The compressed air then is directed to rotate a wind turbine connected to an electric generator.

Table 1. Dimensions of the water tank.

Volume (m^3)	Height (m)	Diameter (m)
0.032	1	0.2012
0.032	2	0.1427
0.032	3	0.1165
0.032	4	0.1009
0.032	5	0.0903
0.032	0.9	0.2128
0.032	0.8	0.2257
0.032	0.7	0.2412
0.032	0.6	0.2606
0.032	0.5	0.2855
0.032	0.4	0.3192
0.032	0.3	0.3685
0.032	0.2	0.4514
0.032	0.1	0.6383

Table 2. Voltmeter readings as function of water height in the prototype.

Test #	Voltage (V)	Water height (m)
1	0	0.06
2	0	0.12
3	1.02	0.18
4	1.52	0.24
5	2.14	0.3
6	3.22	0.36
7	3.73	0.42
8	3.98	0.48
9	4.34	0.55
10	4.76	0.6
11	5.22	0.67
12	5.39	0.73

When the tank base reaches its dead bottom center, there will be an exit valves which allow the water to exit the tank when the tidal level decreases. The inlet water is controlled to move the base in slow speed until the tidal level starts to decrease. In this way, the device can operate during 24 hours a day by using the pressurized air inside the cylinder when the piston is going forward and when the spring is pushing the piston backward as well. Future work should be done on tidal energy convertors, which should focus on economic and social impacts of ocean energy. Focus on the area of maintenance and operation should be expressed and will help in improving the tidal energy conversion devices. More experimental work should be conducted on the proposed device in order to improve its design parameters.

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