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Development of a Simple and Innovative Wave Energy Harvester Suitable for Ocean Sensor Network Application

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Abstract

The article represents a new idea about an innovative, simple and cost effective marine energy harvester for powering offshore sensor nodes working as part of Ubiquitous Sensor Network (USN). Betterment of these aqua farms by including these into wireless sensor network so that they could be remote controlled from far land, is needed to make this offshore farming more popular. For this step to be done one major concern is the powering process of the sensor nodes used as the key part of sensing or monitoring purpose of the offshore projects. So our study focuses on the design and numerical study of a wave energy harvesting device for supplying uninterrupted electric power to offshore sensor nodes serving as part of ocean environment monitoring network or any marine aquaculture farm. Analysis of the environmental and device sizing factors that makes the efficiency to deviate, have been discussed here. It is a novel, floating type, double chambered wave energy converter that uses the Oscillating Water Column technology for conversion of wave power into electrical power.

***Keywords**: USN, ocean monitoring, ocean energy, BBDB and Floating OWC*

1. Introduction

The Monitoring of ocean weather and remote control of many offshore marine industries are the most popular application of USN. Sensors are the most essential equipment for monitoring, collecting the data and conveying control of different system from distant places. For example controlling offshore marine aquaculture industries from distant land is quite easy with USN. So, this paper discusses about development of a self-powering system for these sensor nodes (offshore) using marine energy.

Almost 71% of the whole world is covered by water which is full of energy resources [1]. So monitoring Ocean environment is necessary if we want to utilize the ocean energy as a renewable resource for producing electric power. And also there are many offshore aquaculture farms which can be remote controlled from land with the help of sensor nodes. For powering these offshore sensors ocean energy harvesting is the most feasible option than any other resource.

Only the variety of motion of ocean waves are able to create different routes to produce energy. Waves directly can move turbine or wave power can be converted into wind power and then wind power can run turbine to produce electric power. Many offshore industries need little amount of power supply and serving these industries with electricity from land is real hardship along with wastage of money. The best way for feeding power to these sensor nodes could be wave energy

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harvesting. Among several wave energy converters, since OWC-type device can release the air with high pressure in air chamber and protect the installed turbine and generator in stormy conditions, the OWC-type is considered to be the device with higher safety [2]. Because of safety reasons, recently OWC type harvesters have been getting most of the research attentions. The paper represents a new device that has graphical similarity with backward bend duct buoy with the exception that it is double chambered and it works with the principle of oscillating water column technology.

2. Double Chambered BBDB

2.1 Historical Background

Backward bent duct buoy has been a topics of interest for a few decades. Many researchers have done various experiments based on computer as well as in wave tank [2, 3, 4, 5]. In 1986, Masuda proposed a floating wave energy converter with oscillating water column and it was named Backward Bent Duct Buoy (BBDB). This consists an air chamber, horizontal duct, buoyancy chamber and turbine. Toyota [4] developed a numerical analysis code in time domain to estimate the motion of the floating body and mooring system, the fluctuation of air pressure in the air chamber and the rotational speed of turbine at the same time in irregular waves. In this paper, the validity of numerical method were confirmed by comparing the experimental results found by the wave tank test for hydrodynamic characteristics of the BBDB carried out by Nagata [6]. Due to the good characteristics of BBDB, the research on BBDB has been carried out in Ireland Korea and Japan [4].

Xianguang [7] conducted 2D wave tank tests in regular waves to evaluate the primary conversion efficiency of six kinds of BBDB models with different hull form. They showed that primary conversion efficiency of six kinds of models was 22%~73%. Forestier [8] reported the results of wave tank tests and field tests for the power output of BBDB named “OEBuoy” by OceanEnergy Limited. Falcao and Justino estimated the total performance in time domain considering the air pressure distribution in air chamber and characteristics of turbine [9].

2.2 Structure Detail

The paper describes a new wave energy converter called double chambered Backward Bend Duct Buoy. This includes two L shaped chambers joined back to back where the vertical portions symbolized as draft and two horizontally inclined portions as duct. Ducts stay submerged in water each having an opening mouth just opposite to each other. The duct extends from the lower part of the vertical portion just being 180° opposite faced to each other. The vertical tube that is made double chambered by a partial partition inside. It is said partial partition because there remains a turbine within a tunnel, at the upper portion of the partition, making air connection between the two draft tubes. Each vertical part stays in fluid contact with the horizontal part. It’s a Backward Bend Duct Buoy type structure with the exception that the power extracted is only from the air traversing from one chamber to other without leaving the device.

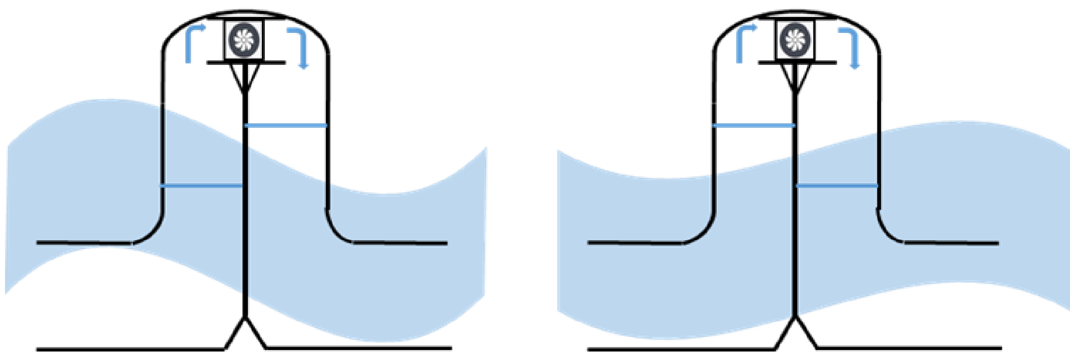

Figure 1. Invented Double Chambered BBDB Device Facing the Wave

Though it is a new structure, but it has the advantages of classical BBDB like the higher primary conversion efficiency, the maximum conversion efficiency at the wavelength that is 4 times the length of the duct [2].The unique feature is that the device is double chambered and the chambers are internally air connected to each other through a narrow tunnel at the upper portion of the device.

2.3 Working Procedure

Though having difference in device structure but the present device assumed to have two basic BBDB characteristics. And the assumptions about optimum sizing parameters were taken, considering these two facts. Firstly, the BBDB possess higher primary conversion efficiency. Secondly, the primary conversion efficiency reaches its maximum at a wavelength that is about four times length of the BBDB [2]. In comparison with the prior studies [2, 3, 4, 5], present invention has two draft tubes though not fully apart and two ducts. Because of the two opposite opening mouth, the two drafts face two different conditions of wave which can make difference in wave water levels between them as well as increases the pressure difference between them contributing to a greater power generation. The difference in water levels between the two drafts causes pressure difference which consecutively makes the air above the water surface to flow through the connecting tunnel across the turbine inside the chamber. For higher efficiency, we have to ensure highest difference between the water levels. Larger the difference in water level, greater the pressure and greater the power extracted from waves.

2.4 Theory

In this analysis each part of the device was gone under individual component study which made the performance study of each part easier and helped to get some interesting characteristic findings. The theory assumed in this study is developed by Setoguchi [10] and described in [11-13] which was basically for classical fixed type OWC. Our BBDB is floating, double chambered and has 3 parts whereas OWC has 2 parts (the water and the air compartment only) but in this analysis, it is assumed that this BBDB works on the same principle as classical OWC. The numerical analysis was done considering the equation of continuity for each pair of chambers of the BBDB.

There is little manipulation from the theory described in [11, 12, 13] because of some structural modification in the present system. Theoretically the power available at the turbine contains two terms the pressure term Pt and the air velocity term Pa [13]. Pressure term is a function of the difference between pressure at the turbine inlet in one chamber and the pressure at the turbine on another side or opposite chamber.

The pressure gradient and volume rate of airflow Q across the turbine gives the pressure term for the turbine inlet power.

$$P_t = (P_{31} - P_{32})Q \quad (1)$$

Where Q = V3 × A3 .And from the kinetic energy of the air flow, the air term for the power can be obtained.

$$p_a = \frac{1}{2}\rho A_3 V_3{}^3 \quad (2)$$

$$P_{in} = P_t + P_a \quad (3)$$

As detailed in [13] and [11]

$$= \left\{\left(\rho\, {}^{A_1}\!/_{A_2}\left[-\frac{(H_1\omega)^2}{4}(2\cos(\omega t)^2 - 1)\right] + \rho\frac{Q}{A_2}(V_2 - V_1)\right) + \frac{1}{2}\rho V_2{}^2\right\}Q \quad (4)$$

$$= \left\{\left(\rho\, {}^{A_2}\!/_{A_3}\left[-\frac{(H_2\omega)^2}{4}(2\cos(\omega t)^2 - 1)\right] + \rho\frac{Q}{A_3}(V_3 - V_2)\right) + \frac{1}{2}\rho V_3{}^2\right\}Q \quad (5)$$

H_2 is the peak-to-trough magnitude of the oscillating water surface in the vertical draft chamber, and ω is the angular velocity of this oscillation in radians per second (*i.e.*, the wave angular velocity). And the equation of continuity used here like,

$$Q = V_1 \times A_1 = V_2 \times A_2 = V_3 \times A_3 \quad (6)$$

For the expression of wave height or $\eta_2(t)$ inside the OWC column an expression for Δp against V3 needs to be determined which was obtained from CFD analysis by Hsieh [12] where they showed the relationship by a curve fitted.

The function obtained from their study was used in this analysis to get the expression for wave height H2 shown below:

$$\Delta p = 14.035V_2{}^2 + 21.06V_2 \quad (7)$$

Considering incompressible air inside and equation of continuity, after some manipulation we can get the expression of V_3 from this. The study in [12] was done considering atmospheric pressure outside the chamber and here there will be pressure in opposite chamber rather than atmospheric pressure which is not taken into consideration in this analysis.

3. Numerical Analysis

The analysis was done in MATLAB and the result was studied for different sizing parameters of the experimental device. As the device is symmetrical about vertical axis so the structure can be divided in three parts the duct A1, vertical draft part A2 and the tunnel carrying the turbine A3.

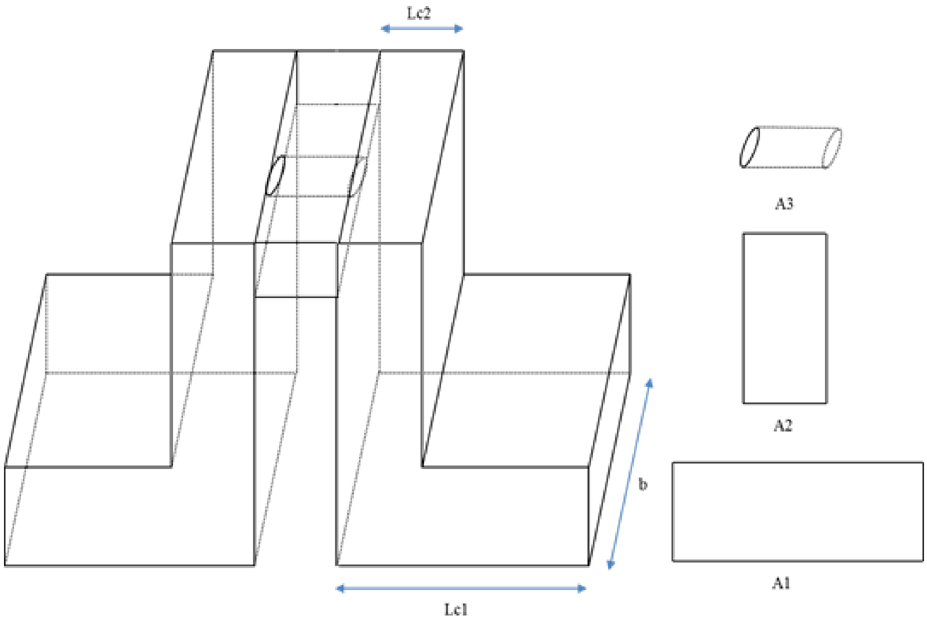

Figure 2. 3D Structure of New Double Chambered BBDB

The BBDB was considered as two single chambered OWC, joined back to back and each works on the same working principle as OWC. The velocity and power available from this chamber was calculated using the theory described by Hsieh [12] and a function found by them from CFD analysis was used here to get an expression for pressure difference. For handiness, study of only one chamber was considered here. A MATLAB program was written considering some wave condition and BBDB configuration like, wave height .3m, wave period, T=2.2s, chamber width b = 1m, Lc1= .452m, A3=.0113 m^2.

Figure 2 above shows 3D structure of new double chambered BBDB. With a view to search for the device parameters that outcomes the best BBDB performance, some calculations have done. The results showed some exclusive findings that are discussed below.

In the previous studies of OWC [11, 12, 13] it was seen that the area ratios have a great impact on its power conversion and the simulations done here also established that among different parameters, most important was the two area ratios M1 and M2. M1 holds for duct to draft ratio and M2 holds for draft to turbine area ratio.

The performance study was done in two separate categories. In both categories, 4 parameters were kept constant, they are wave height, H0 = .3m, wave period, T = 2.2s, chamber width, b = 1m and area of the air chamber, A3 = .0113m2.

4. Results

4.1 Effect of Varying Draft Length (Lc2) on Chamber Power

In the first case there was a theoretical power availability of 34 W for M1 = 2 and M2 = 20 for the environmental condition stated above and Lc1= .452m. Here Lc2 was the variable which made M1 and M2 to vary.

In this case the 4th constant parameter is Lc1 *i.e.*, length of chamber1 or duct. By making Lc1 fixed the area of chamber1 (A1) gets fixed so variable M1 gets dependent only upon varying length of chamber2, (Lc2).

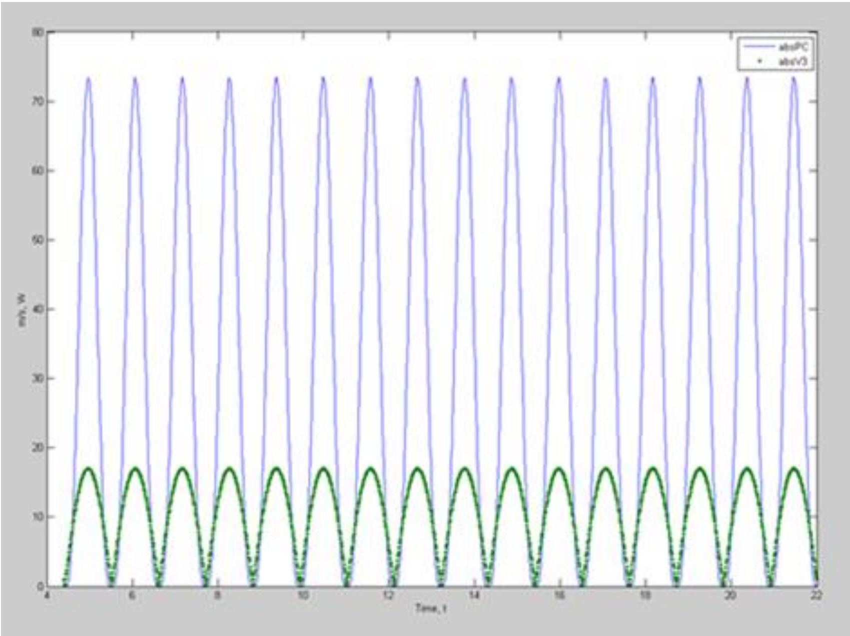

Figure 3. Variation of absV3 (green) and absPc (blue) with Time for M1=8

The simulation was run for M1= 2 to 8 and among the results, Figure 3 shows the variation of absolute wind velocity at the turbine, absV3 and absolute chamber power, absPC with time for area ratio, M1=8. The MATLAB simulated results for M1= 2 to 8 are shown below in Table 1.

Table 1. Velocity and Power Available for M1= 2 to 8

Variable,M1	M2	Lc2 m	avgV3 m/s	avgPC w
2	20	0.23	10.82	34.51
3	13.333	0.15	10.78	33.69
4	10	0.11	10.77	33.04
5	8	0.09	10.77	32.43
6	6.67	0.08	10.76	31.73
7	5.71	0.06	10.74	31.08
8	5	0.06	10.72	30.34

The table shows the result of the experiment as variation of average wind velocity at wind turbine, avgV3 and average chamber power, avgPC with Lc2 and two area ratios M1, M2. From the results it is clear that though the area ratios M1 and M2 varies in a large range but there is no such large variation in wind velocity as well as in wind power.

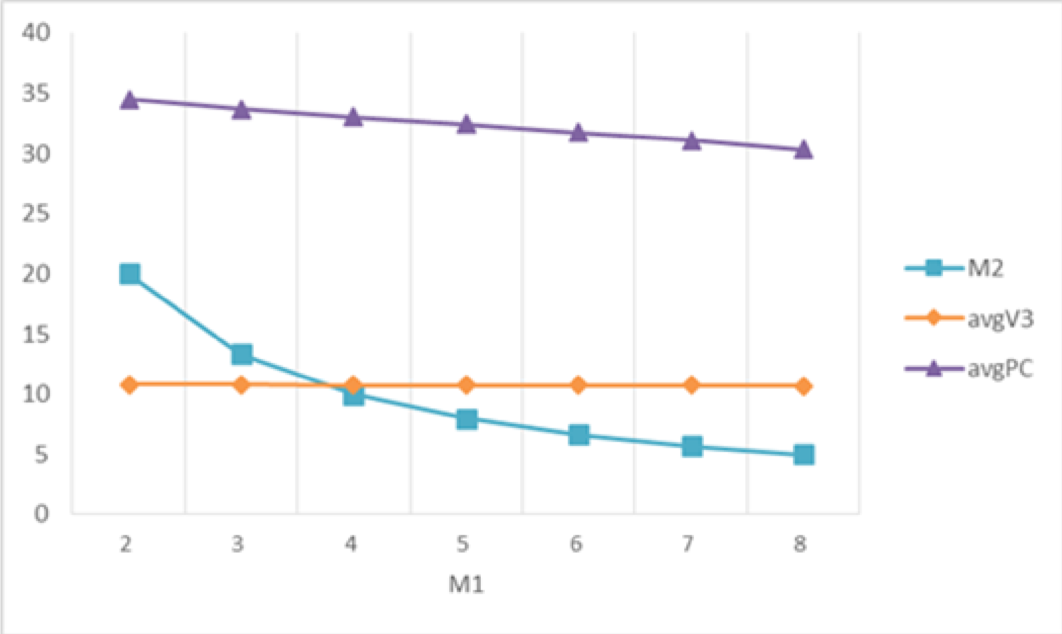

Figure 4. Characteristic of M2, avgV3 and avgPc for M1=2 to 8

Figure 4 shows the variation of M2, avgV3 and avgPC with M1. Here M2 and avgPC shows inversely proportional relation with M1 and avgV3 shows almost linear but slight decrease with increase of M1. As increase in M1 means increasing the duct length, this simulation results shows resemblance with studies in [2], where they showed that increasing duct length doesn't show any improvement in power production.

The total chamber area ratio can be given as, M=M1*M2. So increase in M1 should have a positive effect on chamber power and wind velocity but it is not like this always. The reason behind this is, with constant A1, decrease in M1 means increasing Lc2 which in turn increases M2 (since A3 is fixed change in M2 depends only on Lc2). But the power increases because the increment in M2 is greater than the decrement in M1 and thus M2 effects on the power increment more effectively than M1.

4.2 Effect on Chamber Power for varying both Lc1 and Lc2

In the second case, the simulation was done for variable M2 and for this Lc1 and Lc2 both were made to vary in a certain range. The ocean condition as well as parameters are taken same as last experiment and the 4th constant parameter here is M1=4. The value of M1=4 was chosen from the previous simulation considering the power and velocity output at that area ratio and taking in mind the shape factor of BBDB that has to sustain in diverse ocean condition. From the result analysis of first experiment, M1=4 can be found maintaining good balance between power requirement and good shape.

Since the 4th constant parameter now is M1, keeping M1 fixed if M2 is varied than Lc1 and Lc2 will vary in such a way that the value of M1 remains constant.

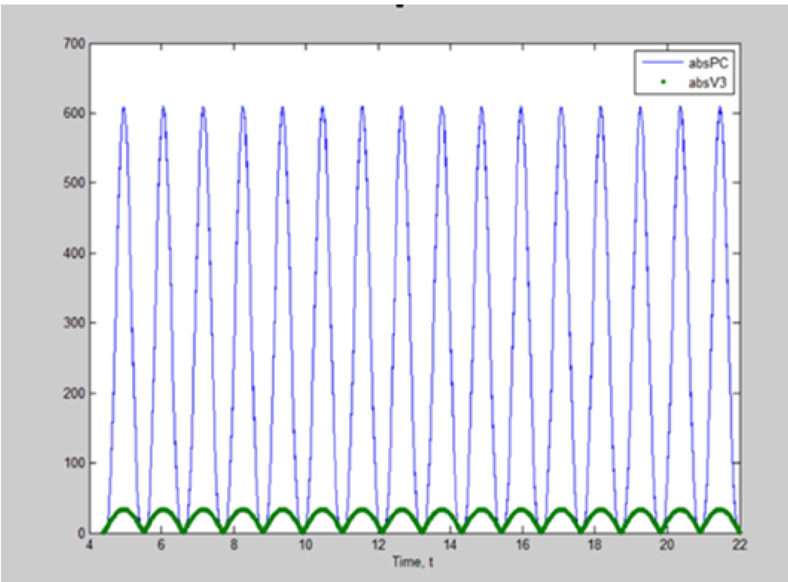

Figure 5. Variation of absV3 (Green) and absPc (Blue) with Time for M2=20

MATLAB simulation shows the absolute velocity (absV3) and absolute chamber power (absPC) characteristic inside the chamber with time for 2nd area ratio M2=20. The figure presents theoretically the largest value of power and velocity, obtainable from the BBDB according to the design parameters. And for M1=4 and M2=20, BBDB shows maximum efficiency of about 78% [Pw = 326.3725 (water power), avgPc = 255.04 (Chamber power)].

Table 2 below represents the variation of average velocity at the turbine, avgV3 and average chamber power, avgPC with Lc1 and Lc2 for M2 ranging from 10 to 20. Highest value for M2 was chosen as 20 considering the shape factor of the BBDB.

Table 2. Velocity and Power Available for M1= 2 to 8

M2	Lc2 m	Lc1 m	avgV3 m/s	avgPC w
10	0.11	0.45	10.77	33.04
11	0.12	0.50	11.83	44.02
12	0.14	0.54	12.89	57.11
13	0.15	0.59	13.93	72.48
14	0.16	0.63	14.98	90.31
15	0.17	0.68	16.01	110.68
16	0.18	0.72	17.04	133.70
17	0.19	0.77	18.06	159.50
18	0.20	0.81	19.09	188.50
19	0.21	0.86	20.09	220.25
20	0.23	0.90	21.08	255.04

Figure 6 shows the graph for the varying characteristics of avgV3, avgPC with M2. Here, both the parameters show positive behavior with the increase in M2. Figure 7 bellow shows a 3D view of the relative characteristics or activities of Lc1, Lc2 and AvgV3.

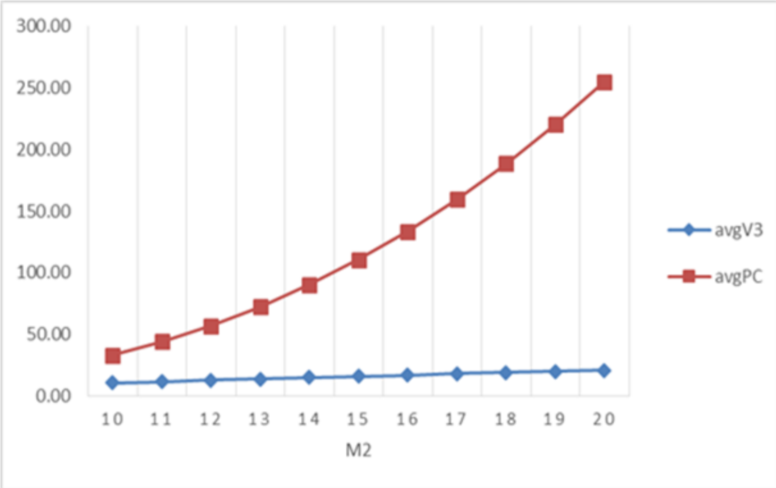

Figure 6. Characteristic of avgV3 and avgPc for M2=10 to 20

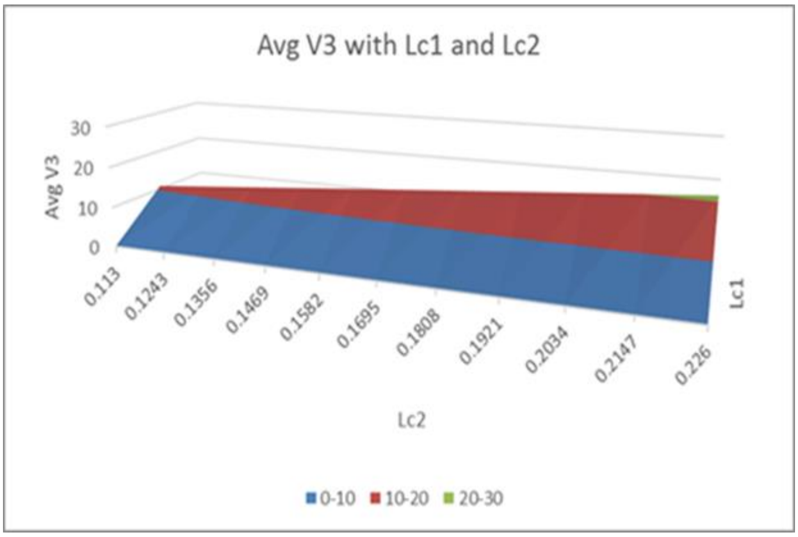

Figure 7. 3D fig Showing Relation of avgV3 with Lc1 and Lc2

5. Application

In future, digital sensing, communication, and processing capabilities will be ubiquitously embedded into everyday objects. In this new paradigm, smart devices will collect data, relay the information or context to each another, and process the information collaboratively using cloud computing and similar technologies. Finally, either humans will be prompted to take action, or the machines themselves will act automatically [14].

Wireless sensor technology plays a pivotal role in bridging the gap between the physical and virtual worlds. Sensors collecting data from the environment, generating information and raising awareness about context. There are many ocean sensor networks. Such as sampling network the Odyssey-class AUVs (AUV Laboratory at MIT Sea Grant), can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment. UW-ASNs can perform pollution monitoring (chemical, biological and nuclear). It may be possible to detail the water quality in situ analysis [15]. Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas [16]. One of the most important drawbacks of sensor node implementation for ocean environment monitoring is their powering process. As these are offshore, these need to be self-powered. In this case, powering ocean sensors from ocean itself through marine energy harvesting can be the most efficient way. The Figure 8 bellow shows how ocean energy harvester, BBDB can be applied to ocean sensor network application. The control circuitry, the transceiver and the sensor node itself needs small but consistent flow of electricity for specific interval of time. Providing power from base grid is quite impractical and use of battery supply is inconvenient in this case because changing battery will be a hurdle. Hence this small but consistent flow of electricity can be obtainable from the development discussed here and the timing requirements can be fulfilled by using battery storage.

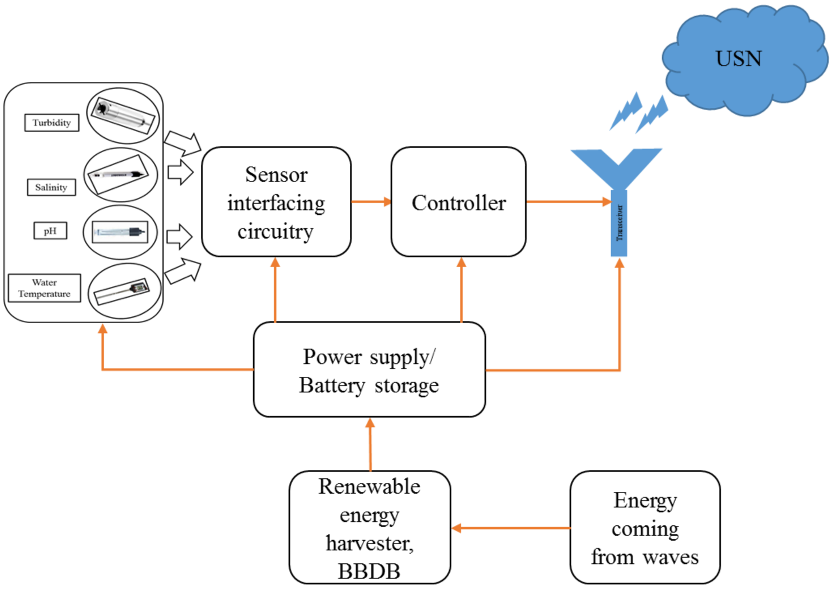

Figure 8. Block Diagram of Device Application for Providing Power to Sensor Nodes

6. Discussion

The proposed new structure has some beneficial characteristics then previous versions of BBDB. Firstly, as per system design, there will be no effect of outside atmospheric pressure on inside pressure calculation since the pressure difference is only between two chambers inside the device. So device installation will be quite easy. Secondly, unlike other inventions which are highly dependent on the direction of the incoming waves, this device because of double opening at opposite direction, can use the waves coming not only from one direction but also from the reverse direction. Thirdly, prior invented power generating systems with complex mechanism needs significant amount of additional costs at the time of manufacturing and installation to ensure the sustainability of the system in case of stormy ocean condition. But our system is of simple structure which is easy to manufacture, install and also needs less security, costing and maintenance effort. Finally, the power take off system remains inside the device ensuring better longevity for this energy converter than other WECs.

The study represents the new better idea for wave energy conversion and predicted performance on the basis of numerical analysis and MATLAB based simulated power calculation. Implementation of the idea needs higher simulation study and before application, lab based small scale wave tank testing. The study can be continued further to get result considering both the chambers. This is the result from only one chamber between the two. The betterment will be ensured if the difference in pressure or water levels inside the device can be made larger.

7. Conclusion

Sensor is an essential element for wireless sensor network. New device is designed specially keeping in mind to provide electric power to sensor nodes which need very small amount of electricity for powering themselves. Aquaculture industries and offshore ocean monitoring system which can be part of USN will need small but consistent flow of electricity for the sensor nodes they use. Present invention can easily provide these type of sensor nodes with necessary electric power through marine energy harvesting and without any sound or environmental pollution which could be harmful for fishes or other living species under the water. Thus this system can be called as environment friendly too. Figure 9 bellow illustrates a 3D image of such an application of the device for sensor nodes used in a fish farm.

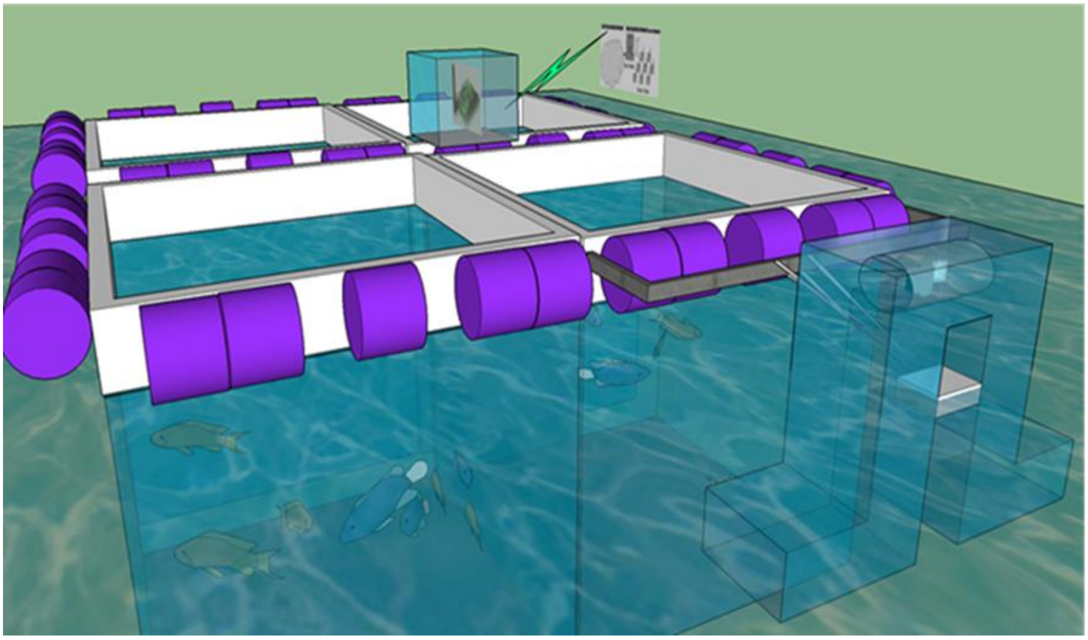

Figure 9. Application of Double Chambered BBDB for Fish Farm Sensor Node

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