Experimental Investigations on Performance Characteristics of Duct Extended Models of Backward Bent Duct Buoy (BBDB)

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Abstract: *An important characteristic of the sea is its wave energy potential which is a highly renewable energy source. Experimental results of a terminator type wave energy converter called Backward Bent Duct Buoy (BBDB), tested in a wave flume are prosecuted. The experiments are developed to study the motion response and pneumatic efficiency of different buoy duct configurations. It is found that the longer ducts may not necessarily improve the efficiency and different orifice openings also have an effect on the performance. In addition to efficiency, Response Amplitude Operator (RAO) for different buoy length is studied. Numerical investigations are also carried out using the Mission Operations Systems Engineering and Software (MOSES) to study the response motion. The experimental results are at variance with the predictions from MOSES computations. This may be attributed to the viscous damping effects, which the MOSES is unable to capture. The heave response is dependent on the duct length, which in turn affects the pneumatic efficiency of the BBDB. Air pressure efficiency is obtained by the displacement of water in the Oscillating Water Column (OWC) chamber which shows that at different wave periods better primary conversion efficiency is achieved by higher compression of air inside the chamber.*

Keywords: Wave Energy Converter, BBDB, MOSES, Pneumatic efficiency, RAO, OWC.

1. Introduction

To meet the growing energy demand and to reduce the dependency on fossil fuels in power production, renewable energy sources have gained importance. Wave energy is a renewable energy whereby we capture the energy that is being generated naturally by waves. The waves get their energy from the wind passing over the surface of the sea as well and can transmit energy over long distances with little degradation. Although wave energy is inexhaustible, the utilization of wave power is limited. Equipment to utilize wind, tidal, wave, geothermal and solar energy are under investigation. To capture energy from waves and thus convert it to useful mechanical energy, Wave Energy Converters (WEC) is used. Different wave energy devices like a frontward facing duct, centre pipe, Kaimei and Backward Bent Duct Buoy (BBDB) were investigated and their results showed that among all the wave energy devices BBDB might be a better wave energy conversion device [5]. BBDB is a terminator type; near shore floating oscillating water column device which uses the Oscillating Water Column (OWC) principle to convert wave energy into electrical energy [6].It consists of an L-shaped duct, a buoyancy module, an air chamber, a turbine, and a generator. Water comes into the duct through a rear opening and pushes the air in the air chamber. This oscillation of air pressure in turn drives a turbine, generating electricity [3].It is observed that the terminator type wave energy devices are associated with better primary conversion effects [7]. Since the BBDB has broad resonance ranges due to surge, pitch and heave motions, it has the advantage in view of wave absorption power compared with the conventional cylinder type OWC wave energy device [4]. Figure 1 explains the concept of BBDB.
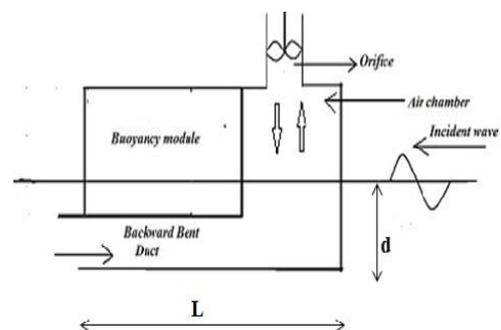

Figure 1.Concept of BBDB (adapted from Imai et al. 2010)

2. Dimensional Considerations of BBDB Model

The oscillations of the water column in the vertical air chamber (Δp) are dependent on the incident wavelength (λ), wave height (H), the depth of the draft (d), the length of the duct (L), the wave period (T), the depth of water (h), density of water (ρ_w), density of air (ρ_{air}) and viscosity (μ).

$$\Delta p = f(\lambda, H, d, L, T, h, \rho_w, \rho_{air}, \mu) \qquad (1)$$

The above variables may be grouped in the following non-dimensional groups

$$\frac{\Delta p T^2}{\rho_w \lambda^2} = \frac{H}{\lambda}\left(\frac{d}{\lambda}, \frac{L}{\lambda}, \frac{h}{\lambda}, \frac{\rho_w}{\rho_{air}}, \frac{\mu T}{\rho_w \lambda^2}\right) \qquad (2)$$

However, the ratios of d/λ, h/λ, ρ_w/ρ_{air} and $\mu T/\rho_w\lambda^2$, are not significant, hence

$$\frac{\Delta p T^2}{\rho_w \lambda^2} = \square\left(\frac{H}{\lambda}, \frac{L}{\lambda}\right) \qquad (3)$$

From the above dimensional considerations, it is observed that the pressure developed in the vertical air chamber depends mainly on the incident wavelength and duct length of the model. A prototype of the BBDB has been developed by the National Institute of Ocean Technology (NIOT). Scaling down the prototype is done using Froude scaling as the gravity forces are predominant. The model is undistorted with 1:8 geometric scale ratios (to adapt to the wave flume). BBDB model is made up of acrylic material and has a size of 462 mm x 280 mm x 255 mm (length, width and height) and weight of 10.44 kg shown in Figure 2. Two other models of varying duct lengths in increments of 50 mm, i.e., 512 mm and 562 mm are also tested. With the same shape and properties, models with two different duct lengths were fabricated. The total weight is maintained constant for all the models and the only parameter altered is the duct length. Stability of the floating body is very important to understand its behavior. Stability tests carried out both experimentally and theoretically show that the models are stable given in Table 1. The experiments were conducted in a regular wave flume at the Centre for Water Resources Laboratory, Anna University.
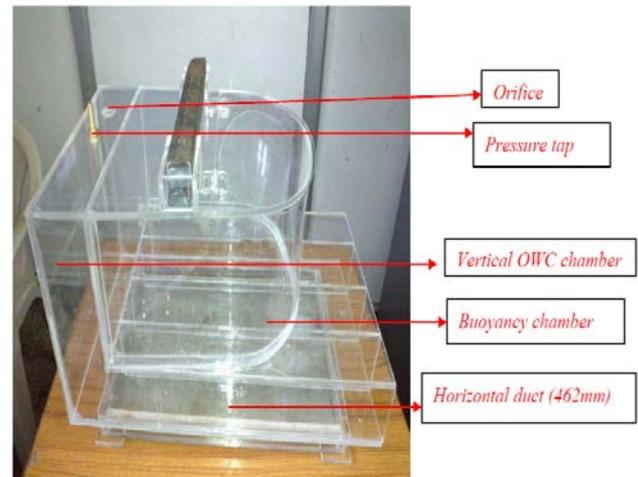

Figure 2. BBDB Model

Table 1. Stability calculations of BBDB models

Duct length (mm)	Mass (kg)	C.G. (mm)	GM$_E$ (mm)	GM$_T$ (mm)
462	10.46	75.43	43.85	45.88
512	10.66	54.43	69.71	73.73
562	10.83	54.92	83.52	85.70

Where,
C.G. – Centre of Gravity, GM$_E$ – Metacentric Height (Experimental) and GM$_T$ = Metacentric Height (Theoretical). The theoretical and experimental values are nearly equal (for example, GM from the analysis was 45.88 mm while the experimental value was 43.85 mm)

3. Hydrodynamic Behavior

A body floating on the surface of the sea is always in an oscillatory motion. The components of the linear body motions that a floating body experiences along the coordinate axes with respect to the centre of gravity of the floating body are called heave, surge and sway, whereas the angular displacements about the respective axes are roll, pitch and yaw shown in Figure 3 [1]. Among the above six components of motions, heave, pitch, roll motion are the motions that affect the operations of any floating object. The heave response is a prime factor in BBDB performance. Heave motion has to be higher for BBDB so that energy conversion is better. Heave response is obtained through an accelerometer. Heave Response Amplitude Operator (RAO) is the ratio of heave amplitude to the wave

amplitude. The heave RAO is considered as the important criteria in the motion studies of floating object. Calculations are similar for roll RAO and pitch RAO

$$\text{Heave amplitude (A)} = \frac{heave\ acceleration}{frequency^2} \qquad (4)$$

$$A = \frac{a}{\omega^2} \qquad (5)$$

Where, $\qquad \omega = \frac{2*\pi}{T}$

$$Heave\ RAO = \frac{A}{A_w} \qquad (6)$$

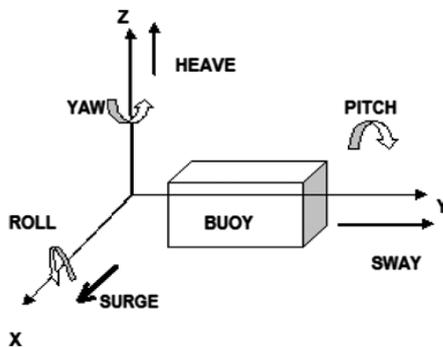Where a – heave acceleration, $\dot\omega$ - frequency, T – time period, A_W – Wave amplitude

Figure 3. Various motions of BBDB (adapted from Arif et al. 2010)

4. Motion Response

Motion response of scaled down BBDB models of various duct lengths namely 462 mm, 512 mm and 562 mm are obtained with the help of an accelerometer. The accelerometer used is a 3 axis digital low voltage linear accelerometer evaluation board. This accelerometer is capable of producing three different motions namely Heave, Roll and Pitch in a single observation. The accelerometer is fixed to the top of buoyancy chamber. The special features of the accelerometer are graphical user interface, USB connector, sensor, and LED indicators. The USB connector of the accelerometer is connected to the computer where it records the motions of the model. The software gives both the digital and graphical representations of motions. This motion response is indicated by RAO. Numerical investigations are carried out using ultramarine software called Mission Operations Systems Engineering and Software (MOSES). MOSES is a software system for hydrostatic and hydrodynamic analysis of all types of offshore platforms and vessels. It is widely used for simulation, analysis, transportation, and installation

of offshore structures as well as performing design calculations of floating objects.

5. Comparison of Experimental and Numerical Investigations

Experiments were conducted at different wave periods in the range of 1.33s – 2.25s and throughout the experiments the water depth of the flume is maintained at 0.6 m. The accelerometer is placed above the top plate of the buoyancy chamber. The accelerometer senses three different motions namely Heave, Roll, and Pitch. The sampling rate is 40 cycles/s. The experiments were conducted for about 120s. First the BBDB model with 462mm duct length was deployed and the readings were taken for a wave period of 2.25s and then the models with increased duct lengths, i.e. 512mm and 562mm were deployed at the same wave period and the readings are compared with MOSES software results. Similarly the models are deployed at various wave periods. Heave response of the models obtained from experimental and numerical investigations are shown in Figure 4. Pitch and roll responses are shown in Figures 5 and 6.
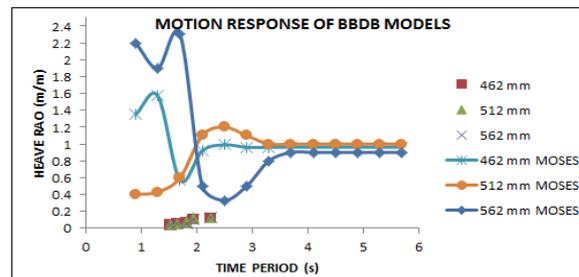

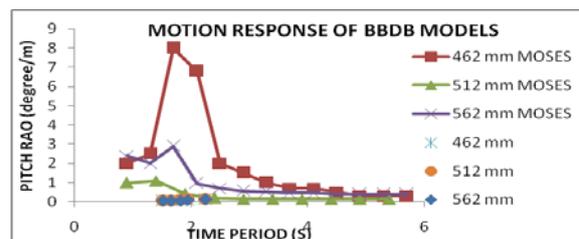**Figure 4. Heave RAO for BBDB models**
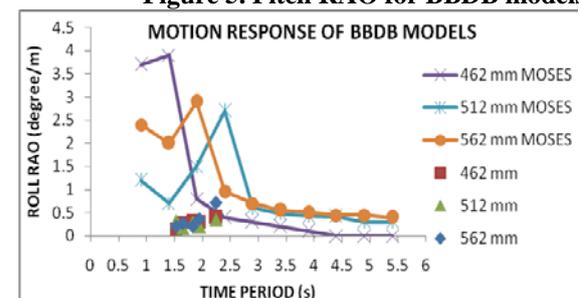

Figure 5. Pitch RAO for BBDB models

Figure 6. Roll RAO for BBDB models

The above figures show the motion response trends obtained using both numerical and experimental investigations. In experimental investigations, it is seen that at a wave period of 2.25s, 512mm duct extended model shows higher heave and pitch responses which is different from the numerical results. Hydrodynamic evaluation carried out by MOSES software shows that the 562mm duct extended model shows higher heave response at 1.5s wave period and 462mm duct extended model shows a higher pitch response at 1.8s wave period. Similarly the roll responses also vary in both the investigations.

6. Pneumatic Efficiency of Duct Extended Models

Pneumatic efficiency is the ratio of output power which is the product of pressure and velocity and input power which depends mainly on wave height and wave period. Duct extended models are deployed in the wave flume. The air pressure which forces out through the nozzle is captured using differential pressure manometer which has two probes one connected to air nozzle of the model and other open to atmosphere.
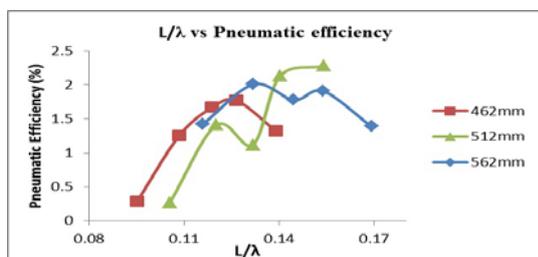

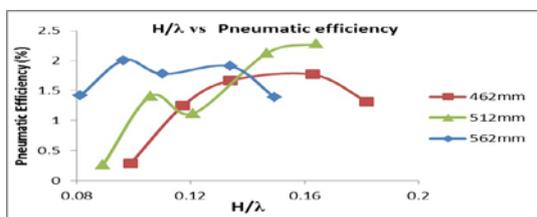**Figure 7. L/λ vs. Pneumatic Efficiency of BBDB models**

Figure 8. H/λ vs. Pneumatic Efficiency of BBDB models

The above figures which are drawn between dimensionless parameters L/λ (duct length/wave length), H/λ (wave height/wave length) and pneumatic efficiency (%) for duct extended models show that the efficiency values are higher at 14 – 15.4% of L/λ and 14 – 16% of H/λ.

7. Effect of Orifice Openings on Pneumatic Efficiency

The duct extended models are tested with different orifice sizes of 8mm, 10mm, 12mm, 14mm and 15mm at different wave periods. The orifice which gives better efficiency is characterized and analyzed. Figures 9, 10 and 11 show the graph drawn between pneumatic efficiency and orifice diameter at different wave periods.
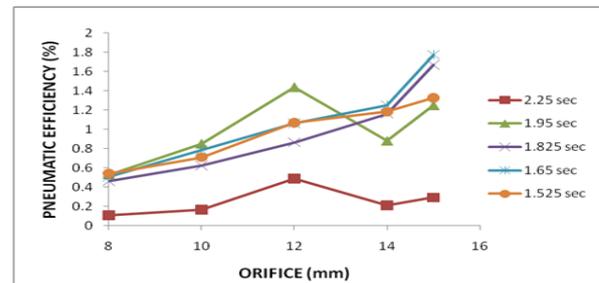

Figure 9. Pneumatic efficiency of BBDB model - 462mm

The above figure shows that 15mm orifice shows higher efficiency at 1.65s wave period. The model shows higher efficiency of 1.77% with 15mm orifice.
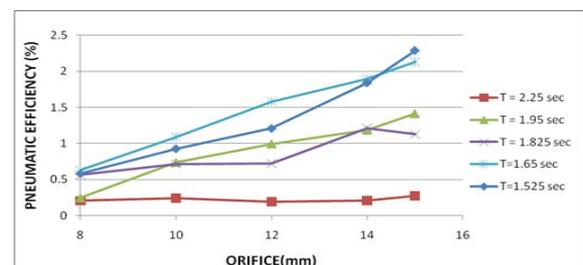

Figure 10. Pneumatic efficiency of BBDB model - 512mm

In the above figure it is found that at 1.525s wave period, 15mm diameter orifice shows higher efficiency of 2.28% for this model.
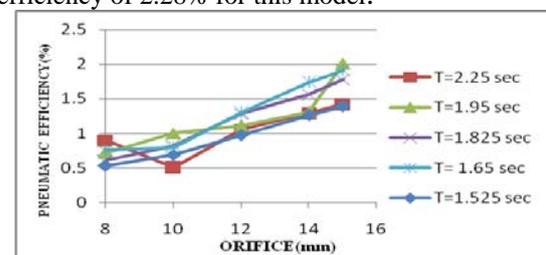

Figure 11. Pneumatic efficiency of BBDB model - 562mm

From the above figure it is found that at 1.95s wave period with 15 mm orifice diameter the 562mm duct model shows higher efficiency of 2%.It is observed that among the duct extended models 512mm model

shows higher efficiency with 15mm orifice and it is found to be optimal orifice diameter which gives better efficiency at various wave periods.

8. Study of Displacement in Oscillating Water Column Chamber

Pneumatic efficiency is obtained by tracking the oscillating water column (OWC) in the vertical air chamber of the BBDB models. The method resembles the working of a reciprocating pump wherein inside the vertical chamber of the BBDB model, the up and down oscillations of water surface takes place with air being expelled out or taken into through an air nozzle **[2].** A wave probe was inserted in the vertical chamber which was connected to the wave channel box and then to the NI Lab View wave recorder. The upward and downward displacement of the wave in the air chamber is recorded every $1/4^{th}$ second. At different wave periods the models with different orifices are tested and it is found that time period inside the oscillating column matches with the wave period in the flume. The wave height of the oscillating water column (H_{OWC}) and the wave height of the incident wave (H_w) is measured. The ratio of (H_{owc}/H_w) is plotted for different ratios of area of orifice (A_o) to area of vertical chamber (A_c). Figures 12,13 and 14 show the graph drawn between ((H_{owc}/H_w) and (A_o/A_c)
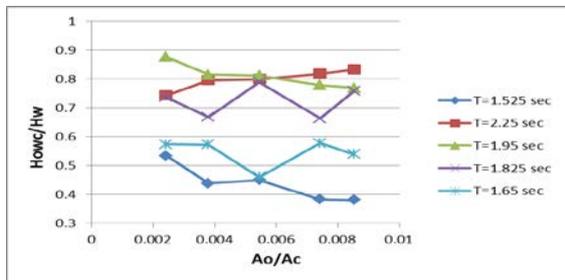

Figure 12. Displacement in OWC chamber of 462mm BBDB model

The above figure shows that at 1.95s wave period the 462mm model shows better displacement inside the chamber to achieve higher primary conversion characteristics.

Figure 13. Displacement in OWC chamber of 512mm BBDB model

The above figure shows that at 1.95s wave period 512mm model shows better displacement inside the chamber to achieve higher primary conversion characteristics.

Figure 14. Displacement in OWC chamber of 562mm BBDB model

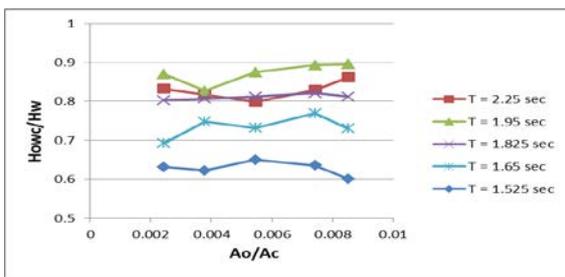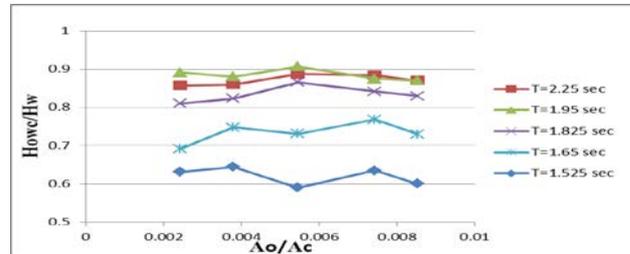The above figure shows that at 1.95s wave period 562mm model shows better displacement inside the chamber to achieve higher primary conversion characteristics. It is observed from the models that oscillations gets amplified at smaller wave period and dampened at larger wave periods.512mm duct length shows good oscillations inside the vertical chamber. At certain point the oscillation inside the column reaches the top of the chamber so the displacement curve flattens. This is because of the damping effect which reduces the performance of the extended models.

9. CONCLUSION

In this paper, motion response of duct increased BBDB model was studied using numerical simulation and laboratory model test. Heave and pitch responses in experimental investigations are higher for the 512 mm duct extended model, but in numerical investigations the heave responses are higher for the 562 mm model, pitch and roll responses are higher for the 462mm model. The results show that the peak values obtained from the experimental investigations are different from the numerical investigations. This may be due to the fact that the viscous damping effects are not considered in MOSES for the simulation and water entry into the duct cannot be sensed in this modeling as done in the experimental work. When the motion response results are compared with pneumatic efficiency test results of duct extended models it is found that higher pneumatic efficiency of 2.28 % is obtained from the 512mm duct extended model. Heave response greatly influence the conversion performance of BBDB. Higher the heave response, higher will be the performance characteristics. It is also observed that heave responses are directly proportional to the wave period. Pneumatic efficiency values were compared with the L/λ and

H/λ dimensionless parameters which show that 14-16 % of L/λ and H/λ provides better results. Orifice openings also has got influence on the primary conversion efficiency. Optimal orifice diameter is characterized and analyzed for the models. Displacement of water inside the oscillating water column is higher for 512mm duct model which reveals that higher the displacement inside the column, higher the air compression and higher is the efficiency.

10. SCOPE FOR FUTURE WORK

Experimental investigations of the BBDB models need to be done with different mooring conditions. With the mooring conditions, the behavior of the BBDB models, motion response and their influence on primary and secondary conversion efficiencies can be studied. Tracking of oscillating water column studies can be further extended by deriving numerical formulas and equations for displacements and air power output. This enables better understanding of functioning of oscillating water column and energy dissipation from the model.

11. References

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