Performance evaluation of power module during demonstration of wave-powered navigational buoy

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The article discusses performance of a power module in a wave-powered navigational buoy developed by National Institute of Ocean Technology. The power module of the buoy consists of an impulse turbine and a generator. Both unidirectional and bidirectional impulse turbine were tested for their performance. The article describes the selection, performance assessment tests and experimentation on these power modules carried out in the laboratory and in open sea trials. It was observed that unidirectional impulse turbine gave better performance than bidirectional impulse turbine for a given range of flow coefficient and pressure drop across the turbine. The performance of the wave powered navigational buoy in the open sea trials has given confidence on its use as a product and has also led to knowledge enhancement for scaling up floating wave energy devices.

Keywords: Impulse turbine, open sea trial, wave-energy, wave-powered navigational buoy.

Introduction

WAVE energy is one of the promising resources in renewable energy sector. The vertical motion of surface ocean waves contains a lot of kinetic (motion) energy that can be captured by wave energy technologies for generating electricity. Among the various technologies available for harnessing wave energy, one of the most popular is oscillating water column (OWC) principle based wave energy converter. OWC principle utilizes pressurization and depressurization of entrapped air column inside a wave energy device which causes the turbine coupled to an electrical generator to rotate thereby generating the electrical power. The National Institute of Ocean Technology (NIOT), MoES is actively involved in the development of various technologies related to wave energy with the aim of harnessing wave energy potential along the coastline of Indian mainland and islands. Recent focus on research and development related to wave energy has been on the floating type wave-energy-device, Backward-Bent-Ducted-Buoy (BBDB) which works on OWC principle. The air inhaled and exhaled by an OWC runs a power module comprising a turbine-generator assembly. OWC-based devices are challenging because the hydrodynamics involved for the floating body, the pneumatic behaviour of the air entrapped in the chamber, the mechanical performance of the turbine and the electrical power generating units, all need to perform in tandem and give best performance in sea. NIOT successfully carried out open sea trials on BBDB during 2011–2015 using unidirectional impulse turbine (UDI)[1]. The results and understandings from these experiences are paving the way for the development of higher capacity wave energy prototype.

Some of the studies related to development of power module for small capacity floating wave energy device are stated below. Pattanaik and co-workers[2] discussed the selection of power module generator and charging battery system for the NIOT floating wave energy device. George and co-workers presented the computational fluid dynamics (CFD) studies on 196mm diameter bidirectional impulse (BDI) turbine power module[3]. Various studies have been carried out globally on BDI turbine for wave energy. Liu and co-workers[4] did a parametric study of the turbine and time series analysis of measured data. Setoguchi and co-workers[5] did experimental work on performance with guide vanes of monovane type. While BDI has been used by many researchers, use of UDI was attempted in the wave powered navigational buoy.

A navigational buoy is commonly used in port/harbour to indicate ship movement in channels, dangerous rocks and for a variety of other navigational purposes. It houses a beacon lamp at the top for guidance. Conventionally, the buoy lighting systems consist of a battery system, flasher and solar panel. Solar panels are susceptible to vandalism and get affected by the salt in the seawater as well. Hence an enclosed power module based on wave energy was proposed.

Studies on performance behaviour of UDI and BDI turbines of similar capacity in open sea conditions for floating devices are limited. The present article discusses in detail the performance of these power modules when connected to the battery load system that serves the power requirement of various sub-systems in the wave-powered

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Table 1. Instruments used for measurement

Parameter	Location	Range and accuracy	Type of sensor
Turbine speed	On turbine shaft	0 to 3000 rpm ± 0.5%	Proximity sensor and frequency converter
Dp across turbine	Across turbine	–4 to 4 kPa ± 0.1%	DP transmitter
Generator voltage	Across generator	0 to 60 V ± 1.0%	Voltage transducer
Generator current	Loading system	0 to 50 A ± 1.0%	Shunt and current transducer

Table 2. Generator particulars

Particulars	Specification
Generator type	Permanent magnet direct current (PMDC) generator
Power	180 W
Voltage	48 V DC
Speed	1500 rpm

navigational buoy system. This article also briefly describes the open sea testing methodology of wave-powered navigational buoy deployed at the port's navigational channel.

Power module design

Initial sizing of turbine

The functional requirement of the wave energy device governs the sizing of the buoy and the turbine for generating the required power. The external geometry chosen for the wave-powered navigational-buoy is the same as the currently used navigational buoys. The power module has to be designed to capture the maximum power from the pneumatic power generated in the oscillating water column of the wave energy device. The sizing of the turbine was made after conducting numerous experiments in laboratory and in the open sea trials on a floating wave energy device called BBDB[1]. Experiments using orifices were conducted to find the initial size of the turbine during the sea trials. Three orifices of diameter 80 mm, 100 mm and 120 mm were used to mimic the equivalent damping (eq. (1))[6] posed by turbine with diameter 165, 196 and 218 mm respectively. Higher pneumatic power was generated for damping posed by 100 mm orifice.

$$\text{Damping } \beta = (\text{Dp} * A)/V_a, \quad (1)$$

where Dp is the differential pressure (kpa), A the area of orifice (m^2) and V_a is the axial velocity of air (m/s).

A 196 mm diameter impulse turbine (damping equivalent to 100 mm orifice) was then selected for further studies to be carried out numerically and experimentally. This turbine was coupled to a generator and tested in the oscillatory flow test rig at IIT Madras.

Laboratory testing of power module

The experiments were carried out in the oscillating test flow rig for finding out performance characteristics of the selected power module. The oscillating air flow test rig is based on crank-shaft mechanism which replicates the working principle of oscillating water column of air flow chamber where power module is operated for performance assessment. The test rig details are described elsewhere[7]. The system has operating capability to produce sinusoidal air flow with amplitudes from 0.2 to 0.6 m. The system can be set to run in different sinusoidal cycle periods ranging from 3 to 15 sec. The pneumatic pressure developed by the piston cylinder arrangement drives the turbine. It is powered with the help of electrical motors. The test rig has been equipped with the high speed data acquisition system and control programme with measuring instruments. The measuring instruments used in open sea trial and test rig for performance monitoring of power module are shown in Table 1.

To extract the maximum power from low wave climate to high wave climate in all weather conditions, the design of the electrical system of this power take-off system plays a vital role, and so proper sizing of generator and battery needs to be done. In order to select the generator to satisfy the above conditions, several experimental studies were conducted on this test rig. Based on the analysis, Permanent Magnet Direct Current (PMDC) generator was chosen and particulars of the same are given in Table 2. The schematic of power module power takeoff system from generator is shown in Figure 1.

Figure 2 shows the CAD image of the wave energy turbine. The wave generated is cyclic to extract the maximum energy of the wave and both UDI and BDI turbines were subjected to sea trial. In order to understand the response of the turbine in both the phases of a cycle in an oscillating water column, both UDI and BDI turbines having matching damping characteristics were tested in the test rig separately. Figure 3 shows the flow rate versus differential pressure characteristics of the turbines.

UDI turbine responds in one half of the wave cycle (i.e. exhaling phase) and during the other half (i.e. inhaling phase) the air is let in through separate flap arrangement. The BDI turbine is designed to work in both the cycles (has one stator at either ends) and hence it is expected to generate more energy per cycle. The particulars of turbine are listed in Table 3.

The turbines were tested in the lab for 0.2 m to 0.4 m stroke length for time periods ranging from 4 to 8 sec time period. Figure 4 shows a typical cycle of the UDI and BDI turbine for a time period 7 sec and 0.4 m stroke length.

As can be seen from Figure 4, BDI, in both the cycles, generate higher Dp for given input wave conditions. Peak speed remains relatively the same in both cases, but in case of UDI it falls to zero for other half of the cycle when it is non-functional, which is as expected. Peak electrical power generated is also the same for both UDI and BDI as can be observed from Figure 5. Again here in the case of UDI, power is not generated in the inhaling phase of the cycle. However, efficiency (eq. (2)) is observed to be lower in the case of BDI as higher Dp and hence higher pneumatic power is required for generating similar power. Efficiency at peak power is found to be around 0.7 and 0.2 for UDI and BDI respectively, for given time series and input conditions. Efficiency of power module for various flow coefficients (eq. (3)) is shown in Figure 6. Similar trends are observed for various input wave conditions. For achieving similar speed, higher Dp has to be generated across the turbine, leading to higher flow required for BDI as compared to UDI.

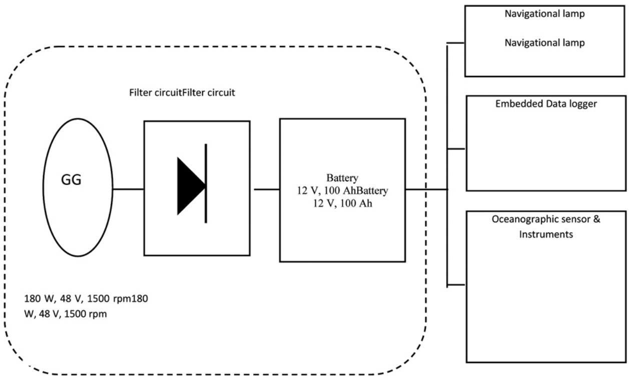

Figure 1. Schematic of power take off system.

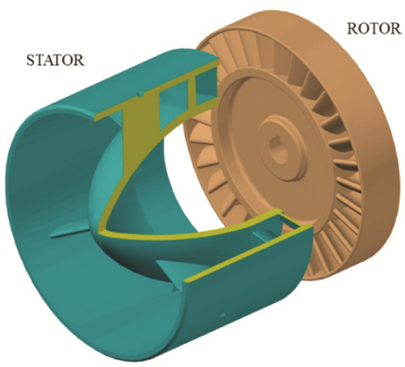

Figure 2. CAD image of the wave energy turbine.

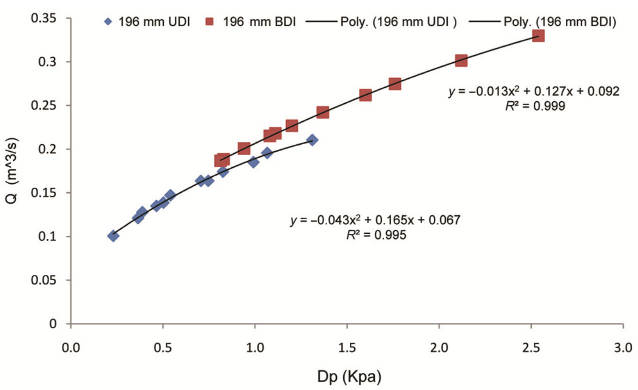

Figure 3. Flow rate versus differential pressure (Dp).

$$\text{Efficiency, } \eta = \text{Pe}/(\text{Dp}^*Q), \quad (2)$$

$$\text{Flow coefficient, } \phi = V_a/(0.5 * \omega * D), \quad (3)$$

where Pe is the generated electrical power (w), Q the volume flow rate (m^3/s), ω the angular velocity (rad/s) and D is the diameter of turbine.

Sea trials

Wave-powered navigational buoy

The functional requirement of navigational buoy, operational power requirement and the wave climate in the location of deployment decides the dimensions of a navigational buoy. The design of the navigational buoy was carried out to suit the 196 mm impulse turbine which was tested successfully in previous sea trials on BBDB of similar capacity. The OWC diameter decides the discharge and pressure across the turbine and hence plays a critical role in the overall sizing of navigational buoy. The numerical study was carried out in RANS based CFD commercial code STAR-CCM+. Physical model experiments were also conducted on scaled-down physical model of the navigational buoy in the wave flume for the various wave conditions. Both the numerical and physical model experimental studies for the buoy sizing are mentioned elsewhere[8]. Based on the structural, hydrostatic and experimental analysis carried out, hull design was finalized and fabricated in a shipyard. Wave-powered navigational buoy structure has four parts: Buoyancy chamber, oscillating water column spar, dome with power module and the mast. The buoy was fabricated of mild

Table 3. Turbine particulars

Particulars	UDI	BDI
Tip diameter (D)	196 mm	196 mm
No. of rotor blades	30	24
Chord length	34 mm	70 mm
Material	Polycarbonate	Polycarbonate

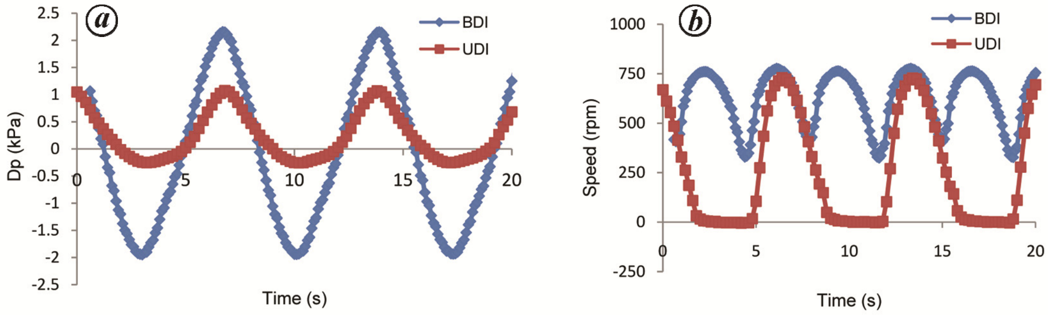

Figure 4. ***a***, Time series of Dp across the turbine; ***b***, Time series of speed across the turbine.

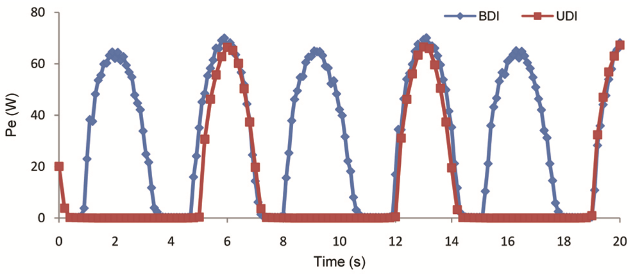

Figure 5. Time series of electrical power generated.

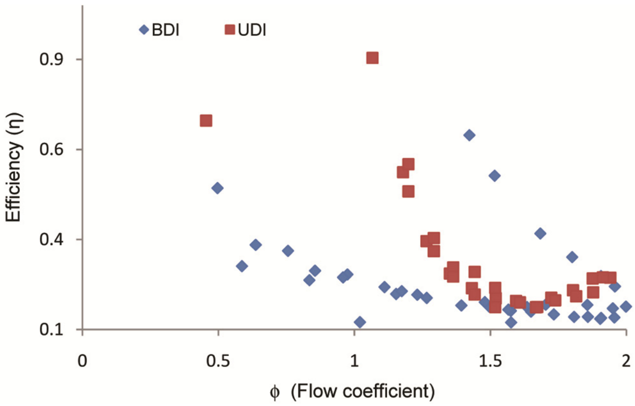

Figure 6. Efficiency versus flow coefficient.

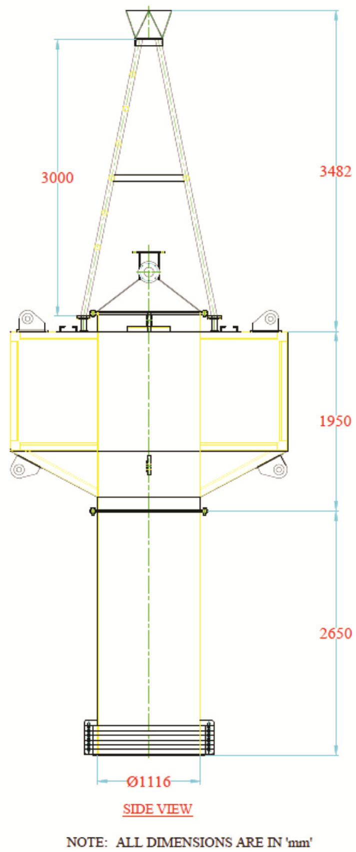

Figure 7. Line diagram of navigational buoy.

steel and painted with marine grade paint. The line diagram of buoy is shown in Figure 7.

The spar portion is open to the sea below the water level, so that when the wave passes over it the water level rises and the air gets pressurized. This pressure forces the air through an aperture at the top of the chamber and drives the turbine which is connected to the electric generator for the generation of electricity. The chamber can be shaped such that its cross-sectional area reduces towards the top creating a high-speed air flow required for driving the turbine from the slow moving surface of water. To keep the buoy in an upright position, a counterweight is attached at the bottom of the spar. Proper mooring arrangement was made for the station-keeping of the buoy.

Deployment and instrumentation description

The buoy was deployed during September–November 2017 and during August–November 2018 off south breakwater, the Kamarajar port in Chennai. Sub-members of buoy, hull consisting of buoyancy chamber, OWC, ballast weights, etc. were assembled at the port jetty. It was lowered in the calm water beside jetty. Power module, instruments, antenna, etc. were then integrated on the buoy. Mooring components were separately towed to the site and deployed initially at desired location. The buoy was then towed to the site and all the mooring ropes

Figure 8. Navigational buoy deployed near Kamrajar port.

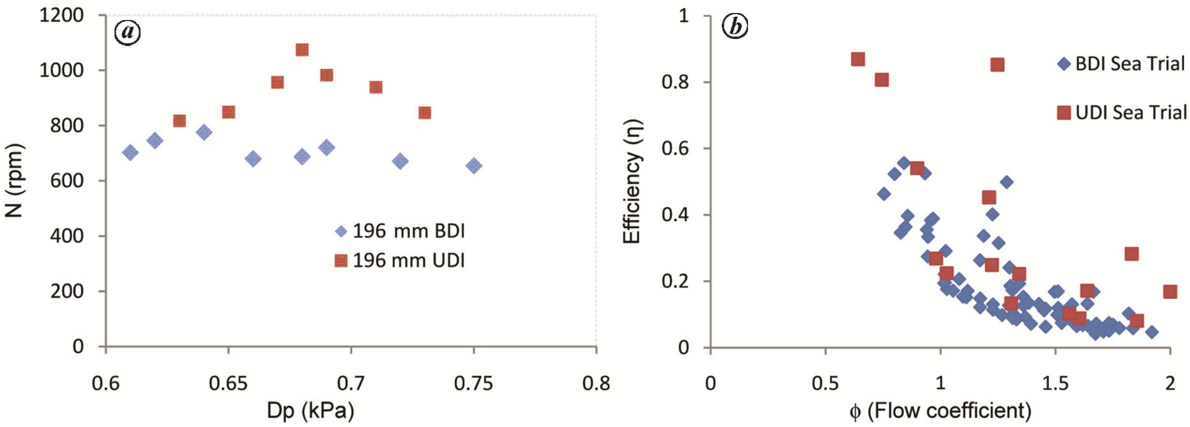

Figure 9. ***a***, Turbine speed versus Dp. ***b***, Turbine efficiency versus flow coefficient.

were connected to it. The buoy was deployed finally at a location off Kamarajar port near south breakwater as shown in Figure 8.

In order to monitor the performance of wave-powered buoy, sensors to measure voltage, current, speed and differential pressure across turbine, battery voltage and GPS/GSM were connected with the embedded data logger. The data logger is configured with five channels of 4 to 20 mA analog input. RS232 port is utilized for data capturing from external devices. Additional instruments such as wind and water current measuring sensors were also integrated in the buoy to measure oceanographic parameters in real time. The data in the form of an SMS was communicated to various users including port officials every hour. Additionally, detailed data are also logged in the NIOT FTP server. The logger was configured with sampling interval of 500 ms, and for every 2 min, a file was stored in a memory card. The GSM transmitter antenna was mounted at the top of the buoy. The complete arrangement was placed inside a waterproof steel box to prevent water leakage into the data logging unit. A wave rider buoy was deployed near the navigational buoy to record the wave climate simultaneously to assess input wave power.

Results

The testing was carried out for more than five months. Both UDI and BDI were tested for selecting the better power module that could optimally cater to power requirement of the wave powered navigational buoy system. Measurements included Dp, turbine speed, current, voltage, water level, etc. which were continuously logged to study the performance. Figure 9 shows performance comparison of both the power modules for similar wave

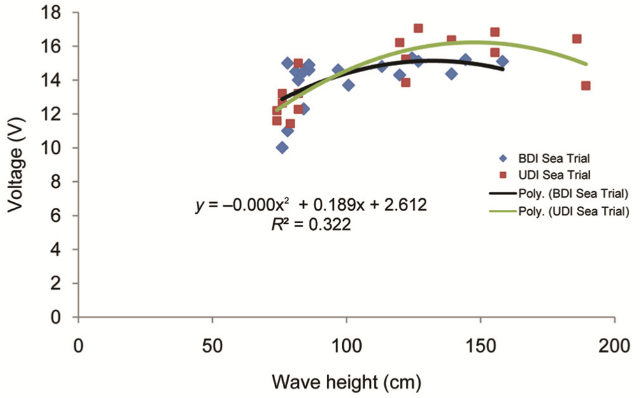

Figure 10. Generated voltage for different wave heights.

conditions measured during the testing period considering peak speed and peak Dp generated.

It was observed that rotational speed of UDI was a bit higher than that of the BDI for given differential pressure across the turbine as shown in Figure 9 *a*. Efficiencies are also observed to be higher in case of UDI for given phase of the cycle of operation as shown in Figure 9 *b*. As expected, the turbine shows lesser efficiencies for higher flow coefficients where they respond with less rotational speeds. Both the power modules were found to cater the energy need for powering the beacon lamp, measuring sensors and communication system in the wave powered navigational buoy system. Figure 10 shows the generator voltage when the buoy is subjected to different wave heights. As expected, higher wave conditions gave higher generated voltage. It may be noted that wave period also has an effect on OWC oscillation and buoy performance and hence the curve fits in Figure 10 may be assessed only up to wave height of 120 cm where no appreciable change in wave period is observed. Below the wave height of 70 cm the generated voltage is not enough to charge the 12 V battery.

Conclusions

The article discusses the development of power module for a floating wave energy device called wave-powered navigational buoy through laboratory testing and sea trials. The power module was designed and developed through a series of investigations carried out using orifices, laboratory tests in flow test rig and finally in the open sea trials of the buoy. Initial sizing and design of 196 mm diameter impulse turbine was arrived at using orifice tests and numerical study performed earlier. Then the fabricated turbines, both UDI and BDI, were tested in the flow test rig to characterize its behaviour. The power module was then integrated into the navigational buoy system for testing its real time performance in open sea. Both power modules catered to the power requirement of the system, however UDI was found to be more efficient and hence it is chosen as the power module for this buoy system. India's first-ever wave-powered navigational buoy is now ready for deployment in various ports in India. The transfer of technology to industries is currently underway.

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