Open Sea Trial of a Wave-Energy Converter at Tuticorin Port – Challenges

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Abstract— **A major challenge of ocean wave energy converter (WEC) development is to deploy it in the ocean. This article reports how a point absorber (PA) WEC, Sindhuja-1, was developed and tested in the ocean. The WEC was developed from concept, numerical modelling, and laboratory testing. The test site was the VOC Port in Tuticorin, India. The WEC consisted of a buoy, a spar, and a power take-off mechanism. The buoy diameter was 0.75m and the spar length was 10m. The whole designing and preliminary testing were done at the wave basin at IIT Madras. The system was transported to the site, and an initial test was conducted at the harbour area, where the water is calm and has a depth of more than 10m. A hired fishing boat pulled the system over the ocean surface to a location having a water depth of 20 m, a distance from the coast of 6 km, and wave heights of 0.5-0.8 m. The electrical and electronics components were insulated and covered by a cylindrical acrylic jacket to avoid water contact or rain damage. The system worked vertically and produced a power of about 100W.**

Keywords— **Marine energy, Open Sea trial, Point absorber, Wave energy.**

Abbreviation

CAD	Computer-aided design
CWR	Capture width ratio
OWC	Oscillating water column
PA	Point absorber
PTO	Power Take-off
WEC	Wave energy converter

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Symbol

A_{wp}	Water plane area
C_{PTO}	PTO damping
C_f	Capacity factor
C_{PTO}	PTO damping coefficient
C_{rad}	Radiation damping coefficient
d	Depth
D_b	Diameter of buoy
D_f	Draft
F_{am}	Added Mass inertia force
F_D	Damping force
F_{Ext}	wave excitation force
F_{Hyd}	Hydrostatic force
F_I	Inertia for force
F_{PTO}	PTO force
g	Acceleration due to Gravity
H	Height
H_s	Significant wave height
K_s	Hydrostatic Stiffness
M_{a33}	Added mass coefficient in heave direction
$\bar{P}_{av}$	Average power absorbed
$x, \dot{x}$ and $\ddot{x}$	Heave Displacement, Velocity, and acceleration
T	Time
T_p	Testing period
η	Efficiency
ρ	Density of water
ω_n	Natural frequency

I. Introduction

The world's increasing focus on renewable energy as a sustainable and clean alternative to fossil fuels has gained significant attention in recent years. Many countries have committed to transition to renewable energy sources, including India, which has seen significant growth in its renewable energy sector. India achieved its target of 175 GW of renewable energy capacity by 2022, focusing on solar and wind energy. In line with UN's sustainable development goals, India has recently set an ambitious target of 500 GW by 2030[1]. Ocean wave energy potential is 2 TW worldwide [2], making it an attractive alternative energy source due to its high energy density and predictability. With a more than 7500 km coastline containing 40 GW of wave energy[3], [4], India can harness this energy and contribute significantly to its energy mix.

A. *Wave energy development in India*

IIT Madras initiated wave energy research in 1983, and India established a pilot plant in 1991 at Vizhinzam [5]. A scaled model was tested at the site for forces and moment analysis, and the full-scale model of 1.1 MW was developed at Thangassery Harbour [6].

The National Institute of Ocean Technology (NIOT) conducted the first ever sea trial of floating OWC. The device was tested at the Kamarajar port in Chennai between 2011 and 2015 and was installed 3km from the port at a depth of 8 to 10m [7]. Power absorption was conducted using a four-point and single-point mooring system. The sea trials showed WECs are suitable for small power-required systems, such as navigational and surveillance devices.

B. *PAWEC development*

Experimental investigations were conducted to determine the power absorbed by a heaving buoy utilizing a Rack and Pinion-based Power Take-Off (PTO) mechanism [8]. A buoy was designed with a 60 cm diameter and 40 cm height to explore wave-structure interaction and hydrodynamic coefficients [9]. The experiment provided insights into the device's wave energy absorption and capture width ratio.

In further research, the same buoy was examined under irregular wave conditions while optimizing the PTO damping of the system[10]. They compared a standard buoy with a heave plate-attached buoy to analyse its stability and power absorption capabilities.

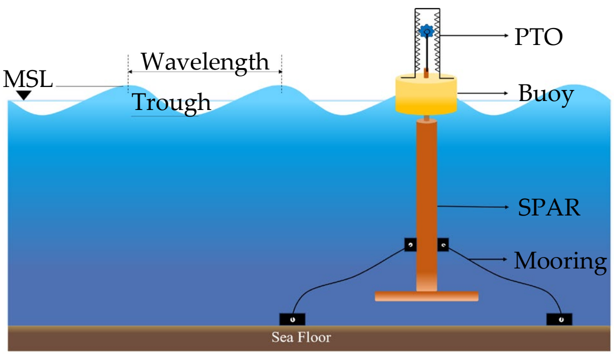

Fig. 1. Moored Point absorber assembly

II. Modelling of PAWEC

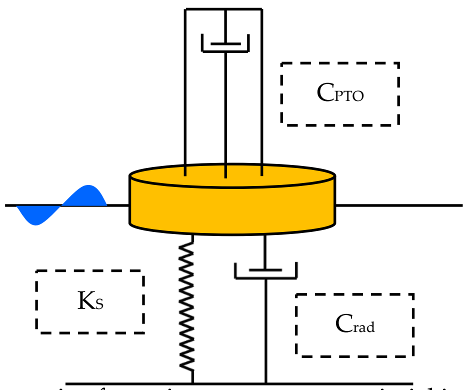

Fig. 2. Schematic of a spring mass system mimicking PA

TABLE I

Equations involved in the analysis of Heaving Buoy

Mathematical formulae	
$F_{Ext} = F_W \sin(\omega t + \phi)$	$F_{Hyd} = (\rho A_{wp} g)x = K_s x$
$F_{PTO} = C_{PTO}\,\dot{x}$	$F_{am} = M_{a33}\ddot{x}$
$F_D = C_{Rad}\dot{x}$	$F_I = M\ddot{x}$
$\omega_n = \sqrt{\dfrac{K_s}{M + M_{a33}(\omega_n)}}$	$\bar{P}_{ab} = \dfrac{1}{T}\int F_{PTO}\,x\,dt$

The superimposed hydrodynamic model and latching technique were used to optimize the power absorption [11]. Overall, these studies highlighted the extensive research on the heaving buoy and its PTO mechanism and the significance of its potential for wave energy absorption.

Point absorber wave energy converters (PAWECs) are conventional to install and has simpler dynamics compared to other kinds of wave energy converters and captures ocean energy from all directions. The assembly consists of three main components: a float, a spar, and a reaction plate. The float rides the ocean's waves and has a relative motion with respect to the spar, which provides stability and integrity to the structure. The reaction plate is connected to the spar, and its role is to provide resistance to the motion of the float. The mechanical energy generated by the motion of the float in the heave direction can be harnessed using a power take-off (PTO) mechanism. The PTO system consists of a rack and pinion in which linear to the rotatory electric generator is connected between the float and spar (Fig. 1). This PTO system converts the bi-directional heave motion of the float into a single-direction rotatory moment of the shaft. The shaft movement generates an electromagnetic flux as it moves with respect to the magnetic coil. This generated flux can be stored in a battery, allowing the converted mechanical energy to be used as electrical energy.

The device can have motion in six degrees of freedom: heave, sway, surge, roll, pitch, and yaw. However, for the purposes of mathematical modelling, we are only interested in the heave motion of the buoy, which is the vertical motion. It is assumed that the SPAR, a vertical cylinder with a lower centre of gravity than the buoy, has negligible motion compared to the buoy due to its geometry and higher mass. The buoy motion is akin to the harmonic motion of a mass-spring-damper system (equation 1). The buoy oscillates under the wave's excitation frequency, with its mass analogous to the system's mass, the stiffness of its structure equivalent to the spring constant, and the damping coefficient related to the energy dissipation in the system.

A PTO system is mounted on top of the device to convert the mechanical energy into electrical energy by having linear to rotatory motion. C_{PTO}, K_s and C_{rad} denote

PTO damping, Hydrostatic stiffness, and Coefficient of radiation damping (Fig. 2). By Newton's second law of motion above, physics can be mathematically expressed as equation (1).

$$F_{Ext} + F_{PTO} = F_I + F_D + F_{Hyd} + F_{am} \quad (1)$$

TABLE II

LIST OF POINT ABSORBER'S SEA TRIALS CONDUCTED BY VARIOUS ORGANISATIONS

S. No.	Name	Developing Organization	Location, year	Rated power	Summary
1	Aqua Buoy[12]	Aqua Energy Group, Ltd	Makah Bay, Washington, 2005	250 kW	D_b: 6m; D_f: 30m; Location: 5.9 km from the shore; d: 46m; and C_f: 12%
2	Lysekil project[13]	Swedish Centre for Renewable Electric Energy Conversion, Uppsala University	Lysekil, Sweden, 2006	10 kW	d:25m; Location: 2 km from Lysekil port Buoy type: cylindrical; D_b:3m; D_f: 0.8m and H_s: 2m
3	OPT PB150 [14]	Ocean power technology	North-east coast, Scottland, 2010	45 kW	T_p: One-month Sea trial Generated power: 45 kW (H_s = 2m); and in storm condition 400 kw and $\bar{P}_{ab}$: 150 kW
5	OPT APB 350[15]	Ocean power technology	New Jersey, USA, 2015	8.4 kW	T_p: 108 days. Location: 22.5 Km off the Atlantic coast of New Jersey and Total energy absorbed:1.3 MWh.
5	WaveEL buoy [16]	wave4power	Ålesund, Norway, 2016	NA	D_b: 8m; Testing period: Survival testing (12,000 hours) and functional testing (4,000 hours)
6	CorPower C3 [17]	CorPower ocean	Orkney Scotland, 2022	300 kW	H: 19m; D_b 9m; T_p: 18 months on-land trial
7	Wave Swing[18]	AWS ocean energy	Orkney, Scotland, 2022	16 kW	D_b: 4m; H:7m; T_p: 12-hour sea trial. Withstood 10 gales; $\bar{P}_{ab}$: 10 kW, peak power of 80 kW.
8	Sigma WEC [19]	Sigma Energy	Montenegro, Europe, 2022	5.2 kW	Sea trials were conducted at 6 locations. D_b: 2m; Phase 1: D_f: 0.4m, 15% ≤ CWR 18%, η: 84%; Phase 2: D_f: 0.8m, 11% ≤ CWR ≤ 17%, 74% ≤ η ≤ 99%.

The coefficients of added mass and Power Take-Off (PTO) damping play a vital role in the efficiency of motion of buoy. The added mass coefficient, which is a measure of the additional mass of water that moves with the buoy during its motion, depends on the geometrical characteristics of the buoy. The added mass coefficient affects the buoy's natural frequency, which is the frequency at which the buoy oscillates without any external force applied. Hence, it is essential to determine the added mass coefficient and tune the PTO damping.

The common experiences faced by participants [10-17] mentioned in Table 2 during the sea trial are as follows.

- **Environmental unpredictability:** The conditions in the ocean can be highly variable and unpredictable, making it difficult to simulate real-world conditions in laboratory tests accurately. In the lab, the device can be tested only with monochromatic waves, but in real sea conditions, the device has to interact with a multi-directional wave. This can lead to difficulties in accurately measuring performance.
- **Technical challenges:** Testing WECs in the ocean requires specialized equipment/sensor, which can record real-time data. Additionally, these WECs can be sensitive to wave and wind conditions, making it challenging to conduct consistent tests.
- **Safety concerns:** Testing devices in the ocean can present safety risks, as the equipment and personnel involved in the testing process must be protected from harsh sea conditions. Although all the sensor and measuring instruments are sealed and made leakage proof but sill due to the extreme conditions, failures can happen.
- **Cost:** As there is no Standard operating procedure for the launch/deploying of such devices, cost increases exponentially, and the risk of failure increases.

III. STEPS INVOLVED IN SINDHUJA-1 SEA TRIAL AT TUTICORIN

A. Design and Fabrication

Developing a new device requires a thorough and iterative approach to design (Fig. 3). The design process involved multiple optimizations that considered both feasibility and economics. The aim was to create a device that would be stable and have sufficient restoring force, which was achieved by ensuring positive metacentric height. The dimension of the buoy was also a key aspect of the design process. The final prototype had a diameter of 75cm and a height of 50cm. These dimensions are carefully opted to ensure efficacy and functionality. In free-floating conditions, the buoy was expected to float by maintaining a draft of 20cm. This was an important criterion of the design, as it ensured that the buoy would remain stable and not tumble.

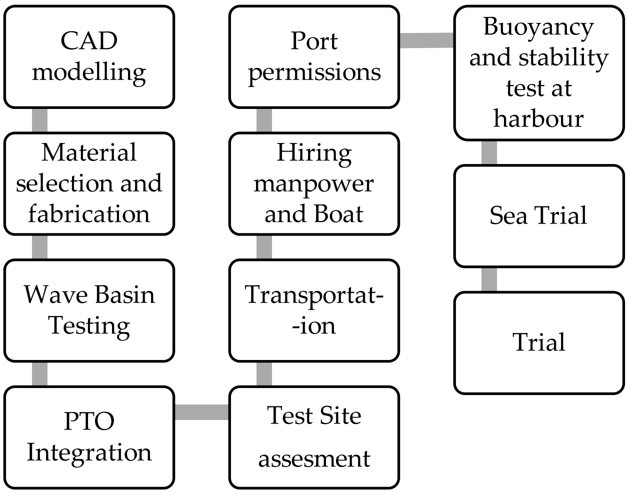

Fig. 3. Steps involved in sea trial testing.

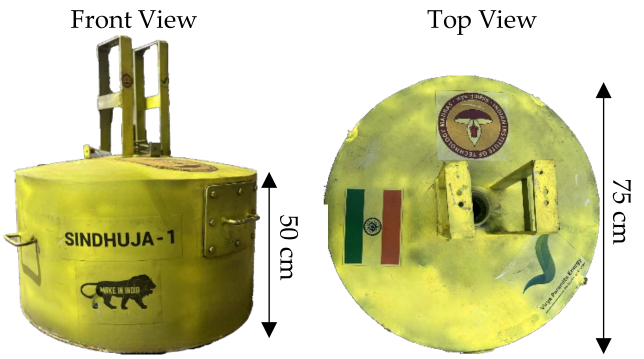

Fig. 4. Fabricated buoy

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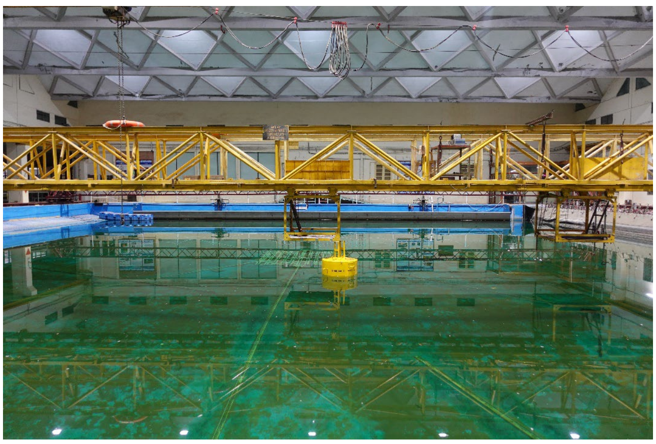

Fig. 5. Wave basin test for buoyancy and stability

During the designing process, material, manufacturing, and economics were decisive factors that enabled the fabrication of an efficient and cost-effective buoy. One of the key materials used in the fabrication of the buoy was SS 316 stainless steel. This material was chosen for its combination of high strength, corrosion resistance, and water resistance properties. While SS 316 has a similar density and strength to SS 304, it is better suited for use in marine environments due to its superior corrosion resistance.

B. Wave Basin Lab Test

The physical testing of the buoy involved leakage, buoyancy and stability tests in the IITM wave basin; the dimension of the wave basin was 30X30X3m. The leakage test was conducted over a duration of 24 hours to ensure that there were no leaks in the buoy. This was a crucial test, as any leaks would compromise the buoy's ability to maintain buoyancy, which is essential for its overall functionality. The centre of gravity (COG) was lowered by adding a ballast weight at the bottom to improve stability. This was an effective way to increase the stability and reduce the likelihood of it tipping over. The wave basin was used to generate waves of various amplitudes and frequencies to simulate real-world conditions. This test involved subjecting the buoy to various wave patterns and recording its oscillation to investigate fluid-structure interaction with the incoming waves.

For Spar, due to the limitation of the wave basin depth, as the spar is 10m long and the wave basin is only 3m deep, a leakage test was performed to ensure that the spar did not leak, and buoyancy was maintained.

C. Power-Take-Off Design

The design of a rack and pinion-based mechanical generator was crucial for optimising wave energy conversion. The generator was connected to a connecting-rod linked to a stable spar for testing. The focus was on fine-tuning PTO damping to maximise energy capture efficiency. The chosen design was reliable, easy to maintain, and efficient in converting wave energy.

D. Test Site Assessment

The wave properties, such as significant wave height and wave period, were determined. Tuticorin in mid-November was assumed as the desired location for the test, as it has been observed to have calmer waves compared to other nearby shorelines, including Chennai. The operation of fishing boats in some locations was halted due to severe rain warnings in November, but Tuticorin was found to have better conditions for the test. In addition to favourable wave conditions, there was easy access to workforce and necessary operational assistance, which was vital for the test's success.

E. Transportation and Legal Formalities

The transportation of the device was a logistical challenge. The device weighed approximately 300 kg, and the long spar added transportation complexity. Due to sufficient carriage capacity and the economics of the cargo train, all necessary permits and approvals were obtained to transport the device safely and legally. Port permission was one of the critical factors that needed to be taken seriously. Therefore, a list of all researchers and workforce was prepared before the visit, and the necessary approvals were obtained.

F. *Tuticorin Sea Trial*

The sea trial of the WEC was conducted in two phases to evaluate its performance and reliability. In phase 1, the device was tested for eighteen hours to check its buoyancy and stability in the harbour area, i.e., behind the breakwaters, where waves were calm. The spar was tested at a water depth of 10m and a reserve buoyancy of 1m above the sea water level, where the buoy and PTO assembly could be mounted. This phase of the sea trial was crucial in ensuring that the device was stable and could withstand the open sea conditions.

During phase 2, an open sea trial was conducted using a 20m steel fishing boat to drag the system to a location 6 km away from the coast, where a minimum water depth of 20m was available. This test aimed to verify that the device was fully floating. A cylinder made of acrylic was used to protect the PTO's sophisticated electronic components from water splashes. Data were recorded for 4 hours, and the power captured from the PTO was stored in a battery. Two LEDs were connected for real-time observation. The first LED indicated that the battery was charging, and the other LED connected at the top of the system displayed the instantaneous power captured by the device.

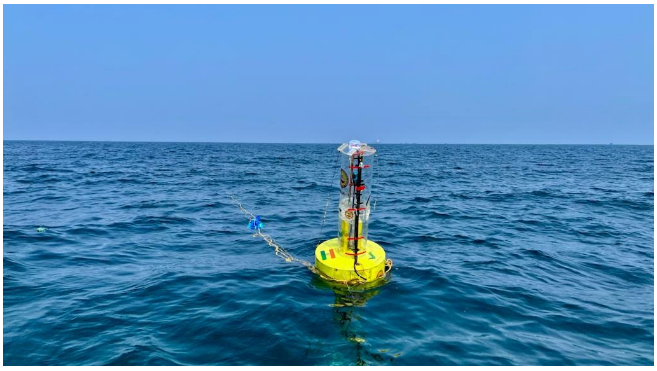

Fig. 6. Sindhuja-1 harbour testing and sea trial at 6 km away from the Tuticorin port.

During the open sea trial, it was observed that the buoy was constantly in heave motion, and the spar was almost stationary, indicating that sufficient restoring forces were provided. However, it was found that the relative motion between the spar and buoy was more than expected, and in higher waves, the buoy was hitting the stopper at the top and bottom. Despite this, the buoy and spar assembly performed exceptionally well, and the device demonstrated its ability to capture energy from the waves.

The sea trial of the wave energy harvesting device was a crucial step in evaluating its performance and reliability in the open sea. The two phases of the trial provided valuable insights into the stability and buoyancy of the device and its ability to withstand the open sea. The observations made during the sea trial will help further optimise the design and performance of the device and pave the way for commercialisation.

III. CHALLENGES FOR THE DEPLOYMENT OF WEC

The first-mover advantage of Sindhuja-1 in India comes with challenges and complications. These challenges include location selection, transportation, skilled workforce, operation costs, permissions and regulations, diver availability, lack of standardised operating procedures, and data recording.

- Choosing the right location for sea trials ensures the project's success. Factors such as wave height, wave period, swell, water depth, and current should be considered when selecting a location. The timing of sea trials is also important, as weather and environmental conditions can affect the device's performance.
- Transportation of device assembly to the desired port can also pose a challenge due to their size and weight. Specialised vessels and equipment are required to transport them, which can add to additional operation costs.
- Wave energy deployment is not a conventional process, which means that the workforce required to operate may not have the necessary skills. Operational costs can increase drastically due to uncertainties during deployment, such as unexpected delays, equipment failures, and additional labour costs.
- Compliance with government regulations and obtaining permission from port authorities can also lead to delays.
- A ship with a crane is required for the deployment. However, due to the lack of standardized operating procedures, an iterative process was followed, which lead to delays and complications.
- Professional divers are required to install and connect the mooring lines from the point absorber to the anchorage. But due to unconventional installation, it can be dangerous.
- Finally, collecting accurate data during sea trials is essential for evaluating the performance of the point absorber. However, collecting data in harsh ocean environments can be challenging, particularly when the sensor is underwater.

IV. FUTURE WORK AND RECOMMENDATIONS

- Developing an optimised and efficient power take-off mechanism that effectively absorbs high wave energy.
- Standardizing operating procedures for transportation and on-site deployment to streamline the process and reduce uncertainties and errors.

• Designing waterproof and rugged sensors that can accurately record data for extended periods, even in harsh ocean conditions.
• Collect extensive wave data to determine the optimal sea trial location and timing, ensuring the project's success.
• Optimizing the geometrical properties of the buoy to enhance fluid-structure interaction and maximize energy absorption.
• Conducting a comprehensive strength analysis of the spar and mooring system to ensure that the point absorber can withstand extreme sea states and operate safely and efficiently over the long term.
• Exploring alternative materials for buoy, SPAR, and mooring fabrication for better economics, reliability, and sustainability.

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