



Research paper

An isomorphic Froude scaling approach to bulbous-bottomed buoys in wave energy converters for smart floating cities

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ABSTRACT

Testing full-scale point absorber buoys with enhanced power absorption is challenging and crucial to improving their viability for applications in smart floating cities and marine infrastructure. Bulbous-bottomed (BB) buoys are efficient in hydrodynamics and power absorption for point absorber wave energy converters (PA-WEC). Their experimental validation demands adaptable scaling algorithms to facilitate model-scale tests. This study utilizes a state-of-the-art theoretical algorithm by combining Froude scaling with an isomorphic buoy design approach, facilitating model-scale tests to investigate whether the BB buoys would equally be efficient compared to the reference hemispherical-bottomed (C-HS) buoy when deployed and tested experimentally under identical conditions. Additively manufactured scaled buoy models were tested in a laboratory-scale wave flume in both regular waves (inside and outside resonance) and irregular waves, followed by a similarity analysis for performance prediction on the prototype scale. A feasibility study was also established to justify the BB buoy application in real-time PA-WECs. The BB buoys outperformed the C-HS buoys within and without resonance in regular and irregular waves, justifying that they can replace them for good. Under the same deployment and test settings, the model-scale BB buoy exhibited a 20–27 % greater heave motion than the reference without resonance. A full-scale BB buoy could absorb significantly greater wave power than the reference. The case study showed that a C-HS-to-BB transition resulted in a 35 % rise in the capture width ratio of a WEC. The WEC, combined with a 5G-IoT and LSTM network, could facilitate self-powered and self-sensing marine applications in a smart floating city.

1. Introduction

Smart floating cities have recently been proposed as a sustainable solution, and various projects have been anticipated for the coastal areas facing land shortages and rising sea levels (Kurniawan et al., 2024; Wright, 2023). The OCEANIX Busan and Maldives Floating City (Varga and Csiszárík-Kocsir, 2023) are breakthrough initiatives incorporating sustainable features such as water treatment, smart farms, smart transportation and renewable energy systems. These projects will be constructed on floating platforms adaptable to rising sea levels and provide housing to climate refugees. However, their feasibility in international

waters is still unclear due to the challenges related to legality, power supply, construction modularity, supply and waste management, community-based development, mooring and stability, environmental impact, flexibility, defense and law enforcement (Pereira et al., 2023). Future research significantly focuses on combining marine renewable energy systems with AI-assisted 5G-IoT networks, which can facilitate offshore renewable energy supply, self-powered and self-sensing coverage and monitoring of the floating marine infrastructure (Azam et al., 2021a).

Wave energy converters (WECs) are devices developed and deployed to capture and convert the energy from ocean waves into electrical power. A wide range of WEC classifications, such as oscillating water

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Nomenclature			
BB	Bulbous bottomed	H_s	Significant wave height
C—HS	Cylindrical-hemispherical	I	Moment of inertia
Hz	Hertz	K_h	Hydrostatic stiffness
J	Joule	L_{max}	Capture width
kW	Kilowatt	L	Sea water depth
kWh	Kilowatt hour	M	Buoy mass
LSTM	Long short-term memory	P_h	Hydraulic power
MTS	Mechanical Testing and Sensing	P_{abs}	Power absorption
m	Meter	P_e	Generator output power
N	Newton	$P_{max-irr}$	Maximum power in the irregular waves
PA-WEC	Point absorber wave energy converter	P_{pto-in}	PTO input power
PTO	Power take-off	p_h	High pressure
rad	Radian	p_l	Low pressure
RAO	Response amplitude operator	Q_a	Flow rate inside the actuator
RMS	Root mean squared	T_e	Energy period
s	Second	T_f	Frictional torque
<i>Greek letters</i>		T_g	Generator torque
α	Added mass	T_p	Peak wave period
β	Swash plate angle	V	Submerged volume
η_o	Hydraulic PTO efficiency	v	Piston rod velocity
λ	Wavelength	Z	Heave displacement
ρ	Seawater density	$\dot{Z}$	Heave velocity
ω_n	Natural frequency of buoys	$\ddot{Z}$	Heave acceleration
ω	Frequency of incident waves	<i>Subscripts</i>	
<i>Symbols</i>		<i>abs</i>	Absorption
A_p	Piston area	<i>e</i>	Electrical
A	Amplitude	<i>eq</i>	Equivalent
C_g	Generator damping	<i>g</i>	Generator
C_{pto}	PTO damping	<i>in</i>	Input
C_r	Radiation damping	<i>irr</i>	Irregular waves
C_w	Capture width ratio	<i>m</i>	Model scale
d	Buoy draft	<i>max</i>	Maximum
d_m	Motor's nominal displacement	<i>o</i>	Overall
D	Buoy diameter	<i>opt</i>	Optimal
F_e	Excitation forces	<i>out</i>	Output
F_{pto}	PTO forces	<i>p</i>	Prototype scale
f	Frequency	<i>pto</i>	Power take-off
		<i>rms</i>	Root mean square

columns, oscillating wave surge converters, point absorbers, attenuators and overtopping devices, play a crucial role in the marine renewable energy industry, leveraging the vast and consistent energy potential of ocean waves (Azam et al., 2024). Significant research has been conducted focusing on improving the efficiency, reliability, and cost-effectiveness of the WEC technology to make it a viable participant in the global renewable energy mix (Azam et al., 2023). Currently, a limited number of devices with capacities of a few megawatts are installed worldwide in several countries, as shown in Fig. 1.

Point absorber wave energy converters (PA-WECs) are currently the most widely investigated machines among oscillating body WECs due to their design flexibility, deployment versatility, operational adaptability and scalability. Besides optimizing their power take-off systems, the hydrodynamic design of their floating bodies plays a substantial role in achieving optimal wave power extraction (Potapenko et al., 2024). Various studies have been conducted using computational models and simulation software to investigate the floater design for PA-WECs over a wide range of wave conditions, and many optimal buoy designs have been developed so far. Gong et al. (2024) employed OpenFOAM® to conduct a computational investigation on the heave response of a lee-side box and demonstrated the effects of varying breadth ratio on the

hydrodynamic characteristics of its gap resonance. Mi et al. (2025) considered a 2D numerical wave tank model to investigate closely installed floating structures subjected to nonlinear wave loads and demonstrated the effects of changing amplitudes and peak wave periods on these nonlinear loads. Song et al. (2025) demonstrated a numerical recessing-type moonpool orientation to investigate the effects of nonlinear wave forces acting on multiple hulls deployed in close proximity.

However, the real-time research, development and deployment (RD&D) of WECs cannot simply rely on the simulations (Xu et al., 2024). Testing point absorber buoys with enhanced power absorption is challenging and crucial to improving their viability for applications in smart floating cities and marine infrastructure. In addition, their experimental validation is essential to verify their performance and substitute the conventional and less efficient buoys. Physical scale modeling has been frequently utilized in literature to facilitate the laboratory-scale testing of the buoys, as it is one of the most convenient and accurate methods after simulations.

Fonseca et al. considered a 1:32 scale model of a spar-buoy-type WEC for lab-scale tests in the Plymouth University ocean basin (da Fonseca et al., 2016). Orphin et al. conducted experiments on the 1:30 scale

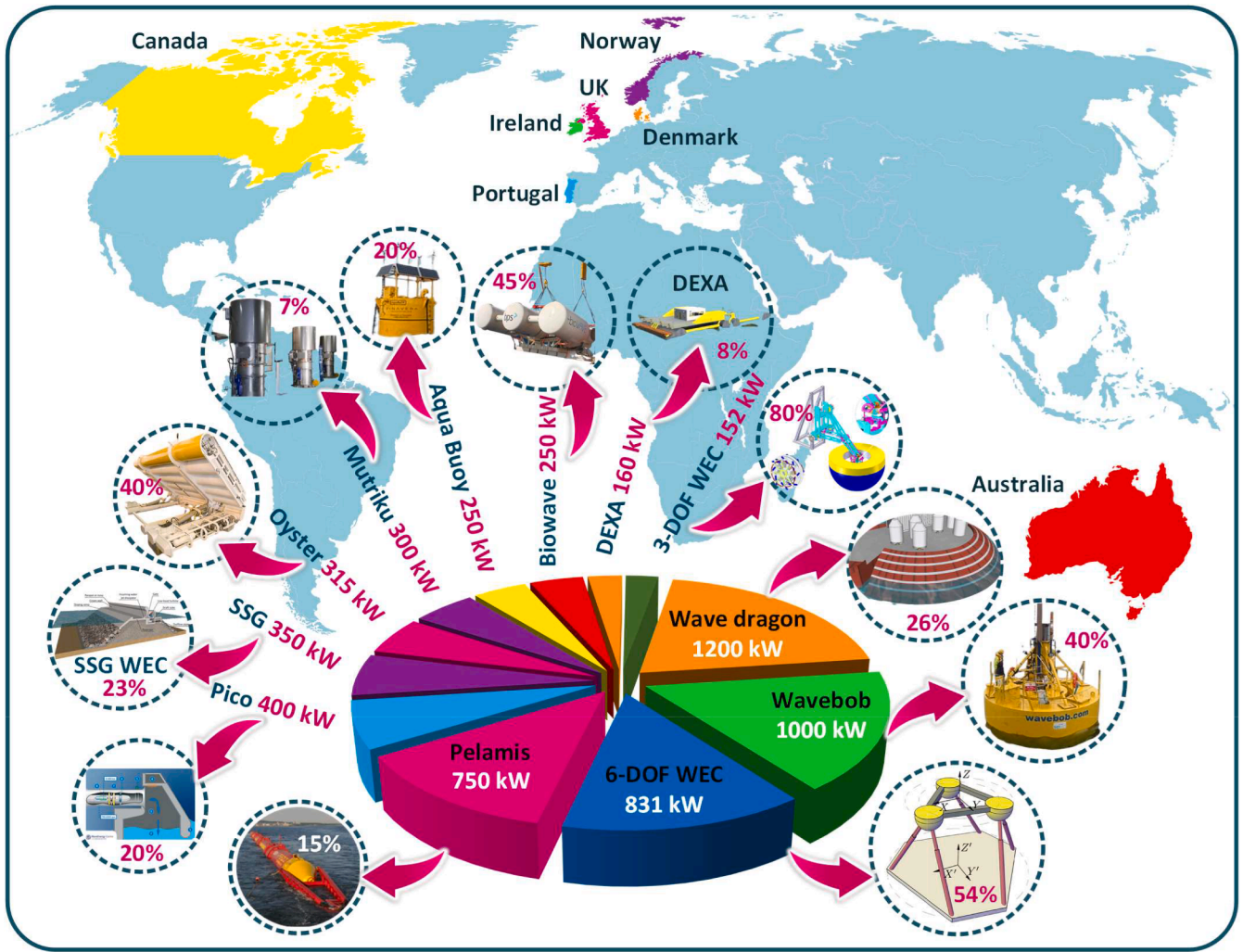


Fig. 1. Previously developed WECs, their power capacities, and hydrodynamic efficiencies.¹¹.

Table 1

Literature review on buoy geometry optimization without the Froude similarity analysis for PA-WECs.

Sr.	References	Buoy shapes	Numerically	Experiments	Froude scaling	Validation
1	(Beirao and Malça, 2014)	Cylindrical, spherical & conical	✓	×	×	×
2	(Pastor and Liu, 2014)	Hemispherical and conical	✓	×	×	×
3	(De Backer et al., 2010)	Conical and hemispherical	✓	×	×	×
4	(Amiri et al., 2016)	Conical & cylindrical	✓	×	×	✓
5	(Chiu and Cheng, 2024)	Ship-based buoys	✓	×	×	×
6	(Jin et al., 2019)	Cylindrical, hemispherical & conical	✓	×	×	×
7	(Chen et al., 2019)	Cylindrical & hemispherical	✓	×	×	×
8	(Ji et al., 2020)	Cylindrical & spherical	✓	×	×	×
9	(Shadman et al., 2018)	Cylindrical	✓	×	×	×
10	(Berenjkoob et al., 2019)	Cylindrical, hemispherical & conical	✓	×	×	×
11	(Tampier and Grueter, 2017)	Hemispherical	✓	✓	×	✓
12	(Guo and Ringwood, 2021)	Cylindrical, spherical & conical	✓	×	×	×
13	(Gao and Xiao, 2021)	Cylindrical, spherical & conical	✓	×	×	×
14	(Tao et al., 2021)	Cylindrical	✓	✓	×	✓
15	(Gao and Yu, 2018)	Cone-cylinder	✓	×	×	×
16	(Al Shami et al., 2021)	Cylindrical, spherical & derivatives	✓	×	×	×
17	(Li et al., 2022)	Cylindrical, hemispherical & conical	✓	×	×	×

model of the WEC model, implementing and suggesting an uncertainty analysis (Orphin et al., 2021). Li et al. used the Froude similarity law to develop and test a 1:5 scale model of a two-body PA-WEC at Shandong Provincial Key Laboratory of Ocean Engineering (Li et al., 2023). Khan et al. conducted a wave tank-based experimental study on a floating WEC with a moonpool on a 1:64 scale model of the MoonWEC, and the

laboratory test conditions were simulated and validated in OpenFOAM® (Khan et al., 2024). An acceptable agreement was found between the tested and simulated scenarios. Kim et al. conducted experiments on a physical 1:10 scale model of a hemisphere WEC array, followed by simulations to validate the experimental outcomes (Kim et al., 2023). The Froude similarity method was employed, and the test results agreed

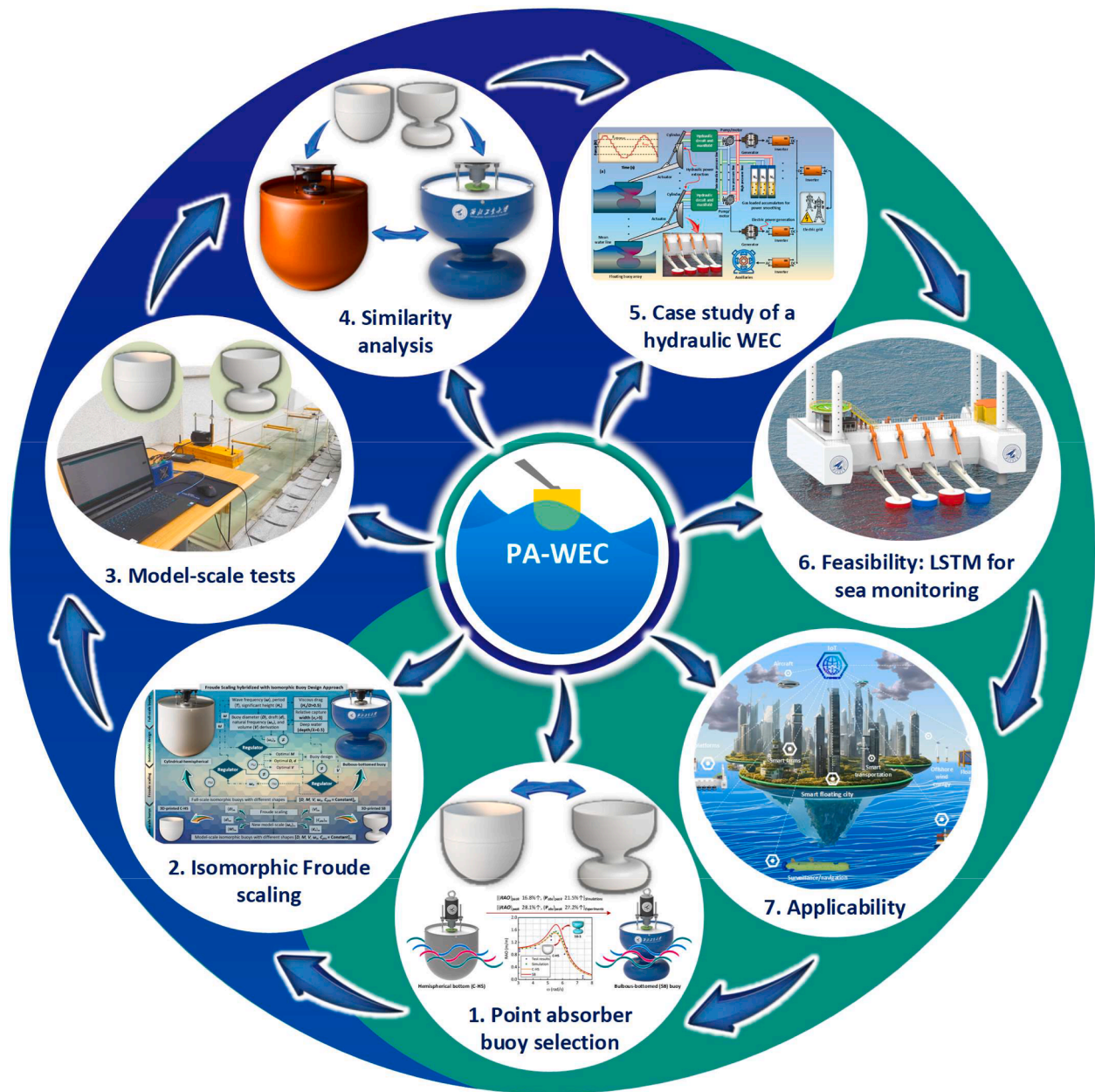


Fig. 2. Brief contents and organization of the current study.

well with the numerical analysis. Portillo et al. also applied the Froude scale to test a co-axial-duct oscillating water column on a 1:40 scale model to investigate its power performance (Portillo et al., 2023).

Li et al. investigated two-body and single-body PA-WECs in WEC-Sim, and the simulation model was validated through lab tests of 1:5 scale models using RAOs and capture width ratio to assess their hydrodynamic performance (Li et al., 2024). Mi et al. faced issues related to a requirement of high-strength materials, fabrication and precision control challenges while testing a full-scale oscillating surge WEC; therefore, the WEC comprising a PTO with belt-arc speed amplifier was downsized to a 1:10 scale model using Froude scaling followed by wave tank tests in regular and irregular waves (Mi et al., 2024). Ivana et al. scaled AquaBuoy and Pelamis WECs over a range of model scales using the Froude similarity for accessing their power absorption in the

Adriatic Sea (Martić et al., 2024). David et al. utilized 1:20 Froude-scaled physical experiments to validate the non-linear computational model for multi-degree-of-freedom WEC arrays (David et al., 2024). Shahroozi et al. discussed the environmental design load of a 1:30 scale PA-WEC through simulations in WEC-Sim, followed by its calibration through lab-scale wave tank tests (Shahroozi et al., 2022).

Hultman developed a robotic six-degree-of-freedom test bench to facilitate model scale tests of PA-WECs and calibrated it using the experimental data of a 1:20 scale PA-WEC through the Froude similarity law (Hultman and Salar, 2023). Chen et al. downsized waves on a 1:10 model scale through the Froude scaling to test a hybrid wave-current WEC prototype (Chen et al., 2022). Cheng et al. (2022) and Ning et al. (2024) used 1:20 Froude scaling laws to test the experimental models of hybrid OWC—OB-WEC system and multi-chambered turbine-based WEC, respectively. Attili et al. elaborated on the effectiveness of various Froude scaling approaches used to investigate wave energy devices, justifying that precise Froude scaling, where both fluid and structure properties are scaled, comes out to be an adequately effective approach

¹ The references to the WEC photos used in this figure are provided in the supplementary file.

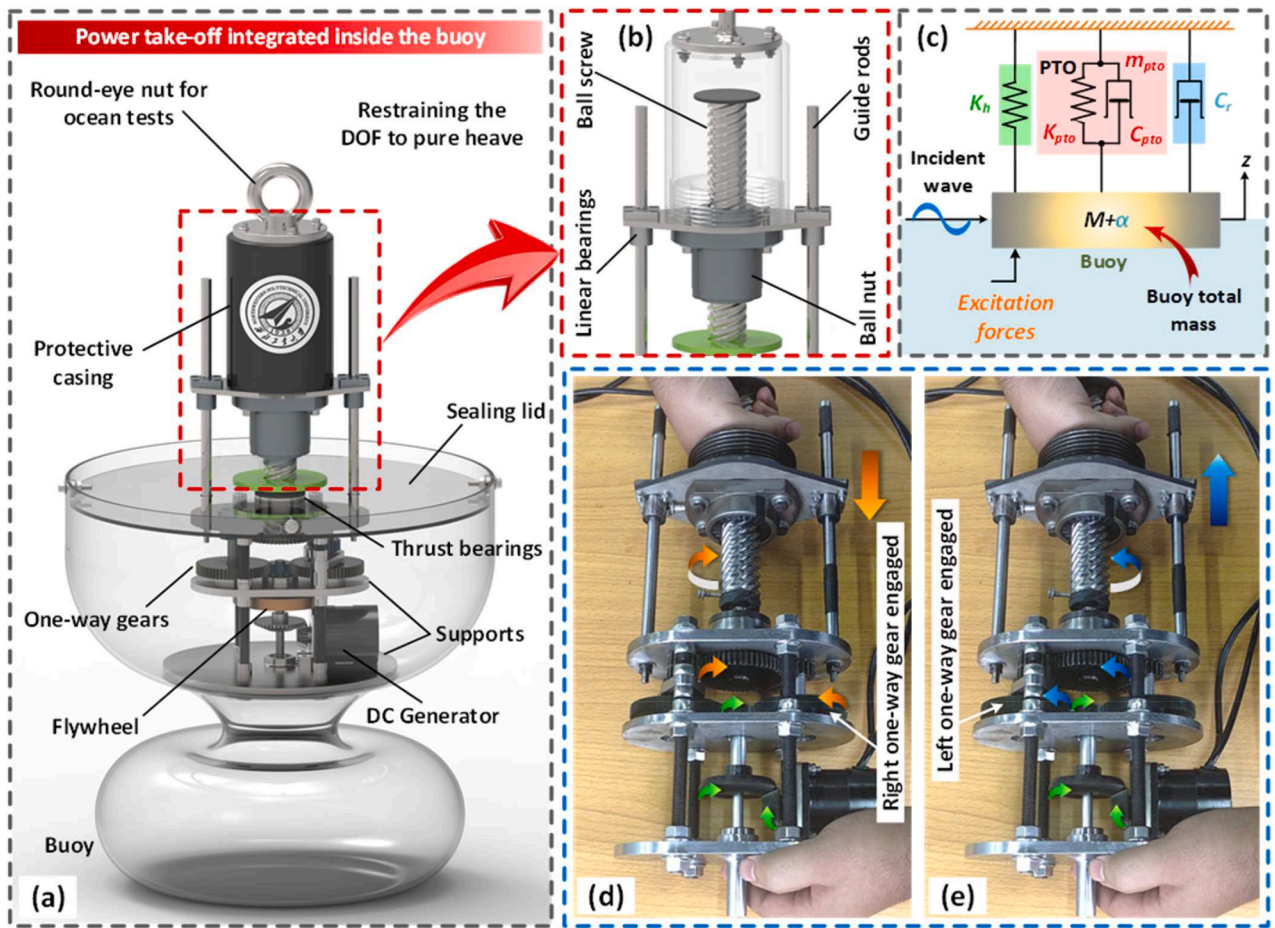


Fig. 3. The BB buoy investigated in (Ahmed et al., 2022, 2023a) (image re-used with permission).

to get accurate estimates of the prototype behavior (Attili et al., 2023). Wang et al. used 1:100 Froude scaling laws for lab-scale wave tank tests to investigate the damping coefficients of large floating structures, followed by a validity of the numerical computational model. The literature review conducted so far represents an acceptable implication of the Froude scaling algorithm for investigating various WEC devices (Wang et al., 2022). It also shows that the application of the Froude scaling laws has rarely been established to compare and examine the optimal buoy designs, specifically to evaluate whether the newly designed efficient buoy shapes can sufficiently replace the conventional buoys in real-time situations or not.

Several studies have been conducted to show that their unique and unconventional buoy shapes were efficient enough to replace conventional ones. For example, Azam et al. analyzed a combination of buoy shapes derived from a traditional cone, suggesting the Cyl-AS could better replace the cone (Azam et al., 2022). They also conducted lab-scale experiments on the Cyl-AS buoy in (Azam et al., 2023) without applying the Froude scaling laws to differentiate between the cone and its optimized derivatives. Similarly, Ahmed et al. investigated the effects of including a bulbous-shaped profile in the design of the floating body of a single-body PA-WEC through simulations (Ahmed et al., 2022). They found that the bulbous-shaped (SB-3, as in (Ahmed et al., 2022)) buoy with the most expansive round bottom was the most favorable replacement for the cylindrical-hemispherical (C-HS) buoy for achieving greater wave power extraction. The study lacked extensive experimental tests to justify the numerical results. Another study (Ahmed et al., 2023a) selected an S-shaped buoy to design a PA-WEC. The precise Froude scaling, however, was not implemented to get an authentic approximation of the buoy-shape-change improvements

against the reference. In a comparative numerical study, Berenjkoo et al. considered the modified conical and hemispherical buoys; the lab-scale experiments were not established (Berenjkoo et al., 2021). Similar investigations on the improved buoy designs are listed in Table 1, where the buoy shape-change effects were investigated numerically or through simulations only and not validated through model or prototype-scale tests at all.

In addition to recommending novel buoy shapes, it is critical to propose a practical investigative approach for evaluating the effects of pure buoy-shape changes experimentally so that their replacement could be advantageous in real-time scenarios. Even the application of Froude scaling alone is insufficient to estimate how much a novel buoy shape can outperform a conventional one in real conditions. There must be a scale on which two physical buoy shapes could be experimentally compared under identical design, deployment and operating conditions. Therefore, this paper not only applies the Froude similarity law for investigating buoy shape changes but also introduces an isomorphic design approach. The isomorphic design approach ensures that design, deployment and operational conditions are identical for all buoys under consideration to accurately analyze whether shifting the buoy shape from the conventional one to a superior one can be equally advantageous on both model and prototype scales. In this approach, the natural frequency (ω_n), power take-off (C_{pto}), operating mass (M), submergence volume (V) and diameter (D) of the full-scale buoys remain constant for all the shapes. These parameters get new values on the model scale but stay constant across all model-scale buoy shapes under consideration. The schematic of buoy design with identical parameters was previously implemented by Berenjkoo et al. (2021) and Ahmed et al. (2022) in their simulation-based studies to investigate the effects of changing buoy

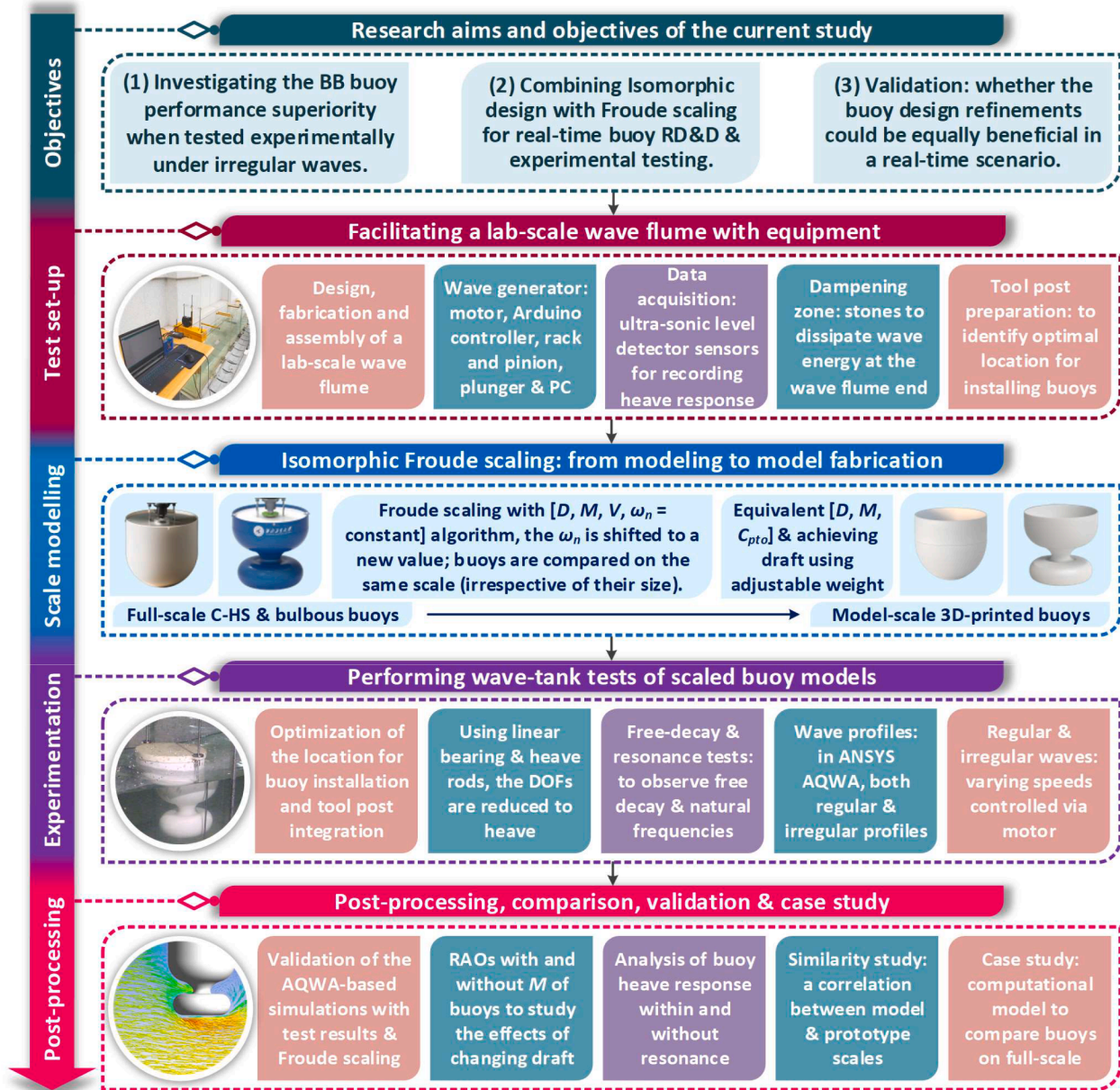


Fig. 4. Overall workflow and sub-contents of the current investigation.

geometries; however, the lab-scale experiments were not established to validate their results in real-time scenarios. This study extends their theoretical methods and merges Froude scaling with an isomorphic buoy design approach to ensure an accurate differentiation of buoys' hydrodynamic performance on an experimental basis.

Bulbous-bottomed (BB) buoys have been found to be outperforming cylindrical-hemispherical buoys in terms of their hydrodynamics and power absorption for PA-WECs (Ahmed et al., 2022). They have been investigated numerically only (in an ANSYS-AQWA-based simulation study), and their wave power extraction needs to be validated against the reference. Therefore, this study applies isomorphic Froude Scaling to Bulbous-bottomed (BB) buoys, facilitating model-scale tests to investigate whether the BB buoys would be equally efficient compared to the C-HS buoys when deployed and tested experimentally. Additively manufactured scaled models of the buoys were tested in a laboratory-scale wave flume in both regular waves (inside and outside resonance) and irregular waves, followed by a similarity analysis.

Overall, the objective function of this article is to introduce state-of-

the-art, robust, and accurate theoretical and testing models for investigating PA-WECs over a range of monochromatic and random waves to evaluate their efficiency enhancement mechanisms. The BB buoy application was justified through a case study based on a hydraulic WEC to analyze its viability for smart sea applications. An applicability study was performed on integrating a long short-term memory (LSTM) model into the WEC. The LSTM is a neural network model widely used to predict real-time environmental conditions using the models trained based on previously recorded datasets, such as structure response, wave height, wavelength, and wave period (He et al., 2024; Aslam et al., 2024). The LSTM model was used to collect, train, and categorize floater response data to distinguish calm and extreme sea states identified with a predefined threshold for the selected marine site. The WEC, combined with a 5G-IoT and LSTM network, could facilitate marine renewable energy supply and self-powered monitoring of the floating marine infrastructure. To be precise, this study aims to address the following major research gaps:

Table 2

Froude scaling and factors for similarity analysis.

Sr.	Definition	Derivation	Eq.	Description	Symbols
1	Froude number (Fr)	$Fr = \frac{v}{\sqrt{gl}}$	(1)	The ratio of the inertial force and the gravitational force (McCormick, 2009) and is used in the scale modeling of marine structures.	g = gravitational acceleration (9.81 m/s ²), v = structure's speed (m/s), l = characteristic length (m).
2	Drag coefficient (C_D)	$C_D = \frac{F_D}{0.5\rho v^2 A}$	(2)	A non-dimensional parameter used to estimate the drag forces.	A = area of the structure to be considered under low or high-speed regimes (m ²), F_D = total drag force experienced by the structure (N).
3	Power coefficient (C_P)	$C_P = \frac{P}{Fv}$	(3)	A non-dimensional parameter used to estimate power terms.	P = power (W), F = force (N).
4	Length scale factor (n_D or n_l)	$n_D = \frac{l_m}{l_p} = \frac{D_m}{D_p}$	(4)	The ratio of the diameters of the model and full-scale prototype.	D_m = diameter on the model scale, D_p = Diameter on the full scale.
5	Velocity scale factor (n_v)	$Fr_m = Fr_p$ $\Rightarrow \frac{v_m}{\sqrt{gD_m}} = \frac{v_p}{\sqrt{gD_p}}$ $\Rightarrow n_v = \sqrt{n_D}$	(5)	Equalizing Fr at model and prototype scales and simplifying. The ratio of v_m and v_p is called n_v .	v_m = speed on the model scale, v_p = speed on the full scale.
6	Time scale factor (n_t)	$\frac{v_m \sqrt{D_p}}{v_p \sqrt{D_m}} = 1$ $\Rightarrow \frac{D_m T_p \sqrt{D_p}}{D_p T_m \sqrt{D_m}} = 1$ $\Rightarrow n_t = \sqrt{n_D}$	(6)	Velocity (v) is substituted by the ratio of distance and time. The ratio of T_m and T_p is called n_t .	T_m = time on the model scale, T_p = time on the full scale.
7	Force scale factor (n_F)	$C_{Dm} = C_{Dp}$ $\Rightarrow \frac{F_m}{0.5\rho v_m^2 A_m} = \frac{F_p}{0.5\rho v_p^2 A_p}$ $\Rightarrow n_F = n_v^2 n_D^2 = n_D^3$	(7)	Equalizing C_D on model and prototype scales, and simplifying. The ratio of F_m and F_p is called n_F .	F_m = force on the model scale, F_p = force on the full scale.
8	Power scale factor (n_P)	$C_{Pm} = C_{Pp}$ $\Rightarrow \frac{P_m F_p v_p}{P_p F_m v_m} = \frac{n_P}{n_F n_v}$ $\Rightarrow n_P = n_F n_v = n_D^{7/2}$	(8)	Equalizing C_P on model and prototype scales, and simplifying. The ratio of P_m and P_p is called n_P .	P_m = power on the model scale, P_p = power on the full scale.
9	Damping scale factor (n_C)	$P_m = n_P P_p$ $\Rightarrow n_P = \frac{(C_{pto})_m \omega_m^2 z_m^2}{(C_{pto})_p \omega_p^2 z_p^2}$ $\Rightarrow n_C = \frac{n_P n_t^2}{n_D^{5/2}}$	(9)	From power scaling, the ratio of C_{pto} at model and prototype scales is called n_C .	m indicates model scale, p indicates prototype scale.

? To investigate whether the bulbous-bottomed buoys are equally efficient in wave energy extraction compared to the C—HS buoys when tested experimentally in irregular waves and out-of-resonance scenarios.

? How can the isomorphic design approach $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ be combined with the Froude scaling for the real-time development and experimental investigation of buoys?

? To validate whether optimal buoy design refinements would be equally beneficial if a PA-WEC is installed with a bulbous buoy in a real-time scenario.

Fig. 2 presents the brief contents and organization of the current study, which is structured as follows: Section 2 demonstrates the research methods, materials, and assessment models used in the wave tank tests. A case study was also established to justify the application of the C—HS and BB buoys in a hydraulic WEC through a comparative assessment. Section 3 includes the results and discussions, which can be categorized into three subsections: (i) the wave tank tests and similarity analysis; (ii) the case study, where the C—HS and BB buoys were comparatively assessed for a hydraulic WEC, and (iii) the applicability study, where the application potential and feasibility of the BB floater-based WEC was evaluated through integrating an LSTM model into the WEC for sea monitoring in smart floating cities. Section 4 discusses outlines, confines and future perspectives of this study.

2. Investigative procedure

2.1. Definition of point absorber buoys

The BB (a bulbous-bottomed buoy with the most expansive bottom (also known as SB-3 in (Ahmed et al., 2022))) and the C—HS (hemispherical-bottomed buoy as a reference) buoys were selected from (Ahmed et al., 2022) for the current investigation. The study conducted in (Ahmed et al., 2022) proposed that the BB (or SB-3) buoy, as shown in Fig. 3, was the most optimal design to achieve the highest wave energy extraction under both optimal and sub-optimal power take-off modes. The isomorphic design criteria $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ was used in our previous simulation-based investigation in (Ahmed et al., 2022) to design the buoys for making a comparison among their hydrodynamic characteristics. The detailed mathematical model involved in their geometrical derivation, {including draft (d), mass (M), diameter (D), natural frequency (ω_n) and submergence volume (V)} in accordance with the marine environment under consideration, is accessible in (Ahmed et al., 2022, 2023a) and also summarized in section S1 in the supplementary file. According to the isomorphic design approach $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$, the buoy shapes should be designed to have the same ω_n using the following algorithm (Ahmed et al., 2022; Berenjkoo et al., 2021): (i) the mass (M) of the buoys with the same diameter (D) should be the same and vice versa, and (ii) the submergence volume (V) of the buoys with the same D should be the same and vice versa. Also, the PTO should be the same for testing all buoy shapes.

2.2. Isomorphic design hybridized with the Froude scaling

The overall workflow and sub-contents of the current investigation are briefly described in Fig. 4. The basic mathematical description of the Froude scaling is summarized in Table 2. The subscripts m and p correspondingly represent the model and prototype (or full) scales.

Fig. 5 explains a simultaneous implementation of an isomorphic buoy design approach hybridized with Froude scaling to develop model-scale buoys from full-scale buoys. It can be described in simple terms, as given below: (i) the full-scale C—HS and BB buoys (designed and investigated under $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ conditions) were adapted from (Ahmed et al., 2022, 2023a). The criteria of

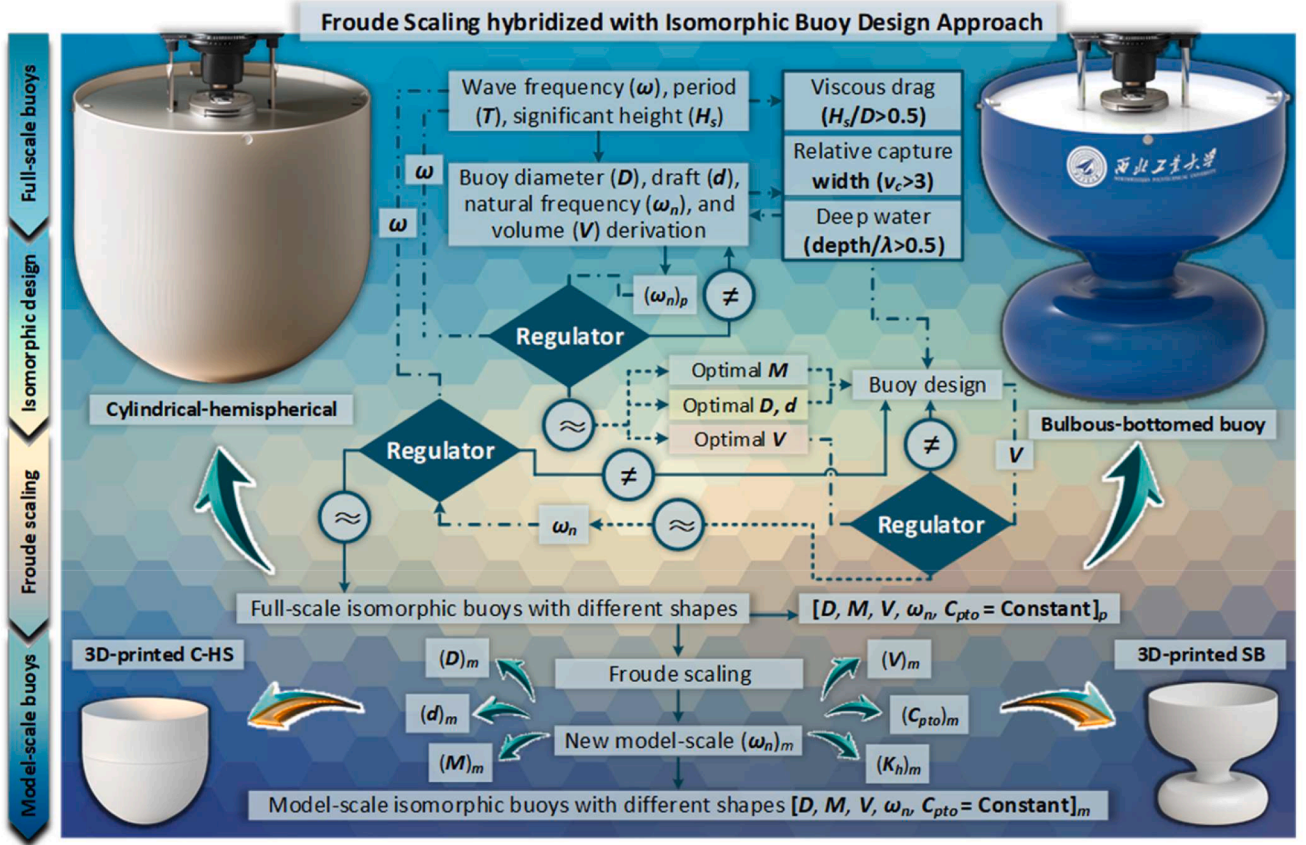


Fig. 5. Isomorphic buoy design approach hybridized with Froude scaling for experimental study.

Table 3

Implication of the Froude scaling hybridized with $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ criteria on buoys.

Selected buoys	D (cm) Based on real-time tests	d (cm)	ω_n (rad/s)	Empty mass (g)	M (kg)	C_r (Ns/m) at ω_n Computed	α (kg) at ω_n
Ref. Hemispherical buoy (C—HS)	18	11.04	8.764	487	2.4 ± 0.03	3.27	0.744
Bulbous-bottomed (BB) buoy	18	13.99	8.697	567	2.4 ± 0.03	2.9	0.95

$\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ was achieved through iterations while developing buoy CAD models in SolidWorks software, as illustrated in (Ahmed et al., 2022). It is worth mentioning that the conditions of viscous drag (Berenjkoob et al., 2019), relative capture width (Shadman et al., 2018), and deep water (Chen et al., 2019) were included in calculating the full-scale size of the buoys, as shown in Fig. 5. (ii) Froude scaling (demonstrated in Table 2) was implemented on the buoys to develop 1:8.33 scale models to ensure that the $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ conditions are still valid on the model scale. The subscripts m and p in Fig. 5 indicate the parameters on model and prototype scales, respectively. (iii) The wave height, period and resonance frequency of the model-scale buoys can be evaluated using $H_m = n_p H_p$, $T_m = n_t T_p$ and $\omega_{nm} = (g/(d_m + 2D_m/3\pi))^{0.5}$. (iv) The resultant scaled buoys along with the geometrical and design parameters after the implication of Froude scaling hybridized with $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ criteria are shown in Table 3. Fig. 5 and Table 3 are showing the implementation of isomorphic buoy design in conjunction with Froude scaling. The identical D , ω_n , M and C_{pto} parameters for both model-scale C—HS and BB buoys in Table 3 are the evidences of isomorphic buoy design approach.

2.3. Experimental set-up

The model-scale buoys (specified in Table 3) were fabricated through fused deposition modeling using R4600 resin. The buoys were designed to be hollow and have lids integrated with adjustable dampers at the center. Fine-grained stones were filled inside the buoys to attain the required $(\omega_n)_m$, operating mass (M_m) and draft (d_m). A lab-scale wave tank (characterized by a length of 500 cm, width of 46 cm and depth of 62 cm, as shown in Fig. 6(a)) was utilized to conduct the hydrodynamic tests of model-scale buoys under regular and irregular waves according to the standards given in (ITTC, 2002; Carapellese et al., 2023). This wave tank has already been used in previously published experimental studies (Azam et al., 2023; Ahmed et al., 2023a).

An oscillatory-type wave generator, as shown in Fig. 6(b), was operated through a DC motor integrated into an Arduino controller circuit to generate waves of various heights and frequencies. The wave profile and buoy displacements were measured and recorded through ultrasonic displacement recognition sensors (version HC-SR04) integrated with the PC through an Arduino controller circuit. The buoy lids were equipped with a pair of linear bearings, as shown in Fig. 6(c), and steel heave rods with a smooth surface finish were passed through these bearings to restrain the degrees of freedom of the buoys while achieving only heave motion during experiments. The upper ends of the rods were

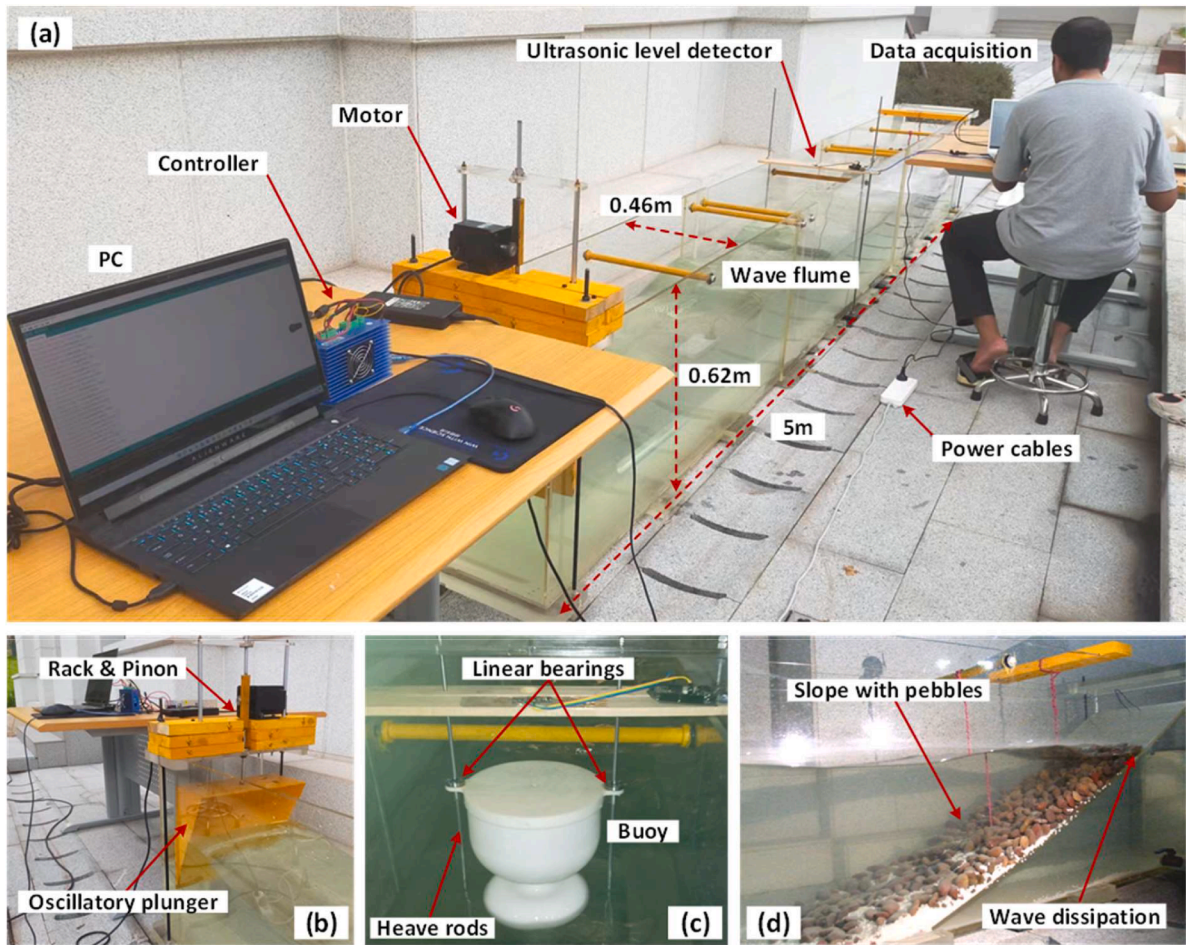


Fig. 6. (a) Experimental set-up consisting of a lab-scale wave flume, (b) the oscillatory plunger, (c) buoy installation and (d) the dampening zone.

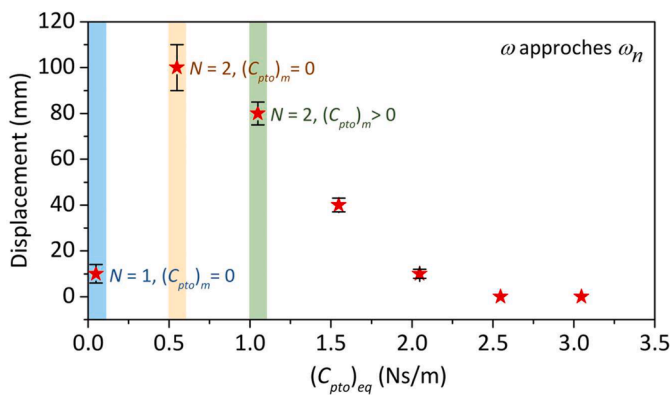


Fig. 7. The PTO damping adjustment study.

tightly clamped above the buoys.

The center of gravity (COG) and moments of inertia (MOI) of the empty and weighted buoys (with the required operating mass (M)) were calculated in Solidworks. A dampening zone was constructed to dissipate waves downstream of the wave tank using coarse small-to-medium-sized pebbles spread over a slope provided at the trailing end of the tank, as shown in Fig. 6(d). Efforts were made to achieve deep water assumptions, presuming the waves were completely dissolved due to the dampening effect.

Before installing buoys, a wave development study was conducted at variable frequencies, and wave profiles were recorded through ultra-

sonic sensors at several locations along the wave tank. Buoys were installed where the wave profile became stable and consistent, as discussed in Section 3. Natural frequencies $(\omega_n)_m$ of empty and weighted scaled buoys were initially calculated from CAD models in Solidworks and subsequently estimated through a series of wave tests conducted at multiple motor speeds after installing buoys. Finally, time-domain hydrodynamic analyses were run in ANSYS AQWA to further validate $(\omega_n)_m$ of the buoys. To minimize the experimental error and uncertainty in M and d , the required mass of the fine stones to be filled inside the buoys was empirically evaluated through iterations. An uncertainty analysis (Azam et al., 2021b) is included in the supplementary file (Section S2) to estimate an overall experimental error in the current study.

2.3.1. The PTO damping adjustment

An adjustable mechanical damper $(C_{pto})_m$ was utilized as a power take-off component fixed between the buoy lid and a rigid support above the floating buoy. The damping losses $(C_{pto})_h$ between the linear bearing and heave rod were calculated empirically through testing on a servo-hydraulic mechanical vibration testing machine. A pair of heave mechanisms consisting of a heave rod inserted inside a linear bearing (with a 0.5 cm nominal shaft diameter) was clamped inside an MTS test bench, and excitations were applied at various frequencies. The damping losses were calculated to be 0.024 ± 0.003 Ns/m from the force-displacement plots. These minor losses were also included in the resultant $(C_{pto})_{eq}$ during analysis, as shown below.

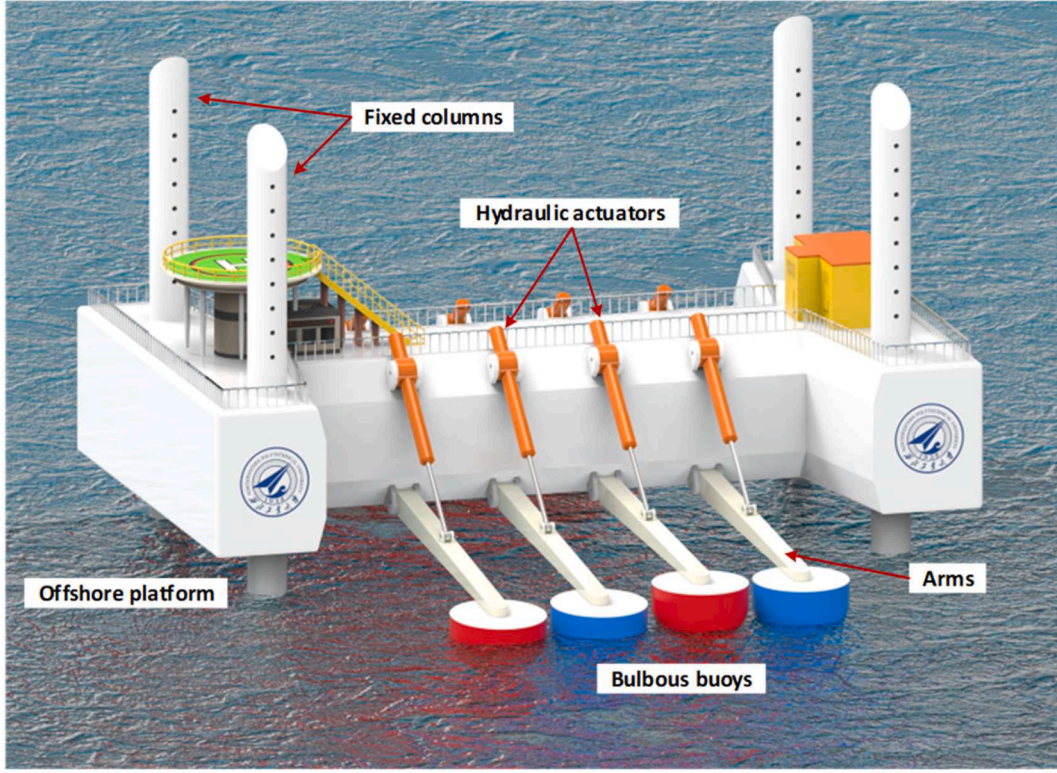


Fig. 8. A case study on a WEC with a hydraulic PTO against the BB buoys.

$$(C_{pto})_{eq} = (C_{pto})_m + \sum_{i=1}^N (C_{pto})_{hi} \quad (10)$$

where N is the total number of heave mechanisms used. A series of wave tank tests were conducted with and without the adjustable damper $(C_{pto})_m$. Fig. 7 shows the experimental results of buoy heave displacement against $(C_{pto})_{eq}$. The buoy exhibited a small displacement when the damper was not used ($(C_{pto})_m=0$), and only a single pair of heave mechanisms (that is $N=1$) was used. Under $N=2$ and $(C_{pto})_m=0$ scenarios, the buoy showed a maximum heave displacement of ~ 100 mm. When the damper was included, the total heave displacement was almost 80 mm at $(C_{pto})_m=1$ Ns/m, and reduced to its half when $(C_{pto})_m$ increased from 1 Ns/m to 1.5 Ns/m. Beyond that point, the buoy displacement began to drop exponentially. The region bounded by $1 < (C_{pto})_{eq} < 1.5$ was therefore considered optimal for subsequent experimental investigation according to the findings elaborated in (Azam et al., 2023). According to a previous study (Ahmed et al., 2023), the heave response of the buoys with varying profiles designed and tested under $[D, M, V, C_{pto}, \omega_n = \text{constant}]$ conditions can somehow accurately differentiate between their hydrodynamic performance. The experiments were performed to justify the computational study of the buoys scaled through the Froude scaling under isomorphic design conditions (Ahmed et al., 2022).

2.4. The WEC computational model

The mathematical representation of a single-body PA-WEC hydrodynamics under heave motion can be given as,

$$\mathbf{F}_e(t) - \int_{-\infty}^t \mathbf{F}_r(t-\tau) \dot{\mathbf{Z}}(\tau) d\tau + \mathbf{F}_h(\mathbf{Z}) + \mathbf{F}_{pto}(\dot{\mathbf{Z}}) - \mathbf{F}_d(\dot{\mathbf{Z}}) = (\mathbf{M} + \boldsymbol{\alpha}) \ddot{\mathbf{Z}} \quad (11)$$

where Z indicates heave motion; F represents forces with subscripts e , r , h , pto and d highlighting excitation, radiation, hydrostatic, power take-off and drag components, respectively; M is the WEC mass; and α is the added mass. The force F_d was included in the analysis similarly to that utilized in (Ahmed et al., 2023). The computational framework used in the simulation study of the buoys in (Ahmed et al., 2023) was used on the model scale in the current study. Simulations were performed in the hydrodynamic diffraction solver in ANSYS AQWA to compute F_e , RAO, α and radiation damping (C_r). The following mathematical model was used to conduct a power performance assessment of the model-scale buoys. From (Ahmed et al., 2023; Wang, 2020), power absorption P_{abs} was calculated by,

$$P_{abs} = 0.5 C_{pto} \frac{F_e^2}{[C_r + C_{pto}]^2 + \left[\omega(M + \alpha) - \frac{K_h}{\omega} \right]^2} \quad (12)$$

The incident wave power flux, to which the buoys are subjected for wave energy extraction in irregular waves, can be given by (Ahmed et al., 2023),

$$P_{max-irr} = \frac{\rho g^3 H_s^2}{32 \omega^3} \quad (13)$$

The capture width ratio (C_w) can be obtained by (Azam et al., 2022),

$$C_w = \frac{P_{abs}}{P_{max-irr} \times D} \times 100 \quad (14)$$

2.5. A case study

The Wavestar® C6-600 kW (Niels and Hansen, 2000) uses hemispherical-bottomed buoys integrated with hydraulic power take-off. The current study compares bulbous buoys against hemispherical buoys using identical design and test conditions. Therefore, a case study was conducted, where a WEC similar to the Wavestar® C6-600 kW was modelled using the BB buoys against a hydraulic PTO to

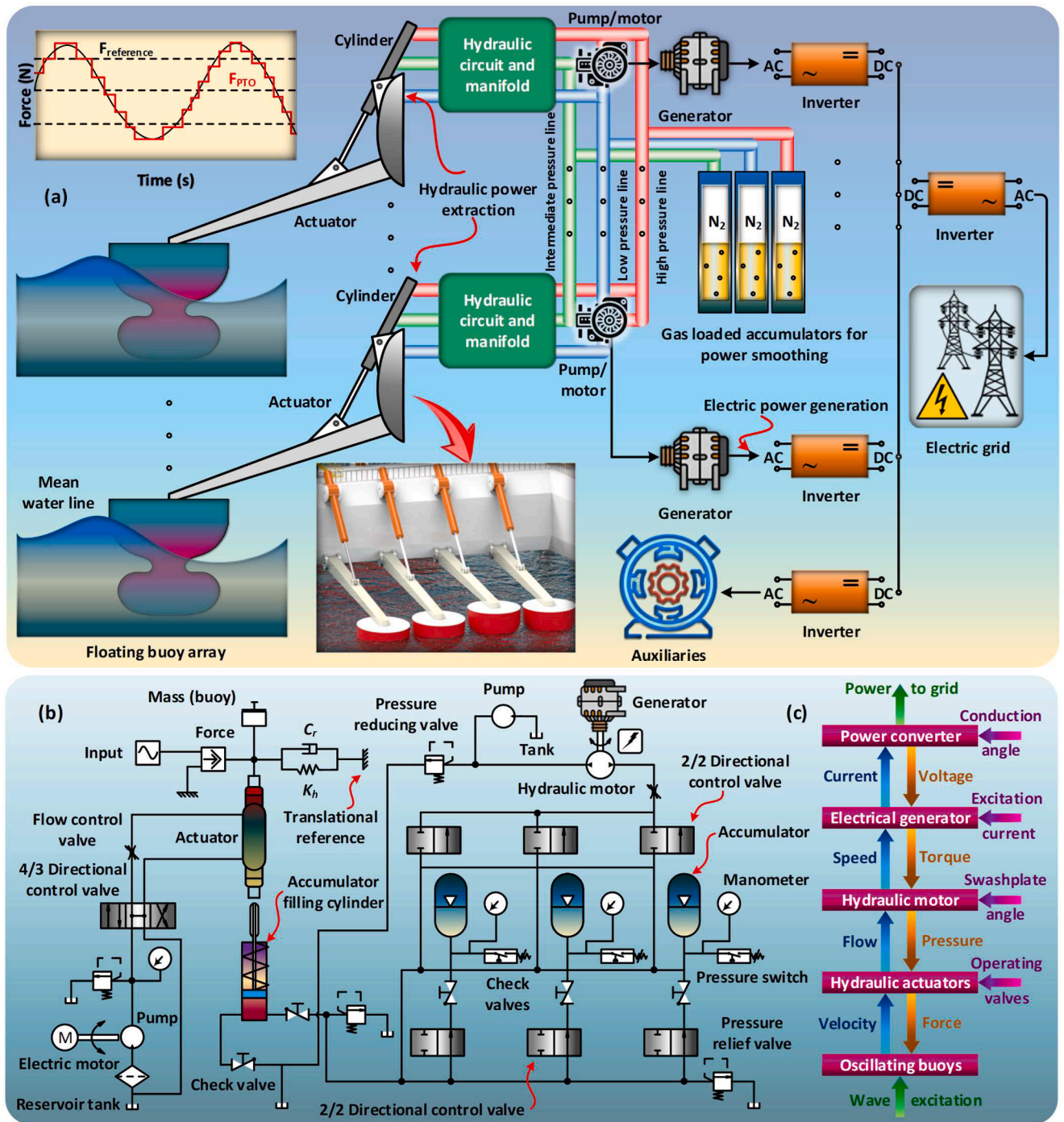


Fig. 9. (a) Schematic of a hydraulic PTO integrated with a buoy, (b) simplified hydraulic circuit of the PTO, and (c) the potential control inputs.

compare the hemispherical and BB buoys, as shown in Fig. 8. Efforts were made to investigate the effects of replacing buoys on P_{abs} and C_w of the WEC model.

A PTO based on a hydraulic actuator coupled with an electrical generator is shown in Fig. 9(a). The actuator consists of a cylinder and a piston or rod, which the floating buoy forces to oscillate inside the cylinder. A double-acting reciprocating pump develops a pressurized flow because of wave-to-floater energy transfer. The cylinder has two chambers with rectifying valves to attain a unidirectional flow directed to the high-pressure gas accumulator. A radial-piston motor is directly coupled to the electrical generator. The generator rotor spins inside the magnetic field, and electricity is generated. The generator and actuator

losses include mechanical friction, viscous losses, generator rotor inertia, and electrical/mechanical damping.

After running the motor, the fluid is transferred to a low-pressure chamber where the accumulator slightly pressurizes it to help prevent damage to the system caused by cavitation. This fluid is then moved to the actuator, where it is pressurized again to complete the cycle. A simplified hydraulic circuit of the hydraulic PTO is shown in Fig. 9(b) based on a unit in (Khalfan and Imrek, 2015). The cycle starts with the oscillating buoy represented by a mass-spring-damper system excited by an external force. The piston of the actuator is directly linked to the oscillator. The hydraulic oil flow inside the actuator is controlled by a 4/3 directional control valve and a hydraulic pump that receives the oil

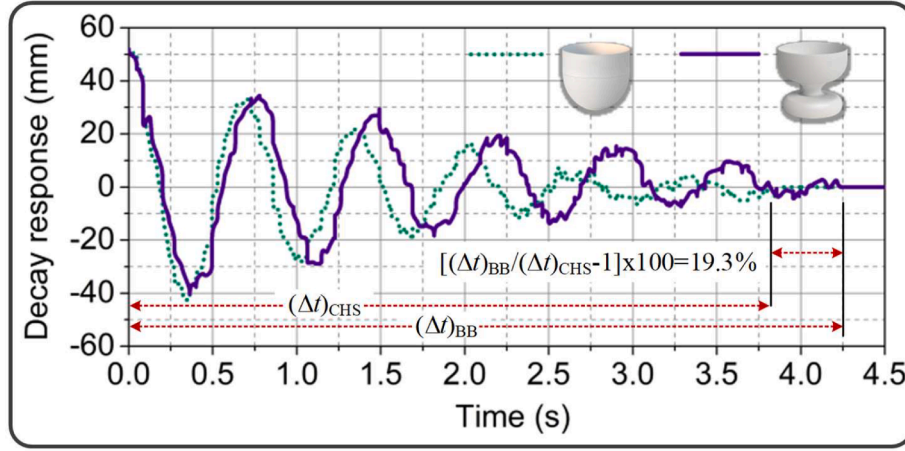


Fig. 10. Decay response of the CHS and the BB buoys.

from a reservoir. A relief valve is provided to adjust the maximum working pressure. The piston speed can be controlled with a flow control valve. The downward stroke of the piston presses the cylinder rod. A compression spring restores its position when the piston goes upward. It causes vacuum formation inside the cylinder, due to which the oil is sucked in from the reservoir. The oil is prevented from going back to the reservoir through a check valve. As a result of further piston strokes, the oil is driven into the accumulator after passing through the 2/2 directional control valves and check valves. The manometers and pressure switches are provided to measure and monitor the maximum operating pressure of the oil leading to the accumulator. The 2/2 directional control valves are controlled so that when the oil is pumped from the accumulators to the motor, the upper 2/2 directional valves are opened, and the lower 2/2 directional valves are closed. The flow control valve is provided to adjust the motor's rotational speed. Fig. 9(c) shows the hydraulic PTO components and the critical control inputs.

2.5.1. The assessment models

The maximum recorded hydraulic PTO efficiency (η_o ; that is the output electrical power (P_e) divided by hydraulic power (P_h)) of the Wavestar WEC is 60 % (Niels and Hansen, 2000). The WEC model under consideration uses buoys of $D=5$ m, with a single WEC unit's $C_{pto}=10$, 000 Ns/m (in accordance with (Ahmed et al., 2022)) and $\eta_o=55\%$. It can be assumed that the piston rod velocity (v) is the same as the buoy's velocity ($\dot{Z}$) (Sun et al., 2021) since they are directly coupled. The F_{pto} can be estimated from (Sun et al., 2021),

$$F_{pto} = (-\text{sign}(v)) \cdot (p_h - p_l) A_p \quad (15)$$

The maximum and minimum pressures in the actuator are represented by p_h and p_l , respectively; A_p is the cylinder's internal cross-sectional area. The mean hydraulic power that the WEC absorbs is given by (Sun et al., 2021),

$$P_h = F_{pto} \cdot v = (-\text{sign}(v)) \cdot (p_h - p_l) A_p v \quad (16)$$

The output power P_e can be calculated from the following relation,

$$P_e = \eta_o P_h \quad (17)$$

where η_o can be given as

$$\eta_o = \eta_h \cdot \eta_m \cdot \eta_g \cdot \eta_e \quad (18)$$

where η_h is the efficiency of the hydraulic actuator, accounting for all the losses related to the fluid flow inside the valves, tubes, and accumulators, η_g is the generator efficiency, η_m is the hydraulic motor/pump efficiency and η_e accounts for the electrical losses. The η_o was selected to be 55 % in the current study. The volume flow rate inside the actuator

(Q_a) is given by,

$$Q_a = A_p v \quad (19)$$

The angular acceleration of the motor (α_m) is given by (Sun et al., 2021),

$$\alpha_m = \frac{(p_h - p_l) \cdot \beta d_m - T_g - T_f}{I} \quad (20)$$

where β is the swashplate angle, d_m is the motor's nominal displacement volume, T_g is the generator torque, T_f is the torque used to overcome the frictional losses, and I is the overall MOI of the rotary equipment. The damping losses in the generator can be estimated by (Sun et al., 2021),

$$C_g = \frac{(P_h - P_l) \cdot \beta d_m \cdot \omega_m}{\omega_d} \cdot (0.95) \quad (21)$$

where C_g is the generator damping, ω_d is the required generator speed. The factor 0.95 is introduced as mechanical efficiency (Sun et al., 2021).

3. Results and discussion

The results of the wave tank tests under regular and irregular waves were discussed separately to develop a similarity analysis. Then, the buoys used in the case study were compared.

3.1. Experimental study in the wave flume

This section elaborates on the outcomes of the experimental research performed in the wave tank.

3.1.1. Decay tests

Free decay tests were conducted by manually pushing the buoys downward in such a way that the buoys were completely submerged with only the lid left unsubmerged. The buoys were then released to restore their original equilibrium position. The conclusions of the decay tests are shown in Fig. 10. The C—HS and BB buoys exhibited almost similar peaks right after the buoys were released to oscillate freely in the free decay tests. However, the BB buoy attained greater peaks in the subsequent wave cycles. A parameter named “free decay period (Δt)” was introduced to characterize the hydrodynamics of the C—HS and BB buoys. The free decay period is the duration between the moments, t_m and t_o , where t_m is the moment when the buoys start oscillating freely upon releasing after a manual push along the vertical direction and t_o is the moment when the instantaneous displacement of the freely oscillating buoy approaches zero. The free decay period of the BB buoy was approximately 19.3 % longer than the C—HS buoy. Overall, the BB buoy showed a better heave response for a longer time than the C—HS buoy.

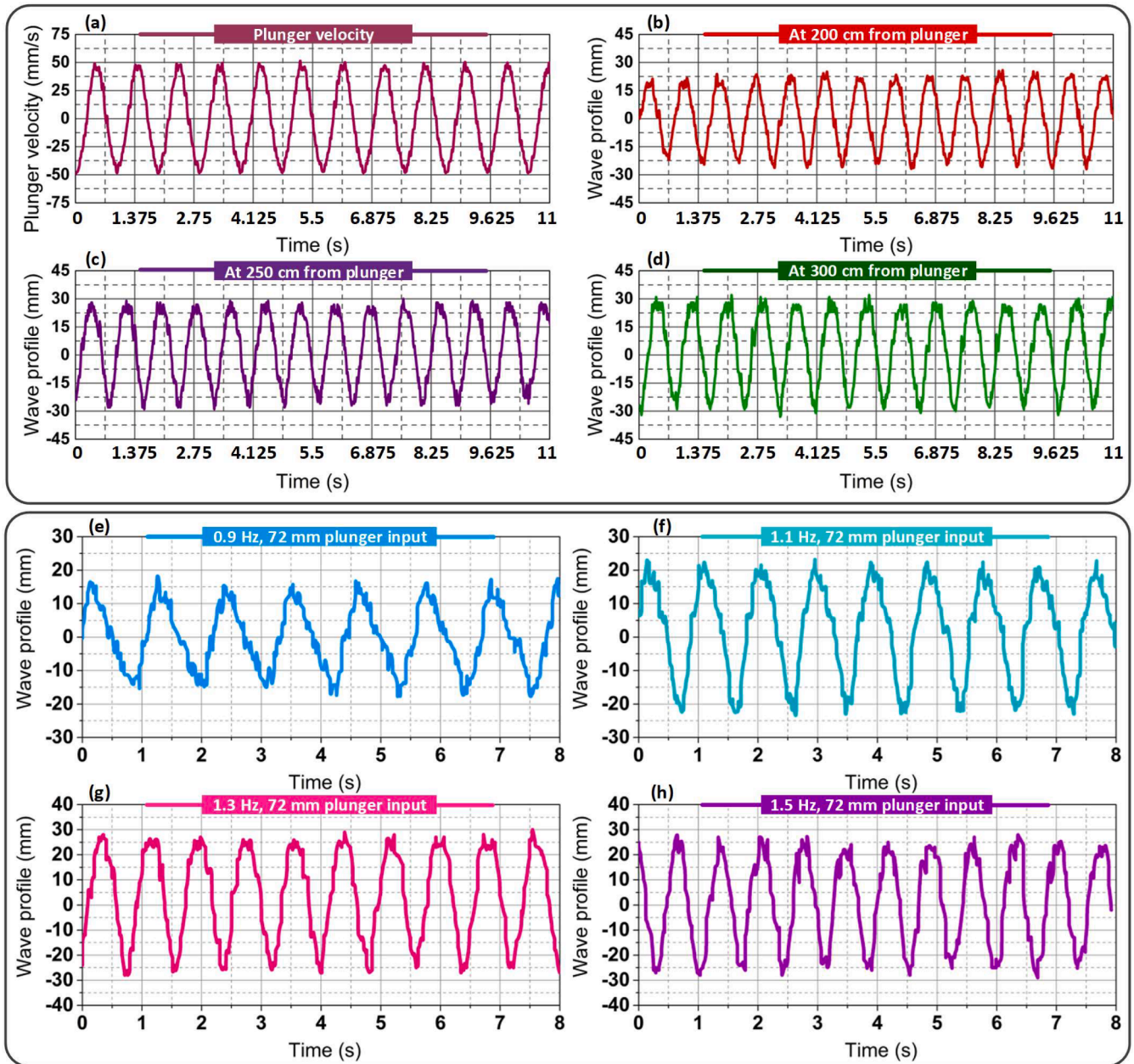


Fig. 11. (a) Plunger velocity, (b-d) wave development at (A) 2 m, (B) 2.5 m and (C) 3 m away from the wave generator. (e-h) wave profiles at a 2.5 m distance from the wave generator at various input frequencies and a fixed total plunger displacement of 72 mm.

3.1.2. Wave development

A wave development study was conducted to find the optimal position for installing buoys in the wave tank. Therefore, the wave surface elevation was measured at various locations in the tank. Fig. 11(a) shows the speed of the wave plunger and Fig. 11(b-d) show the wave profiles at three different locations marked at the following distances from the wave generator: (A) 2 m, (B) 2.5 m and (C) 3 m. The wave is not fully developed; rather, it develops between (A) and (B), whereas it is fully developed between (B) and (C). The wave amplitude is almost constant at (B) and (C), indicating that the buoys can be installed between these locations.

Fig. 11 (e-h) illustrates the effects of adjusting the plunger's input frequency while maintaining a constant total plunger displacement of 72 mm. Wave profiles were recorded at a distance of 2.5 m from the wave generator. In the lower-frequency range (0.9 – 1.1 Hz), the wave height is not constant and shows variation across the scenarios considered. In

contrast, in the higher-frequency range (1.3 – 1.5 Hz), the wave height is relatively well-developed and stabilizes in proportion to the plunger displacement. It can also be observed that the wave amplitude remains below 30 mm compared to the plunger's amplitude of 36 mm.

3.1.3. Tests in regular waves

The photographs of the heaving C—HS and BB scaled models tested without damper in the waves of 0.08 m height and 1.28 Hz frequency are presented in Fig. 12.

Fig. 13 presents the heave motions of the buoys with $(C_{pto})_{eq}$ deployed in regular waves (0.04 m amplitude and 1.28 Hz frequency) (that is $\omega/\omega_n \cong 1$) according to the settings in Table 2. The plunger's total displacement was recorded to be ~ 80 mm, as plotted in Fig. 13(a). The experimentally recorded and simulated wave surface elevation is plotted against time in Fig. 13(b). A comparison of Fig. 13(c) and (d) shows that the BB buoy exhibits a maximum total displacement of 75

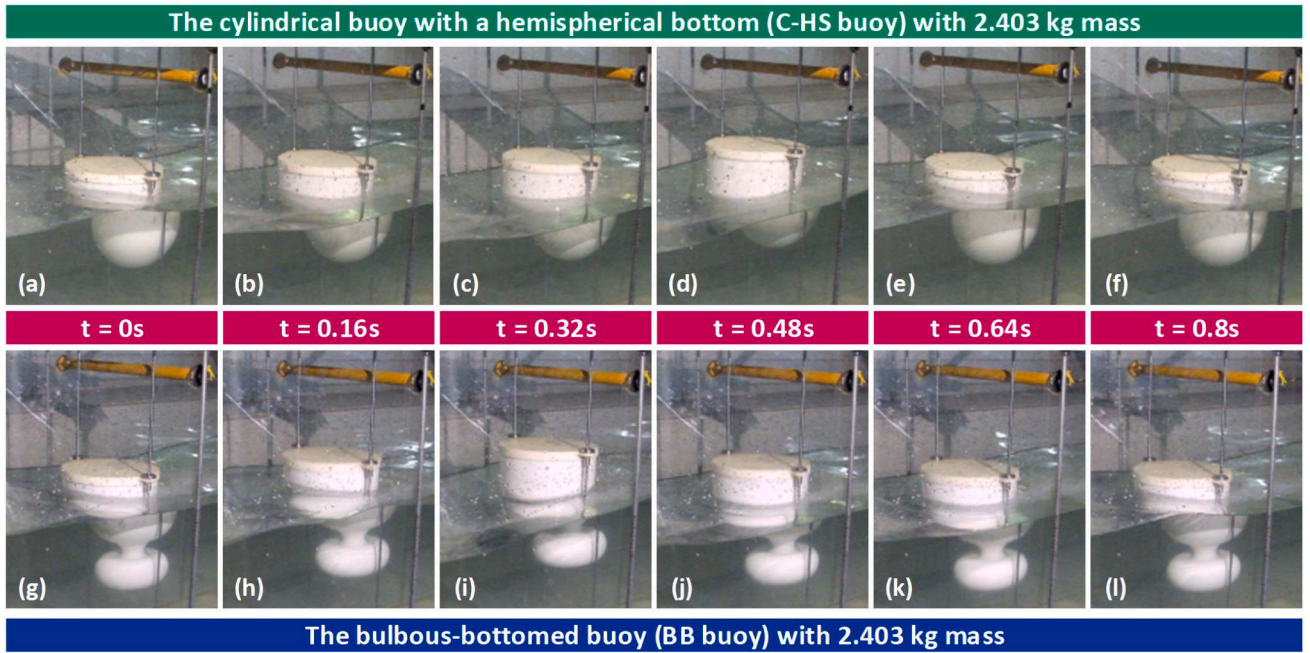


Fig. 12. Heave motion of (a-f) the C—HS and (g-l) the BB buoys in regular waves.

mm, which was ~ 60 mm for the C—HS. Under $\omega/\omega_n \cong 1$ condition, the BB gains 25 % greater heave response than the C—HS. Fig. 13(e) and (f) show that the BB heave velocity is 33 % higher than the C—HS.

The simulations in ANSYS AQWA are also plotted with the experimental results, and their close fitting significantly verifies their authenticity. The following reasons can justify the error between the experimental and computed responses:

- Although lube oil was used, the unavoidable frictional losses in the heave mechanism could cause disruptions in the buoy motion.
- Despite the smoothly surfaced and tightly clamped heave rods, there could be unpredicted tolerances when the components were assembled and deployed, interrupting the heave profile.
- The ultrasonic level detector gets numerous recordings in under a second, and some errors are introduced during the processing and filtering of the results, causing a roughly profiled heave response.

The buoys' peak and RMS RAOs were calculated for the tests conducted with and without adding mass inside the buoys, as shown in Table 4. The BB profile exhibited 44.4 % and 36.3 % greater RMS and peak RAOs compared to the C—HS when d was achieved by gaining the required M of the buoys. The corresponding increments are 11.2 % and 16.98 %, respectively, when there is no mass inside the buoys and the draft is significantly smaller (only 1 – 1.5 cm) than the required d . The higher percentage of increase in RAOs when the buoys have attained the necessary d can be attributed to the fully submerged profile of the buoys. Here is when the effects of changing buoy geometry come into action. At smaller d , a considerable portion of the buoy's significant profile remains above water, and the pure effects of changing buoy geometry are not apparent. These findings are in accordance with the simulation study conducted in (Ahmed et al., 2023).

To further investigate the buoys in the conditions when there is no resonance, the experiments were repeated with the following frequencies: (i) $0.836\omega_n$ (or $f=1.07$ Hz), (ii) $0.938\omega_n$ (or $f=1.2$ Hz) and (iii) $1.094\omega_n$ (or $f=1.4$ Hz), as shown in Fig. 14. It was witnessed that the BB buoy was characterized by a larger heave motion than the C—HS in all wave frequencies. The BB profile exhibited 25 %, 27 % and 20 % greater peak heave displacements than the C—HS at 1.07 Hz, 1.2 Hz and 1.4 Hz,

respectively. The significant enhancement in the buoy heave response as a result of its profile adjustment at frequencies other than ω_n justify that the BB profile could replace the conventional C—HS floaters for good.

3.1.4. Tests in irregular waves

Fig. 15 shows the irregular wave profile computed using the JONSWAP wave spectrum in ANSYS AQWA based on the wave characteristics mentioned in our previous study (Ahmed et al., 2022) and scaled through the method given in Section 2.2. The wave silhouette was simulated in the wave tank apparatus, and tests were run relatively longer to filter out the unstable response and get the stabilized buoy displacement as per the standards mentioned in (Azam et al., 2023).

Fig. 16 compares the heave displacements for the BB and C—HS profiles at three different motor speeds tested in irregular waves. The wave profile specified in Fig. 15 is calibrated to be $\nu = 0$ % (as it is), resulting in little or no heave displacement of the buoys. Then, motor speed was increased iteratively, getting the most stable heave responses at 12 %, 15 % and 18 %. A detailed comparison of the buoys in terms of RMS and peak responses is shown in Table 5. The maximum peak-to-peak heave displacements of the BB profile were 14.7 %, 6.5 % and 28.1 % greater than the C—HS at the speeds 1, 2 and 3, respectively. The RMS heave displacements of the BB profile, however, were 9.5 % and 13.6 % smaller than the C—HS profile at motor speeds 1 and 2, respectively, and 36.1 % greater than the C—HS at motor speed 3, which is clearly visible upon comparing Fig. 16(a-d).

3.2. The similarity analysis

The wave tank experiments were performed on the buoys scaled through Froude scaling. Therefore, a similarity analysis was performed to correlate the model and prototype scales and to approximate the power performance of the prototype-scale buoys. Reversing the Froude scaling and using the $\{D, M, V, \omega_n, C_{pto} = \text{constant}\}$ approach, we get the prototype-scale C—HS and BB floaters with $D=1.5$ m. Table 6 shows the scale factors calculated for the wave tank tests conducted in the current study.

The P_{abs} of the scaled buoys from regular waves can be calculated using the following relation (Azam et al., 2022),

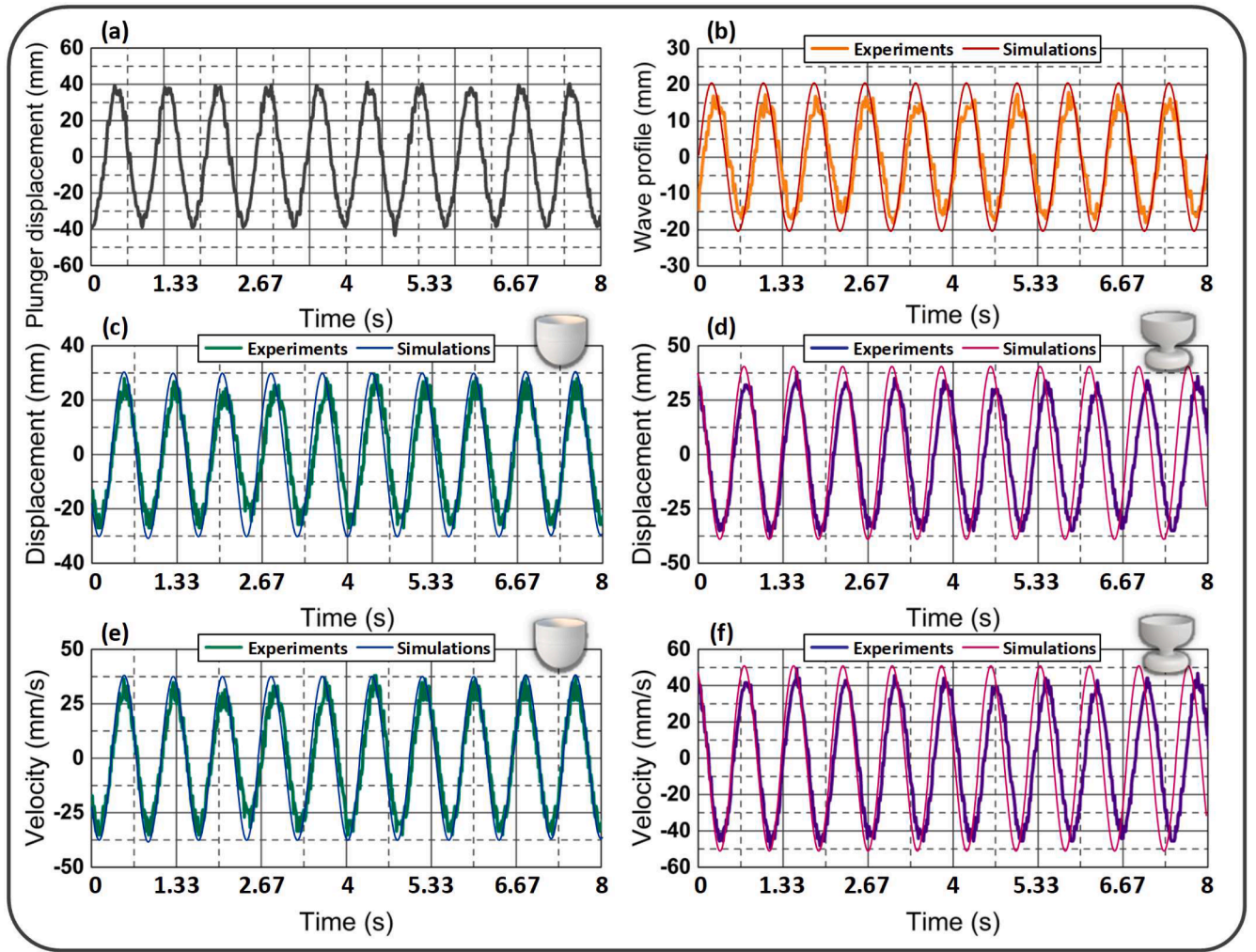


Fig. 13. (a) Plunger displacement (b) wave surface elevation (c) C—HS displacement (d) BB displacement (e) C—HS heave velocity (f) BB heave velocity (tested in 0.04 m amplitude and 1.28 Hz frequency waves ($\omega/\omega_n \cong 1$)).

Table 4
Experimentally calculated RAOs of the buoys.

Test case	With no mass inside ($d =$ negligible)		With mass inside ($d =$ required)	
	Peak RAO (m/m)	RMS RAO (m/m)	Peak RAO (m/m)	RMS RAO (m/m)
The C—HS profile	1.06	1.08	1.52	1.35
The BB profile	1.24	1.201	2.072	1.95
$\Delta(\%) = (RAO_{BB}/RAO_{CHS} - 1) \times 100$	16.98 % $\uparrow$	11.2 % $\uparrow$	36.3 % $\uparrow$	44.4 % $\uparrow$

$$P_{abs} = 0.5(C_{pto})_{eq}\omega^2 Z^2 \quad (22)$$

The P_{abs} of the scaled buoys during the regular wave tests were numerically calculated and plotted in Fig. 17 in terms of their instantaneous and RMS components. The peak and RMS P_{abs} were recorded to be 0.072 W and 0.033 W for the BB profile and 0.043 W and ~ 0.019 W for the C—HS profile, with 67.4 % and 73.6 % increments for the BB profile compared to the C—HS one, respectively.

The design and operating parameters were evaluated from the Froude scale factors on the model and prototype scales, as given in Table 7. If a prototype-scale C—HS buoy of $D=1.5$ m could attain an RMS P_{abs} of 31.1 W and an RMS heave displacement of 0.467 m in a wave of $\omega=2.72$ rad/s and $H=0.33$ m at a C_{pto} of ~ 310 Ns/m, then the

BB buoy of the same size would attain an RMS P_{abs} of 55.3 W and an RMS heave displacement of 0.667 m in the same wave at the same C_{pto} . The same calculations extended to the tests at no resonance and in irregular waves clearly show that the BB profile is notably more proficient than the C—HS for wave energy extraction. These findings are in accordance with the simulation-based investigation conducted in (Ahmed et al., 2022).

3.3. The case study

The WEC model proposed in Section 2.5 was computed for the buoys using the mathematical assessment model of the hydraulic PTO and the computational model given in Section 2.4. It is worth mentioning here that only a single WEC unit consisting of a hydraulic PTO integrated into a buoy was studied instead of investigating the whole WEC array in Fig. 8. Time-domain analysis was performed in ANSYS AQWA to attain the structure forces and velocities over a range of waves. The case was solved with the reference and BB buoys of $D=5$ m and PTO of $C_{pto}=10,000$ Ns/m, considering the irregular waves defined by $H_s \in \{0.5\text{ m} - 3\text{ m}\}$ and specified by the JONSWAP spectrum in ANSYS AQWA according to the methodology specified in (Ahmed et al., 2022). The hydraulic PTO characteristics were evaluated with the C—HS and BB buoys and plotted against H_s , as shown in Fig. 18.

The F_{pto} delivered to the PTO by the BB profile was greater than by the hemispherical one across all waves, with a maximum increment of

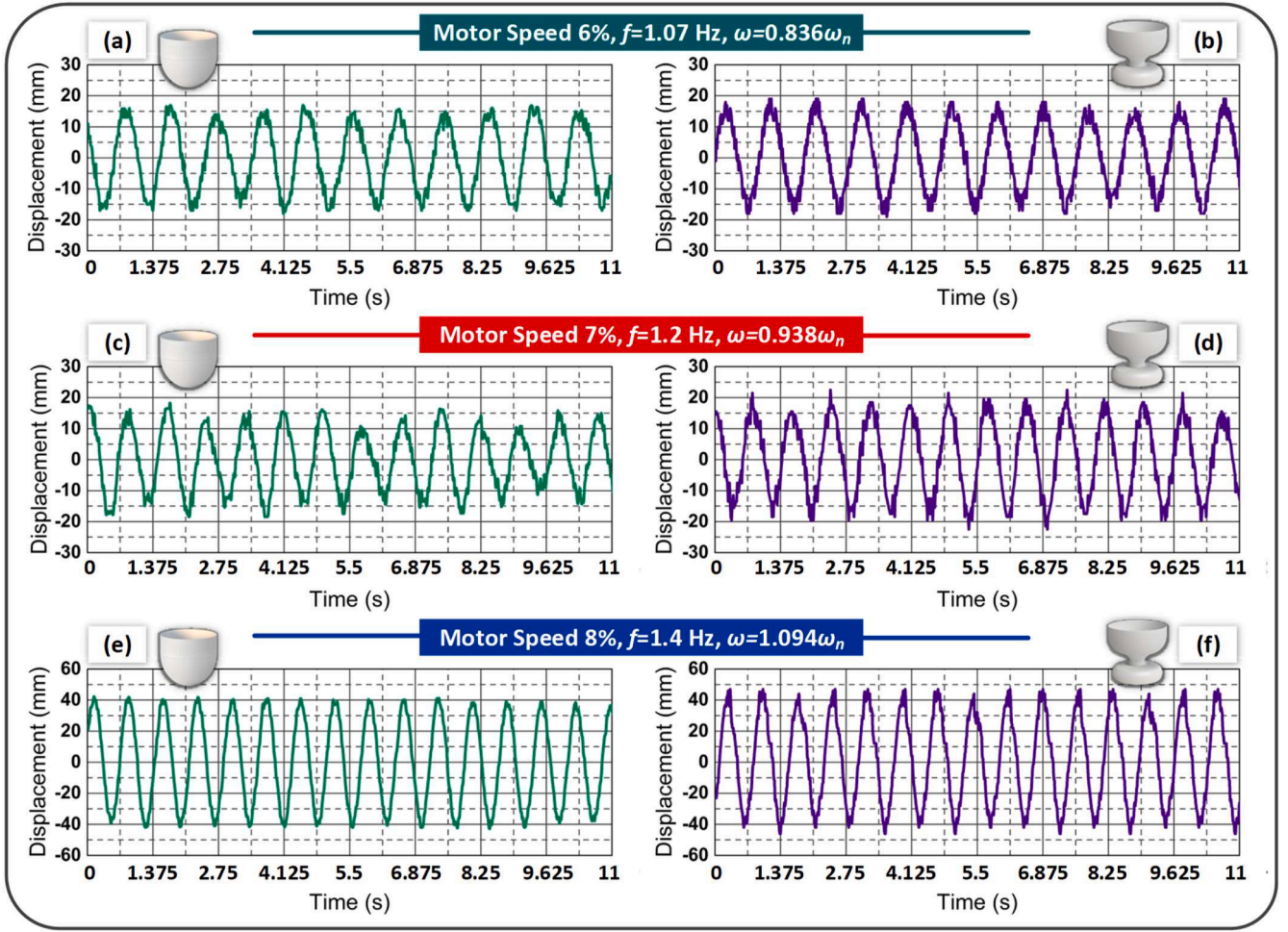


Fig. 14. Analysis in regular waves at frequencies other than ω_n : (a, c, e) the C—HS and (b, d, f) the BB profiles.

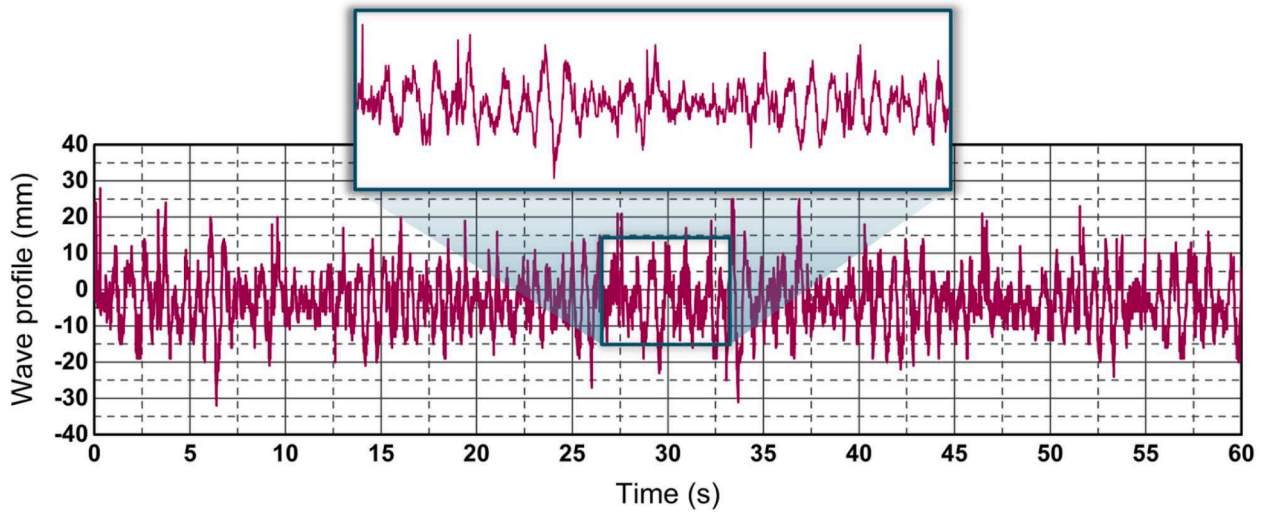


Fig. 15. Irregular wave profile.

14 % in F_{pto} due to the BB profile, as shown in Fig. 18(a). The BB buoy can facilitate using a larger electrical generator (with a 12.5 % greater C_g on average, Fig. 18(b)). The pressure difference ($p_h - p_l$) attainable across the hydraulic cylinders of various piston cross-sectional areas $A_p \in \{0.02\text{m}^2 - 0.2\text{m}^2\}$ is represented in the contour graphs in Fig. 18(c, d) with both buoy profiles across $H_s \in \{0.5\text{m} - 3\text{m}\}$. The hydraulic PTO

integrated with the BB buoy could achieve 14 – 24 % greater $p_h - p_l$ than with the C—HS buoy across all waves.

The performance characteristics, including P_h , P_e and C_w of the proposed WEC with the specified buoys are shown in Fig. 19. It can be noticed that the WEC with the BB floater achieved a significantly greater peak and RMS P_h than with the hemispherical buoy in all waves.

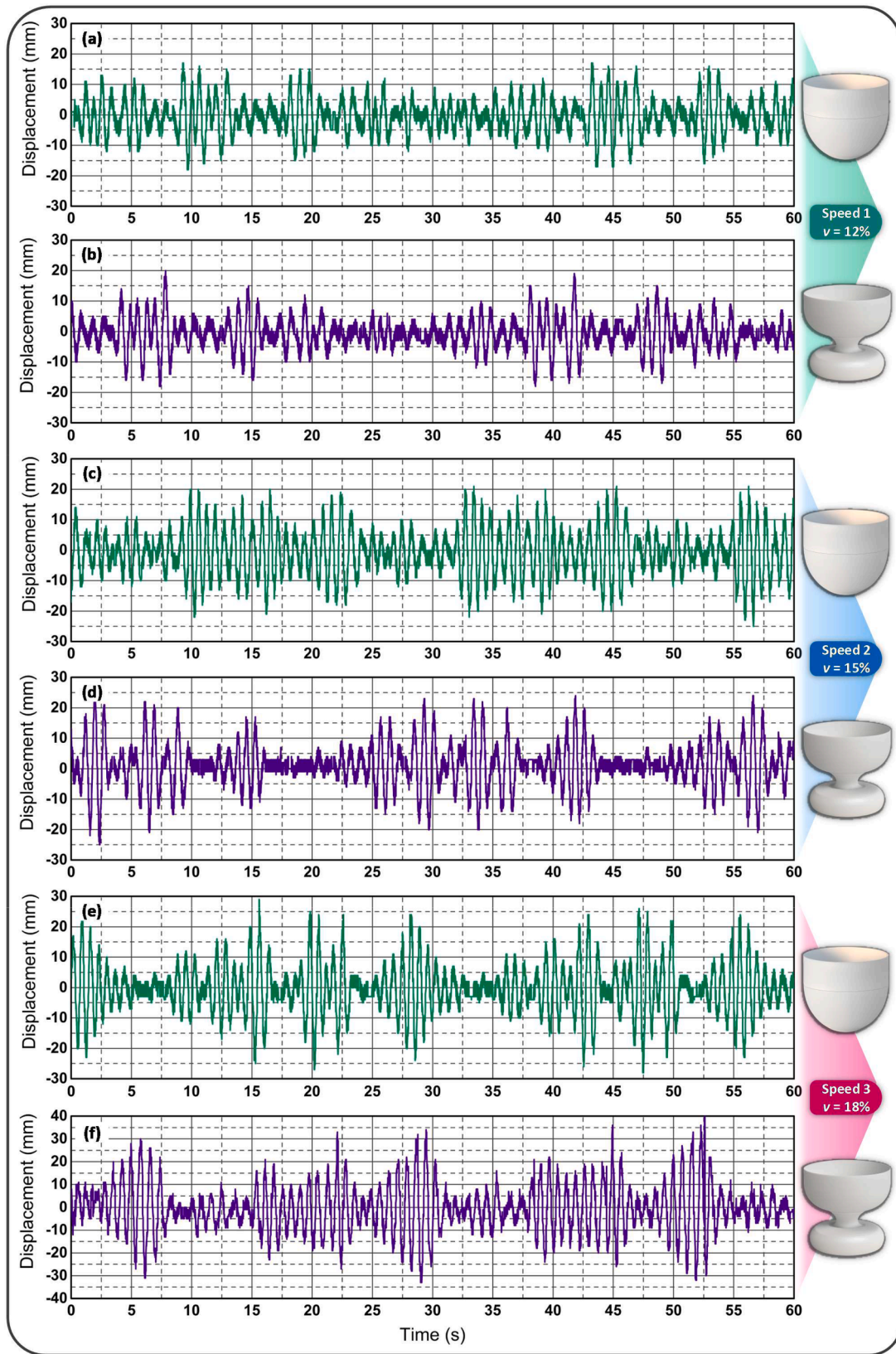


Fig. 16. Buoy heave responses in irregular waves at three different speeds.

Considering $\eta_o=55\%$, the maximum increase in the peak and RMS P_e due to the BB floaters was observed to be 23.2 % and 32.4 %, respectively. The corresponding increment was 41.8 % and 35 %, respectively, in the peak and RMS C_w . It is worth mentioning that the increase in P_h

and P_e caused by changing buoy shapes is maximum at higher H_s , whereas the C_w experiences the highest increments in its peak and RMS values at $H_s=1.5$ m. Beyond $H_s=1.5$ m, the RMS C_w drops significantly, and the peak C_w is reduced slightly for the BB profile. The C_w in the case

Table 5
Irregular wave test results (C—HS as a reference).

Test case	Response at Speed 1 (mm)		Response at Speed 2 (mm)		Response at Speed 3 (mm)	
	RMS	Peak-to-peak (max)	RMS	Peak-to-peak (max)	RMS	Peak-to-peak (max)
The C—HS profile	6.11	34	8.71	46	8.03	57
The BB profile	5.53	39	7.52	49	10.93	73
$\Delta(\%)$	↓9.5 %	↑14.7 %	↓13.6 %	↑6.5 %	↑36.1 %	↑28.1 %

Table 6
Scale factors for the similarity analysis.

Scale factors	n_D	n_t	n_v	n_F	n_p	n_C
Magnitude	0.12	0.34641	0.34641	1.728×10^{-3}	5.98597×10^{-4}	4.988×10^{-3}

of C—HS, remains unchanged across $H_s \in \{0.5\text{m} - 3\text{m}\}$. Considering Figs. 18 and 19, it can be summarized that the BB profile could be a favourable replacement for the hemispherical buoy for wave energy extraction.

3.4. Application potential of the BB-assisted WEC

3.4.1. Smart floating cities

Smart floating cities have recently been proposed as a sustainable solution, and various projects have been anticipated for the coastal areas facing land shortages and rising sea levels (Kurniawan et al., 2024; Wright, 2023). The OCEANIX Busan and Maldives Floating City (Varga and Csiszárík-Kocsir, 2023) are breakthrough initiatives incorporating sustainable features such as water treatment, smart farms, smart transportation and renewable energy systems. These projects will be constructed on floating platforms adaptable to rising sea levels and provide housing to climate refugees. However, their feasibility in international waters is still unclear due to the challenges related to legality, power supply, construction modularity, supply and waste management, community-based development, mooring and stability, environmental impact, flexibility, defence and law enforcement (Pereira et al., 2023). The concept of a futuristic smart floating city, along with its modular design, is shown in Fig. 20, and the WEC proposed in the case study combined with a 5G-IoT network can facilitate marine renewable energy supply and self-powered coverage and monitoring of the floating fish farms, law enforcement, navigation and surveillance for and around the floating city. The applicability assessment of the proposed WEC concept is conducted in the subsequent section.

3.4.2. The LSTM-based self-sensing & self-powered sea monitoring

The long short-term memory (LSTM) is a neural network (RNN) model that is widely used in predicting real-time environmental conditions using the models trained based on previously recorded datasets (He et al., 2024). The wave conditions can be directly represented by the displacement-time series of the floating structures as input signals

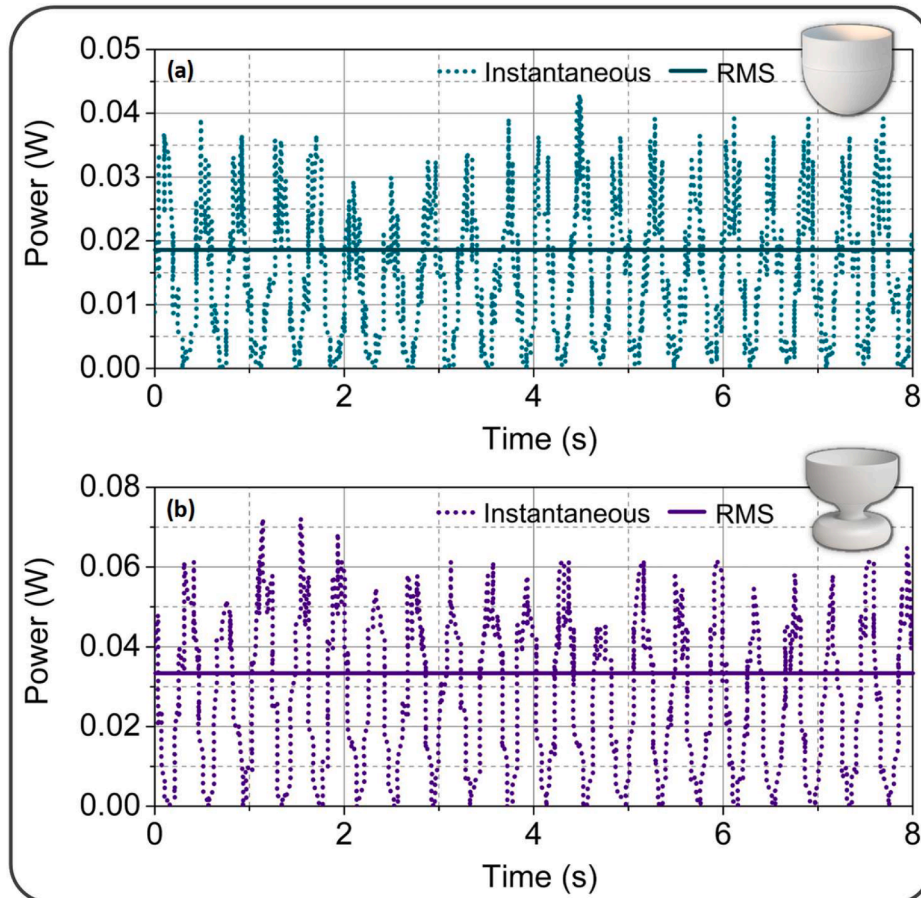


Fig. 17. Power absorption of the model-scale buoys during regular wave tests.

Table 7

The similarity analysis.

	$D(m)$	$d(m)$	$\omega_n(\text{rad/s})$	$H(m)$	$T(s)$	$\omega(\text{rad/s})$	C_{pto} (Ns/m)	RMS heave response (m)	RMS heave velocity (m/s)	RMS P_{abs} (W)
The CHS_m	0.18	0.1104	~ 8.09	0.04	0.8	7.85	1.548	0.056	0.075	0.0186
The CHS_p	1.5	1.137	~ 1.9	0.333	2.31	2.72	~ 310	0.467	0.217	31.1
The BB_m	0.18	0.1399	~ 8.09	0.04	0.8	7.85	1.548	0.08	0.1	0.0331
The BB_p	1.5	1.46	~ 1.9	0.333	2.31	2.72	~ 310	0.667	0.289	55.3

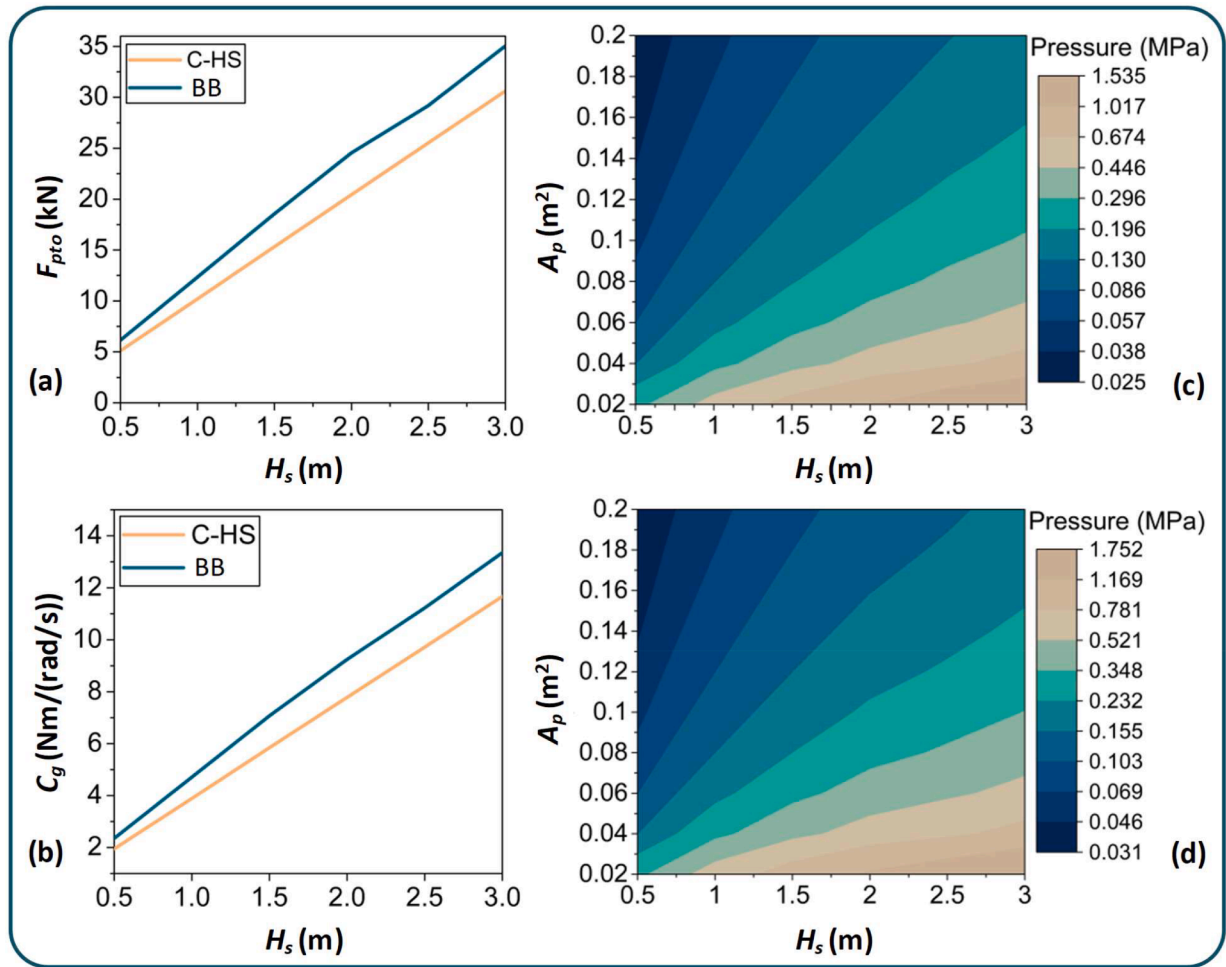


Fig. 18. Characteristics of the hydraulic PTO of $C_{pto}=10,000$ Ns/m integrated with the BB and C-HS buoys of $D=5$ m, (a) F_{pto} (kN) (b) C_g (Nm/(rad/s)) (c) $p_h - p_l$ with the C-HS buoy (d) $p_h - p_l$ with the BB buoy.

measured through displacement sensors installed in a WEC. Therefore, structure response can be used to distinguish calm and extreme sea states, using parameters such as wave height, wavelength, and wave period. The LSTM model can be used to collect, train and categorize the floater response data. The calm and extreme wave conditions can be identified with a predefined threshold for the selected marine site where WEC will be installed, enabling real-time self-sensing-based sea monitoring. The experimental method with the processing models for this is shown in Fig. 21.

Removing noise from the raw data through data filtering is crucial. The displacement signals are then sliced under normal and abnormal scenarios. The corresponding labels are attributed to the sliced data to enable supervised learning. Irrevocably, the sliced data is shuffled to optimize diversity. The displacement data is partitioned into 80 % and 20 % proportions for training and test sets, respectively. The data is used to train the LSTM model, followed by passing the data through the SoftMax activation function to obtain the final classification data. The

training accuracy and losses during the LSTM training process are shown in Fig. 21. A final accuracy of 99.3 % and a training loss of ~ 3.1 % were obtained for 100 iterations, and the accuracy and loss curves were demonstrated to be converged. The confusion matrix compares the classification results and actual measurements, and the accuracy evaluations are all greater than 95 %. It can be concluded that the LSTM-based algorithm can attain high accuracy and reliability in monitoring real-time wave conditions and marine environments.

3.4.3. The applicability assessment

Currently, the National Shallow Sea Comprehensive Test site (in the East China Sea) and Guangdong Wanshan Wave Energy Test site (in the South China Sea) are the two Chinese marine test sites for RD&D of wave energy devices, with the annual average significant wave heights (H_s) ranging over 0.4 m – 0.6 m and 0.8 m – 1.2 m, respectively (Ahmed et al., 2023; Qiu et al., 2019). The overall distributions of their annual average H_s and wave power density are provided in (Ahmed et al., 2022,

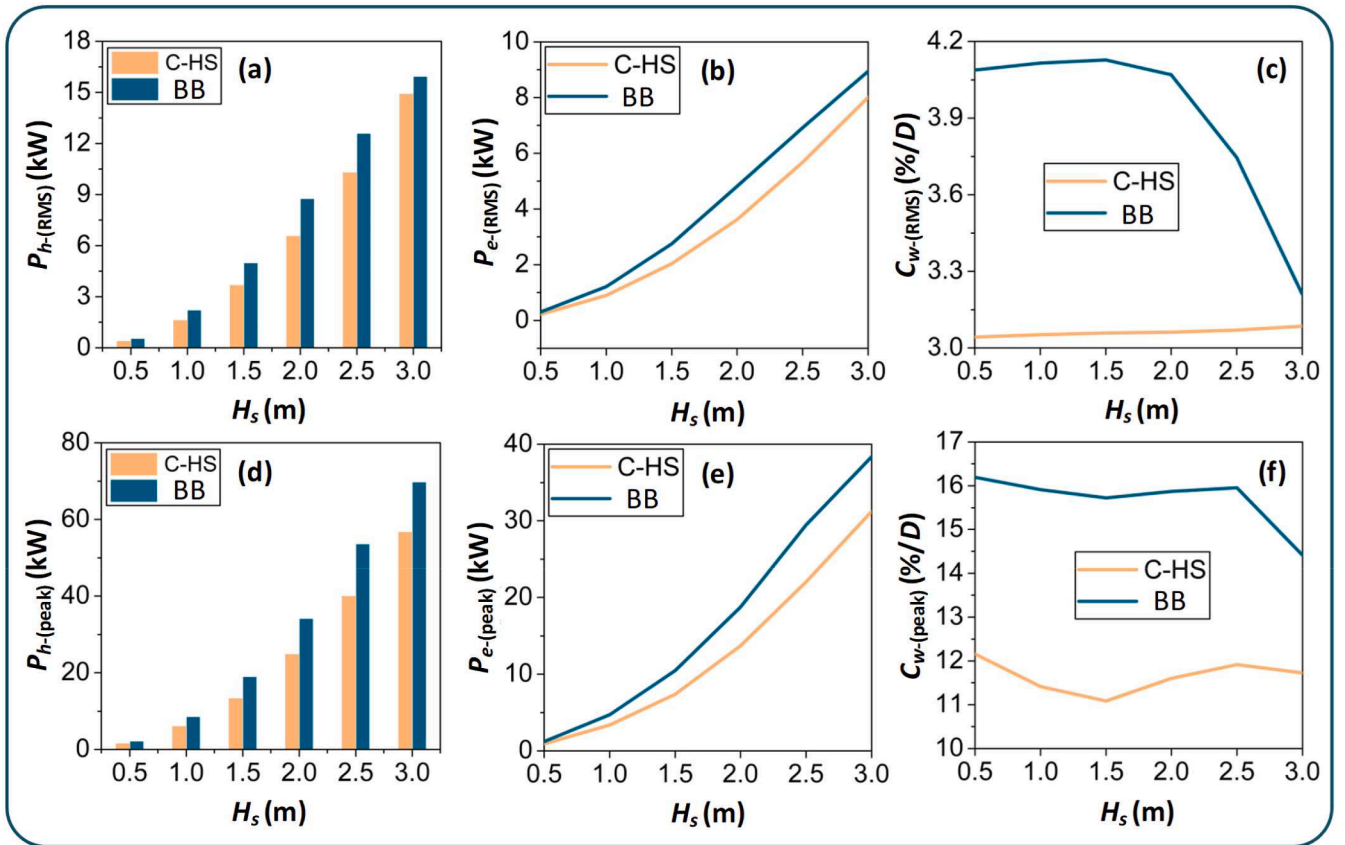


Fig. 19. Comparison of the C—HS and BB buoys in terms of (a-c) RMS values of P_h , P_e and C_w and (d-f) peak values of P_h , P_e and C_w in irregular waves.

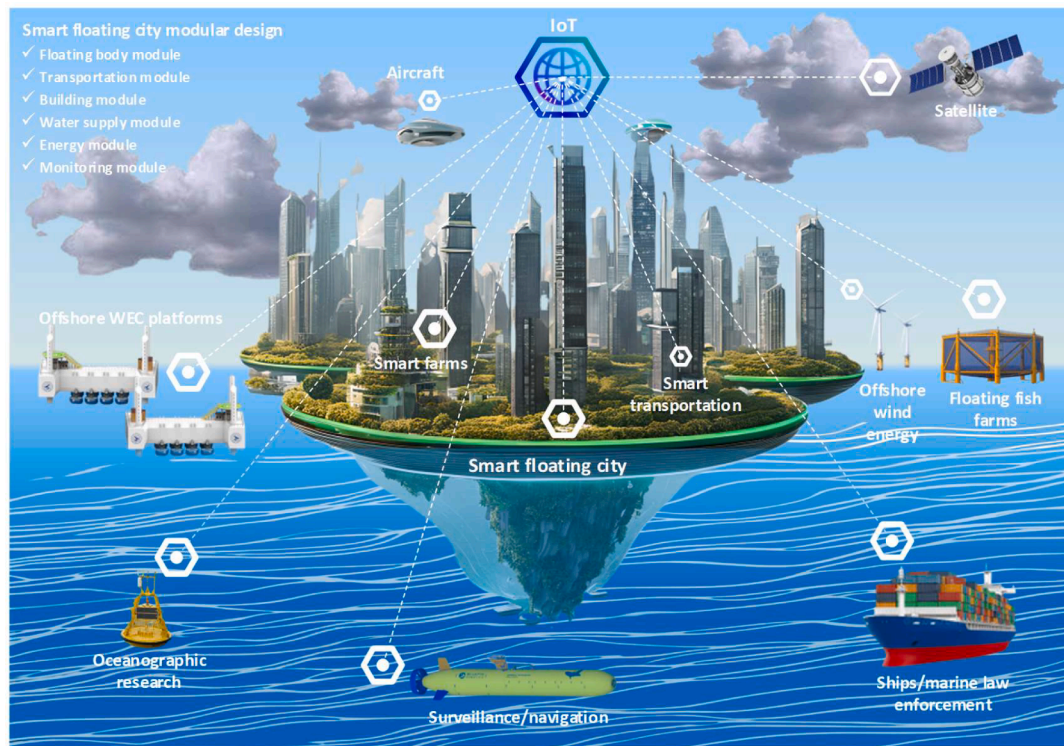


Fig. 20. The anticipated self-powered and self-sensing WEC applications in a futuristic smart floating city.

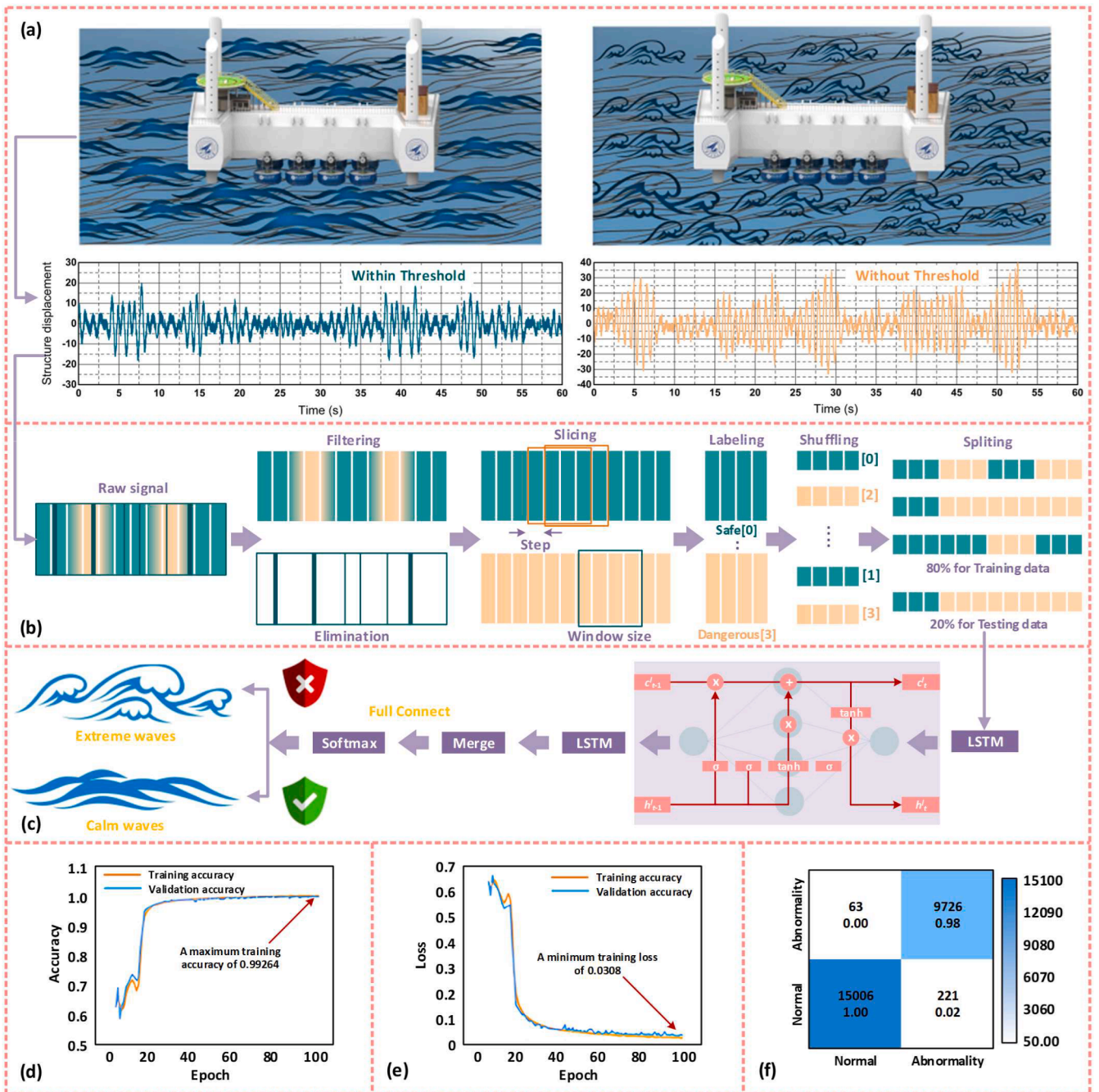


Fig. 21. The LSTM-based self-sensing & self-powered sea monitoring: (a) the floating structure response in calm and extreme waves, (b) pre-processing, (c) training of the LSTM, (d) training and test accuracy, (e) training and test loss, (f) the resultant confusion matrix.

2023b). The wave power matrix for a range of H_s and T_p available on these sites is shown in the form of a scatter diagram in Fig. 22.

Using the JONSWAP spectrum (Ahmed et al., 2022), the wave climate data was used to approach the realistic waves for these marine sites. Time-domain analyses were run in ANSYS AQWA in irregular waves for the BB floater proposed in the case study. The simulations were run long enough to get a stable response from the floater. The P_{abs} was evaluated and analyzed for the WEC by multiplying the F_e and $\dot{Z}$, as shown in Fig. 23. The RMS P_{abs} averaged over 200 s came out to be 0.56 kW and 4.93 kW for the National Shallow Sea Comprehensive Test site (in the East China Sea) and Guangdong Wanshan Wave Energy Test site (in the South China Sea), respectively. It is because the wave power density and H_s are significantly greater for the latter, justifying that the South China Sea will be a better option for deploying the specified WEC.

4. Outlines, confines and future perspectives

4.1. Outlines of the study

In conclusion, the current investigation can be covered by the following outlines:

- ✓ **Decay tests** – The C—HS and BB buoys exhibited almost similar peaks right after the buoys were released to oscillate freely in the free decay tests. However, the BB buoy attained greater peaks in the subsequent wave cycles. The free decay period of the BB buoy was approximately 19.3 % longer than the C—HS buoy. Overall, the BB buoy showed a better heave response for a longer time than the C—HS buoy.

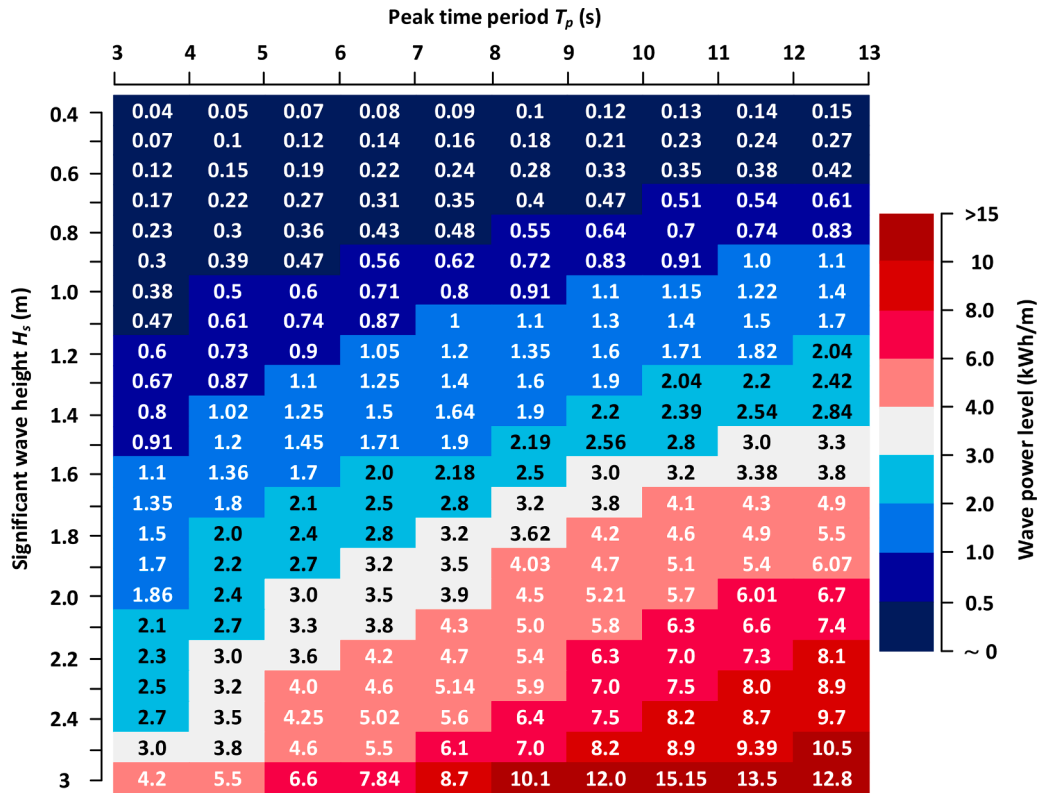


Fig. 22. Wave power matrix of the wave energy test sites in China.

- ✓ **Within resonance** – Within the $\omega/\omega_n \cong 1$ condition, the model-scale BB floater gains 25 % and 33 % greater heave response and velocity than the C—HS when the model-scale PTO damping was applied. The BB profile exhibited 44.4 % and 36.3 % greater RMS and peak RAOs than the C—HS when the operating draft and required mass were achieved in the regular wave tests.
- ✓ **Without resonance** – Without the $\omega/\omega_n \cong 1$ condition, the model-scale BB profile is characterized by a 20 – 27 % greater heave response than the C—HS in regular waves. The significant enhancement in the buoy heave response because of its profile adjustment at frequencies other than ω_n justify that the BB floater could replace the conventional C—HS floaters for good.
- ✓ **Irregular wave tests** – The maximum peak-to-peak heave displacements of the BB profile were 14.7 %, 6.5 % and 28.1 % greater than the C—HS at speeds 1, 2 and 3, respectively. The RMS heave displacements of the BB profile, however, were 9.5 % and 13.6 % smaller than the C—HS profile at motor speeds 1 and 2, respectively, and 36.1 % greater than the C—HS at motor speed 3.
- ✓ **The similarity study** – The similarity study showed that if a prototype-scale C—HS buoy could attain an RMS power absorption of 31.1 W and an RMS heave displacement of 0.467 m in a wave of 2.72 rad/s frequency and 0.33 m height at a PTO damping of ~ 310 Ns/m, then the BB buoy of the same size would attain an RMS power absorption of 55.3 W and an RMS heave displacement of 0.667 m in the same wave at the same PTO damping. The findings were in accordance with the previous studies.
- ✓ **The case study with a hydraulic PTO** – The case study showed that replacing a C—HS floater with a BB floater could result in 14 % and 14 – 24 % increments in the PTO forces and pressure difference in a hydraulic power take-off, 23.2 % increment in the generator's RMS output power and 35 % rise in the capture width ratio of a hydraulic WEC.
- ✓ **The applicability study** – The LSTM network, integrated into the WEC and trained with the structure response in various wave states,

can classify real-time wave states, henceforth enabling self-sensing and self-powered marine environmental monitoring.

4.2. Confines of the study

This study considered only the vertical wave motion while investigating the PA-WEC. In the simulations, the wave-structure interactions were accommodated by introducing a fixed structure above the floating buoy through the cylindrical and rigid joints, according to the methods elaborated in (Ahmed et al., 2023). During the experimental study, the deep water assumptions were expected to be fully achieved while presuming that simulated waves were thoroughly wasted in the damping region of the wave tank. The tolerances in measurements, manufacturing, fitting, and assembly of the investigational test platform and occasional water leakage in the wave tank were neglected. The measurements recorded by ultrasonic displacement sensors were scrutinized to exclude roughly recorded data during experiments. In the case study, only a single WEC (a hydraulic PTO with a buoy) was investigated instead of considering the whole WEC array. The case and applicability assessment study was conducted through simulations merely, and no experiments were performed on a prototype-scale hydraulic WEC.

4.3. Future recommendations

Other wave extraction modes, including pitch, surge and hybrid WEC motions, should also be considered in future investigations. The on-shore, off-shore and near-shore WEC devices need significant RD&D to advance the blue economy and renewable energy generation in China. Funding is required at the government and institutional levels to facilitate the full-scale RD&D of the ongoing WEC projects. The case study in this study can be extended to investigate the WEC arrays, their orientation, alignments, inter-buoy distance and their effects on overall WEC power performance.

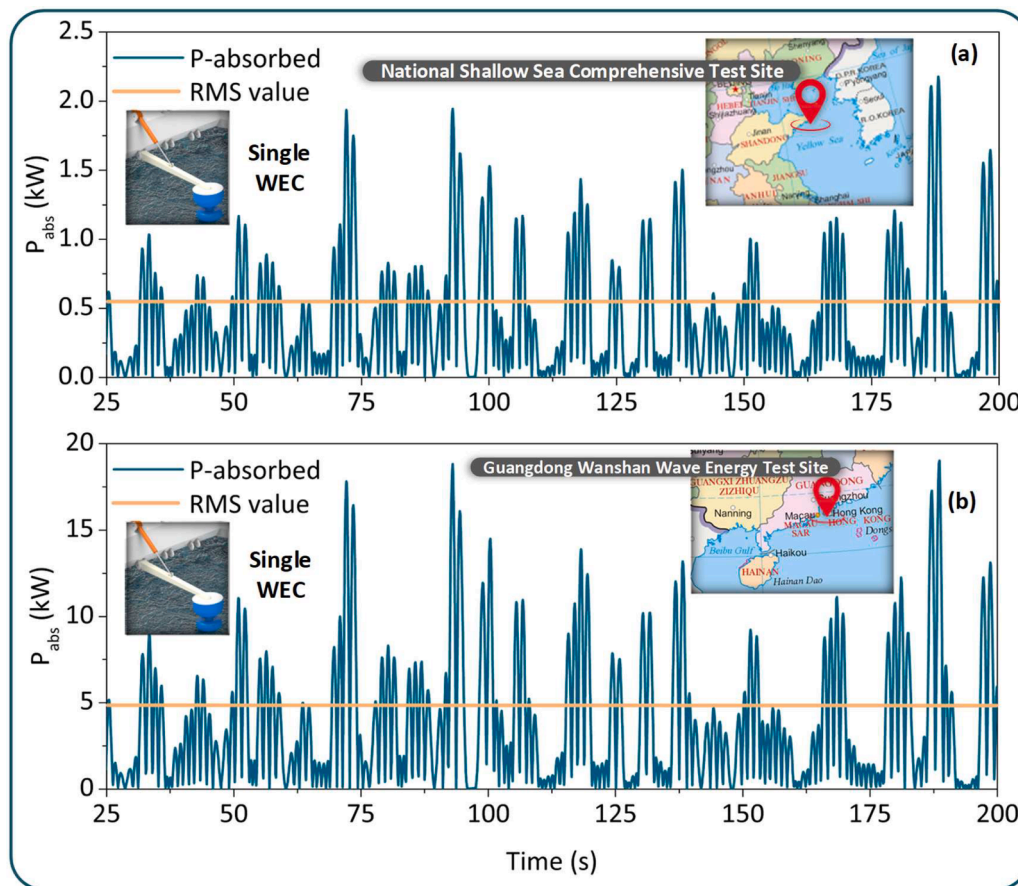


Fig. 23. The P_{abs} of the specified WEC with the BB floater (a) at the National Shallow Sea Comprehensive Test site (in the East China Sea) and (b) at the Guangdong Wanshan Wave Energy Test site (in the South China Sea).

CRediT authorship contribution statement

Ammar Ahmed: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Azam:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Investigation, Conceptualization. **Zutao Zhang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Minyi Yi:** Visualization, Software, Resources. **Touqeer Aslam:** Writing – review & editing, Visualization, Software, Resources. **Shoukat Ali Mugheri:** Writing – review & editing, Visualization, Software, Resources. **Danling Hao:** Writing – review & editing, Visualization. **Mansour Abdelrahman:** Writing – review & editing, Visualization. **Alaeldin M. Tairab:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.apor.2025.104485](https://doi.org/10.1016/j.apor.2025.104485).

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